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ORIGINAL ARTICLE

Characterization of GPS/GIOVE sensor stations in the CONGO network

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Abstract The Cooperative Network for GIOVE Observation (CONGO) is a global network of real-time capable multi-constellation GNSS receivers, which has been established by the German Aerospace Center (DLR) and the German Federal Agency for Cartography and Geodesy (BKG) as a test bed for experimentation with the new Galileo signals. The CONGO network employs a variety of different antennas and receivers which have become available for public use over the last 2 years. Following an overview of the network and the employed user equipment, the paper discusses the achieved GPS/GIOVE tracking performance. This includes a characterization of antenna gain patterns as well as receiver noise and multipath errors. Special attention is given to the discussion of inter-system biases. The nature and variation of these biases is illustrated based on a set of three different receivers operated in a zero-baseline configuration at the Wettzell site.

Keywords GIOVE · Multi-constellation GNSS · Antenna gain · Multipath · Inter-system biases · CONGO

Introduction

The Cooperative Network for GIOVE Observation (CONGO) has been established by the German Aerospace Center (DLR) and the German Federal Agency for Cartography and Geodesy (BKG) as an early test bed for experimentation with new GNSS signals (Montenbruck et al. 2009). Key aspects that distinguish CONGO from other GNSS networks include the capability of GIOVE (Galileo) signal tracking, its fully global coverage and the real-time capability. As of May 2010, CONGO comprises a total of ten different sites around the world. GIOVE satellites can simultaneously be observed from 2 to 3 CONGO stations for most of their orbit (Fig. 1).

A summary of CONGO network stations currently in use is provided in Table 1. Some stations are equipped with multiple receivers to support a better performance characterization and to assess receiver-specific aspects such as inter-system biases. Measurements from all receivers are streamed at a 1 Hz data rate via the NTRIP transport protocol (Weber et al. 2005) to a central server at BKG, Frankfurt, where they can be accessed by multiple concurrent users. A permanent CONGO data archive is hosted by Technische Universität München (TUM), where all data streams are received and decoded in real-time. Besides the original data transmitted by each receiver, RINEX 3 observation files (at 10 s sampling) and navigation files are generated and stored for off-line analyses on a daily basis. TUM, furthermore, generates daily orbit and clock products in SP3 format (Steigenberger et al. 2010).

Receivers and antennas

The CONGO network presently employs three different types of multi-frequency, multi-constellation receivers on a

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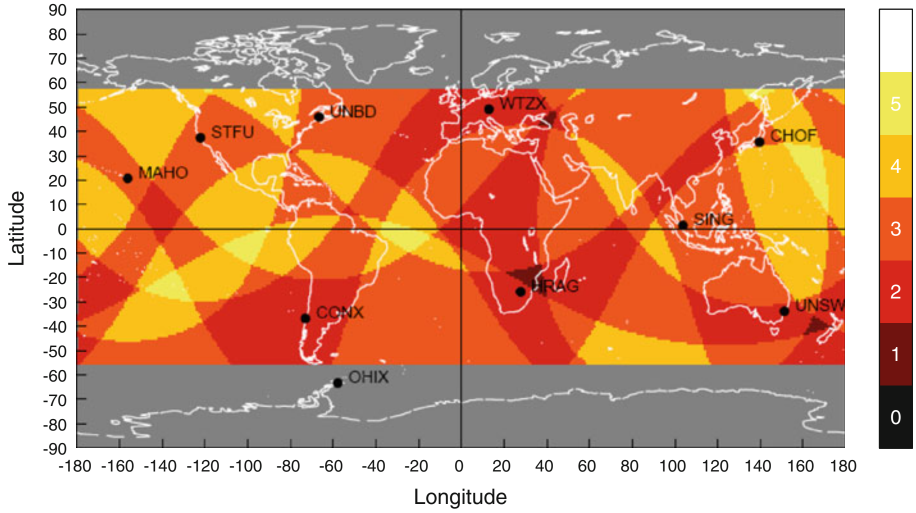

Fig. 1 Depth of coverage (DOC) for GIOVE observation with the CONGO network (10° elevation limit)

Table 1 Location and equipment of CONGO sites as of 1 May 2010. Stations and receivers are identified by their NTRIP mount point names

Name	Location	Long	Lat	Receiver	Antenna	Constellations
CHOF0	Chofu	+139.6°	+35.7°	Delta-G2T	Zephyr Geod. II	GPS + GAL + SBAS
CONX1	Concepcion	+287.0°	−36.8°	GeNeRx1	AX1203+	GPS + GAL
HRAG0	Hartebeesthoek	+27.7°	−25.9°	Delta-G2T	AR25R3	GPS + GAL + SBAS
MAHO0	Maui	−156.2°	+20.7°	Delta-G3TH	AR25R3	GPS + GLO + GAL + SBAS
OHIX0	O'Higgins	−57.9°	−63.3°	GRX1200	AR25R3	GPS + GLO + GAL + SBAS
SING0	Singapore	+103.6°	+1.4°	Delta-G2T	AX1203+	GPS + GAL + SBAS
STFU0	Stanford	−122.2°	37.4°	Delta-G3TH	Zephyr Geod. II	GPS + GLO + GAL + SBAS
UNBD0	Fredericton	+293.4°	+46.0°	Delta-G2T	Zephyr Geod. II	GPS + GAL + SBAS
UNSX1	Sydney	+151.2°	−33.4°	GeNeRx1	AX1203+	GPS + GAL
UNSX2				Delta-G3TH		GPS + GLO + GAL + SBAS
WTZX1	Wettzell	+12.9°	+49.1°	GeNeRx1	AR25R3	GPS + GAL
WTZX2				GRX1200		GPS + GLO + GAL + SBAS
WTZX3				Delta-G2T		GPS + GAL + SBAS

routine basis (Fig. 2, Table 2). All receivers support the tracking of the GPS legacy signals on the L1 and L2 frequency as well as the GIOVE open service signals on E1 and E5a. This enables a combined, dual-frequency processing of GPS and GIOVE observations using ionosphere-free, linear combinations of the respective.

The GeNeRx1 receiver is a commercially available version of the Galileo Experimental Test Receiver (GETR) developed by Septentrio for the Galileo Experimental Sensor Station (GESS) network of the European Space Agency (ESA) (Simsky et al. 2006; Spelat et al. 2006). For GIOVE tracking, a total of seven channels can be assigned to collect measurements for any of the ten E1, E5a, E5b or E6 signal components. In addition, a dedicated AltBOC channel is available for tracking the combined E5ab signal of a single satellite. Since the GeNeRx1 receivers in the CONGO network make use of an early firmware version, the E1 Open Service signal of GIOVE-B is always tracked in the legacy BOC(1,1) mode. The actual Composite BOC (CBOC) signal transmitted by GIOVE-B offers a better multipath performance for path delays beyond 25 m (Simsky et al. 2008) and is supported by more recent GeNeRx1 firmware versions.

