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# Ocean tide loading displacements from VLBI and the long term ocean tide variability

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# Outline

- Analysis of the IVS 24-h sessions using VieVS (Böhm et al. 2018)
- Estimation of the principal semi-diurnal and diurnal tidal constituents of OTLD from the 2-h PLO coord. of the stations
- Comparisons between the tidal constituents from the GOTM and the VLBI
- Changes are detected at some tides within about 30 years
- Conclusions

- global ocean tide models (GOTM): TPXO9-Atlas (Egbert and Erofeeva 2002), FES2014b (Carrère et al. 2012, 2016), GOT4.10c (Ray 2013)
- harmonic coefficients of the GOTM were downloaded from http://holt.oso.chalmers.se/loading

# Analysis of the IVS 24-hour sessions

**a priori values**

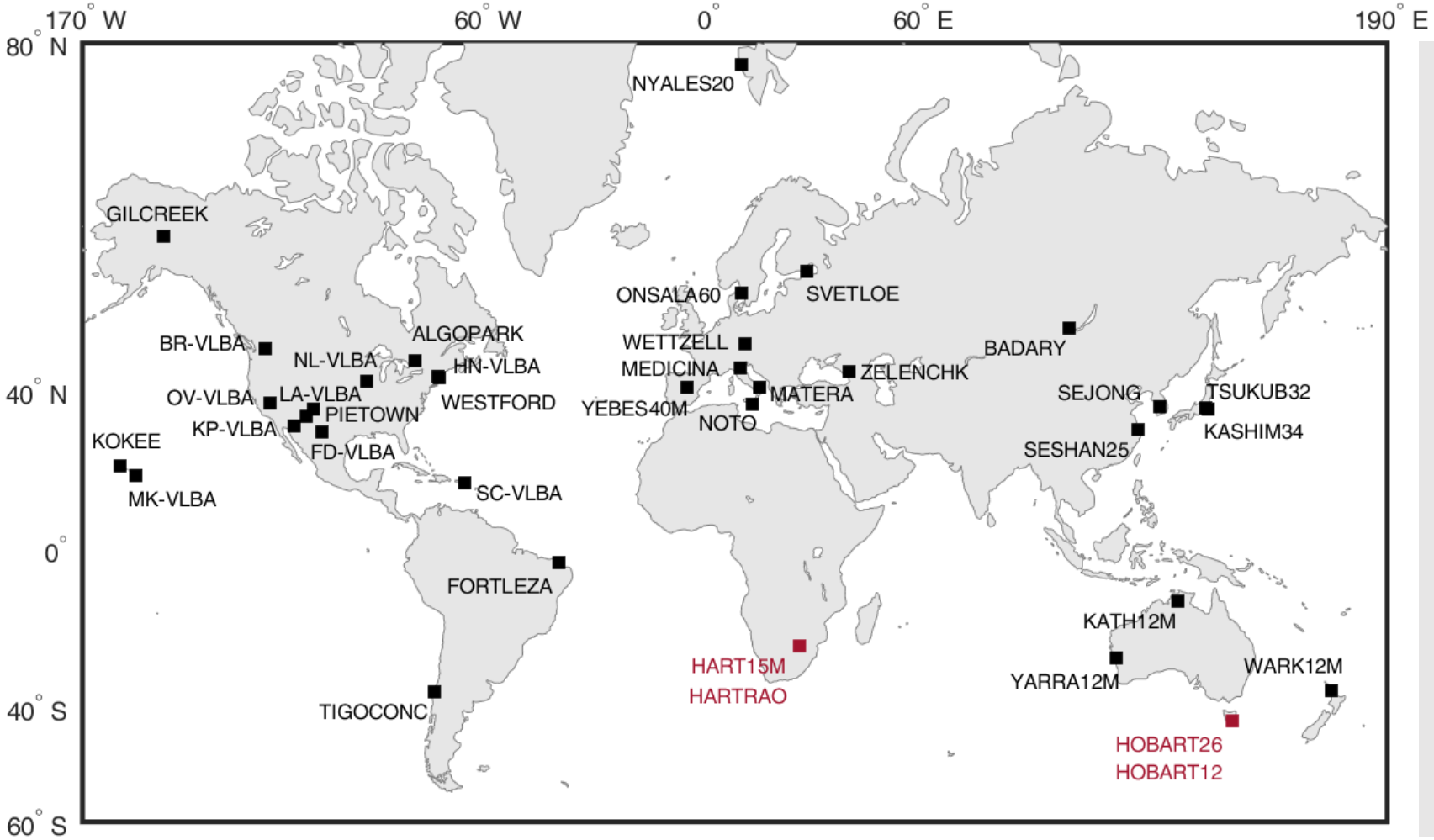
- Slant troposphere delays were reduced from the observations a priori to the adjustment (Ref: Saastamoinen 1972, 1973; Landskron and Böhm 2017; Chen and Herring 1997; Davis et al. 1985, 1993. N.B.: ZWD and gradients had been estimated from a previous analysis of all daily sessions in which the **daily positions of the stations** were estimated with the datum constraints of NNT/NNR w.r.t. ITRF2014.
- EOP were formed based on IERS Conventions 2010 (Petit and Luzum 2010; Bizouard et al. 2019; Desai and Sibois 2016).
- Positions of the stations were reduced to due several geodynamic effects (Petit and Luzum 2010; Carrère et al. 2012, 2016; Wijaya et al., 2013; after the adjustment the non-tidal ocean loading displacements were corrected, http://massloading.net/nto).
- Ocean tide (FES2014b, Carrère et al. 2012, 2016) loading displacements (http://holt.oso.chalmers.se/loading) were introduced to the a priori positions of all stations **except the one station of which coordinates will be estimated as piecewise linear offsets (PLO) at 2 hour intervals**.

