TECHNISCHE UNIVERSITÄT WIEN
Vienna University of Technology

Dissertation

Sub-Daily Parameter Estimation in VLBI Data Analysis

Supervisors
o.Univ.-Prof. Dipl.-Ing. Dr.techn. Harald Schuh
Priv.-Doz. Dr.-Ing. Axel Nothnagel
Examiners
Prof. Dr. Hansjörg Kutterer
Dr. Johannes Böhm

MSc Kamil Teke
Vienna University of Technology,
Institute of Geodesy and Geophysics, Vienna, Austria.
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Overview

- The aim of this thesis.
- Continuous piece-wise linear offset (CPWLO) functions.
- VLBI clock error and modelling clock breaks.
- Troposphere delay in VieVS.
- Comparisons of troposphere zenith delays and gradients during IVS-CONT08.
- Analyses on VieVS hourly antenna coordinate estimates during IVS-CONT05.
- Conclusions.
- Outlook and future perspectives.

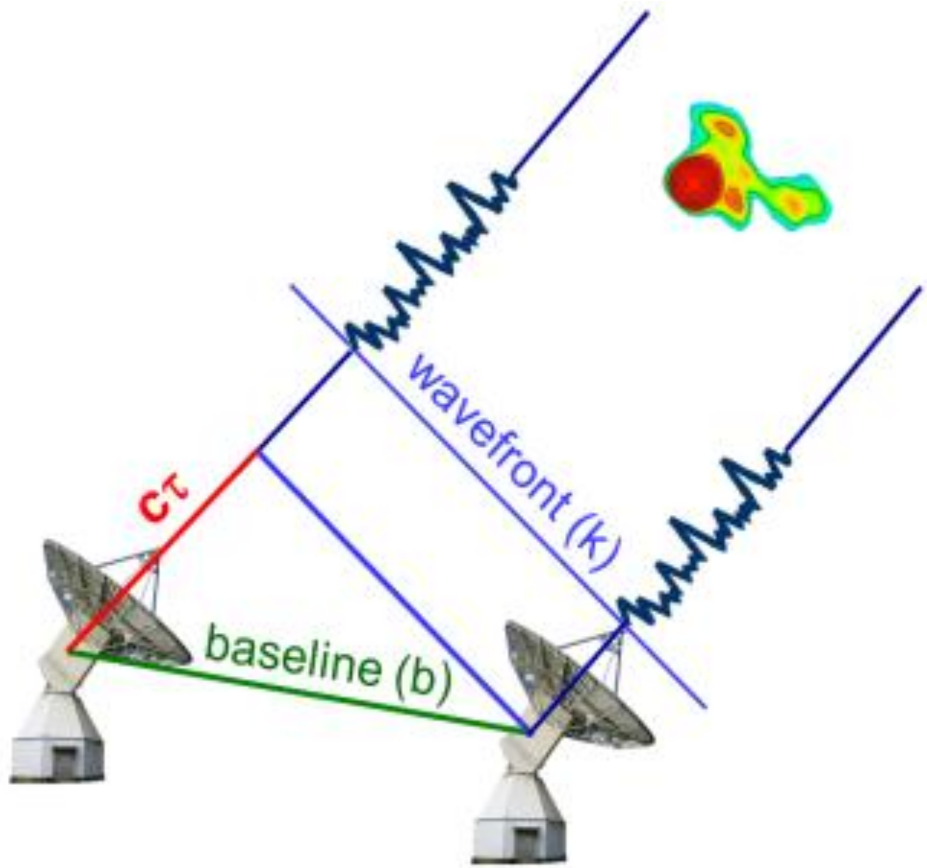
Aim of the thesis

- In the past usually one parameter set (i.e. station coordinates, troposphere parameters, clock parameters, ...) for one 24h session was estimated.

- Nowadays we want to increase the time resolution to 3h, 2h, 1h or even shorter because many geodynamical and astronomical effects contain sub-diurnal periods.

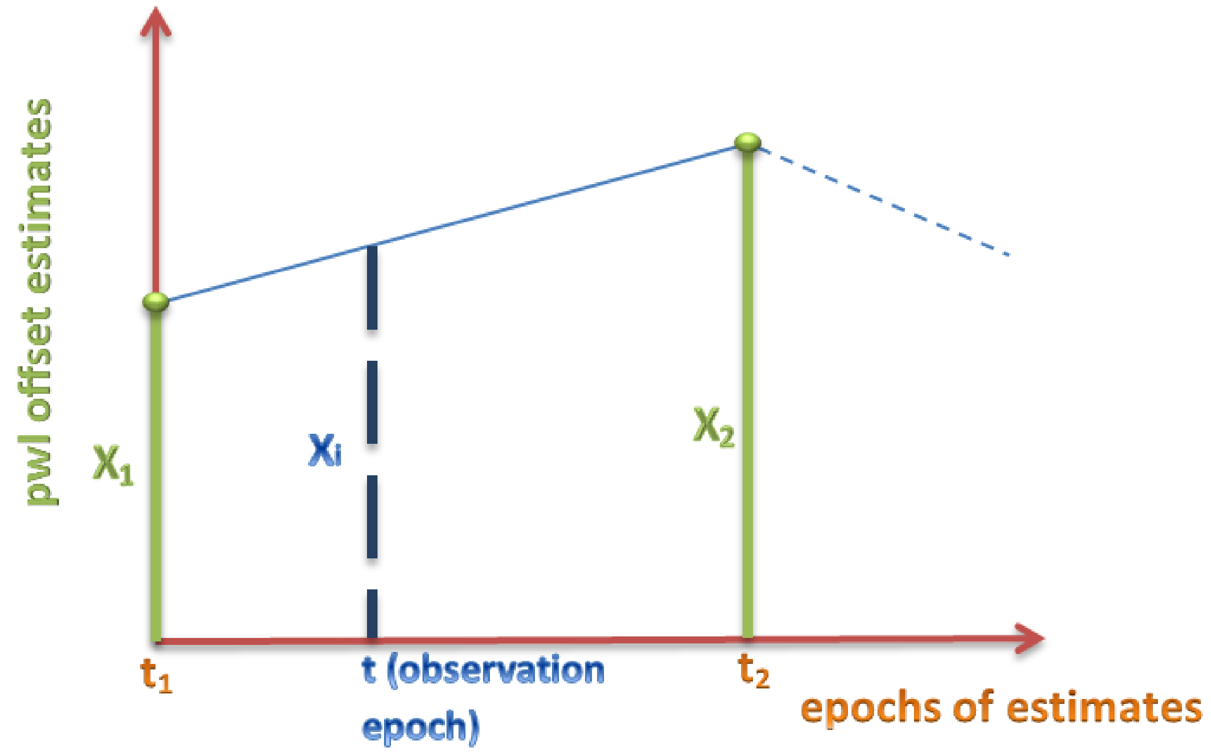
- Thus, aim of this thesis is to demonstrate that these parameters can be reliably determined from VLBI with high time resolution.

VLBI delay model



$$\tau = -\frac{1}{c}.b^T.W.R.Q.k + \tau_{corrections}$$

Continuous piece-wise linear offset (CPWLO) functions



$$x_i = x_1 + \frac{t - t_1}{t_2 - t_1}(x_2 - x_1)$$

Partial derivatives of the delay model w.r.t. a sub-daily parameter to be estimated at consecutive epochs

$$\frac{\partial \tau(t)}{\partial x_1} = \frac{\partial \tau(t)}{\partial x_i} \cdot \frac{\partial x_i}{\partial x_1} \rightarrow \frac{\partial x_i}{\partial x_1} = 1 - \frac{t - t_j}{t_{j+1} - t_j}$$

$$\frac{\partial \tau(t)}{\partial x_2} = \frac{\partial \tau(t)}{\partial x_i} \cdot \frac{\partial x_i}{\partial x_2} \rightarrow \frac{\partial x_i}{\partial x_2} = \frac{t - t_j}{t_{j+1} - t_j}$$

$$t_j < t < t_{j+1}$$

x_i is the estimated parameter at epochs t_j and t_{j+1}

e.g. **ΔUT1** is the estimated parameter at epochs **15:00** and **16:00 UTC**

Least-squares adjustment

offset(t+1) - offset(t) = 0 ± m_{c_rel} → **relative constraints**
Example: m_{c_rel} = 30 mas/day → X_{pol} CPWLO relative constraints are loose.
m_{c_rel} = 0.001 mas/day → X_{pol} CPWLO relative constraints are tight.

offset(t) = 0 ± m_{c_abs} → **absolute constraints**
Example: m_{c_abs} = 2 mm → Troposphere east gradients absolute constraints are loose.
m_{c_abs} = 0.01 mm → Troposphere east gradients absolute constraints are tight.

$$N = \begin{bmatrix} A^T P A + H^T P_H H & C^T \\ C & 0 \end{bmatrix} \quad b = \begin{bmatrix} A^T P oc + H^T P_H och \\ b_c \end{bmatrix}$$

parameter vector
(estimates)

$$x = N^{-} b$$

$$m_0 = (v^T P v + v_H^T P_H v_H) / (n_{obs} + n_{constr} - n_{unk})$$

$$K_x = m_0 N^{-}$$ → variance-covariance matrix of the estimates

VLBI clock error

$$\Delta\tau_{clk}^{poly}(t) = \beta_0 + \beta_1(t - t_0) + \beta_2(t - t_0)^2$$

➡ quadratic polynomial for each clock

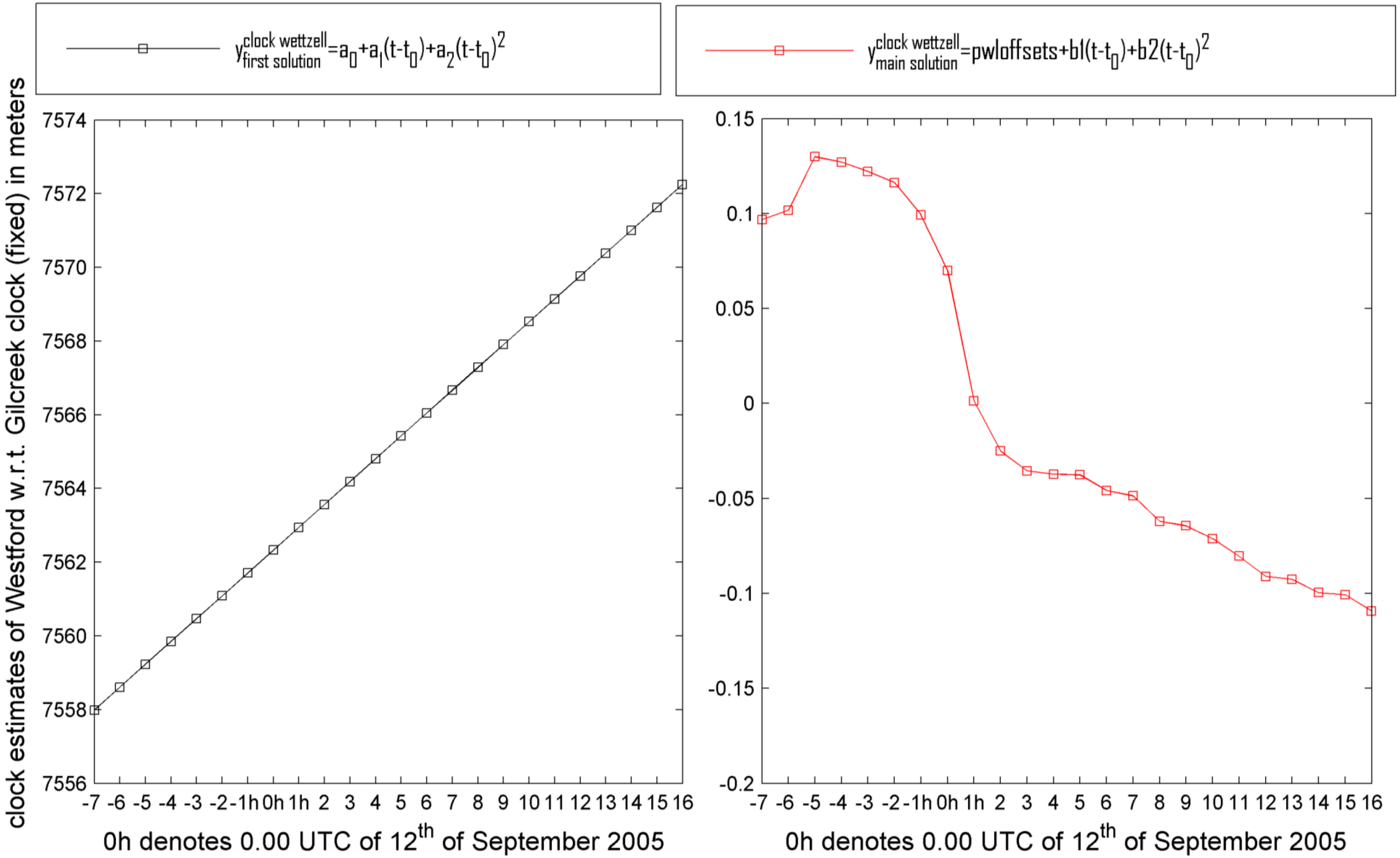
$$\Delta\tau_{clk}^{CPWLO}(t) = x_1 + \frac{t - t_1}{t_2 - t_1}(x_2 - x_1)$$

➡ CPWLO for each clock e.g. at each UTC integer hour (t_1 and t_2)

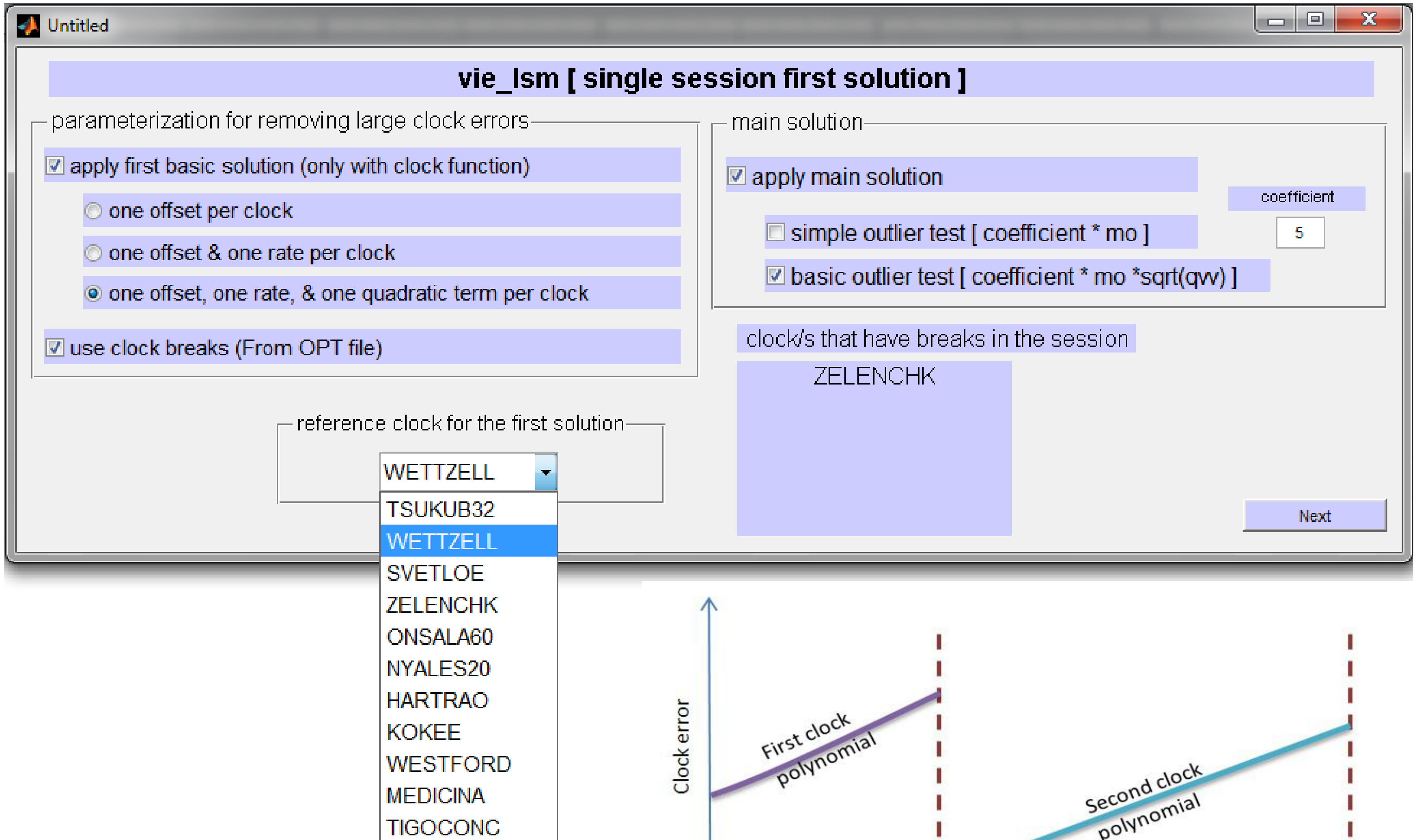
$$\Delta\tau_{clk}(t) = \Delta\tau_{clk}^{poly}(t) + \Delta\tau_{clk}^{CPWLO}(t)$$

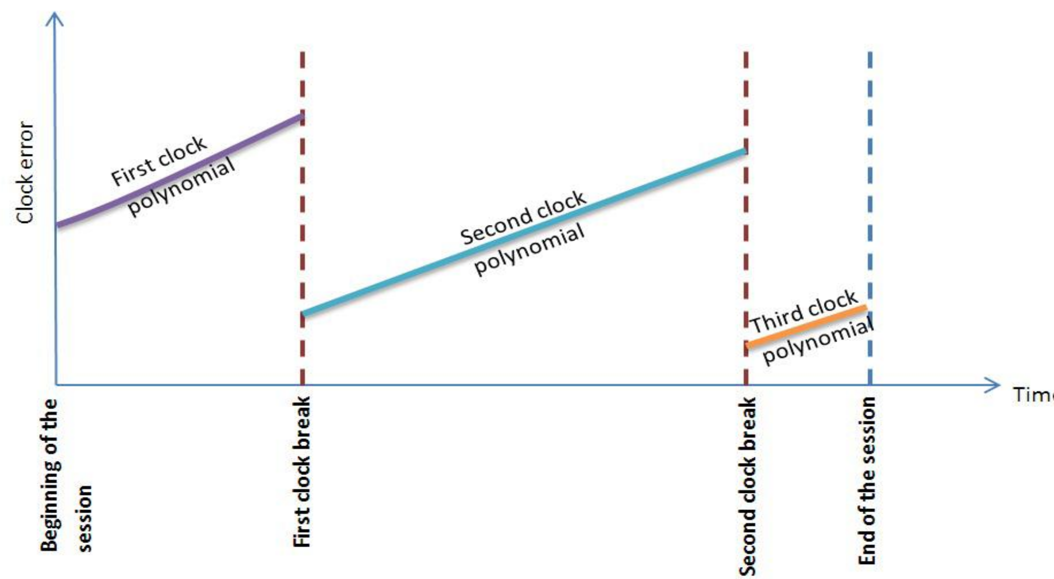
➡ Total clock error at epoch t

VLBI clock error

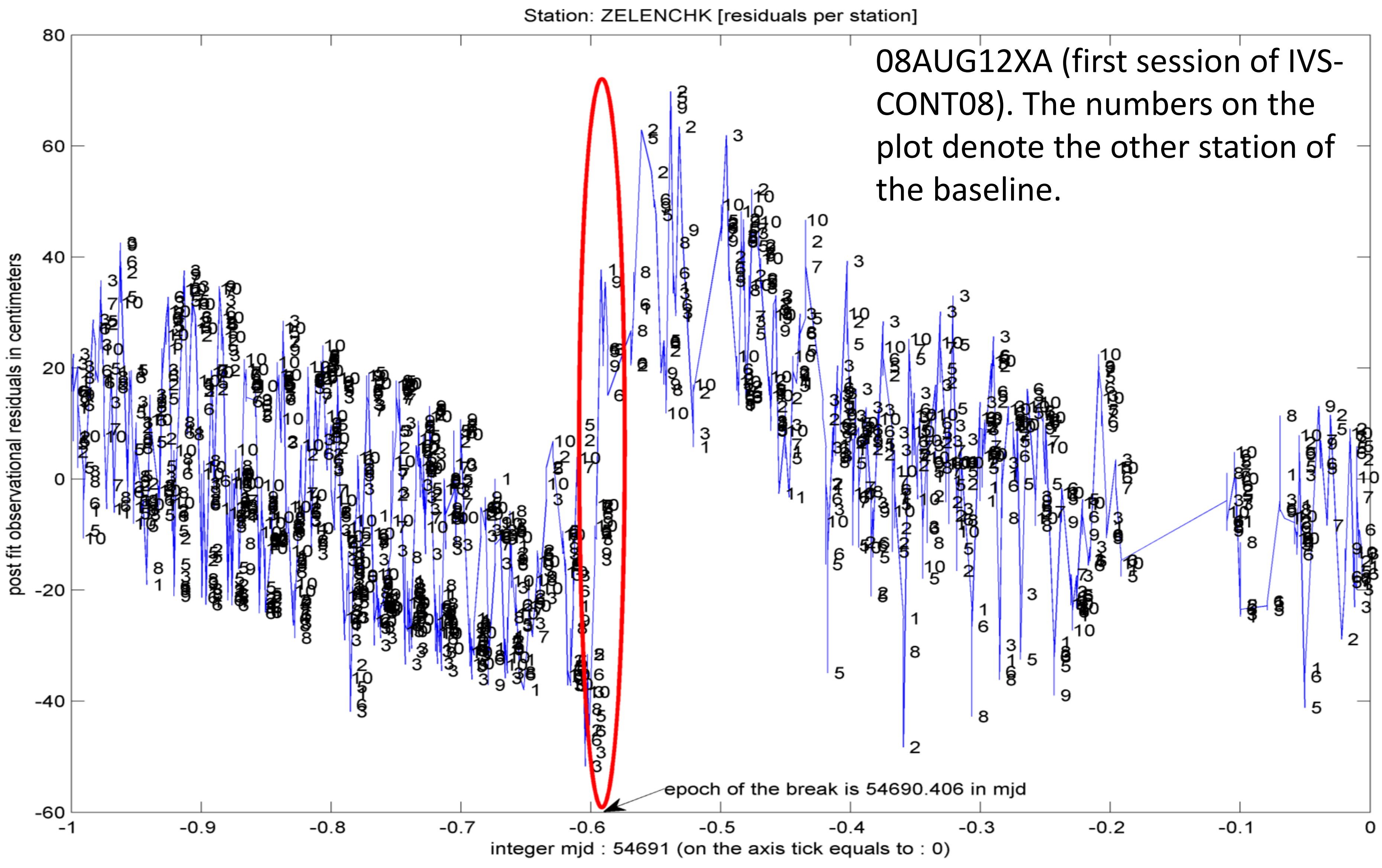


Modeling clock breaks

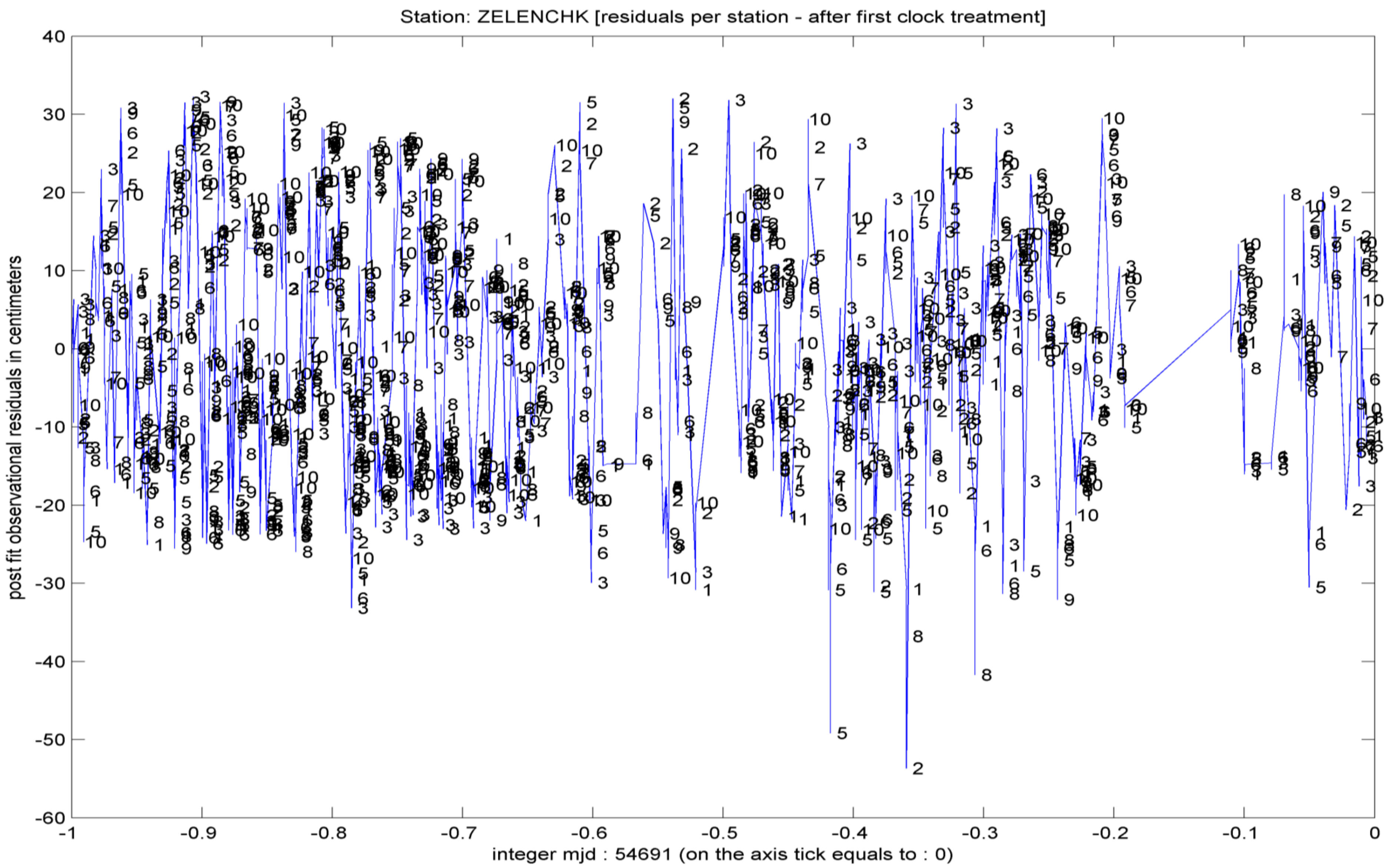




Clock break (Zelenchukskaya) is not corrected (08AUG12XA)