The Javad Triumph Delta-G2T and -G3TH receivers, which form the backbone of the CONGO network, are part of a family of multi-frequency, multi-constellation receivers based on the Triumph ASIC. A total of 216 channels with up to 10 correlators and support of both shift register and memory codes enable all-in-view tracking of GPS, GLONASS (Delta-G3TH only), SBAS and GIOVE/Galileo satellites in the L1/E1, L2 and L5/E5a frequency bands. The GIOVE satellites are tracked with a combined tracking loop for the pilot and data component, and the E1 CBOC signal of GIOVE-B is tracked through a combination of BOC(1,1) and BOC(6,1) correlators. The Triumph receivers make use of an advanced, ultra-narrow correlator design, which offers a highly efficient multipath suppression and superior

Fig. 2 Multi-frequency multi-constellation GNSS receivers and wideband GNSS antennas used within the CONGO network. From *upper left* to *lower right*: Septentrio GeNeRx1, Javad Triumph Delta, Leica GRX1200+ GNSS, Leica AX1203+, Leica AR25r3, Trimble Zephyr Geodetic II

Table 2 CONGO GNSS receiver characteristics

Receiver	GNSS	Frequencies	Signals
Septentrio GeNeRx1	GPS	L1, L2	L1 C/A, L1 P(Y), L2 P(Y)
	GAL	E1, E5, E6	E1-A/B/C, E5a-I/Q, E5b-I/Q, E5-I/Q, E6-A/B/C
Javad Delta-G2T/G3TH	GPS	L1, L2, L5	L1 C/A, L1 P(Y), L2C, L2 P(Y), L5
	GLO	L1, L2	L1 C/A, L1 P, L2 C/A, L2 P (Delta-G3TH only)
	GAL	E1, E5a	E1-B&C, E5a-I&Q
	SBAS	L1, L5	L1, L5
Leica GRX1200+GNSS	GPS	L1, L2, L5	L1 C/A, L2C, L2 P(Y), L5
	GLO	L1, L2	L1 C/A, L1 P, L2 C/A, L2 P
	GAL	E1, E5	E1-B&C, E5a-I&Q, E5b-I&Q, E5-Q
	SBAS	L1, L5	L1, L5

robustness against signal reflections in the vicinity of the receiving antenna.

The GRX1200+GNSS receivers employed at BKG's Wettzell and O'Higgins stations represent Leica's latest model of tri-band, multi-constellation receivers for geodetic reference stations and surveying applications. Aside from the tracking of GPS, GLONASS and SBAS satellites, the measurement engine of the new receivers is specifically designed to support the new Galileo signals. For use within the CONGO network, a prototype firmware has been made available by the manufacturer that enables tracking of the GIOVE-A and -B satellites, but does not necessarily reflect the performance envisaged for the future Galileo constellation. For GIOVE (Galileo) satellites, the receivers offer tracking of the Open Service E1-B&C and E5a-I&Q as well as E5b-I&Q and E5ab AltBOC signal.

In the early deployment stage of the CONGO network, only a limited number of multi-band antennas supporting the full range of GPS and Galileo signal frequencies were offered by GNSS equipment manufacturers. Within the GIOVE pre-development program of ESA, a dedicated wideband antenna had been developed by Space Engineering, Italy, for the Galileo Experimental Sensor Stations. The same antenna was temporarily employed with BKG's and DLR's GeNeRx1 receivers. However, use of this antenna within the CONGO network was deprecated, because of systematic elevation and signal dependent group delay variations (Crisci et al. 2007; Giraud et al 2008).

Leica's AR25 chokering antenna was henceforth selected as a baseline for the CONGO network. The antenna features a wideband Dorne-Margolin element and a unique, 3-dimensional chokering that offers an increased gain at low elevations. Initial GIOVE tracking results, obtained in early 2009, revealed an excessive multipath sensitivity of the initial lots of AR25 antenna in the L5/E5a band. Based on extensive analysis and anechoic chamber tests conducted by the manufacturer, a modified design has been developed and validated in test campaigns of BKG and DLR at the Wettzell ground station. The revised version (AR25 rev.3), shown in Fig. 2, employs a supplementary insert for the innermost chokering element to improve the gain pattern and forward/backward ratio at the lower end of the GNSS frequency spectrum. The antenna now offers consistent multipath properties over the full range of frequencies and is presently in routine use at four CONGO stations.

The AX1203+ antenna used as a preliminary substitute for the AR25 chokering antenna is a highly compact antenna for surveying applications. It is based on NovAtel's pinwheel design (Kunysz 2001), which offers a good multipath and interference rejection despite the small form factor.

Finally, Trimble Zephyr Geodetic II antennas are used at three stations of the CONGO network. Like the aforementioned antennas, it supports the tracking of GPS, GLONASS, Galileo and SBAS signals over the full range of signal frequencies. It employs a larger ground plane than the pinwheel antenna and offers a particularly high gain of 50 dB, which facilitates remote installations without a need for intermediate amplification.

Signal strength

The carrier-to-noise density ratio (C/N_0) and its variation with elevation provide a key figure-of-merit for the characterization of the employed GNSS equipment and for comparing the performance of the wide variety of signals accessible with modern receivers. The subsequent discussion is based on data collected in February and March 2010, including a phase when GIOVE-B was transmitting in the E6 band. Ten-day intervals have been selected in all cases to match the nominal repeat cycle of the Galileo constellation and to achieve a reasonable diversity of viewing directions, despite the limited number of satellites.

A comparison of C/N_0 values obtained with different antennas is shown in Fig. 3 (left) for the new and legacy signals of the GPS satellites. For improved uniformity of the results, the data are confined to Block IIR-M satellites, which offer a slightly higher P(Y) code signal power level than the Block IIA and IIR-A/B satellites and make up about one quarter of the entire constellation in the period of interest.

Differences between the various antennas are generally smaller than 2–3 dB-Hz for the L1 C/A, L2C and L5 signals. The AR25 antenna shows a distinctly different gain pattern than the other antennas as a result of the special chokering design. Down to an elevation of about 40°, the L1 C/A carrier-to-noise density differs by less than 1.5 dB-Hz from the value at zenith and remains about 2 dB-Hz higher compared to the other antennas down to the horizon. For L2C and L5 tracking, the gain differences between the antennas are less pronounced, even though a slightly more focused pattern can be noted for the Trimble Zephyr antenna. A clear benefit of the AR25 antenna is obvious for the semi-codeless P(Y) code tracking, where a C/N_0 performance improvement of up to 5 dB can be observed relative to the non-chokering antennas. For completeness, we note that the anomalous variation of the L5 C/N_0 values does not reflect the gain pattern of the receiving antennas in this frequency band, but is caused by a narrow beam transmission of the L5 test signal through the outer antenna ring of the SVN49 spacecraft (Erker et al. 2009).

Complementary to the assessment of different antennas, Fig. 3 (right) provides a comparison of different receivers operated from the same AR25 antenna at the Wettzell station. Differences are obvious for all signals, but are apparently dominated by different algorithms for the C/N_0 estimation (see e.g. Falletti et al. 2010) rather than the actual performance differences of the respective receivers. This is particularly true for the P(Y) tracking results, where the GRX1200 receiver appears to report an estimate of the L2 C/N_0 excluding semi-codeless tracking losses, whereas

