XXIX INTERNATIONAL SYMPOSIUM ON
“MODERN TECHNOLOGIES, EDUCATION AND PROFESSIONAL PRACTICE IN GEODESY AND RELATED FIELDS”
05-06 November 2019, Istanbul, Turkey

Ocean tide loading displacements observed by very long baseline interferometry during IVS-CONT14 campaign

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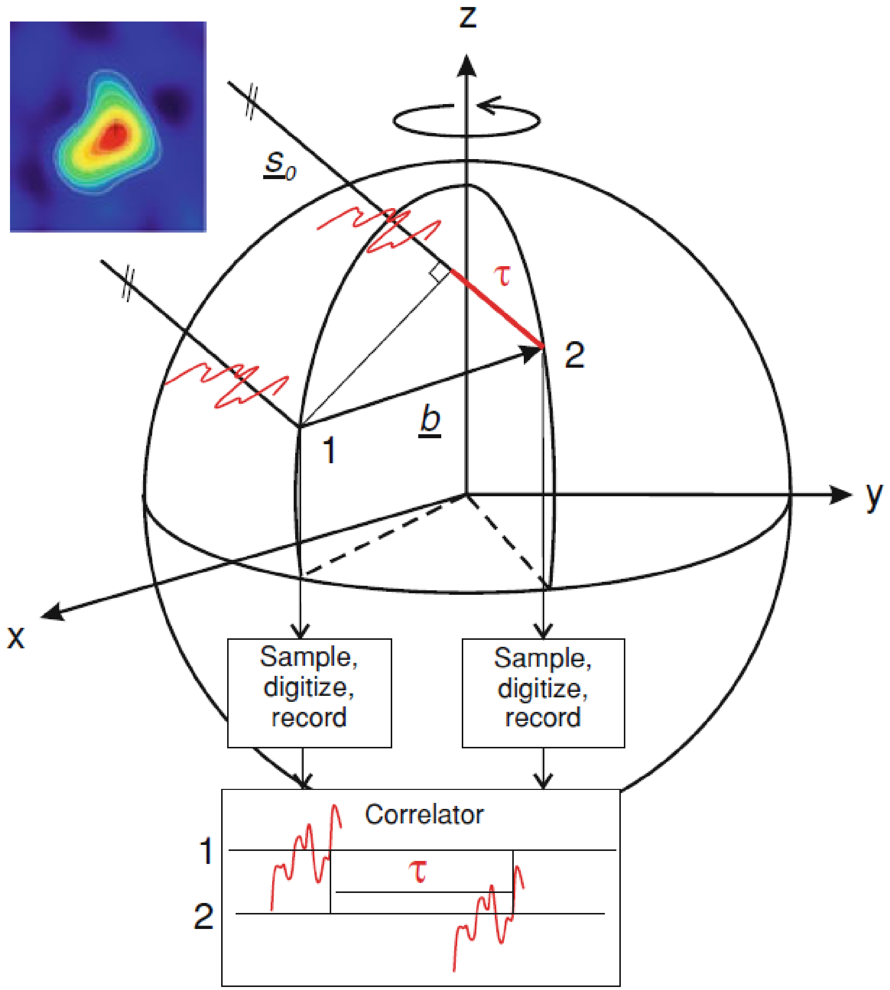
Motivation of this study and the applied methodology to solve?

- PROBLEM: Is it possible to estimate reliable and accurate sub-daily (e.g. hourly) station positions from the observations of space geodetic techniques?
- CONSTRAINT: Large correlations between sub-daily station positions and troposphere delays.
- SOLUTION: Troposphere delays estimated from daily sessions are reduced from the observations of hourly sessions a priori to the analysis .
- VALIDATING the results e.g. with those of OTL model predictions.