**least squares**

- Gauss Markov least-squares method for the parameter estimation was used (VieVS, Böhm et al. 2018).
- The coordinates of the sources were fixed to ICRF2 (Fey et al. 2015).
- Clock errors were estimated as one rate and quadratic term plus PLO at 20 minutes intervals w.r.t. a fixed clock.
- EOP were estimated as one offset for each daily session w.r.t. the a priori values mentioned above.
- The coordinates of the stations were fixed to ITRF2014 (Altamimi et al. 2016), **except the one station of which a priori coordinates have not been corrected due to the OTLD, were estimated as PLO with 2 hour intervals, exactly at the UTC integer hours i.e. 0 UT, 2 UT, …, 22 UT**.

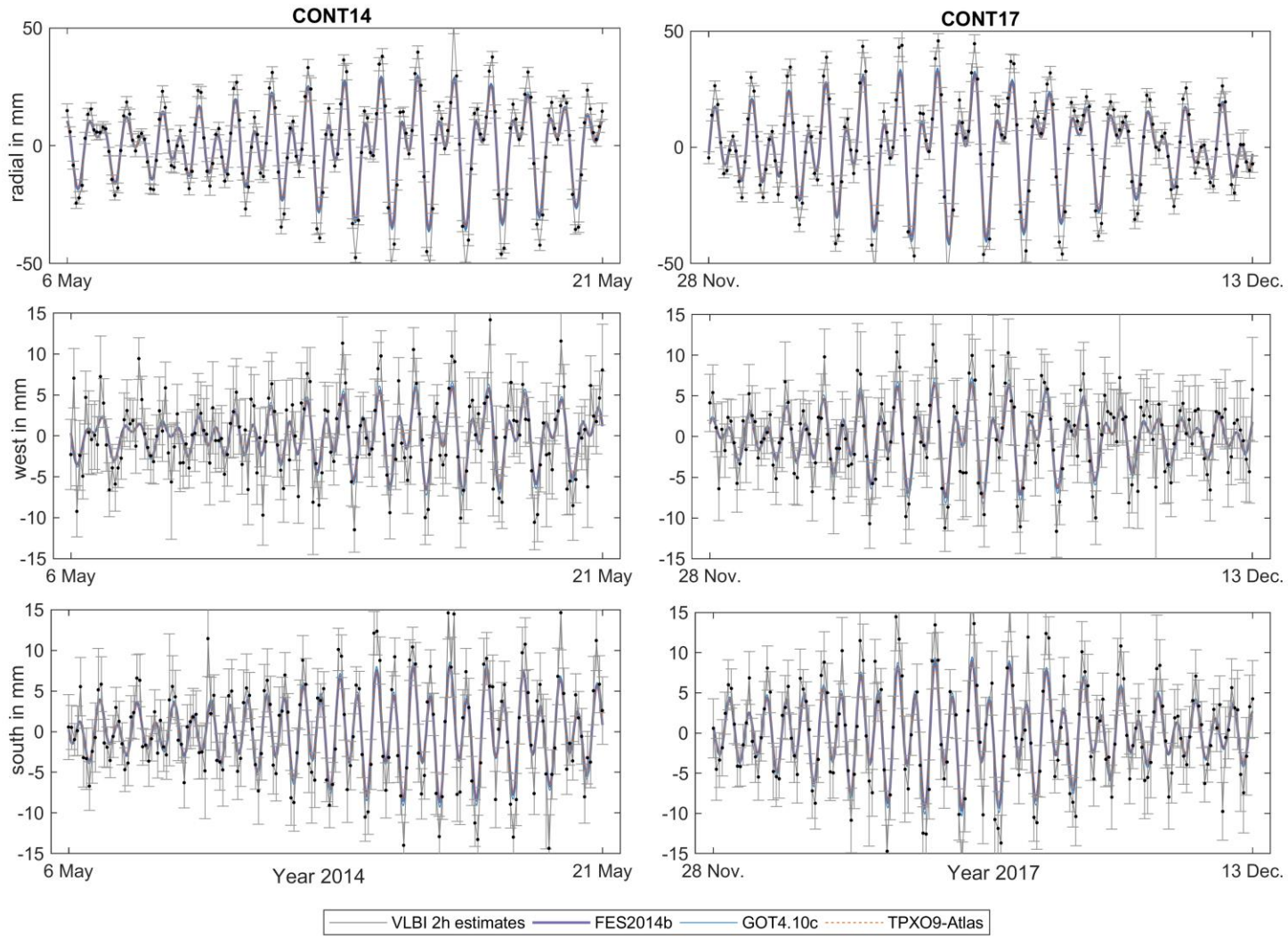
The analysis was repeated 37 times, for each station, over all daily sessions from 1984 to 2020.

