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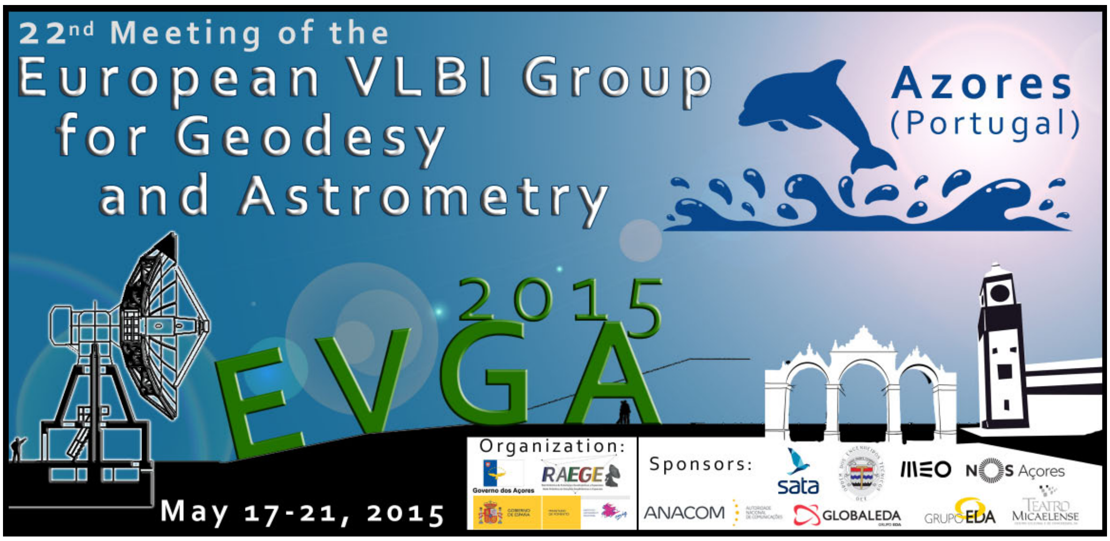


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# Baseline dependent weights in VieVS

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**Abstract** It is well known that in processing VLBI data $\chi^2$ is usually larger than 1, typically in the range of 4-8. This results from either too small measurement errors or mismodeling the data. By reweighting the data, that is, by increasing the errors of the observation, we can make $\chi^2 \sim 1$ (Gipson et al., 2008). In Solve's (Ma et al., 1990) operational solutions baseline dependent weights are always applied. Vienna VLBI Software (VieVS, Böhm et al. (2009)) uses global weighting, i.e., a constant weight is added to each observation. Adding baseline dependent weights in VieVS is a two step process. Firstly, we calculate the reweights for each baseline in an observation, secondly, we run the least squares adjustment a second time. Our study shows that baseline dependent weighting improves baseline length repeatability significantly. The Weighted Root Mean Square (WRMS) values of 71% of the baselines participating in CONT08 improved. UT1 adjustment scatter, and discrepancy between VieVS and Solve are also reduced.

**Keywords** Reweighting, UT1, VieVS, Solve, IVS

## 1 Introduction

There are many other error sources besides measurement noise which can affect the $\chi^2$ (Gipson et al., 2008):

1. phase cal errors;
2. RFI in the signals;
3. other correlator related errors;
4. source structure;
5. source position errors;
6. errors in geophysical models;
7. mis-modeling clocks and/or atmospheres;
8. underparametrizing the time variation of clocks and/or atmospheres;
9. etc.

All of the listed errors increase the noise of individual observations, which leads to $\chi^2$ of being too large, e.g., in the range of 4-8. The data needs to be reweighted to bring $\chi^2 \sim 1$. In other words an additional noise term needs to be added to the observations.

In our study we will use two data sets; CONT08, and one year of International VLBI Service for Geodesy and Astrometry (IVS, Schuh and Behrend (2012)) Intensive series data. We will evaluate the effect caused by reweighting the data by analyzing baseline length repeatability, calculating VieVS minus Solve UT1 adjustment values, and calculating Weighted Root Mean Square (WRMS) differences between VieVS and Solve results.