Outline

- Basics of geodetic VLBI
- Handling troposhere delays in hourly session analysis
- Analysis of IVS CONT14 hourly sessions
- Estimating principal semi-diurnal and diurnal constituents of ocean tidal loading displacements
- Results and discussion

Basics of geodetic VLBI



$$t_2 - t_1 = \tau_{geo} = -\frac{1}{c} \cdot b^T \cdot W \cdot R \cdot Q \cdot k +$$

$$\Delta\tau_{clock} = \tau_{clock2} - \tau_{clock1} +$$

$$\Delta\tau_{trop} = \tau_{trop2} - \tau_{trop1} +$$

$$\Delta\tau_{ion} = \tau_{ion2} - \tau_{ion1} + \ldots$$

Schuh and Böhm 2013, Sciences of Geodesy, Chapter 7, 2013

Troposphere delays in hourly session analysis (Davis et al. 1985)

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

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

- ZHD: calculate with surface pressure values (Saastamoinen 1972)
- ZWD: from 24h sessions
- G_n: from 24h sessions
- G_e: from 24h sessions

ZHD: Saastamoinen 1972
VMF1: Böhm et al. 2006
gradients: Chen and Herring 1997

IVS CONT14 Campaign

17 stations at 16 sites

from 6 MAY (0 UT) 2014
to 20 MAY (24 UT) 2014

NASA Sked
Bonn correlator

<u>Co-locations:</u>
All stations with GNSS
3 with SLR
4 with DORIS

Analysis of IVS CONT14 hourly sessions

- Vienna VLBI and Satellite Software (VieVS 3.1, Böhm et al. 2018).
- Gauss-Markov least-squares adjustment.
- Troposphere delays, from 24h sessions, are reduced from the observations a priori to the adjustment
- Source coordinates are fixed to ICRF2 (Fey et al. 2009).
- Antenna coordinates are fixed to CONT14TRF except the station of which OTL displacements will be estimated.
- EOP are fixed to CONT14EOP.
- AL: Petrov and Boy (2004).
- OTL displacements from FES2014 (Carrère et al. 2016) except the station of which OTL displacements will be estimated.

Estimating principal semi-diurnal and diurnal constituents of ocean tidal loading displacements

Constituent	M2	S2	N2	K2	K1	O1	P1	Q1
Period in days	0.5175	0.4999	0.5271	0.4986	0.997	1.078	1.003	1.119
Period in hours	12.421	12.000	12.659	11.967	23.935	25.819	24.066	26.868

$$\Delta_{n,k} = \sum_j A_{n,j,k} \cos(\chi_j(t) - \varphi_{n,j,k})$$

<u>Linearized form of the above harmonic function:</u>

$$\Delta_{n,k} = \sum_j R_{n,j,k} \cos \chi_j(t) + I_{n,j,k} \sin \chi_j(t)$$

$$R_{n,j,k} = A_{n,j,k} \cos \varphi_{n,j,k}$$

$$I_{n,j,k} = A_{n,j,k} \sin \varphi_{n,j,k}$$

- ❑ Tidal coefficients are not corrected for geocenter motions due to OTL.
- ❑ In-phase and quadrature parts were spline interpolated from 11 to 342 tides using the Matlab version of «hardisp.f» as recommended by IERS2010 conventions.

Gauss markov and Kalman Filter methods of Least Squares

- Gauss markov method (Carl Friedrich Gauss 1795; Adrien Marie Legendre 1805),

$$x=(A^T PA)^- A^T Pl$$

$$Kx=m_0^2(A^T PA)^-$$

- and Kalman filter method (Swerling 1958; Rudolf Emil Kálmán 1960)

