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Reduction of temporal variations in tidal parameters by application of the local response models at globally distributed SG stations

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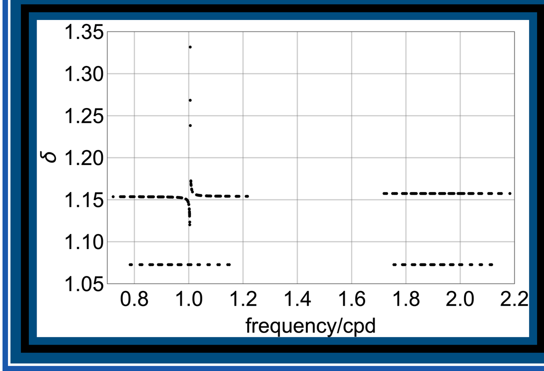
1. Introduction: Tidal Analysis

Tidal forcing - known from astronomy - is decomposed into a set of harmonics at different frequencies. The gravimetric factor δ and phase Φ describe Earth's response to this forcing. They are found by comparing observed and predicted gravity signals in a least-squares fit.

$$E^2 = \left[g^{obs}(t) - g^{syn}(t, \delta_l, \Phi_l)\right]^2 \qquad (1)$$

The inverse problem is usually solved by tidal software `Eterna 3.40` or `Baytap08`. The approximate tidal response can be independently derived from seismological Earth models that account for elasticity.

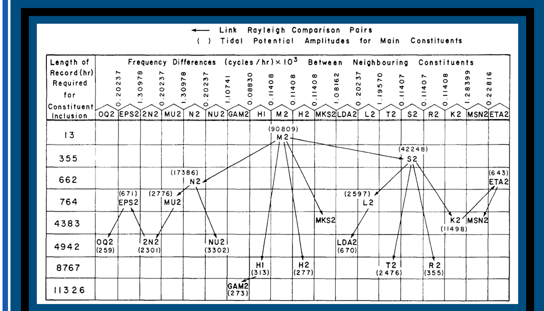


In tidal analysis, the Earth model is assumed a priori, of which the Wahr-Dehant-Zschau Dehant et al. (1999) model is the most common choice. **In fact, tidal analysis seeks adjustments to this model.**

Figure 1: Wahr-Dehant-Zschau visco-elastic tidal response model computed for BFO, Schiltach.

2. Context: Wave Grouping Bias

Since there are thousands of tidal harmonics at a large dynamic scale, it is impossible to obtain meaningful results for each one.



Hence, to be able to determine gravimetric parameters at all, Venedikov (1962) and Chojnicki (1973) introduced the concept of wave groups that are sums of assumed inseparable harmonics.

Figure 2: Suggested wave grouping scheme that depends on the time series length. Adapted from Foreman & Henry (1989).

Up to now, wave grouping is a standard procedure in tidal analysis (only Ciesielski et al. (2023) recently proposed another approach). Therefore, the predicted gravity signal has a form:

$$g^{syn}(t, \delta_l, \Phi_l) = \sum_{j=1}^{J}\left(\delta_j \sum_{l=J_j}^{J_{j+1}-1} \delta_l^{\mathrm{WDZe}} A_l \cos(2\pi f_l t + \Phi_j)\right) \qquad (2)$$

The index j sums over J groups, and each harmonic at frequency f_l has an astronomical amplitude A_l. Terms δ_j and Φ_j describe common factors to the group, regardless of the factors that harmonics constituting the group have. The ratios of parameters by the a priori Earth tidal model, δ_l^{WDZe} are taken into account (e.g., `Eterna 3.40`). **This still leads to a bias if apparent ratios strongly differ from the model assumed by δ_l^{WDZe}, which turned out to be the case**.

3. Method: Moving Window Analysis (MWA)

Tidal analysis performs a least-squares regression on data fitted to wave groups, not single harmonics. However, the solution to the problem is less stable when less data is used, given a constant number of groups. Therefore, in order to investigate shorter periods of data, the number of groups decreases (as seen in panel 2; figure 2). Hence, coarse groups contain more harmonics for shorter periods. **Consequent analysis of overlapping periods with the same grouping scheme is called Moving Window Analysis (MWA).**

4. Problem: Temporal Variations

The application of MWA on gravity records led to **the discovery of significant parameter variations of unknown origin**, which was first reported by Dittfeld (1991) and later investigated by Calvo et al. (2014), Meurers et al. (2016), and Schroth et al. (2018). Since **tidal parameters should not vary**, such observations might indicate changes in global water or glacier distributions, instrumental problems, etc.

