# GNSS slant delays in the analysis of VLBI Intensive sessions


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## 1. Abstract:

So-called VLBI Intensive sessions of the International VLBI Service for Geodesy and Astrometry (IVS) are dedicated to the rapid production of UT1-UTC estimates. However, the accuracy achieved with those sessions is still below what could be expected from formal uncertainties of the estimates. One of the reasons for that might be the inappropriate modelling of azimuthal asymmetries of the tropospheric delays, because usually no gradients are modelled or estimated. To overcome that deficiency, we apply tropospheric zenith delays and gradients from the analysis of Global Navigation Satellite Systems (GNSS) observations in the analysis of all VLBI Intensive sessions in 2013 and compare our results to length-of-day estimates determined with GNSS. We find significant improvement for certain types of VLBI Intensive sessions compared to the state-of-the-art analysis.


## 2. VLBI Intensive sessions

- The International VLBI Service for Geodesy and Astrometry (IVS) realises mostly 1-hour one-baseline sessions to estimate the Earth's phase of rotation, expressed as Universal Time (UT1).
- For this purpose dedicated sessions are:
  - ✓ INT1: WETTZELL (Germany) and KOKEE (Hawaii, USA) observe from Monday to Friday (session code XU).
  - ✓ INT2: TSUKUB32 (Japan) and WETTZELL observe on Saturday and Sunday (session code XK).
  - ✓ INT3: WETTZELL, TSUKUBA, and NYALES20 (Norway) observe on Monday (session code XK) (see Figure 1).
- For further information: http://ivscc.gsfc.nasa.gov

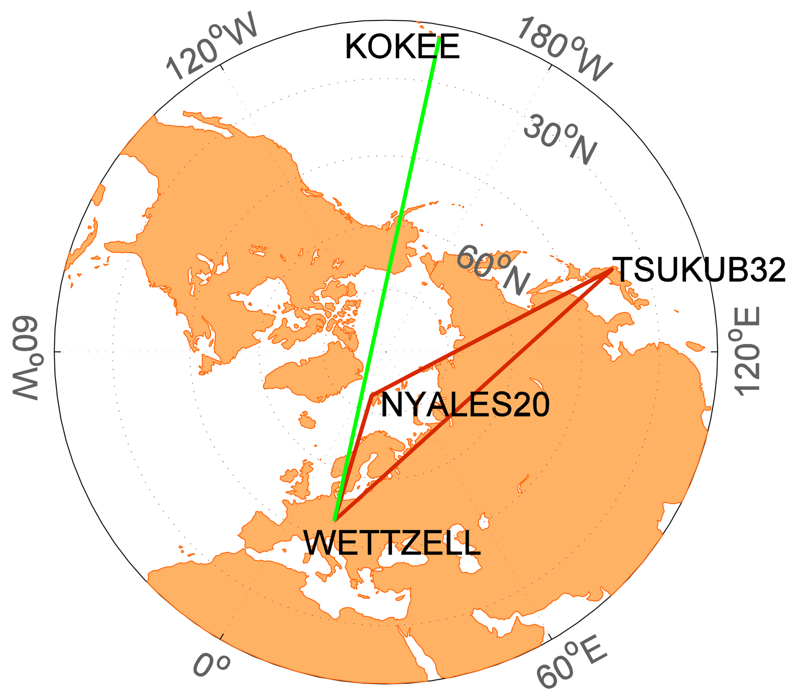


*Figure 1: Baseline geometry of the VLBI Intensive sessions with session codes XU and XK. The XU baseline is plotted in green and the XK baselines in red (stereographic map projection).*

## 3. Solution Descriptions

*Table 1: VLBI Intensive sessions (XU and XK) solution types*

| Solution Type | Slant wet delays | Azimuthal asymmetric delay | Additional information about solutions |
|---|---|---|---|
| Solution1 | Zenith Wet Delay (ZWD) estimated | Troposphere gradients not estimated | Standard solution of VLBI Intensive sessions with 5 estimated parameters: a ZWD offset for each VLBI site, one offset and a rate for the clock, UT1-UTC (ΔUT1). |
| Solution2 | ZWD estimated | Gradients from CODE | Center for Orbit Determination in Europe (CODE) and International GNSS Service (IGS) gradients were introduced a priori to the parameter estimation. |
| | | Gradients from IGS | |
| Solution3 | ZWD from CODE | Gradients from CODE | A constant total troposphere delay correction due to the height difference between GNSS and VLBI sites were added to ZHD and a ZWD offset was estimated per VLBI site. |
| | ZWD from IGS | Gradients from IGS | |
| Solution4 | ZWD from CODE | Gradients from CODE | Neither troposphere delay correction due to the height difference between GNSS and VLBI sites were added to ZHD nor a ZWD offset was estimated per VLBI site. |
| | ZWD from IGS | Gradients from IGS | |