$$x_t(-)=Fx_{t-1}(+)+\cancel{Bu}$$ **constant parameters**

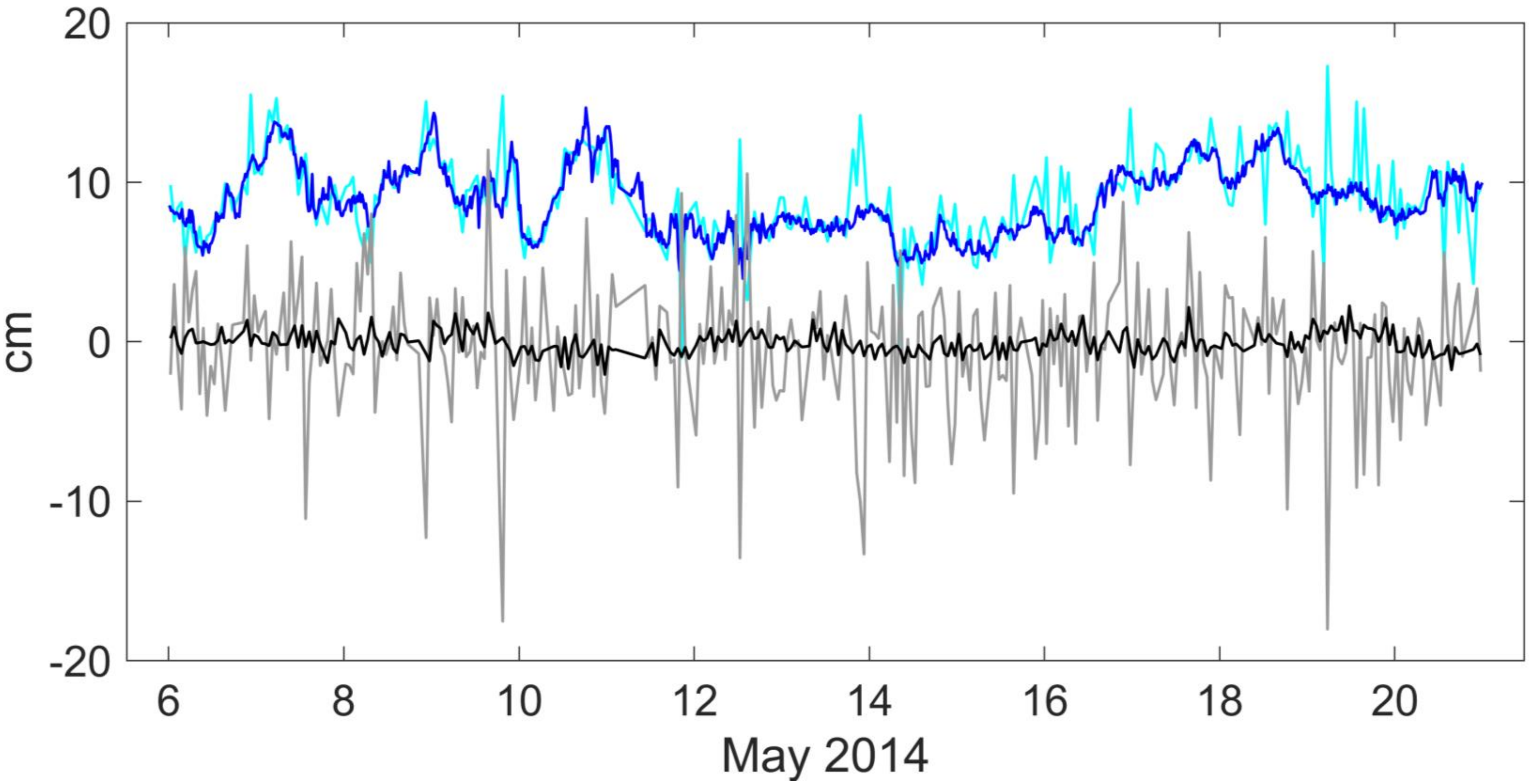
$$P_t(-)=FP_{t-1}(+)F^T\cancel{+Q} \quad Q=\left\langle w\cdot w^T\right\rangle \quad w=0$$

$$K=P_t(-)H^T\left[HP_t(-)H^T+R\right] \quad Q=\left\langle v\cdot v^T\right\rangle \quad v=z-Hx_t(-)$$