Clock break (Zelenchukskaya) is corrected (08AUG12XA)



Troposphere delay in VieVS

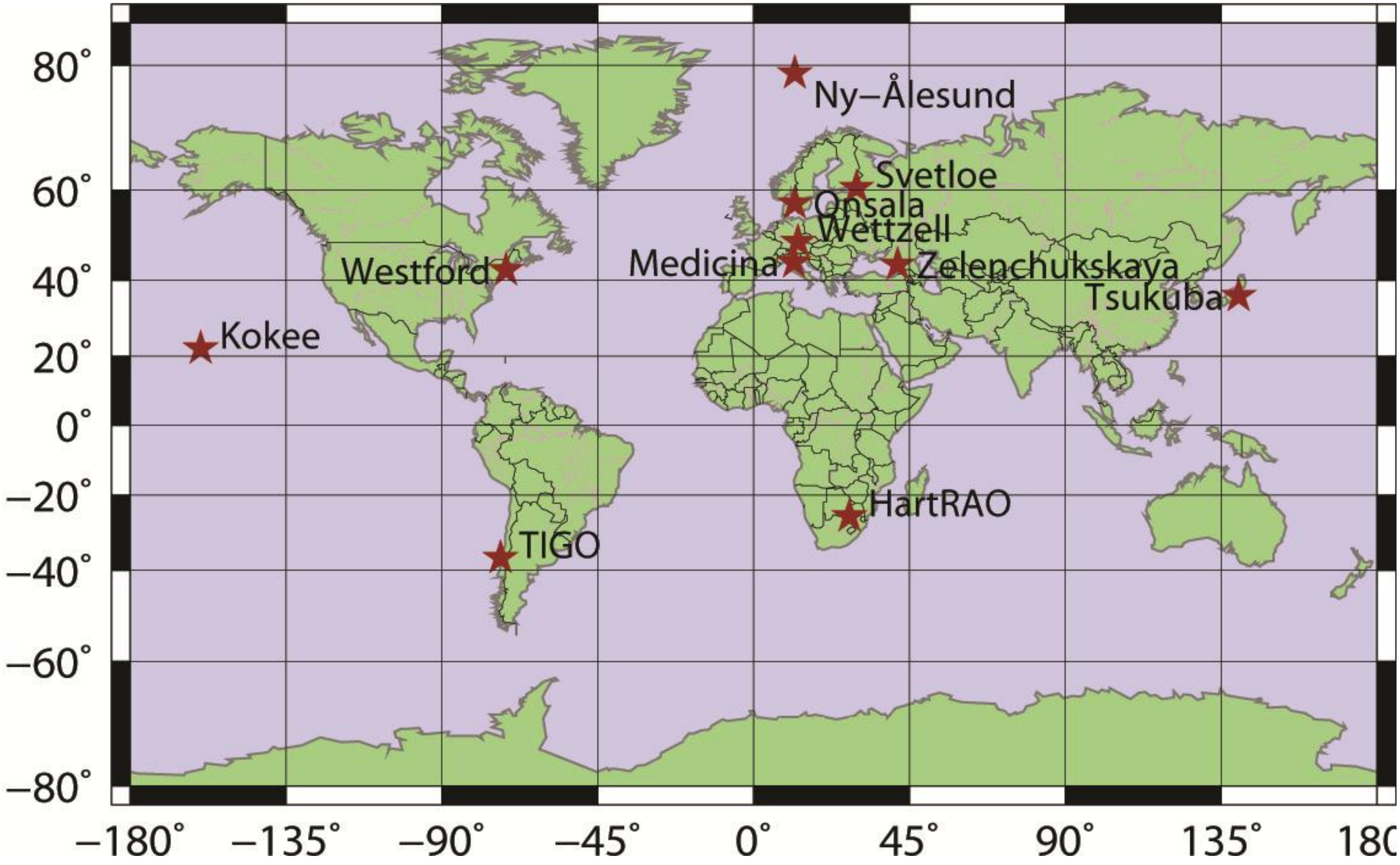
$$\Delta\tau_{trop} = 10^{-6}\int_0^{H_{trop}} \left[N_h(s) + N_w(s)\right] ds$$

$$\Delta\tau_{trop}(\alpha,\varepsilon) = ZHD\, m_h(\varepsilon) + ZWD\, m_w(\varepsilon) + m_w(\varepsilon)\cot(\varepsilon)\left[G_n\cos(\alpha) + G_e\sin(\alpha)\right]$$

- ZHD: reduced from observations a priori to the adjustment (Saastamoinen, 1972)
- ZWD: estimated
- G_n: estimated
- G_e: estimated

Comparisons of troposphere zenith delays and gradients during IVS-CONT08.

IVS-CONT08 co-located sites



first observation: Tuesday August 12, 2008 @ 00:00:00 UT

last observation: Tuesday August 26, 2008 @ 23:59:59 UT

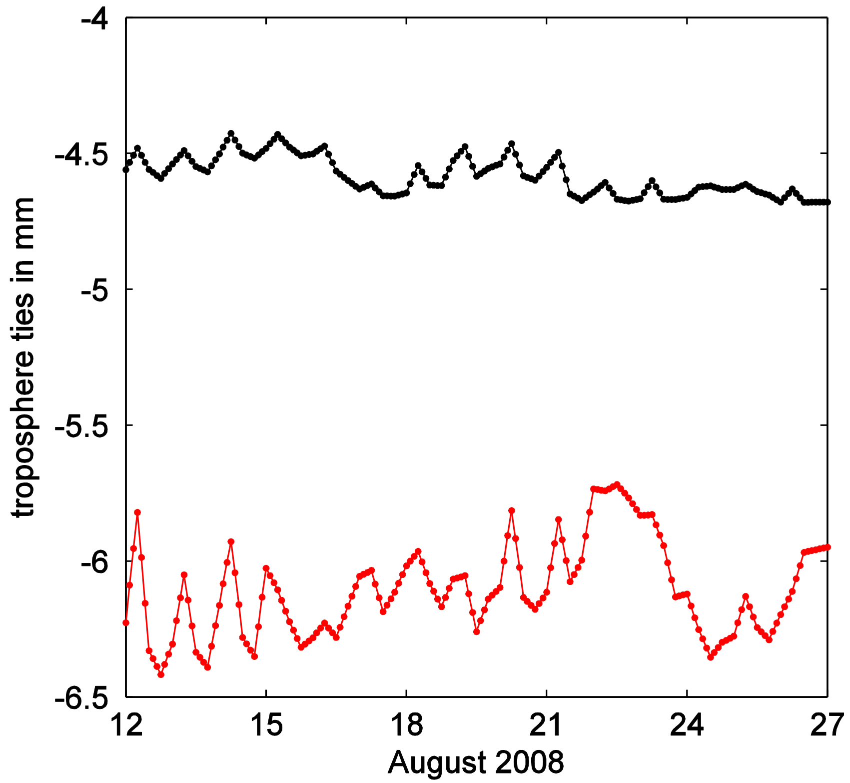
Comparisons of troposphere zenith delays and gradients during IVS-CONT08 at co-located sites

Technique	Zenith total/wet delay	Estimation interval of zenith delays	Estimation interval of gradients
VLBI – VieVS	ZWD, ZTD	30 minutes	2 hours
VLBI – IVS	ZWD, ZTD	1 hour	1 hour
GPS – IGS	ZTD	5 minutes	-
GPS – CODE	ZTD	2 hours	1 day
DORIS	ZTD	Per satellite pass	1 day
WVR	ZWD	30 minutes	2 hours
ECMWF	ZWD, ZTD	6 hours	6 hours
JMA-KARAT	ZTD	3 hours	3 hours
JMA-CReSS	ZTD	1 hour	1 hour
HIRLAM	ZWD	3 hours	-

VieVS: Vienna VLBI Software, IVS: International VLBI Service for Geodesy and Astrometry, IGS: International GNSS Service, CODE: Center for Orbit Determination, DORIS: Doppler Orbitography and Radiopositioning Integrated by Satellite, WVR: Water Vapor Radiometer, ECMWF: European Center for Medium-Range Weather Forecasts, JMA-KARAT: Japan Meteorological Agency - Kashima Ray Tracing Tools, JMA-CReSS: Japan Meteorological Agency – Cloud Resolving Storm Simulator, HIRLAM: High Resolution Limited Area Model.

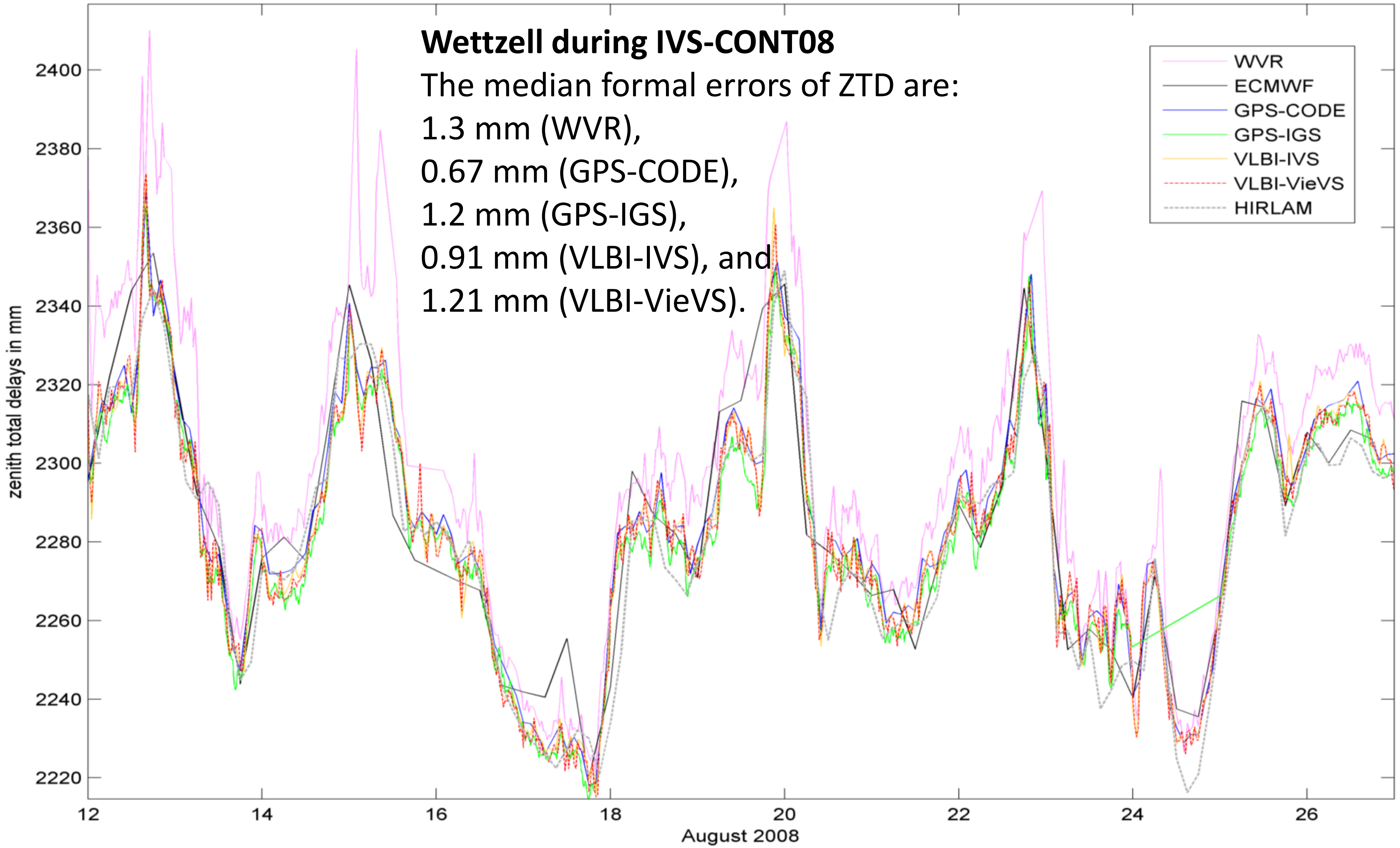
Troposphere ties

- The reference height were selected as the VLBI reference points heights.
- The troposphere ZTD ties were calculated at each common epoch.

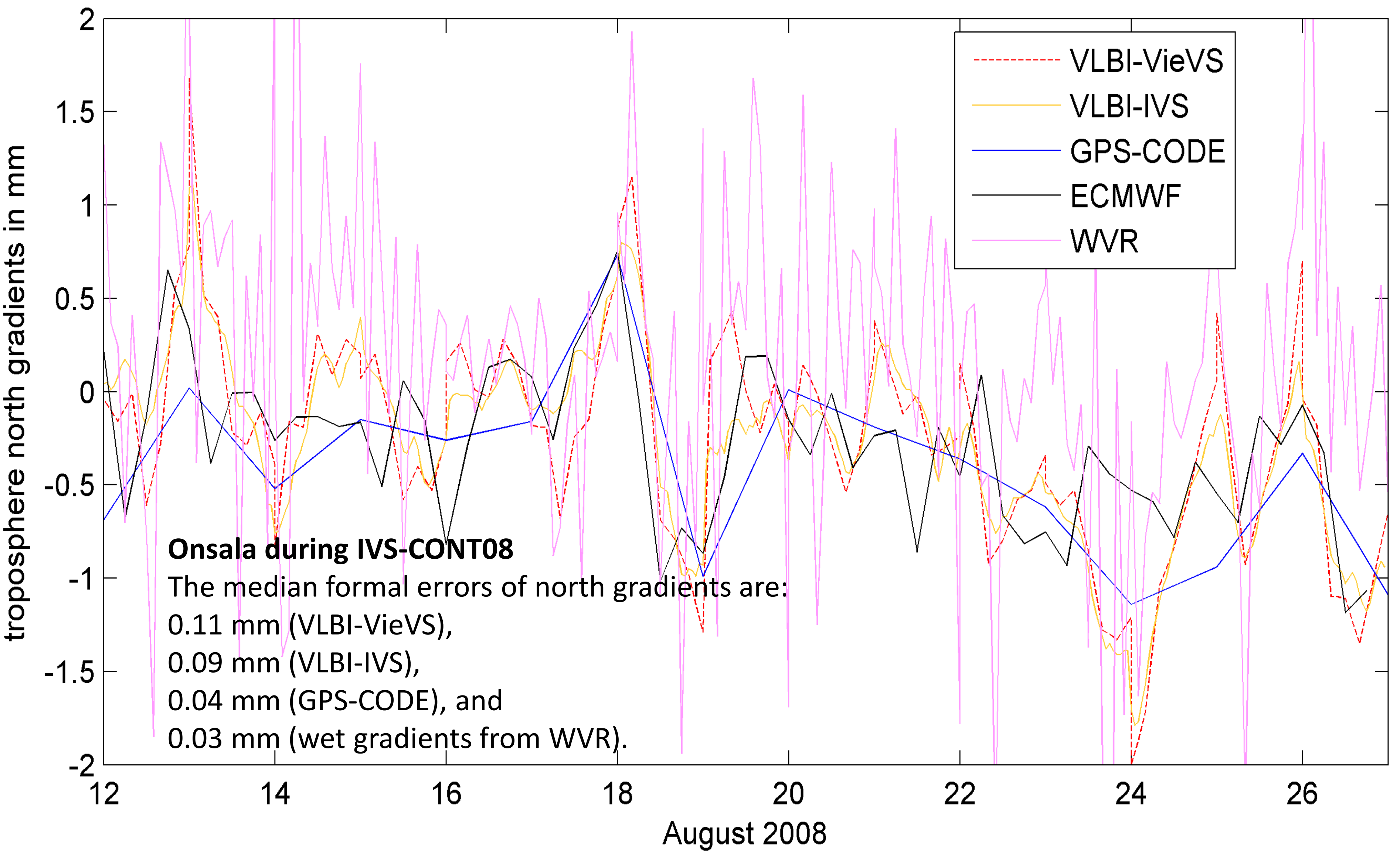


Troposphere ties between the GPS antenna TSKB and the VLBI antenna TSUKUB32 during IVS-CONT08, calculated for all common epochs. Red and black dotted lines illustrate total and hydrostatic ties, respectively.

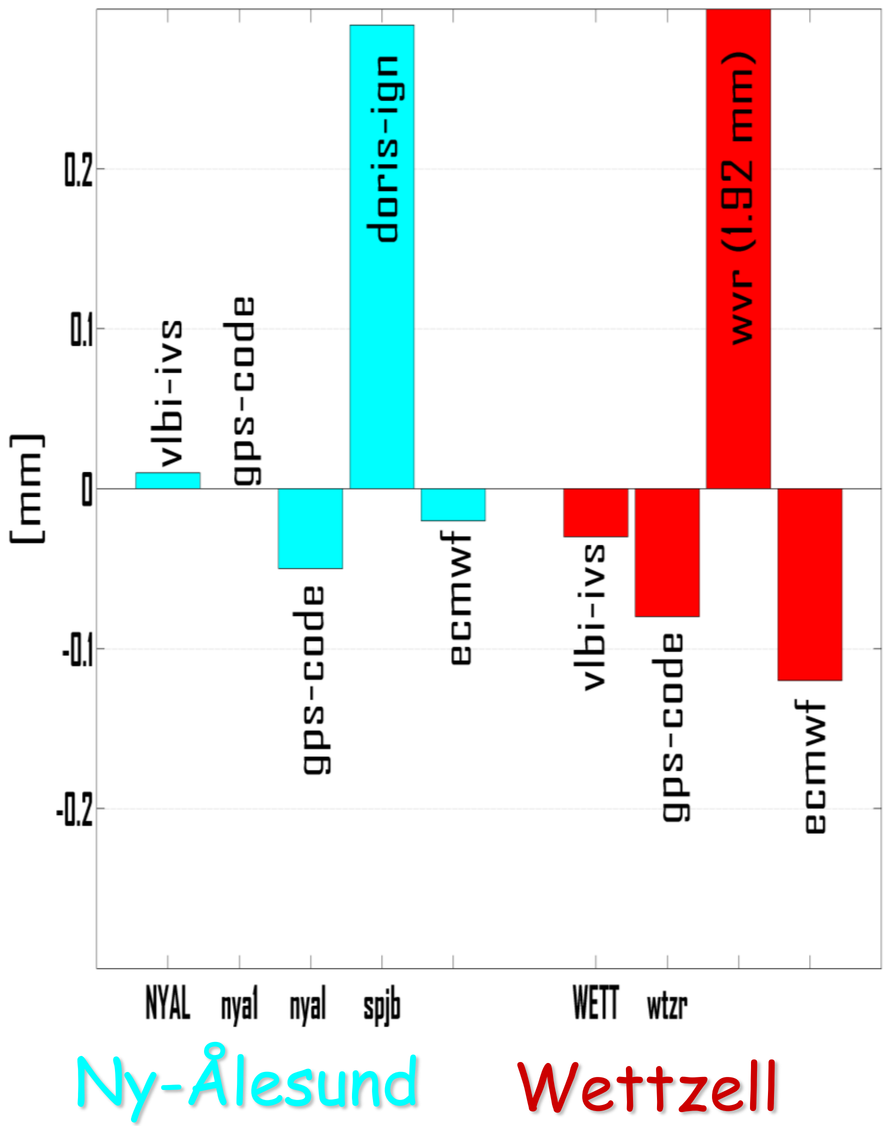
Troposphere zenith total delays at co-located site Wettzell during IVS-CONT08

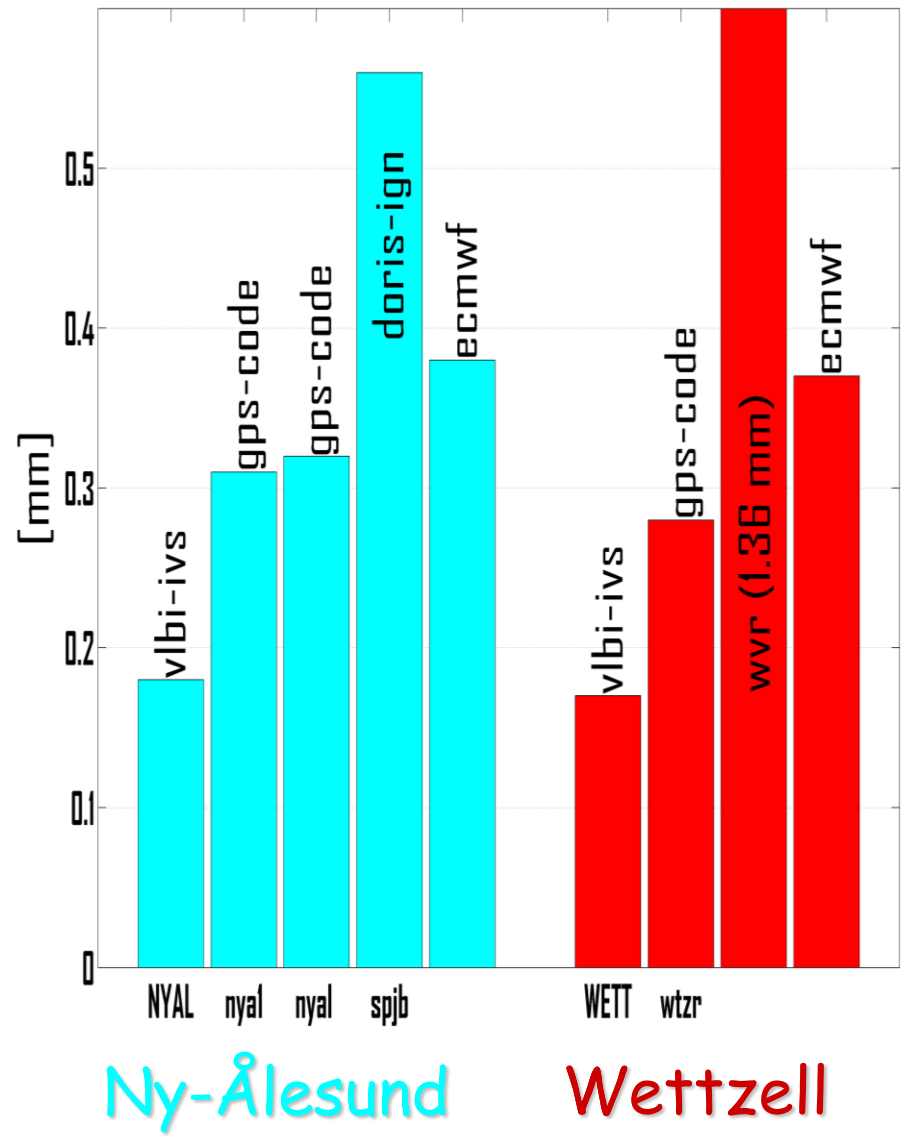


Troposphere north gradients at co-located site Onsala during IVS-CONT08

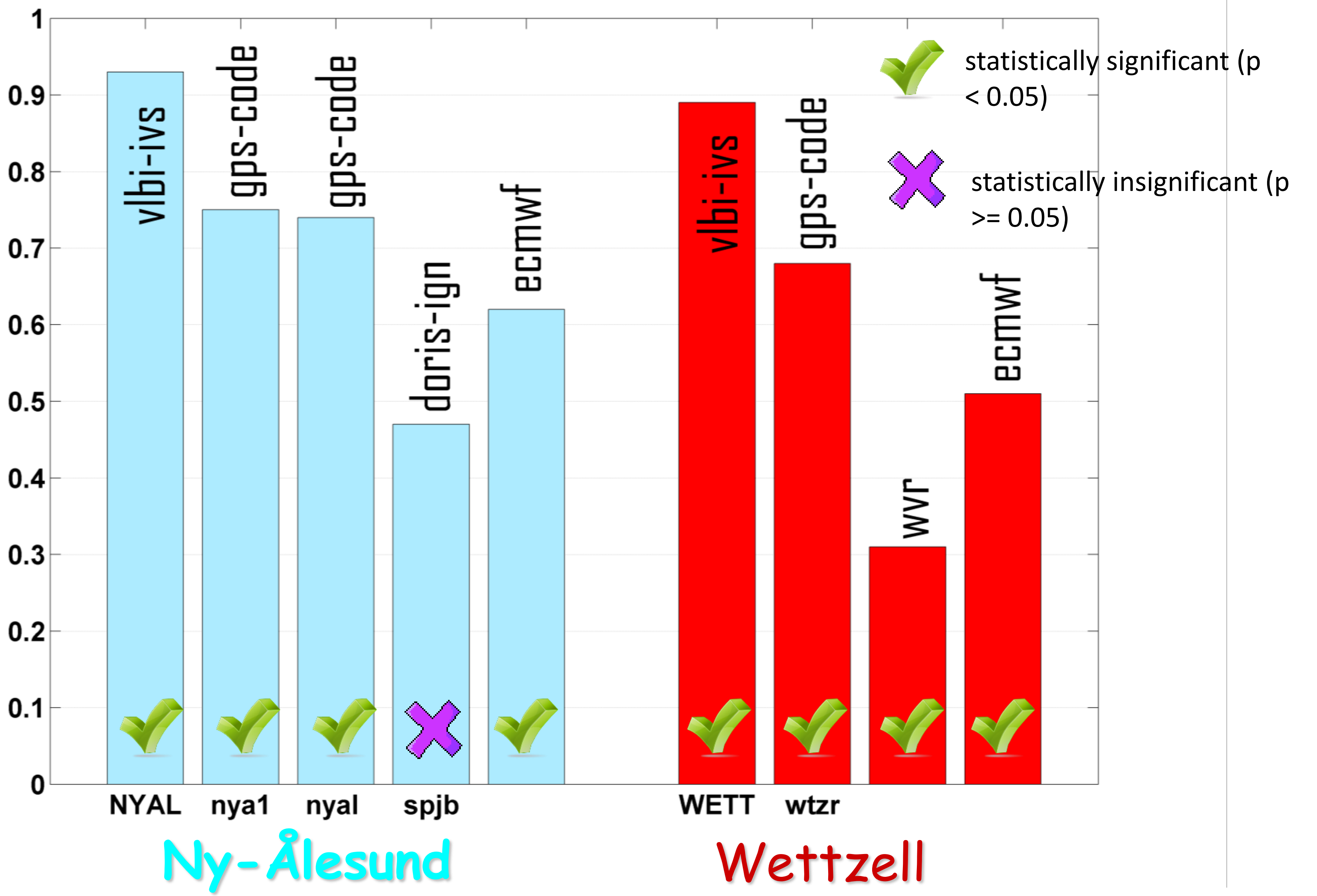


Biases and std. dev. of troposphere north gradients between VieVS and other solutions



