Summary of the VLBI2010 Monte Carlo simulations

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Abstract

In the process of defining the specifications for VLBI2010, the IVS next generation VLBI system, a lot of effort has been put into Monte Carlo simulation studies. Artificial delay observables were generated taking into account the three most important stochastic error sources in VLBI: the wet troposphere, station clock and delay measurement error. Based on real physical properties of the troposphere and clocks the simulation results served as a basis for the VLBI2010 Committee to give recommendations to the IVS Directing Board concerning antenna specifications, network size and clock accuracy required to reach VLBI2010's goal of 1 mm position accuracy and 0.1 mm velocity accuracy per year on a global scale. With three independent simulation software packages - based on the VLBI analysis software packages Calc/Solve and Occam, and a special precise point positioning (PPP) software - we tested the impact of scheduling strategies, source-switching interval, analysis strategies, random errors, and network size on the repeatability of station positions and baseline lengths. We present a summary of the results and discuss future simulation ideas. More details can be found in Petrachenko et al. 2009.

1. Introduction

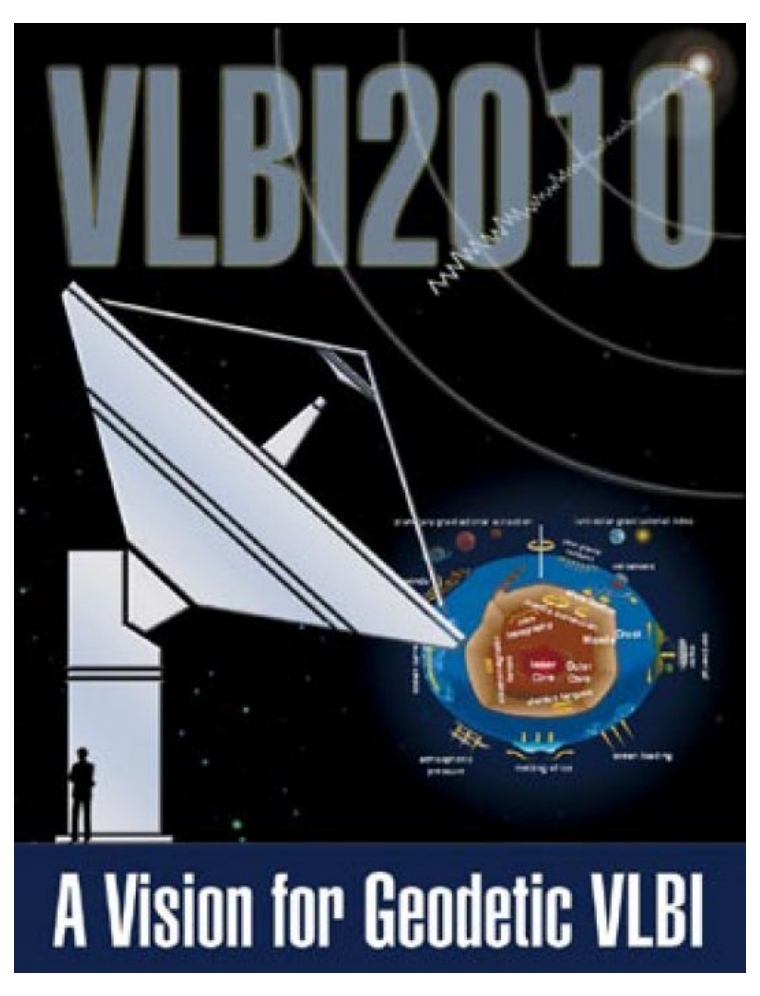


Fig. 1 VLBI2010 logo

In September 2005 the IVS Working Group 3 (WG3) presented its final report "VLBI2010: Current and Future Requirements for Geodetic VLBI Systems" (Niell et al. 2006) to the IVS Directing Board. Within this report the capabilities of the next-generation VLBI system were outlined:

- 1-mm position accuracy on global scales,
- continuous measurements for time series,
- initial geodetic results within 24 hours after a VLBI session.

