



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.

30 May 2011

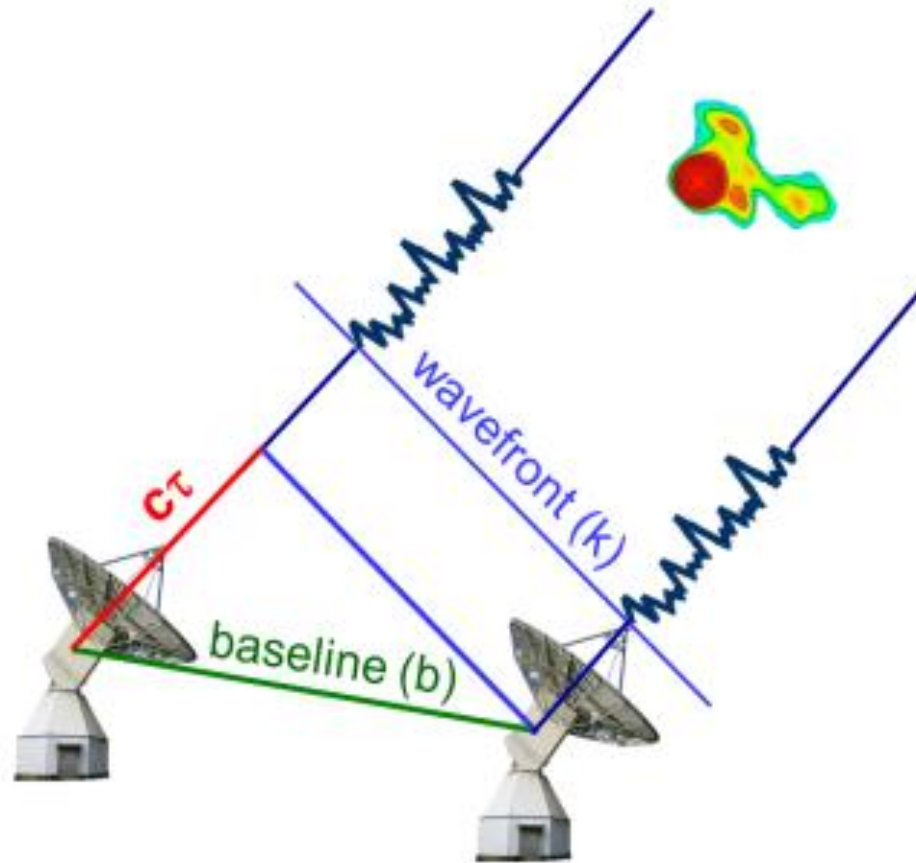
# Overview

- 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.

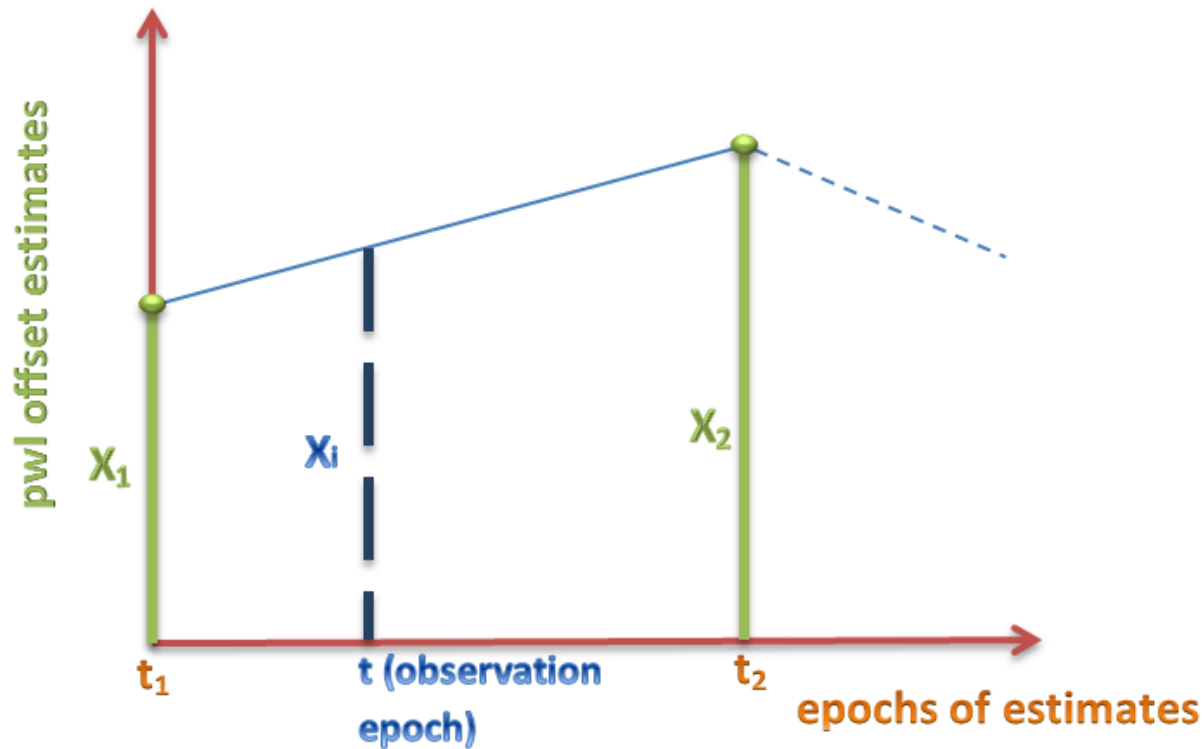
# VLBI delay model



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



# 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.  $\Delta\text{UT1}$  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.

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

parameter vector  
(estimates)

$$x = N^{-1} b$$

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

$$K_x = m_0 N^{-1} \rightarrow \text{variance-covariance matrix of the estimates}$$

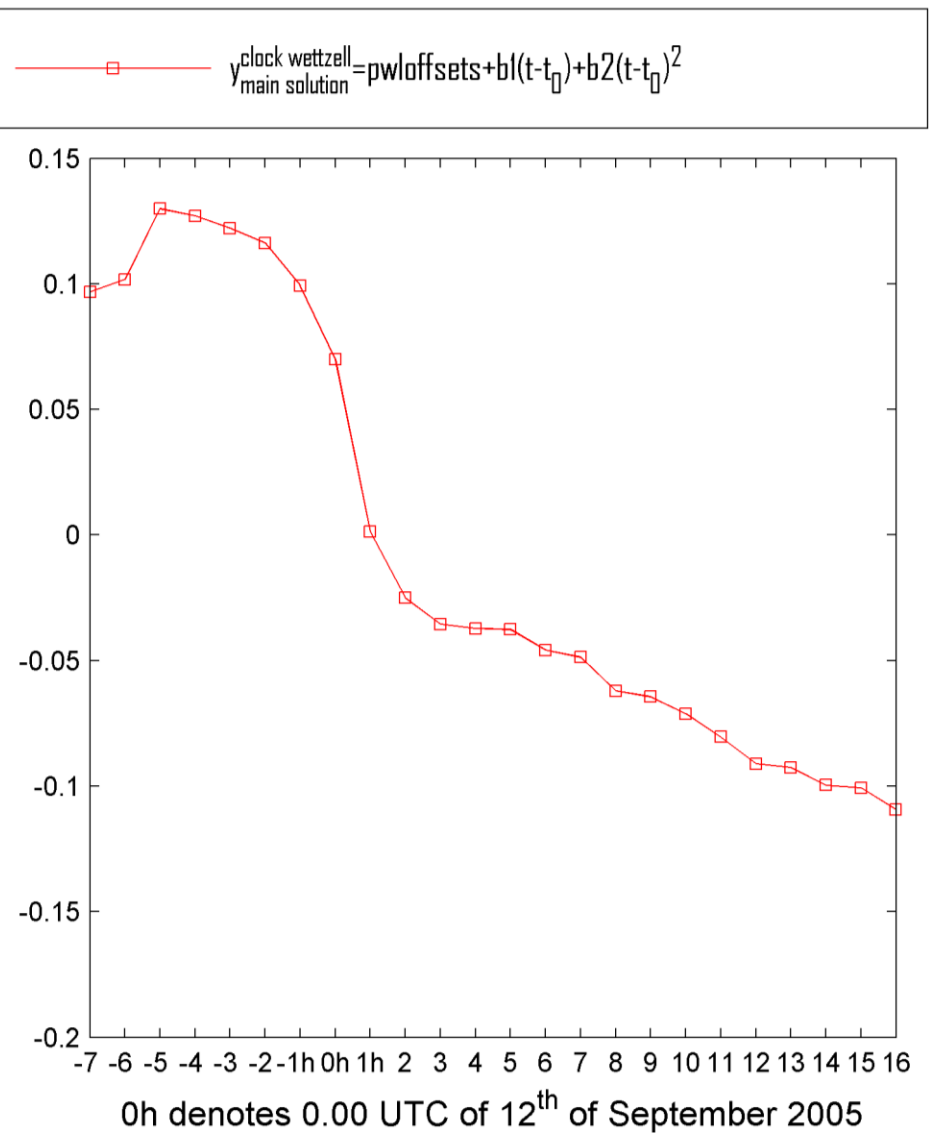
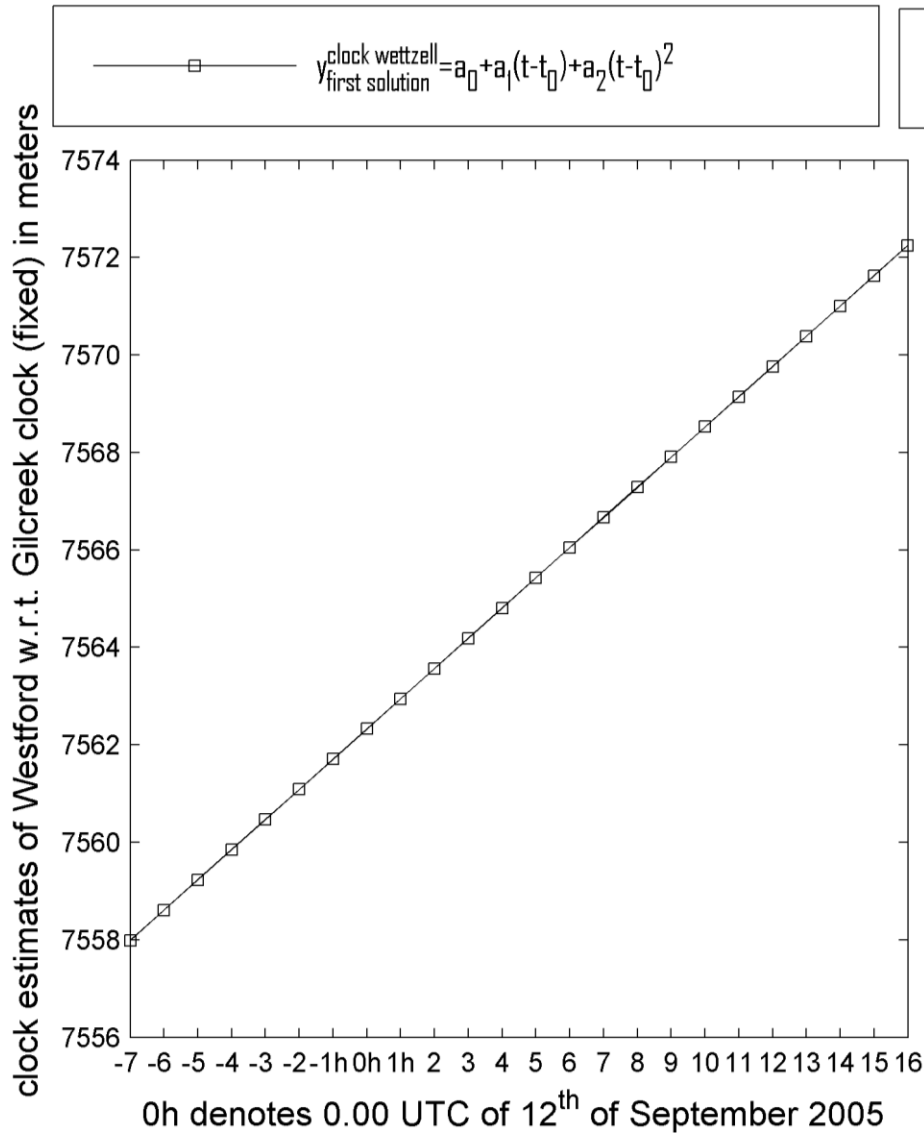
# VLBI clock error

$$\Delta \tau_{clk}^{poly}(t) = \beta_0 + \beta_1(t - t_0) + \beta_2(t - t_0)^2 \Rightarrow \text{quadratic polynomial for each clock}$$

$$\Delta \tau_{clk}^{CPWLO}(t) = x_1 + \frac{t - t_1}{t_2 - t_1} (x_2 - x_1) \Rightarrow \text{CPWLO for each clock e.g. at each UTC integer hour (t}_1 \text{ and t}_2)$$

$$\Delta \tau_{clk}(t) = \Delta \tau_{clk}^{poly}(t) + \Delta \tau_{clk}^{CPWLO}(t) \Rightarrow \text{Total clock error at epoch t}$$

# VLBI clock error



# Modeling clock breaks

Untitled

### vie\_ism [ single session first solution ]

parameterization for removing large clock errors—

- apply first basic solution (only with clock function)
  - one offset per clock
  - one offset & one rate per clock
  - one offset, one rate, & one quadratic term per clock
- use clock breaks (From OPT file)

reference clock for the first solution—

WETTZELL  
TSUKUB32  
WETTZELL  
SVETLOE  
ZELENCHK  
ONSALA60  
NYALES20  
HARTRAO  
KOKEE  
WESTFORD  
MEDICINA  
TIGOCONC

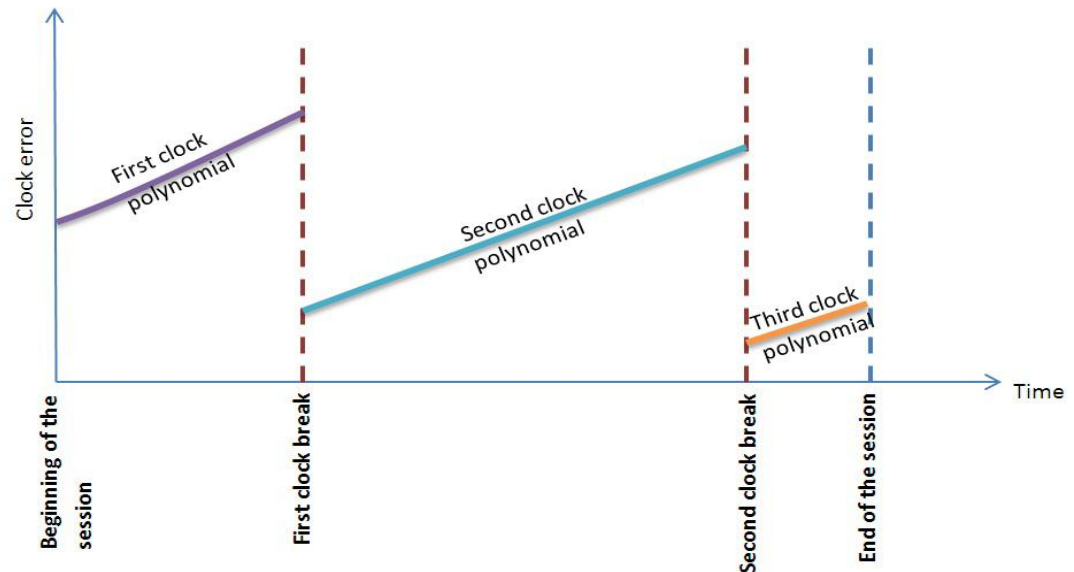
main solution—

- apply main solution
  - simple outlier test [ coefficient \* mo ]  coefficient
  - basic outlier test [ coefficient \* mo \*sqrt(qw) ]

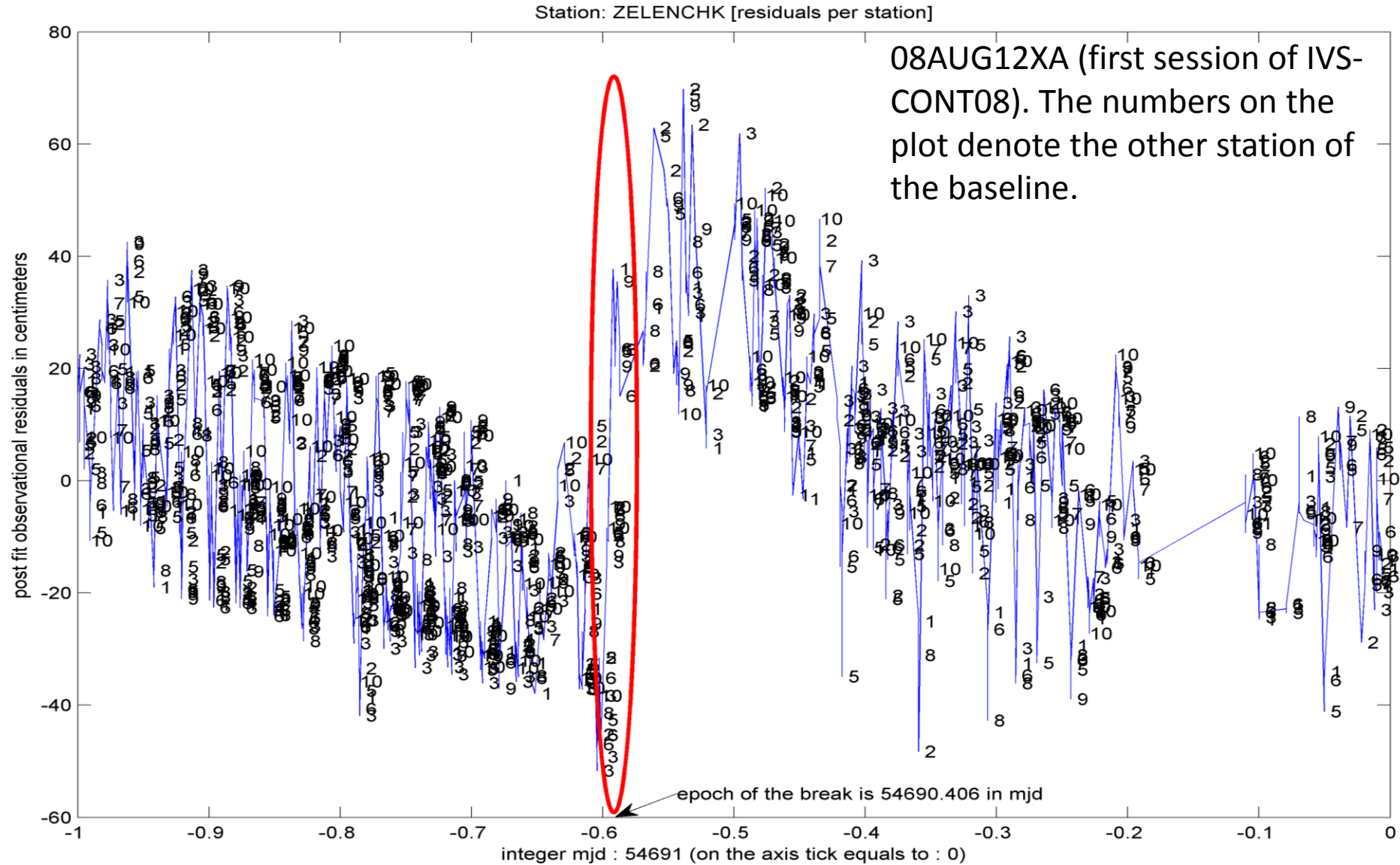
clock/s that have breaks in the session

ZELENCHK

Next



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







# Troposphere delay in VieVS

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

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

reduced from  
observations a priori to  
the adjustment  
(Saastamoinen, 1972)

