3.6.3 Jet Propulsion Laboratory (JPL)

Introduction

The Jet Propulsion Laboratory is continuing to develop an approach to determining ITRF-like terrestrial reference frames based upon the use of a Kalman filter/smoother (Wu et al., 2015). Kalman filters are commonly used to estimate 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 2017, besides continuing to analyze the JTRF2014 solution, JPL also continued 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

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. In order to investigate the difference between the VLBI and SLR scales, a number of special solutions were determined using only VLBI and SLR data and in which the scale was fixed to the VLBI scale. In these solutions, because of the sequential estimation approach taken at JPL, a time series of the Helmert parameters mapping the VLBI scale to SLR is obtained, allowing the time-variable structure of the scale difference between VLBI and SLR to be studied. In all, six special solutions were determined in which different models for the station motion were used (linear only; linear and annual; linear, annual and semiannual) and in which the process noise was either turned on or kept off. All six solutions showed a bias between the VLBI and SLR scales, ranging between 5.6 mm and 9.0 mm at 2010, and a rate difference ranging between 0.08 mm/yr and 0.25 mm/yr. The VLBI baselines were found to be larger (on average) than SLR's.

The process noise used to determine JTRF2014 was estimated from atmospheric, oceanic, and hydrologic loading models. While the process noise used in JTRF2014 varied spatially, being different at different observing stations, it did not vary with time. The effect on the TRF of time variations in the process noise was studied using just VLBI data (Soja et al., 2018a). Time-independent process noise was estimated from the entire history of the modeled load at each station; time-dependent process noise was estimated from monthly values of the modeled load. The coordinates of individual stations were found to differ by as much as 1 cm between the solutions with time-dependent and time-independent process noise; nearly 1/3 of the stations had vertical coordinates that differed by more than 1 mm. However, when averaged over the entire history of the observations, the cyclic effect of the time-dependent process noise on the station coordinates averaged out, resulting in wrms differences at just the 0.01 mm level between the time-dependent and time-independent solutions.

Besides studying the effect on the TRF of time-dependent process noise, the effect of the level of process noise was also studied during 2017, again using just VLBI data and focusing on the predictions (Soja et al., 2018b). Predictions were computed from the TRF solutions by extrapolating the deterministic part of the station motion model. VLBI data spanning 1980 to 2016.5 were used with the TRFs being determined from the data spanning 1980 to the end of 2013. Predictions from these solutions for 2014-2016.5 were then compared to the 2014–2016.5 observations in order to evaluate the accuracy of the predictions. Not surprisingly, it was found that the accuracy of the predictions significantly depended on the level of the process noise. While larger values of the process noise allowed the smoothed station coordinates to better fit the observed positions, the predictions were found to be worse. On the other hand, lower levels of process noise improved the accuracy of the predictions, making them more similar to the predictions from a solution determined without any process noise.

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 2017, JPL continued its efforts 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 measurements and geophysical fluid 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 2017, 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. After removing linear trends as well as annual and semiannual periodic terms from each data set, the spatial correlation patterns from these data sets generally agreed with each other on regional (sub-continental) scales, but major disagreements were seen on larger (inter-continental) scales. A regional filter on the correlation maps was therefore applied in order to extract only the continental-scale spatial patterns common in all the data sets. Trial reference frame solutions using the continental-scale correlations were determined with the geocenter and scale parameters of the solutions being found to exhibit improved stability.

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 the Earth Orientation Parameters (EOPs) that link them together, consequently degrading their quality. During 2017, JPL continued its efforts to improve terrestrial reference frames by continuing to develop the capability to jointly and consistently determine the TRF with the CRF and EOPs. To do this, KALREF is being extended to include the processing of celestial pole offsets and source coordinates. This will allow the proper motions of radio sources, which are not accounted for in current CRF solutions, to be taken into account.

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 been 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).

However, because determining a CRF with a Kalman filter is compute intensive, and since many radio sources exhibit no variability, a two-step approach to determining CRFs was explored. In the first step, a conventional CRF is determined by least-squares in which the source positions are assumed to be constant in time. In the second step, the observed residuals are Kalman filtered to determine time-variable corrections to the constant source CRF. The two-step approach was found to take less computer time and to yield CRFs comparable to those determined by using just the Kalman filter to determine the CRFs.

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., 122, 8474-8510, 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.

Soja, B., R. S. Gross, C. Abbondanza, T. M. Chin, M. B. Heflin, J. W. Parker, X. Wu, K. Balidakis, T. Nilsson, S. Glaser, M. Karbon, R. Heinkelmann, and H. Schuh (2018a), Application of time-variable process noise in terrestrial reference frames determined from VLBI data, Adv. Space Res., 61, 2418–2425, doi:10.1016/j.asr.2018.02.023.

Soja, B., R. S. Gross, C. Abbondanza, T. M. Chin, M. B. Heflin, J. W. Parker, X. Wu, T. Nilsson, S. Glaser, K. Balidakis, R. Heinkelmann, and H. Schuh (2018b), On the long-term stability of terrestrial reference frame solutions based on Kalman filtering, J. Geodesy, 92(9), 1063–1077, doi:10.1007/s00190-018-1160-0.

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