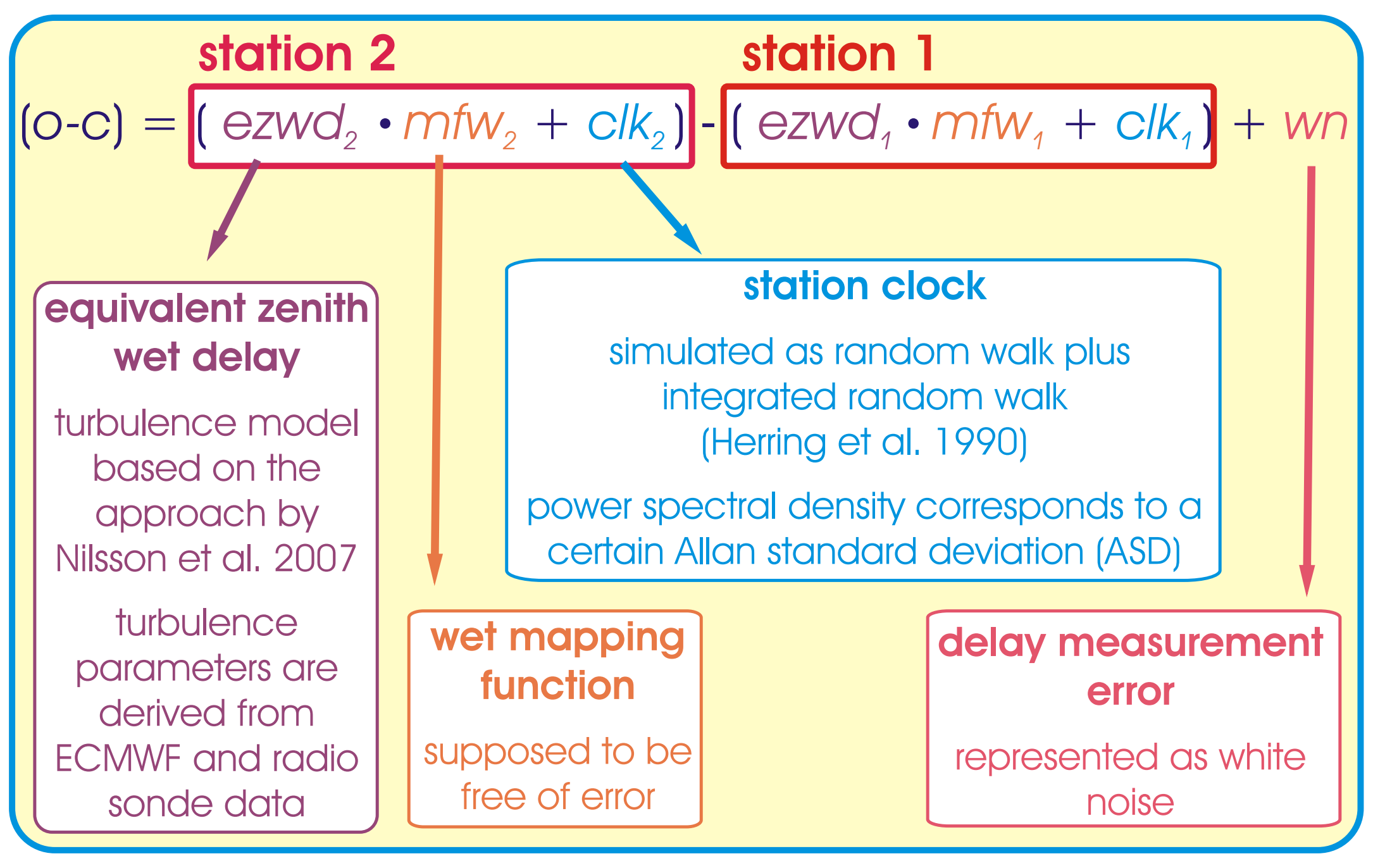
As a next step the VLBI2010 Committee (V2C) was established to carry out studies recommended by WG3, to guide research aiming at the improvement of geodetic VLBI and to encourage the realization of the VLBI2010 system.

To design the next-generation VLBI system it is indispensable to understand the impact of new strategies on the quality of the final results. Serving this purpose Monte Carlo simulators were developed to investigate the impact of the most important stochastic error sources (wet troposphere delay, reference clock and delay measurement error) and to study the benefit of new strategies proposed by WG3 (such as shorter source-switching intervals, new analysis and scheduling strategies)

2. The Monte Carlo simulators

Using theoretical models for the error processes 25 sets of delay observables are generated, where each set is driven by different random numbers. The data are processed like real VLBI data and the sample of output parameters is analyzed statistically.

The VLBI2010 Monte Carlo simulations take into account the three most important stochastic error sources in VLBI, which are the wet troposphere delay, the station clock, and the delay measurement error. The 'observed minus computed' (o-c) VLBI delay observables are generated by (Petrachenko et al. 2009):



$$(o\text{-}c) = \underbrace{(ezwd_2 \cdot mfw_2 + clk_2)}_{\text{station 2}} - \underbrace{(ezwd_1 \cdot mfw_1 + clk_1)}_{\text{station 1}} + wn$$

equivalent zenith wet delay
turbulence model based on the approach by Nilsson et al. 2007
turbulence parameters are derived from ECMWF and radio sonde data

station clock
simulated as random walk plus integrated random walk (Herring et al. 1990)
power spectral density corresponds to a certain Allan standard deviation (ASD)

wet mapping function
supposed to be free of error

delay measurement error
represented as white noise

For each schedule being investigated twenty-five 24-hour sessions are simulated with the same turbulence parameters, ASD, and white noise variances, but different sets of random numbers. For each session geodetic parameters, such as station coordinates, are estimated. Then, for each schedule statistical parameters such as the rms of the 3D position error are calculated. It was decided within the V2C that the figure of merit be the median of the rms 3D position error.

Three software packages were used:

Occam	Solve	PPP
Kalman filter estimation	classical Gauss-Markov model	classical Gauss-Markov model and Kalman filter estimation
Jörg Wresnik, IGG, TU Vienna	Dan MacMillan, NVI, GSFC, NASA	Andrea Pany, IGG, TU Vienna
Wresnik and Böhm (2006)	MacMillan (2006)	Pany et al. (2008a)

It is clear that a PPP approach, treating only one antenna at a time, is somewhat unrealistic in terms of VLBI. Nevertheless, the PPP results agree reasonably well with the results of Solve and Occam. The big advantage of the PPP software is that it can be enhanced easily for new processing modes.

3. VLBI2010 scheduling strategies

VLBI2010, with globally distributed networks and very short source-switching intervals, puts new demands on scheduling strategies. Within the VLBI2010 Monte Carlo simulations two types of schedules have been investigated:

- Schedules of the first type were generated with an extended version of the Goddard Space Flight Center scheduling program *sked*. The criteria for this type of schedules were to maximize the number of stations in a scan, and to minimize the slew times between scans.
- Schedules of the second type were produced at Natural Resources Canada. They were designed to have uniform sky coverage over short intervals of a few minutes and are characterized by regular source-switching intervals.