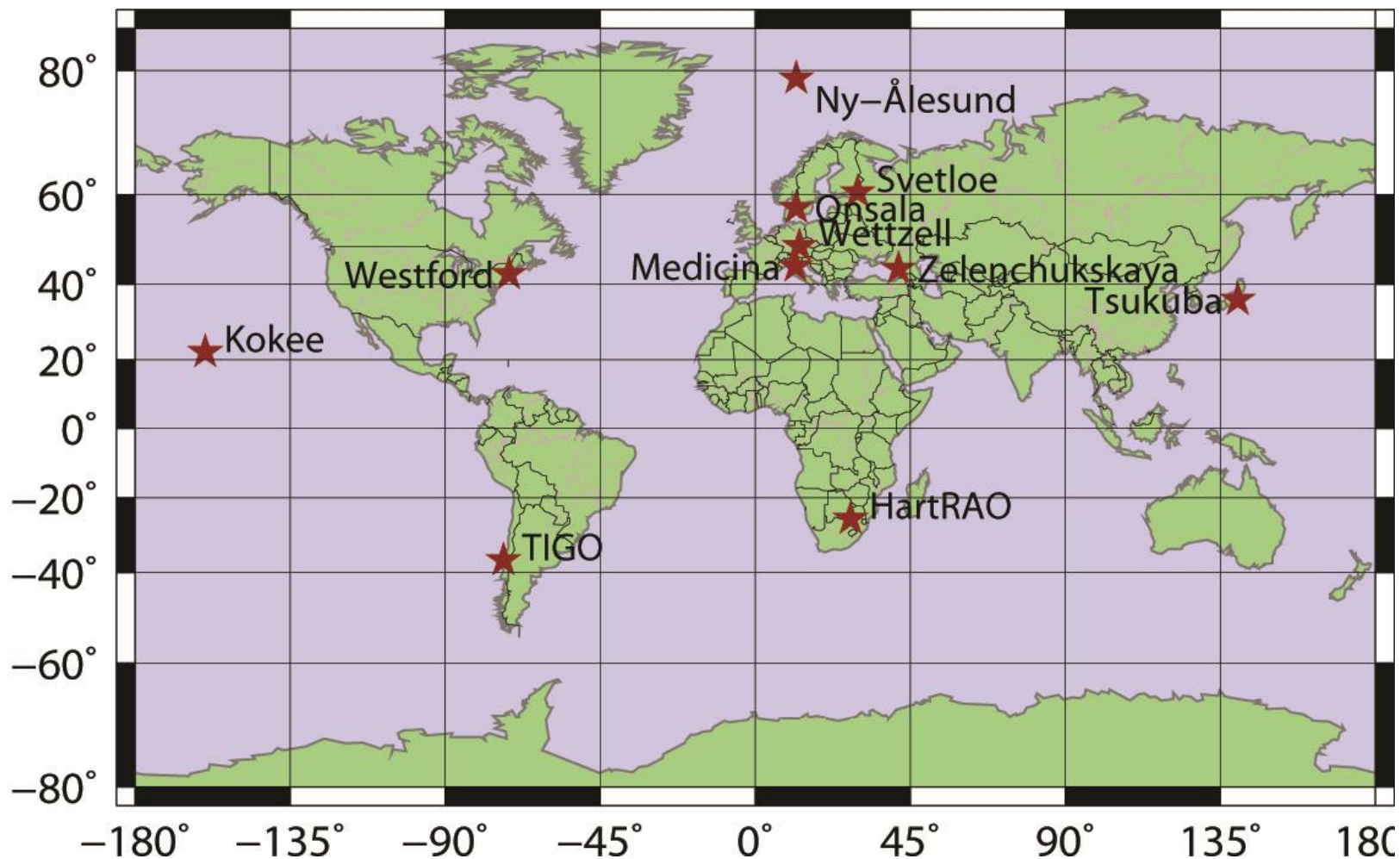
estimated

estimated

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**

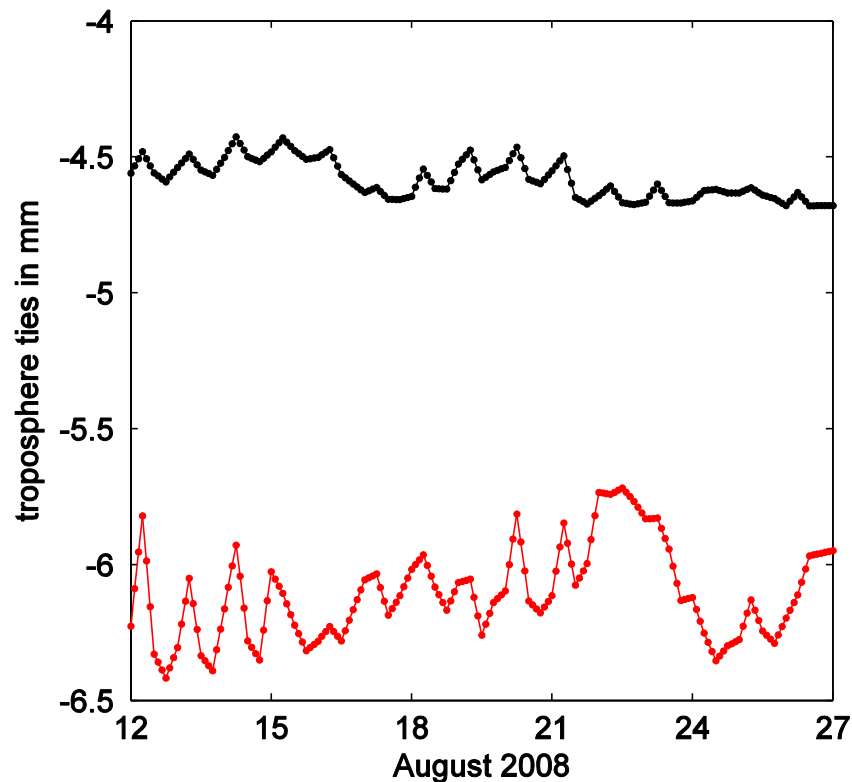
# Comparisons of troposphere zenith delays and gradients during IVS-CONT08 at co-located sites

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.

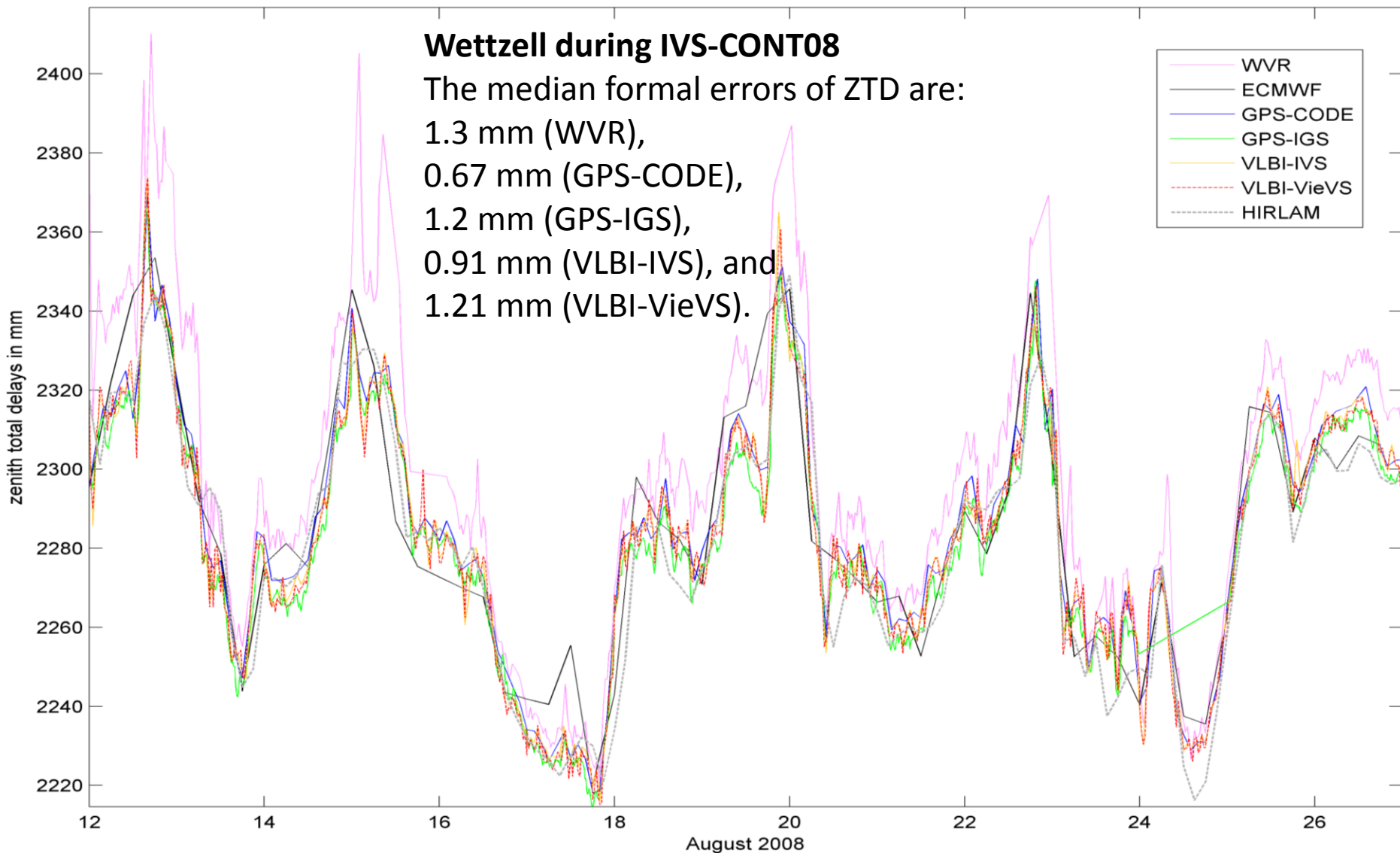
# Troposphere ties

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

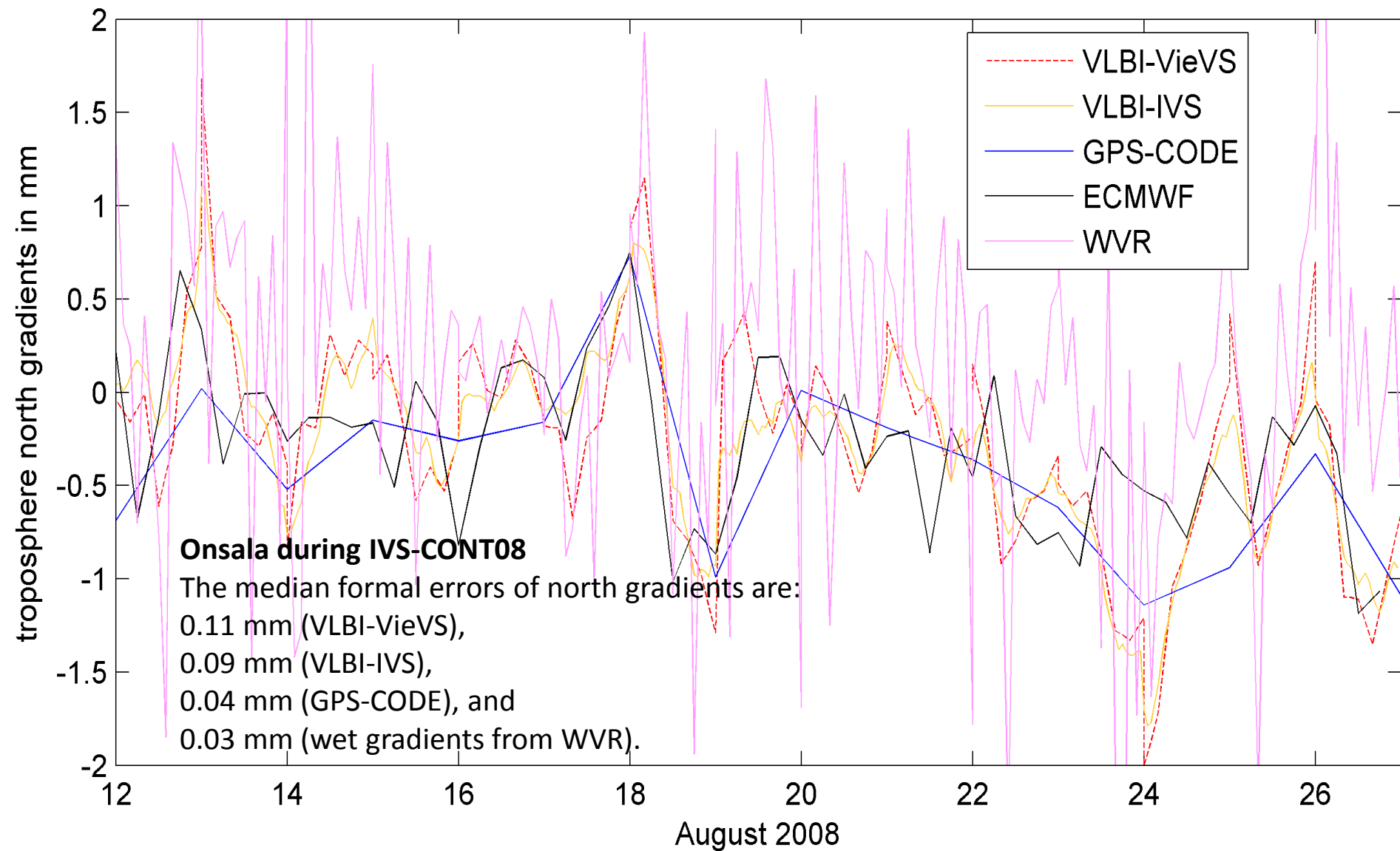


Troposphere ties between the GPS antenna TSKB and the VLBI antenna TSUKUB32 during IVS-CONT08, calculated for all common epochs. Red and black dotted lines illustrate total and hydrostatic ties, respectively.

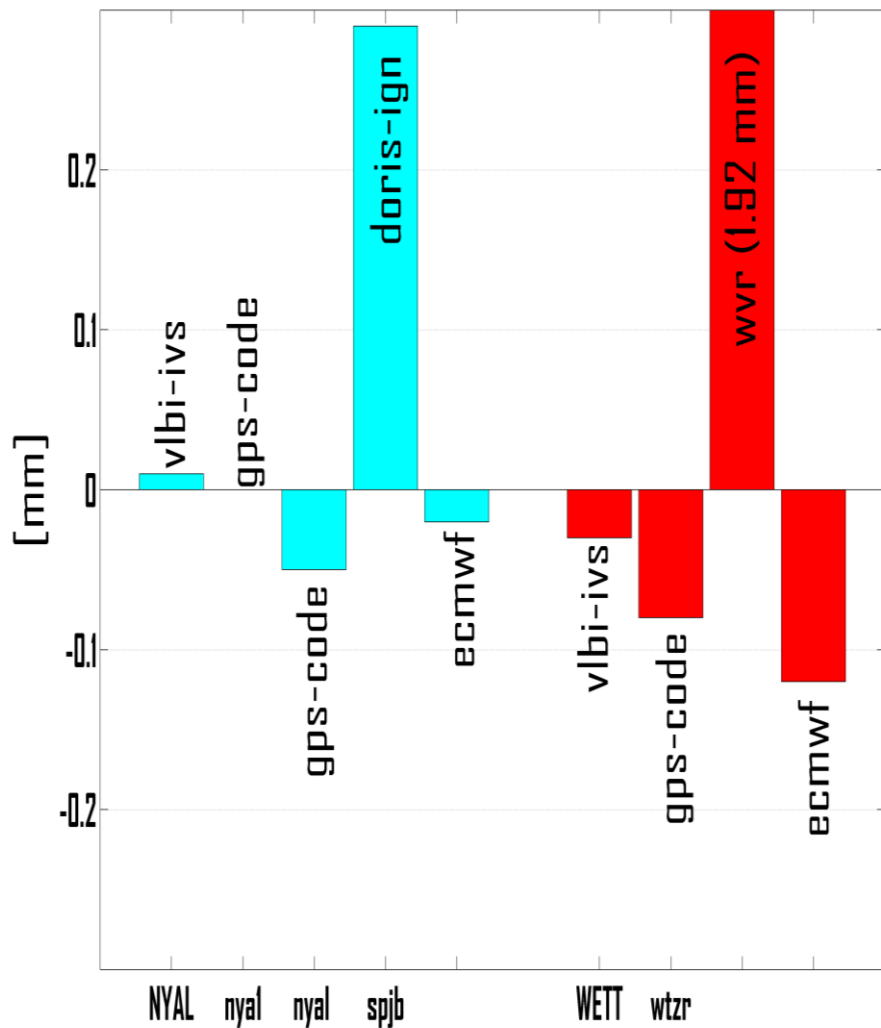
# Troposphere zenith total delays at co-located site Wettzell during IVS-CONT08