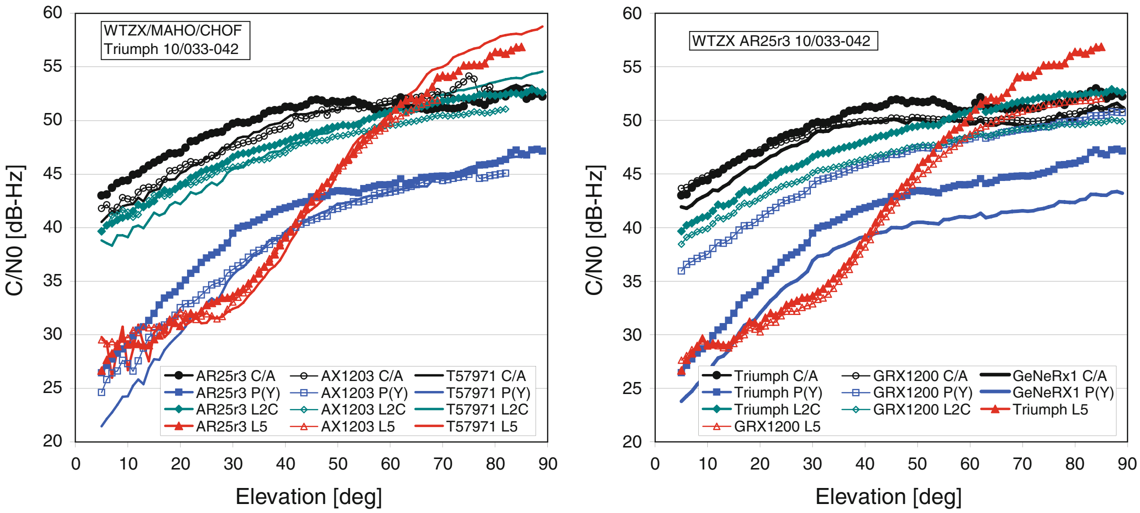

Fig. 3 Comparison of average C/N_0 values versus elevation for GPS Block IIR-M satellites using a Triumph Delta receiver with different antennas (*left*) and a Leica AR25r3 antenna with different receivers (*right*)

the results for the GeNeRx1 and Triumph receivers are more consistent with the losses expected from the Z-tracking theory (Woo 2000).

For the GIOVE satellites, the variation of C/N_0 with elevation is illustrated in Fig. 4 for the various receivers collocated at the Wettzell station. Separate plots are provided for the GIOVE-A and-B satellites in view of the different transmit antenna characteristics. For the E1 signal, a small difference in the received signal level at high elevations can be noted between the two satellites. Also, the overall power of the E1B/C signal transmitted by GIOVE-B is moderately higher than that of GIOVE-A, due to a slight repartitioning of the relative E1A and E1B/C powers in the CASM modulation (Crisci and Giraud 2008). The reported C/N_0 values are fairly similar for the GeNeRx1 and GRX1200+GNSS receivers, but differ by roughly 4 dB-Hz from the results obtained with the Triumph Delta-G2T receiver. It is unclear whether this difference is related to the combined tracking of the E1B and E1C signals, which could also explain a 3 dB-Hz higher C/N_0. In comparison with GPS, the E1B and E1C signal power received from GIOVE-A on ground is roughly 4–5 dB lower than that of the C/A code signal. The corresponding results obtained with the CONGO GeNeRx1 receivers are consistent with those obtained in the GESS network (Crisci and Giraud 2008).

For the E5a signal, the measured carrier-to-noise density ratio is generally several dB-Hz lower than that of the E1B/C signals (Fig. 4). This is quite different from analyses in the GESS network, where the E5 band shows a higher signal strength. The difference can, however, be readily understood by the specific characteristics of the Space Engineering antenna employed in the GESS network. Earlier tests conducted with the same antenna type at the Wettzell station have shown a 5–7 dB higher E5 antenna gain than the Leica AX1203 and AR25 antennas presently in use. Taking into account the different antenna characteristics, the E5a performance in the current CONGO network is consistent with the results reported for the GESS network.

Finally, E6 measurements of GIOVE-B obtained with the GeNeRx1 in early February 2010 during a period of E1 + E6 transmission are shown in Fig. 4. Below an elevation of 40°, the C/N_0 values obtained with the AR25 antenna in the E6 band closely match those of the E1B/C measurements from the same receiver, while an improvement of up 2–3 db-Hz may be recognized at higher elevations. However, a much more pronounced difference has been reported for the GESS network, where the carrier-to-noise density ratio in the E6 band always exceeds the E1 performance by 2–4 dB-Hz (Crisci and Giraud 2008). Most likely, these differences are again related to an improved gain of the Space Engineering antenna in the lower part of the GNSS frequency range.

Comparing the C/N_0 ratios for the GPS Block IIR-M and GIOVE-A/B satellites, the former certainly exhibit a better overall performance as far as the unencrypted signals in the L1 and L2 band are concerned. It should be kept in mind, however, that the GIOVE satellites transmit a lower signal power than specified for the final Galileo constellation (cf. Crisci et al. 2007). In the L5/E5a aviation band, which is common to both satellite navigation systems, a direct comparison is not yet possible due the non-nominal antenna configuration employed for the L5 test signal transmission on SVN49. GIOVE E5a signal-to-noise ratios measured in the E5a band are obviously weaker than those of the GPS L2C signal, but much more favorable than those obtained from a semi-codeless tracking of the encrypted P(Y) signals. The high C/N_0 values obtained for the GIOVE E5a/b tracking in the GESS network appear to be

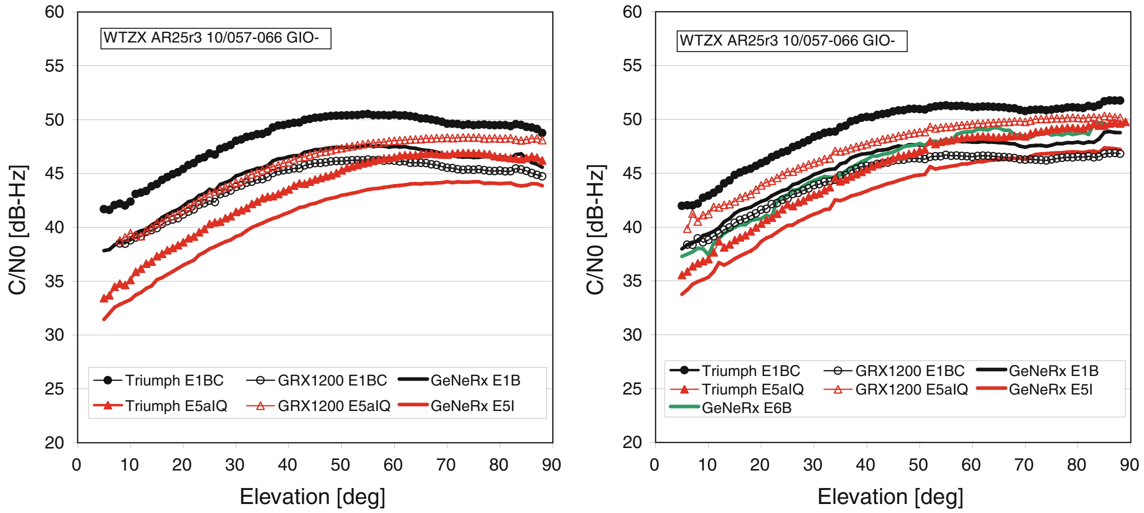

Fig. 4 Comparison of average C/N_0 values versus elevation for GIOVE-A (*left*) and GIOVE-B (*right*) using a Leica AR25r3 antenna with different receivers

specific to the Space Engineering antenna, but could not be reproduced with the commercial antennas employed in the CONGO network. Finally, our results suggest that the C/N$_0$ measurements provided by the various receivers are well suited for relative signal quality assessments with a given receiver type, but cannot easily be compared across different receiver families. Further effort may therefore be required to improve the consistency of results and to enable absolute C/N$_0$ calibrations for the multitude of new signals.

User equipment errors

Receiver noise and multipath constitute the primary components of the User Equipment Error (UEE), which serves as a key performance indicator of equipment and site quality.

Among these contributions, thermal receiver noise is essentially a white noise random error that is driven by the signal strength (C/N$_0$) and the tracking loop bandwidth, but also depends on the signal type and correlator design. Since the CONGO GNSS receivers employ substantially different tracking loop configurations for the various GPS and GIOVE signals, the observed noise values of the raw pseudorange measurements alone do not provide a meaningful indicator of receiver quality. We therefore made use of carrier phase smoothing to largely eliminate the impact of different tracking loop bandwidths and achieve better compatibility in the comparison of site and signal quality.