# VLBI stations




- 5458 daily sessions, observed from 1984 to 2020 were analyzed.
- The sessions in which at least 4 stations observed were considered.
- 19 VLBI stations out of 37 are assumed as inland stations and 18 stations as coastal.
- All considered stations participated in at least 180 daily sessions. This criteria is to resolve the nearest $S_2$ (period: 12h) and $K_2$ (11.967236h) tides based on the Rayleigh criteria (Foreman 1977) defining the theoretical minimum period of data needed to separate the two neighboring spectral lines.

# OTLD as 2 hourly PLO coordinates of the stations




The 2 hourly ocean tide loading displacement estimates at *Kokee* over 15 days long CONT14 and CONT17 continuous VLBI campaigns are shown as the black dots with their formal errors in grey.

**<u>Accounting for the effect of the nodal modulation of the principle tides with the one rotation of the lunar node about the ecliptic plane in 18.6 years.</u>**
Loading tide spectra with 342 tidal constituents were derived through spline interpolation of the R and I of the principle tides when calculating the OTLD from harmonic coefficients (Matlab functions converted from “hardisp.f”, Petit and Luzum 2010).

# The amplitudes and the Greenwich phase-lags

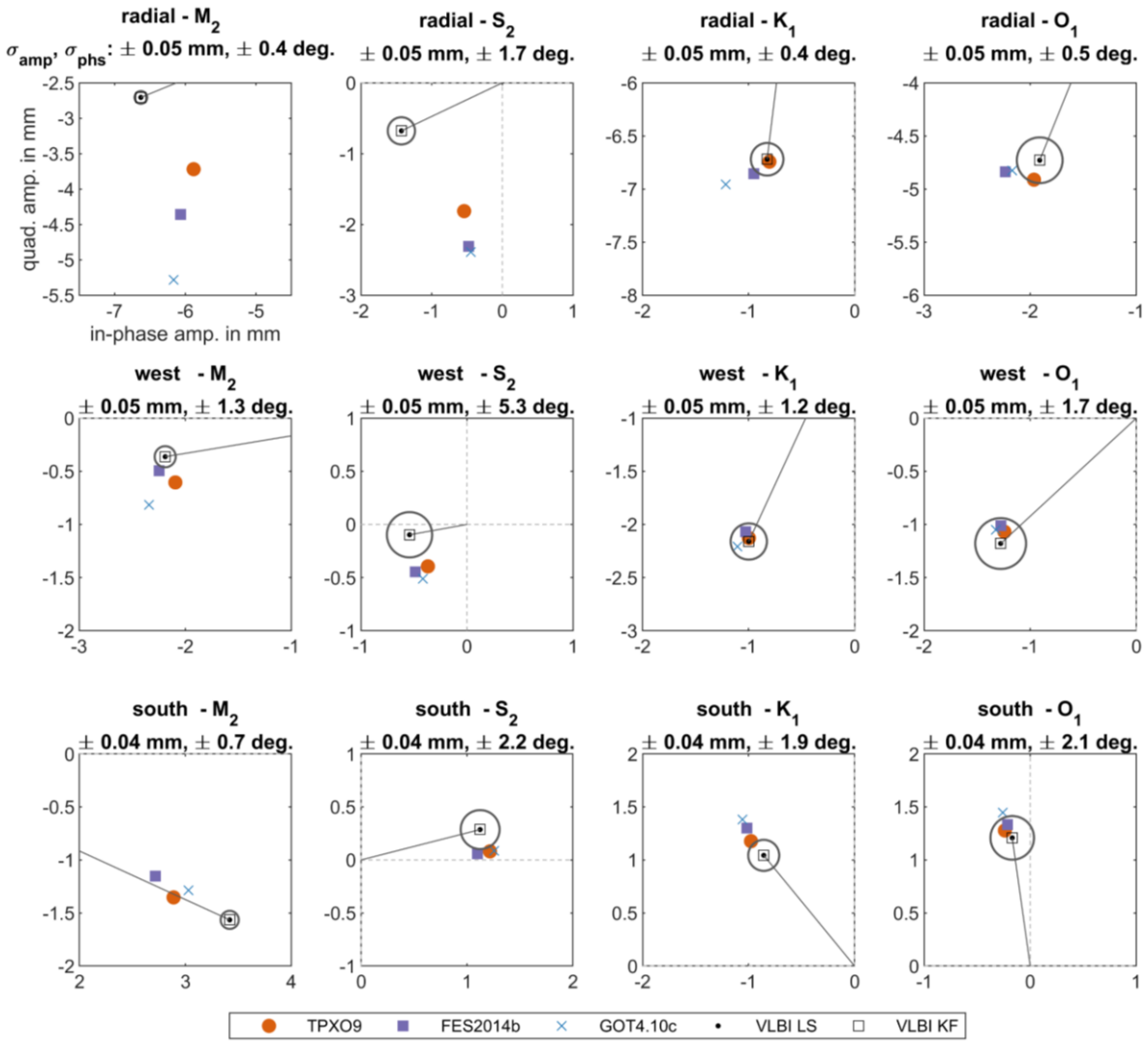
- The amplitudes and the phase-lags of the principal semidiurnal ($M_2$, $S_2$, $N_2$, $K_2$) and the diurnal tides ($K_1$, $O_1$, $P_1$, $Q_1$) were estimated at all VLBI stations in radial, west, and south coordinate components using a basic Kalman filter.
- The 2-hourly unevenly spaced OTLD as PLO coordinates estimated from the VLBI daily sessions were handled as observations. The weights of the observations were calculated from the formal errors of the PLO coordinates.
- The long-period tidal displacements, i.e. $M_f$, $M_m$, and $S_{sa}$ were reduced from the VLBI OTLD (Δ) a priori to the estimation.