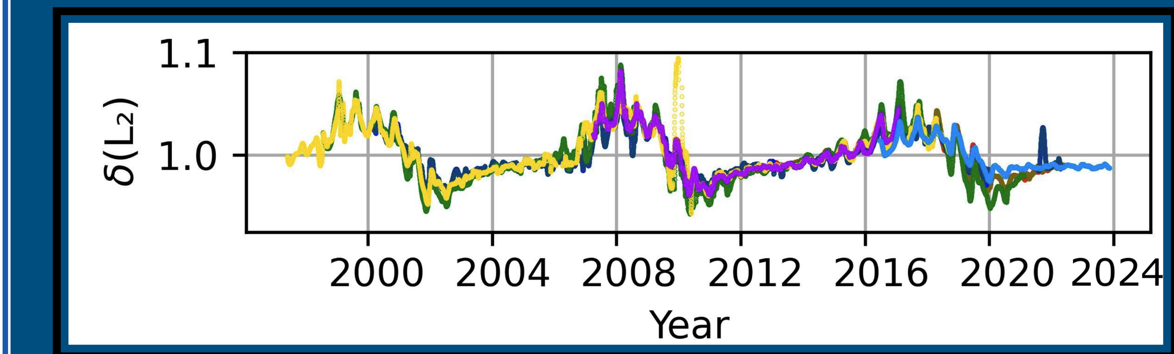


Figure 3: Results of MWA for the gravimetric factor of group L_2 for 10 European stations. It is a combined result of thousands of consecutive analyses of 3-month overlapping windows over 30 years for one of the 12 discriminated groups. The factor δ is normalized to 1.

5. Solution: Local Response Model

The apparent Earth response to tides is significantly more complex than assumed in the theoretical model - the model used in analysis prior to grouping. **Since the mismatch** - caused by different ocean and radiation loads - is not taken into account before grouping, **this bias produces significant observed temporal variations in MWA**. Hence, this effect should be somehow mitigated in the analysis. **By applying the correction for local response, each gravity contribution is properly treated** in terms of amplitude and phase prior to summing up as a common group:

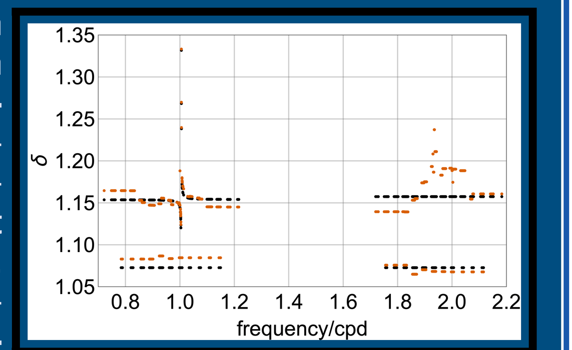


Figure 4: The local response model for BFO, Schiltach (orange dots) and the Wahr-Dehant-Zschau elastic Earth model (black dots).

$$g^{syn}(t, \delta_l, \Phi_l) = \sum_{j=1}^{J}\left(\delta_j \sum_{l=J_j}^{J_{j+1}-1} \delta_l^{\mathrm{WDZe}} \delta_l^{\mathrm{LRM}} A_l \cos(2\pi f_l t + \Phi_j + \Phi_l^{\mathrm{LRM}})\right) \qquad (3)$$