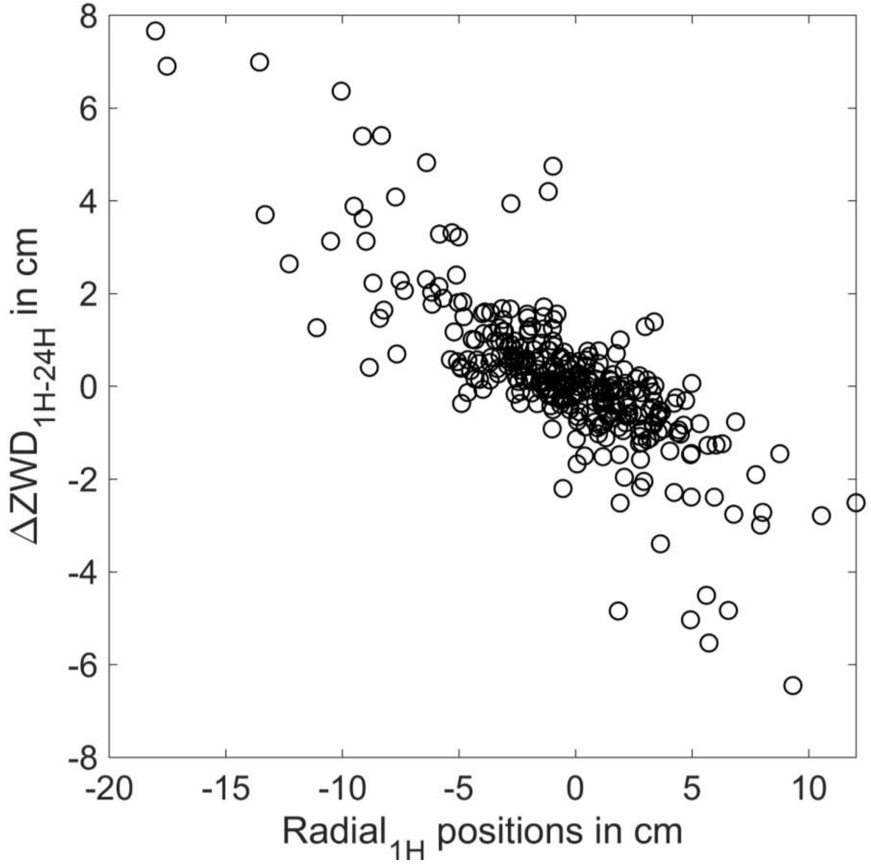
$$x_t(+)=x_t(-)+K\left[z-Hx_t(-)\right]$$