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

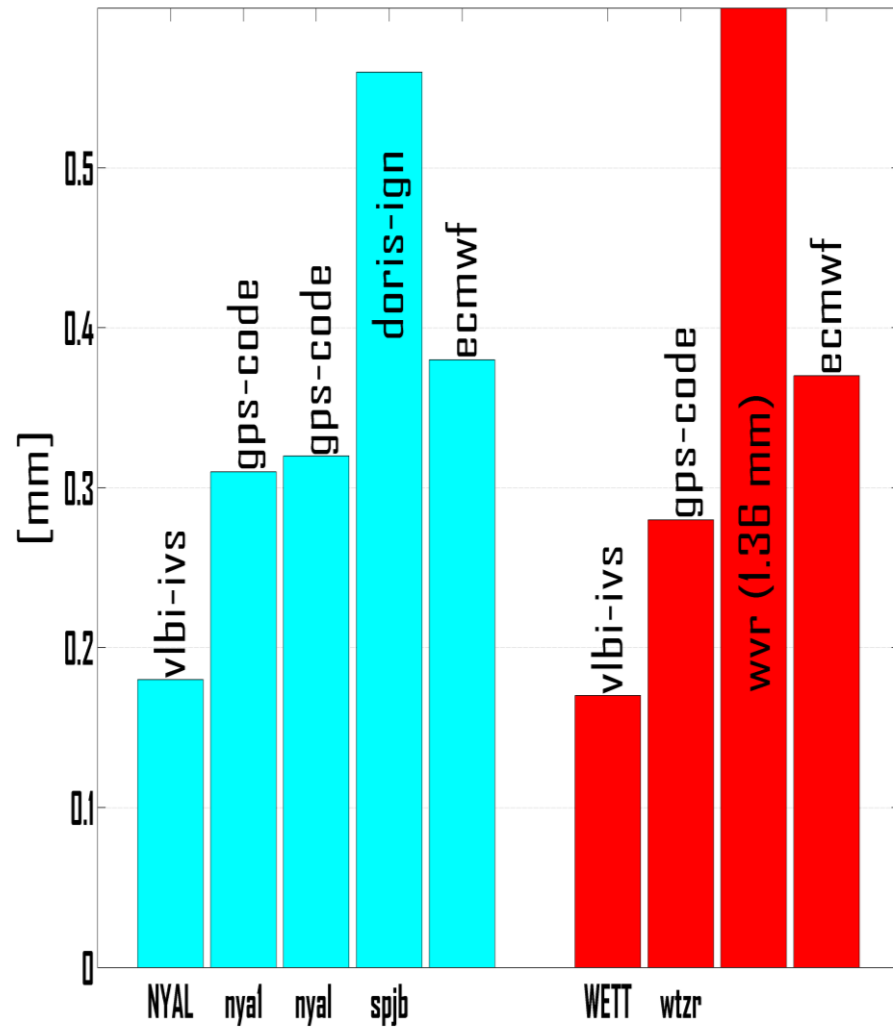


# Biases and std. dev. of troposphere north gradients between VieVS and other solutions



Ny-Ålesund

Wettzell

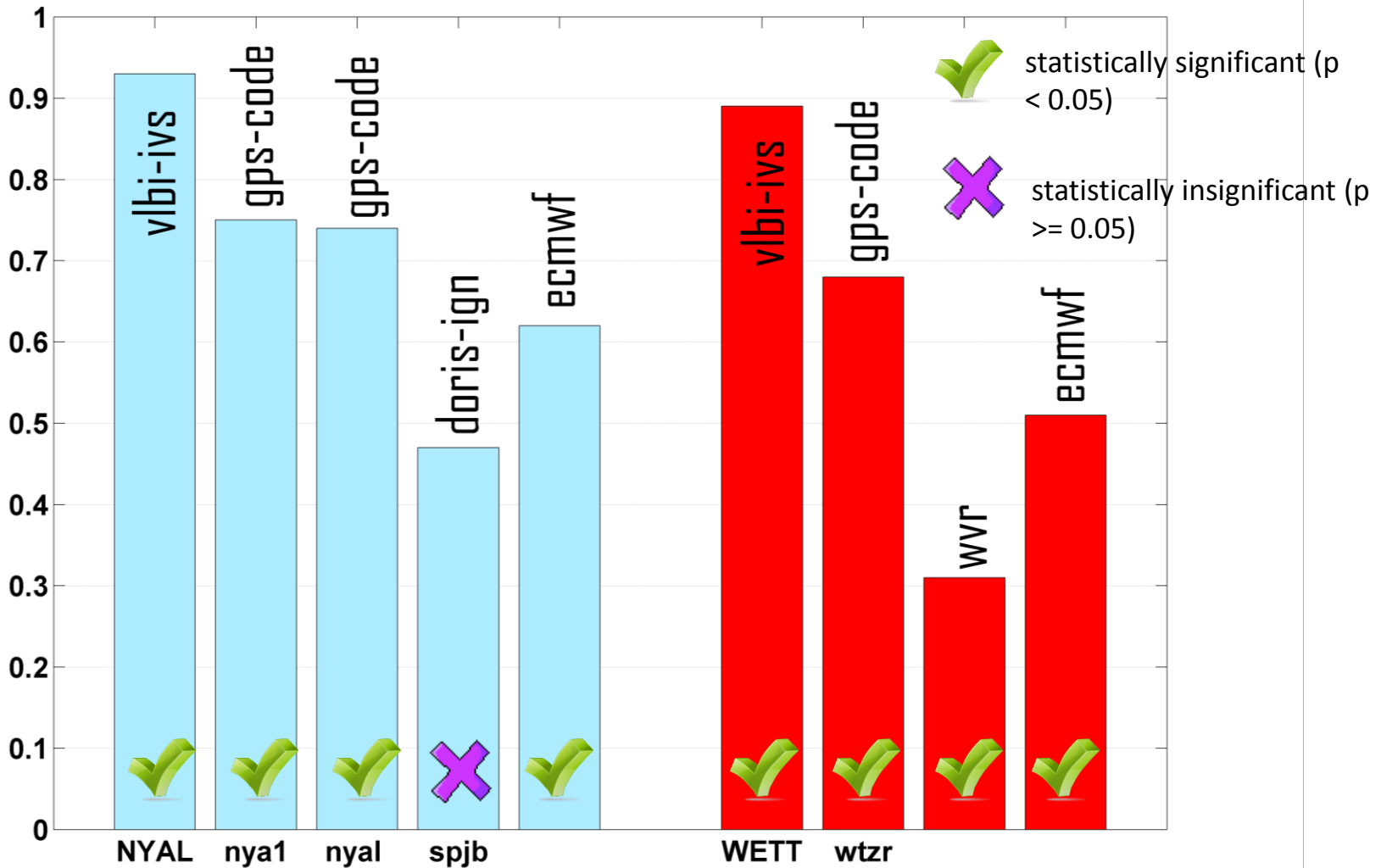


Ny-Ålesund

Wettzell



# Correlations of troposphere north gradients between VieVS, and other solutions

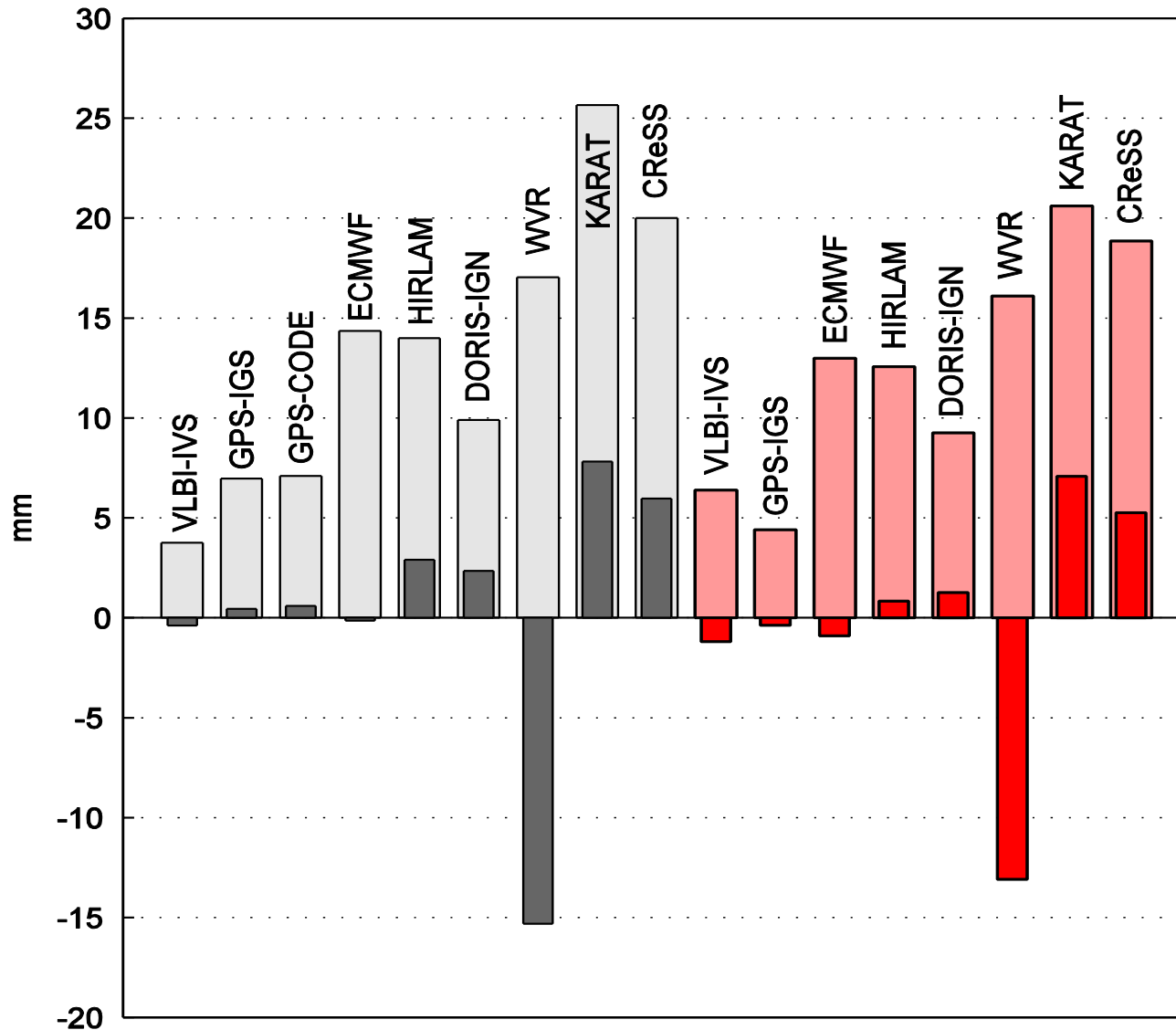


Ny-Ålesund

Wetzell

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**

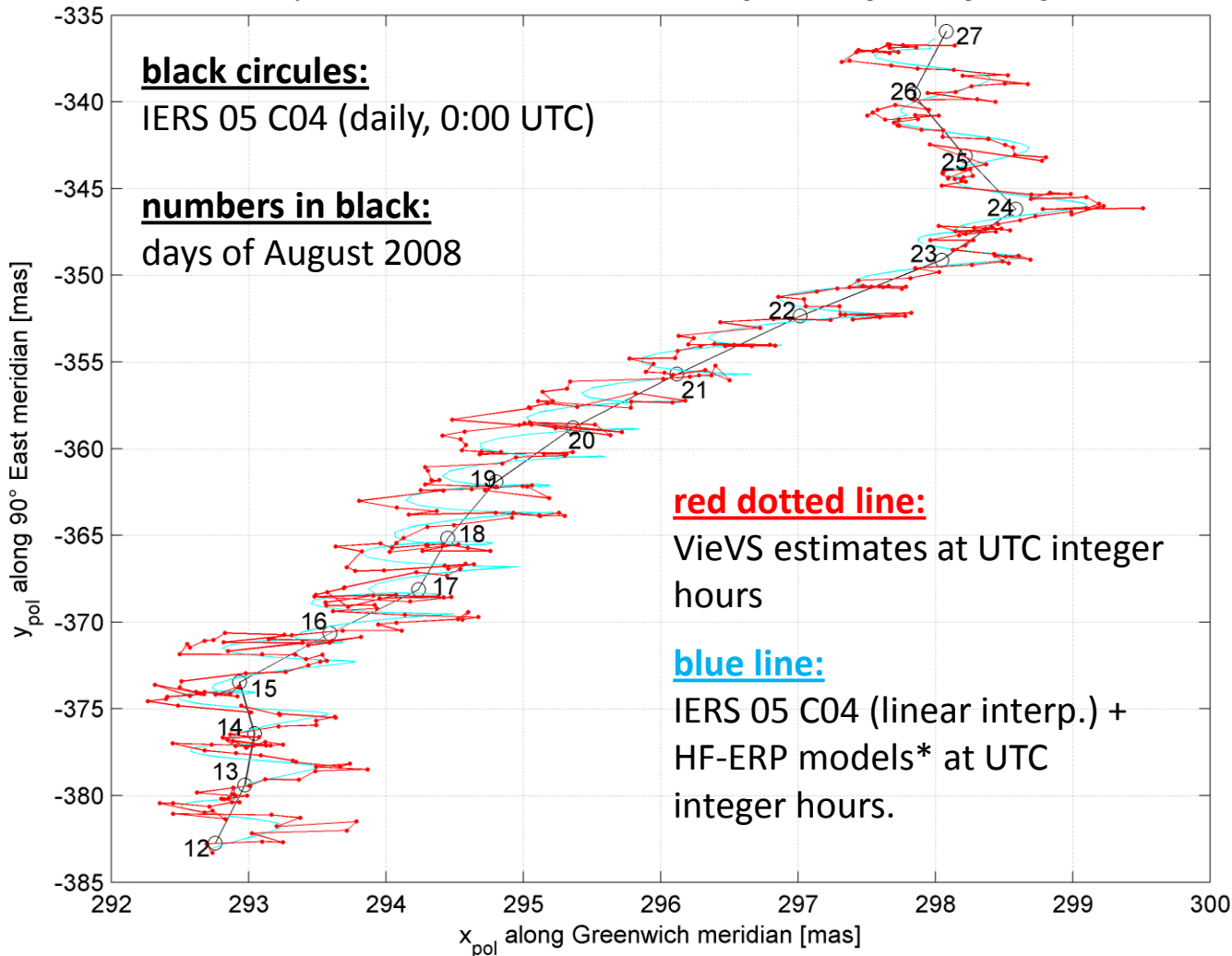
dark red: bias

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

Hourly CIP, CPWLO coordinates in TRF during CONT08 [ 12 - 27 ] of August

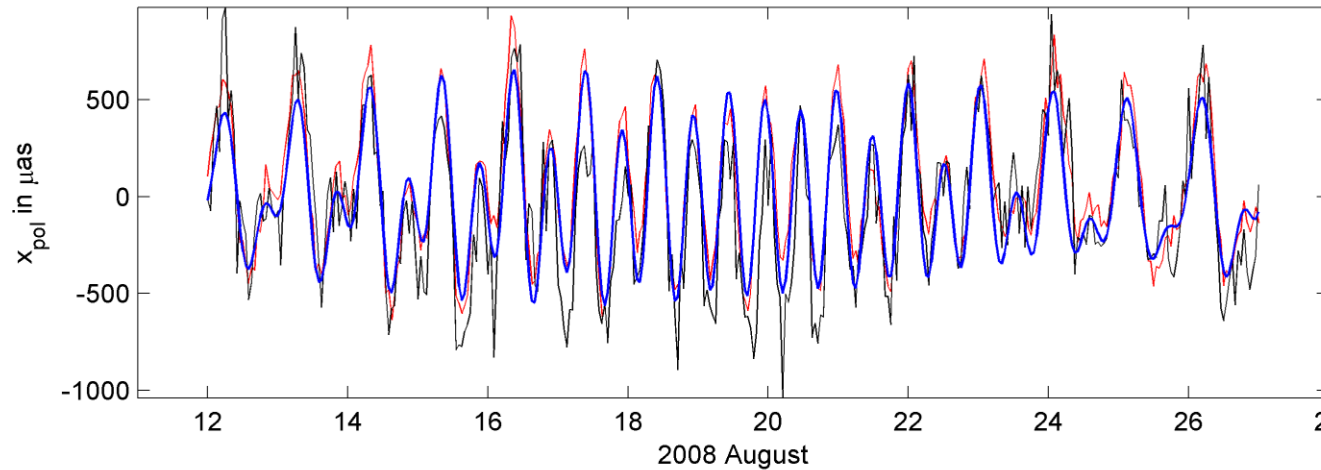


- Nutation offsets were fixed to their a priori values.
- **A priori nutation offsets:** IAU 2000A precession-nutation model plus IERS 05 C04 corrections.
- **A priori ERP:** IERS 05 C04 (linearly interpolated).
- No constraints were imposed on the hourly ERP estimates.

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

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

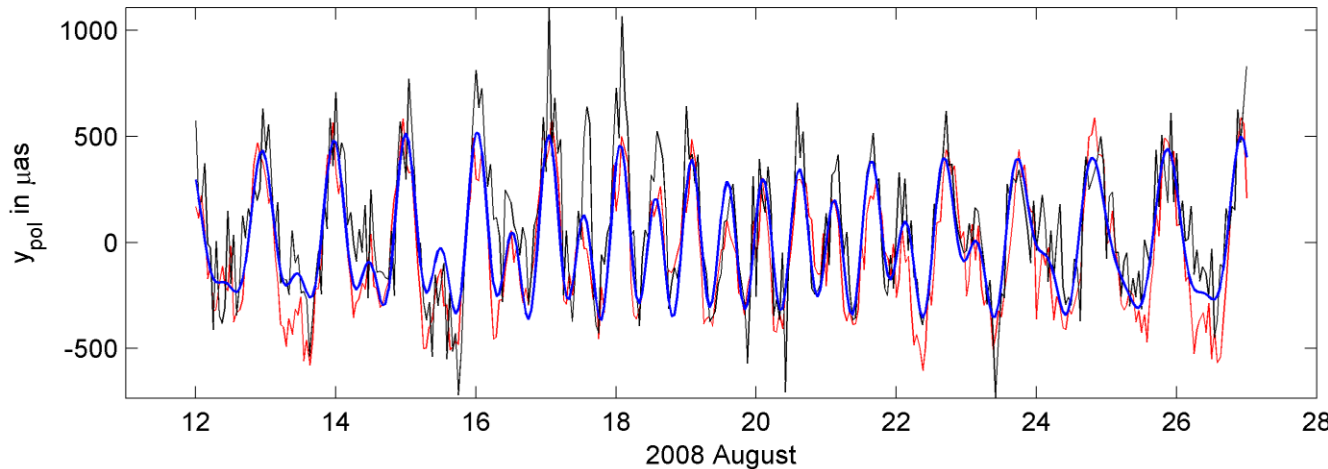
HF-ERP models versus hourly VLBI and GPS  $x_{\text{pol}}$  estimates during CONT08



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

The standard deviations of the hourly ERP differences:  
 $x_{\text{pol}}(\text{VLBI-HF ERP})$ : 224.5  $\mu\text{as}$   
 $x_{\text{pol}}(\text{GPS-HF-ERP})$ : 122.0  $\mu\text{as}$

HF-ERP models versus hourly VLBI and GPS  $y_{\text{pol}}$  estimates during CONT08



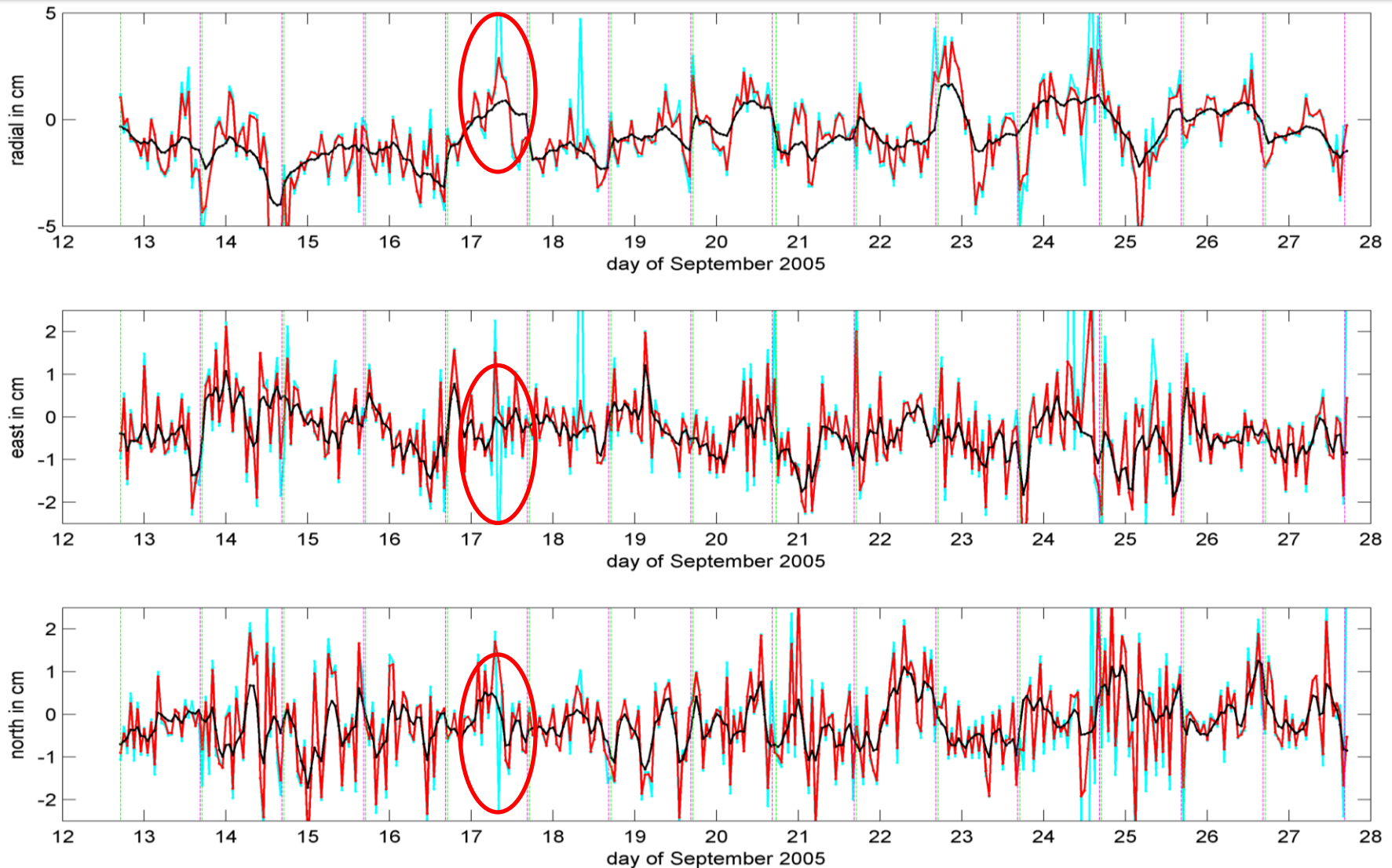
$y_{\text{pol}}(\text{VLBI-HF ERP})$ : 187.2  $\mu\text{as}$   
 $y_{\text{pol}}(\text{GPS-HF-ERP})$ : 139.3  $\mu\text{as}$

UT1-UTC (VLBI-HF ERP): 22.9  $\mu\text{s}$

VLBI ERP are noisier than to those of GPS.