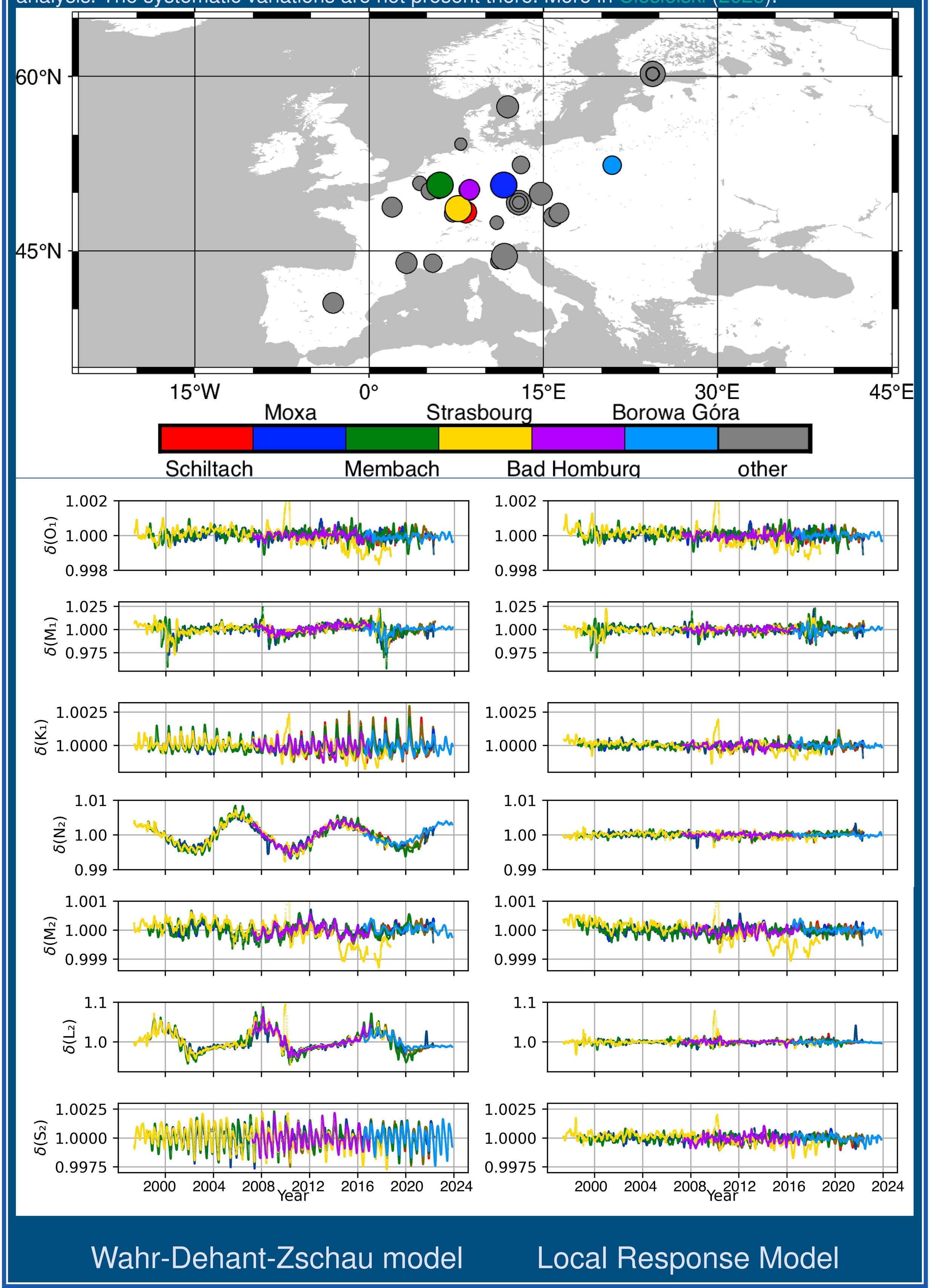
Apart from the general Earth model δ_l^{WDZe}, we apply the inferred local tidal model, i. e. δ^{LRM} and Φ^{LRM}. It takes into account time-invariant local effects. In MWA results we display normalized parameters $\tilde{\delta}_j = \frac{\delta_j}{\delta_l^{\mathrm{WDZe}}\delta_j^{\mathrm{LRM}}}$ that are expected to be around 1 and $\tilde{\Phi}_j = \Phi_j + \Phi_j^{\mathrm{LRM}} \approx 0$. The local response models should be as detailed as possible. **For this purpose, tidal analysis of the many-years-long time series was performed with the new software,** `RATA` (Ciesielski et al., 2023; Ciesielski, 2023), on various stations. By means of regularization, this approach allowed us to resolve more contributions with reliable estimates than previous methods. The approach was first demonstrated in Ciesielski et al. (2023) on gravity recordings from Black Forest Observatory (Schiltach).

6. Data: Superconducting Gravimeters

The IGETS database provides gravity data recorded by superconducting gravimeters (SGs) from observatories associated with the Global Geodynamics Project (GGP). We used Level-2 data (corrected for local effects) and locally recorded air pressure. The data were pre-processed by EOST (Boy, 2019). **The stations used for display are marked on maps (panels 7 and 8).**