The simulations revealed that both types of schedules have the same performance with respect to position error. However, the schedules with regular source-switching intervals (second type) allow a more generalized study of antenna slew requirements and all results presented on this poster were obtained from such schedules.

The schedules are based on a list of 230 strong, almost structureless radio sources (Petrov 2007) and were generated for hypothetical networks of 16, 24, and 32 globally distributed stations (Niell 2007).

4. Simulation results

This section is to summarize the simulation work done so far within the VLBI2010 Monte Carlo simulations. If not otherwise stated the turbulent *ezwd* was generated using the set of VLBI2010 turbulence parameters provided by T. Nilsson (Petrachenko et al. 2009), the clock was simulated with an ASD of 1e-14 @ 50 min (state-of-the-art clock performance), and a white noise of 4 ps was added to the baseline delay observable. As the PPP simulator is treating single antennas the white noise was divided by sqrt(2).

4.1 Source-switching interval

To test the impact of a dramatic decrease of the source-switching interval uniform sky schedules with switching intervals of 15, 30, 60, 90, 120, 240, and 360 s were generated, where the source-switching interval of 360 s is representative for the performance of current schedules. Figure 2 shows the median rms 3D position error in units of mm versus the source-switching interval in seconds for all three simulators.

All three softwares show an impressive improvement if the source-switching interval is decreased. These results served as constraints for the V2C's recommendations concerning the required data rate, antenna diameter, and slew rates.

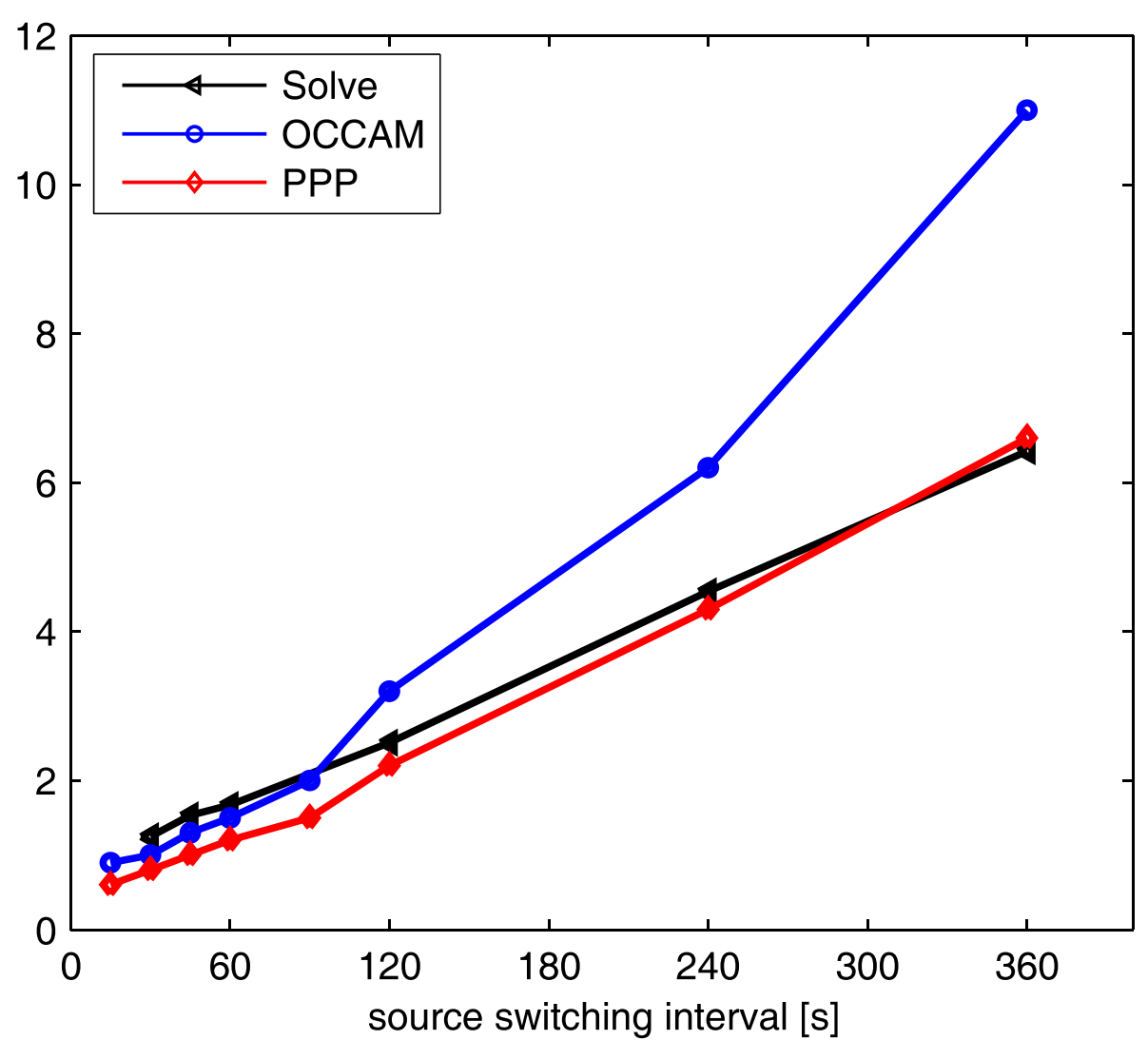


Fig. 2 Median of the rms 3D position errors vs. length of the source-switching intervals of the 16-station uniform sky schedules. The troposphere was simulated using the VLBI2010 turbulence parameters, the clock ASD was set to 1e-14 @ 50 min and a white noise of 4 ps per baseline observation was added. The poorer performance of the Occam simulator at longer switching intervals is believed to be due to the fact that the filter solutions were specifically tuned for shorter source-switching intervals.