## 4. Providing external troposphere slant delays

- ZHD were calculated from the pressure values at VLBI sites for each observation epoch (ZHD_VLBI) of VLBI Intensive sessions.
- ZWD and gradient estimates of GNSS were linearly interpolated to the observation epochs.
- Total troposphere delay correction due to the height difference at co-located sites (ΔZTD = ΔZHD + ΔZWD ) was added to ZHD_VLBI.
- ZWD at VLBI site for each observation epoch was derived as: ZWD_GNSS@VLBI = ZTD_GNSS - (ZHD_VLBI + ΔZTD).
- ZHD_VLBI and ZWD_GNSS@VLBI were mapped to slant direction using VMF.
- Gradients were mapped to slant direction as: $\Delta L = mfg(e)\cdot(Gn\cdot\cos(az)+Ge\cdot\sin(az))$ with the gradient mapping function mfg(e): $mfg(e)=1/(\sin(e)\cdot\tan(e)+0.0032)$.
- For each observation, troposphere slant delays SD are derived as: $SD = ZHD\_VLBI\cdot mfh_{VMF} + ZWD\_GNSS@VLBI\cdot mfw_{VMF} + \Delta L$

*Table 2: Summary of the properties of external troposphere delays in the analyses of VLBI Intensive sessions*

| | Zenith total / wet delay | Estimation interval of zenith delays | Estimation interval of gradients | Troposphere mapping function | Elevation cut off angle | Co-located GNSS sites with VLBI |
|---|---|---|---|---|---|---|
| GNSS CODE | ZTD | 2 hours | 2 hours | VMF | 3 degrees | wtzr, kokb, nyal, tskb |
| GNSS IGS | ZTD | 5 minutes | 5 minutes | GMF | 7 degrees | wtza, kokb, nya1, tskb |