Linearized form of the harmonic function with the unknown parameters: in-phase and quadrature parts of the tidal constituents

$$\Delta_{s,k} = \sum_j A_{s,k}^j \cos(\chi_j(t) - \varphi_{s,k}^j) \quad \Rightarrow \quad \Delta_{s,k} = \sum_j R_{s,k}^j \cos\chi_j(t) + I_{s,k}^j \sin\chi_j(t)$$

$$A_{s,k}^j = \sqrt{\left(R_{s,k}^j\right)^2 + \left(I_{s,k}^j\right)^2} \qquad \varphi_{s,k}^j = \arctan\left(\frac{I_{s,k}^j}{R_{s,k}^j}\right)$$

# Phasors

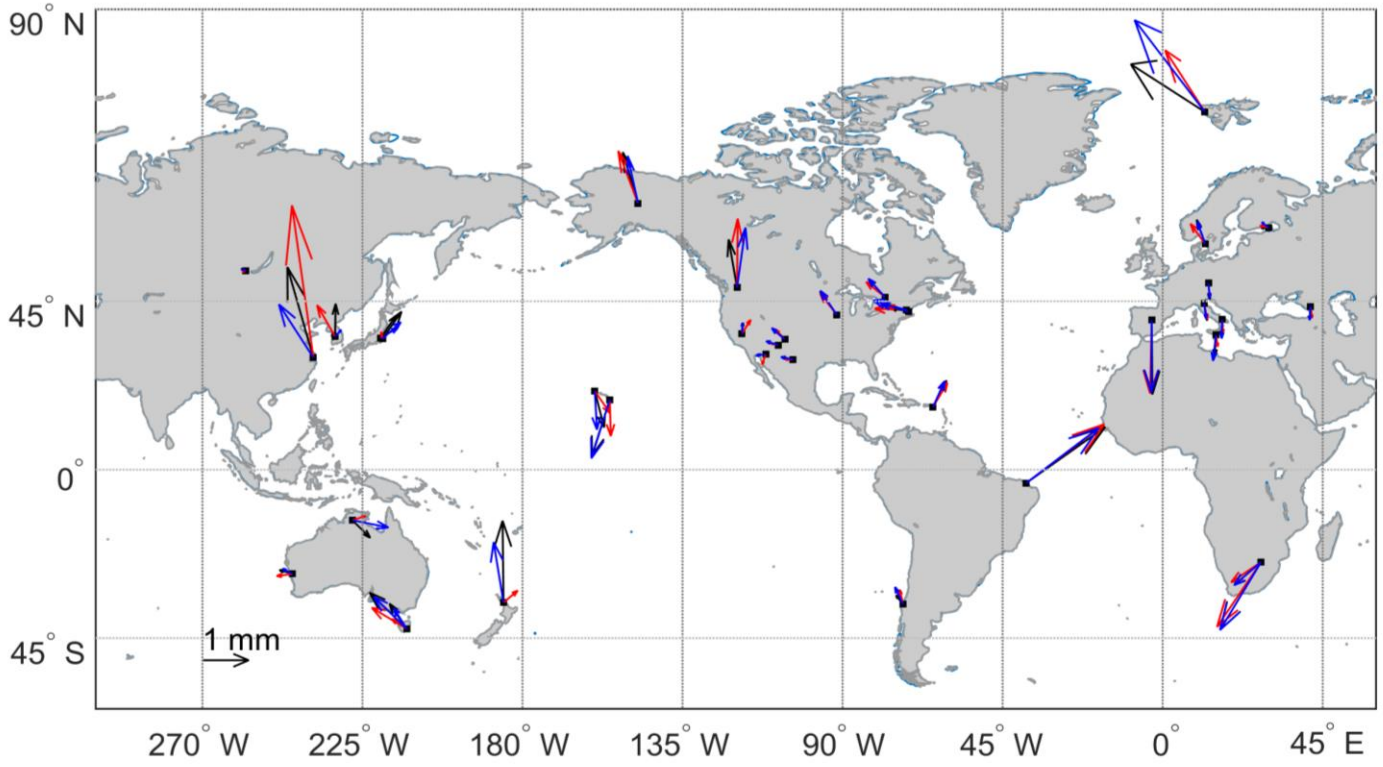



- $M_2$, $S_2$, $K_1$ and $O_1$ tides with the one sigma error ellipses at Seshan VLBI site.
- At both *Sejong* (South Korea) and *Seshan* (Shangai, China), large differences are detected in the amplitudes of the phasor vectors of the $M_2$, $S_2$, $K_1$, $K_2$, and $O_1$ tides for all coordinate components, not only between the VLBI OTLD model and the GOTM (FES2014b, GOT4.10c, and TPXO9-Atlas) but also among the GOTM.