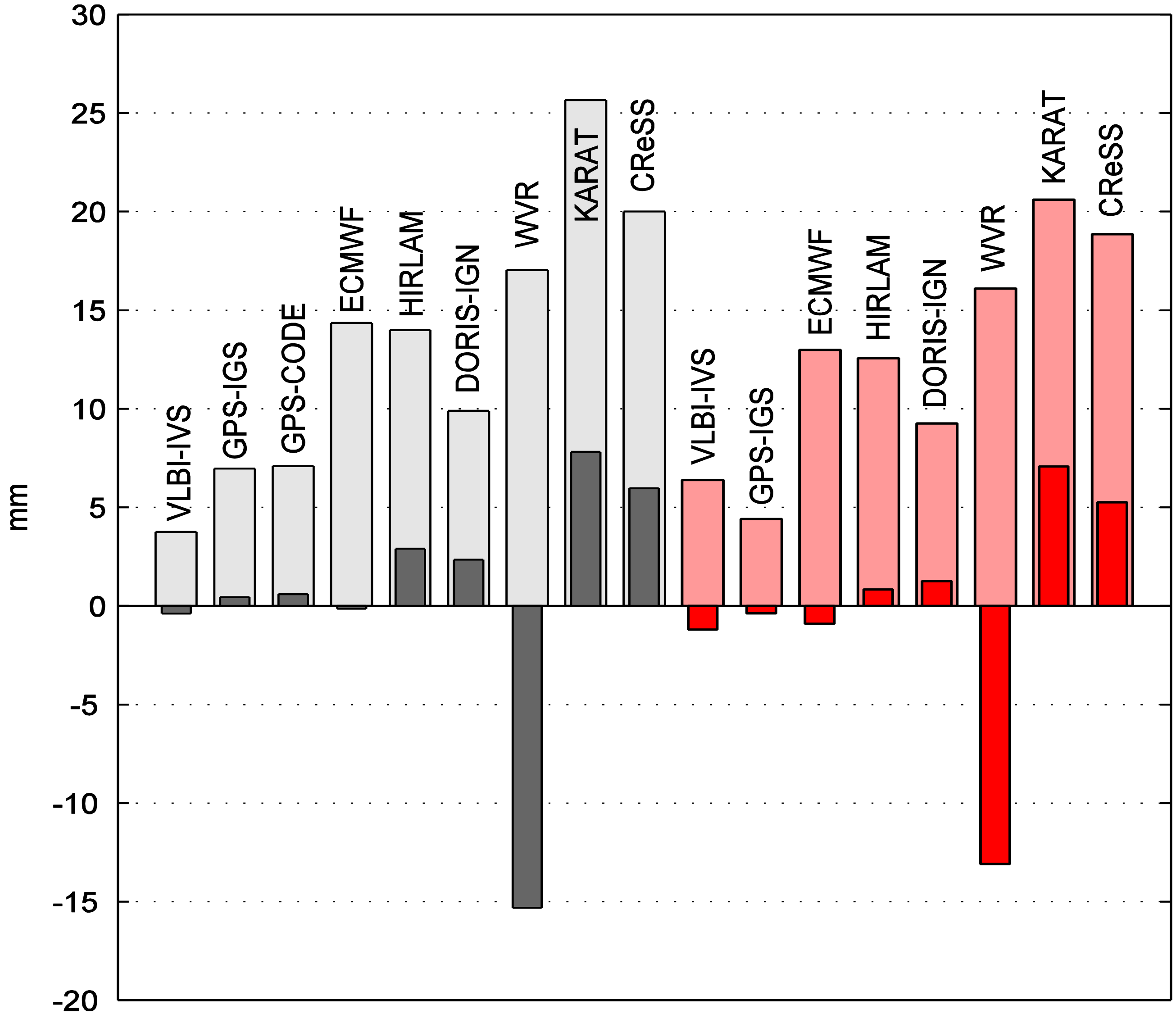


Correlations of troposphere north gradients between VieVS, and other solutions



solutions and stations at co-located sites

Mean biases and standard deviations of all ZTD during CONT08 w.r.t. VLBI-VieVS and GPS-CODE solutions



w.r.t. VLBI-VieVS

dark grey : bias

light grey : std. dev.

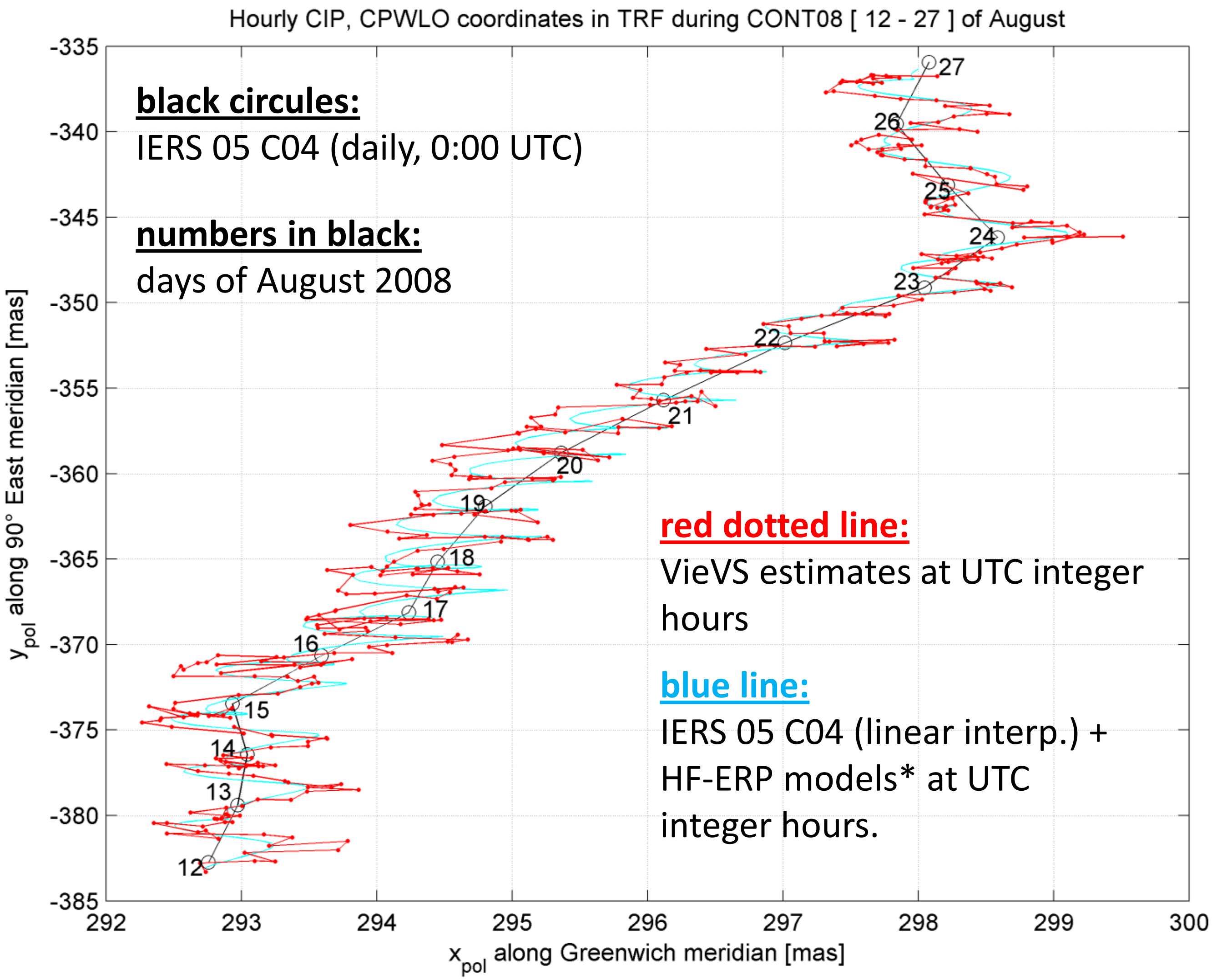
w.r.t. GPS-CODE

dark red: bias

light red : std. dev.

Comparisons of hourly ERP estimates from VLBI, GPS, and High Frequency (short period) ERP models during IVS-CONT08.

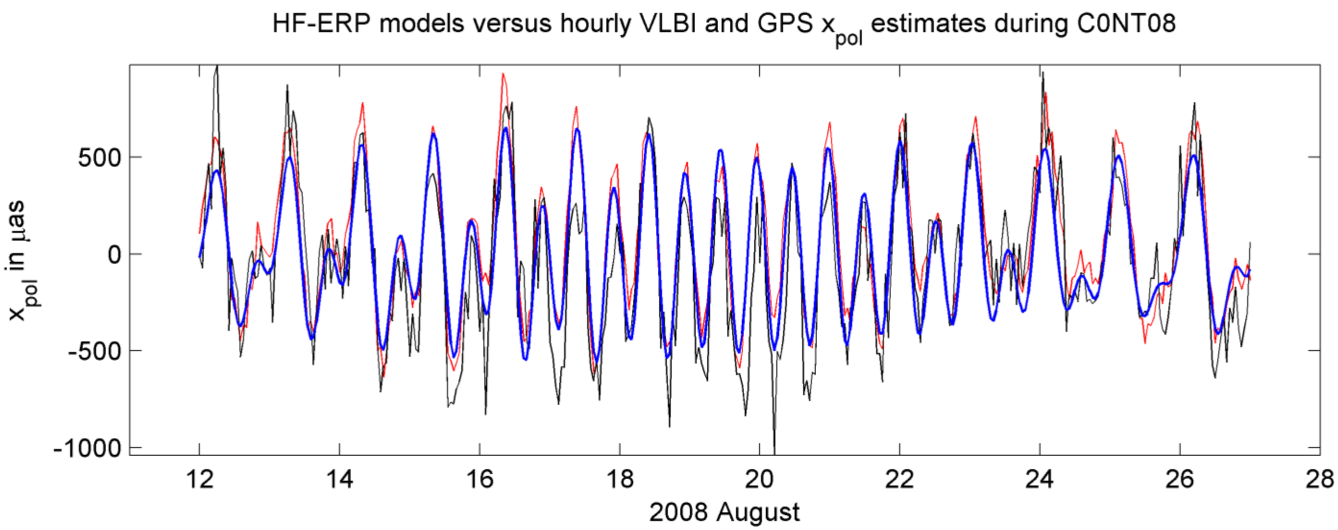
Hourly polar motion during IVS-CONT08

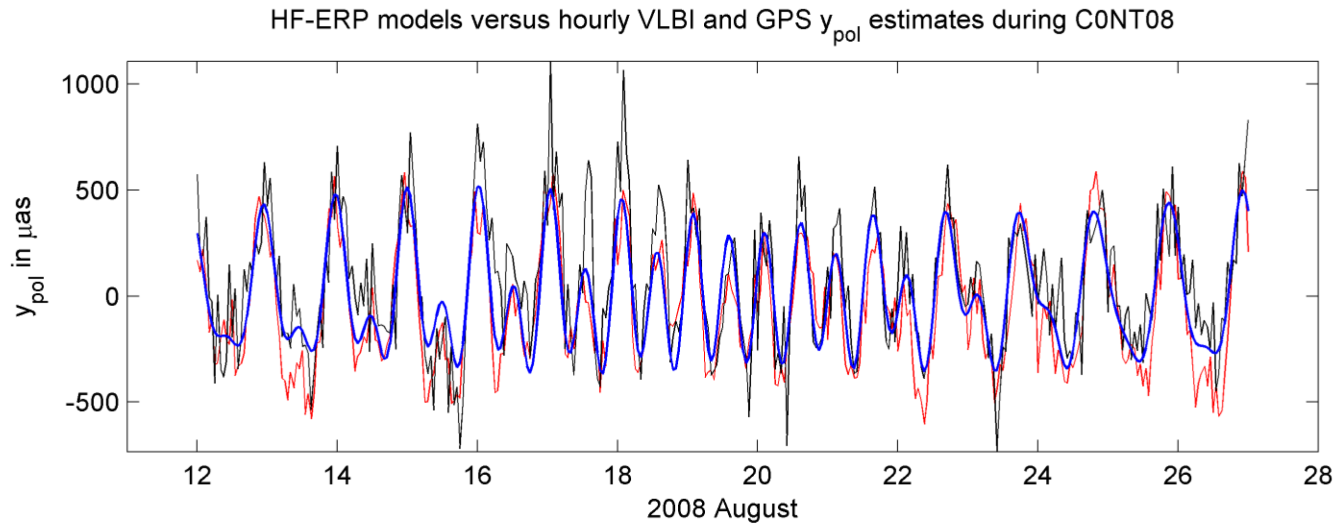


- Nutation offsets were fixed to their a priori values.
- **A priori nutation offsets:** IAU 2000A precession-nutation model plus IERS 05 C04 corrections.
- **A priori ERP:** IERS 05 C04 (linearly interpolated).
- No constraints were imposed on the hourly ERP estimates.

*ocean tides + libration (McCarthy and Petit (2004), Chapter 5 and 8)

Hourly polar motion from: HF-ERP models, GPS and VLBI during IVS-CONT08





Red line : GPS hourly

Black line : VLBI hourly

Blue line : HF-ERP models hourly

The standard deviations of the hourly ERP differences:

x_{pol}(VLBI-HF ERP): 224.5 µas

x_{pol}(GPS-HF-ERP): 122.0 µas

y_{pol}(VLBI-HF ERP): 187.2 µas

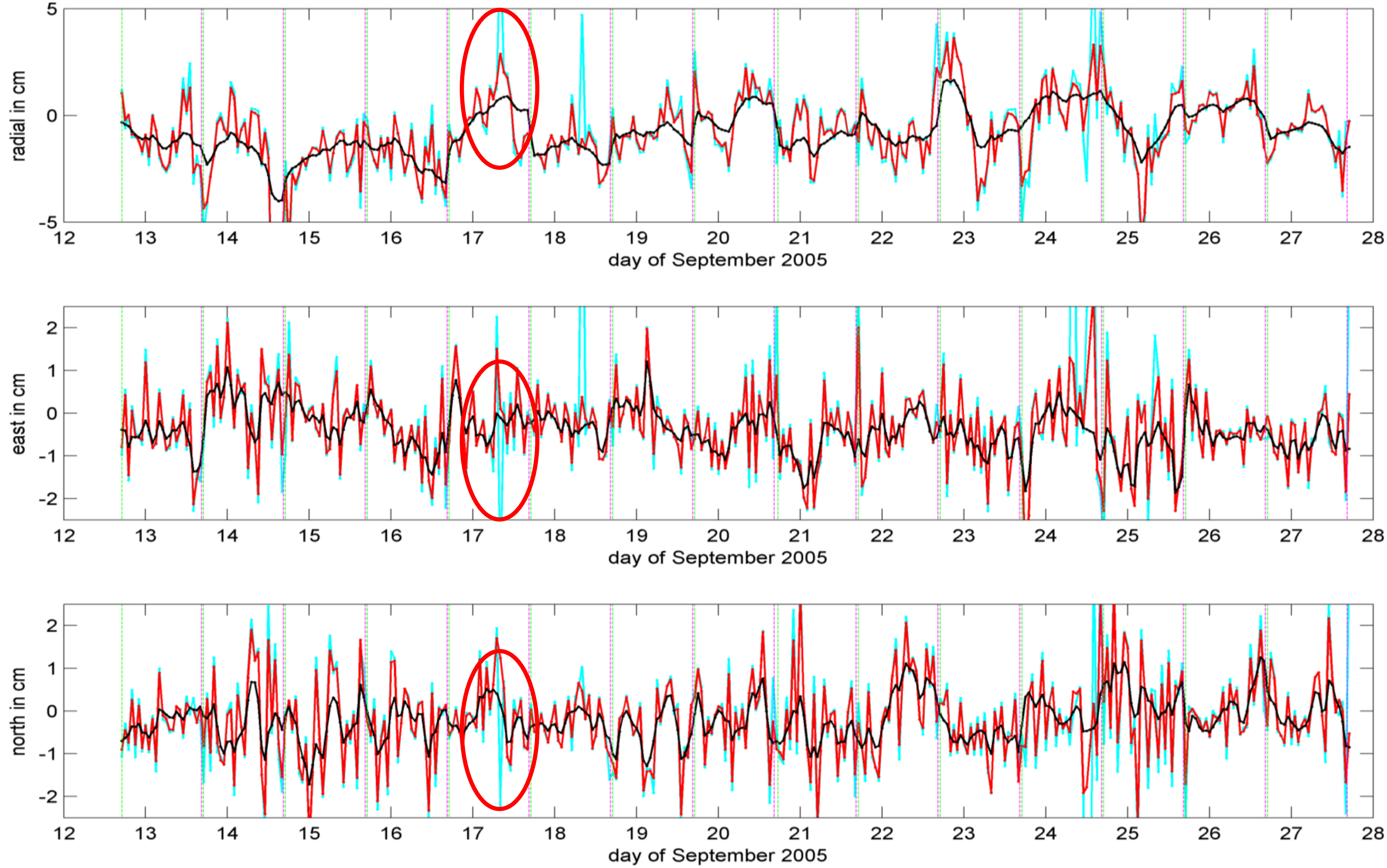
y_{pol}(GPS-HF-ERP): 139.3 µas

UT1-UTC (VLBI-HF ERP): 22.9 µs

VLBI ERP are noisier than to those of GPS.

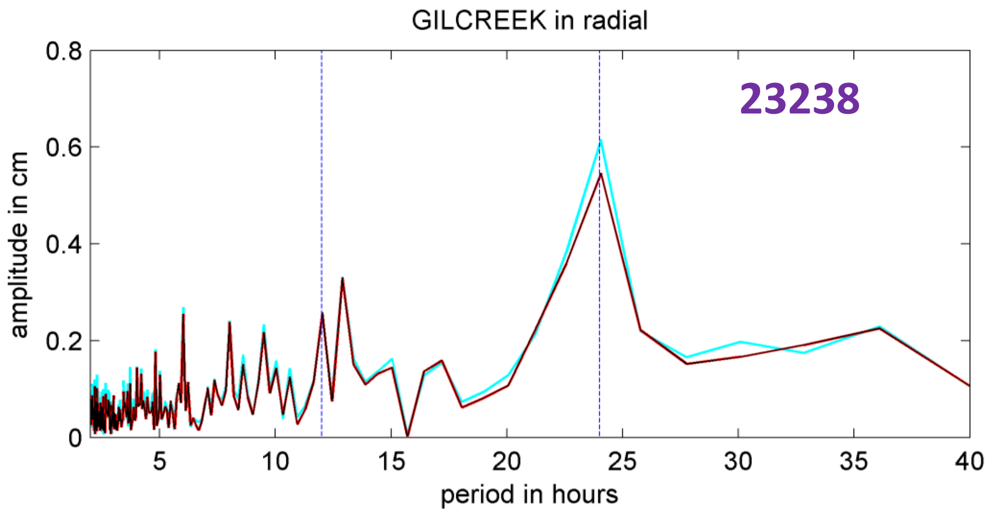
Analyses of VieVS hourly antenna coordinate estimates in TRF during IVS-CONT05

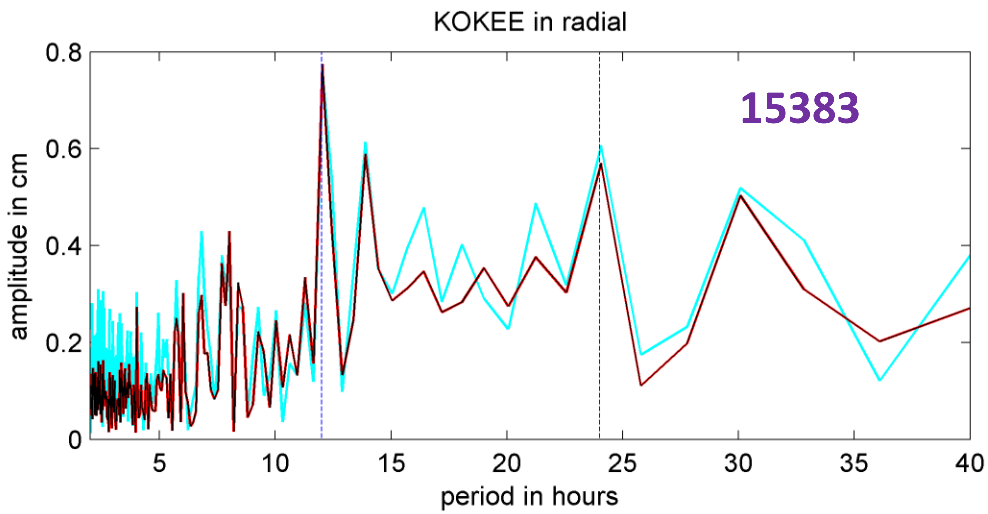
Hourly coordinate estimates of Wettzell VLBI antenna



Black, red and cyan lines show VieVS, hourly (at UTC integer hours) CPWLO coordinate estimates of the VLBI antenna Tsukub32 during IVS-CONT05 when loose constraints were applied on the hourly coordiate estimates as 4 mm/hour, 3 cm/hour and 21 cm/hour, respectively.

Fourier spectra of radial components of the hourly CPWLO antenna coordinate estimates during IVS-CONT05





black : 4 mm/hour (tight, relative)
red : 3 cm/hour (loose, relative)
cyan : 21 cm/hour (very loose, realtive)
purple : total obs. during IVS-CONT08

- Peaks of the spectra could be caused by:

- Errors in modelling e.g. troposphere, clocks, antenna deformation.
- Systematic effects on the observation which are not considered.
- Errors in tidal model.

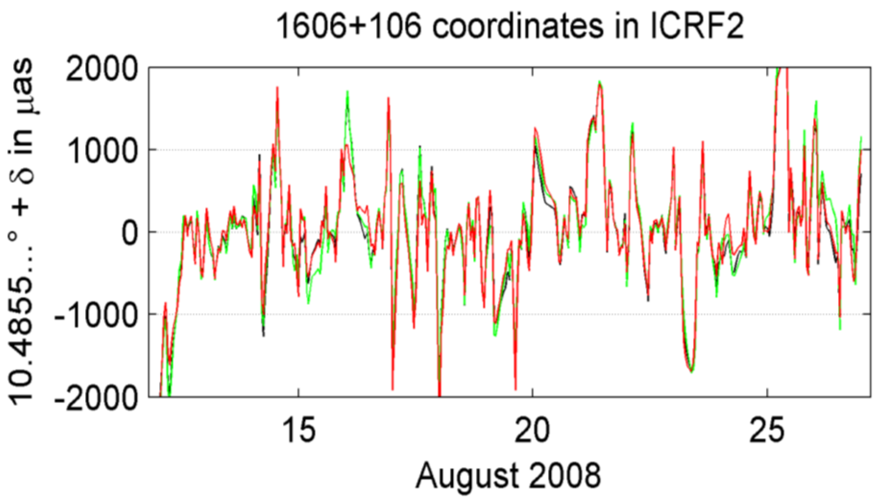
Analyses on hourly source coordinates in CRF during IVS-CONT08

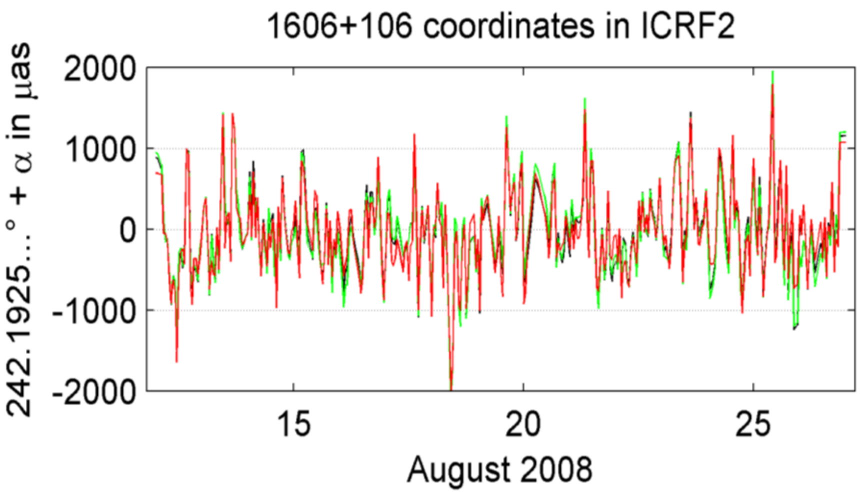
Hourly source coordinates time series in CRF during IVS-CONT08

Black : all EOP were estimated once per day.