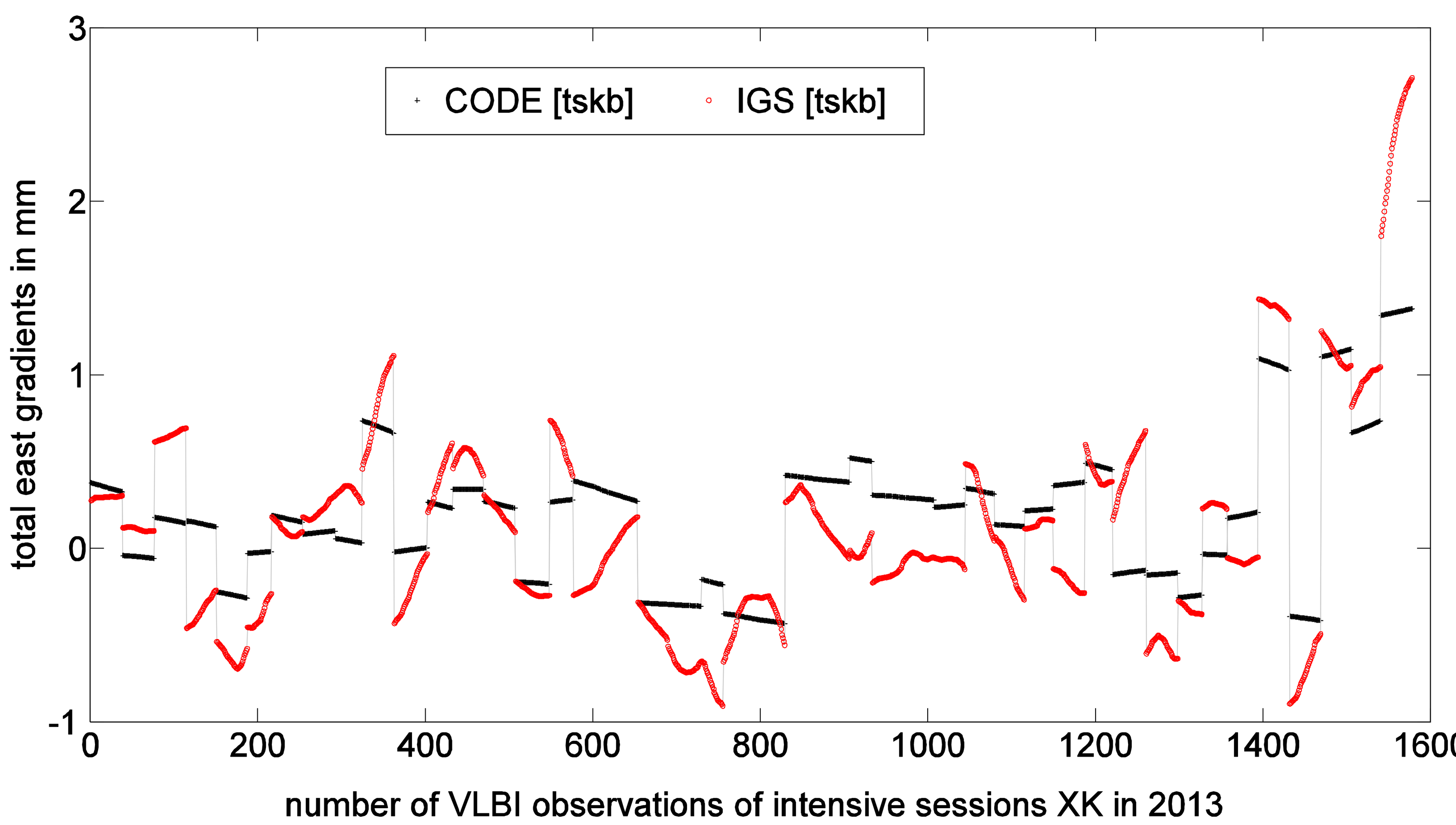


*Figure 2: Troposphere total east gradients at Tsukuba from GNSS CODE and GNSS IGS solutions at each observation epoch of VLBI Intensive sessions XK in 2013.*

## 5. Comparison of troposphere parameters

*Table 3: Biases and standard deviations of ZWD differences between GNSS CODE and GNSS IGS solutions in mm. Calculation of biases and standard deviations consists of all observation epochs of VLBI Intensive sessions when both GNSS CODE and GNSS IGS troposphere delays are available.*

| VLBI Intensive session code | GNSS CODE | GNSS IGS | bias ± std. dev. in mm [CODE(ZWD) – IGS(ZWD)] | total number of common epochs |
|---|---|---|---|---|
| XU | kokb | kokb | -0.9 ± 3.3 | 2844 |
| XU,XK | wtzr | wtza | 1.3 ± 2.9 | 4394 |
| XK | tskb | tskb | -0.8 ± 3.0 | 1578 |
| XK | nyal | nya1 | -2.0 ± 1.8 | 230 |

*Table 4: Biases and standard deviations of ZWD differences between GNSS CODE - VLBI and GNSS IGS - VLBI solutions in mm.*

| VLBI sites | GNSS CODE | bias ± std. dev. in mm [CODE(ZWD) – VLBI(ZWD)] (total number of observations) | GNSS IGS | bias ± std. dev. in mm [IGS(ZWD) – VLBI(ZWD)] (total number of observations) |
|---|---|---|---|---|
| KOKEE | kokb | 2.7 ± 6.6 (2915) | kokb | 3.7 ± 7.1 (2884) |
| TSUKUB32 | tskb | 8.1 ± 6.7 (1829) | tskb | 9.4 ± 7.1 (1578) |
| WETTZELL | wtzr | 4.4 ± 5.2 (4712) | wtza | 2.9 ± 5.8 (4434) |
| NYALES20 | nyal | 5.8 ± 1.8 (261) | nya1 | 7.7 ± 2.1 (230) |

*Table 5: Biases and standard deviations of north and east gradient differences between GNSS CODE and GNSS IGS solutions in mm.*

| GNSS CODE | GNSS IGS | bias ± std. dev. in mm [CODE(NGR) – IGS(NGR)] | bias ± std. dev. in mm [CODE(EGR) – IGS(EGR)] | Total number of common epochs |
|---|---|---|---|---|
| kokb | kokb | 0.0 ± 0.5 | 0.1 ± 0.5 | 2915 |
| tskb | tskb | -0.1 ± 0.5 | 0.1 ± 0.4 | 1829 |
| wtzr | wtza | -0.1 ± 0.4 | -0.1 ± 0.3 | 4712 |
| nyal | nya1 | -0.4 ± 0.3 | 0.1 ± 0.2 | 261 |