# Phasor vector differences

$M_2$ tide radial phasor vector differences (***d***) between the VLBI OTLD model and the GOTM i.e. FES2014b, GOT4.10c, and TPXO9 are shown as black, red, and blue vectors, respectively.

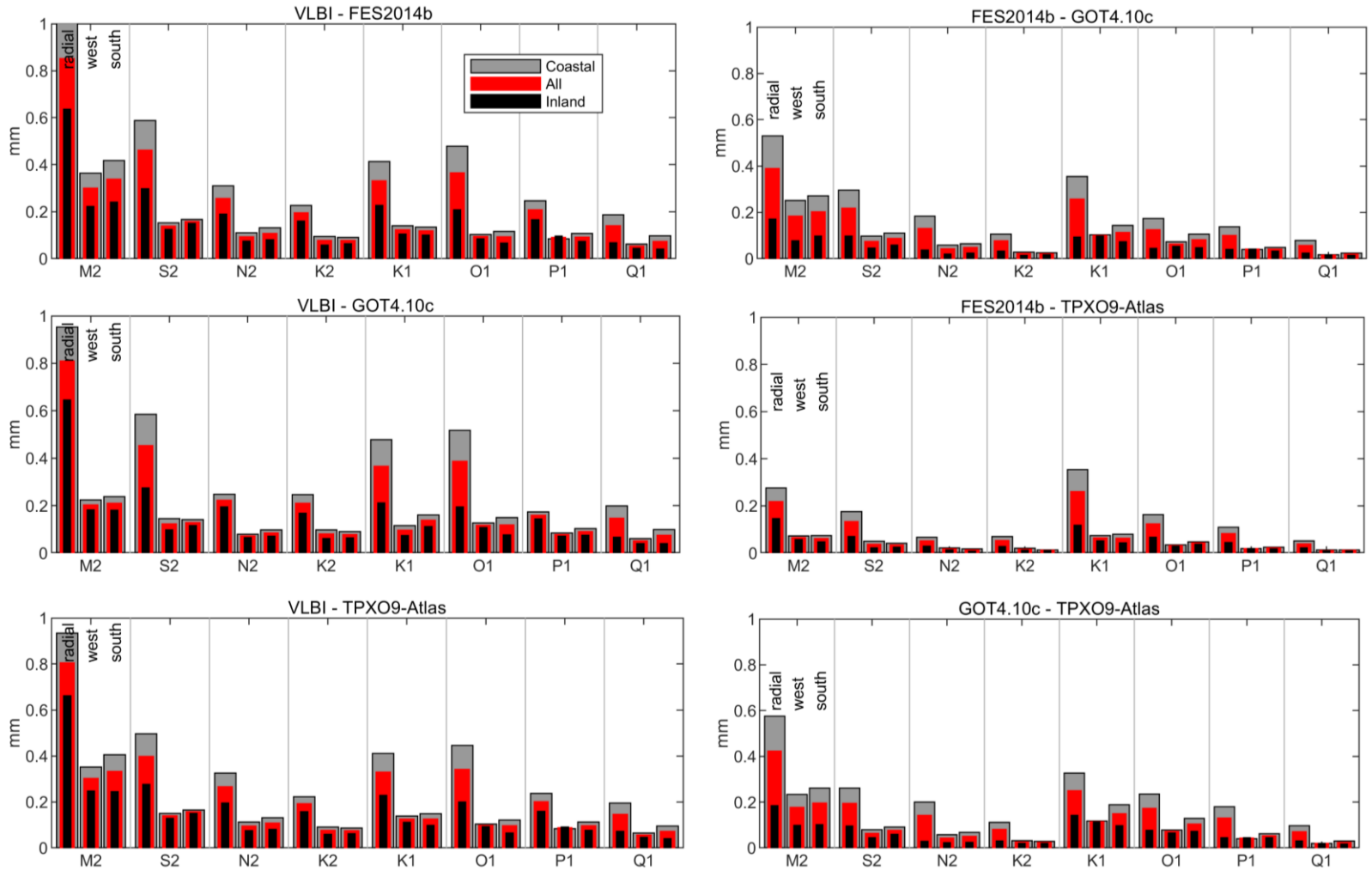
$$d_{s,k}^{j} = A_{VLBI}(\cos\varphi_{VLBI} + i\sin\varphi_{VLBI})_{s,k}^{j} - A_{MODEL}(\cos\varphi_{MODEL} + i\sin\varphi_{MODEL})_{s,k}^{j}$$




- The lunar only $M_2$ tide radial phasor vector differences between the VLBI OTLD model and the GOTM are found as the largest among all the principal tides, the VLBI sites, and the coordinate components.