Green : all EOP were fixed to their a priori values.

Red : all ERP were estimated hourly. nutation offsets were fixed.





all sources‘ coordinates were fixed to ICRF2 except two sources‘ coordinates were estimated in each process.

The formal errors do not change from one solution to another.

Conclusions

- The Least-Squares (LS) parameter estimation module of VieVS, vie_lsm, has been developed. Parameters are modeled as continuous piece-wise linear offset (CPWLO) functions.

- Tropospheric parameters from different techniques were compared:
  - Good agreement between different space geodetic techniques
  - Decent agreement between space geodetic techniques and NWM or WVR
  - The standard deviations are generally larger at low latitude sites because of higher humidity.
  - The higher humidity caused larger standard deviations at northern hemisphere stations during CONT08 (summer) in comparison to CONT02 which was observed in October 2002.

Conclusions

- Hourly ERP from VieVS agree well with those from GPS and with the IERS high frequency ERP model.
- Unexplained peaks at diurnal and semi-diurnal periods are seen in the spectra of hourly station coordinates.
- As a test study source coordinates with hourly resolution have been estimated.

Outlook and future perspectives

- Estimating reliable and accurate sub-daily geodetic parameters, e.g. sub-daily antenna positions, from VLBI observations will lead to compare, validate, and improve geophysical models. Thus, 1 mm VLBI antenna reference point position accuracy in global scale, one of the goal of VLBI2010 project, can be achieved.

- Multi-technique comparison of ZTD and troposphere gradients will contribute the combination studies in the framework of the Global Geodetic Observing System (GGOS) of the International Association of Geodesy (IAG).

Acknowledgements

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- I want to forward my special thanks to the VieVS working group.
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- I want to acknowledge IVS, IGS, ECMWF and other international services for the data that I used in this thesis.

Danke für Ihre Aufmerksamkeit !

Appendix

Parameterisation for estimating ZTD and gradients during IVS-CONT08

Very Long Baseline Interferometry (VLBI)

- **Vienna VLBI Software (VieVS):**

- NNT/NNR on ITRF2005.
- VMF1, above 5°.
- 0.7 picosec^2/sec for ZTDs (relatively loose).
- 2 mm/day for gradients (relatively loose).
- 30 minutes for ZTDs, and 120 for gradients.
- APL applied a priori (Petrov and Boy, 2004)

- International VLBI Service for Geodesy and Astrometry (IVS):

-Intra-technique combined solution for ZTDs and troposphere gradients.
-60 minutes for ZTDs and for gradients

Global Positioning System (GPS)

- Center for Orbit Determination in Europe (CODE)

- Bernese GPS software.
- NNR on IGS05.
- 120 minutes interval for ZTDs and 24 h for gradients.
- VMF1, 3° + elevation dependent weighting.
- No constraints for zenith delays and gradients.
- APL applied.

- International GNSS Service (IGS)

- GIPSY/Oasis software.
- PPP solution, Kalman filter.
- IGS final combined : orbits, clocks, and EOP.
- NMF, 7°.
- 5 minutes for ZTDs.
- Estimated parameters are: clocks, station position, zenith wet delay, troposphere gradients, phase biases (Byun S.H. and Bar-Sever Y.E., 2009).

Doppler Orbitography and Radio Positioning Integrated by Satellite (DORIS)

- Institut Géographique National (IGN)

- Software is GIPSY/Oasis.
- TRF is fixed to ign09d02.
- VMF1, 10°.
- DORIS reset at no regular interval.
- It is reset at start of pass and only if the previous reset is 20 minutes before or earlier.
- ZTD epochs interpolated linearly from the irregular epochs to 120 minutes (epochs at UTC integer hours).
- No interpolation between the data gaps larger than 60 minutes.
- Co-located sites are Ny-Ålesund (spjb), Kokee Park (kolb), Hartebeesthoek (hbmb).

Water Vapor Radiometer (WVR)

- Slant wet delays inferred from measurements of the sky brightness temperature at about 22 GHz and 31 GHz.
- ZWDs and gradients obtained by a least-squares fit. 30 minutes estimation interval for ZWDs and 120 minutes estimation intervals for troposphere gradients.
- ZHDs calculated from surface pressure measurements at the VLBI antenna.
- Cut off 20°.
- Data aquired during rain removed.
- Co-located sites: Wettzell, Tsukuba, and Onsala.

Numerical Weather Models (NWMs)

- Japan Meteorological Agency - Kashima Ray-Tracing Tools (JMA-KARAT).
- High Resolution Limited Area Model (HIRLAM).
- European Centre for Medium-Range Weather Forecasts (ECMWF).

NWM	The regions for which the models provide data	Spatial resolution	Time Resolution (hours)	Number of levels at each profile	Troposphere gradients estimated ?
JMA-KARAT	Japan	0.1°	3	21	YES
HIRLAM	Europe	0.2°	3	40	NO
ECMWF	Global	0.25°	6	21	YES

Agreement criteria

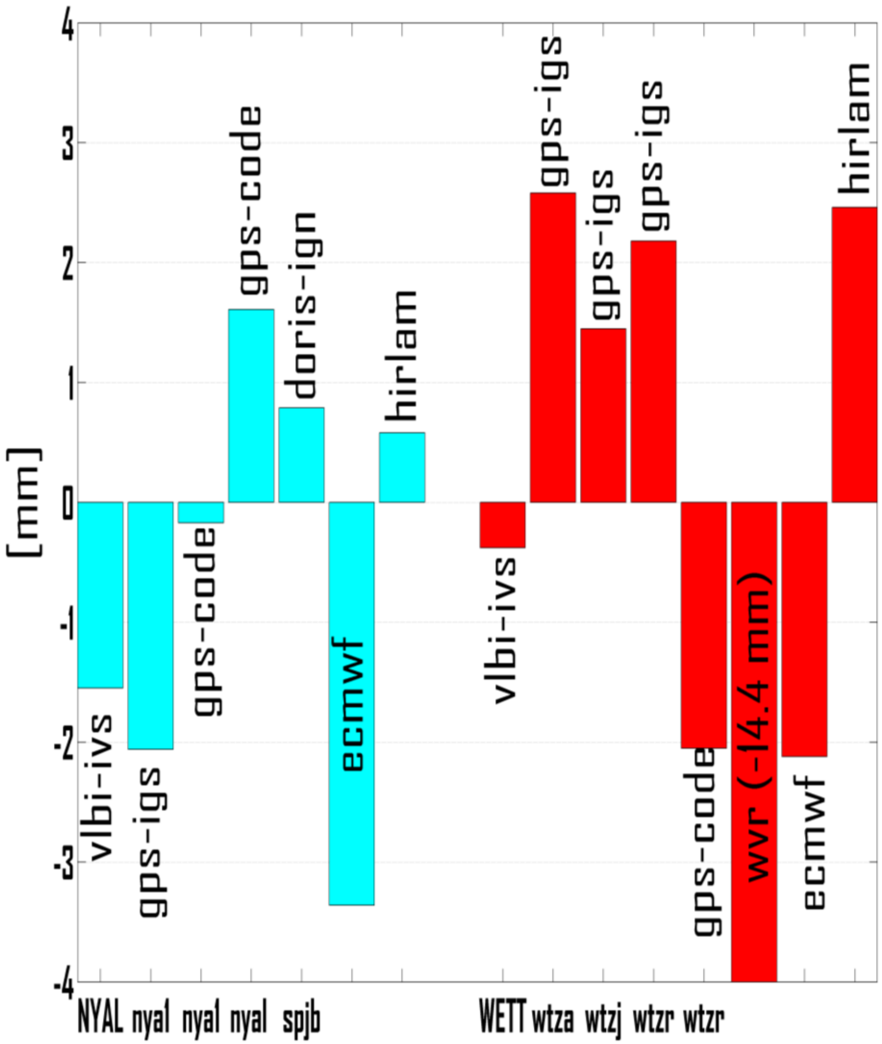
$$e.g. \quad x_i = ZTD_i^{VLBI-VieVS} \quad y_i = ZTD_i^{GPS-CODE} \quad \Delta_i = x_i - y_i$$

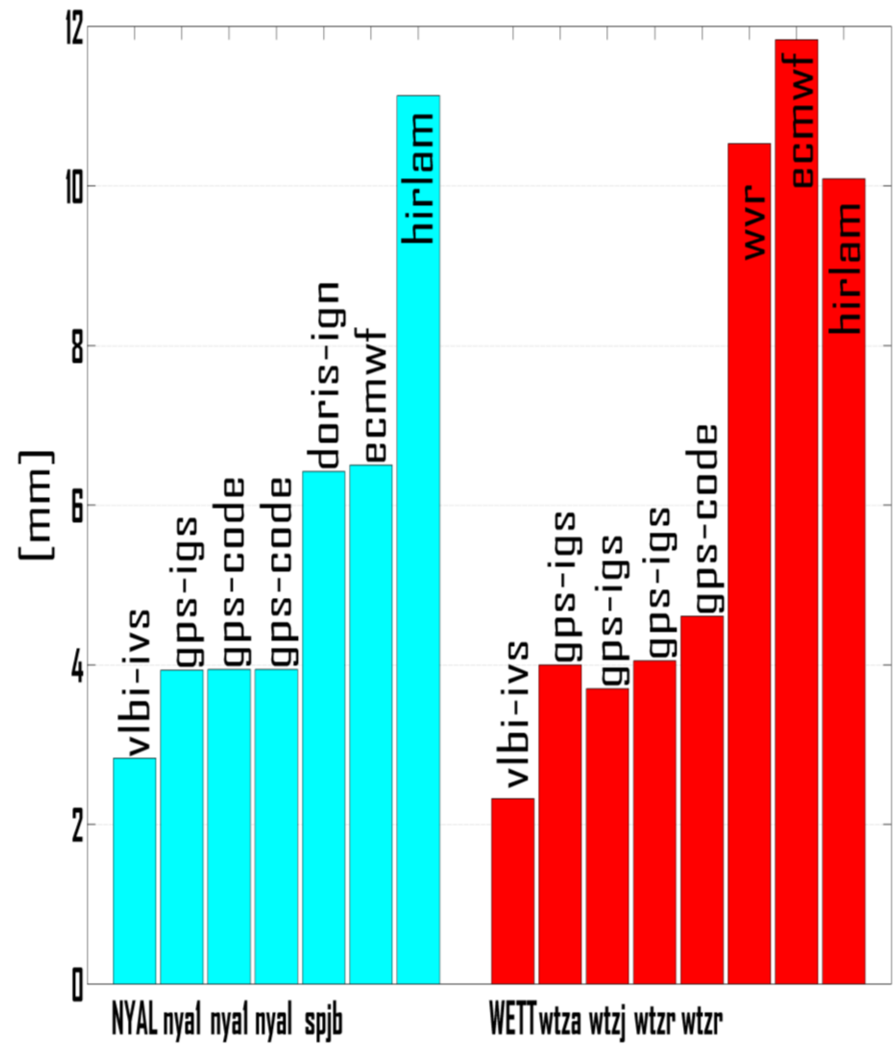
$$\bar{\Delta} = \frac{1}{n}\sum_{i=1}^{n}\Delta_i \qquad i = 1, 2, \cdots, n$$

$$Sx = [\frac{1}{n-1}\sum_{i=1}^{n}(\Delta_i - \bar{\Delta})^2]^{\frac{1}{2}}$$

$$r_{xy} = \frac{Cov(x, y)}{S_x S_y} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\left[\sum_{i=1}^{n}(x_i - \bar{x})^2 \cdot \sum_{i=1}^{n}(y_i - \bar{y})^2\right]^{\frac{1}{2}}} \qquad (p < 0.05)$$

Biases and std. dev. of ZTD between VieVS and other solutions





Ny-Ålesund Wettzell Ny-Ålesund Wettzell

solutions and stations at co-located sites

Calculation of troposphere ties (Brunner and Rüeger, 1992)

$$p = p_0 \left(1 - \frac{\gamma (H - H_0)}{T_0}\right)^{\frac{g}{\gamma R_L}}$$

$$\Delta ZHD = \frac{0.0022768 (p - p_0)}{1 - 0.00266 \cos(2\varphi_0) - 0.28 \times 10^{-6} H_0}$$

$$\Delta ZWD = \frac{-2.789 e_0}{T_0^2} \left(\frac{5383}{T_0} - 0.7803\right) \gamma (H - H_0)$$

H_0 : Reference height (VLBI reference point height),

e_0, : Water vapor pressure (hPa) at the reference height,

p_0, : Total pressure (hPa) at the reference height,

T_0 : Temperature (Kelvin) at the reference height,

H and p : The height and total pressure at the co-located site,

$\gamma = -0.0065$ K m^{-1} (average temperature lapse rate),

$R_L = 287.058$ m^2 s^{-2} K^{-1} (specific gas constant),

g = the gravity in m s^{-2} ,

ϕ_0 = latitude of the co-located site in degrees.

Troposphere delay in VieVS

$$\Delta\tau_{trop} = 10^{-6} \int_0^{H_{trop}} \left[N_h(s) + N_w(s)\right] ds$$

$$\Delta\tau_{trop}(\alpha,\varepsilon) = ZHD\, m_h(\varepsilon) + ZWD\, m_w(\varepsilon) + m_w(\varepsilon)\cot(\varepsilon)\left[G_n \cos(\alpha) + G_e \sin(\alpha)\right]$$

ZHD: reduced from observations a priori to the adjustment

ZWD: estimated

G_n: estimated

G_e: estimated

partial derivative w.r.t. ZWD first CPWLO

$$\frac{\partial\tau_{trop}(t)}{\partial(ZWD)x_1} = \frac{\partial\tau_{trop}(t)}{\partial(ZWD)} \cdot \frac{\partial(ZWD)}{\partial x_1}$$

$$= m_w(\varepsilon)(1 - \frac{t - t_1}{t_2 - t_1})$$

$$= m_w(\varepsilon) - m_w(\varepsilon)\frac{t - t_1}{t_2 - t_1}$$

partial derivative w.r.t. ZWD second CPWLO

$$\frac{\partial\tau_{trop}(t)}{\partial(ZWD)x_2} = \frac{\partial\tau_{trop}(t)}{\partial(ZWD)} \cdot \frac{\partial(ZWD)}{\partial x_2}$$

$$= m_w(\varepsilon)(\frac{t - t_1}{t_2 - t_1})$$

Partial derivative of the delay w.r.t. north gradient CPWLO

partial derivative w.r.t. north gradient **first** CPWLO

$$\frac{\partial \tau_{trop}(t)}{\partial (G_n) x_1} = \frac{\partial \tau_{trop}(t)}{\partial (G_n)} \cdot \frac{\partial (G_n)}{\partial x_1}$$

$$= m_w(\varepsilon)\cot(\varepsilon)\cos(\alpha)(1 - \frac{t - t_1}{t_2 - t_1})$$

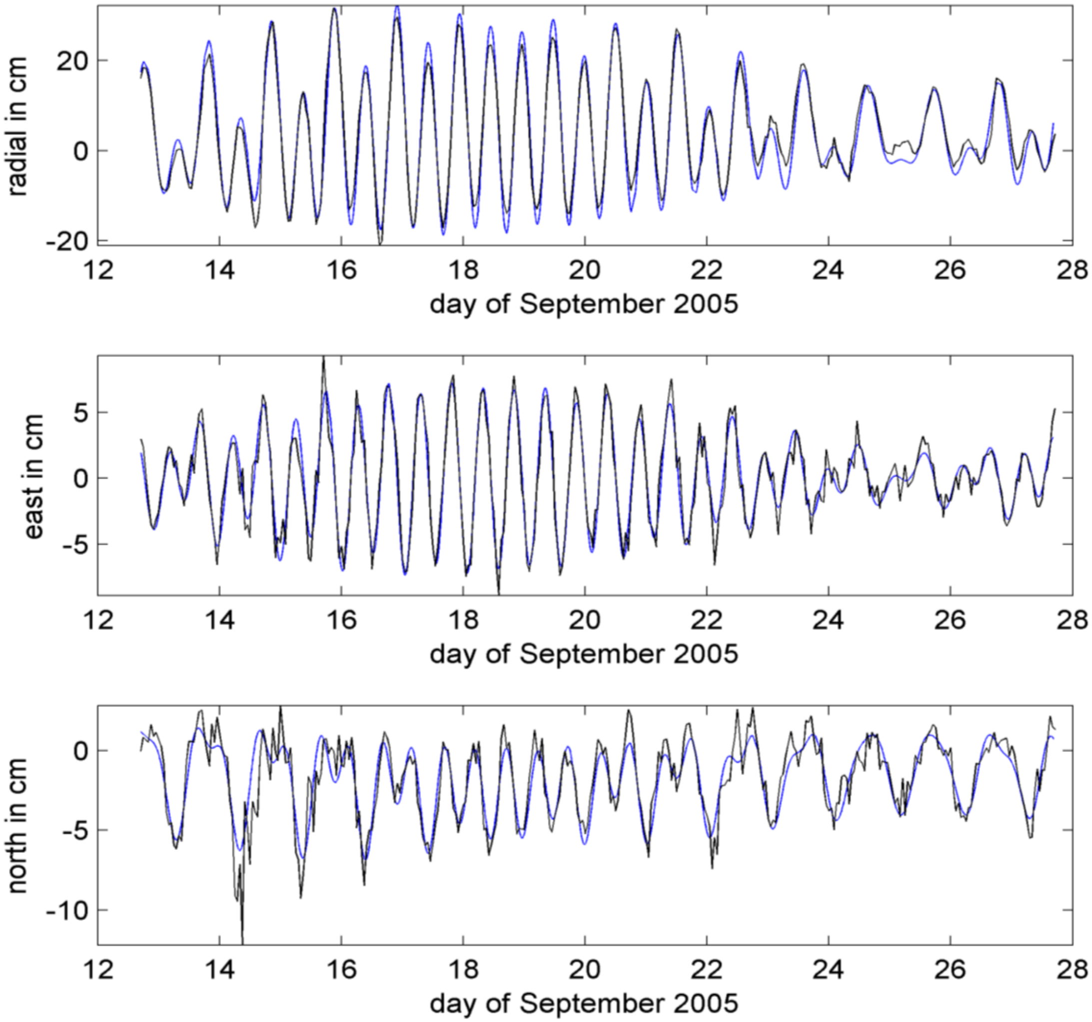
partial derivative w.r.t. north gradient **second** CPWLO

$$\frac{\partial \tau_{trop}(t)}{\partial (G_n) x_2} = \frac{\partial \tau_{trop}(t)}{\partial (G_n)} \cdot \frac{\partial (G_n)}{\partial x_2}$$

$$= m_w(\varepsilon)\cot(\varepsilon)\cos(\alpha)(\frac{t - t_1}{t_2 - t_1})$$

VieVS hourly antenna coordinate estimates in TRF versus solid Earth tides during IVS-CONT05

Kokee VLBI antenna hourly CPWLO coordinates



- All antenna coordinates were fixed to their a priori values* except one antenna (e.g. Kokee).

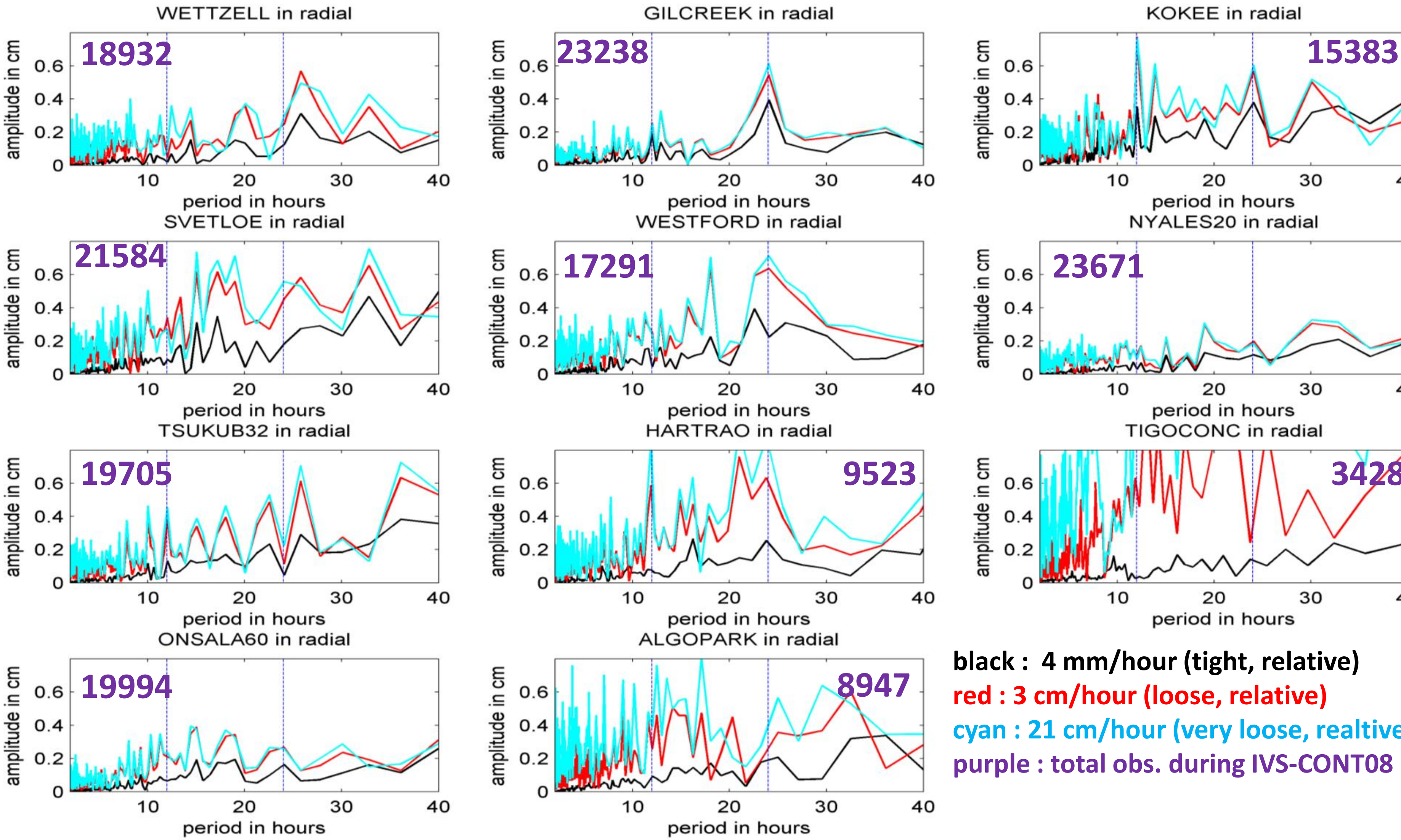
* VTRF2008+velocity+all tide and load displacements

- Solid Earth tide displacements were reduced from all VLBI observations for all antenna coordinates except one antenna (e.g. Kokee).
- Hourly CPWLO coordinates of this one antenna (e.g. Kokee) were estimated.
- Loose relative constraints were introduced on hourly CPWLO antenna coordinate estimates: 3 cm/hour.

Blue line : Solid Earth tide model displacements (McCarthy and Petit (2004), Chapter 7.1.1)

Black line : VieVS hourly CPWLO antenna coordinates

Fourier spectra of radial components of the hourly CPWLO antenna coordinate estimates during IVS-CONT05



black : 4 mm/hour (tight, relative)
red : 3 cm/hour (loose, relative)
cyan : 21 cm/hour (very loose, realtive)
purple : total obs. during IVS-CONT08

Least-squares adjustment constraints on the estimates

$$H = \begin{bmatrix} H(1).sm & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & H(15).sm \end{bmatrix}$$

$$H(i).sm = \begin{bmatrix} 1 & -1 & 0 & \cdots & 0 & 0 \\ 0 & 1 & -1 & \cdots & 0 & 0 \\ 0 & 0 & 1 & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & 1 & -1 \end{bmatrix}$$

$$\begin{bmatrix} x_{est\_i} \\ y_{est\_i} \\ z_{est\_i} \end{bmatrix} = \begin{bmatrix} x_{apr\_i} \\ y_{apr\_i} \\ z_{apr\_i} \end{bmatrix} + C_i^T \begin{bmatrix} T_x \\ T_y \\ T_z \\ \alpha \\ \beta \\ \gamma \\ \mu \end{bmatrix}$$

$$C_i = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & -z'_i & y'_i \\ z'_i & 0 & -x'_i \\ -y'_i & x'_i & 0 \\ x'_i & y'_i & z'_i \end{bmatrix}$$

$$P_H(i).sm = \begin{bmatrix} 1/m_{1c\_rel}{}^2 & 0 & \cdots & 0 \\ 0 & 1/m_{2c\_rel}{}^2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 1/m_{(k-1)c\_rel}{}^2 \end{bmatrix}$$

$$C = \begin{bmatrix} C_1 & C_2 & \cdots & C_s \end{bmatrix}$$

$$x'_i = norm * x_{0i}$$

$$norm = \frac{1}{\sqrt{\sum (x_{0i}{}^2 + y_{0i}{}^2 + z_{0i}{}^2)}}$$

Sub-daily estimates of VieVS

- CPWLO of clocks...

A(1).sm [1], H(1).sm [1], Ph(1).sm [1/cm^2]

- rate and quadratic terms of clock polynomials...

A(2).sm [day day^2]

- CPWLO of zenith wet delays...

A(3).sm [1], H(3).sm [1], Ph(3).sm [1/cm^2]

- CPWLO of troposphere north gradients...

A(4).sm [1], H(4).sm [1], Ph(4).sm [1/cm^2]

- CPWLO of troposphere east gradients...

A(5).sm [1], H(5).sm [1], Ph(5).sm [1/cm^2]

- CPWLO of polar motion coordinate in TRF along Greenwich meridian, xp ...

A(6).sm [cm/mas], H(6).sm [1], Ph(6).sm [1/mas^2]

Sub-daily estimates of VieVS

- CPWLO of polar motion coordinate in TRF along 270° east meridian, yp...

