

# Combination of Two Radio Space-Geodetic Techniques with VieVS during CONT14

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**Abstract** Unlike CONT11, CONT14 does not have official information on common frequency standards for co-located sites. Nevertheless, according to Kwak et al. (2015) [1], we have the possibility to find the co-located sites that used the same clocks through comparing clock rates from single technique solutions. Moreover, CONT14 includes co-located VLBI radio telescopes, i.e., HOBART26 and HOBART12. Therefore, it is also a good test bed to develop the analysis strategy for future twin/sibling telescopes. In this study, we compute VLBI-like GNSS delays (GNSS single differences) between the ranges from two stations to a satellite, using phase measurements with most of the errors corrected by the c5++ software. We estimate station coordinates and site common parameters ( i.e., zenith wet delays, troposphere gradients, and clock parameters) with the Vienna VLBI Software. Common clock parameters are limited to the sites sharing the same frequency standard and having good performance of it during CONT14. Local tie vectors are introduced as fictitious observations for co-located instruments: GNSS–VLBI and at Hobart even VLBI–VLBI. In this paper, we show the comparison results between the combination solutions and the single technique solutions in terms of station position repeatability during 15 days.

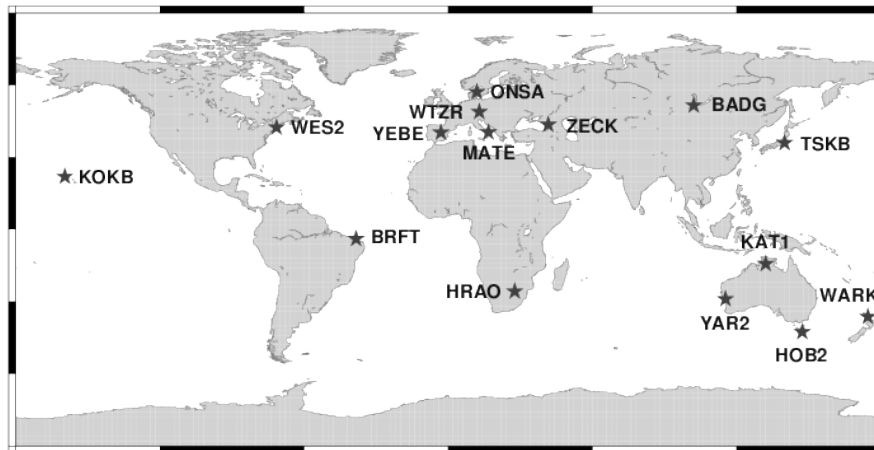
**Keywords** VLBI, GNSS, combination at the observation level, CONT14

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## 1 Introduction

The local tie vectors of co-located sites with several space-geodetic techniques play a key role to tie different terrestrial reference frames. However, the local tie vectors at many sites show doubtful quality and, furthermore, there is no independent method to validate them. In order to address this vulnerability, the International VLBI Service for Geodesy and Astrometry (IVS) has organized a working group on Satellite Observations with VLBI which studies possibilities to observe Earth satellites with the VLBI ground network affiliated with the IVS (<http://ivscc.gsfc.nasa.gov/about/wg/wg7>). Other than technical issues, it also puts a premium on developing the geometric model of satellites for analysis. The geometric model for GNSS satellites has been implemented in the Vienna VLBI Software (VieVS [2]) according to Klioner (1991) [3] and Plank et al. (2014) [4], and it was tested by Kwak et al. (2015) [5] using real GNSS data. The current accuracy of the model involved for GNSS data in VieVS is at the cm-level [5].

IVS schedules CONT campaigns, which are sets of continuous VLBI sessions during 15 days having well balanced the geographical distribution of the observation sites. Most of the CONT sites have co-located International GNSS Service (IGS) stations and simultaneously receive GNSS data. Therefore, the CONT campaign is a proper test bed for handling both VLBI and GNSS data in a common analysis software, e.g., VieVS in this study. Of course, GNSS data, usually GNSS phase measurements, need to be distilled for processing with VieVS. For more details, see Kwak et al. (2015) [5].



**Fig. 1** A global network of co-located sites of IVS and IGS during CONT14. The station codes are written following IGS station code names.

## 2 Data

CONT14 was observed between May 6 and May 20, 2014. For the 15-day period of CONT14, there were 15 sites co-located with IGS stations (Figure 1). Especially Hobart (HOB2) had two IVS stations and one IGS station co-located.