- For instance, the $M_2$ tide radial phasor vector differences between VLBI OTLD model and GOTM are found larger than 1 mm at the sites: *Seshan*, *Ny-Ålesund*, *Fortaleza*, and *Warkworth*.

# RMS of the phasor differences over all stations

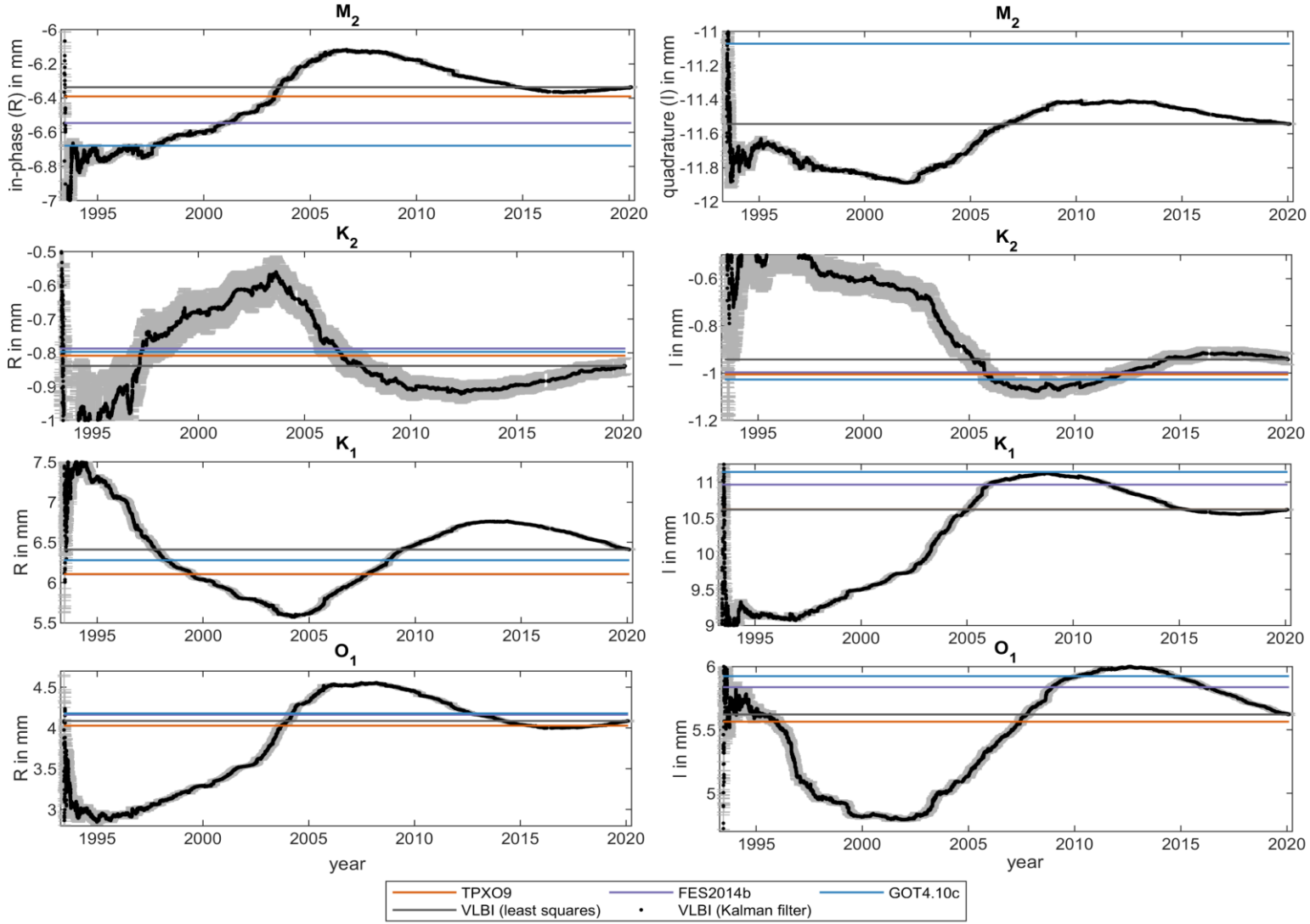



RMS misfits of the principal semidiurnal and diurnal phasor vector differences of the ocean tide loading displacements between the GOTM and the VLBI OTLD model over coastal (18 stations), inland (19 stations) and all stations.