$$P_t(+)=P_t(-)-KHP_t(-)$$

Results and discussion

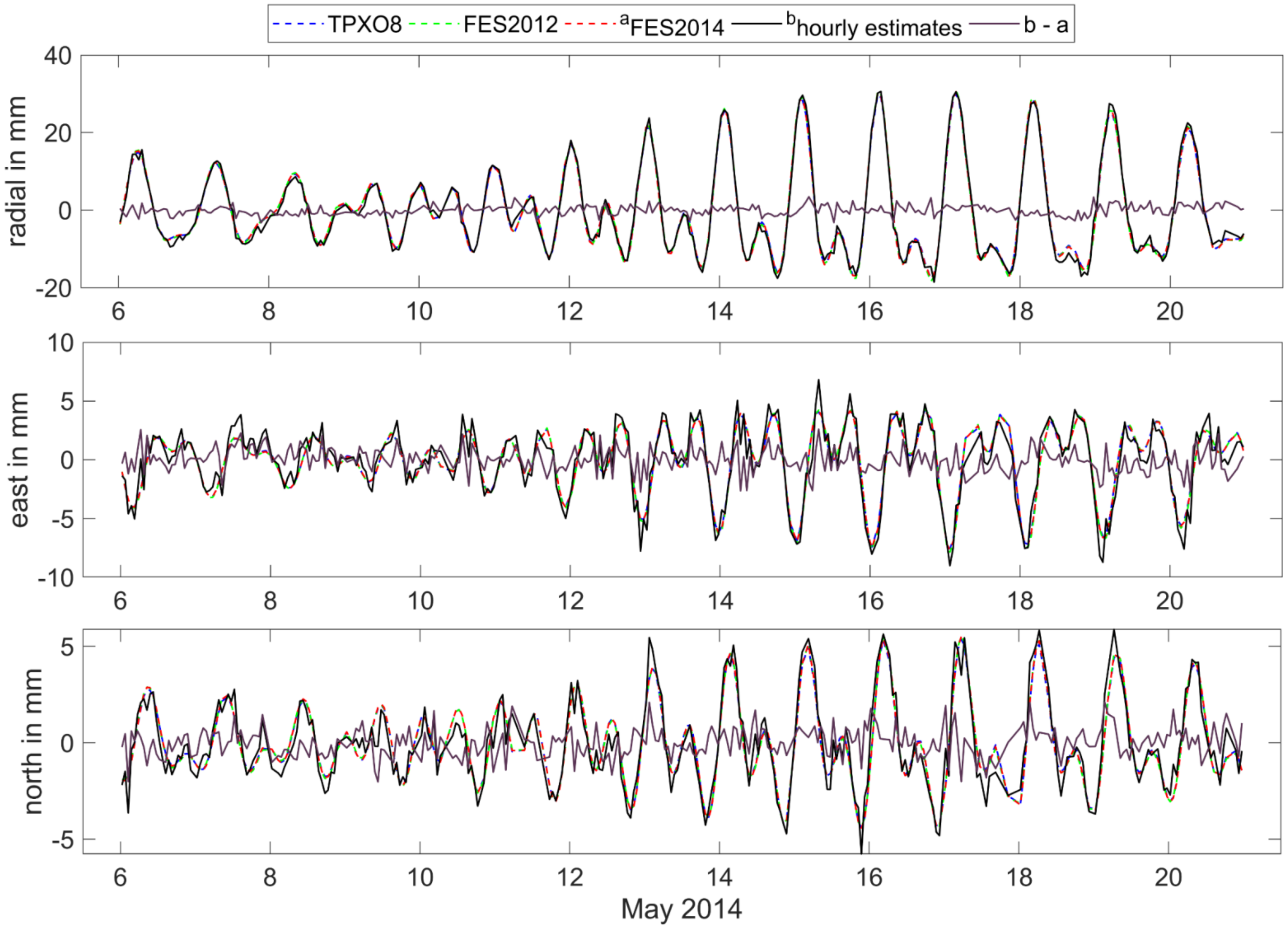


- Cyan and grey lines: hourly ZWD and the radial coordinates at Wettzell (Germany), respectively.
- Blue line: ZWD estimated from 24 hour sessions. Blackline the radial coordinate components estimated from 1 hour sessions when ZWD from 24 hour sessions (blue line) are reduced.