The smoothing interval of 50 s adopted in our Hatch filter is sufficiently long to reduce uncorrelated receiver noise below the level of common multipath errors, but short enough to avoid the build-up of systematic errors due to code-carrier divergence under normal ionospheric conditions and to retain a notable fraction of the overall multipath errors. For comparison, a much larger carrier-filtering constant of 600 s has been employed in the GESS performance characterization (Crisci et al. 2007; Giraud et al. 2008), which obviously suppresses not only receiver noise but also a substantial amount of short-term multipath.

Following Estey and Meertens (1999), we make use of an ionosphere corrected code-carrier difference (or "multipath combination") to determine the UEE, i.e. the noise plus multipath pseudorange error. Results are given in Fig. 5 for both legacy and modernized GPS signals. The graphs are based on a 10-day data arc (April 24–May 3, 2010) and reflect the CONGO configuration and site performance in this time frame. At mid to high elevations, a UEE of 10–20 cm is typically obtained for all signals. For low elevations, on the other hand, improved performance can be observed for L1 C/A and L2C code tracking at most sites in comparison with the P(Y)-code tracking.

Results for GPS L5 tracking are exclusively based on the SVN49 test signal, which differs in multiple respects from the final signal specification (Hsu et al. 2009). In particular, the signal is transmitted via the outer, narrow beam antenna ring, which results in a rapid decrease in the signal strength below an elevation of about 45°. Furthermore, a strong, satellite-induced multipath similar to that of the L1/L2 signals can also be observed in the L5 band. We have therefore presented only the standard deviation of the UEE for this signal, which is more representative of the site and receiver-specific noise than the total RMS value. Despite their preliminary nature, the results already demonstrate a very good tracking performance for the GPS L5 signal in the applicable elevation range.

The individual CONGO stations clearly exhibit a non-uniform performance with UEE differences of up to 100% between the best and worst cases. A low UEE level is generally obtained for the Triumph receivers, which evidences a particularly high level of multipath mitigation achieved with the proprietary correlator design. Aside from this observation, the station performance appears to be dominated by site-specific characteristics, and no immediate relations between station performance and antenna type has become obvious.

For GIOVE tracking, the RMS noise and multipath errors are shown in Fig. 6. It covers the tracking of E1 Open Service (O/S) and E5a signals for all CONGO sites as well as the E5 AltBOC and E6 O/S tracking supported by a subset of the employed receivers.

It may be noted that the UEE performance for the GIOVE E1B/C tracking is strikingly similar to that of the GPS L1 C/A signal and exhibits fully consistent site-specific variations. Even though the given results represent a mixture of GIOVE-A BOC(1,1) and GIOVE-B CBOC tracking, we may add that no pronounced performance differences could be observed for the two signal types. This is consistent with previous analyses (Simsky et al. 2008; Crisci and Giraud 2008) of GIOVE-A and -B tracking in the GESS network, which showed a decreasing benefit of the CBOC signals with increasing carrier phase smoothing interval. While the CBOC signal offers a better multipath suppression than the BOC(1,1) signal for path delays of more than 25 m, the associated multipath is of short periodic nature and can thus be effectively compensated by the Hatch filtering. On the other hand, the multipath errors are virtually identical for both signals in the case of short delay multipath that varies over longer time scales and dominate the overall error budget after the carrier phase smoothing.

The E5a tracking of the GIOVE satellites yields a UEE of 10–20 cm, which is closely comparable with the E1 O/S performance. An excellent performance is obviously obtained for the E5 AltBOC signal, which can be tracked by both the GeNeRx1 and GRX1200+GNSS receivers. Compared to the E5a-only tracking, the signal provides up to a factor-of-two UEE reduction. Given the very low

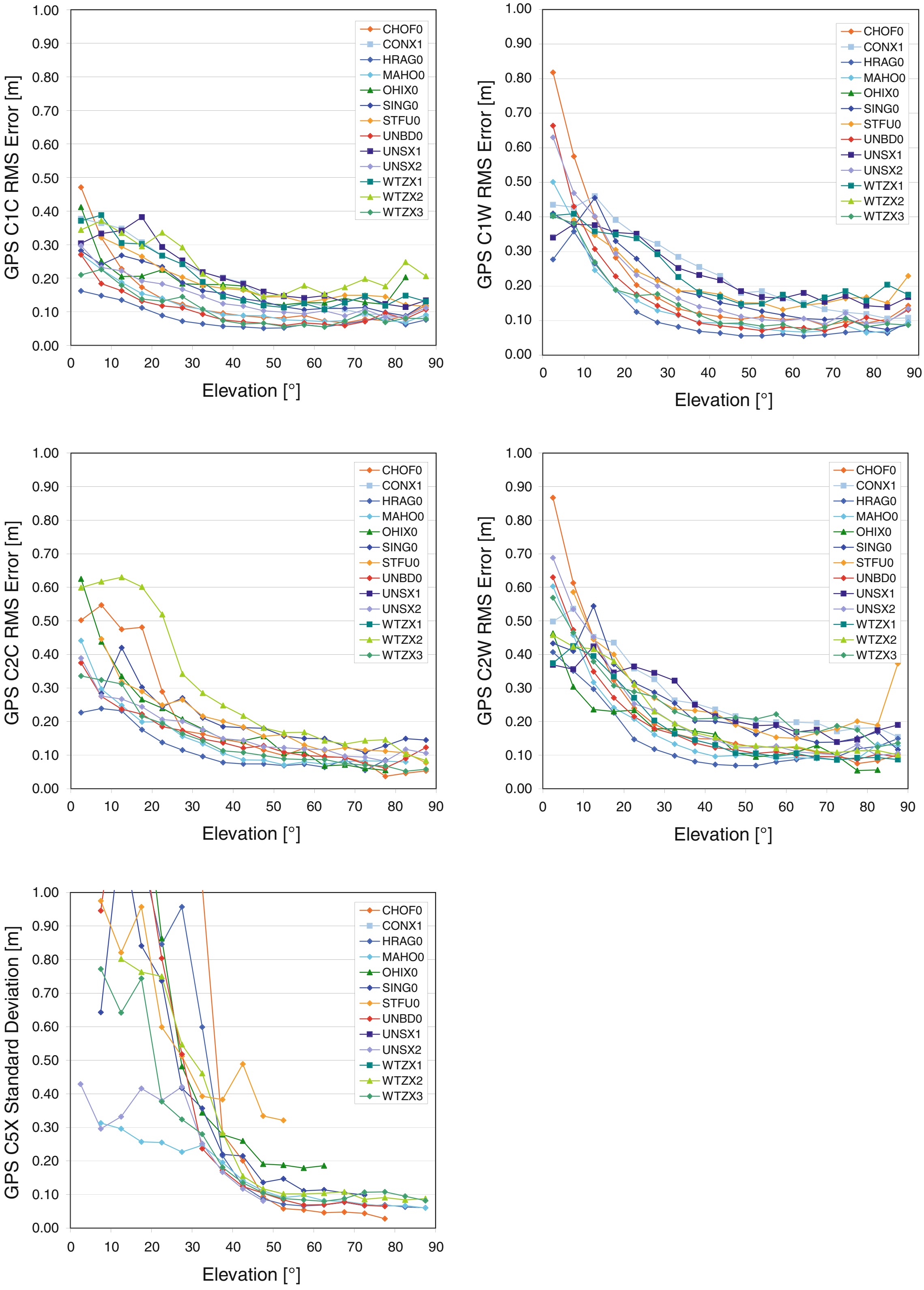

Fig. 5 Diagrams of the User Equipment Error (RMS pseudorange noise and multipath at 50 s smoothing in 5° elevation bins) for GPS tracking at the CONGO stations. Individual receiver types are distinguished by different symbols (*square*: GeNeRx1, *diamond*: Triumph Delta-G2T/G3TH, triangle: GRX1200+GNSS