A(7).sm [cm/mas], H(7).sm [1], Ph(7).sm [1/mas^2]

- CPWLO of Earth‘s rotation phase (ΔUT1=UT1-UTC) ...

A(8).sm [cm/mas], H(8).sm [1], Ph(8).sm [1/mas^2]

- CPWLO of celestial intermediate pole (CIP) X coordinate in CRF...

A(9).sm [cm/mas], H(9).sm [1], Ph(9).sm [1/mas^2]

- CPWLO of celestial intermediate pole (CIP) Y coordinate in CRF...

A(10).sm [cm/mas], H(10).sm [1], Ph(10).sm [1/mas^2]

- CPWLO of right ascensions of sources in CRF...

A(11).sm [cm/mas], H(11).sm [1], Ph(11).sm [1/mas^2]

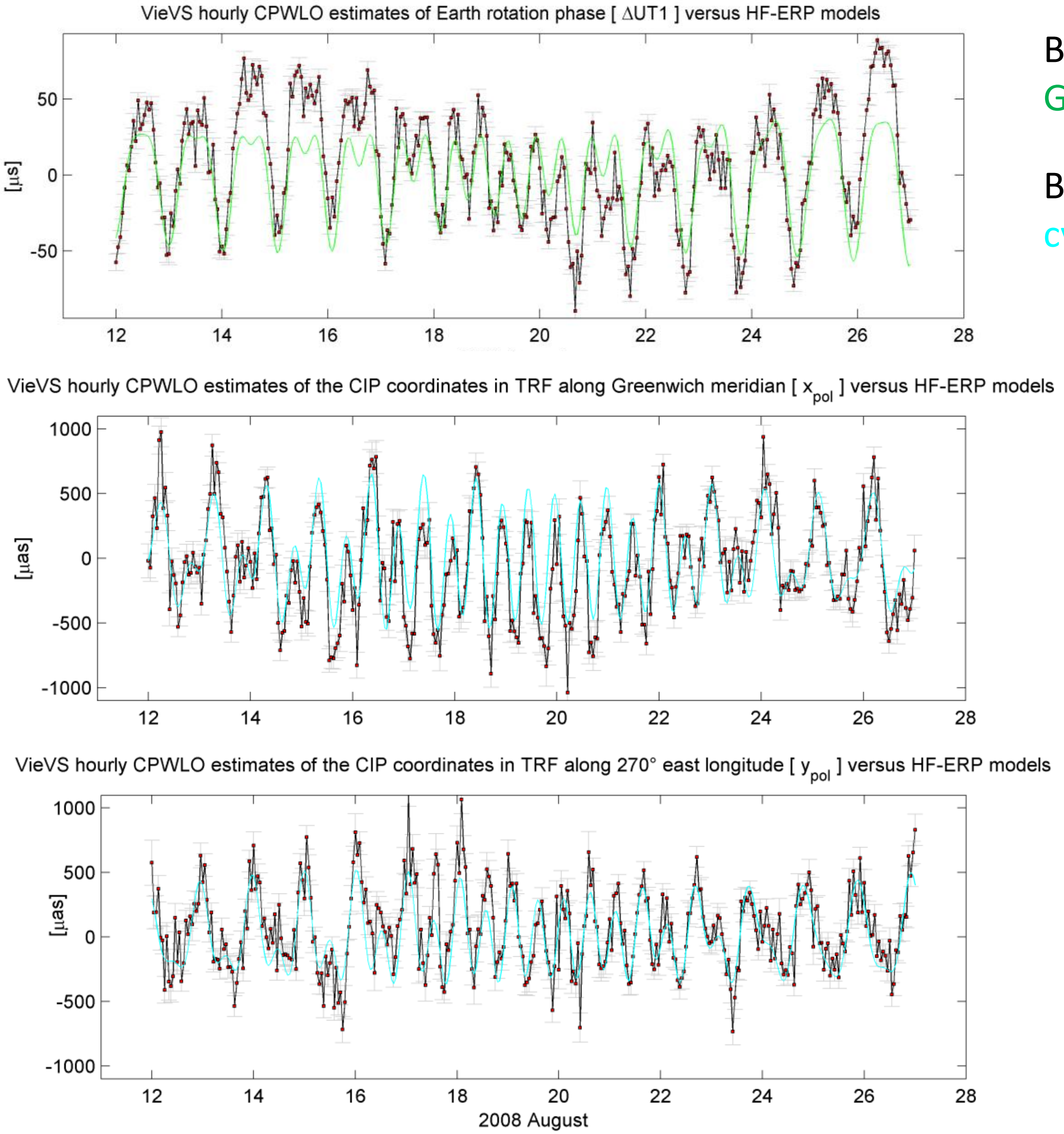
- CPWLO of declinations of sources in CRF...

A(12).sm [cm/mas], H(12).sm [1], Ph(12).sm [1/mas^2]

- CPWLO of VLBI antenna cartesian coordinates in TRF: X, Y, Z...

A(13,14,15).sm [1], H(13,14,15).sm [1], Ph(13,14,15).sm [1/cm^2]

Hourly ERP during IVS-CONT08



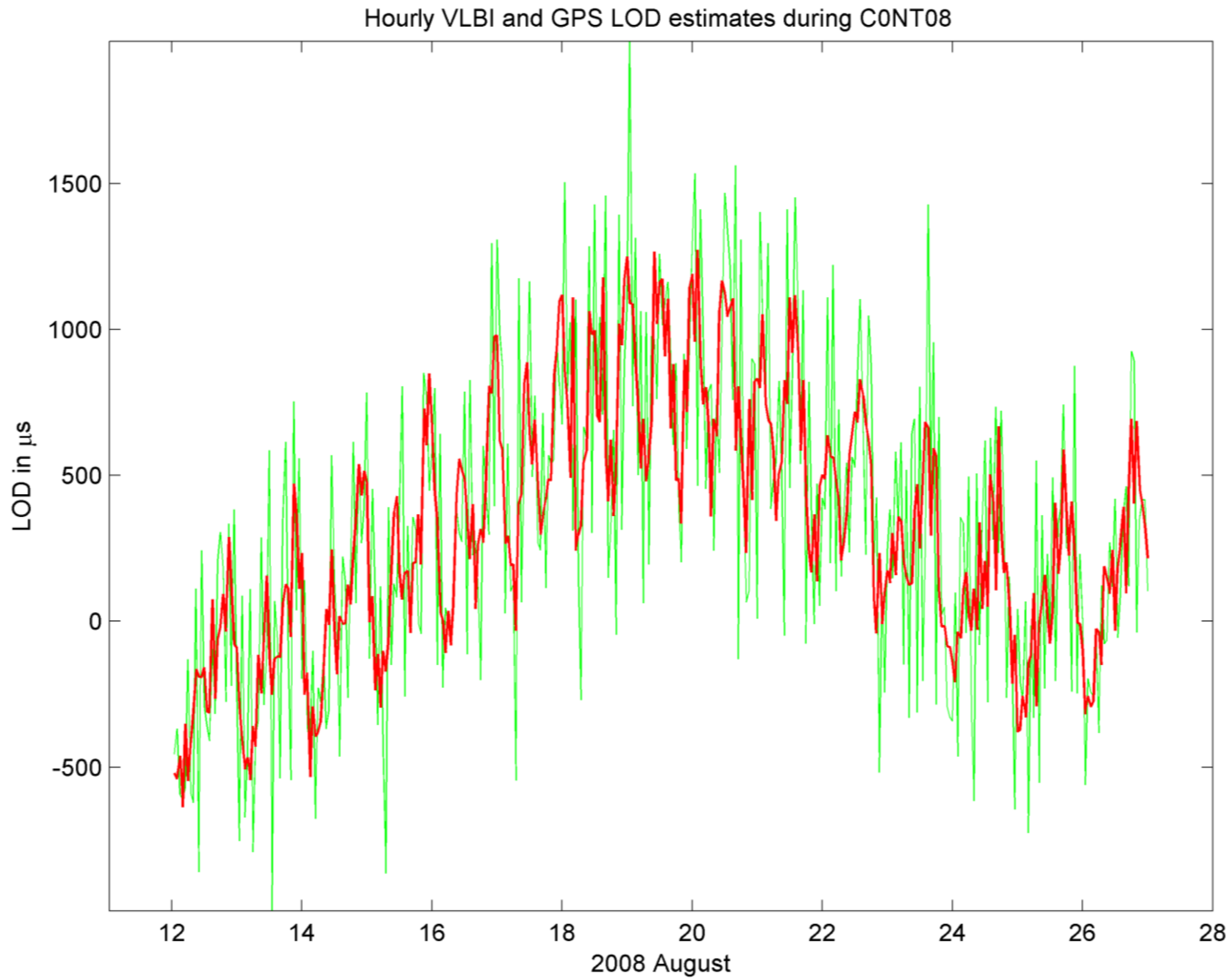
Black line : VLBI hourly
Green line : HF-ERP models* hourly

Black line : VLBI hourly
cyan line : HF-ERP models hourly

* ocean tides and libration (McCarthy and Petit (2004), Chapter 5 and 8)

- Nutation offsets were fixed to their a priori values.
- **A priori ERP:** IERS 05 C04 (linearly interpolated).
- **A priori nutation offsets:** IAU 2000A precession-nutation model plus IERS 05 C04 corrections.
- No constraints were imposed on the hourly ERP estimates.

Hourly length of day (LOD) from: HF-ERP models, GPS and VLBI during IVS-CONT08



Red line : GPS hourly LOD estimates

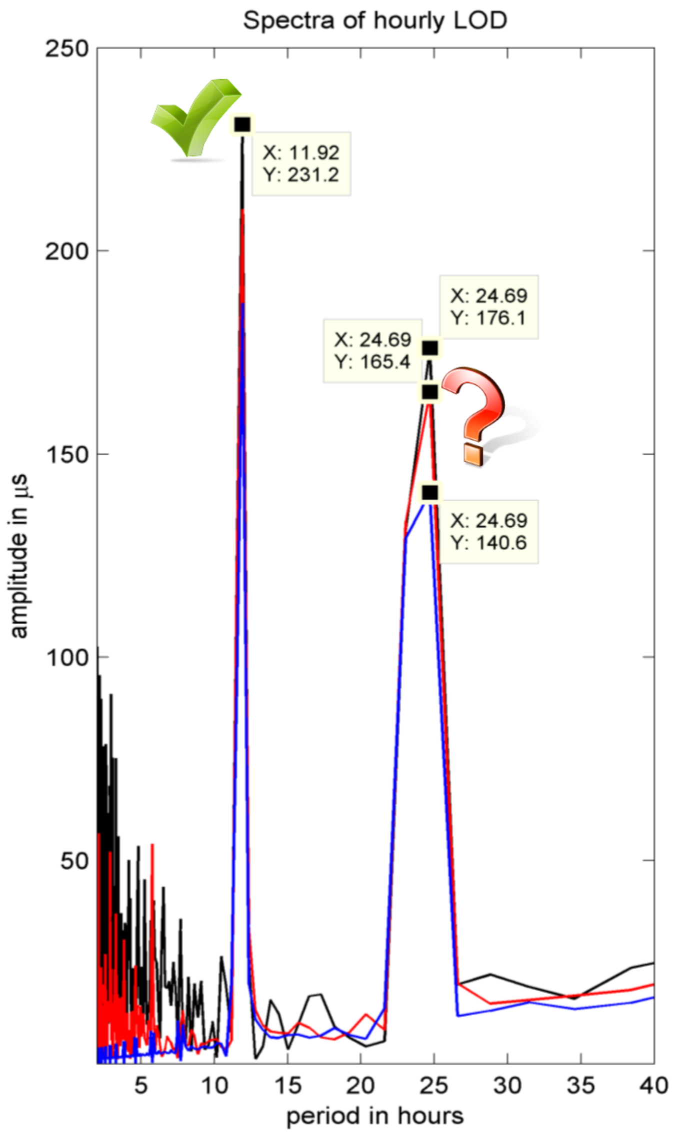
Green line : VLBI hourly LOD estimates

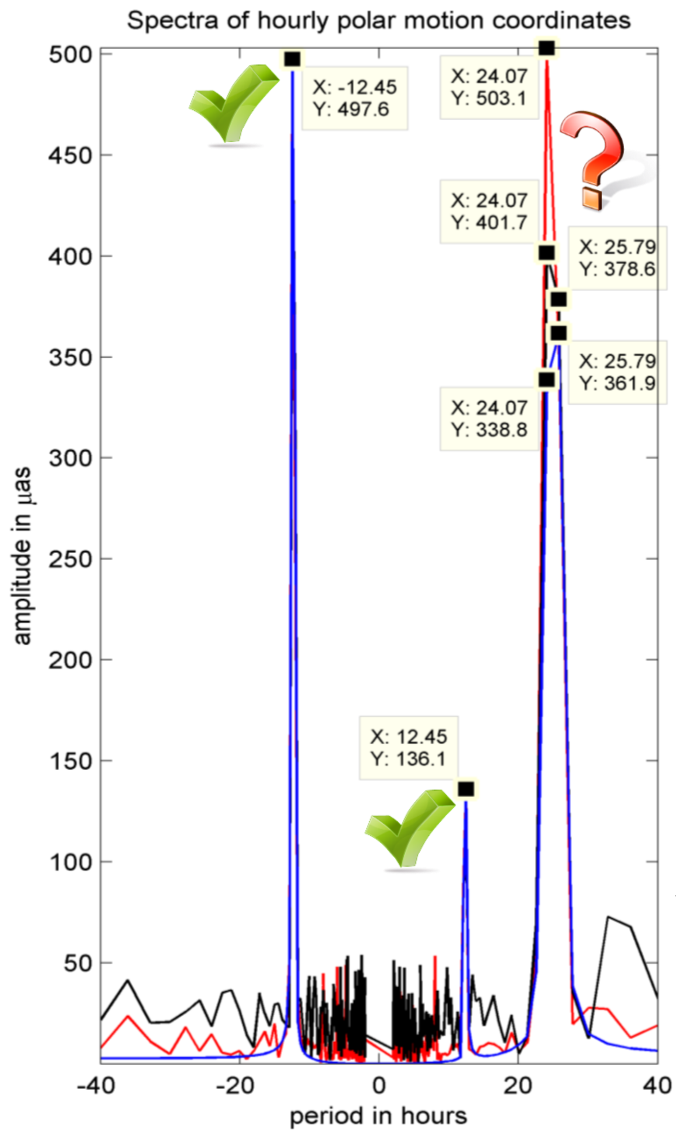
Blue line : HF-ERP models hourly LOD values

LOD calculation from UT1-UTC, estimated from VLBI (when t_1 and t_2 are in seconds)

$$LOD(t_1) = \frac{\Delta UT1(t_2) - \Delta UT1(t_1)}{t_2 - t_1} .86400$$

Fourier spectra of hourly ERP from HF-ERP models, GPS, and VLBI during IVS-CONT08



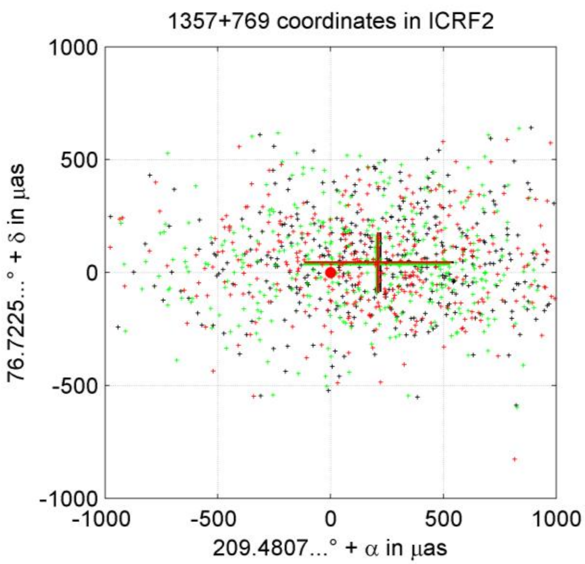


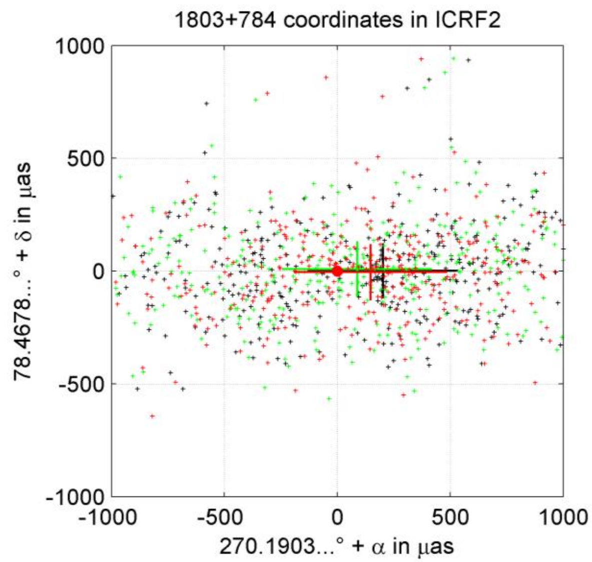
Red line : GPS
Black line : VLBI
Blue line : HF-ERP models

at 24 hours prograde polar motion amplitudes:
GPS > VLBI (~100 µas)
GPS > HF-ERP (~160 µas).

at 24 hours period LOD amplitudes:
GPS > HF-ERP (~25 µs)
VLBI > HF-ERP (~36 µs).

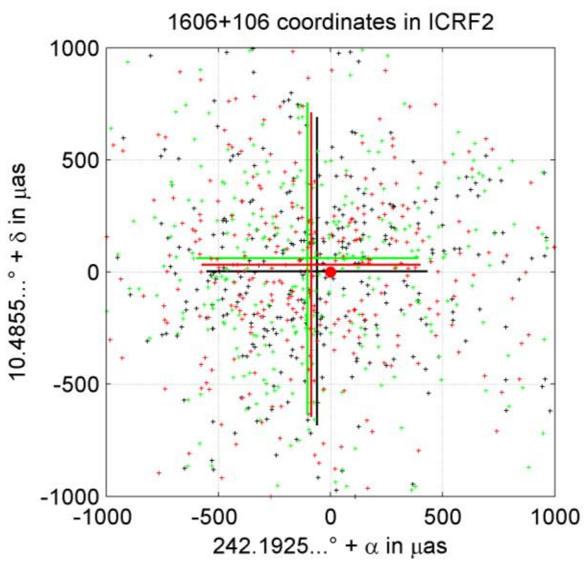
Hourly source coordinates in CRF during IVS-CONT08

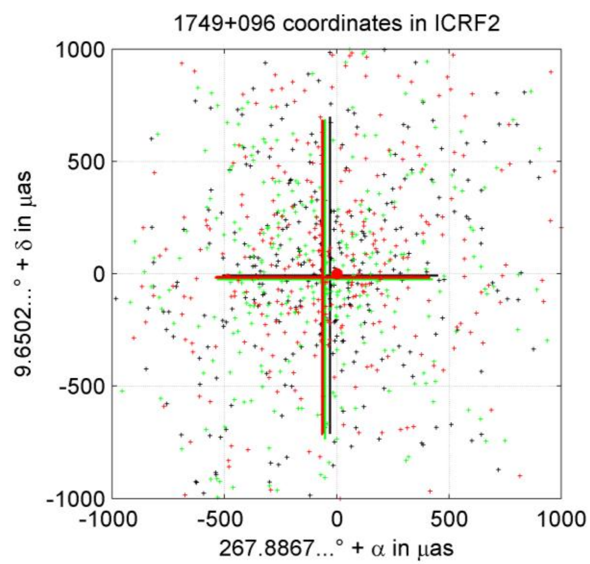




all sources‘ coordinates were fixed to ICRF2 except two sources‘ coordinates were estimated in each process.

Above figures: defining sources near to north pole. Below figures: defining sources near to celestial equator.





Black : all EOP were estimated once per day, relatively tight constraints were introduced.

Green : all EOP were fixed to their a priori values.

Red : all ERP were estimated hourly, relatively loose constraints were introduced. Nutation offsets were fixed to a priori values.

Medians and formal errors of the hourly source coordinates in CRF during IVS-CONT08

Median of the hourly (UTC integer hours) CPWLO estimates and of their formal errors during IVS-CONT08. **All EOP were estimated as CPWLO with one day estimation interval (at 0:00 UTC).**

Source	Total number of observations	$\bar{\alpha} \pm m_{\bar{\alpha}}$	$\bar{\delta} \pm m_{\bar{\delta}}$
1357+769	12592	220±324	46±131
1803+784	12411	201±333	2±122
1606+106	3238	-61±493	4±687
1749+096	2922	-58±495	2±764

Median of the hourly (UTC integer hours) CPWLO estimates and of their formal errors during IVS-CONT08. **All EOP were fixed to their a priori values*.**

Source	Total number of observations	$\bar{\alpha} \pm m_{\bar{\alpha}}$	$\bar{\delta} \pm m_{\bar{\delta}}$
1357+769	12592	204±324	37±132
1803+784	12411	87±331	10±122
1606+106	3238	-103±495	62±694
1749+096	2922	-79±495	-12±768

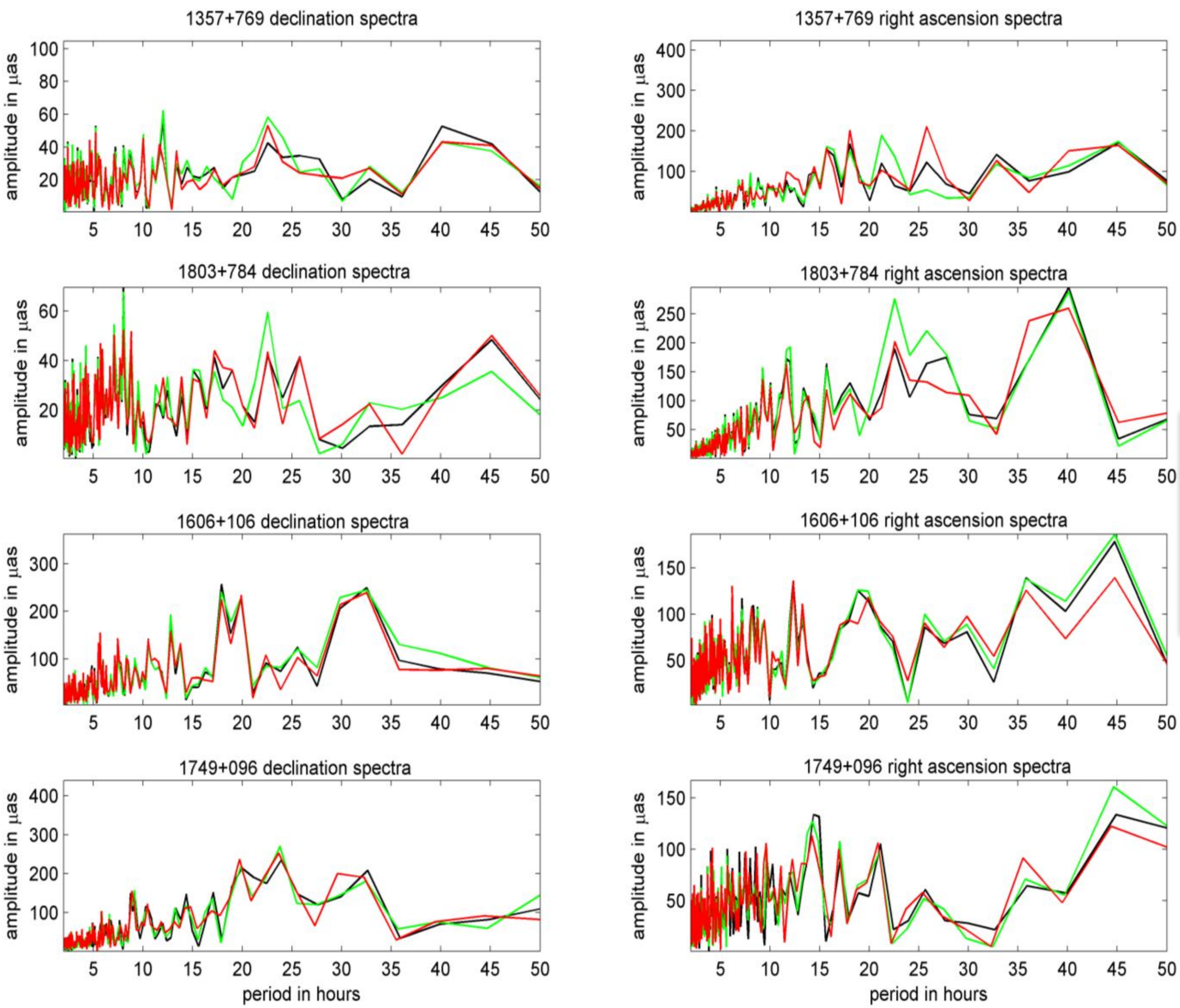
The formal errors do not change from one solution to another.

The magnitude of the formal errors depends on the total number of observations to the source per estimation interval.

The median of the estimates show the biases between 15 days long hourly CPWLO solution and the ICRF2 catalogue.

* ERP: IERS 05 C04 (Bizouard and Gambis, 2009) + ocean tides + libration (McCarthy and Petit (2004), Chapter 5 and 8)
* nutation offsets : IAU 2000A precession-nutation model + IERS 05 C04 corrections

Fourier spectra of the hourly CPWLO source coordinate estimates during IVS-CONT08



Black : all EOP were estimated once per day.