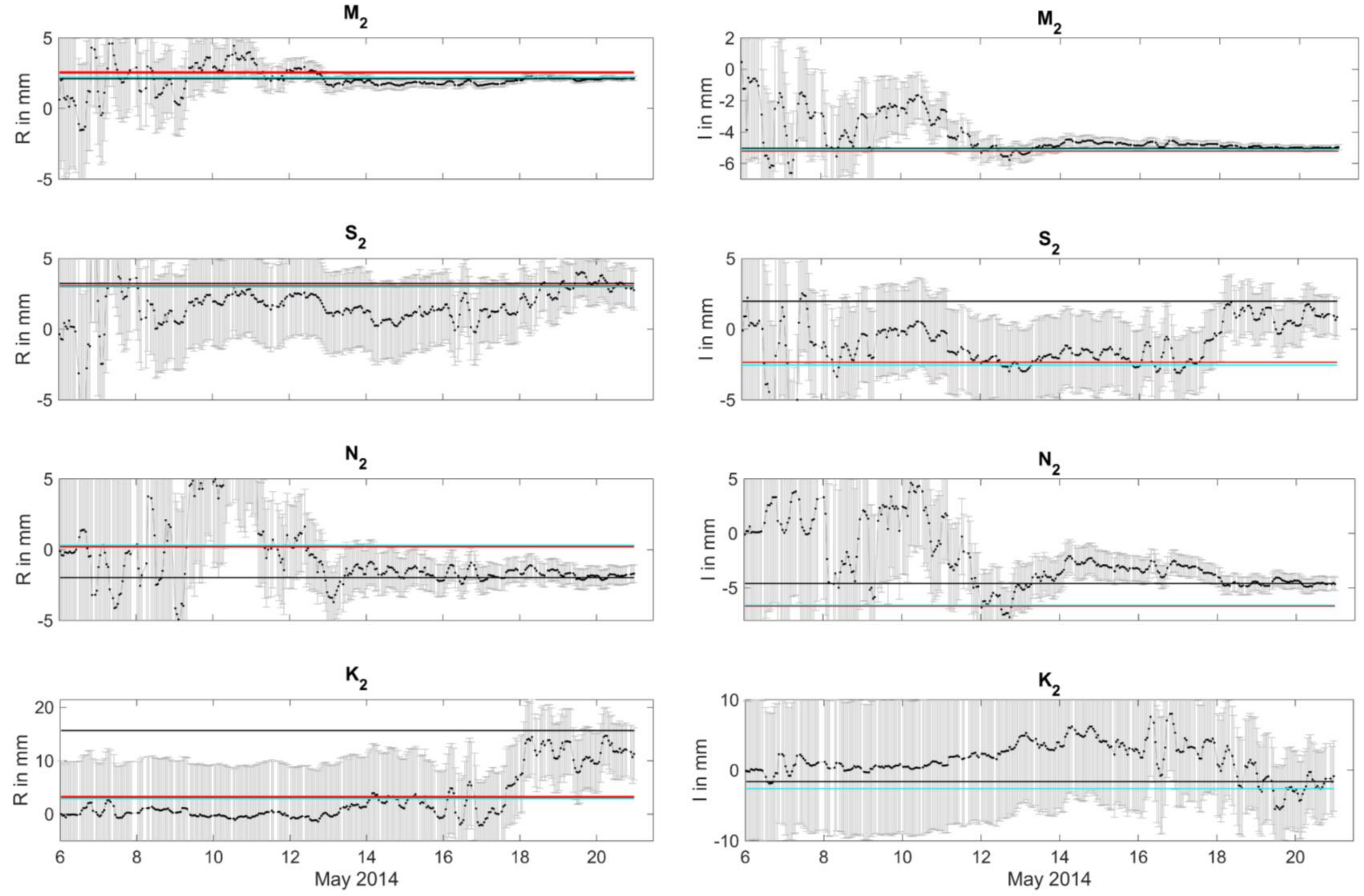
ZWD_{1H} - ZWD_{24H} versus hourly radial positions at Wettzell VLBI station.

Results and discussion



- Hourly OTL displacements estimated from VLBI (in black)
- w.r.t. TPXO8 (Egbert et al. 2010),
- FES2012 (Carrère et al. 2012),
- and FES2014 (Carrère et al. 2016)
- predictions at e.g. Tsukuba (Japan) geodetic colocation site.