$$RMS_k^j = \sqrt{\frac{1}{s}\sum_{s=1}^{S}\left|d_{s,k}^j\right|^2}$$

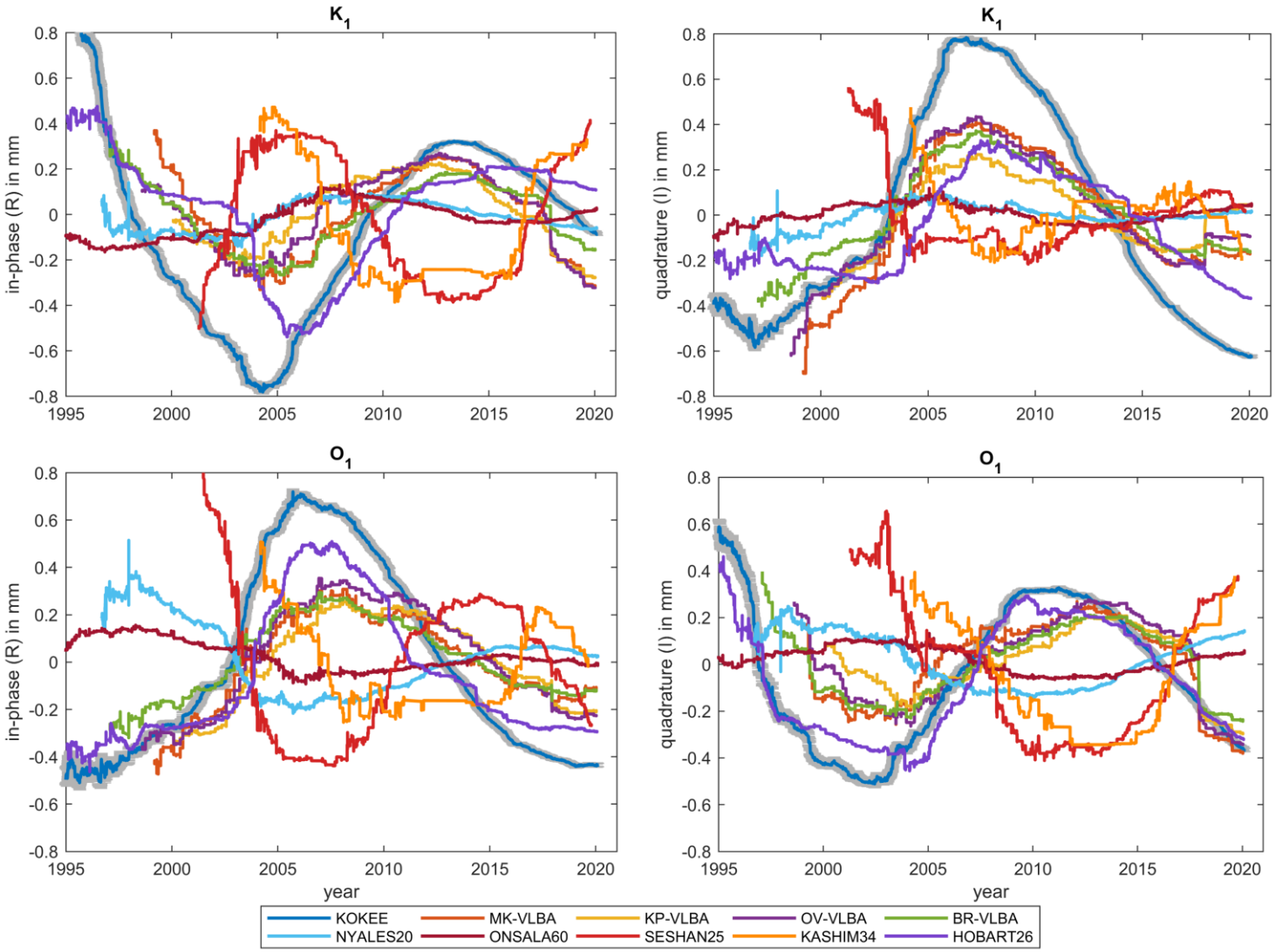
- The phasor vectors RMS misfits between the VLBI OTLD model and the GOTM are largest for the radial components over the coastal sites at the tides:
  - $M_2$ (within 0.9 mm – 1.0 mm)
  - $O_1$ (0.4 mm – 0.5 mm)
  - $S_2$ (0.5 mm – 0.6 mm),
  - $K_1$ (0.4 mm – 0.5 mm).

# The long-term variations of the $M_2$, $K_2$, $K_1$ and $O_1$ tides




The in-phase and quadrature parts of ocean tide loading radial displacements of the $M_2$, $K_2$, $O_1$, and $K_1$ tides at the *Kokee* site.