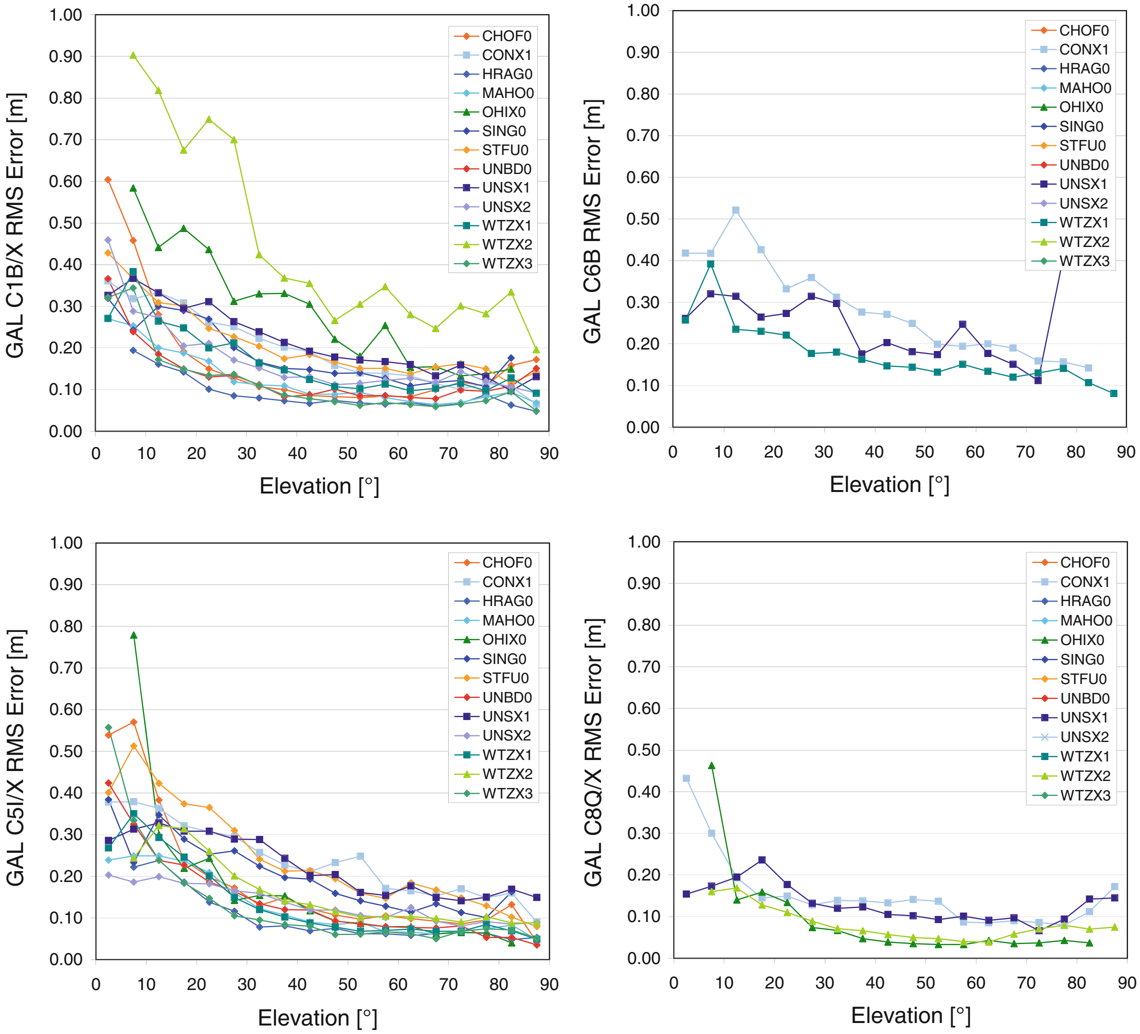

Fig. 6 Diagrams of the User Equipment Error (RMS pseudorange noise and multipath at 50 s smoothing in 5° elevation bins) for GIOVE signals at the CONGO stations. Individual receiver types are distinguished by different symbols (*square*: GeNeRx1, *diamond*: Triumph Delta-G2T/G3TH, *triangle*: GRX1200+GNSS. E6 results have been obtained in Feb 2010, all others in April/May 2010

thermal noise level of the AltBOC tracking derived in Simsky et al. (2006) and Crisci and Giraud (2008) from the difference of GeNeRx1 pilot and data observables as well as the fact that a further noise reduction is achieved by the carrier phase smoothing, we may conclude that the observed AltBOC tracking errors in Fig. 6 reflect primarily multipath errors.

Inter-signal and inter-system biases

GPS receivers and satellites are known to introduce systematic differential code biases (DCB) between pseudorange measurements obtained on different frequencies or, more generally, different signals. These biases are related to differences in the group delay of the entire signal chain for different center frequencies and modulations of the various signals. While DCBs are often absorbed in the receiver clock offset or canceled through appropriate differencing, a proper consideration of systematic code biases is mandatory in a heterogeneous, multi-constellation network when combining measurements from different constellations.

Conceptual background

For the discussion of differential code biases in the CONGO network, we consider a generalized measurement equation

$$P = \rho + cdt_{\mathrm{Rcv}} - cdt^{\mathrm{Sat}} + B_{\mathrm{Rcv}} - B^{\mathrm{Sat}} + T + I + M + \varepsilon \tag{1}$$

Here, the modeled pseudorange measurement P for a specific signal is described as the sum of the geometric range ρ, the receiver and satellite-specific clock offset terms (cdt_{Rcv} and cdt^{Sat}), tropospheric and ionospheric path delays (T and I) as well as code multipath M and noise ε. The equipment-related group delays are split into a receiver-specific bias B_{Rcv}, which is assumed to be the same for all tracked satellites, and a satellite-specific bias B^{Sat}, which is assumed to be the same for all receivers tracking this satellite.

Obviously, the biases cannot be properly separated from the clock offset terms, and only the *differences* of biases are directly accessible to observation in a network of multiple receivers tracking multiple satellites. Independent of the actual size of this network, one receiver and satellite bias each (or the respective ensemble average) can always be constrained to zero, which then defines a unique reference for all clock offset terms.

When operating two receivers ("A" and "B") with a common antenna (also called a zero-baseline configuration), we may difference the respective pseudoranges for a given signal (sig) to eliminate all geometry, path and satellite-specific terms in (1) and retain only the receiver clock and bias terms. Taking the average over all tracked satellites, we thus obtain the expression

$$\overline{\Delta P^{\mathrm{sig}}_{\mathrm{B-A}}} = \Delta(cdt)_{\mathrm{B-A}} + \Delta B^{\mathrm{sig}}_{\mathrm{B-A}} = \Delta(cdt)^{\mathrm{sig}}_{\mathrm{B-A}} \tag{2}$$

that effectively describes a signal-specific differential clock offset that is the sum of the true clock difference between the receivers and a differential pseudorange bias. Differencing, furthermore, the measurements obtained from two ranging signals (subsequently denoted by superscripts x and y), we obtain the receiver-receiver and signal-signal double difference bias

$$\begin{aligned}\nabla\Delta B^{\mathrm{y-x}}_{\mathrm{B-A}} &= \Delta B^{\mathrm{y}}_{\mathrm{B-A}} - \Delta B^{\mathrm{x}}_{\mathrm{B-A}} = \overline{\Delta P^{\mathrm{y}}_{\mathrm{B-A}}} - \overline{\Delta P^{\mathrm{x}}_{\mathrm{B-A}}}\\ &= \Delta(cdt)^{\mathrm{y}}_{\mathrm{B-A}} - \Delta(cdt)^{\mathrm{x}}_{\mathrm{B-A}}\end{aligned} \tag{3}$$

The concept of double difference biases is not restricted to GPS measurements alone, but can also be applied across different constellations. This enables a characterization of receiver- and signal-specific biases in a multi-constellation environment in relation to a selected reference receiver and signal.