4.2 Analysis strategies

In order to gain the greatest benefit of the new VLBI2010 operation modes, providing many more observations, more precise delay observables, and a larger number of observations per scan, the state-of-the-art analysis strategies were reviewed.

With a significantly higher observation density the estimation intervals for the troposphere parameters (zenith wet delays and gradients) can be reduced to a few minutes (e.g. 6 min). The improvement in the position error can be a factor of two for stations near the equator that have a turbulent atmosphere, but is considerably less for stations at higher latitudes.

Another promising approach is the application of elevation angle dependent weighting. We applied a downweigthing of low observations by adding mfw*10 ps in quadrature to the sigma of the observations. The largest improvement (~ 30 %) was found for low latitude stations (see Figure 3).

Other analysis options such as larger a priori variance for the Kalman filter and low-order spherical harmonic functions for the atmosphere have been investgated as well (Pany et al. 2008b).

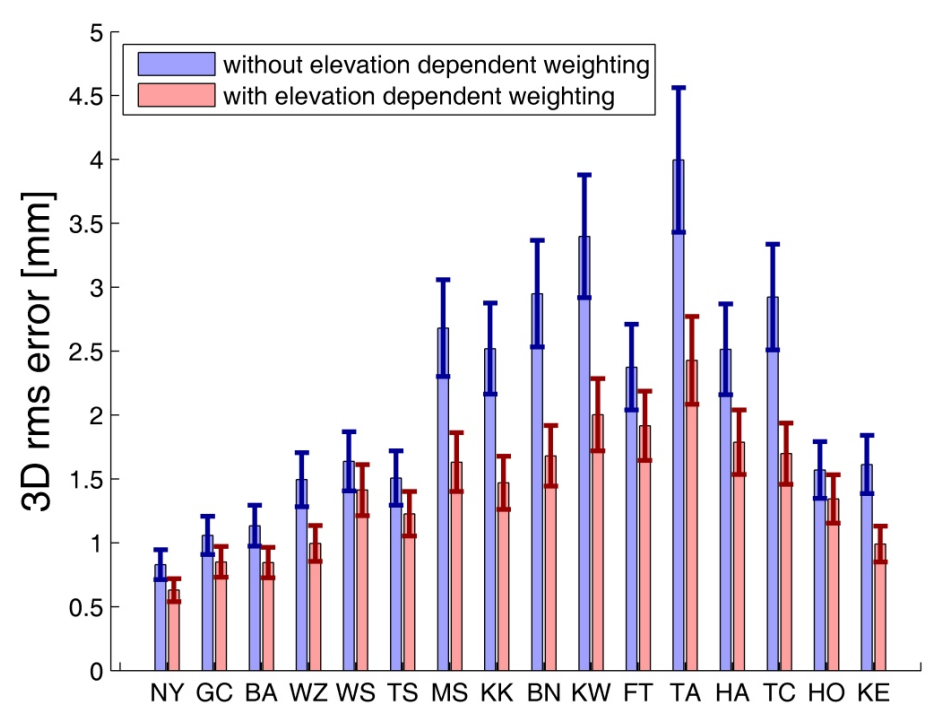


Fig. 3 rms 3D position errors as obtained with the PPP simulator without elevation angle weighting (blue bars) and with elevation angle weighting applied (red bars). The results were computed with the classical Gauss-Markov estimation method.

4.3 Random errors

Simulations were carried out to investigate the impact of the three main stochastic error sources - wet troposphere delay, station clock, and measurement error one at a time (more details can be found in Pany et al. 2010).

If not being varied, the following **default settings** have been used:

clock:	ASD = 1e-14 @ 50 min
measurement error:	4 ps white noise per baseline
atmosph. turbulence:	structure constant Cn = 1e-7 $m^{-1/3}$
	effective height H = 2 km
	wind velocity v = 10 m/s towards East