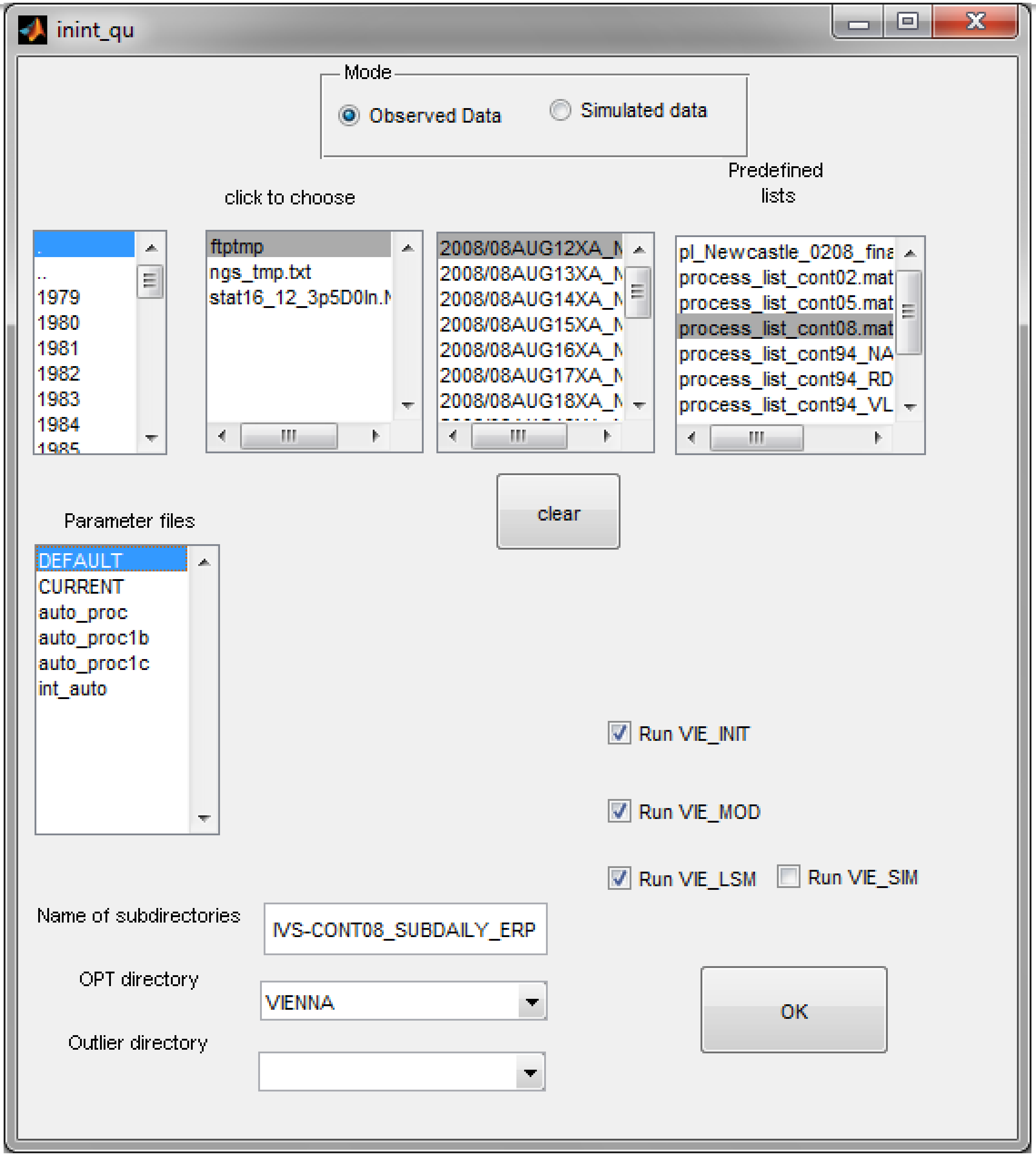
Green : all EOP were fixed to their a priori values.

Red : all ERP were estimated hourly. Nutation offsets were fixed.

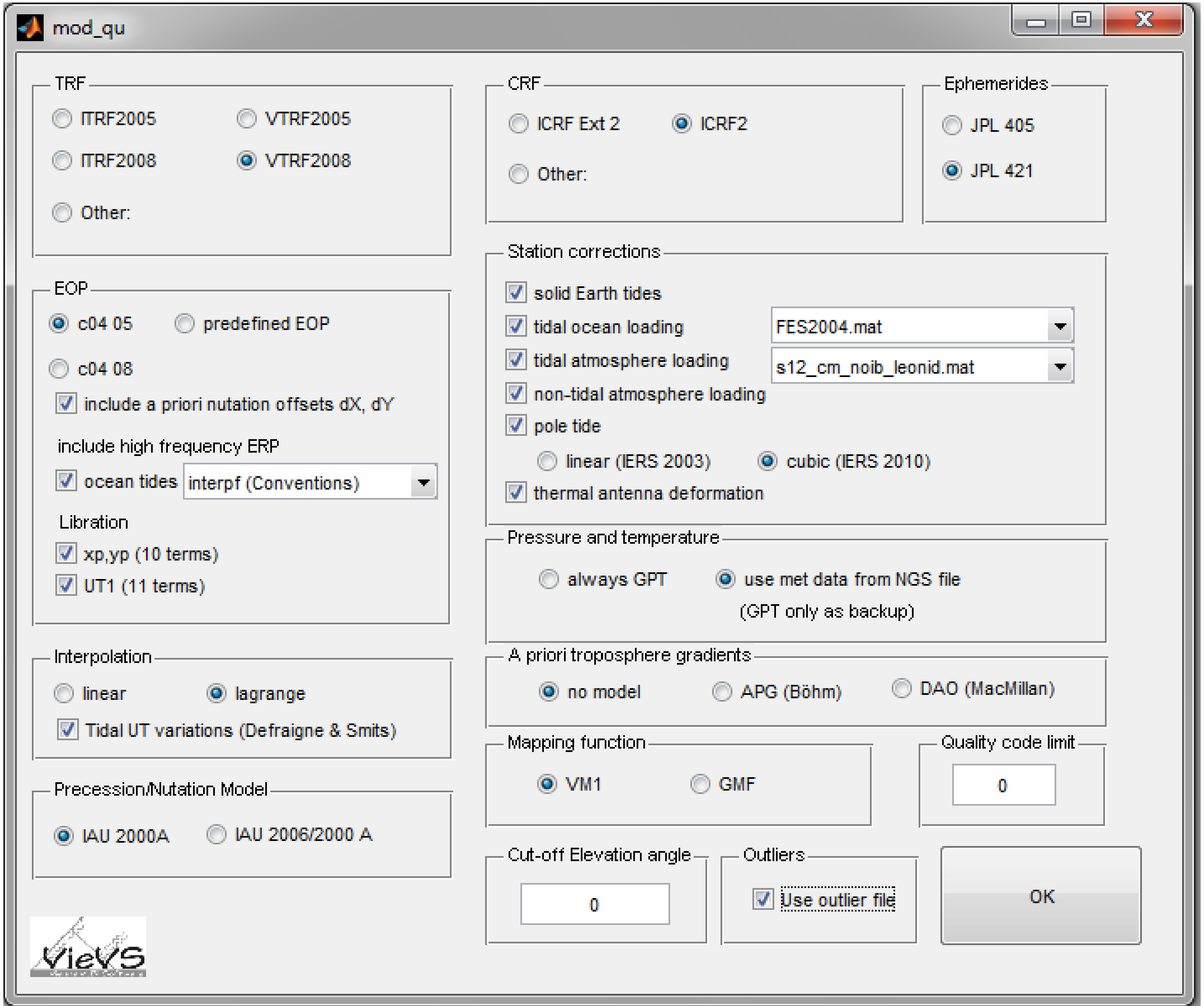
not any harmonic variation detected from the Fourier spectra of the hourly source coordinates.

EOP parameterization do not effect hourly source coordinates when all sources are fixed except two sources are estimated.

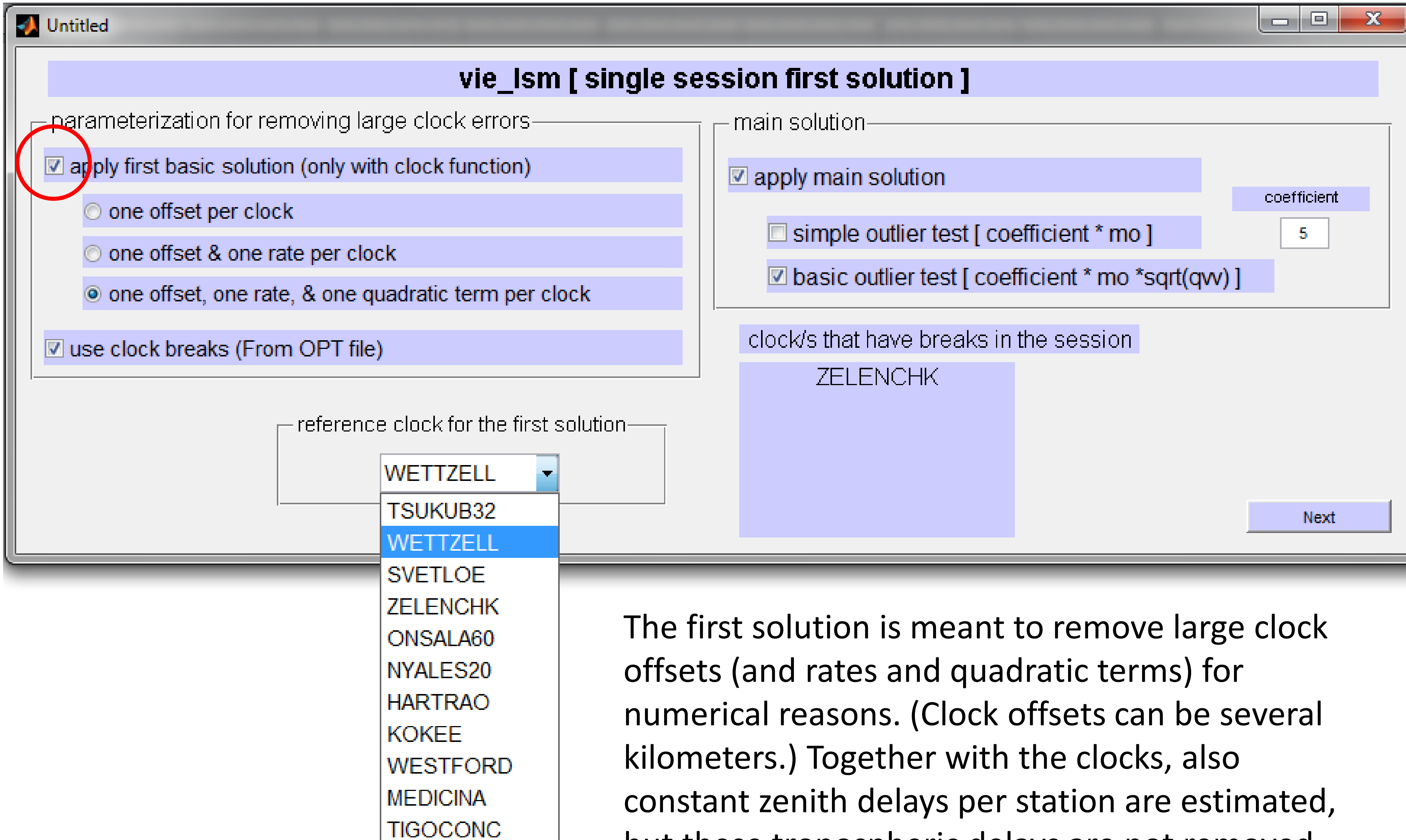
Graphical user interfaces of VieVS



Graphical user interfaces of VieVS

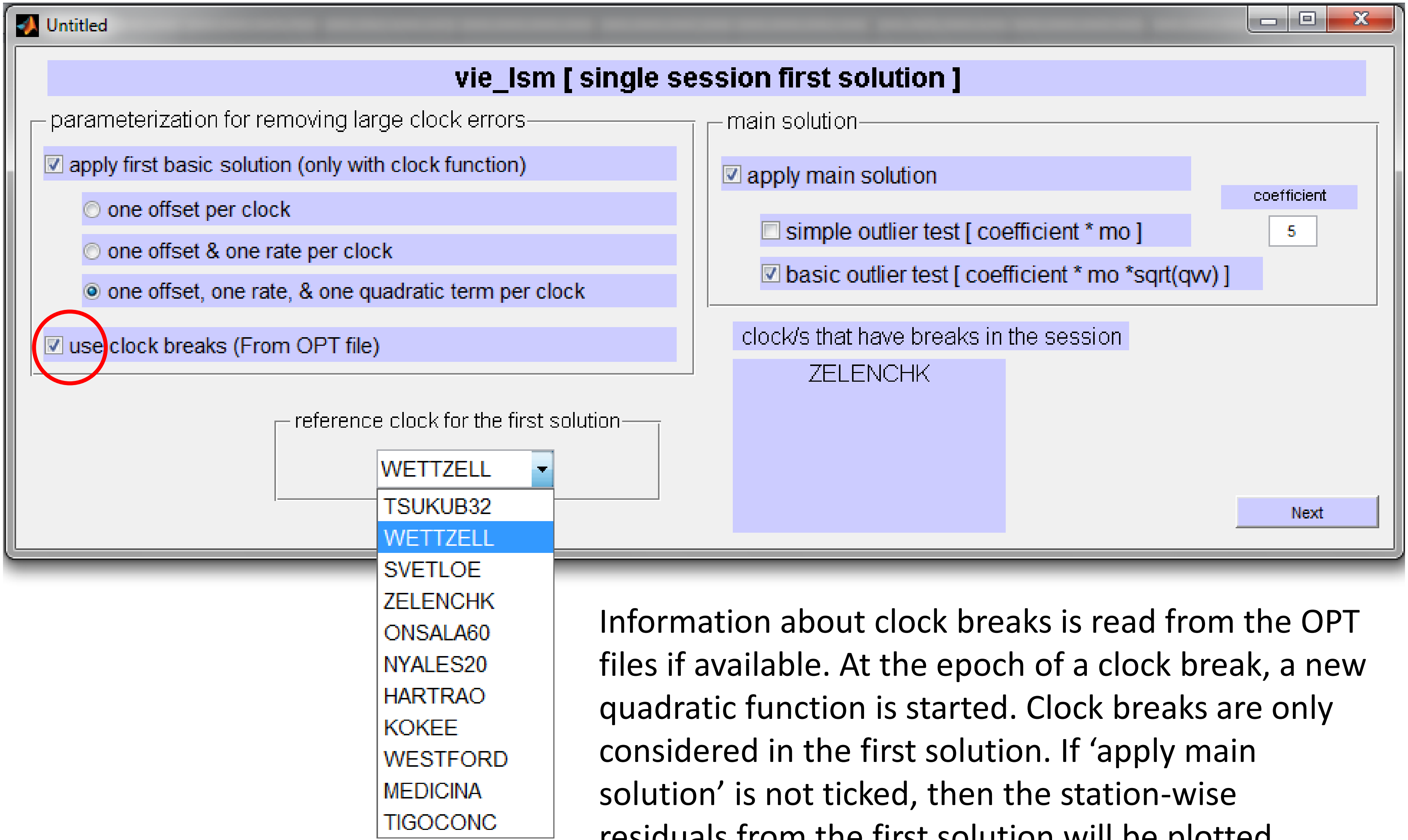


Graphical user interfaces of VieVS



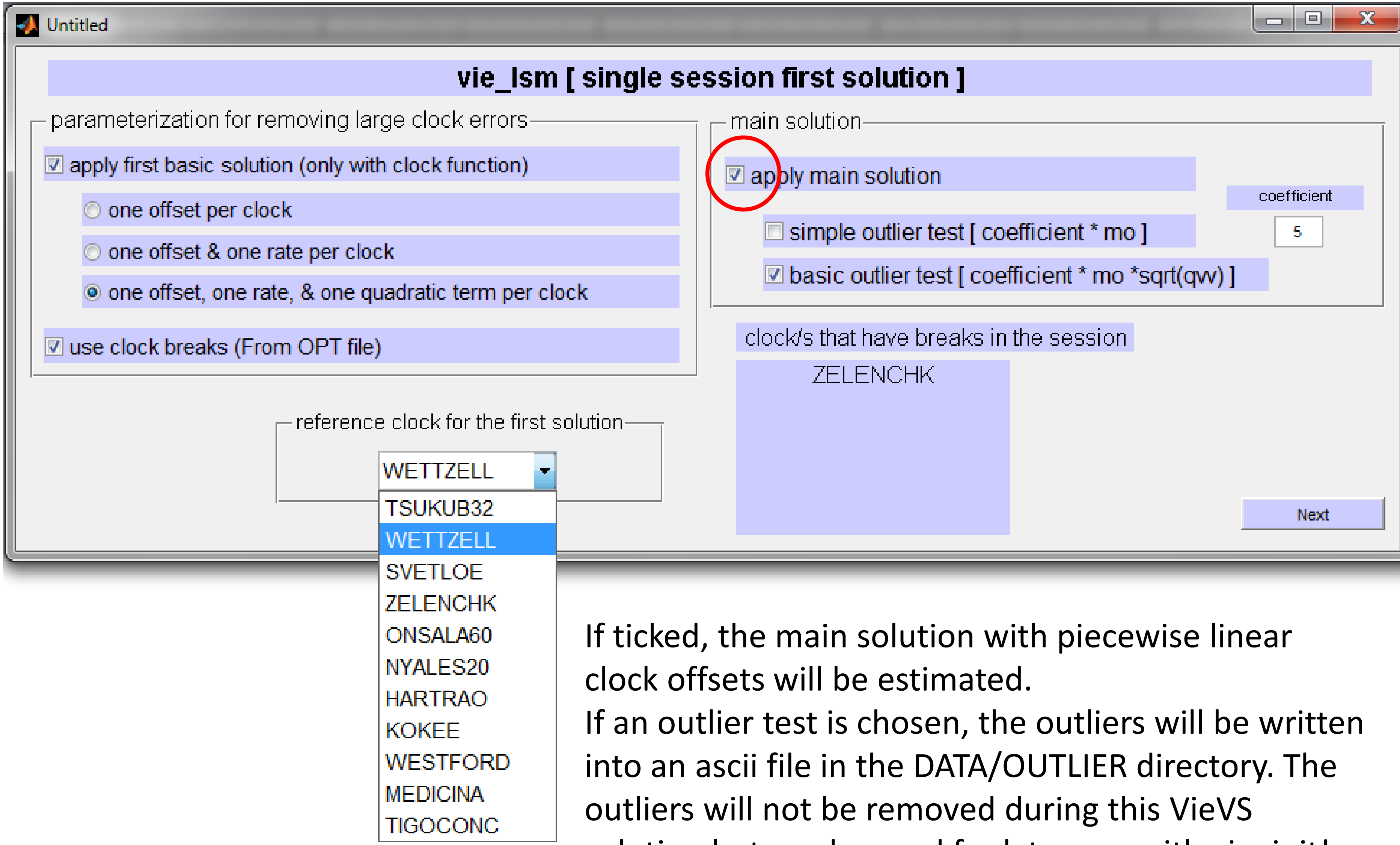
The first solution is meant to remove large clock offsets (and rates and quadratic terms) for numerical reasons. (Clock offsets can be several kilometers.) Together with the clocks, also constant zenith delays per station are estimated, but these tropospheric delays are not removed from the observations.

Graphical user interfaces of VieVS



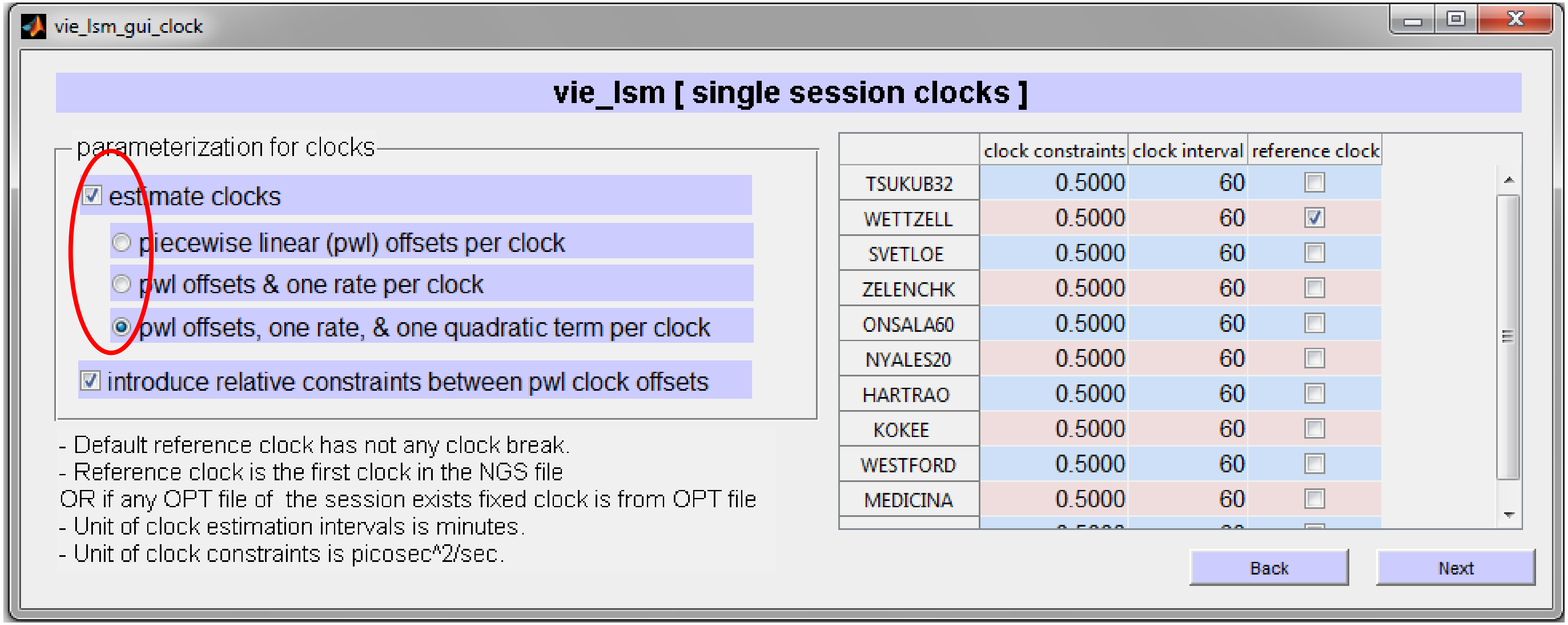
Information about clock breaks is read from the OPT files if available. At the epoch of a clock break, a new quadratic function is started. Clock breaks are only considered in the first solution. If 'apply main solution' is not ticked, then the station-wise residuals from the first solution will be plotted. These plots are important to locate clock breaks.

Graphical user interfaces of VieVS



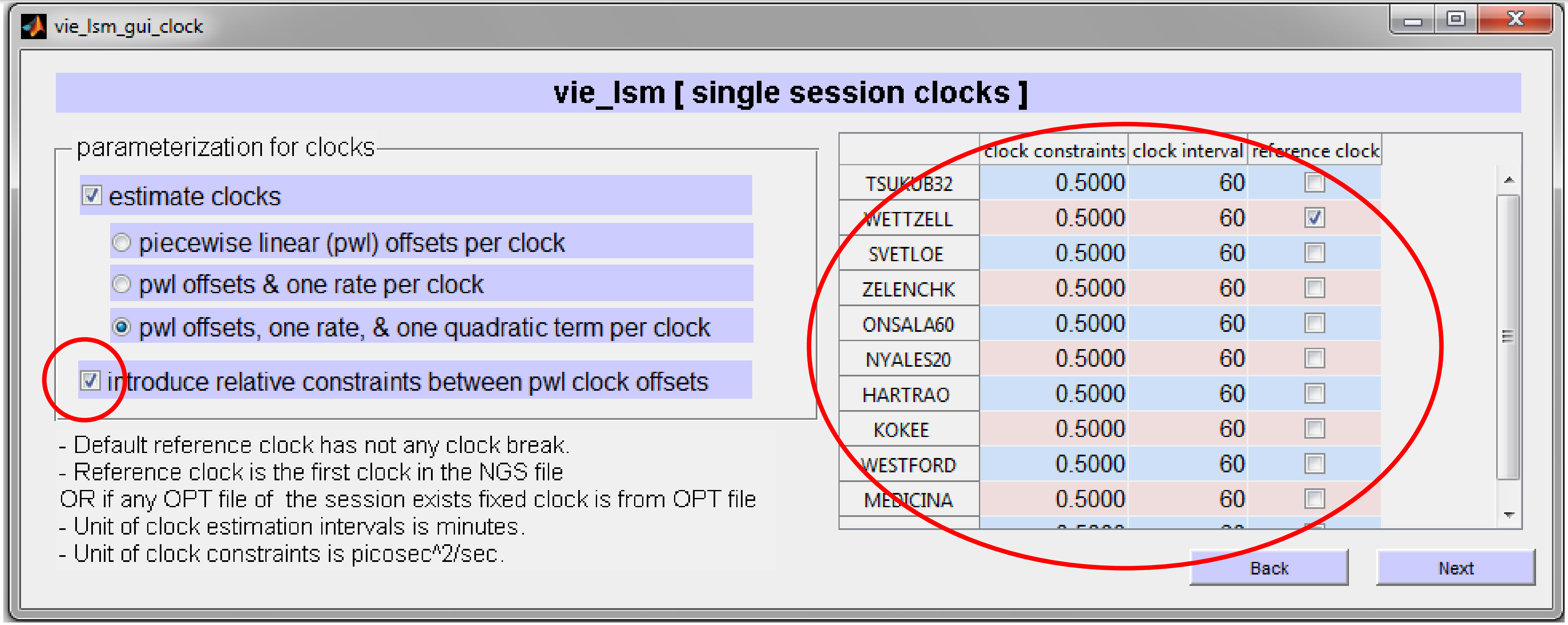
If ticked, the main solution with piecewise linear clock offsets will be estimated.
If an outlier test is chosen, the outliers will be written into an ascii file in the DATA/OUTLIER directory. The outliers will not be removed during this VieVS solution but can be used for later use with vie_init!

Graphical user interfaces of VieVS



In addition to the piecewise linear clocks, also a rate and a quadratic term can be estimated for the whole session. The reference epoch for the quadratic clock function is at the epoch of the first piecewise linear clock offset.