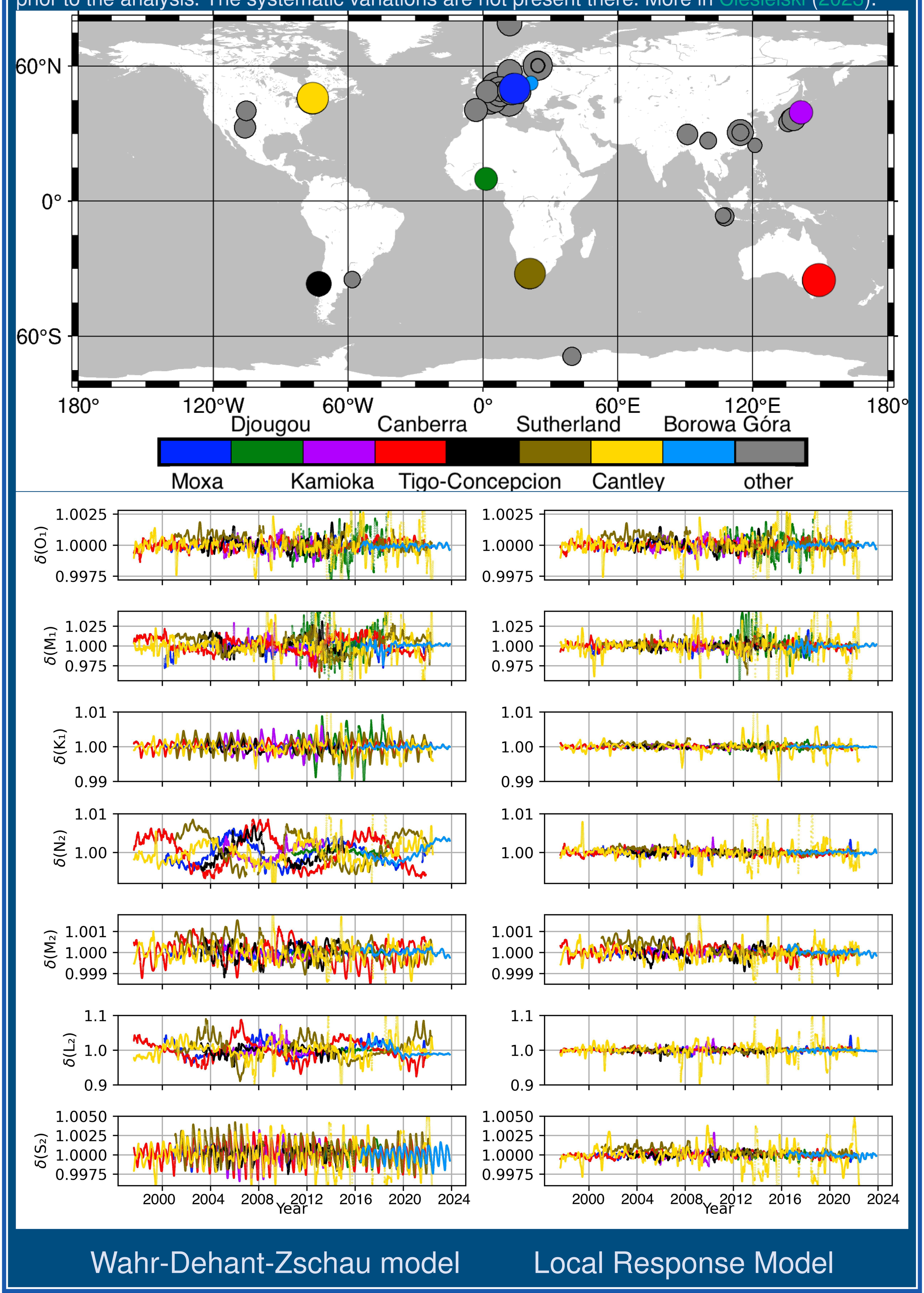
7. Results: European Stations

Figure 5: European SG stations selected for display (top) and corresponding MWA results (bottom). Left panels: MWA with the standard, biased technique that does not include local effects. Right panels: MWA for the same factors, but with the Local Response Model adjustment applied prior to the analysis. The systematic variations are not present there. More in Ciesielski (2023).



8. Results: Global Stations

Figure 6: SG stations distributed globally selected for display (top) and corresponding MWA results (bottom). Left panels: MWA with the standard, biased technique that does not include local effects. Right panels: MWA for the same factors, but with the Local Response Model adjustment applied prior to the analysis. The systematic variations are not present there. More in Ciesielski (2023).



9. Conclusions

- **Local Models capture systematic effects in all stations**
- **Local Models should be applied prior to MWA for studying parameter variations**
- **Wrong ratios between significant harmonics assumed a priori in groups are the main cause of systematic parameter variations**
- **Amplitudes of variations are reduced by up to a factor of seven**
- **Too coarse group resolution, time-varying ocean loading, improper data processing, and unstable instruments are minor effects**
- **The remaining stochastic variations are due to varying ocean and noise**

10. References

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