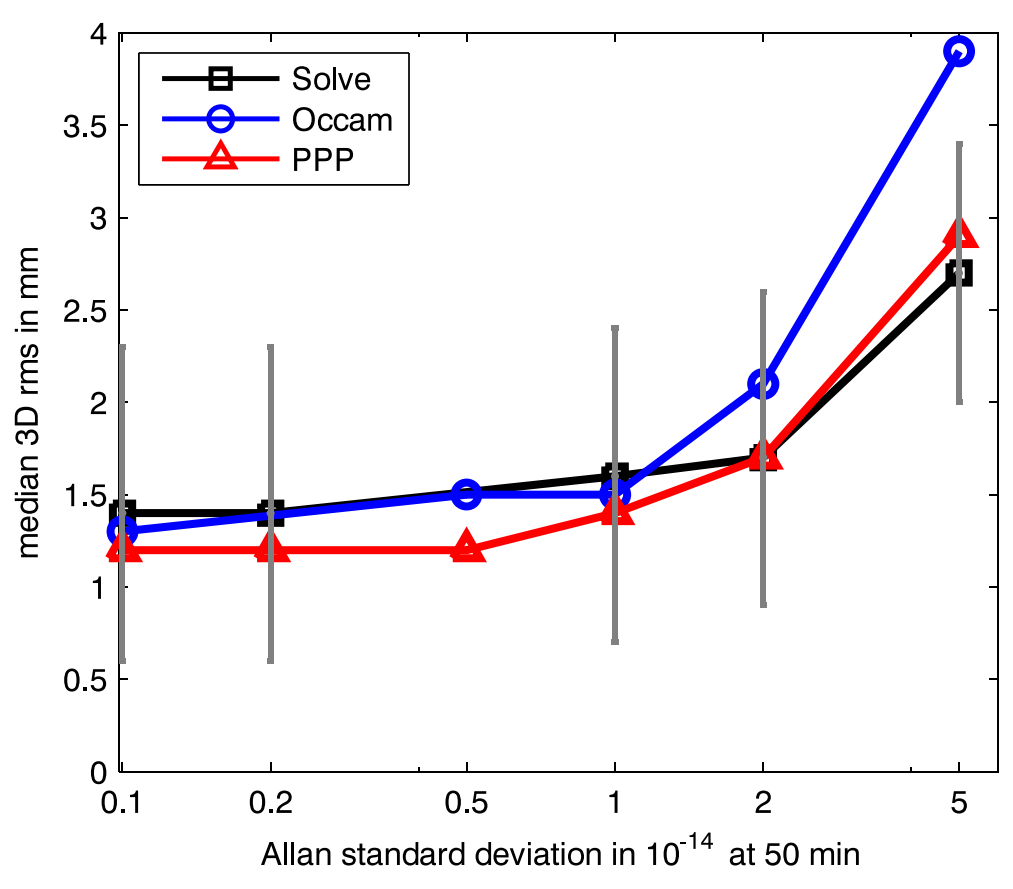


Fig. 4 median rms 3D position errors in mm vs. clock ASD for all three estimation softwares. The grey whiskers indicate min and max values of the Solve solution.

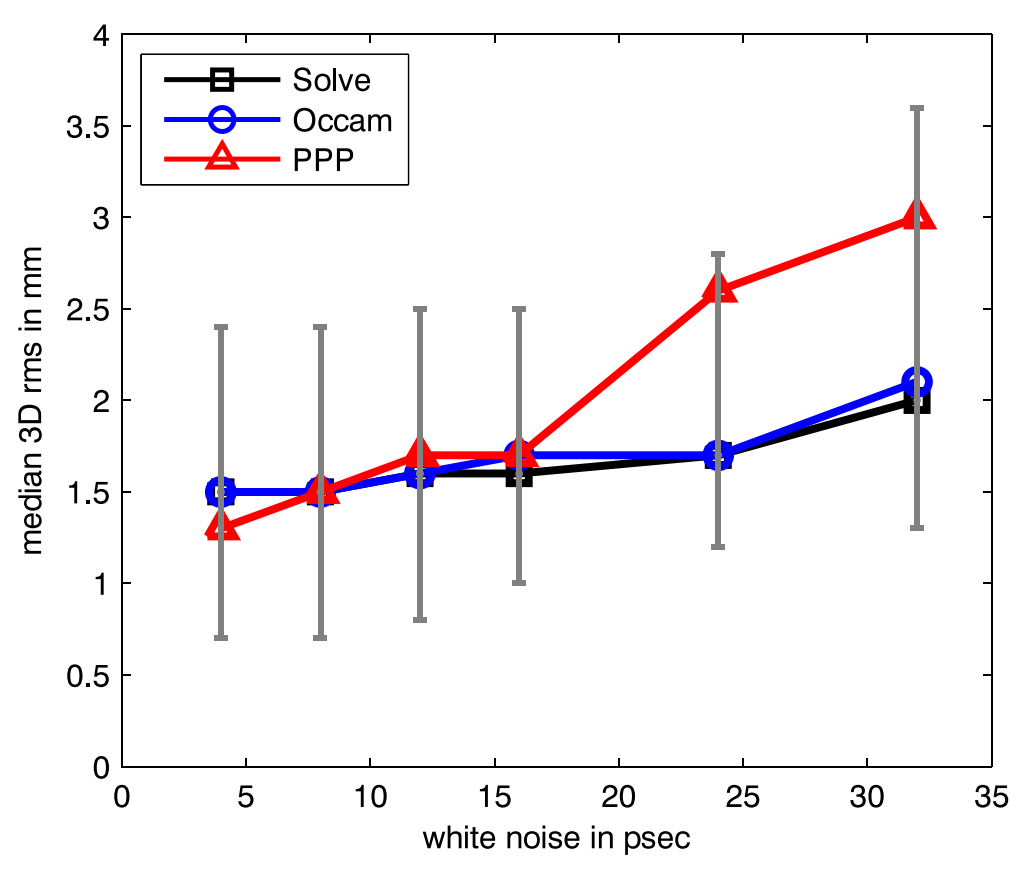


Fig. 5 median rms 3D position errors in mm vs. white noise standard deviation for all three estimation softwares. The grey whiskers indicate min and max values of the Solve solution.