## 6. Results

- In total 204 VLBI Intensive sessions (XU and XK) with the GNSS CODE delays and 196 sessions with the GNSS IGS delays were analysed. The XU and XK sessions with ΔUT1 formal errors in Solution 1 larger than 30 µs were excluded from the statistical comparisons.
- LOD were calculated from the estimated ΔUT1 values of XU and XK sessions using the equation below:

$$LOD(t_0)=\left[\frac{\Delta UT1(t_2)-\Delta UT1(t_1)}{t_2-t_1}\right].1\ \text{day},\qquad (t_2-t_1< 1.2\ \text{day})$$

  where $t_2$ and $t_1$ are the consecutive estimation epochs of ΔUT1, $t_0$ denotes the epoch of LOD and calculated as: $(t_1+t_2)/2$.
- The daily LOD values from GNSS CODE solution and IERS C04 08 series were interpolated to the LOD epochs of XU and XK VLBI Intensive sessions using ±5 point Lagrange interpolation.

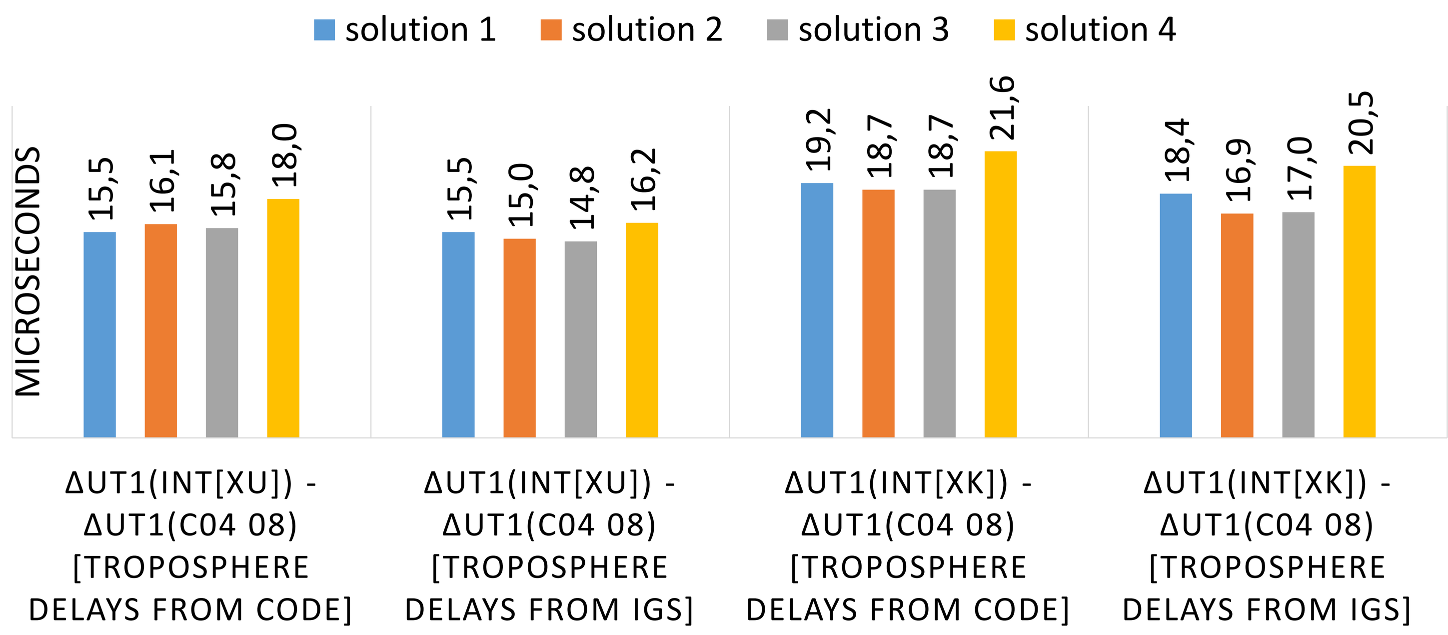


*Figure 3: Standard deviations of ΔUT1 which were estimated from VLBI Intensive sessions, i.e. XU and XK, observed in 2013. The a priori EOP series was set to IERS C04 08 when analysing the sessions.*

