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Application of time-variable process noise in terrestrial reference frames determined from VLBI data

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Abstract

In recent years, Kalman filtering has emerged as a suitable technique to determine terrestrial reference frames (TRFs), a prime example being JTRF2014. The time series approach allows variations of station coordinates that are neither reduced by observational corrections nor considered in the functional model to be taken into account. These variations are primarily due to non-tidal geophysical loading effects that are not reduced according to the current IERS Conventions (2010). It is standard practice that the process noise models applied in Kalman filter TRF solutions are derived from time series of loading displacements and account for station dependent differences. So far, it has been assumed that the parameters of these process noise models are constant over time. However, due to the presence of seasonal and irregular variations, this assumption does not truly reflect reality. In this study, we derive a station coordinate process noise model allowing for such temporal variations. This process noise model and one that is a parameterized version of the former are applied in the computation of TRF solutions based on very long baseline interferometry data. In comparison with a solution based on a constant process noise model, we find that the station coordinates are affected at the millimeter level.

Keywords: Terrestrial reference frames; VLBI; Kalman filter; Non-tidal loading; Process noise

1. Introduction

Kalman filtering has become an established approach for the determination of terrestrial reference frames (TRFs). Recently, JTRF2014 (Abbondanza et al., 2017) by the International Earth Rotation and Reference Systems Service (IERS) International Terrestrial Reference System (ITRS) Combination Center at Jet Propulsion Laboratory (JPL) has been released as a candidate solution for the International Terrestrial Reference Frame (ITRF). JTRF2014 was computed using the software KALREF (Wu et al., 2015), based on Kalman filter and smoother algorithms. The time series nature of the solution allows irregular and short-term variations in the station coordinates of the space-geodetic techniques to be taken into account and has been shown to reliably represent non-tidal station loading and geocenter motion (Zelensky et al., 2018). Coordinate predictions can be calculated by extrapolating the functional model, which includes linear and seasonal terms in the case of the JTRF2014.

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In Kalman filter TRF solutions like the JTRF2014, certain amounts of process noise are applied, controlling the magnitude of the temporal coordinate variations of the individual stations. The process noise model, which comprises the process noise values for the different parameters estimated in the filter, is conventionally derived from three-dimensional time series of geophysical non-tidal loading displacements, with station-dependent differences taken into account. Soja et al. (2016) additionally scaled the process noise values for certain stations during times of severe post-seismic deformations. Aside from earthquake-related modifications, process noise has so far always been assumed constant over time when determining TRFs.

However, the stochastic properties of geophysical loading displacements exhibit temporal variations over various time scales, which ideally should be accounted for when using these data to create a model of process noise. An improvement in the noise model should yield an increase in the accuracy of the TRF's station coordinates, which is, for example, of great interest in navigation tasks or geophysical investigations (Plag and Pearlman, 2009). Since no ground truth data is available, assessing the accuracy of station coordinates is a delicate issue (Collilieux et al., 2014). At the very least, it is worth to assess the impact of assuming constant or time-variable process noise on the resulting TRF station coordinates to give recommendations for future TRF realizations. For this reason, we derive (Section 2) and apply (Section 3) for the first time a process noise model for station coordinates that is time-dependent for every single station. We conduct our investigations based on very long baseline interferometry (VLBI) data, but the results should be in large parts transferable to other space geodetic techniques and combinations thereof.

2. Time-dependent process noise model

The process noise model utilized in Kalman filter reference frames is conventionally based on the assumption that irregular variations in the coordinates are caused by unmodeled non-tidal loading displacements. According to the IERS Conventions (2010), the non-tidal displacements due to the atmosphere (NTAL), oceans (NTOL), and hydrology (HYDL) should not be corrected in the analysis of space-geodetic techniques and are therefore the constituents of station coordinate process noise models.

2.1. Geophysical loading data

In this study, time series of NTAL, NTOL, and HYDL between 1985 and the end of 2015 as provided by Helmholtz Centre Potsdam – GFZ German Research Centre for Geosciences (Dill and Dobslaw, 2013)[1] are used to derive the process noise models. For every VLBI site (cf. Section 3.1), the sum of the three displacement time series is computed with a temporal resolution of 1 day. Additionally, trend and annual signal are removed, since they are commonly parameterized and estimated as part of the functional model unlike the random coordinate variations the process noise model aims to address. As an example, Fig. 1 shows the sum of the loading displacements for station Algonquin Park, Canada after trend and annual signals have been removed. Here, the temporal variability of the residual displacements is one of the largest among the VLBI stations. Harmonic signals at other periods than annual, such as semi-annual or to a lesser extent five-yearly, are discernible as well in the case of Algonquin Park, but removing them would not significantly affect the noise estimates, which are derived from time differences of only a few days (c.f. next section). Even removing annual signals is not required when considering such short time differences, since the process noise would only be affected at the 1 part-per-million level (as found in test solutions). If the process noise was derived based on different assumptions, the handling of long-periodic signals would be more critical.

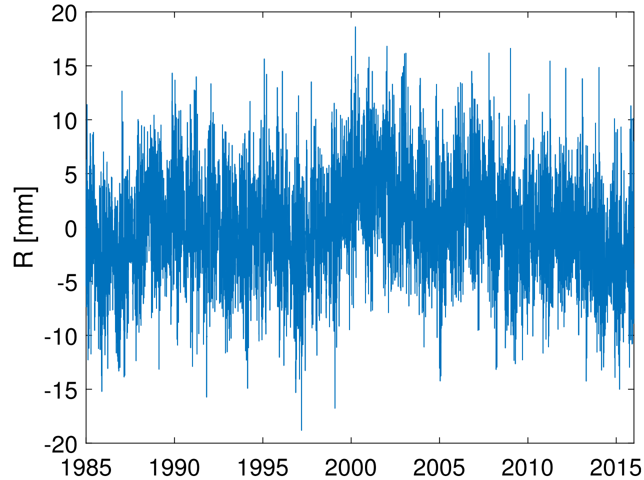

Fig. 1. Sum of the time series of non-tidal loading deformations at station Algonquin Park, radial component, with trend and annual signal removed.

2.2. Derivation of process noise models

The derivation of process noise models followed the methodology established in Soja et al. (2016). Assuming random walk (RW) processes for station coordinate variations, the Allan standard deviation (ADEV, σ_y) was used to compute the power spectral densities (PSD, Φ) of white noise driving the random walks utilized in the Kalman filter: $\Phi_{\mathrm{RW}} = \sigma_y^2(\tau) \cdot \tau$ with time differences $\tau \in \{1, 2, 3, 4\}$ days. We selected this time range since it is the typical interval between VLBI experiments used within this study and thus the state updates in the Kalman filter, and because in this time range the ADEV most closely resembles a

[1] http://www.gfz-potsdam.de/en/esmdata/loading/.

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