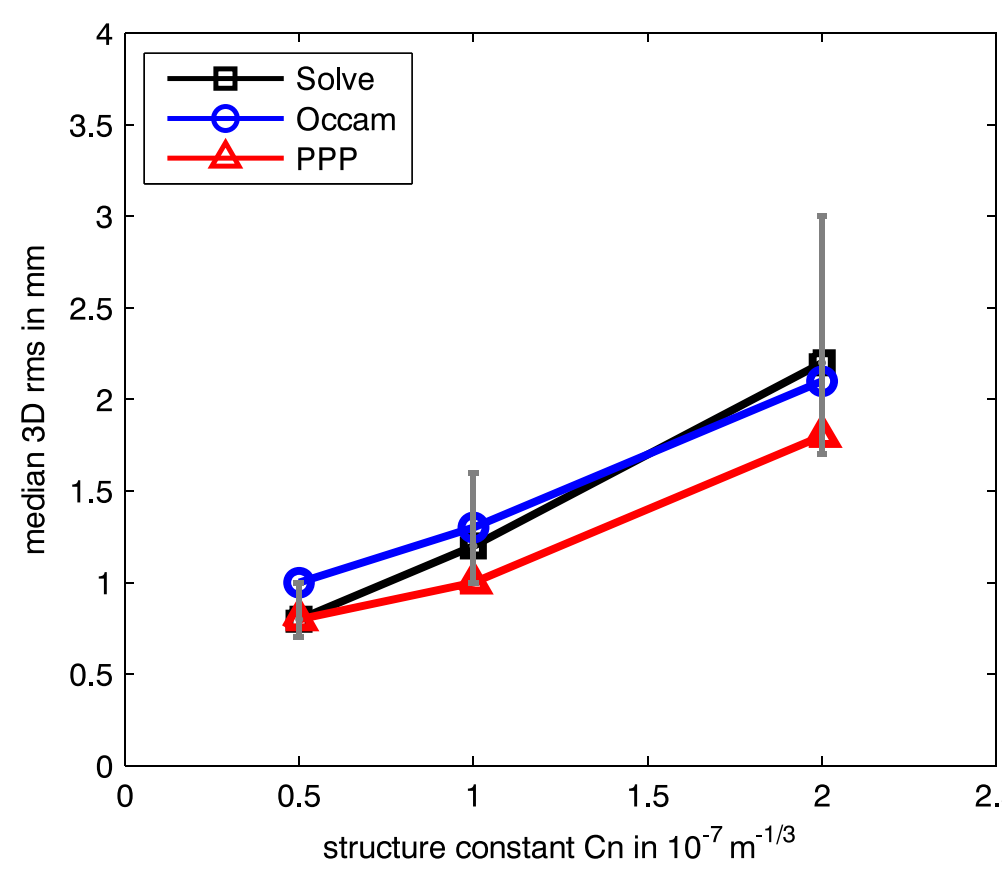


Fig. 6 median rms 3D position errors in mm vs. structure constants for all three estimation softwares. The grey whiskers indicate min and max values of the Solve solution.

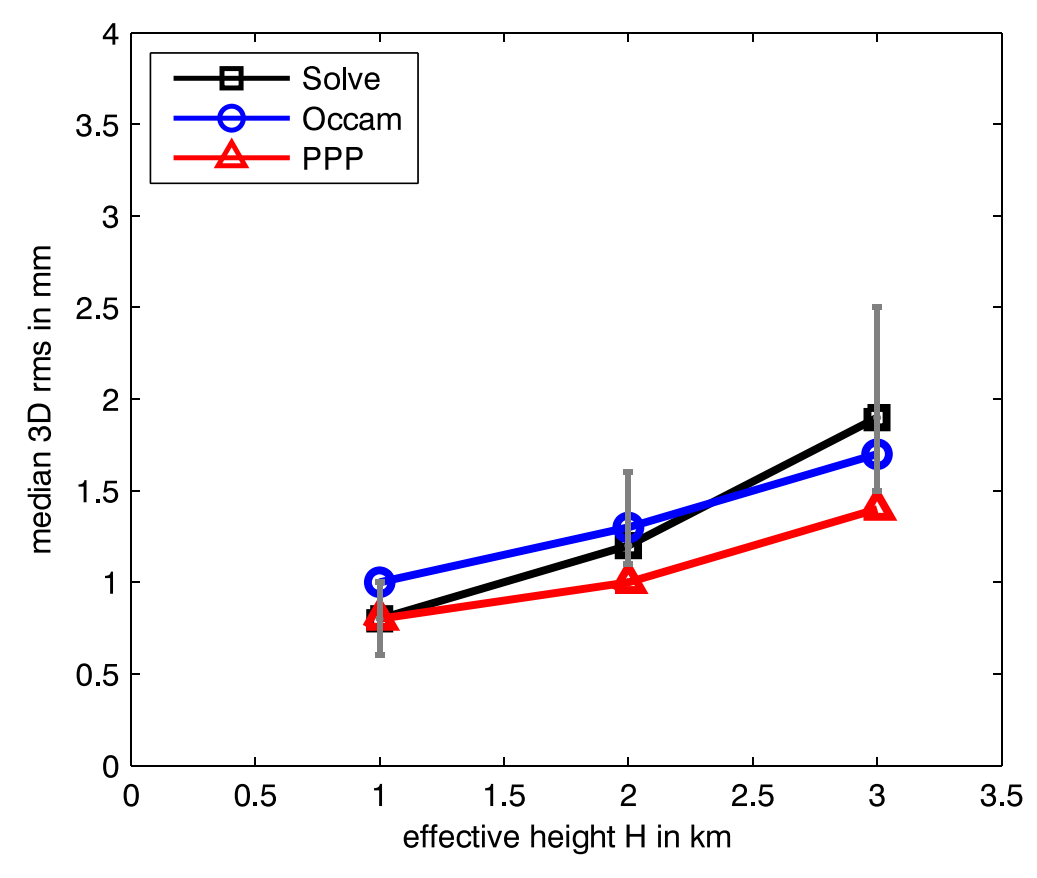


Fig. 7 median rms 3D position errors in mm vs. effective height for all three estimation softwares. The grey whiskers indicate min and max values of the Solve solution.

