

3.6.3 Jet Propulsion Laboratory (JPL)

Introduction The Jet Propulsion Laboratory is developing an approach to determining ITRF-like terrestrial reference frames based upon the use of a Kalman filter/smoothen (Wu et al., 2015). Kalman filters are commonly used for estimating the parameters of some system when a stochastic model of the system is available and when the data contain noise. For the purpose of determining a terrestrial reference frame, the system consists of the positions and velocities of geodetic observing stations and associated EOPs along with their full covariance matrices. The data consist of time series of observed VLBI, SLR, GNSS, and DORIS station positions and EOPs along with the data measurement covariance matrices. In addition, measurements from ground surveys of the positions of reference marks of co-located stations are used to tie the technique-specific station networks to each other. The Kalman filter and smoother for reference frame determination software (KALREF) being developed at JPL combines these measurements to determine ITRF-like reference frames subject to constraints imposed on the allowed evolution of the station positions. KALREF includes options for constraining the stations to move linearly or to move linearly and seasonally. Through the use of stochastic models for the process noise, the station positions can be constrained to exactly follow this linear or linear and seasonal motion (by setting the process noise to zero), to exactly recover the observed station positions (by setting the process noise to a large value), or to follow a smoothed path (by setting the process noise to some intermediate value). The sequential estimation approach to determining terrestrial reference frames that is being developed at JPL has been used to determine JTRF2014, JPL's realization of a terrestrial reference frame using the ITRF2014 input data sets (Abbondanza et al., 2017). During 2016, besides continuing to analyze the JTRF2014 solution, JPL also started to both explore the possibility of accounting for regional deformation of the crust and mantle when determining TRFs and to develop a sequential estimation approach to jointly determine terrestrial and celestial reference frames (CRFs).

JTRF2014 JTRF2014 was submitted to the IERS and released to the community on March 8, 2016. Following its release, a journal article describing its determination and comparing it to ITRF2014 was prepared and has been accepted for publication by the Journal of Geophysical Research Solid Earth (Abbondanza et al., 2017). The JTRF2014 reference frame is represented by time series of the smoothed positions of the 972 GNSS, VLBI, SLR, and DORIS stations that comprise the frame. JTRF2014's origin is located at the quasi-instantaneous center-of-mass of the Earth as determined from SLR observations and its scale is a

weighted average of the quasi-instantaneous VLBI and SLR scales. The dynamic model of the station positions, used to predict the positions of the stations in the absence of observations, consists of a linear secular term and periodic terms at the annual and semi-annual frequencies. The stochastic model of the station positions consists of a random walk whose strength is given by the scatter evident in models of atmospheric, oceanic, and hydrologic loading. JTRF2014 is highly consistent with ITRF2014 with time derivatives of the Helmert transformation parameters between the two frames being at most 0.18 mm/yr and with wrms differences of the respective polar motion and polar motion rate values being at most 30 μas and 17 $\mu\text{as/day}$. JTRF2014's geocenter also agrees well with the geophysical inversion results of Wu and Heflin (2015) with differences in the amplitudes of the annual terms being only 0.5 to 0.8 mm.

Regional Deformation

Current generation terrestrial reference frames, like JTRF2014, suffer from biases introduced by the space-time sampling pattern of the input space-geodetic measurements, particularly by the gaps in the spatial distribution and temporal history of the space-geodetic observing stations. During 2016, JPL started a project to improve terrestrial reference frames by developing procedures to account for gaps in the spatial distribution and temporal history of observing stations by: (1) reconstructing the history of the deformation of the Earth's global surface from GRACE and GRACE-FO measurements and models of the processes that are causing the Earth's surface to be deformed and observing stations to be displaced, (2) using the reconstructed deformation field to construct spatial and temporal correlations of the expected station displacements, and (3) including the spatial and temporal correlations in a Kalman filter solution for an ITRF-like reference frame. By accounting for gaps in the spatial distribution and temporal history of observing stations when determining the frame, biases caused by those gaps are expected to be reduced, particularly in the geocenter and scale parameters of the frame because those parameters are determined solely from observations taken by the non-uniformly distributed SLR and VLBI stations.

During 2016, GRACE gravity data and atmospheric, oceanic, and hydrologic loading models were used to compute the correlation between the GRACE-observed or modeled load at some test point on the Earth's surface (e.g., a space-geodetic observing station) and all other grid points of the data or model. The resulting correlation maps clearly show patterns of regionally correlated deformation.

Joint Determination of Terrestrial and Celestial Reference Frames

Currently, terrestrial and celestial reference frames are determined separately from each other. This leads to inconsistencies between the frames and Earth Orientation Parameters (EOPs) that link the frames together,

consequently degrading their quality. During 2016, JPL started a project in which a joint and consistent determination of TRF/EOP/CRF will be achieved by extending the Kalman filter and smoother for reference frame (KALREF) software developed at JPL to include the processing of celestial pole offsets and source coordinates. In particular, the Kalman filter will be able to take into account proper motions of radio sources, which are not taken into account in current CRF solutions.

But before attempting a joint TRF/EOP/CRF solution, procedures must be developed to determine just the CRF using a Kalman filter/smoother. A Kalman filter and smoother to determine CRFs from VLBI-only observations has started to be developed. In previous CRF determinations, the coordinates of radio sources have always been considered to be constant. However, a number of radio sources show clear apparent proper motions. The use of a Kalman filter/smoother allows the time variability of the radio source coordinates to be taken into account via a stochastic model. In an initial test, observations of 334 radio sources spanning 1994 to 2016.5 were used to determine a CRF wherein the positions of 66 of the sources were modeled as a random walk whose strength was derived from the Allan standard deviations of the observed positions of the radio sources. The ability of the Kalman filter to track changes in the apparent positions of those sources that were modeled as a random walk was demonstrated (Soja et al., 2017).

References

- Abbondanza, C., T. M. Chin, R. S. Gross, M. B. Heflin, J. W. Parker, B. S. Soja, T. van Dam, and X. Wu (2017), JTRF2014, the JPL Kalman filter and smoother realization of the International Terrestrial Reference System, *J. Geophys. Res.*, in press, doi:10.1002/2017/JB014360.
- Soja, B., R. Gross, C. Jacobs, T. Chin, C. Abbondanza, M. Heflin, J. Parker, X. Wu, M. Karbon, T. Nilsson, R. Heinkelmann, and H. Schuh (2017), A celestial reference frame based on Kalman filtering, in *Proceedings of the 23rd Working Meeting of the European VLBI Group for Geodesy and Astrometry (EVGA)*, Gothenburg, Sweden, May 15–19, 2017.
- Wu, X., and M. B. Heflin (2015), A global assessment of accelerations in surface mass transport, *Geophys. Res. Lett.*, 42(16), 6716–6723, doi:10.1002/2015GL064941.

Wu, X., C. Abbondanza, Z. Altamimi, T. M. Chin, X. Collilieux, R. S. Gross, M. B. Heflin, Y. Jiang, and J. W. Parker (2015), KALREF—A Kalman filter and time series approach to the International Terrestrial Reference Frame realization, *J. Geophys. Res. Solid Earth*, 120(5), 3775–3802, doi:10.1002/2014JB011622.

*Richard Gross, Claudio Abbondanza, T. Mike Chin, Mike Heflin,
Jay Parker, Benedikt Soja, Xiaoping Wu*