For orbit/clock determination and point positioning, ionosphere-free linear combinations of dual-frequency measurements are typically employed and care has to be taken of the fact that different combinations have to be employed for GPS and GIOVE observations in a multi-constellation scenario.

In accord with adopted conventions, semi-codeless P(Y) code measurements on the L1 and L2 frequency are employed for GPS processing in the CONGO network, while the Open Service E1B/C and E5aI/Q signals are used for GIOVE-A/B (or Galileo). Drawing from the designations employed in the RINEX 3.0 format (Gurtner 2007), we denote the respective measurements as GPSC1W/GPSC2W and GALC1X/GALC5X, respectively. The ionosphere-free GPS pseudoranges are then given by

$$\begin{aligned}P^{\mathrm{IF(GPS)}} &= (1+\alpha)P^{\mathrm{GPSC1W}} - \alpha P^{\mathrm{GPSC1W}}\\ P^{\mathrm{IF(GAL)}} &= (1+\beta)P^{\mathrm{GALC1X}} - \beta P^{\mathrm{GALC1X}}\end{aligned} \tag{4}$$

with the well-known frequency-specific factors

$$\alpha = \frac{f^2_{\mathrm{L2}}}{f^2_{\mathrm{L1}} - f^2_{\mathrm{L2}}} \sim 1.55 \quad \text{and} \quad \beta = \frac{f^2_{\mathrm{E5a}}}{f^2_{\mathrm{E1}} - f^2_{\mathrm{E5a}}} \sim 1.26 \tag{5}$$

When determining the receiver clock offset as part of the point positioning from GPS observations, the GPS-related receiver biases is normally ignored in the processing. As a result, a modified clock offset term is obtained

$$cdt^{\mathrm{(GPS)}}_{\mathrm{Rcv}} = \left[cdt_{\mathrm{Rcv}} + (1+\alpha)B^{\mathrm{GPSC1W}}_{\mathrm{Rcv}} - \alpha B^{\mathrm{GPSC2W}}_{\mathrm{Rcv}}\right] \tag{6}$$

that differs from the actual clock offset by a combination of the aforementioned biases. Here, the superscript "(GPS)" indicates that the associated quantity is the clock offset value derived from the GPS-only observations. In order to use this value also in the processing of GIOVE observations, the ionosphere-free E1/E5a Galileo measurements is described as

$$\begin{aligned}P^{\mathrm{IF(GAL)}} &= \rho + cdt^{\mathrm{(GPS)}}_{\mathrm{Rcv}} + \mathrm{ISB} - \left(cdt^{\mathrm{Sat}} - B^{\mathrm{Sat}}\right)\\ &\quad + T + I + M + \varepsilon\end{aligned} \tag{7}$$

with

$$\begin{aligned}\mathrm{ISB}^{\mathrm{GAL}}_{\mathrm{Rcv}} &= \left[(1+\beta)B^{\mathrm{GALC1X}}_{\mathrm{Rcv}} - \beta B^{\mathrm{GALC5X}}_{\mathrm{Rcv}}\right.\\ &\quad \left. - (1+\alpha)B^{\mathrm{GPSC1W}}_{\mathrm{Rcv}} + \alpha B^{\mathrm{GPSC2W}}_{\mathrm{Rcv}}\right]\end{aligned} \tag{8}$$

All biases can thus be merged into a single GPS/Galileo inter-system bias when modeling the GIOVE observations. The ISB is specific to the employed receiver and may differ from one station to another. Likewise, the bias is specific to the set of signals selected for the processing. Thus, a different ISB would occur when processing E5b or E5 AltBOC measurements instead of the E5a measurements considered here.

It may be noted that (8) is based on "absolute" biases, which are not, however, observable in practice. Instead, a reference station (receiver "A") in the network is normally selected, for which the ISB can be assumed to be zero. The ISB can then be expressed as a function

$$\begin{aligned}\mathrm{ISB}^{\mathrm{GAL}}_{\mathrm{Rcv}} &= \left[(1+\beta)\nabla\Delta B^{\mathrm{GALC1X-x}}_{\mathrm{B-A}} - \beta\nabla\Delta B^{\mathrm{GALC5X-x}}_{\mathrm{B-A}}\right.\\ &\quad \left. - (1+\alpha)\nabla\Delta B^{\mathrm{GPSC1W-x}}_{\mathrm{B-A}} + \alpha\nabla\Delta B^{\mathrm{GPSC2W-x}}_{\mathrm{B-A}}\right]\end{aligned} \tag{9}$$

of the elementary double-difference biases for an arbitrary reference signal "x". For the reference signal, we select the GPS L1 C/A code measurements, which are collected by all receivers in the network for a sufficiently large number of simultaneously observed satellites.

CONGO receiver biases

The co-location of a GeNeRx1 receiver, a Delta-G2T receiver and a GRX1200 receiver at the Wettzell station provides unique opportunity to derive signal-specific double difference biases for any pair of receivers employed in the CONGO network.

A representative set of bias values with respect to GPS L1 C/A code measurements is shown in Table 3, which provides 1-week averages for the Apr. 21–28, 2010 time frame. Furthermore, Fig. 7 illustrates the variation of these biases for a selected subset of signal. Considering only GPS signals, differences in the inter-frequency and inter-signal biases of up to about 10 m can be observed among the various receivers. A good consistency is obtained for the L1 GPS/Galileo inter-signal biases in case of the Delta-G2T and GeNeRx1 receivers, whereas the results for the GRX1200 differ from either of the two other receivers by about 17 m. On the other hand, large differences among the various receivers are obvious for the GALC5X-GPSC1C inter-signal/inter-frequency bias. While the Delta-G2T and GRX1200 results show an expected level of consistency (about 14 m), either of the two differs from the GeNeRx1 value by roughly 270 m.

This striking discrepancy is ultimately related to an anomalous bias in the GIOVE E5 (or E5a, E6b) signal tracking that has first been reported for measurements collected with the GeNeRx1 receiver, but appears to affect all other receivers built in conformance with the GIOVE Open Service Signal ICD ESA (2008) in a similar manner. According to Simsky et al (2008), the GeNeRx1 E5a and E5b measurements of GIOVE-A/B show a positive pseudorange bias of about 265–275 m compared to what can be expected from the E1 measurements and the ionospheric delays along the signal path. The measured value of this excess bias depends also on the group delays of the receiving antenna, but differences of a few meters between GIOVE-A and GIOVE-B have likewise been identified.

Without further justification, the E5 bias has been attributed to the GIOVE satellites themselves in the previous reference, even though it is not possible to distinguish a group delay in the transmitter chain from a group delay in the receiver chain using measurements from GESS measurements alone. An independent calibration yielding matching group delays of 888 ns (266.5 m) for GIOVE-A and -B was later reported in Hidalgo et al. (2009). However, it is not clear, whether this covers the entire transmitter chain (i.e. signal generator and transmit antenna) or only parts thereof.