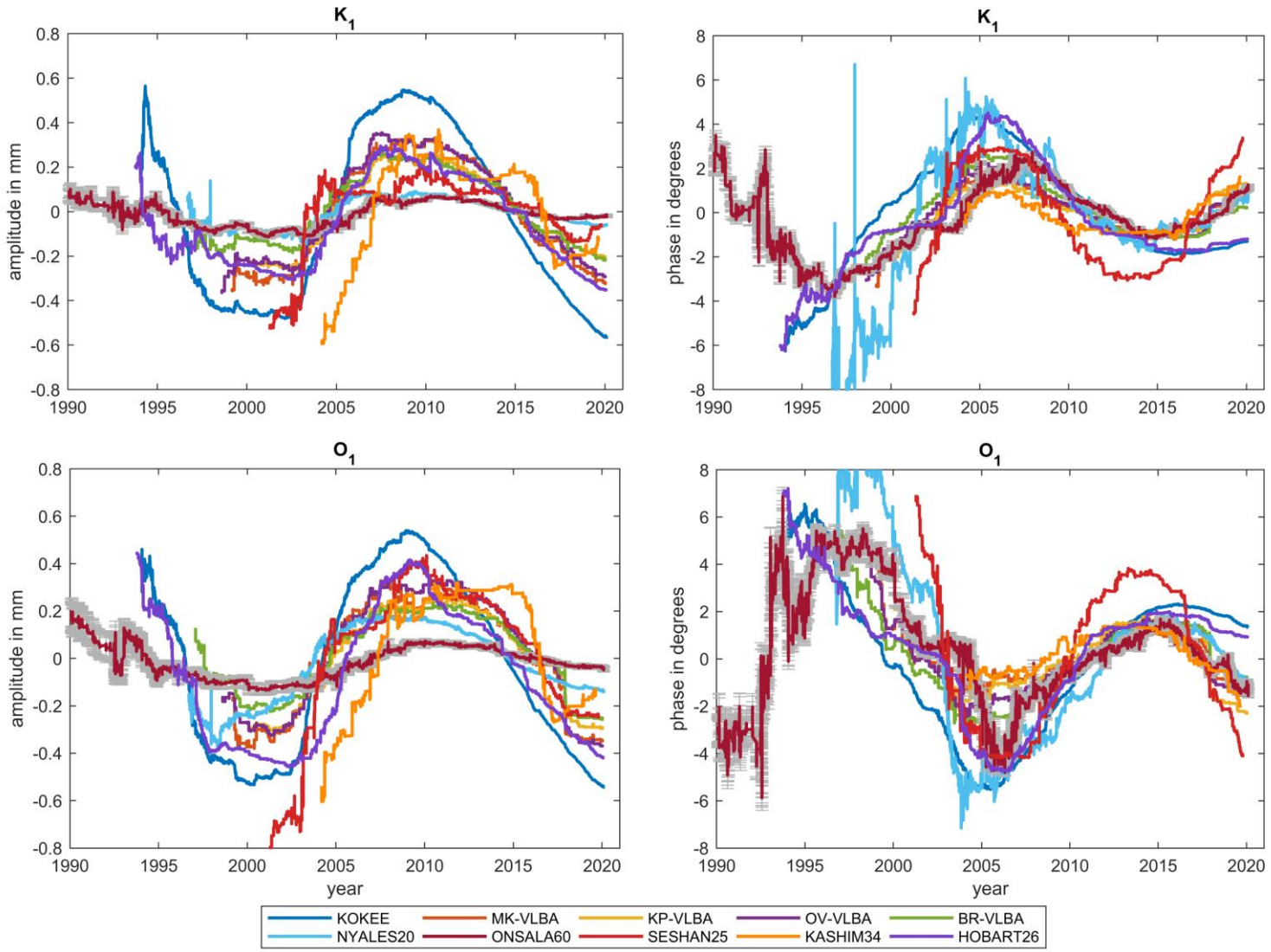
# The long-term variations of the $K_1$ and $O_1$ tides




The long-term variations of the in-phase (R) and quadrature (I) parts of the radial $K_1$ and $O_1$ tides, located at the

- Hawaii Islands: *Kokee and Mk-vlba*,
- the northeast pacific coasts: *Kp-vlba, Ov-vlba, and Br-vlba*,
- the northwest pacific coasts: *Kashim34* and *Seshan25*,
- the arctic circle: *Nyales20*,
- the north of Europe: *Onsala60,* and
- the southernmost point of this study: *Hobart26*.

# The long-term variations of the $K_1$ and $O_1$ tides




The long-term variations of the amplitudes and Greenwich phase-lags of the radial $K_1$ and $O_1$ tides, calculated from the values (R and I) of the previous slide.

# Conclusions

- The lunar only $M_2$ tide radial phasor vector differences between the VLBI OTLD model and the GOTM i.e. TPXO9-Atlas (Egbert and Erofeeva 2002), FES2014b (Carrère et al. 2012, 2016), and GOT4.10c (Ray 2013) are revealed as the largest among all the principal tides, the VLBI sites, and the coordinate components.
- The phasor vectors RMS misfits between the VLBI OTLD model and the GOTM are found as the largest for the radial components over the coastal sites at the $M_2$ (0.9 mm – 1.0 mm), $O_1$ (0.4 mm – 0.5 mm), $S_2$ (0.5 mm – 0.6 mm), and $K_1$ tide (0.4 mm – 0.5 mm).
- One of the main findings of this study is the long-term variations of the semidiurnal and diurnal tidal coefficients, i.e. the variations in the amplitudes and phase-lags, as detected from the recursive solutions of the Kalman filter.
- The $K_1$ and $O_1$ amplitudes and phase-lags vary for all stations up to about 1.2 mm and 12 degrees over about 30 years.
- The long-term variations in the principal semi-diurnal and diurnal tides of the OTLD, so the ocean tides, might be influenced by the mean sea level rise or falls. For instance, several studies (e.g. Munk et al. 1965, Devlin et al. 2017, Haigh et al. 2019) infer that among several coupled ocean dynamics (e.g. spatio-temporal changes of the ocean density, water temperature, stratification, internal tides, amphidromic points, ocean depth, tidal energy propagation and dissipation), there is also a nonlinear interaction of the long-term fluctuations of the mean sea level with the ocean tides.

# Thank you very much for your attention.