Graphical user interfaces of VieVS

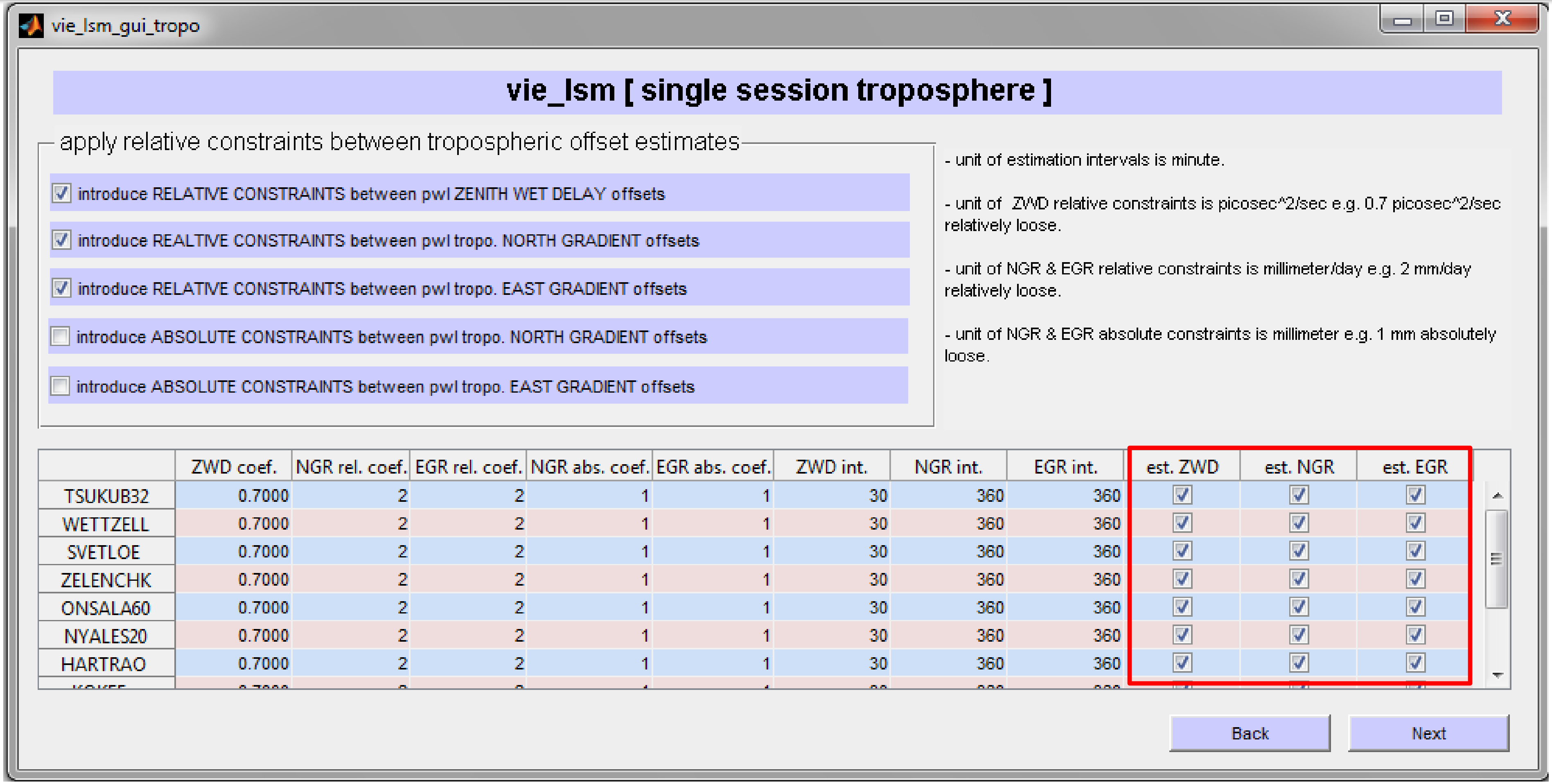


This combination adds relative constraints on the clock offsets. Actually, observation equations are added to the design matrix which tell that the difference between two adjacent piecewise linear clock offsets is zero ±a certain standard deviation σ. (These constraints are mainly important to bridge gaps without observations to avoid singularity of the normal equation system.)

How to interpret this constraint of 0.5 ps^2/s ?

Our time interval between piecewise linear offsets is 60 minutes, i.e. we have a variance of 1800 ps^2 after one hour. This standard deviation of 42 ps is the standard deviation σ which is used for the observation equation.

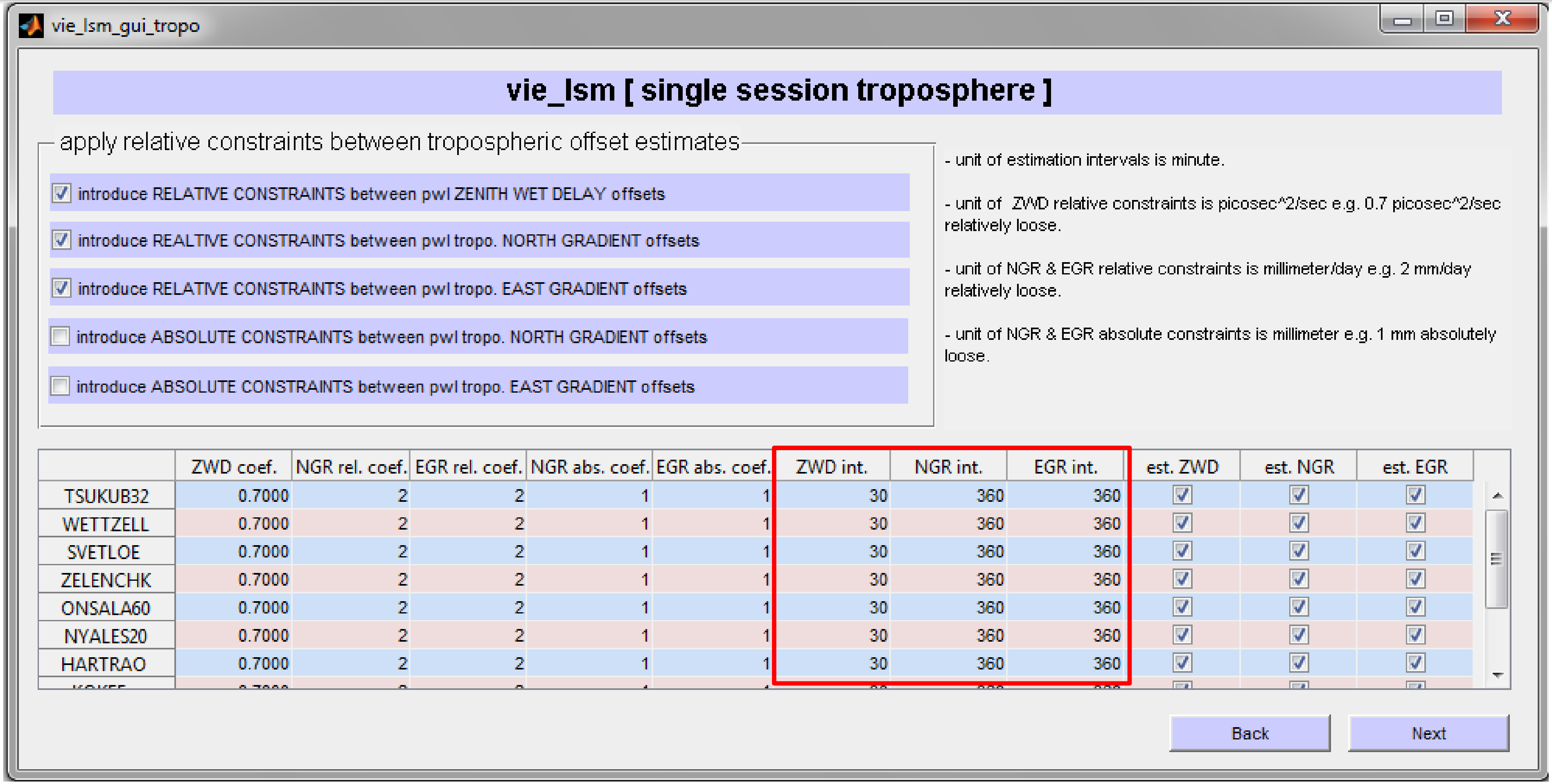
Graphical user interfaces of VieVS



	ZWD coef.	NGR rel. coef.	EGR rel. coef.	NGR abs. coef.	EGR abs. coef.	ZWD int.	NGR int.	EGR int.	est. ZWD	est. NGR	est. EGR
TSUKUB32	0.7000	2	2	1	1	30	360	360	✓	✓	✓
WETTZELL	0.7000	2	2	1	1	30	360	360	✓	✓	✓
SVETLOE	0.7000	2	2	1	1	30	360	360	✓	✓	✓
ZELENCHK	0.7000	2	2	1	1	30	360	360	✓	✓	✓
ONSALA60	0.7000	2	2	1	1	30	360	360	✓	✓	✓
NYALES20	0.7000	2	2	1	1	30	360	360	✓	✓	✓
HARTRAO	0.7000	2	2	1	1	30	360	360	✓	✓	✓

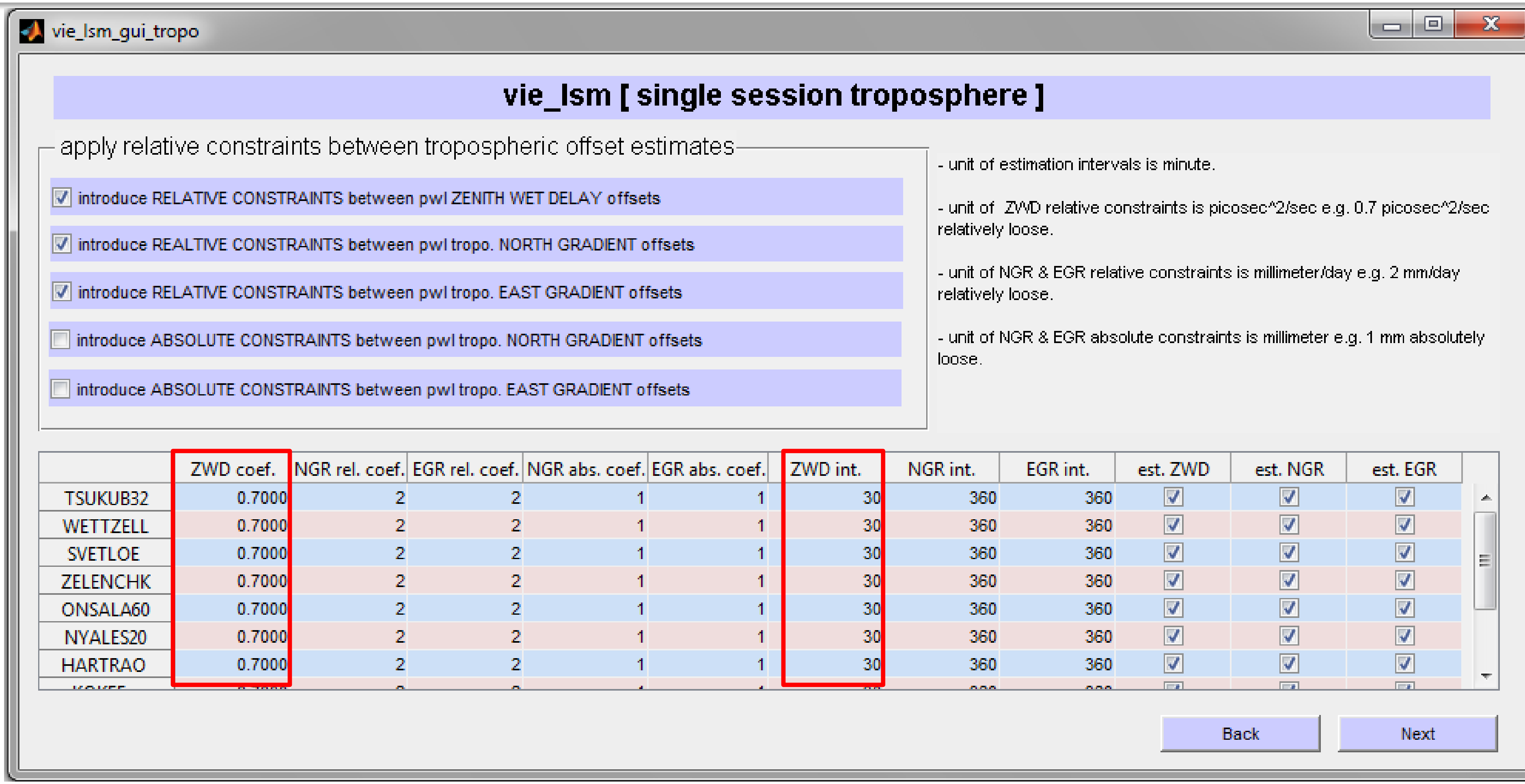
These ticks define whether zenith wet delays, north gradients and east gradients are estimated.

Graphical user interfaces of VieVS



These are the corresponding time intervals in minutes.

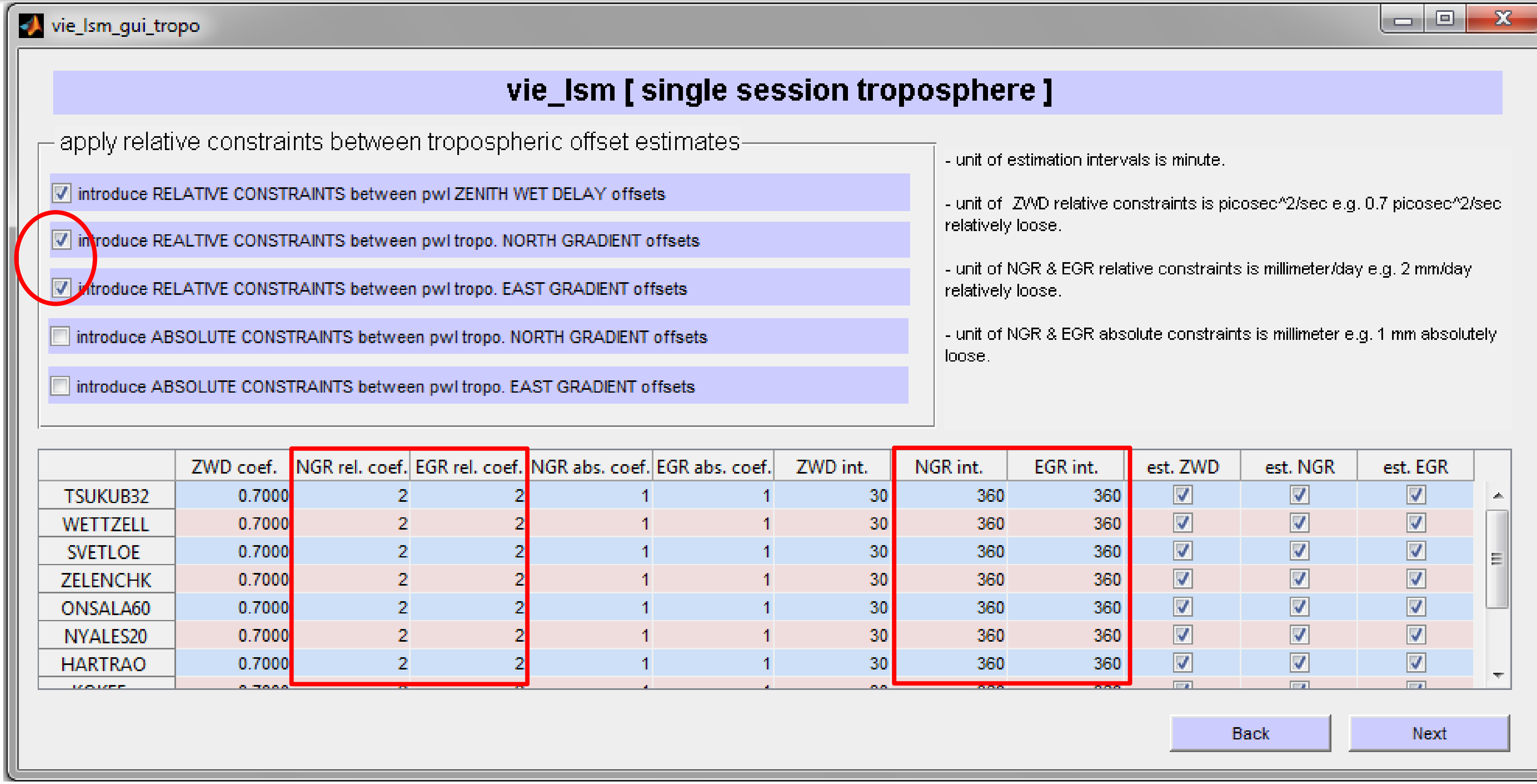
Graphical user interfaces of VieVS



How to interpret this constraint of 0.7 ps²/s for the zenith wet delays? (This is similar to the clocks.)

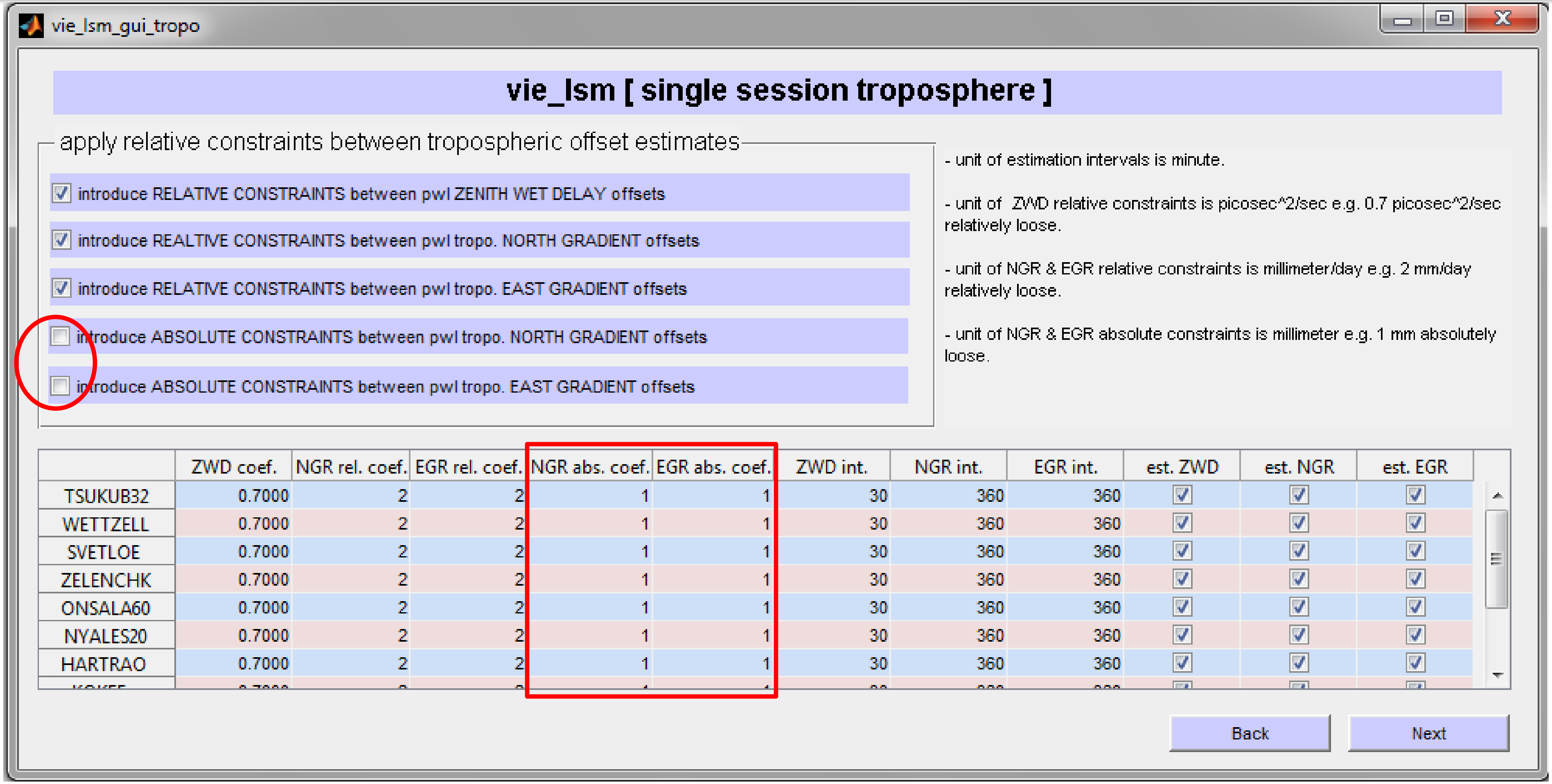
Our time interval between piecewise linear offsets is 30 minutes, i.e. we have a variance of 1260 ps² after one hour. This is a standard deviation of 35 ps. 35 ps is the standard deviation σ, which is used for the observation equation.

Graphical user interfaces of VieVS



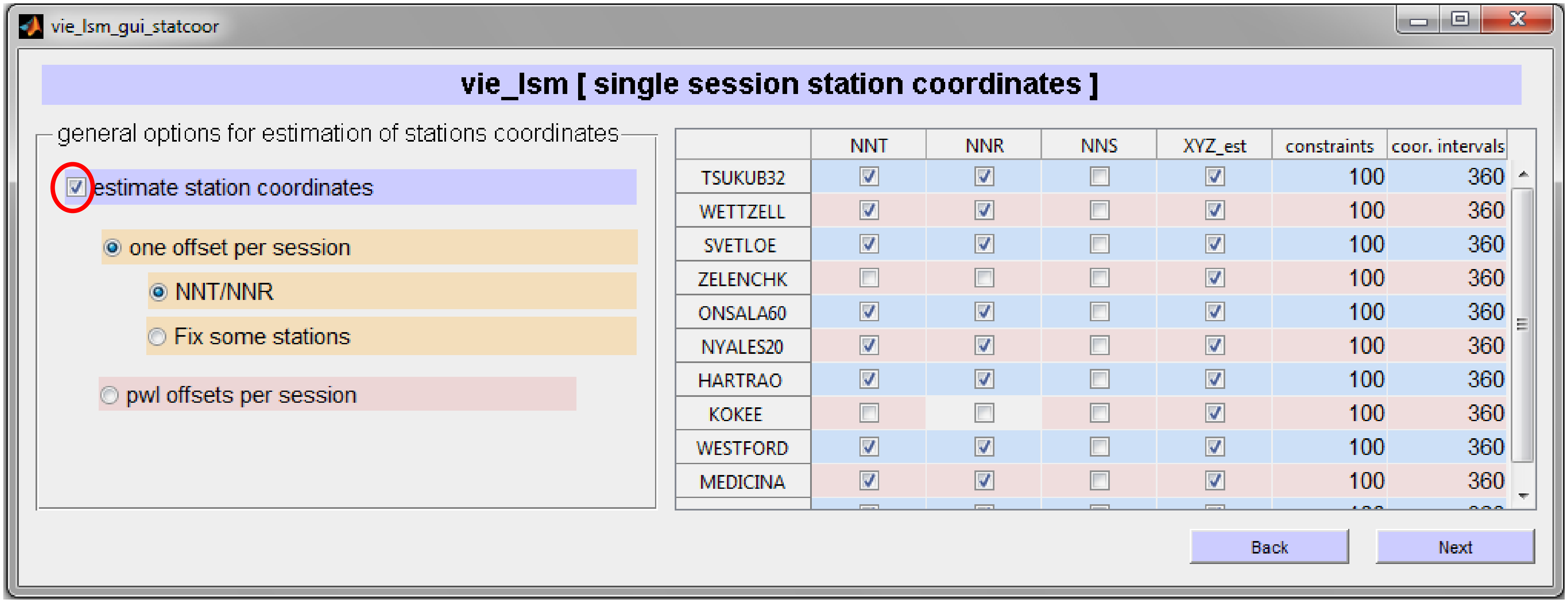
How to interpret these constraints of 2 mm/day for the gradients? Unlike clocks and zenith wet delays, these relative constraints scale linearly, i.e. 2 mm/day correspond to 0.5 mm after 6 hours (360 minutes).

Graphical user interfaces of VieVS



If ticked, absolute constraints of 1 mm are applied on the gradient offsets, i.e., additional observation equations are added which tell that the gradient offset is zero ± 1 mm. (This feature might be necessary in early VLBI sessions.)