The lack of public discussion of the GIOVE-A/B E5-E1 group delay difference and its actual cause has led various manufacturers to implement empirical ad hoc corrections to the native E5 pseudorange measurements (Javad, Leica, and IfEN; priv. comm.). In case of the Triumph Delta and GRX1200 receivers, a correction by nine E5a code chips (approx. 263.75 m) is employed, which explains the consistency of the respective double-difference biases in Table 3. On the other hand, uncorrected E5 measurements are provided by the GeNeRx1 receivers (Septentrio, priv. comm.). This different treatment then results in large apparent biases relative to the Delta-G2T and GRX1200 measurements. Without this correction, the GALC5X-GPSC1C inter-signal/inter-frequency bias for the Delta-G2T and GeNeRx1 receiver would differ by only 4 m and the GRX1200 value would differ from the GeNeRx1 by about 17 m (i.e. roughly the same value as for the E1B/C measurements).

When taking into account the proper frequency factors for the GPS and GIOVE dual-frequency combinations, inter-system biases of up to ±320 m (or ±1,070 ns) arise depending on the choice of the reference receiver. Since the CONGO network is highly heterogeneous, the station-specific ISBs cover a much wider range of values than with just a single receiver type as is the case for the GESS network.

Table 3 Double-difference biases for pairs of receivers operated with a common antenna at the Wettzell station of the CONGO network

Signals	Satellites	Delta-G2T–GeNeRx1 (m)	Delta-G2T–GRX1200 (m)	GRX1200–GeNeRx1 (m)
GPSC1W-GPSC1C	GPS	+0.40	−0.45	+0.85
GPSC2W-GPSC1C	GPS	+9.21	+10.88	−1.66
GALC1X-GPSC1C	GIOA + GIOB	+0.48	−16.90	+17.37
	GIOA	+0.52	−16.47	+16.99
	GIOB	+0.45	−17.26	+17.71
GALC5X-GPSC1C	GIOA + GIOB	+267.42	−13.89	+281.32
	GIOA	+267.58	−13.80	+281.38
	GIOB	+267.29	−13.98	+281.26

The values represent averages over a 10-day period (day 2010/057–066)

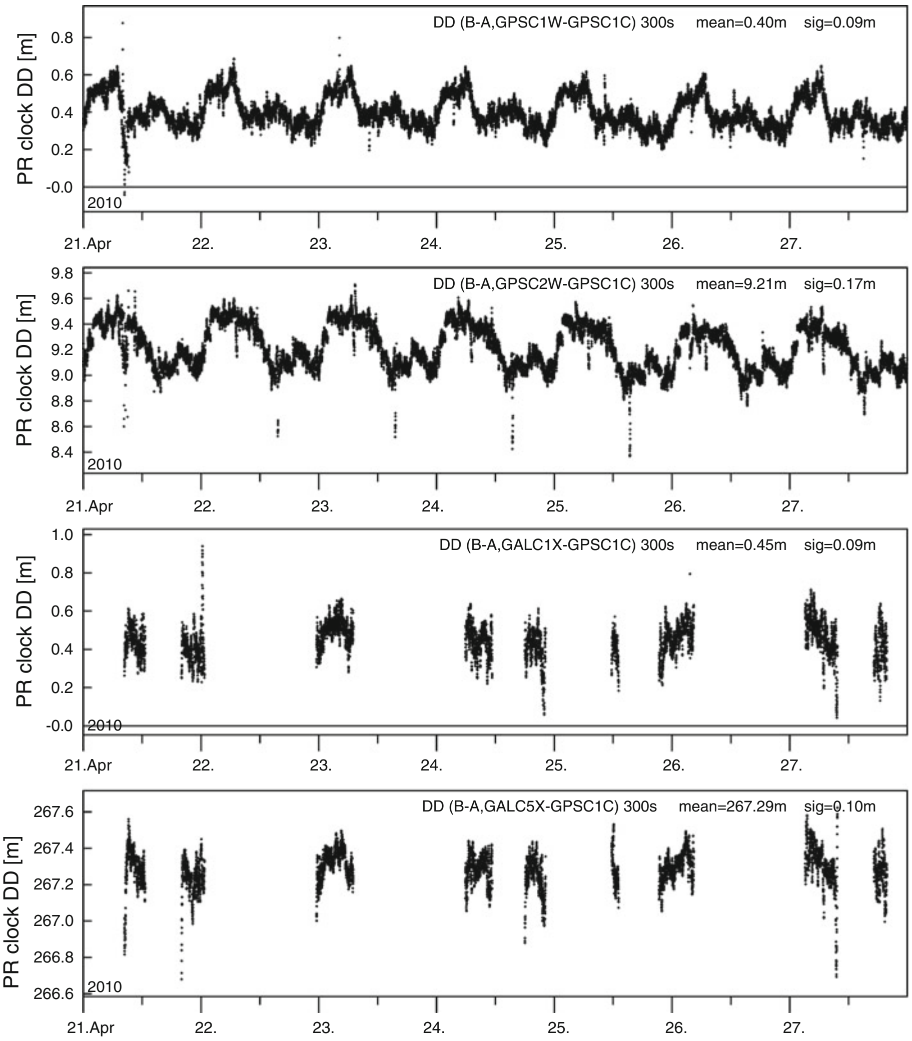

Fig. 7 Variations in the epoch-wise double difference pseudorange biases based on GPS and GIOVE-B observations for the Delta-G2T—GeNeRx1 receiver pair at the Wettzell ground station. A 300 s smoothing has been applied to the single difference pseudoranges in order to reduce the impact of receiver noise

Based on the majority of receivers in the CONGO network and the fact that the Triumph Delta and GRX1200 receivers almost compensate the observed GIOVE E5 group delay through an adequate correction, a decision has been taken to adopt a station with Triumph Delta receiver as ISB reference station and to define the ISB for this station as zero. Accordingly, ISBs of about +320 m (or +1,070 ns) arise for the GeNeRx1 receivers in the CONGO network (Table 4), while the GRX1200 receivers show ISBs of about +3 m (or 10 ns). A practical consequence of this choice is a systematic difference in the GIOVE satellite clock offsets relative to GPS time as determined in the GESS network (Schönemann et al. 2007; Garcia et al. 2009) and CONGO network (Hugentobler et al. 2010; Steigenberger et al. 2010), respectively. Thus, appropriate care has to be taken by users of the respective orbit and clock products in mixed constellation, point position applications (Cao et al. 2010; Bonhoure et al. 2009).

The CONGO stations equipped with the same receiver type show a typical scatter of several ns (about 1 m) in their ISBs, which is also a characteristic value for the day-to-day ISB variation. ISB differences of the same order of magnitude can also be observed for some stations when considering individual ISBs for the GIOVE-A and -B satellite. Multipath errors that do not average out in the same manner for the different ground tracks of the GIOVE satellites are therefore considered as an alternative explanation for the observed ISB differences. Further analyses taking into account the long-term variation of the GIOVE visibility conditions will be required to decide whether a combined ISB or separate ISBs should be employed in the CONGO network.

Summary and conclusions

CONGO is a global network of sensor stations for research and early experimentation with the new Galileo signals. Unlike ESA's GESS network for GIOVE mission operation, the CONGO network is a highly heterogeneous

Table 4 Approximate GPS/GIOVE inter-system biases for different choices of the reference receiver in the CONGO network

Reference	Receiver		
	Delta-G2T (m)	GRX1200 (m)	GeNeRx1 (m)
Delta-G2T	–	+2.7	+322.8
GRX1200	−2.7	–	+320.1
GeNeRx1	−322.8	−320.1	–

All ISBs refer to the ionosphere-free combination of L1 & L2 P(Y) code measurements for GPS tracking and E1 O/S & E5a GIOVE measurements

network. This enabled a characterization of a wide range of equipment and contributed to continuous improvements of receivers and antennas.