*Table 6: Total number of ΔUT1 and LOD values used for the statistical comparisons.*

| | GNSS CODE DELAYS | | GNSS IGS DELAYS | |
|---|---|---|---|---|
| | XU | XK | XU | XK |
| ΔUT1 | 159 | 41 | 157 | 35 |
| LOD | 85 | 24 | 81 | 18 |

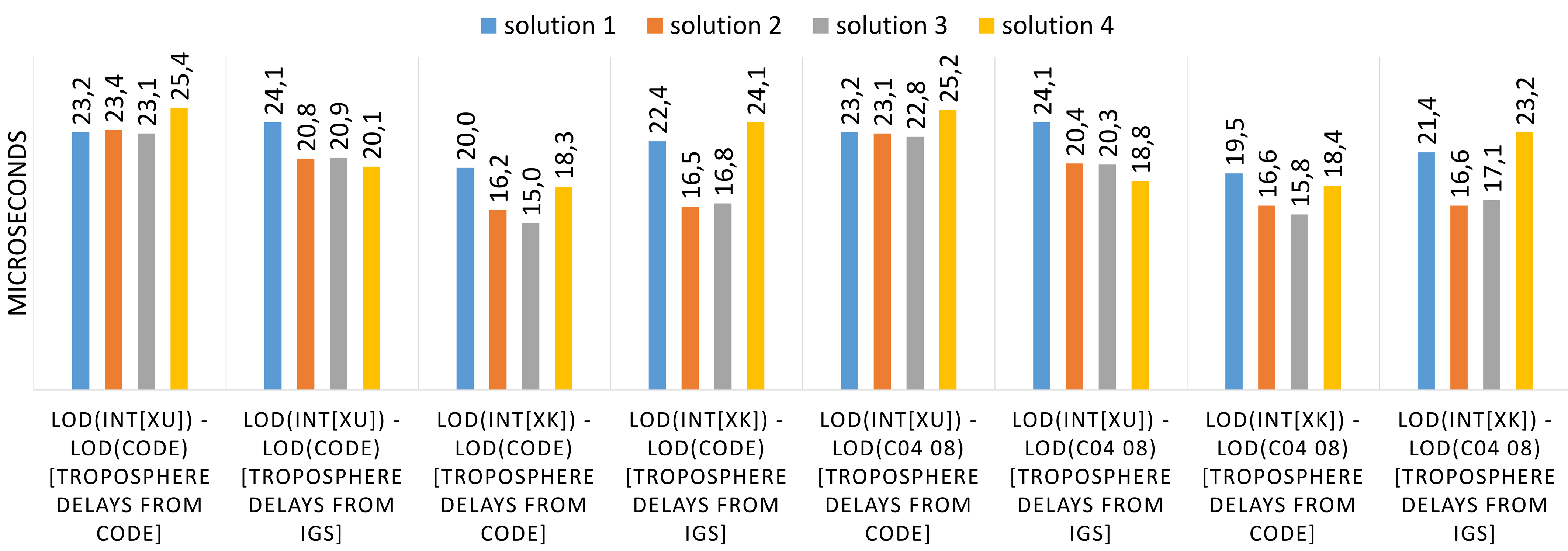


*Figure 4: Standard deviations of LOD differences between the estimates of VLBI Intensive sessions and those derived from a GNSS CODE solution and IERS C04 08 combined EOP series.*

## 7. Conclusions

- Compared to UT1 values from IERS C04 08, there is no improvement when introducing external tropospheric delays from GNSS for XU sessions and only a small improvement for XK sessions. It should be stressed here that the UT1 values of the IERS C04 08 series heavily rely on UT1 values from VLBI Intensive sessions derived without external delays.
- There is a clear improvement in LOD when compared to LOD estimates from the solutions of GNSS when applying external tropospheric delays. The improvement is largest for XK sessions with gradients from GNSS IGS and GNSS CODE and for XU sessions with gradients by GNSS IGS (improvement by up to 5 µs).
- We do not see any additional significant improvement of LOD agreement when external ZWD are introduced.
- Additional ZWD need to be estimated.