For clocks with a performance better than 1e-14 @ 50 min, which corresponds to the state-of-the-art clock performance, there is only a marginal improvement in the median 3D rms error .

The median 3D rms error is only slightly dependent on the delay measurement error (the anomalous behavior of the PPP solution is not yet understood).

The clear dependence of the median 3D rms error on Cn indicates that the troposphere remains the dominant stochastic error source even for VLBI2010.

4.4 Network size

To test the impact of the network size on the performance of the Earth orientation parameters (EOP) determination and the scale of the terrestrial reference frame (TRF) uniform sky schedules with 45 seconds source-switching intervals were generated for the VLBI2010 16-, 24-, and 32-station networks. The turbulence parameters were set to the following values: Cn = 2.4e-7 m-1/3, H = 1 km, v = 8 m/s towards East for all stations. Figure 8 shows rms EOP errors versus network size.

There is an improvement of ~ 30 % when increasing the number of stations from 16 to 32.

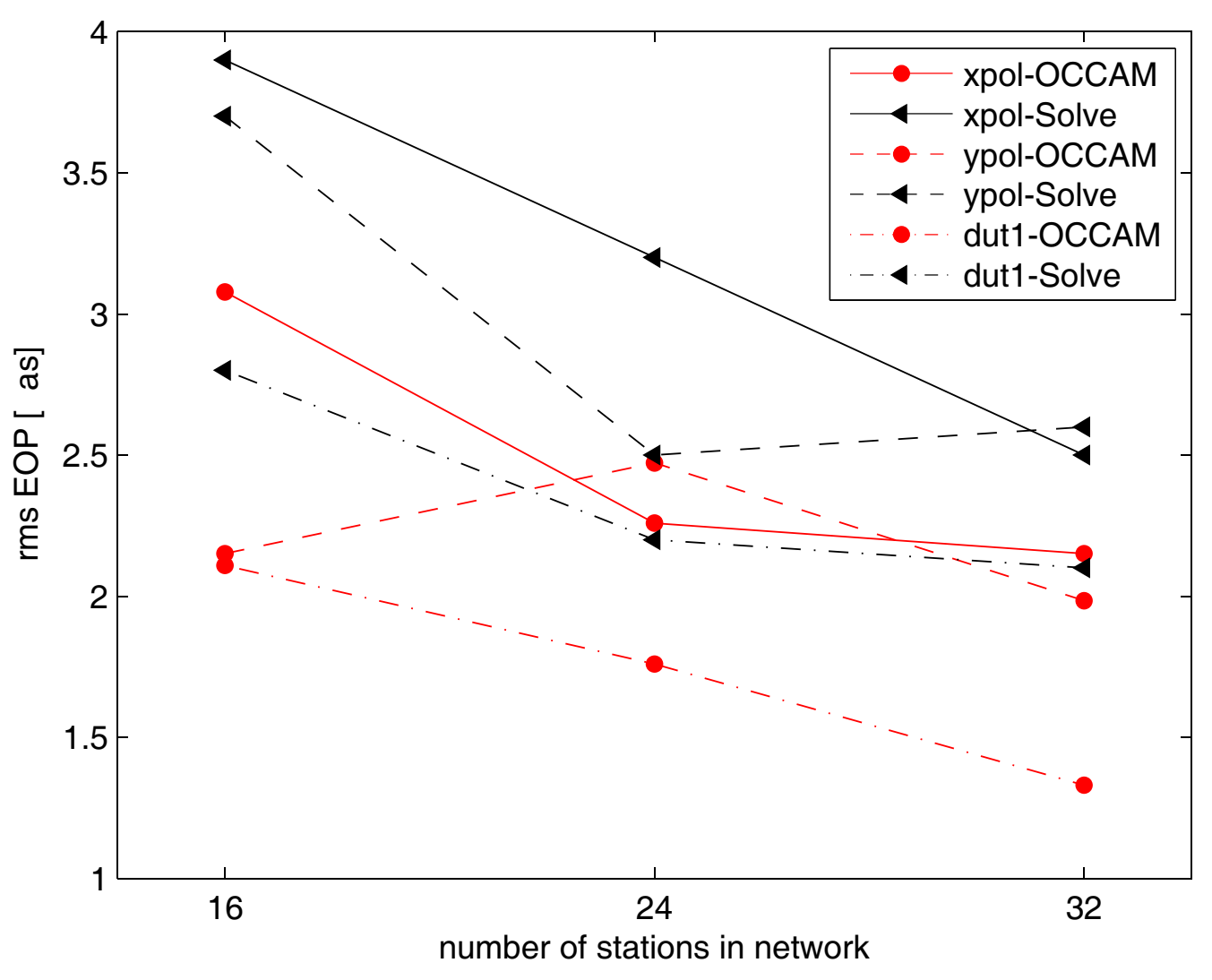


Fig. 8 rms of EOP versus network size by Occam (red dots) and Solve (black triangles) as derived from uniform sky schedules with source-switching intervals of 45 seconds.

4.5 Validation of the Monte Carlo simulators

The validation of the Monte Carlo simulators was done by comparing baseline repeatabilites obtained from the real CONT05 data to baseline repeatabilities obtained from simulated data for a 24-hour CONT05 schedule. Clock performance was set to an ASD of 1e-14 @ 50 min, the measurement errors were set to the formal delay errors reported for the CONT05 experiment, and the turbulent troposphere was generated using the list of VLBI2010 turbulence parameters (Petrachenko et al. 2009). Although it was expected that the results from the simulated data would be close to the results from the real data, they cannot be exactly the same, because in reality the turbulence parameters depend on the prevailing weather conditions and can vary considerably, while they are kept fix for the simulations.