## 2 Adding noise

There are three common ways to add noise to VLBI measurements (Gipson et al., 2008):

1. Global reweights, e.g., 33 ps for all observations, which is the VieVS default;
2. Station reweights, which depend only on the stations in an observation;
3. Baseline reweights, which only depend on the baselines in an observation.

Weight is added to the observations as follows.

$$\sigma^2_{t,ij,obs} = \sigma^2_{t,ij,meas} + \epsilon^2_{t,ij} \quad (1)$$

where $\sigma_{t,ij,meas}$ is the actual measured value, and $\epsilon_{t,ij}$ is the re-weight constant.

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**Fig. 1** The 11 stations participating in CONT08 (Schuh and Behrend, 2012).

All three ways can be chosen in Solve. In operational solutions baseline dependent weigthing is always used. VieVS deploys global reweights by default, but one can choose to use baseline dependent weighting in the latest version of VieVS, 2.2.

In VieVS we used the baseline dependent weights calculated as follows:

$$\epsilon_{ij}^2 = \frac{1}{n_{ij}} \sum v_{ij}^2 \qquad (2)$$

Where the sum is over all observations involving baseline $ij$, $n_{ij}$ are the number of observations involving this baseline, and $v_{ij}$ are the residuals in pico-seconds.

## 3 Data sets

We use two different data sets; one to study baseline length repeatability, and another to calculate WRMS differences between VieVS and Solve solutions. The data sets are described in the following subsections.

### 3.1 Baseline length repeatability

We chose CONT08 as the data set for investigating the baseline length repeatability. CONT08 was a two-week campaign of continuous VLBI sessions, scheduled for observing during the second half of August 2008. The 11 stations that participated in CONT08 are displayed in Fig. 1 (Schuh and Behrend, 2012). The CONT08 campaign continued the series of the very successful continuous VLBI campaigns that were observed at irregular intervals: CONT94 (January 1994), CONT95 (August 1995), CONT96 (fall 1996), CONT02 (October 2002), and CONT05 (September 2005). After CONT08 two CONT series have been measured, CONT11 (September 2011) and CONT14 (May 2014).

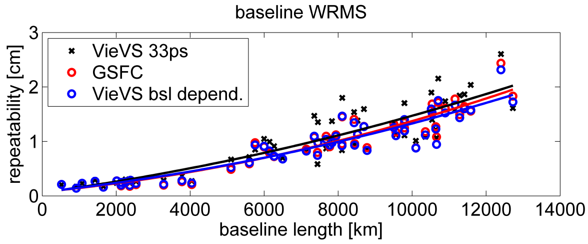


**Fig. 2** WRMS of baseline length repeatablity. Baseline length repeatability using global weights in VieVS is marked with black x's, VieVS using baseline weight files from Solve are marked with red circles, and from implementing a function to calculate baseline dependent weighting in VieVS are marked with blue circles, respectively.

### 3.2 VieVS minus Solve UT1 adjustments

For the VieVS minus Solve data set, we chose all Intensives from 2012 that had 12 or more observations. Weighted Root Mean Square (WRMS) values were calculated as follows.

$$WRMS = \sqrt{\frac{\sum_{i=1}^{N} \frac{(UT1_{VieVS,i} - UT1_{Solve,i} - WM)^2}{\sigma_{VieVS,i}^2 + \sigma_{Solve,i}^2}}{\sum_{i=1}^{N} \frac{1}{\sigma_{VieVS,i}^2 + \sigma_{Solve,i}^2}}} \qquad (3)$$

Here, $UT1_{VieVS,i}$, and $UT1_{Solve,i}$ denote the estimates of the UT1 from VieVS and Solve analysis, respectively, and $\sigma_{VieVS,i}$ and $\sigma_{Solve,i}$ denote their respective formal uncertainties.

## 4 Results

We used VieVS version 2.2 and Solve release 2014.02.21 in our analysis. We calculated baseline length repeatability from VieVS solutions using CONT08 data with three different weighting schemes:

1. VieVS using global weights, e.g. a constant of 33 ps is added to each observation (VieVS 33 ps);
2. VieVS using external baseline dependent weight files calculated with Solve (GSFC);
3. VieVS deploying baseline dependent weights using a dedicated function (VieVS bsl depend.).