We process group delays from CONT14 sessions for VLBI data as usual. In order to process and combine GNSS data together with VLBI data in VieVS, we generate VLBI-like GNSS delays (GNSS single differences) based on real GNSS phase measurements. For more details on production of GNSS delays, see Kwak et al. (2015) [5]. Two kinds of data (group delays for quasars and VLBI-like GNSS delays for GNSS satellites) are merged into single files per 24-hour session.

## 3 Common Clock Check

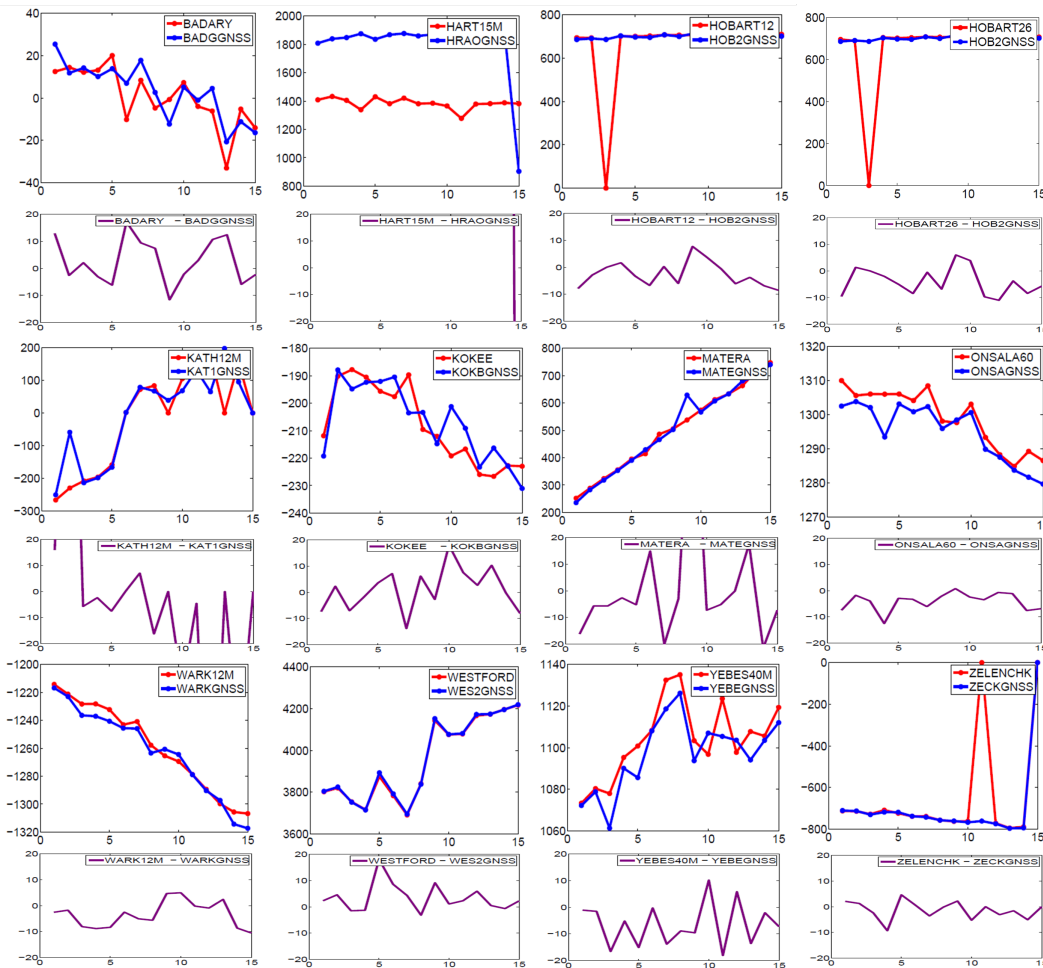
Unlike CONT11, CONT14 has no information about common frequency standards for co-located sites. However, according to Kwak et al. (2015) [1], it is possible to gauge which co-located sites shared the common clocks by way of comparing clock rates from single technique solutions. Figure 2 shows the comparison of clock rates. Here, the clock rates are relative rates with respect to the reference clock of Wettzell (WTZR). During 15 days, the clock rates of each site except HRAO look comparable between

the two techniques and are mostly in the range of  $\pm 20$  cm/day, which corresponds to around 0.008 ps/s. Some instant peaks of HOB2, KAT1, MATE, and ZECK signify clock breaks which are revealed through simple least-squares estimation (clock offsets and a ZWD). We exclude these sites and HRAO, which did not share the clock, for clock rate combination. The sites, which do not appear in Figure 2, are initially excluded from the clock rate combination. Meanwhile, clock offsets cannot be used for comparison, because the cable delay variations and other instrumental delays are also absorbed into the clock parameters. We also do not consider quadratic terms in this study.