Figure 9 shows baseline length repeatabilities versus baseline length by Occam (left plot) and Solve (right plot). While for Occam the repeatabilities are close, the simulated repeatability by the Solve solution is sligthly better than the real one. The reason for this is at present not fully understood.

We conclude that the predicted performance would not be too optimistic by more than 30 %.

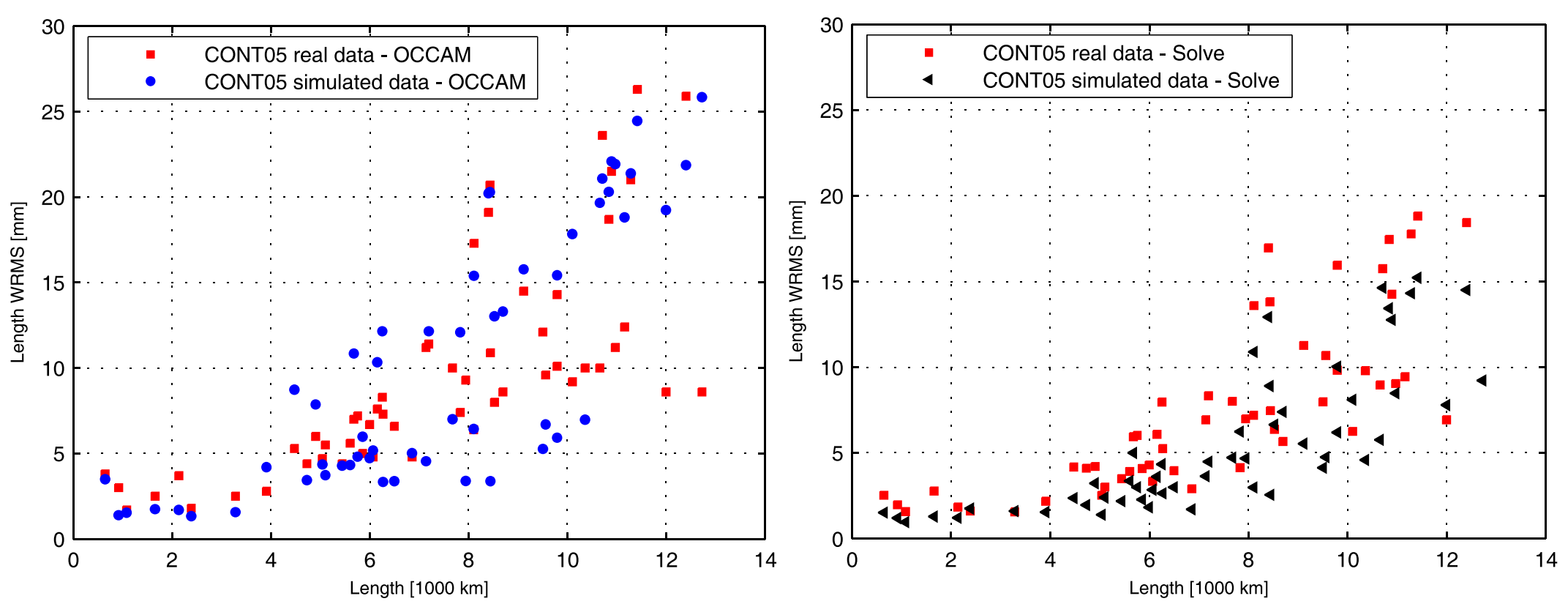


Fig. 9 baseline length repeatabilities obtained from real (red squares) and simulated (blue dots and black triangles, respectively) CONT05 data by Occam (left plot) and Solve (right plot).

5. Summary, conclusions and outlook

As Figure 2 shows, a significant improvement can be expected when decreasing the source-switching interval to less than one minute. The question where there is more potential for improvement once the observation density has been increased can be answered by looking at Figures 6 and 7, which show a clear dependence of the median 3D rms error on Cn and H. This indicates that the atmosphere remains the dominant stochastic error source for VLBI2010 (see also Nilsson and Haas 2009). Efforts to improve the troposphere models continue.

The significant decrease of the source switching-interval requires a reduction of the on-source time on one hand and of the slew time between sources on the other. Based on these considerations and the simulation results presented in Figure 2 the V2C recommended to install preferably either a single 12-m diameter antenna with high slew rate (e.g. 12°/s in azimuth) or a pair of 12-m diameter antennas with more moderate slew rates of e.g. 5°/s in azimuth (Petrachenko et al. 2009).

From Figure 4 it becomes clear that there is only a marginal improvement in the median 3D rms error when improving the clock performance beyond 1e-14 @ 50 min, i.e. beyond the state-of-the-art performance. Similar conclusions can be drawn from Figure 5 for a white noise below 4 ps. Nevertheless, the improvement of clock performance and the reduction of the delay measurement error are important to further reduce errors stemming from the troposphere and from various systematic error sources. Also, it is important to increase the quality of clock performance and delay measurements as the modeling of troposphere and other systematic errors might considerably improve in the near future.

Future simulation studies might include source structure effects, use more realistic VLBI2010 networks, address the transition period with mixed networks, and look into strategies to improve the delay measurement accuracy beyond 4 ps.

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