The Open Service E1 and E5a tracking commonly supported by all CONGO receivers provides adequate basis for GIOVE orbit and clock determination except during periods of E6 transmission. The tracking performance was found to be fully satisfactory and compatible with GPS signals except for E5 AltBOC, which offers a factor-of-two improvement. However, this improvement can only partly be realized when combined with the O/S E1 signals in an ionosphere-free combination. Widely different tracking loop characteristics imposed a need for carrier phase smoothing for proper comparison of the UEE performance. Using a 50 s smoothing, a 10–20 cm RMS pseudorange error was obtained at mid elevations (45°) for most signals and receivers. No practical benefit could be recognized for the GIOVE-B E1 CBOC signal in comparison with the E1 BOC(1,1) signal transmitted by GIOVE-A.

The various antennas used in the CONGO network exhibit only small gain pattern differences of a few dB for GPS L1, L2 and L5 as well as GIOVE E1 and E5 signals among each other. The Space Engineering antenna of the GESS network, in comparison, exhibits a notably higher gain in the lower frequency bands. C/N_0 values reported by individual receiver types under equal conditions show systematic differences of up to 5 dB-Hz, which most probably reflects differences in the employed algorithms for C/N_0 computation rather than actual performance differences.

Large inter-system biases of about 320 m in the CONGO network are caused by different treatment of a satellite-specific E5 group delay in the individual receiver types. While the GeNeRx1 reports uncorrected E5 pseudoranges, a correction by nine code chips, of 29.3 m length each, is applied in the Triumph Delta and GRX1200 receivers. This empirical correction compensates the bias almost completely and is essentially equivalent to a satellite-specific group delay correction on the user side. It has therefore been decided to employ a Triumph Delta receiver as the primary reference for GIOVE inter-satellite biases in the CONGO network. However, care must be taken when using the resulting clock products, because the values will differ from the corresponding solutions in the GESS network by roughly one micro-second.

Despite the limited number of stations, the global coverage and typical dual-site visibility of the CONGO network already enables a proper GIOVE orbit & clock determination on a routine basis. CONGO, furthermore, offers a real-time transmission of all measurements, which distinguishes it from the GESS network and provides the basis for the generation of GIOVE ephemerides in real-time. A combined product based on predicted GIOVE orbits and real-time reconstructed satellite clock offsets has recently been released for public use (http://igscb.jpl.nasa.gov/mail/igsmail/2010/msg00081.html). Future extensions of the network are foreseen within 2010 to avoid small areas with single site visibility and to improve the overall robustness and product quality.

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References

Bonhoure B, Boulanger C, Legenne J (2009) GPS-GIOVE Mixed PVT experimentation. ION-GNSS-2009; 22–25 Sep, Savannah, Georgia

Cao W, Hauschild A., Steigenberger P, Langley RB, Santos M, Montenbruck O (2010) GPS/GIOVE Integrated precise point positioning performance evaluation. ION International Technical Meeting, 25–27 Jan, San Diego, California

Crisci M, Giraud J (2008) Receiver experimentation and sensor station performance characterization. GIOVE Workshop, ESA/ESTEC 13 Noordwijk

Crisci M, Hollreiser M, Falcone M, Colina M, Giraud J (2007) GIOVE mission sensor station performance characterization: overview of the results; ION-GNSS-2007, 26–28 Sep, Fort Worth, Texas

Erker S, Thölert S, Furthner J, Meurer M, Häusler M (2009) GPS L5 "Light's on!"—A first comprehensive signal verification and performance analysis. ION-GNSS-2009; 22–25 Sep, Savannah, Georgia

ESA (2008) GIOVE-A + B (#102) Navigation signal-in-space interface control document; ESA-DTEN-NG-ICD/02837; issue 1.1, 8 Galileo project office, ESA, Noordwijk

Estey LH, Meertens CM (1999) TEQC: the multi-purpose toolkit for GPS/GLONASS data. GPS Solutions 3(1):42–49

Falletti E, Pini M, Lo Presti L (2010) Are C/N0 algorithms equivalent in all situations? Inside GNSS pp. 20–27

Garcia AM., Piriz R, Fernandez V, Navarro-Reyes D, Gonzalez F, Hahn J (2009) GIOVE orbit and clock determination and prediction: experimentation results. ENC GNSS 2009

Giraud J, Lobert B, Crisci M, Hollreiser M, Colina M (2008) Station measurement quality with new Galileo signals. ENC GNSS 2008

Gurtner W (2007) RINEX: the receiver independent exchange format version 3.00; Astronomical institute, University of Berne; November 28, 2007

Hidalgo I, Rodríguez D, Cueto M, Prieto-Cerdeira R, Binda S (2009) GIOVE mission experimentation: ionospheric and inter-frequency bias analysis and results. 2nd Int. colloquium on scientific and fundamental aspects of the Galileo program, 14–16 Oct, Padua, Italy

Hsu J, Choy A, Powell TD, Utter AC, Dafesh PhA (2009) Initial on-orbit observations of the L5 demo Payload on GPS IIR-20; ION-GNSS-2009; 22–25 Sep, Savannah, Georgia

Hugentobler U, Steigenberger P, Montenbruck O, Hauschild A, Weber G, Hessels U (2010) Evaluation of GIOVE satellite clocks using the CONGO network. 24th European frequency and time forum; 13–16 Apr, Noordwijk, The Netherlands

Kunysz W (2001) Advanced pinwheel compact controlled reception Pattern Antenna (AP-CRPA) designed for interference and multipath mitigation. ION-GPS-2001, Salt Lake City

Montenbruck O, Hauschild A, Hessels U, Steigenberger P, Hugentobler U (2009) CONGO—First GPS/GIOVE tracking network for science. Research; GPS World, 36–41

Schönemann E, Springer T, Otten M, Becker M, Dow J (2007) GIOVE-A precise orbit determination from microwave and satellite laser ranging data—first perspectives for the Galileo constellation and its scientific use; 1st colloquium on the scientific and fundamental aspects of the Galileo program, 1–7 Oct, Toulouse, France

Simsky A, Sleewaegen J-M, Hollreiser M, Crisci M (2006) Performance assessment of Galileo ranging signals transmitted by GSTB-V2 satellites. ION-GNS-2006, 25–26 Sep, Fort Worth, Texas

Simsky A, Mertens D, Sleewagen J-M, Willems T, Hollreiser M, Crisci M (2008) Multipath and tracking performance of Galileo ranging signals transmitted by GIOVE-B. ION-GNSS-2008, 16–19 Sep, Savannah, Georgia

Spelat M, Hollreiser M, Crisci M, Falcone M (2006) GIOVE-A signal-in-space test activity at ESTEC. ION-GNS-2006, 25–26 Sep, Fort Worth, Texas

Steigenberger P, Hauschild A, Montenbruck O, Hugentobler U, Hessels U, Weber G, Noack T (2010) GIOVE orbit and clock determination based on the CONGO network. general assembly of the European geosciences union, 2–7 May, Vienna, Austria

Weber G, Dettmering D, Gebhard H, Kalafus R (2005) Networked transport of RTCM via internet protocol (Ntrip)—IP-streaming for real-time GNSS applications. ION-GPS-2005; 13–16 Sep, Long Beach, CA

Woo KT (2000) Optimum semi-codeless carrier phase tracking of L2; navigation. J Inst Navig 47(2):82