Results and discussion

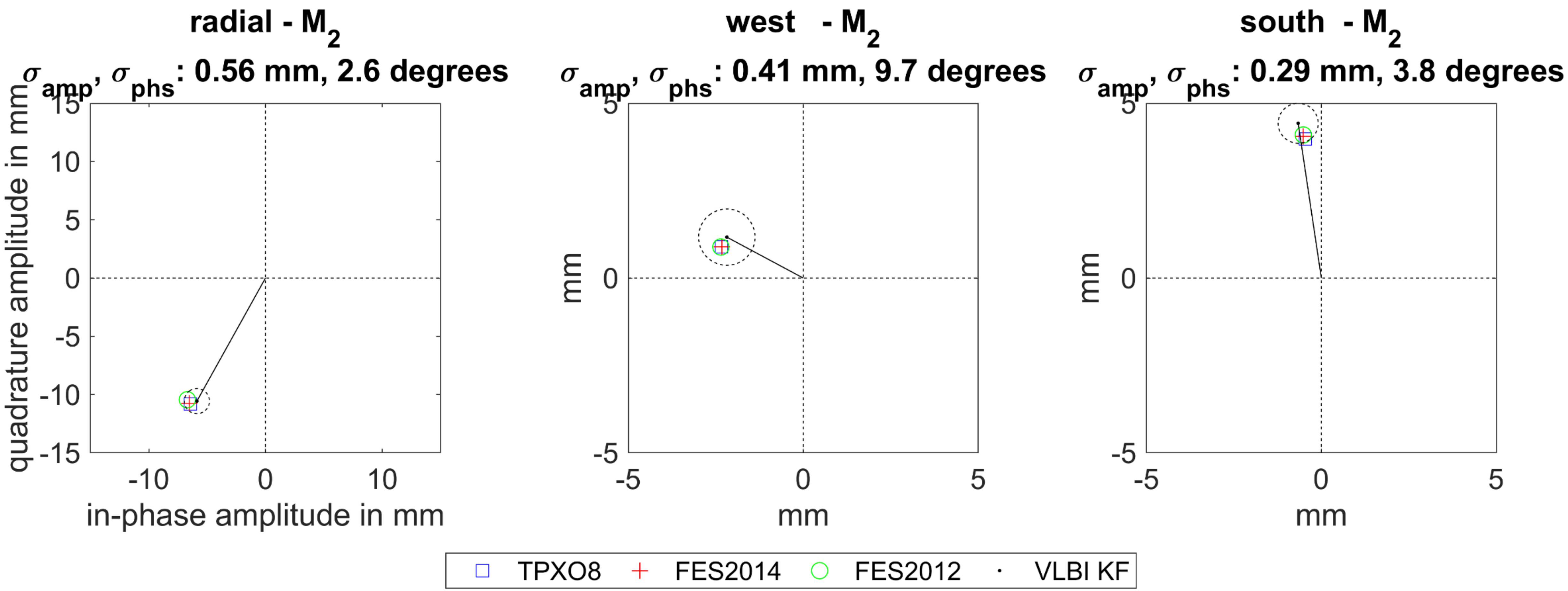


<u>Using such a small data set, covering 15 days of observations (hourly positions and their formal errors)</u>

- at all stations R and I of M2 converges to those of OTL models at sub-millimeter level.
- at most of the stations R and I of S2, N2 and O1 tides do converge at a few millimeters level (would be assumed as not converged).

In-phase (real: R) and out-of-phase (imaginary: I) parts of the semi-diurnal tides of radial component at Onsala (ONSALA60) Sweden. Red line: FES2014, cyan line: TPXO8, **black line: Gauss-Markov LS estimates**.

Results and discussion



M2 tide phasor vector plots of OTL displacements for all coordinate components at Kokee (Kauai island, Hawaii, USA).

Green circle: FES2012 , red plus: FES2014, blue square: TPXO8

Conclusions

- When troposphere delays from daily sessions are reduced from the observations of 1 hour sessions, accurate hourly station positions, to a level of sub-centimeter, can be estimated.
- M2 constituent of OTL displacements can be resolved to sub-millimeter level from these hourly station coordinate time series covering 15 days.
- Other tides can not be resolved. This is basically resulted from the 15 days long time series do not satisfy the minimum period (T) of Rayleigh criterion ($T > 1/(f1-f2)$, Godin 1972; Foreman 1977) to distinguish between neighboring frequencies.
- Gauss Markov and Kalman Filter methods of LS that both minimize the mean post-fit observational residuals, as expected outputs the same results in sub-millimeter level for the R and I of the M2 tide.
- At subdaily intervals, reduction of accurate troposphere delays from the observations a priori to the estimation and fixing the delays to zero (not estimating) is suggested to get accurate (e.g. geodynamic) parameters e.g. hourly station coordinates.

Thank you for your attention!