## 4 Combination and Results

In the combination, we do not deal with products (estimated parameters) or normal equations but construct a combined design matrix which contains the partial derivatives of VLBI and GNSS with common geophysical models (Figure 3).

All the parameters are estimated separately and the constraints for common parameters (i.e., ZWD, troposphere gradients, and clock rates) are additionally given. ZWDs greatly depend on the height, because they signify the vertical delay values while the radio signals go through the wet troposphere. Hence, ZWD corrections have to be introduced to account for the height differences between the co-located techniques.



**Fig. 2** Clock rates of each site which are derived from single technique solutions (red: VLBI, blue: GNSS, purple: difference) during the 15 days of the CONT14 campaign. The units of the horizontal and vertical axes are days and cm/day, respectively. The clock of WTZZ is set as reference clock. Except for HRAO, the clock rate differences are in the range of  $\pm 20$  cm/day corresponding to  $\pm 0.008$  ps/s. The instant peaks indicate clock breaks at HOB2, KAT1, MATE, and ZECK. The sites that have been excluded in the analysis at least once because of their data quality do not appear in this figure.

We apply mean ZWD correction values in accordance with Teke et al. (2011) [7] and use 1-cm constraints. When the horizontal distances between the co-located techniques are close enough, troposphere gradients are supposed to be the same [6]. For troposphere gradients, we apply loose constraints (2 cm). For all the sites, common parameter constraints of ZWDs and troposphere gradients are applied while common clock rates are constrained (10 cm/day) only for chosen sites due to sharing and/or performance of the common clock (Section 3 and Figure 2) during CONT14.

Besides, we add extra fictitious observations with known local tie vectors (survey measurements) only for

several stations: HRAO, KOKB, ONSA, WES2, and HOB2 (only for VLBI–VLBI). We apply 3 cm for the constraints, since the formal errors of the local tie measurements are usually too optimistic.

We have implemented the above combination features in VieVS also for general purposes, e.g., co-located twin/sibling telescopes.

An overview of the general analysis strategies is shown in Table 1. The EOP values are fixed to IERS 08 C04, since the partial derivatives of the EOP have not been introduced in the GNSS part.

In order to evaluate the combination performance, we compare the mean station position repeatabilities

**Table 1** Models and a prioris used in this work.

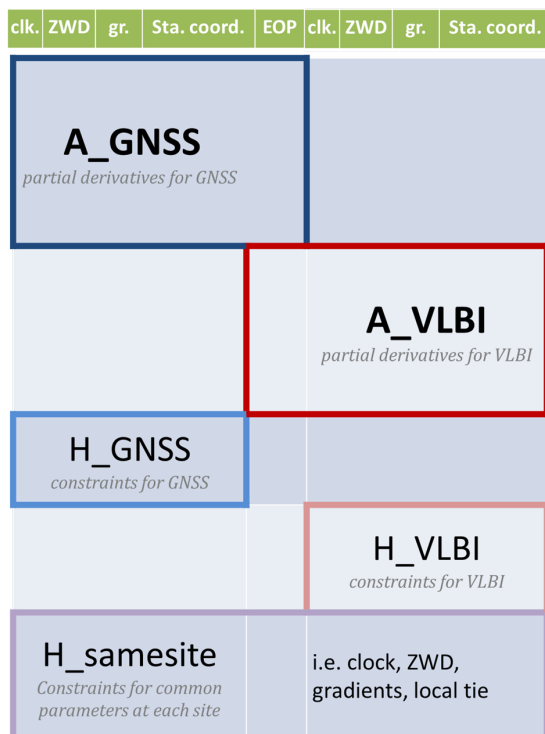
Geometric models	VLBI: Consensus model GNSS: Klioner (1991) [3]
Satellite position	IGS final orbit ( <a href="http://www.igs.org">http://www.igs.org</a> )
Station position	ITRF2014 [8]
Solid Earth tide	IERS 2010 Conventions [9]
Ocean loading	FES2004 [10]
Earth orientation parameters	IERS 08 C04 ( <a href="http://hpiers.obspm.fr">http://hpiers.obspm.fr</a> )
Troposphere delay	Zenith hydrostatic delays from GPT [11] VMF [12]
Ionosphere	No a priori for troposphere gradient Corrected by using ionospheric linear combination in the PPP processing