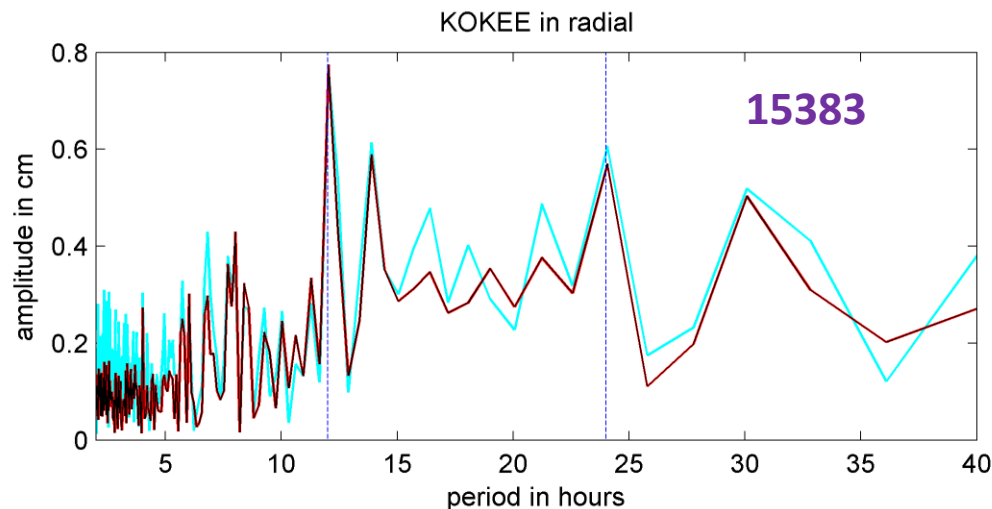
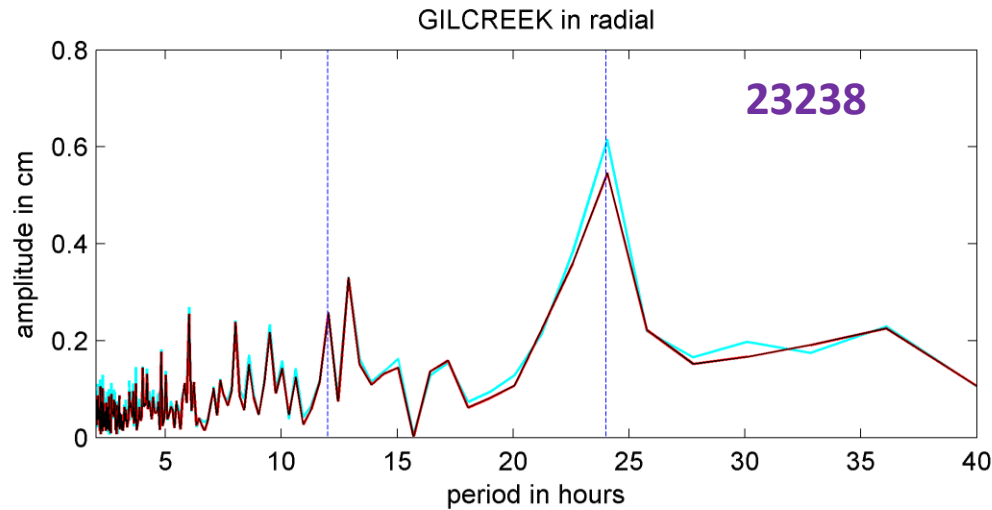
Analyses of VieVS hourly antenna  
coordinate estimates in TRF  
during IVS-CONT05

# 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 coordinate 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, relative)  
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.



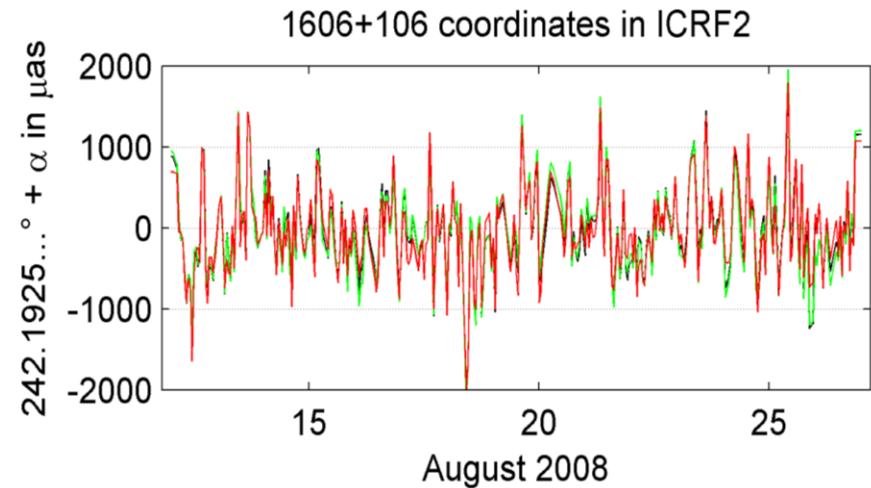
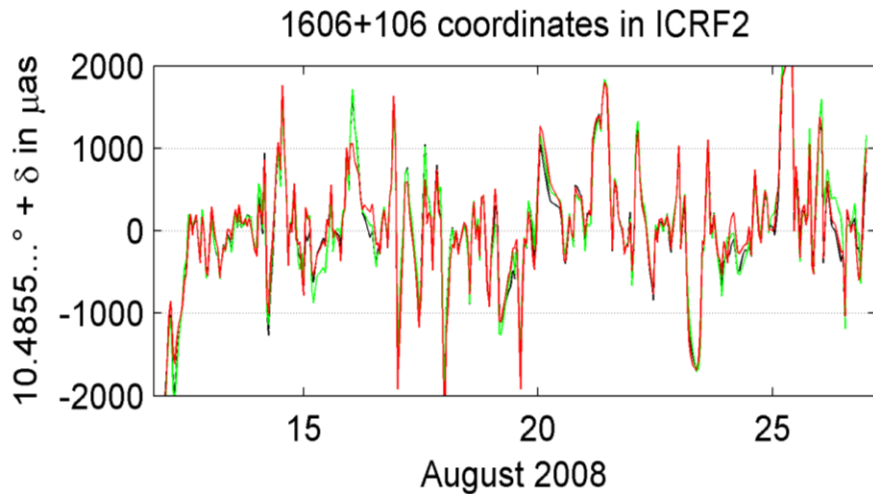
Analyses on hourly source coordinates  
in CRF during IVS-CONT08

# 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.  
nutration 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

- I am grateful to Prof. Dr. Harald Schuh and Priv.-Doz. Dr. Axel Nothnagel for supervising my PhD studies.
- I am thankful to Dr. Johannes Böhm and Dr. Tobias Nilsson for their scientific supports on the thesis.
- I want to acknowledge Dr. Johannes Böhm and Prof. Dr. Hansjörg Kutterer for being examiners.
- I am grateful to Dipl. Ing. Hana Spicakova and MSc. Mahdi Alizadeh for dealing with the formal procedures on submitting my thesis.
- I want to forward my special thanks to the VieVS working group.
- I am thankful to all the members of IGG, TU Wien for their sincere helps from the beginning to the end of my stay in Vienna.
- 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  $5^\circ$ .
- $0.7 \text{ picosec}^2/\text{sec}$  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,  $3^\circ$  + 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,  $7^\circ$ .
- 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 acquired 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

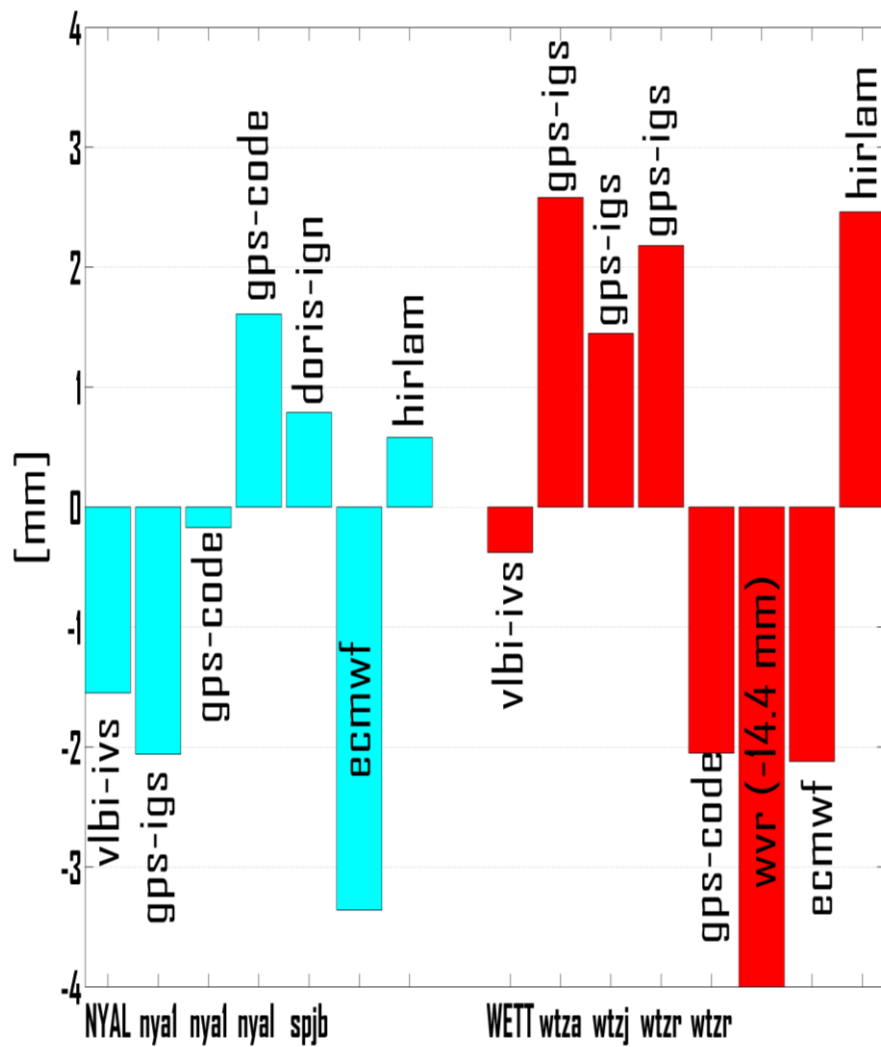
$$e.g. \quad x_i = ZTD_i^{VLBI-VieVS} \quad y_i = ZTD_i^{GPS-CODE} \quad \Delta_i = x_i - y_i$$

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

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

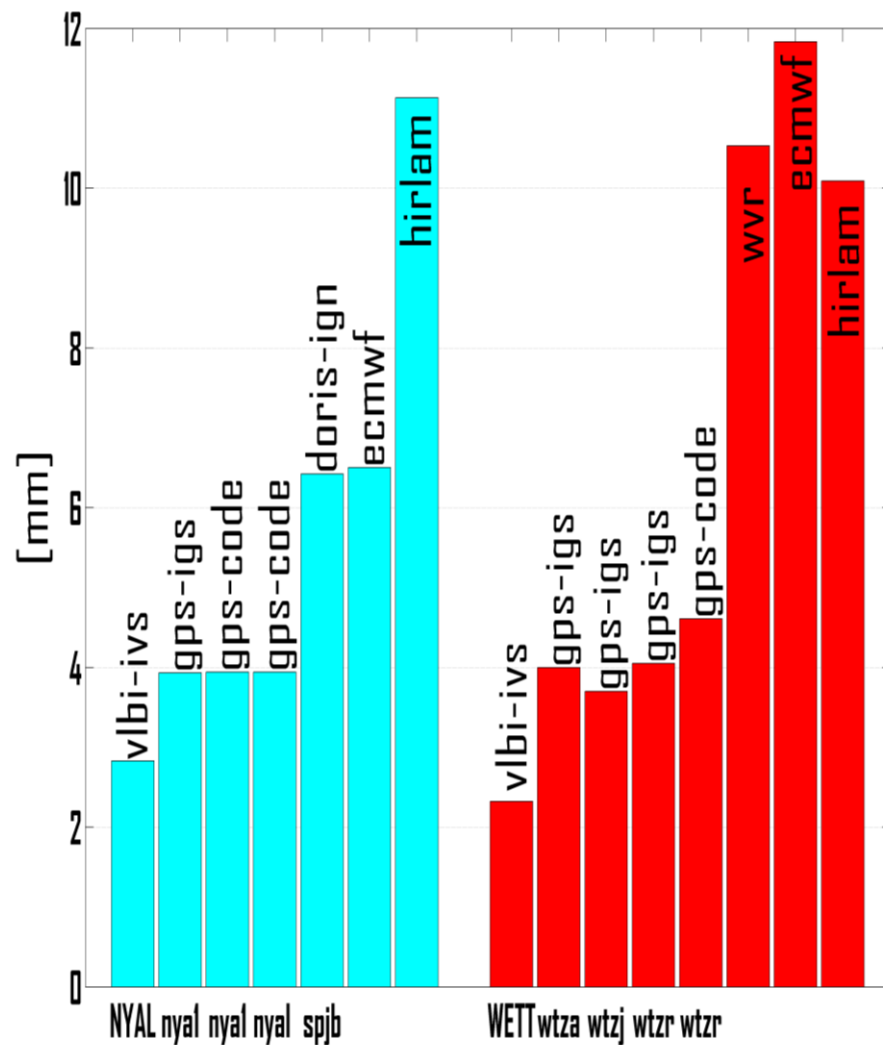
$$r_{xy} = \frac{Cov(x, y)}{S_x S_y} = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{\left[ \sum_{i=1}^n (x_i - \bar{x})^2 \cdot \sum_{i=1}^n (y_i - \bar{y})^2 \right]^{\frac{1}{2}}} \quad (p < 0.05)$$

# 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 Rieger, 1992)

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

$$\Delta ZHD = \frac{0.0022768(p - p_0)}{1 - 0.00266 \cos(2\phi_0) - 0.28 \times 10^{-6} H_0}$$

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

$H_0$  : 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,

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

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

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

$\phi_0 = \text{latitude of the co-located site in degrees.}$





# Troposphere delay in VieVS

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

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

reduced from observations a priori to the adjustment

estimated

estimated

estimated

partial derivative w.r.t. ZWD first CPWLO

$$\begin{aligned} \frac{\partial \tau_{trop}(t)}{\partial (ZWD)_{x_1}} &= \frac{\partial \tau_{trop}(t)}{\partial (ZWD)} \cdot \frac{\partial (ZWD)}{\partial x_1} \\ &= m_w(\varepsilon) \left(1 - \frac{t-t_1}{t_2-t_1}\right) \\ &= m_w(\varepsilon) - m_w(\varepsilon) \frac{t-t_1}{t_2-t_1} \end{aligned}$$

partial derivative w.r.t. ZWD second CPWLO

$$\begin{aligned} \frac{\partial \tau_{trop}(t)}{\partial (ZWD)_{x_2}} &= \frac{\partial \tau_{trop}(t)}{\partial (ZWD)} \cdot \frac{\partial (ZWD)}{\partial x_2} \\ &= m_w(\varepsilon) \left(\frac{t-t_1}{t_2-t_1}\right) \end{aligned}$$

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

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

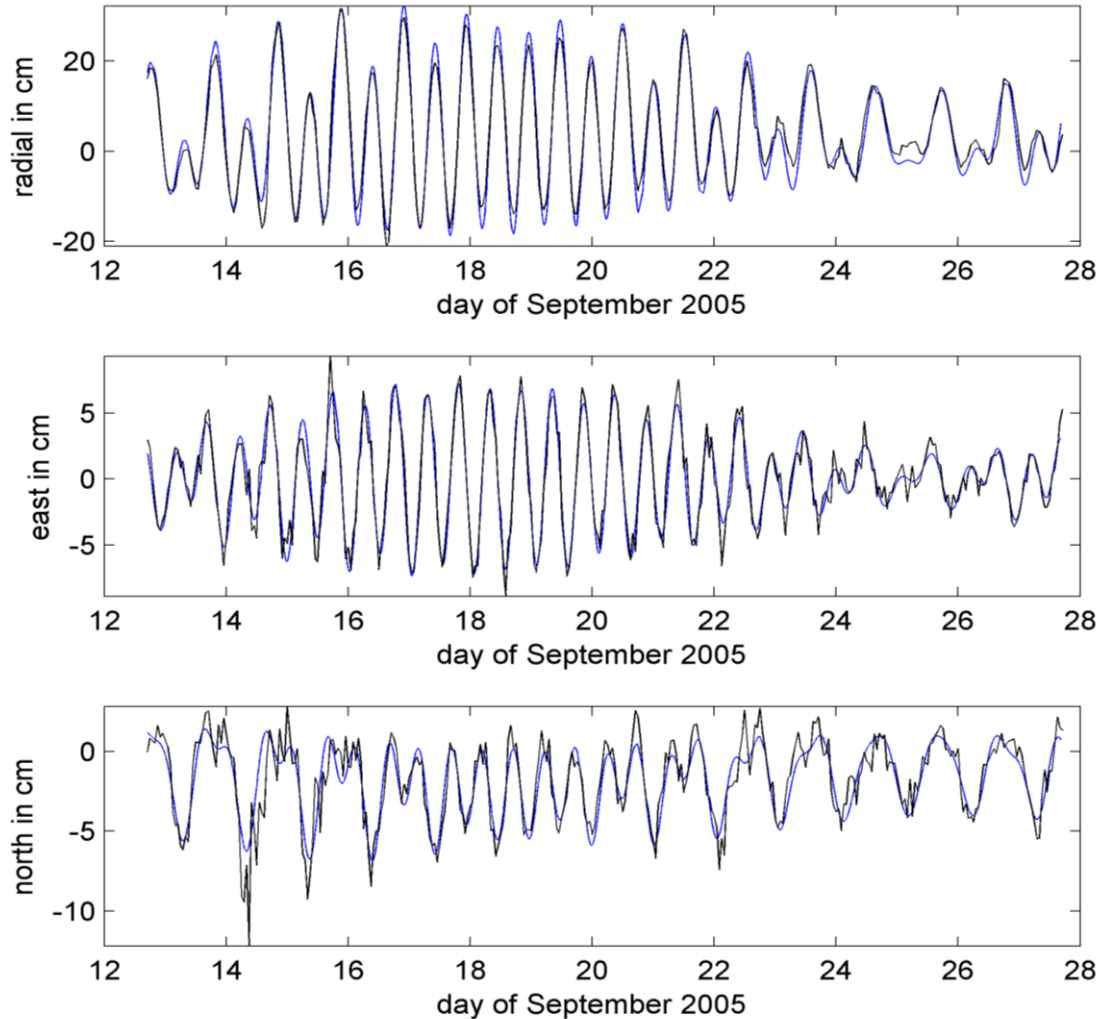
$$\begin{aligned}\frac{\partial \tau_{trop}(t)}{\partial (G_n) x_1} &= \frac{\partial \tau_{trop}(t)}{\partial (G_n)} \cdot \frac{\partial (G_n)}{\partial x_1} \\ &= m_w(\varepsilon) \cot(\varepsilon) \cos(\alpha) \left(1 - \frac{t - t_1}{t_2 - t_1}\right)\end{aligned}$$

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

$$\begin{aligned}\frac{\partial \tau_{trop}(t)}{\partial (G_n) x_2} &= \frac{\partial \tau_{trop}(t)}{\partial (G_n)} \cdot \frac{\partial (G_n)}{\partial x_2} \\ &= m_w(\varepsilon) \cot(\varepsilon) \cos(\alpha) \left(\frac{t - t_1}{t_2 - t_1}\right)\end{aligned}$$

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

Kokee VLBI antenna hourly CPWLO coordinates

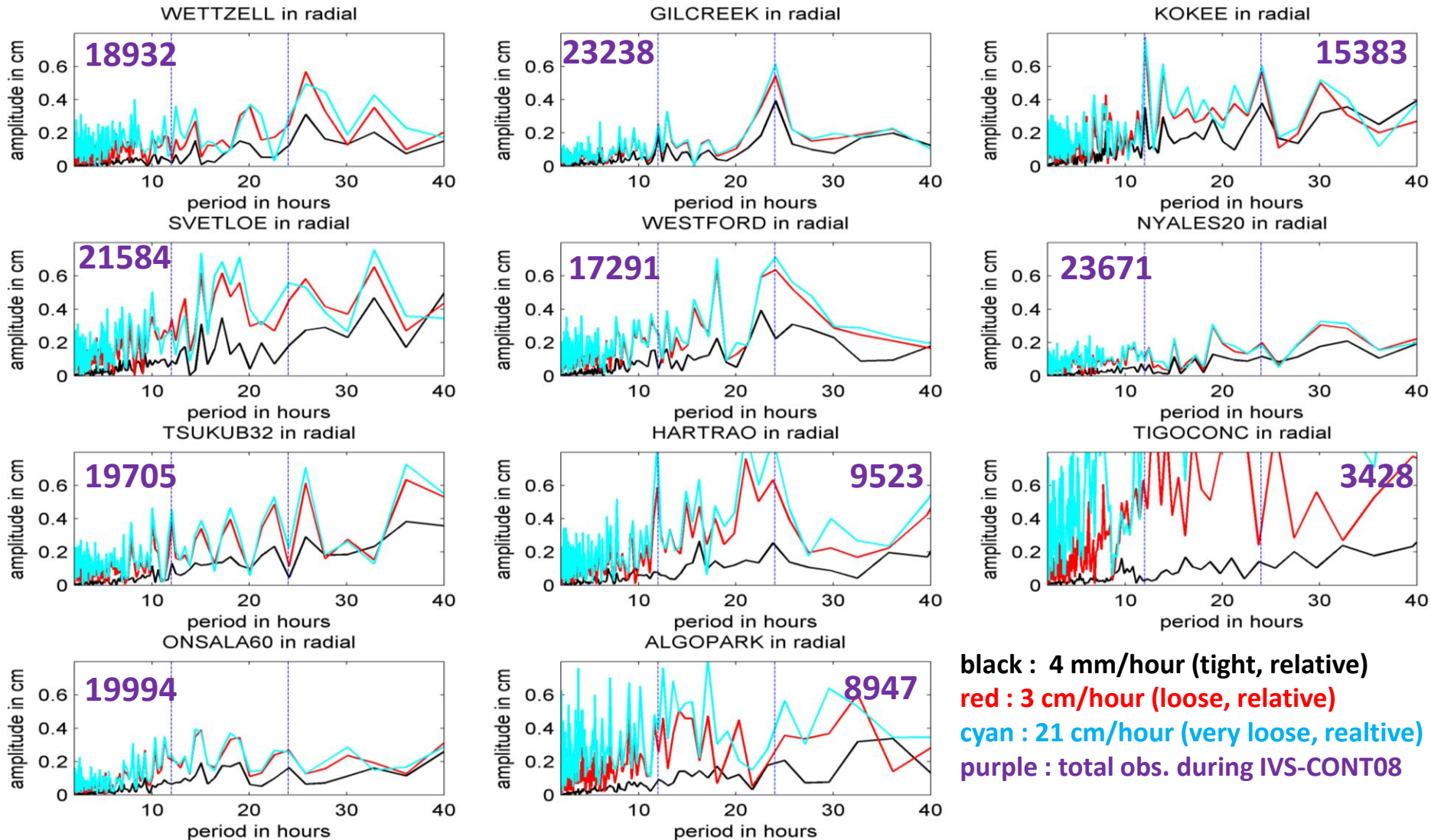


- All antenna coordinates were fixed to their a priori values\* except one antenna (e.g. Kokee).
- \* VTRF2008+velocity+all tide and load displacements
- Solid Earth tide displacements were reduced from all VLBI observations for all antenna coordinates except one antenna (e.g. Kokee).
- Hourly CPWLO 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



# Least-squares adjustment constraints on the estimates

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

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

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

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

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

$$C = [C_1 \quad C_2 \quad \dots \quad C_s]$$

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

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

# Sub-daily estimates of VieVS

- CPWLO of clocks...