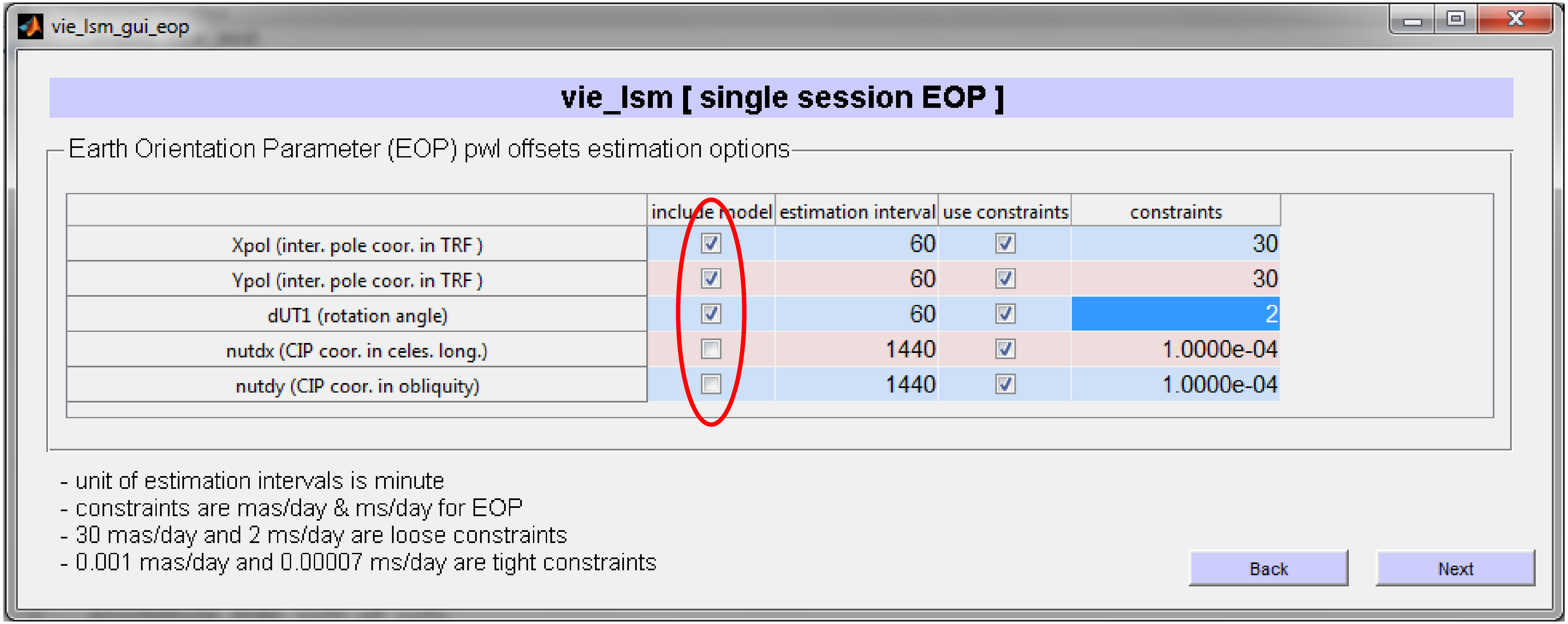
Graphical user interfaces of VieVS



If like this, the NNR and NNT conditions are applied on all stations which are available in the selected TRF. (If e.g. the station is not in the TRF, the a priori coordinates are taken from the header of the NGS file and the station is not part of the datum.) Typically, the scale is not ticked because the scale is taken from the VLBI observations. (Please mind the possibility of station-wise parameterization to change the datum stations.)

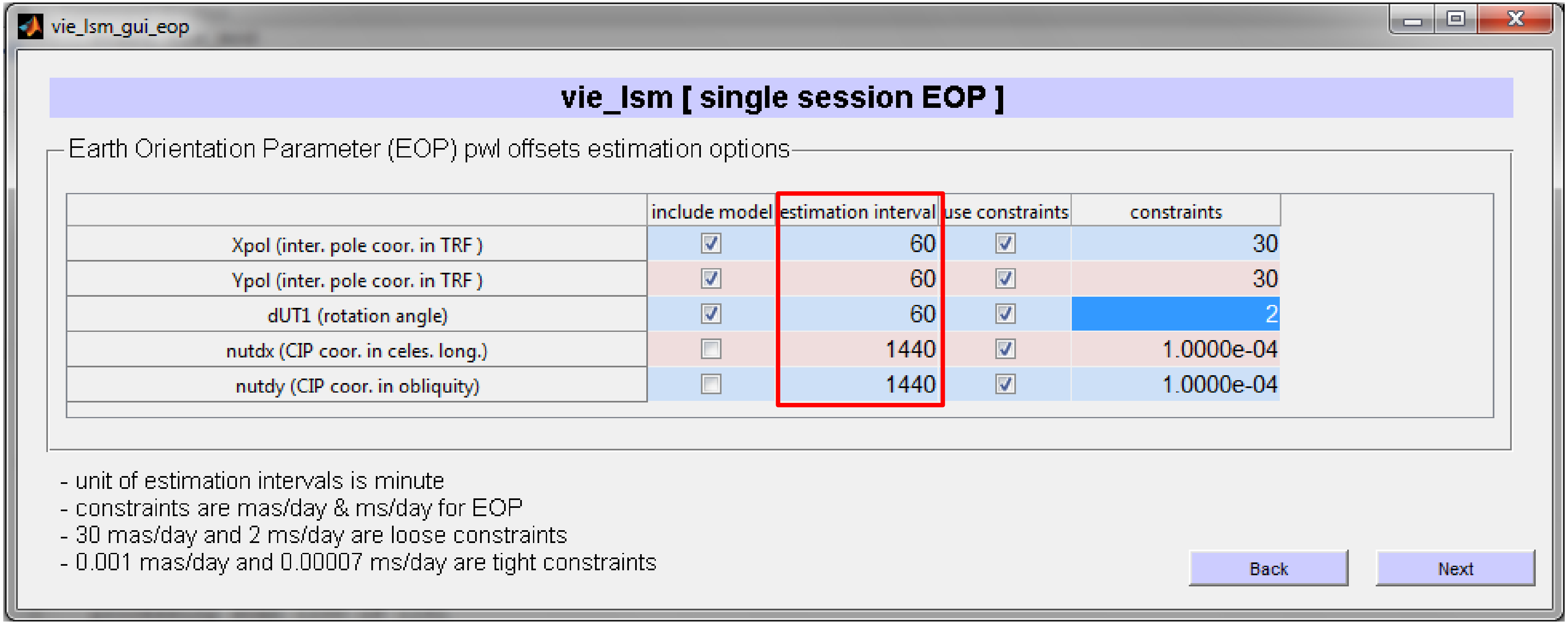
If red circle is not ticked all stations coordinates are fixed which are available in the selected TRF. (If e.g. the station is not in the TRF, the coordinates are taken from the header of the NGS file and the station is not fixed to those a priori values but the station coordinates are estimated.) (Please mind the possibility of station-wise parameterization.)

Graphical user interfaces of VieVS



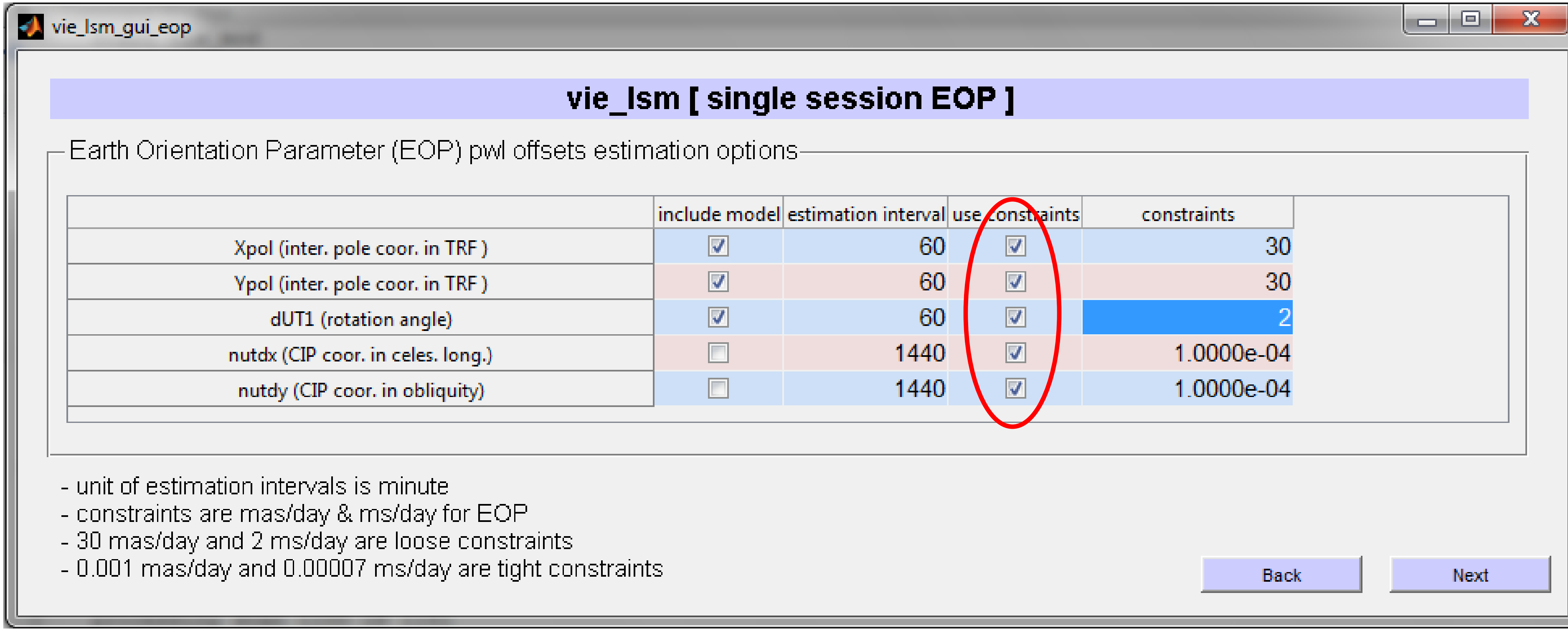
Tick here, if you want to estimate polar motion (x, y), UT1-UTC, and nutation (X, Y). Everything is carried out in the new system with the non-rotating origin.

Graphical user interfaces of VieVS



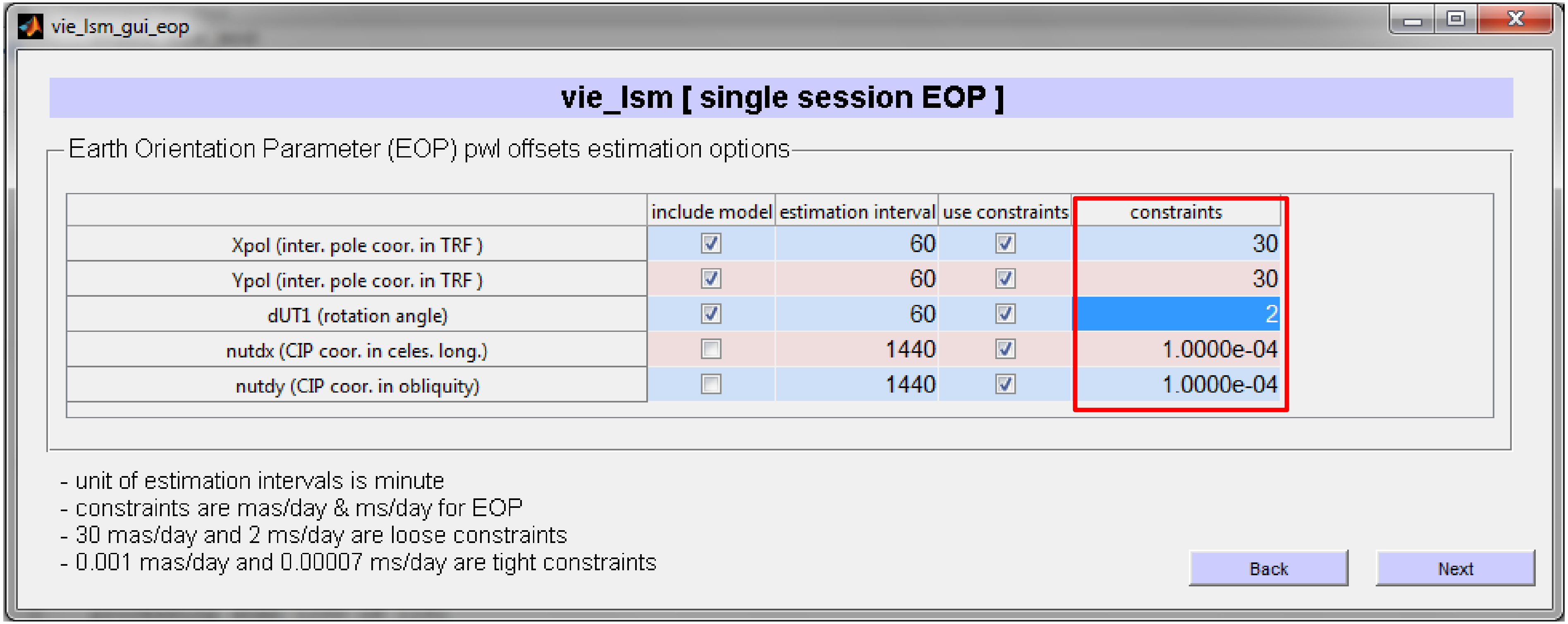
These are the time (estimation) intervals in minutes.

Graphical user interfaces of VieVS



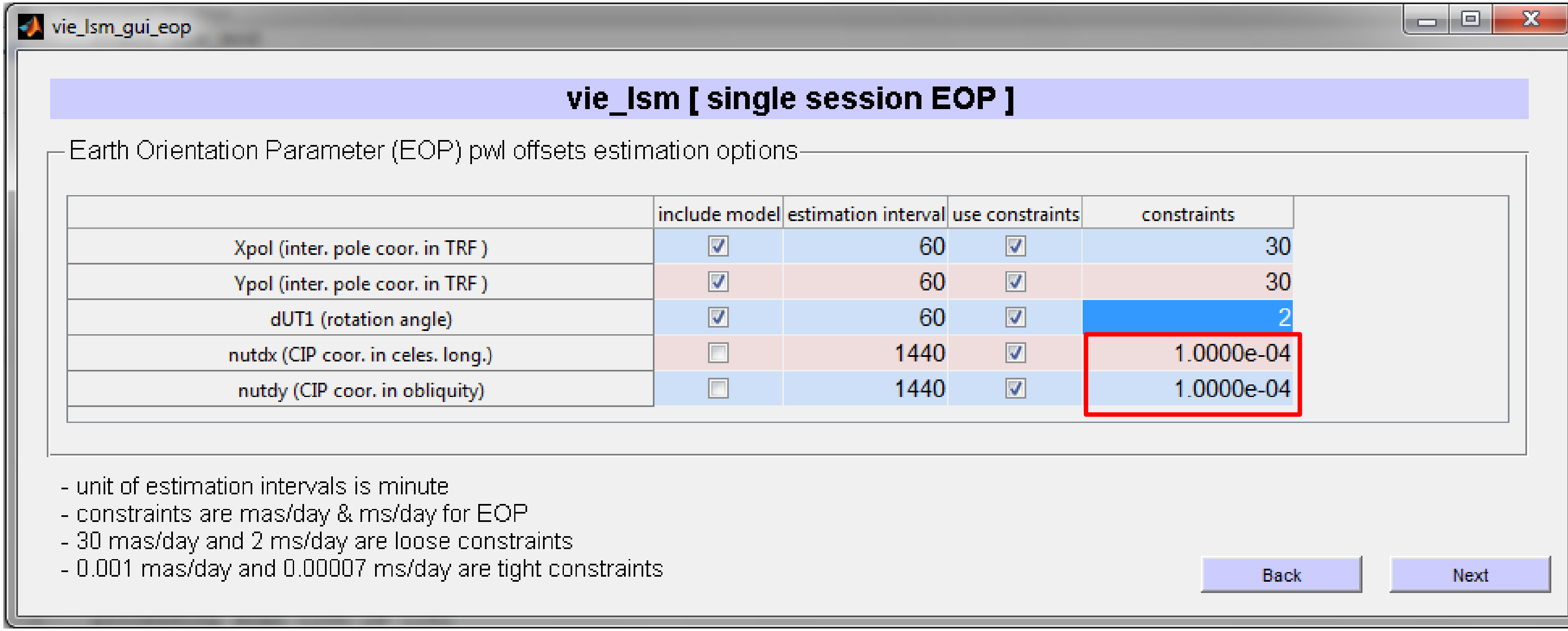
Tick here if you want to use relative constraints between the piecewise linear offsets for the respective Earth orientation parameter.

Graphical user interfaces of VieVS



Similar to the gradients, these constraints scale linearly. The units are mas/day for polar motion and nutation, and ms/day for UT1-UTC.

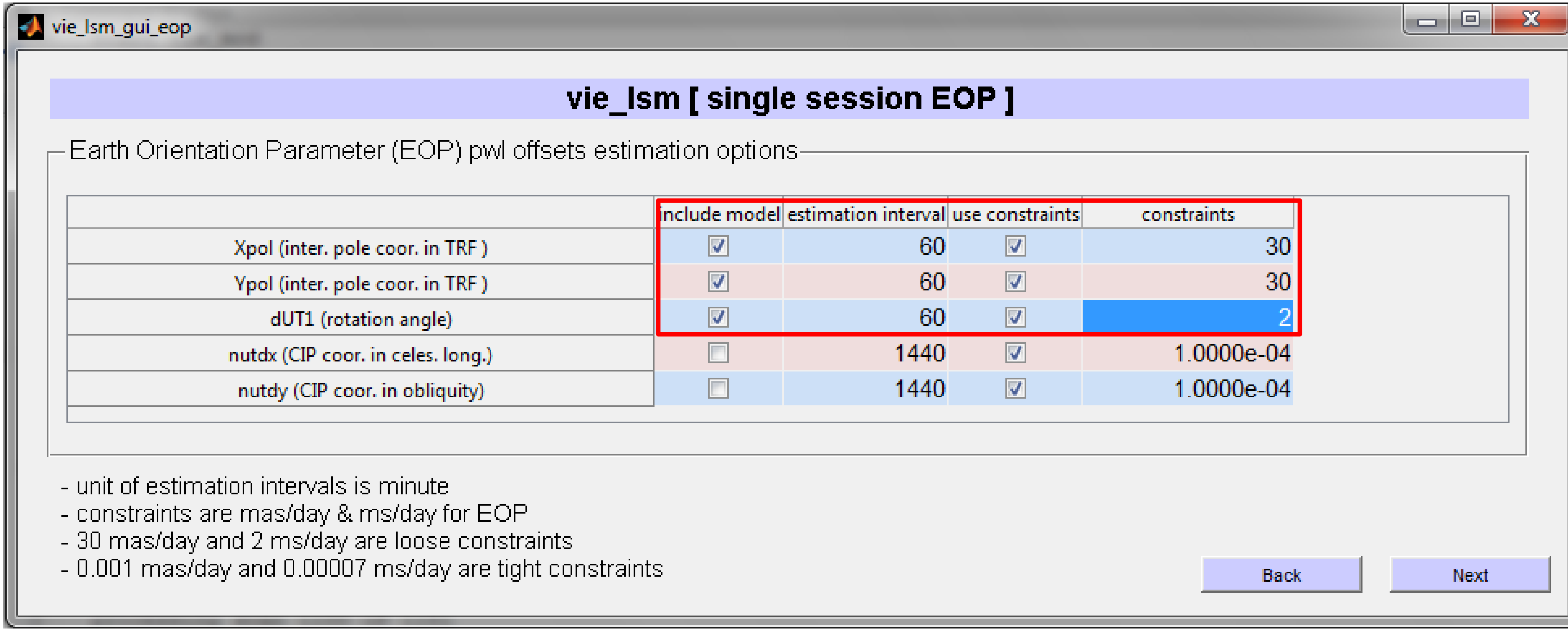
Graphical user interfaces of VieVS



If you want to estimate one constant value per session, the recommendation is to set the parameterization as shown above. Very strong relative constraints of 1e-4 m(a)s/day take care that the estimates are the same over the session.

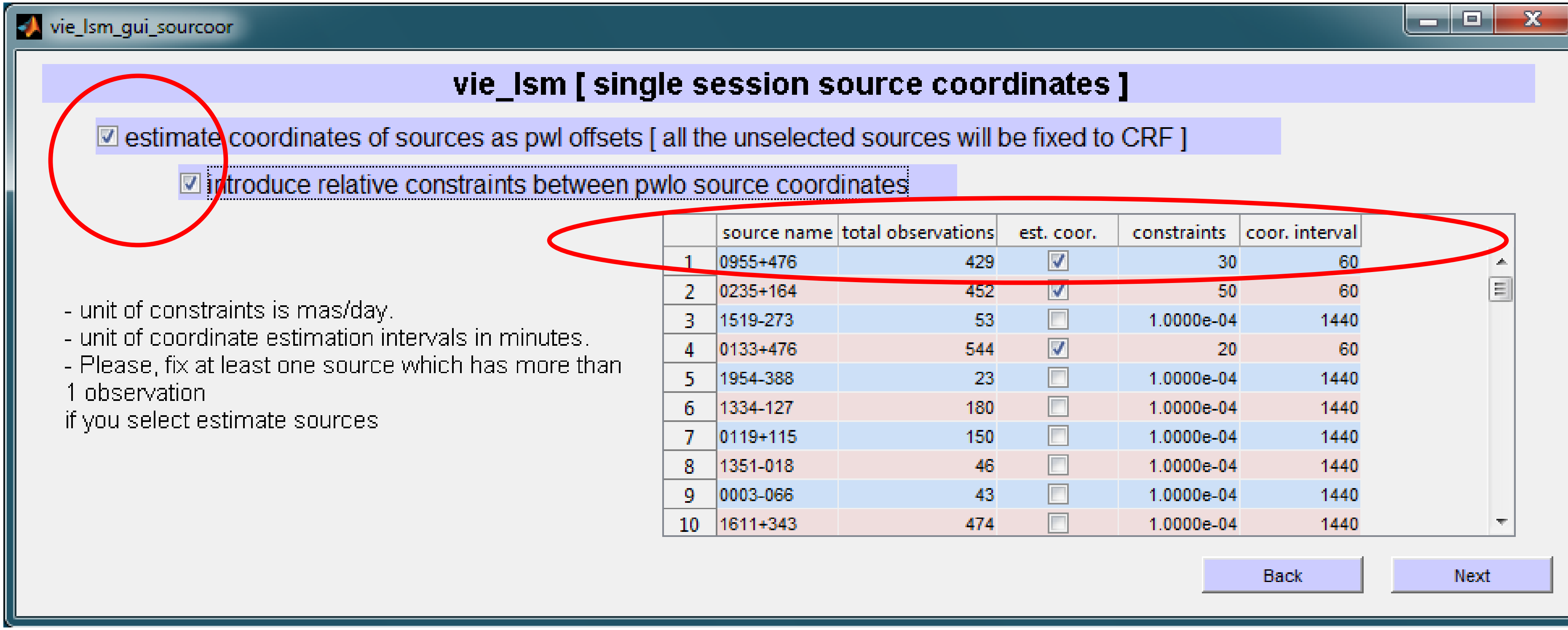
Example: The session is from 18 UT to 18 UT. Then, three piecewise linear offsets are set up for each EOP. (They are set up a midnight before the session, at midnight during the session, and at midnight after the session.) The strong constraints take care that all three estimates per session are the same.

Graphical user interfaces of VieVS



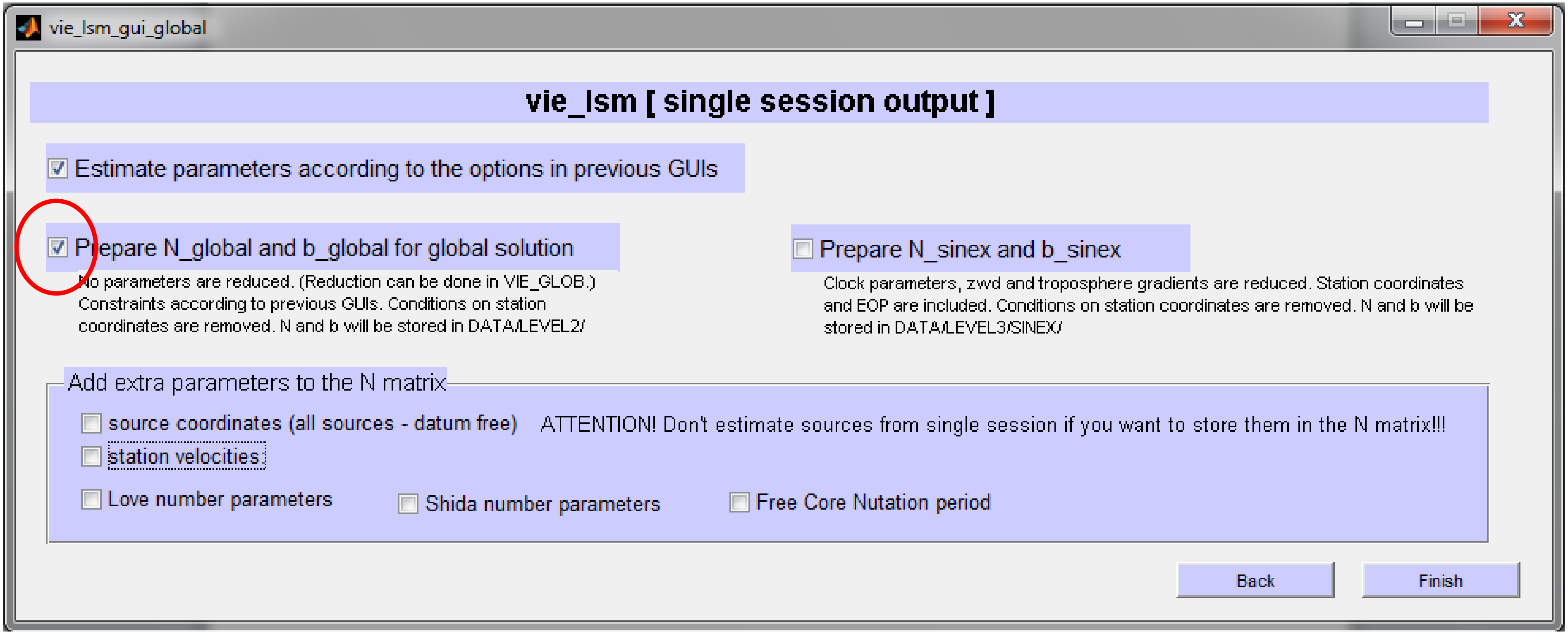
If you want to estimate hourly Earth rotation parameters (polar motion and UT1-UTC), you should not estimate nutation, and you should use loose constraints like 30 mas per day and 2 ms per day (1.25 mas per hour and 83 µs per hour).

Graphical user interfaces of VieVS



Typically, if you do want to estimate sources as piecewise linear offsets e.g. one hour interval. You could do so by selecting certain sources via the source-wise parameterization.

Graphical user interfaces of VieVS



Tick this, if you want to use the normal equations for later use in a global solution with vie_glob. Datum free normal equation coefficient matrix and right hand side vector will be prepared. This normal equation system will include as default : clocks, ZWD, troposphere gradients, antenna coordinates in TRF, and EOP if selected.