of the single solutions and the combinations. As mentioned in Section 1, the current accuracy of the model involved for GNSS data in VieVS is at the cm-level [5] and thus the station position repeatability of GNSS stations is worse than the repeatability of standard GNSS solutions. Therefore, in this paper, we focus on the comparison between single and combination solutions of each technique and the impact of common parameter constraints on combination solutions.

As a result of the combination, the mean station position repeatabilities of the GNSS solutions are improved by 5, 9, and 13% for the north, east, and up components, while the VLBI solutions are improved by 4, 6, and 16% for each component (Figure 4). The results indicate that both techniques benefit equally from the combination.

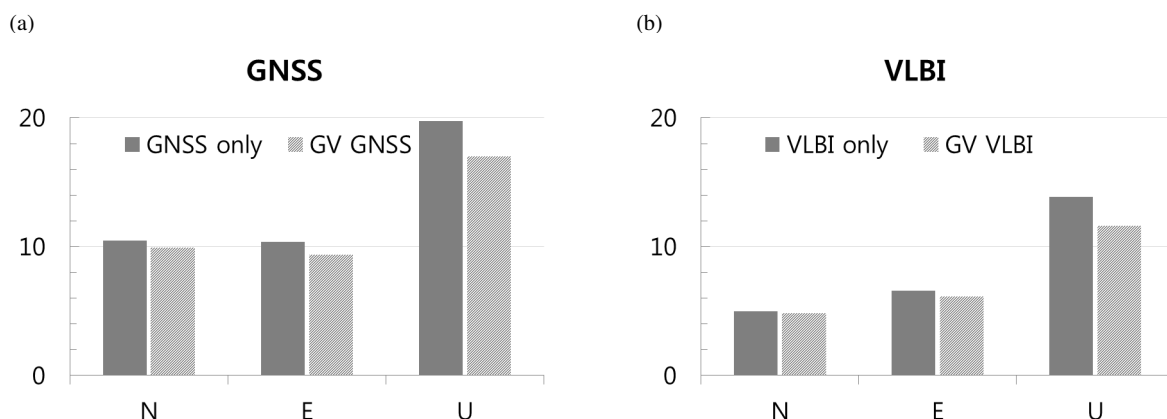
## 5 Conclusions

In this paper, we combined VLBI data and VLBI-like GNSS delays for 15 co-located sites during CONT14. Both data types were analyzed with the VLBI software VieVS individually and combined. Comparing clock rates, we could assess if co-located instruments shared the clock at the CONT14 sites. For the combination, the common site parameters (ZWD, troposphere gradients, and clock rates) were constrained between the two techniques. Furthermore, the local ties of the reference points at the co-located site were selectively introduced. The combination solutions improve the mean station position repeatability in comparison with the single technique solutions. The analysis strategy of common parameter constraints and local ties can also be applied to co-located VLBI observations with



**Fig. 3** Construction of the design matrix which consists of partial derivatives (**A\_GNSS** and **A\_VLBI**) of GNSS and VLBI with respect to clock (column clk.), zenith wet delays (column ZWD), troposphere gradients (column gr.), station coordinates (column Sta. coord.), and Earth orientation parameters (column EOP) and constraints (**H\_GNSS** and **H\_VLBI**) for them. The partial derivatives with respect to EOP for GNSS have not been implemented yet. The constraints (**H\_samesite**) for common parameters and fictitious observations for local ties can be additionally attached for co-located sites.

twin/sibling telescopes in the future. As we see from the GNSS results, the GNSS geometric model (near-field model) in VieVS still needs to be improved. Furthermore, the partial derivatives with respect to EOP



**Fig. 4** Mean station position repeatabilities of single solutions (solid box) and combination solutions (box with a pattern of diagonal lines) for north, east, and up components. Plot (a) shows the results of GNSS stations and plot (b) the results of VLBI stations. The unit is mm.

for GNSS need to be implemented in VieVS and then one can estimate EOPs and expect better GNSS single solutions and combination results.

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