A(1).sm [1], H(1).sm [1], Ph(1).sm [1/cm<sup>2</sup>]

- rate and quadratic terms of clock polynomials...

A(2).sm [day day<sup>2</sup>]

- CPWLO of zenith wet delays...

A(3).sm [1], H(3).sm [1], Ph(3).sm [1/cm<sup>2</sup>]

- CPWLO of troposphere north gradients...

A(4).sm [1], H(4).sm [1], Ph(4).sm [1/cm<sup>2</sup>]

- CPWLO of troposphere east gradients...

A(5).sm [1], H(5).sm [1], Ph(5).sm [1/cm<sup>2</sup>]

- 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<sup>2</sup>]

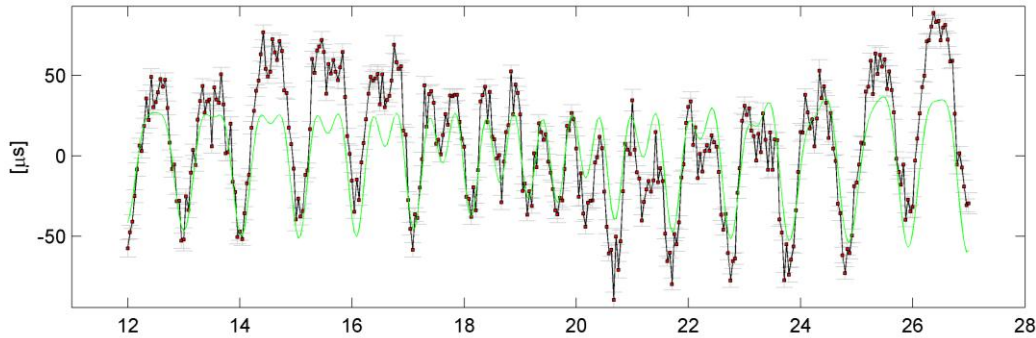
# Sub-daily estimates of VieVS

- 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<sup>2</sup>]
- CPWLO of Earth's rotation phase ( $\Delta\text{UT1}=\text{UT1}-\text{UTC}$ ) ...  
A(8).sm [cm/mas], H(8).sm [1], Ph(8).sm [1/mas<sup>2</sup>]
- CPWLO of celestial intermediate pole (CIP) X coordinate in CRF...  
A(9).sm [cm/mas], H(9).sm [1], Ph(9).sm [1/mas<sup>2</sup>]
- CPWLO of celestial intermediate pole (CIP) Y coordinate in CRF...  
A(10).sm [cm/mas], H(10).sm [1], Ph(10).sm [1/mas<sup>2</sup>]
- CPWLO of right ascensions of sources in CRF...  
A(11).sm [cm/mas], H(11).sm [1], Ph(11).sm [1/mas<sup>2</sup>]
- CPWLO of declinations of sources in CRF...  
A(12).sm [cm/mas], H(12).sm [1], Ph(12).sm [1/mas<sup>2</sup>]
- 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<sup>2</sup>]



# Hourly ERP during IVS-CONT08

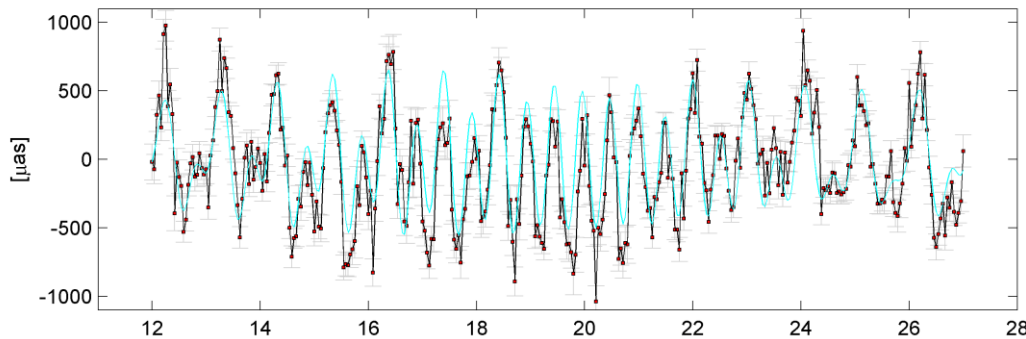
VieVS hourly CPWLO estimates of Earth rotation phase [  $\Delta UT1$  ] versus HF-ERP models



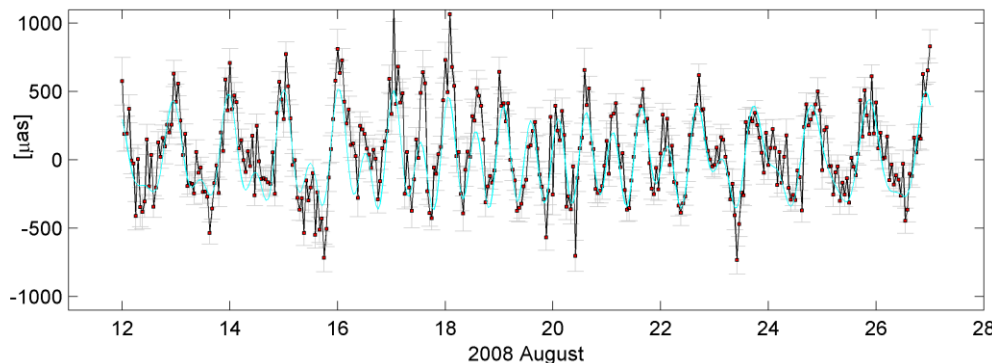
Black line : VLBI hourly  
Green line : HF-ERP models\* hourly

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

VieVS hourly CPWLO estimates of the CIP coordinates in TRF along Greenwich meridian [  $x_{pol}$  ] versus HF-ERP models



VieVS hourly CPWLO estimates of the CIP coordinates in TRF along 270° east longitude [  $y_{pol}$  ] versus HF-ERP models

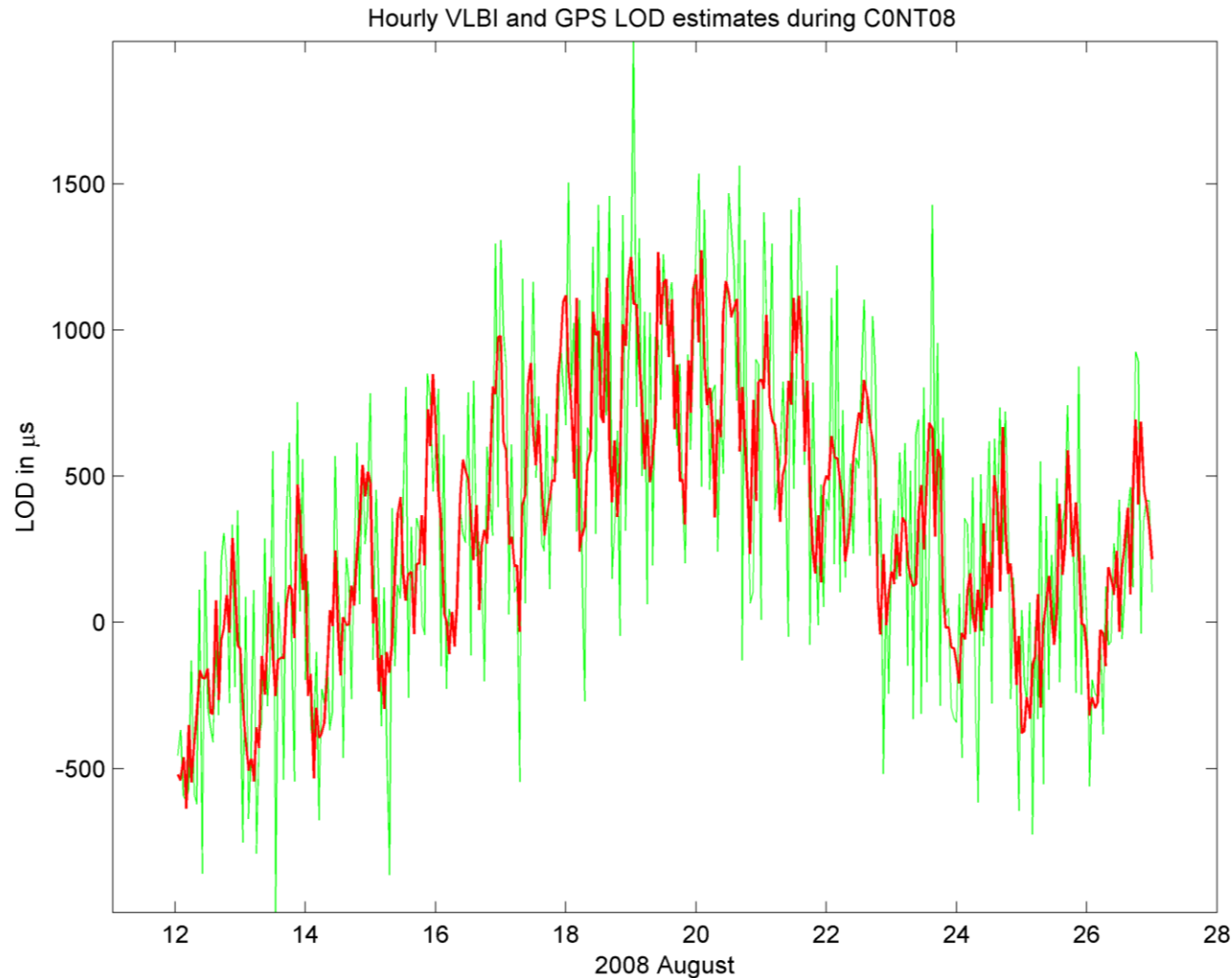


\* ocean tides and libration  
(McCarthy and Petit (2004), Chapter 5 and 8)

- 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

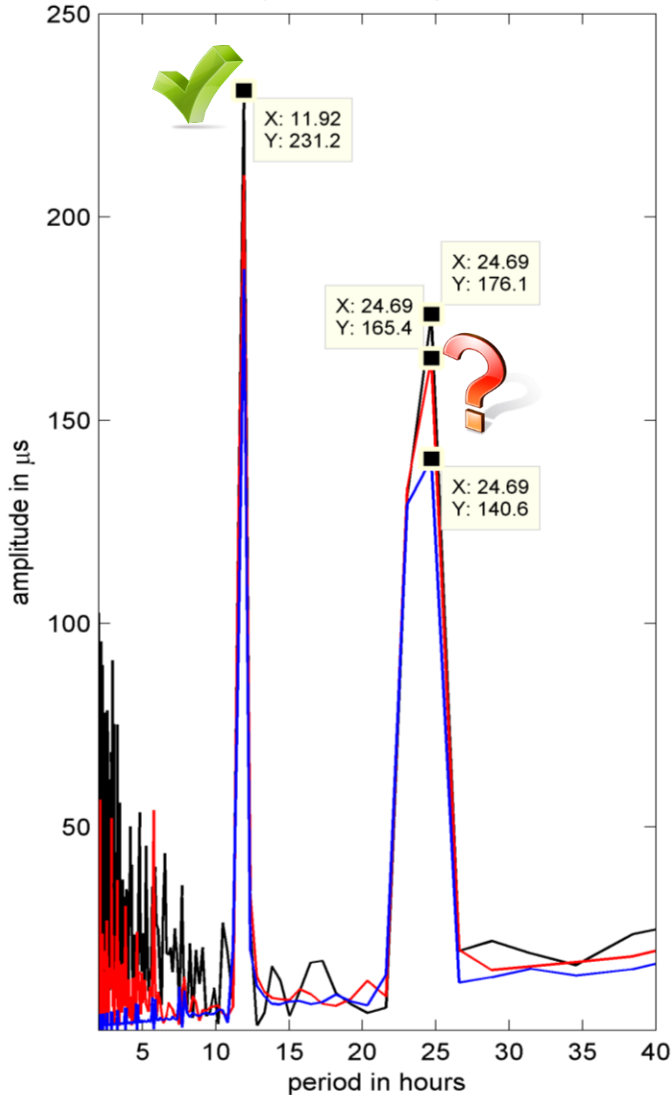
Blue line : HF-ERP models hourly LOD values

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

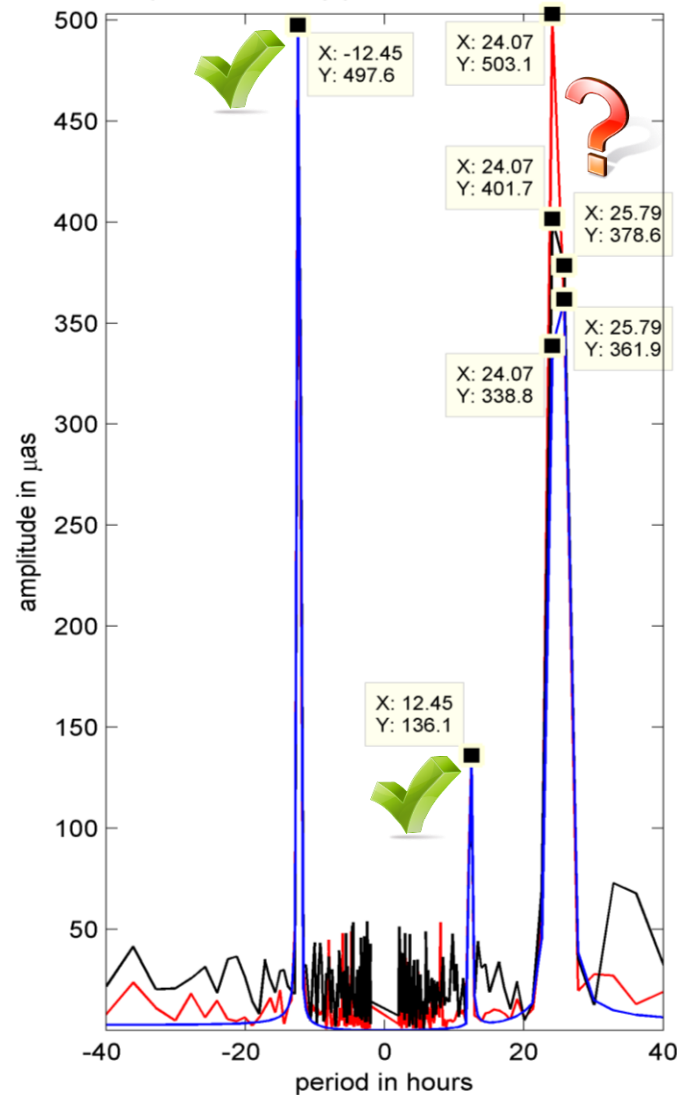
$$LOD(t_1) = \frac{\Delta UT1(t_2) - \Delta UT1(t_1)}{t_2 - t_1} .86400$$

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

Spectra of hourly LOD



Spectra of hourly polar motion coordinates

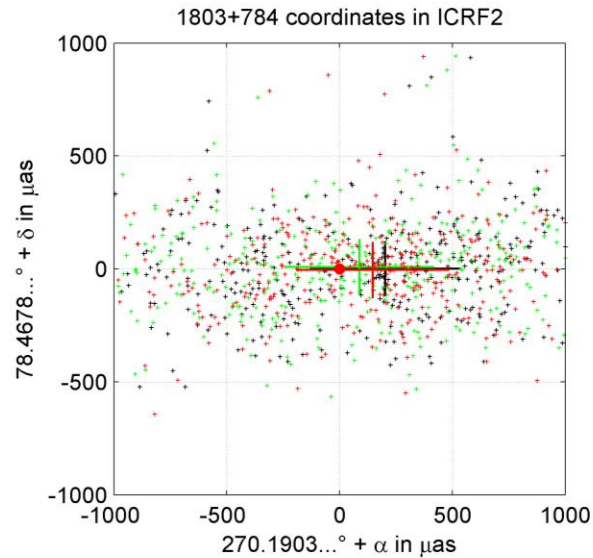
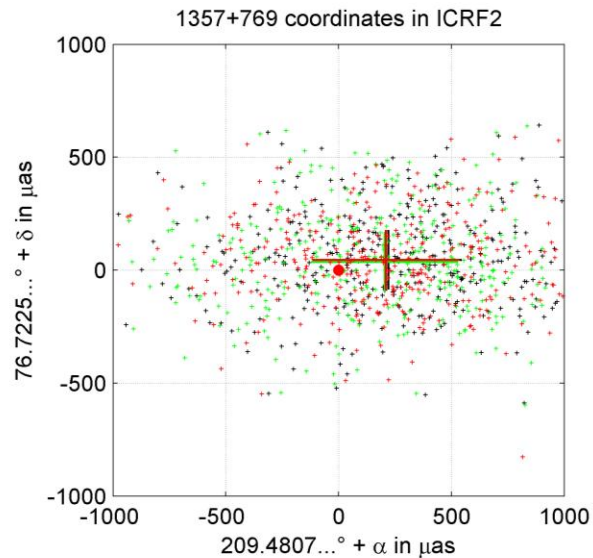


Red line : GPS  
 Black line : VLBI  
 Blue line : HF-ERP models

at 24 hours prograde polar motion amplitudes:  
 GPS > VLBI (~100  $\mu\text{s}$ )  
 GPS > HF-ERP (~160  $\mu\text{s}$ ).