The WRMS improved in 64 % of the baselines when external weight files created by Solve were used, and in 71 % of the baselines when VieVS used baseline dependent weights (Fig. 2). The effect is larger with longer baselines.

We calculated baseline length repeatability differences with the respect to VieVS using global weights in two cases: 1) VieVS using Solve's baseline weight files, and 2) VieVS using a function to calculate baseline dependent weights. Baseline length repeatability differences are shown in Fig. 3.

Additionally, one year (2012) of data from IVS intensive sessions was analyzed with VieVS and Solve in order to see the effect on baseline weighting in UT1 results. VieVS minus

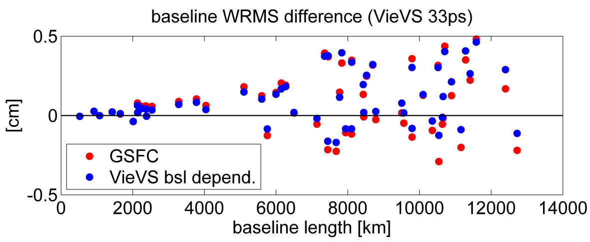


**Fig. 3** Baseline length repeatability difference with respect to VieVS using global weights. Results using baseline weight files from Solve are marked with red dots, and from implementing a function to calculate baseline dependent weighting in VieVS are marked with blue dots, respectively. Baselines where the baseline weight solution are improved are above the horizontal axis.

**Table 1** Weighted Root Mean Square (WRMS) differences in microseconds between VieVS and Solve.

| setup | WRMS: All INTs | WRMS: INT01s |
|---|---|---|
| default | 8.84 | 7.38 |
| baseline weights | 7.14 | 5.18 |

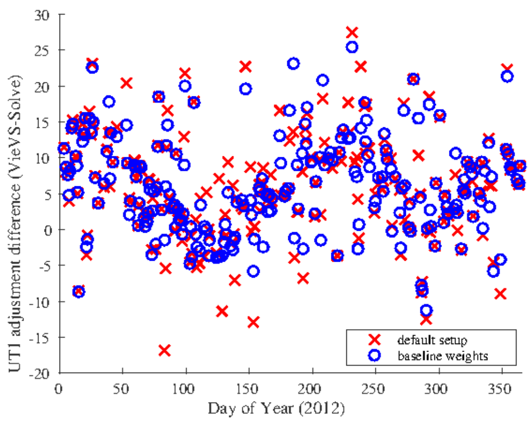


**Fig. 4** VieVS minus Solve UT1 adjustments in microseconds. VieVS minus Solve UT1 adjustment values using the default setup of VieVS are shown with red x's, and VieVS minus Solve values with using baseline dependent weighting in VieVS are marked with blue circles.

Solve UT1 adjustment values using the default setup of VieVS are shown with red x's, and VieVS minus Solve values with using baseline dependent weighting in VieVS are marked with blue circles, Fig. 4. Most data points from deploying baseline dependent weights also in VieVS show noticeable improvement in comparison to VieVS using a constant weight of 33 ps in each observation.

The use of baseline weighting reduces the discrepancy between VieVS and Solve's estimates of UT1 adjustments in the IVS Intensive session solutions as shown in Table 1 and Fig. 4. WRMS differences reduced from 8.84 to 7.14 microseconds in the case of Intensives solutions, and from 7.38 to 5.18 microseconds in the case of INT01 solutions (Kokee–Wettzell baseline).

## 5 Conclusions

The WRMS improved in 64 % of the baselines of the CONT08, when we used weight files created with Solve. When we used baseline dependent weighting in VieVS, the WRMS reduced even more as 71 % of the baselines showed improvement. Fig. 2 shows significant improvement in the baselines length repeatability after implementing baseline dependent weights in VieVS.

UT1 WRMS difference between the two software packages reduced 19 % for all Intensive sessions and 30 % for INT01 sessions when baseline dependent weighting was used also in VieVS, when we analyzed one year of IVS Intensive sessions data.

In the future it would be worthwhile to add more iterations to the weighting process when necessary. We could also test using partial redundancy of baselines instead of Eq. 2, and see if it affects on the results. To derive baseline-dependent variance components using partial redundancy, the squared sum of the residuals is calculated for each baseline and scaled by the partial redundancy of this particular baseline (Artz et al., 2012).

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