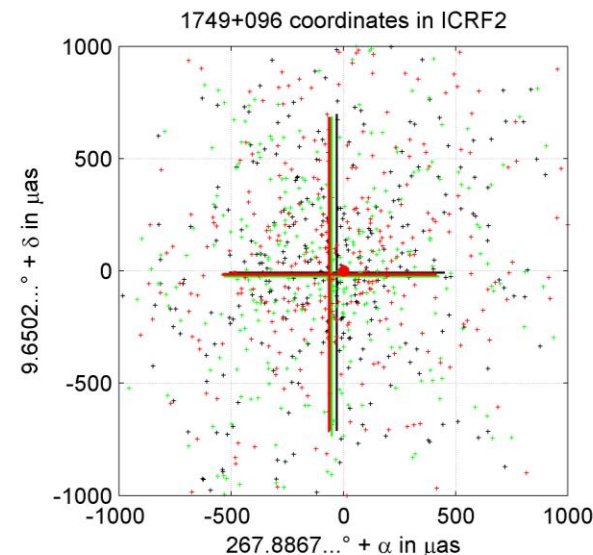
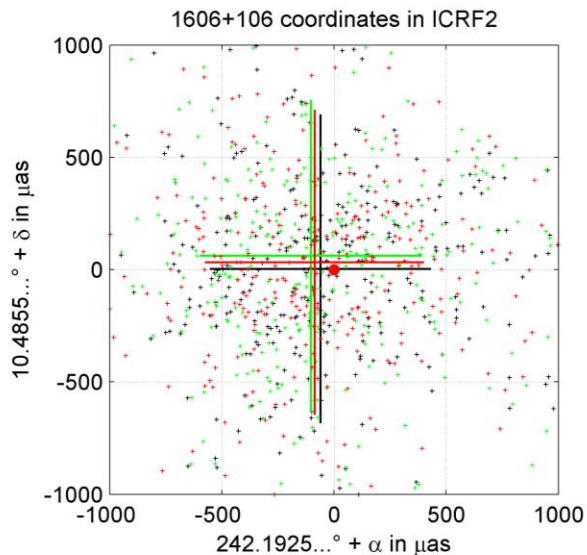
at 24 hours period LOD amplitudes:  
 GPS > HF-ERP (~25  $\mu\text{s}$ )  
 VLBI > HF-ERP (~36  $\mu\text{s}$ ).

# 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	$\bar{\alpha} \pm m_{\alpha}$	$\bar{\delta} \pm m_{\delta}$
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	$\bar{\alpha} \pm m_{\alpha}$	$\bar{\delta} \pm m_{\delta}$
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.*

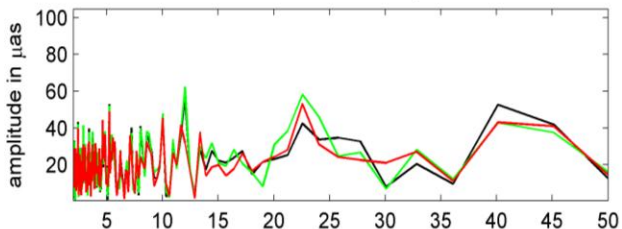
*The median of the estimates show the biases between 15 days long hourly CPWLO solution and the ICRF2 catalogue.*

\* ERP: IERS 05 C04 (Bizouard and Gambis, 2009) + ocean tides + libration (McCarthy and Petit (2004), Chapter 5 and 8)

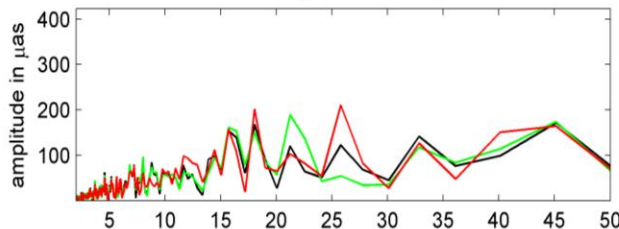
\* nutation offsets : IAU 2000A precession-nutation model + IERS 05 C04 corrections

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

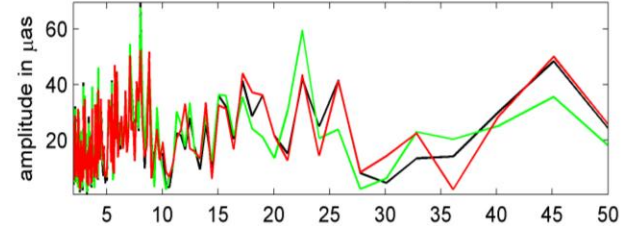
1357+769 declination spectra



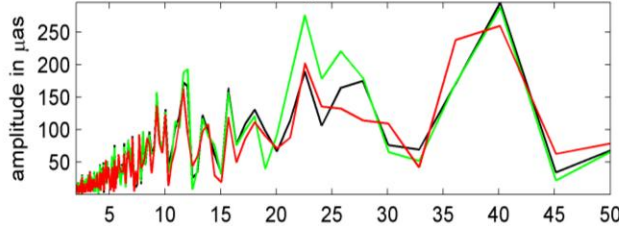
1357+769 right ascension spectra



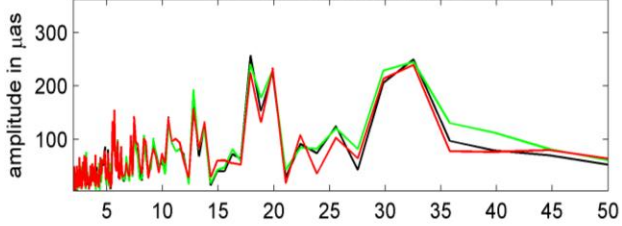
1803+784 declination spectra



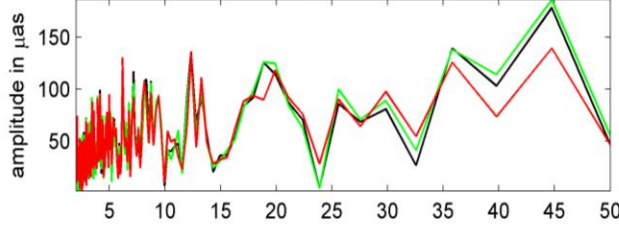
1803+784 right ascension spectra



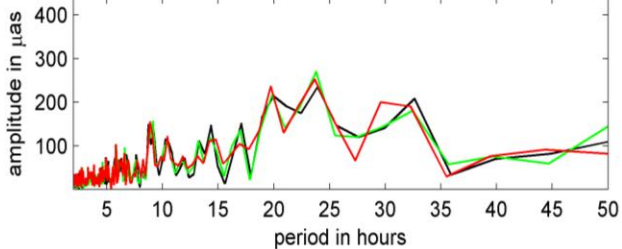
1606+106 declination spectra



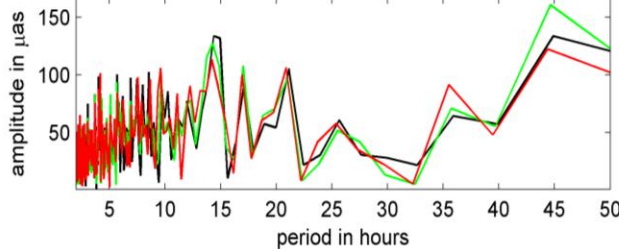
1606+106 right ascension spectra



1749+096 declination spectra



1749+096 right ascension spectra



Black : all EOP were estimated once per day.

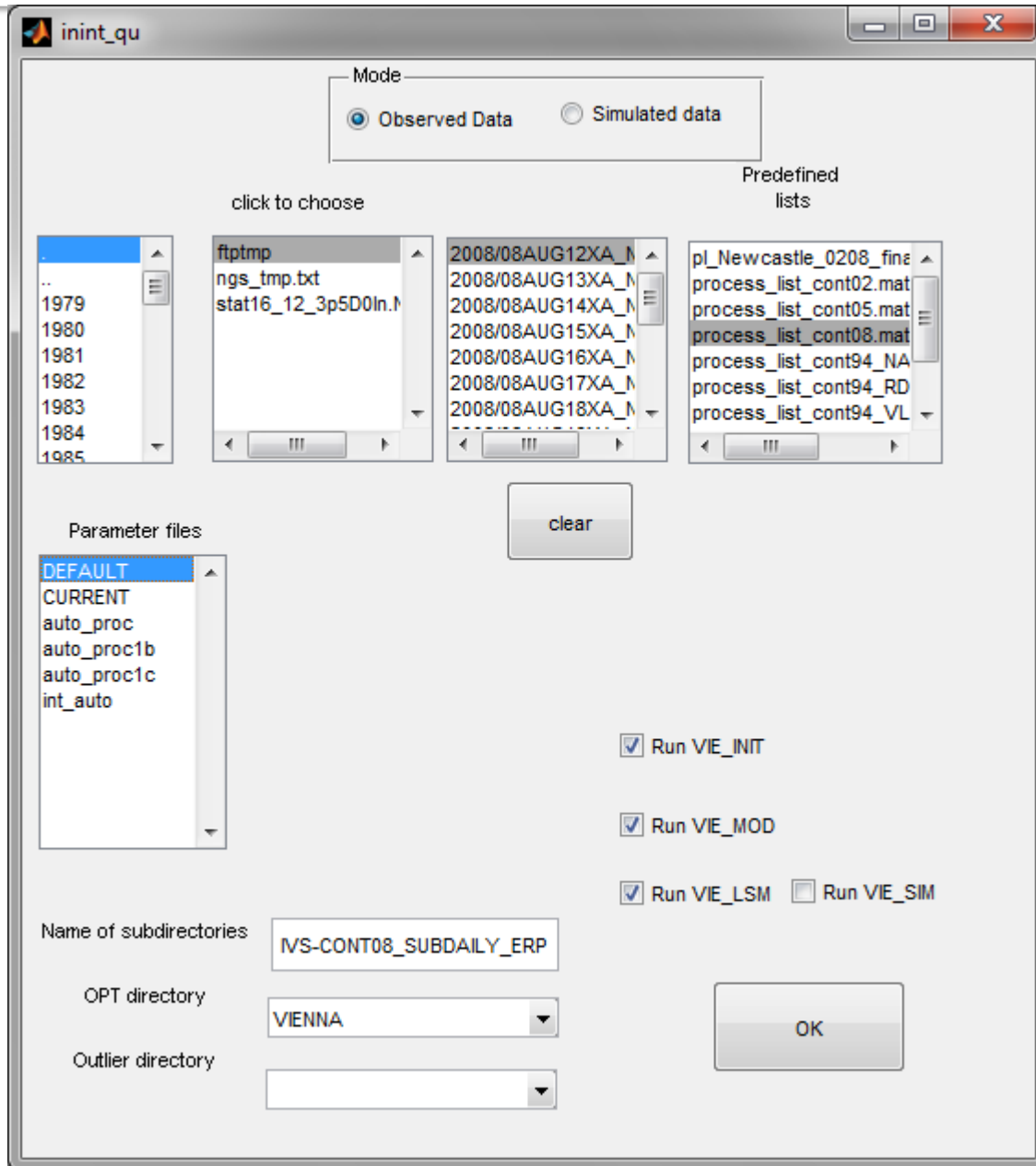
Green : all EOP were fixed to their a priori values.

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

mod\_qu

TRF

ITRF2005     VTRF2005

ITRF2008     VTRF2008

Other:

EOP

c04 05     predefined EOP

c04 08

include a priori nutation offsets dX, dY

include high frequency ERP

ocean tides   

Libration

xp,yp (10 terms)

UT1 (11 terms)

Interpolation

linear     lagrange

Tidal UT variations (Defraigne & Smits)

Precession/Nutation Model

IAU 2000A     IAU 2006/2000 A

CRF

ICRF Ext 2     ICRF2

Other:

Ephemerides

JPL 405

JPL 421

Station corrections

solid Earth tides

tidal ocean loading   

tidal atmosphere loading   

non-tidal atmosphere loading

pole tide

linear (IERS 2003)     cubic (IERS 2010)

thermal antenna deformation

Pressure and temperature

always GPT     use met data from NGS file  
(GPT only as backup)

A priori troposphere gradients

no model     APG (Böhm)     DAO (MacMillan)

Mapping function

VM1     GMF


Quality code limit

Cut-off Elevation angle

Outliers

Use outlier file

OK



# Graphical user interfaces of VieVS

Untitled

**vie\_lsm [ single session first solution ]**

parameterization for removing large clock errors

- apply first basic solution (only with clock function)
- one offset per clock
- one offset & one rate per clock
- one offset, one rate, & one quadratic term per clock

use clock breaks (From OPT file)

reference clock for the first solution

- WETZELL
- TSUKUB32
- WETZELL
- SVETLOE
- ZELENCHK
- ONSALA60
- NYALES20
- HARTRAO
- KOKEE
- WESTFORD
- MEDICINA
- TIGOCONC

main solution

- apply main solution
- simple outlier test [ coefficient \* mo ] coefficient: 5
- basic outlier test [ coefficient \* mo \*sqrt(qw) ]

clock/s that have breaks in the session

ZELENCHK

Next

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

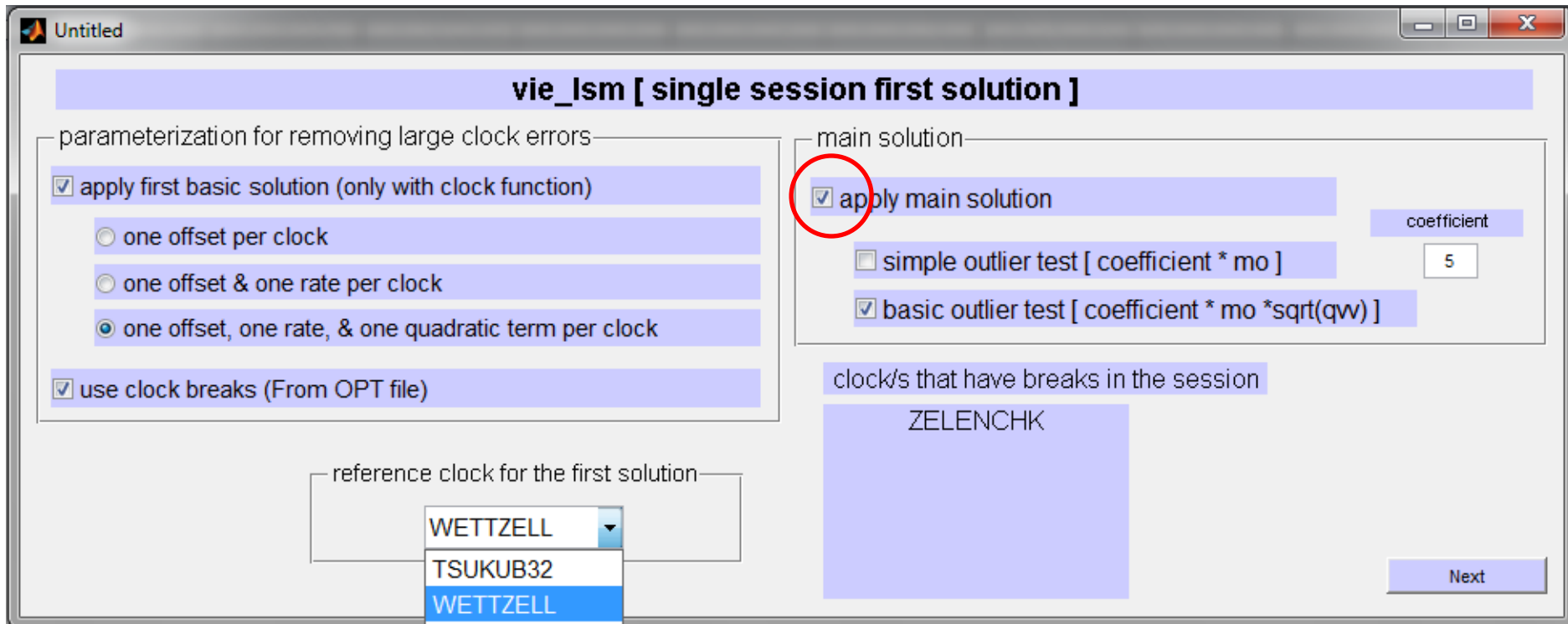
The screenshot shows the 'vie\_lsm [ single session first solution ]' window. It is divided into several sections:

- parameterization for removing large clock errors:**
  - apply first basic solution (only with clock function)
    - one offset per clock
    - one offset & one rate per clock
    - one offset, one rate, & one quadratic term per clock
  - use clock breaks (From OPT file) (highlighted with a red circle)
- reference clock for the first solution:**
  - WETTZELL (selected in dropdown menu)
  - TSUKUB32
  - WETTZELL (highlighted)
  - SVETLOE
  - ZELENCHK
  - ONSALA60
  - NYALES20
  - HARTRAO
  - KOKEE
  - WESTFORD
  - MEDICINA
  - TIGOCONC
- main solution:**
  - apply main solution
  - simple outlier test [ coefficient \* mo ] (coefficient: 5)
  - basic outlier test [ coefficient \* mo \*sqrt(qw) ]
- clock/s that have breaks in the session:**
  - ZELENCHK

A 'Next' button is located at the bottom right of the window.

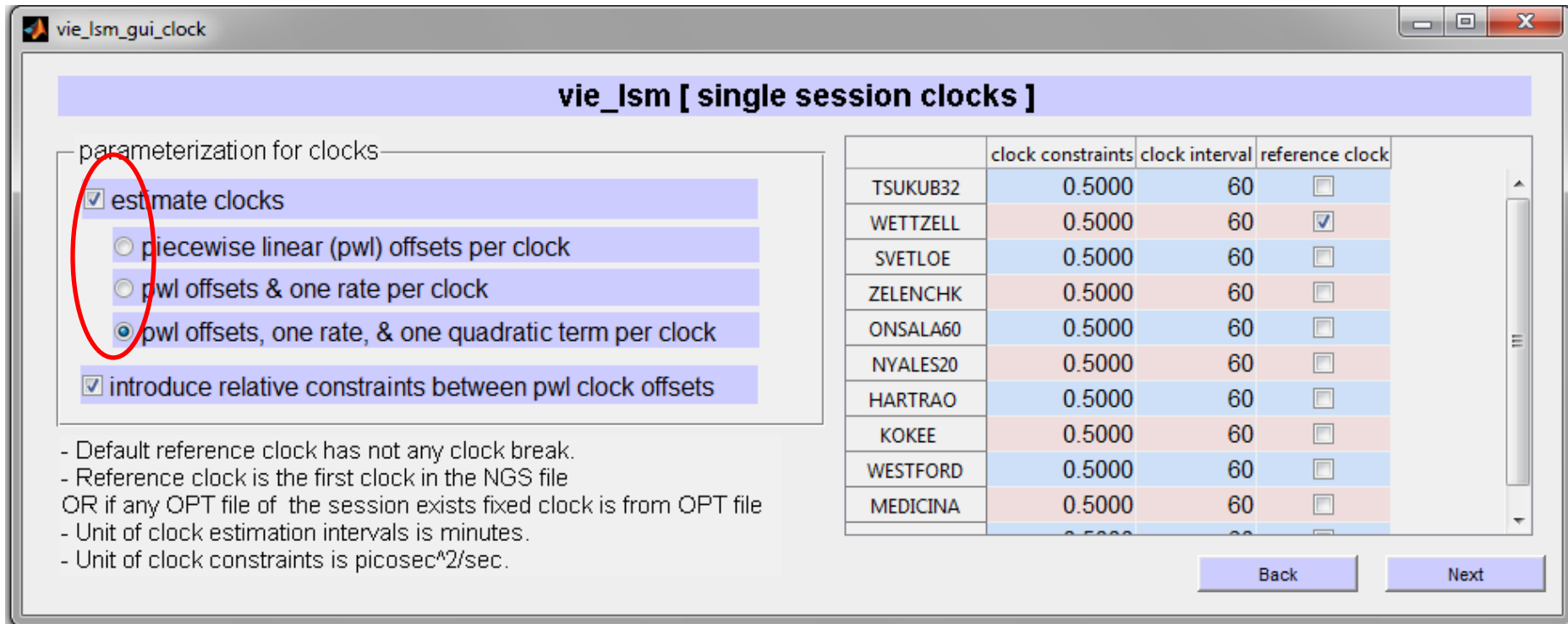
Information about clock breaks is read from the OPT files if available. At the epoch of a clock break, a new quadratic function is started. Clock breaks are only considered in the first solution. If 'apply main solution' is not ticked, then the station-wise residuals from the first solution will be plotted.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



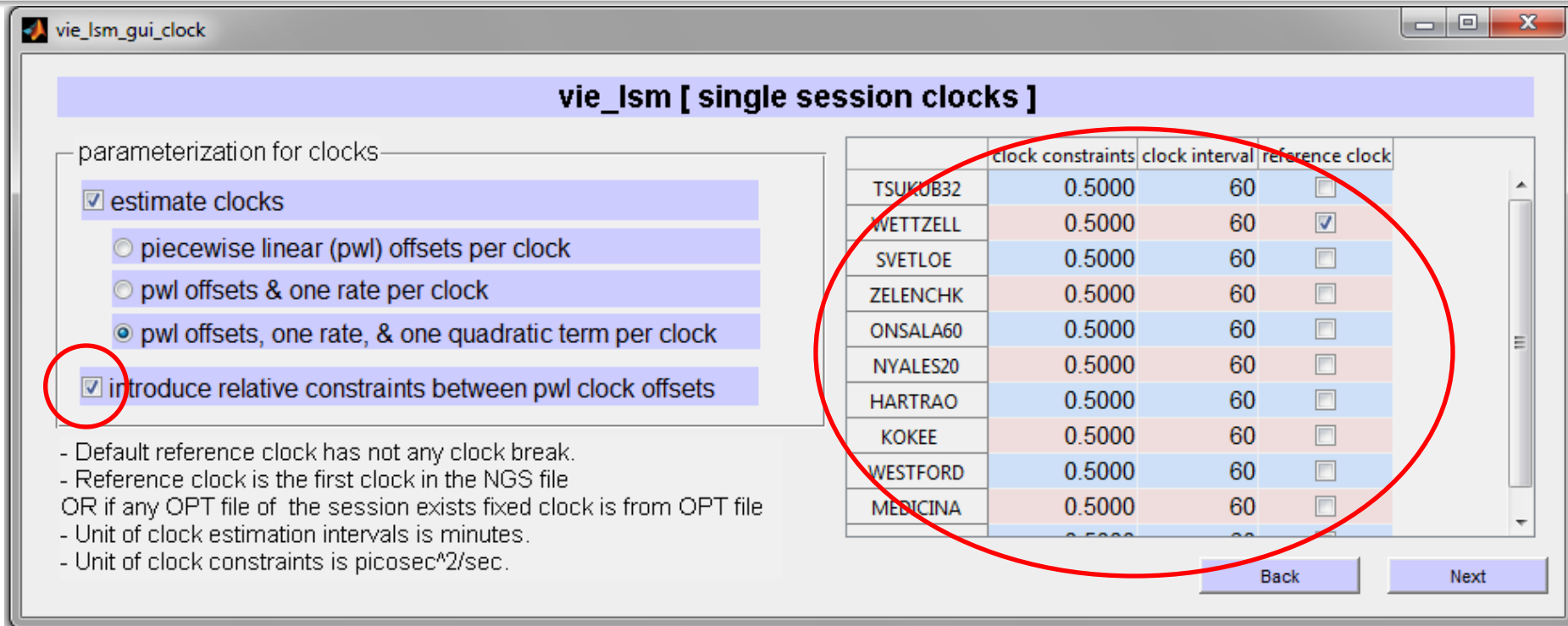
The screenshot shows the 'vie\_Ism [ single session clocks ]' window. On the left, under 'parameterization for clocks', there are several options: 'estimate clocks' (checked), 'piecewise linear (pwl) offsets per clock' (radio button), 'pwl offsets & one rate per clock' (radio button), 'pwl offsets, one rate, & one quadratic term per clock' (radio button, circled in red), and 'introduce relative constraints between pwl clock offsets' (checked). Below these are four bullet points: '- Default reference clock has not any clock break.', '- Reference clock is the first clock in the NGS file OR if any OPT file of the session exists fixed clock is from OPT file', '- Unit of clock estimation intervals is minutes.', and '- Unit of clock constraints is  $\text{picosec}^2/\text{sec}$ .' On the right, a table lists clock constraints for various clocks. The 'WETTZELL' row is highlighted in pink and has its 'reference clock' checkbox checked.

	clock constraints	clock interval	reference clock
TSUKUB32	0.5000	60	<input type="checkbox"/>
WETTZELL	0.5000	60	<input checked="" type="checkbox"/>
SVETLOE	0.5000	60	<input type="checkbox"/>
ZELENCHK	0.5000	60	<input type="checkbox"/>
ONSALA60	0.5000	60	<input type="checkbox"/>
NYALES20	0.5000	60	<input type="checkbox"/>
HARTRAO	0.5000	60	<input type="checkbox"/>
KOKEE	0.5000	60	<input type="checkbox"/>
WESTFORD	0.5000	60	<input type="checkbox"/>
MEDICINA	0.5000	60	<input type="checkbox"/>

Buttons: Back, Next

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



The screenshot shows the 'vie\_Ism [ single session clocks ]' window. On the left, under 'parameterization for clocks', the 'introduce relative constraints between pwl clock offsets' checkbox is checked and circled in red. The table on the right is also circled in red and contains the following data:

	clock constraints	clock interval	reference clock
TSUKUB32	0.5000	60	<input type="checkbox"/>
WETTZELL	0.5000	60	<input checked="" type="checkbox"/>
SVETLOE	0.5000	60	<input type="checkbox"/>
ZELENCHK	0.5000	60	<input type="checkbox"/>
ONSALA60	0.5000	60	<input type="checkbox"/>
NYALES20	0.5000	60	<input type="checkbox"/>
HARTRAO	0.5000	60	<input type="checkbox"/>
KOKEE	0.5000	60	<input type="checkbox"/>
WESTFORD	0.5000	60	<input type="checkbox"/>
MEDICINA	0.5000	60	<input type="checkbox"/>

Below the table are 'Back' and 'Next' buttons.

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  $\pm$  a certain standard deviation  $\sigma$ . (These constraints are mainly important to bridge gaps without observations to avoid singularity of the normal equation system.)

## How to interpret this constraint of $0.5 \text{ ps}^2/\text{s}$ ?

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

# Graphical user interfaces of VieVS

vie\_lsm\_gui\_tropo

## vie\_lsm [ single session troposphere ]

apply relative constraints between tropospheric offset estimates

- introduce RELATIVE CONSTRAINTS between pwl ZENITH WET DELAY offsets
- introduce REALTIVE CONSTRAINTS between pwl tropo. NORTH GRADIENT offsets
- introduce RELATIVE CONSTRAINTS between pwl tropo. EAST GRADIENT offsets
- introduce ABSOLUTE CONSTRAINTS between pwl tropo. NORTH GRADIENT offsets
- introduce ABSOLUTE CONSTRAINTS between pwl tropo. EAST GRADIENT offsets

- unit of estimation intervals is minute.

- unit of ZWD relative constraints is picosec<sup>2</sup>/sec e.g. 0.7 picosec<sup>2</sup>/sec relatively loose.

- unit of NGR & EGR relative constraints is millimeter/day e.g. 2 mm/day relatively loose.

- unit of NGR & EGR absolute constraints is millimeter e.g. 1 mm absolutely loose.

	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	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
WETZELL	0.7000	2	2	1	1	30	360	360	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
SVETLOE	0.7000	2	2	1	1	30	360	360	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
ZELENCHK	0.7000	2	2	1	1	30	360	360	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
ONSALA60	0.7000	2	2	1	1	30	360	360	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
NYALES20	0.7000	2	2	1	1	30	360	360	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
HARTRAO	0.7000	2	2	1	1	30	360	360	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>

Back Next

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

# Graphical user interfaces of VieVS

**vie\_lsm [ single session troposphere ]**

apply relative constraints between tropospheric offset estimates

- introduce RELATIVE CONSTRAINTS between pwl ZENITH WET DELAY offsets
- introduce REALTIVE CONSTRAINTS between pwl tropo. NORTH GRADIENT offsets
- introduce RELATIVE CONSTRAINTS between pwl tropo. EAST GRADIENT offsets
- introduce ABSOLUTE CONSTRAINTS between pwl tropo. NORTH GRADIENT offsets
- introduce ABSOLUTE CONSTRAINTS between pwl tropo. EAST GRADIENT offsets

- unit of estimation intervals is minute.

- unit of ZWD relative constraints is picosec^2/sec e.g. 0.7 picosec^2/sec relatively loose.

- unit of NGR & EGR relative constraints is millimeter/day e.g. 2 mm/day relatively loose.

- unit of NGR & EGR absolute constraints is millimeter e.g. 1 mm absolutely loose.

	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	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
WETZELL	0.7000	2	2	1	1	30	360	360	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
SVETLOE	0.7000	2	2	1	1	30	360	360	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
ZELENCHK	0.7000	2	2	1	1	30	360	360	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
ONSALA60	0.7000	2	2	1	1	30	360	360	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
NYALES20	0.7000	2	2	1	1	30	360	360	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
HARTRAO	0.7000	2	2	1	1	30	360	360	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
KOVSF	0.7000	2	2	1	1	30	360	360	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

Back Next

These are the corresponding time intervals in minutes.

# Graphical user interfaces of VieVS

**vie\_lsm [ single session troposphere ]**

apply relative constraints between tropospheric offset estimates

- introduce RELATIVE CONSTRAINTS between pwl ZENITH WET DELAY offsets
- introduce REALTIVE CONSTRAINTS between pwl tropo. NORTH GRADIENT offsets
- introduce RELATIVE CONSTRAINTS between pwl tropo. EAST GRADIENT offsets
- introduce ABSOLUTE CONSTRAINTS between pwl tropo. NORTH GRADIENT offsets
- introduce ABSOLUTE CONSTRAINTS between pwl tropo. EAST GRADIENT offsets

- unit of estimation intervals is minute.  
- unit of ZWD relative constraints is picosec^2/sec e.g. 0.7 picosec^2/sec relatively loose.  
- unit of NGR & EGR relative constraints is millimeter/day e.g. 2 mm/day relatively loose.  
- unit of NGR & EGR absolute constraints is millimeter e.g. 1 mm absolutely loose.

	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	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
WETZELL	0.7000	2	2	1	1	30	360	360	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
SVETLOE	0.7000	2	2	1	1	30	360	360	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
ZELENCHK	0.7000	2	2	1	1	30	360	360	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
ONSALA60	0.7000	2	2	1	1	30	360	360	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
NYALES20	0.7000	2	2	1	1	30	360	360	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
HARTRAO	0.7000	2	2	1	1	30	360	360	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>

Back Next

**How to interpret this constraint of  $0.7 \text{ ps}^2/\text{s}$  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  $1260 \text{ ps}^2$  after one hour. This is a standard deviation of 35 ps. 35 ps is the standard deviation  $\sigma$ , which is used for the observation equation.

# Graphical user interfaces of VieVS

The screenshot shows the 'vie\_lsm [ single session troposphere ]' window. It features a list of constraint options on the left, a table of station parameters at the bottom, and explanatory text on the right. A red circle highlights the 'introduce REALTIVE CONSTRAINTS between pwl tropo. NORTH GRADIENT offsets' option. A red box highlights the 'NGR rel. coef.' and 'EGR rel. coef.' columns in the table, which both have a value of 2. Another red box highlights the 'NGR int.' and 'EGR int.' columns, which both have a value of 360.

apply relative constraints between tropospheric offset estimates

- introduce RELATIVE CONSTRAINTS between pwl ZENITH WET DELAY offsets
- introduce REALTIVE CONSTRAINTS between pwl tropo. NORTH GRADIENT offsets
- introduce RELATIVE CONSTRAINTS between pwl tropo. EAST GRADIENT offsets
- introduce ABSOLUTE CONSTRAINTS between pwl tropo. NORTH GRADIENT offsets
- introduce ABSOLUTE CONSTRAINTS between pwl tropo. EAST GRADIENT offsets

- unit of estimation intervals is minute.

- unit of ZWD relative constraints is  $\text{picosec}^2/\text{sec}$  e.g. 0.7  $\text{picosec}^2/\text{sec}$  relatively loose.

- unit of NGR & EGR relative constraints is millimeter/day e.g. 2 mm/day relatively loose.

- unit of NGR & EGR absolute constraints is millimeter e.g. 1 mm absolutely loose.

	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	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
WETZELL	0.7000	2	2	1	1	30	360	360	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
SVETLOE	0.7000	2	2	1	1	30	360	360	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
ZELENCHK	0.7000	2	2	1	1	30	360	360	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
ONSALA60	0.7000	2	2	1	1	30	360	360	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
NYALES20	0.7000	2	2	1	1	30	360	360	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
HARTRAO	0.7000	2	2	1	1	30	360	360	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>

Back Next

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

The screenshot shows the 'vie\_lsm [ single session troposphere ]' window. It features a list of five checkboxes for applying constraints, with the last two (absolute constraints) circled in red. To the right, there are three explanatory text blocks. Below is a table with columns for various coefficients and intervals, with the last two columns circled in red. At the bottom right are 'Back' and 'Next' buttons.

apply relative constraints between tropospheric offset estimates

- introduce RELATIVE CONSTRAINTS between pwl ZENITH WET DELAY offsets
- introduce REALTIVE CONSTRAINTS between pwl tropo. NORTH GRADIENT offsets
- introduce RELATIVE CONSTRAINTS between pwl tropo. EAST GRADIENT offsets
- introduce ABSOLUTE CONSTRAINTS between pwl tropo. NORTH GRADIENT offsets
- introduce ABSOLUTE CONSTRAINTS between pwl tropo. EAST GRADIENT offsets

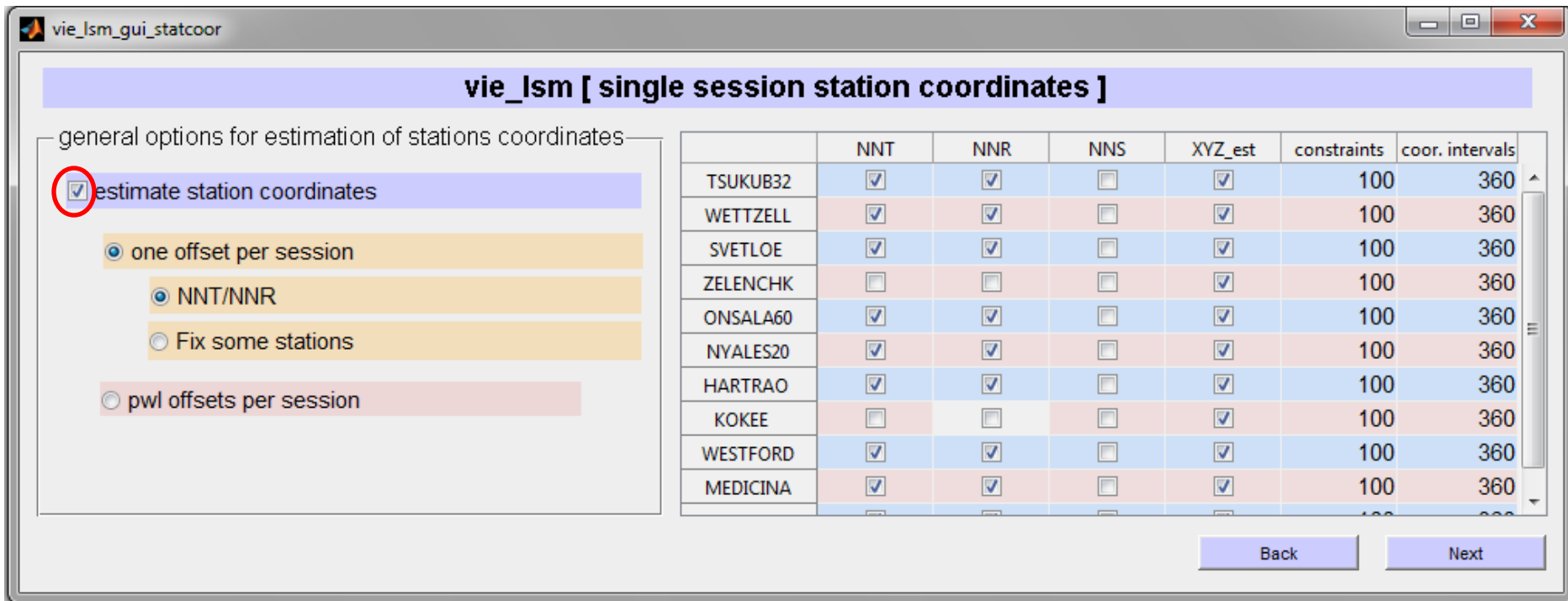
- unit of estimation intervals is minute.  
- unit of ZWD relative constraints is picosec^2/sec e.g. 0.7 picosec^2/sec relatively loose.  
- unit of NGR & EGR relative constraints is millimeter/day e.g. 2 mm/day relatively loose.  
- unit of NGR & EGR absolute constraints is millimeter e.g. 1 mm absolutely loose.

	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	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
WETZELL	0.7000	2	2	1	1	30	360	360	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
SVETLOE	0.7000	2	2	1	1	30	360	360	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
ZELENCHK	0.7000	2	2	1	1	30	360	360	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
ONSALA60	0.7000	2	2	1	1	30	360	360	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
NYALES20	0.7000	2	2	1	1	30	360	360	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
HARTRAO	0.7000	2	2	1	1	30	360	360	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
KRVS	0.7000	2	2	1	1	30	360	360	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>

Back Next

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  $0 \pm 1$  mm. (This feature might be necessary in early VLBI sessions.)

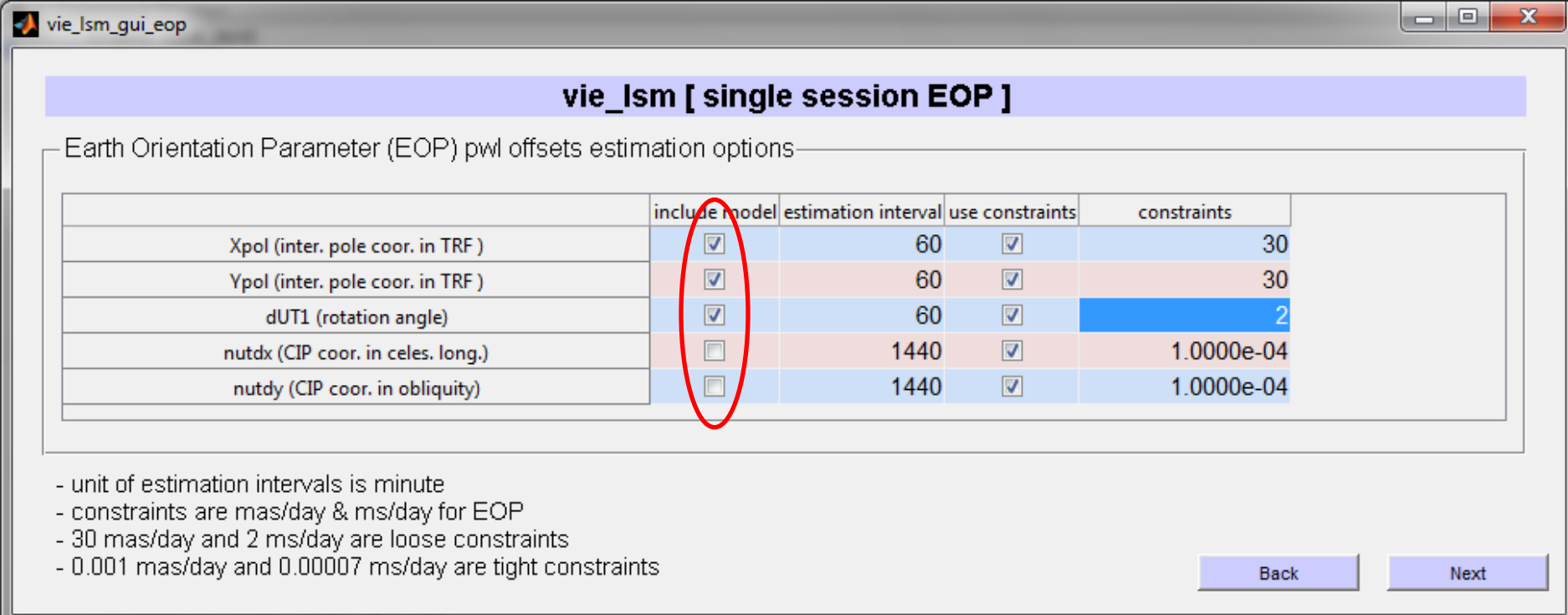
# Graphical user interfaces of VieVS



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



**vie\_lsm [ single session EOP ]**

Earth Orientation Parameter (EOP) pwl offsets estimation options

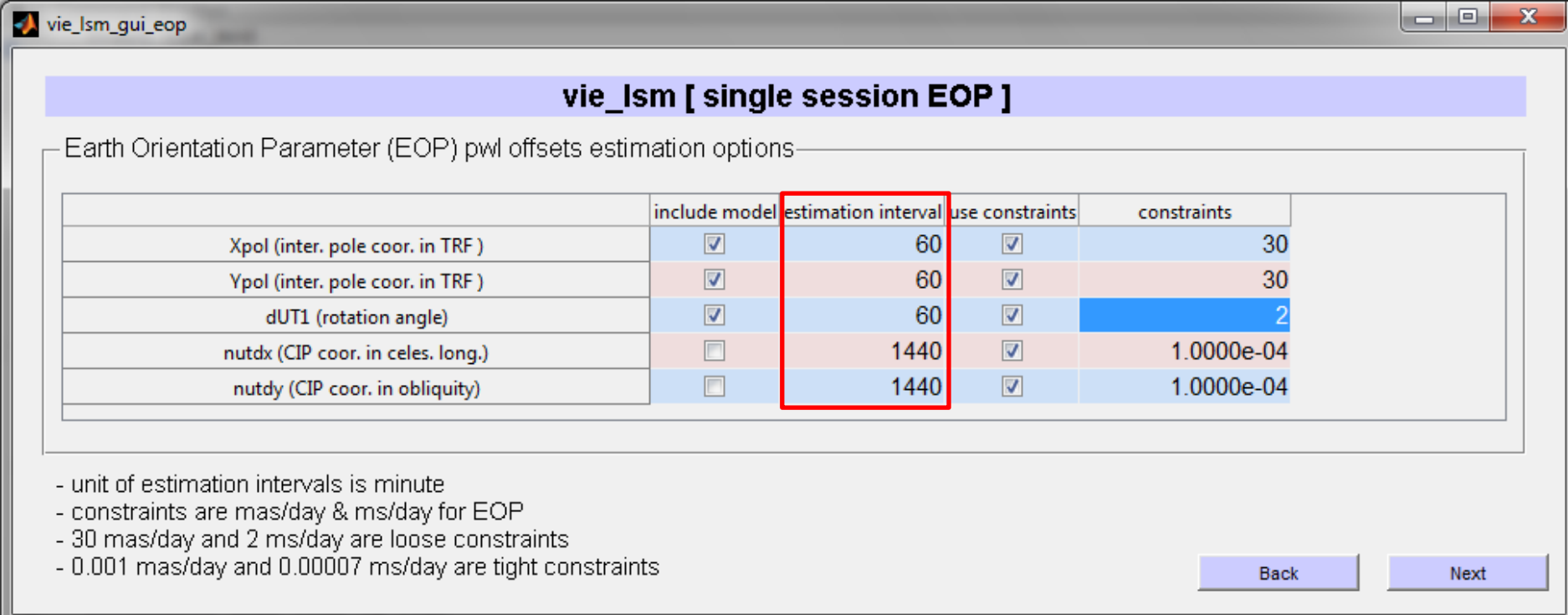
	include model	estimation interval	use constraints	constraints
Xpol (inter. pole coord. in TRF)	<input checked="" type="checkbox"/>	60	<input checked="" type="checkbox"/>	30
Ypol (inter. pole coord. in TRF)	<input checked="" type="checkbox"/>	60	<input checked="" type="checkbox"/>	30
dUT1 (rotation angle)	<input checked="" type="checkbox"/>	60	<input checked="" type="checkbox"/>	2
nutdx (CIP coord. in celes. long.)	<input type="checkbox"/>	1440	<input checked="" type="checkbox"/>	1.0000e-04
nutdy (CIP coord. in obliquity)	<input type="checkbox"/>	1440	<input checked="" type="checkbox"/>	1.0000e-04

- unit of estimation intervals is minute  
- constraints are mas/day & ms/day for EOP  
- 30 mas/day and 2 ms/day are loose constraints  
- 0.001 mas/day and 0.00007 ms/day are tight constraints

Back Next

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



The screenshot shows a window titled "vie\_lsm\_gui\_eop" with a purple header bar containing the text "vie\_lsm [ single session EOP ]". Below the header, the text "Earth Orientation Parameter (EOP) pwl offsets estimation options" is displayed. A table with five columns is shown: "include model", "estimation interval", "use constraints", and "constraints". The table lists five parameters: Xpol, Ypol, dUT1, nutdx, and nutdy. The "estimation interval" column is highlighted with a red box. Below the table, there are four bullet points explaining the units and constraints. At the bottom right, there are "Back" and "Next" buttons.

	include model	estimation interval	use constraints	constraints
Xpol (inter. pole coord. in TRF)	<input checked="" type="checkbox"/>	60	<input checked="" type="checkbox"/>	30
Ypol (inter. pole coord. in TRF)	<input checked="" type="checkbox"/>	60	<input checked="" type="checkbox"/>	30
dUT1 (rotation angle)	<input checked="" type="checkbox"/>	60	<input checked="" type="checkbox"/>	2
nutdx (CIP coord. in celes. long.)	<input type="checkbox"/>	1440	<input checked="" type="checkbox"/>	1.0000e-04
nutdy (CIP coord. in obliquity)	<input type="checkbox"/>	1440	<input checked="" type="checkbox"/>	1.0000e-04

- unit of estimation intervals is minute
- constraints are mas/day & ms/day for EOP
- 30 mas/day and 2 ms/day are loose constraints
- 0.001 mas/day and 0.00007 ms/day are tight constraints

Back Next

These are the time (estimation) intervals in minutes.

# Graphical user interfaces of VieVS

vie\_lsm\_gui\_eop

**vie\_lsm [ single session EOP ]**

Earth Orientation Parameter (EOP) pwl offsets estimation options

	include model	estimation interval	use constraints	constraints
Xpol (inter. pole coor. in TRF)	<input checked="" type="checkbox"/>	60	<input checked="" type="checkbox"/>	30
Ypol (inter. pole coor. in TRF)	<input checked="" type="checkbox"/>	60	<input checked="" type="checkbox"/>	30
dUT1 (rotation angle)	<input checked="" type="checkbox"/>	60	<input checked="" type="checkbox"/>	2
nutdx (CIP coor. in celes. long.)	<input type="checkbox"/>	1440	<input checked="" type="checkbox"/>	1.0000e-04
nutdy (CIP coor. in obliquity)	<input type="checkbox"/>	1440	<input checked="" type="checkbox"/>	1.0000e-04

- unit of estimation intervals is minute  
- constraints are mas/day & ms/day for EOP  
- 30 mas/day and 2 ms/day are loose constraints  
- 0.001 mas/day and 0.00007 ms/day are tight constraints

Back Next

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

The screenshot shows a window titled "vie\_lsm\_gui\_eop" with a purple header bar containing the text "vie\_lsm [ single session EOP ]". Below the header, the text "Earth Orientation Parameter (EOP) pwl offsets estimation options" is displayed. A table with five columns is shown: "include model", "estimation interval", "use constraints", and "constraints". The "constraints" column is highlighted with a red border. The table contains five rows of parameters. Below the table, there are four bullet points explaining the units and constraints. At the bottom right, there are "Back" and "Next" buttons.

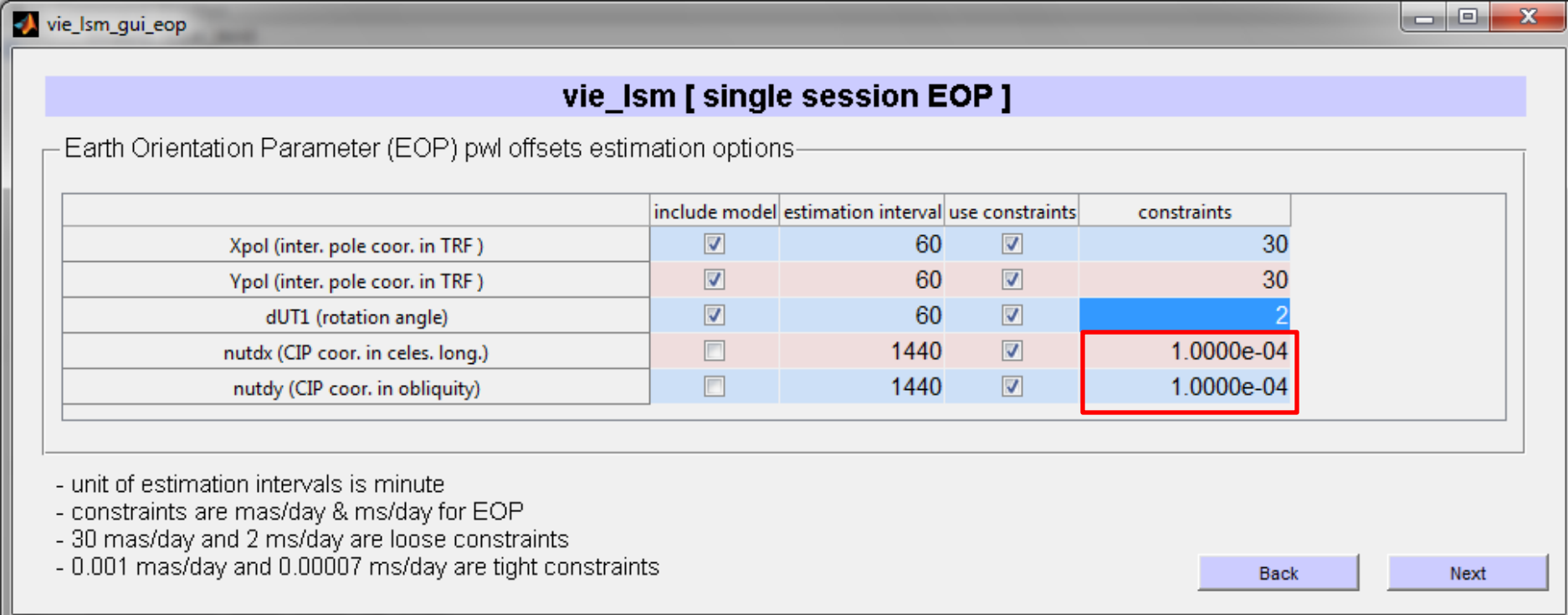
	include model	estimation interval	use constraints	constraints
Xpol (inter. pole coor. in TRF)	<input checked="" type="checkbox"/>	60	<input checked="" type="checkbox"/>	30
Ypol (inter. pole coor. in TRF)	<input checked="" type="checkbox"/>	60	<input checked="" type="checkbox"/>	30
dUT1 (rotation angle)	<input checked="" type="checkbox"/>	60	<input checked="" type="checkbox"/>	2
nutdx (CIP coor. in celes. long.)	<input type="checkbox"/>	1440	<input checked="" type="checkbox"/>	1.0000e-04
nutdy (CIP coor. in obliquity)	<input type="checkbox"/>	1440	<input checked="" type="checkbox"/>	1.0000e-04

- unit of estimation intervals is minute
- constraints are mas/day & ms/day for EOP
- 30 mas/day and 2 ms/day are loose constraints
- 0.001 mas/day and 0.00007 ms/day are tight constraints

Back Next

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



The screenshot shows a window titled "vie\_lsm\_gui\_eop" with a purple header bar containing the text "vie\_lsm [ single session EOP ]". Below the header, the text "Earth Orientation Parameter (EOP) pwl offsets estimation options" is displayed. A table with five columns is shown: "include model", "estimation interval", "use constraints", and "constraints". The rows represent different EOP parameters: Xpol, Ypol, dUT1, nutdx, and nutdy. The "constraints" column for nutdx and nutdy is highlighted with a red box, showing a value of 1.0000e-04. Below the table, there are four explanatory bullet points and two buttons labeled "Back" and "Next".

	include model	estimation interval	use constraints	constraints
Xpol (inter. pole coord. in TRF)	<input checked="" type="checkbox"/>	60	<input checked="" type="checkbox"/>	30
Ypol (inter. pole coord. in TRF)	<input checked="" type="checkbox"/>	60	<input checked="" type="checkbox"/>	30
dUT1 (rotation angle)	<input checked="" type="checkbox"/>	60	<input checked="" type="checkbox"/>	2
nutdx (CIP coord. in celes. long.)	<input type="checkbox"/>	1440	<input checked="" type="checkbox"/>	1.0000e-04
nutdy (CIP coord. in obliquity)	<input type="checkbox"/>	1440	<input checked="" type="checkbox"/>	1.0000e-04

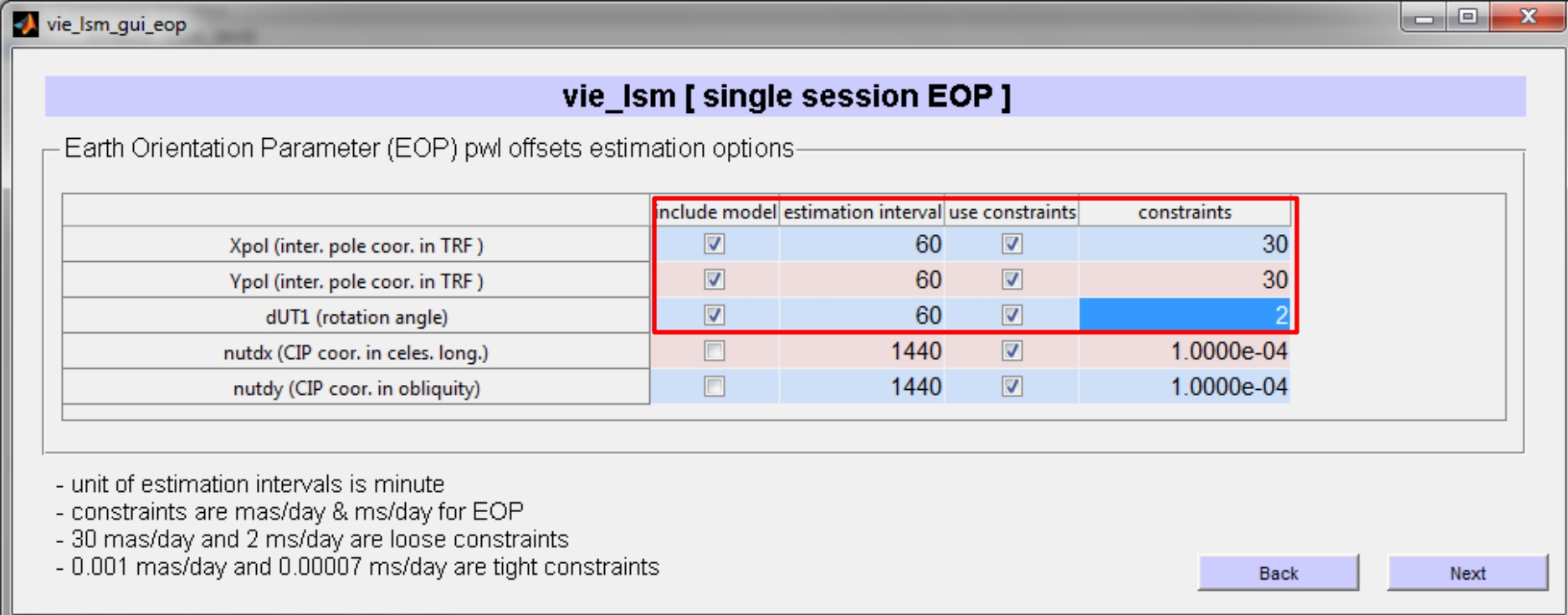
- unit of estimation intervals is minute
- constraints are mas/day & ms/day for EOP
- 30 mas/day and 2 ms/day are loose constraints
- 0.001 mas/day and 0.00007 ms/day are tight constraints

Back Next

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



The screenshot shows a window titled "vie\_lsm\_gui\_eop" with a purple header bar containing the text "vie\_lsm [ single session EOP ]". Below the header, the text "Earth Orientation Parameter (EOP) pwl offsets estimation options" is displayed. A table with five columns is shown: "include model", "estimation interval", "use constraints", and "constraints". The table contains five rows of parameters. A red box highlights the first three columns for the first three rows. The "constraints" column for the third row (dUT1) is highlighted in blue.

	include model	estimation interval	use constraints	constraints
Xpol (inter. pole coor. in TRF)	<input checked="" type="checkbox"/>	60	<input checked="" type="checkbox"/>	30
Ypol (inter. pole coor. in TRF)	<input checked="" type="checkbox"/>	60	<input checked="" type="checkbox"/>	30
dUT1 (rotation angle)	<input checked="" type="checkbox"/>	60	<input checked="" type="checkbox"/>	2
nutdx (CIP coor. in celes. long.)	<input type="checkbox"/>	1440	<input checked="" type="checkbox"/>	1.0000e-04
nutdy (CIP coor. in obliquity)	<input type="checkbox"/>	1440	<input checked="" type="checkbox"/>	1.0000e-04

- unit of estimation intervals is minute  
- constraints are mas/day & ms/day for EOP  
- 30 mas/day and 2 ms/day are loose constraints  
- 0.001 mas/day and 0.00007 ms/day are tight constraints

Back Next

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  $\mu$ s per hour).



# Graphical user interfaces of VieVS

**vie\_lsm [ single session source coordinates ]**

estimate coordinates of sources as pwl offsets [ all the unselected sources will be fixed to CRF ]

introduce relative constraints between pwlo source coordinates

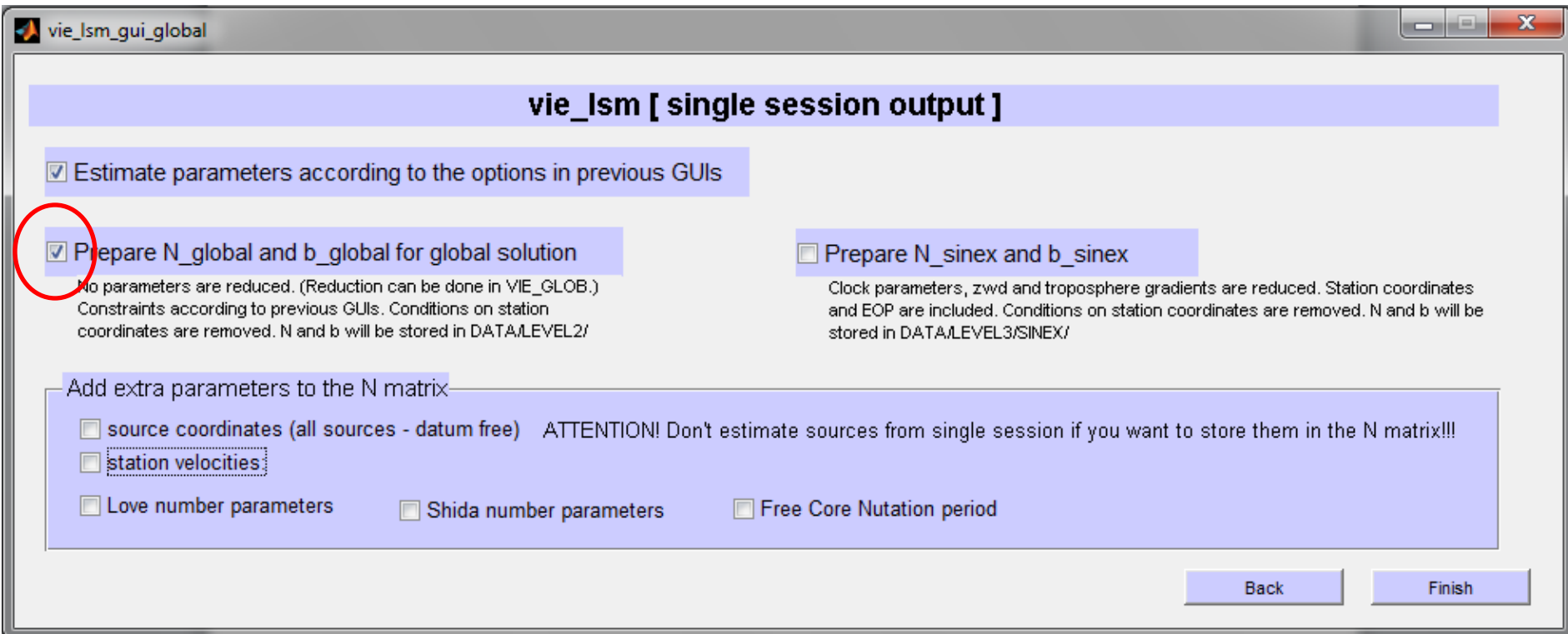
	source name	total observations	est. coord.	constraints	coord. interval
1	0955+476	429	<input checked="" type="checkbox"/>	30	60
2	0235+164	452	<input checked="" type="checkbox"/>	50	60
3	1519-273	53	<input type="checkbox"/>	1.0000e-04	1440
4	0133+476	544	<input checked="" type="checkbox"/>	20	60
5	1954-388	23	<input type="checkbox"/>	1.0000e-04	1440
6	1334-127	180	<input type="checkbox"/>	1.0000e-04	1440
7	0119+115	150	<input type="checkbox"/>	1.0000e-04	1440
8	1351-018	46	<input type="checkbox"/>	1.0000e-04	1440
9	0003-066	43	<input type="checkbox"/>	1.0000e-04	1440
10	1611+343	474	<input type="checkbox"/>	1.0000e-04	1440

- unit of constraints is mas/day.  
- unit of coordinate estimation intervals in minutes.  
- Please, fix at least one source which has more than 1 observation if you select estimate sources

Back Next

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.