Earth Orientation Analyis from the U.S. Naval Observatory VLBI Program

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Abstract

As part of its participation in the National Earth Orientation Service (NEOS) the U.S. Naval Observatory (USNO) operates a program in Very Long Baseline Interferometry (VLBI) data acquisition and analysis to monitor changes in the orientation of the Earth on a regular basis. This report describes the VLBI observations conducted by the USNO, the methods of data reduction and analysis, and the Navy 1999-3 reference frame created for use in operational VLBI data reduction for Earth orientation. The major differences between Navy 1999-3 and the previously used 1998-10 system consist of changes in the atmospheric parameterization, and a change in the *a priori* Terrestrial Reference Frame (TRF) used from ITRF-96 to ITRF-97. This reports provides details both of recent NEOS VLBI operations, and of the Navy 1999-3 system.

1. VLBI Operations

Current NEOS operations consist of one 24-hour duration NEOS-A observing session, on Tuesday-Wednesday of each week, for Earth orientation, together with daily one hour duration "intensives" for UT1 determination. The NEOS VLBI data are correlated at the Washington Correlator, which is located at the U.S. Naval Observatory and run by the NEOS. After correlation, fringe fitting, and the removal of any remaining bandwidth synthesis delay ambiguities, data from all available multiple baseline VLBI sessions are used in a series of weighted least-squares solutions to define a USNO VLBI reference frame and to estimate the Earth orientation within that reference frame. This report provides details on the procedures and models used at the USNO in the reduction of these data.

2. The Navy 1999-3 Reference System

The current USNO VLBI practice is to define a reference system and to realize the frame anew from each (weekly) global solution. For some purposes, however, such as the reduction of the UT1 Intensive data, it is desirable to use a fixed reference frame based on a particular solution in the Navy 1999-3 system; this will be called the "reference" solution. The results from both the reference solution and the "current" (i.e., most up-to-date) solution are available on the World-Wide-Web [2], and the technical description for this system is described in [3]. All of the VLBI results described in this report are based on the reference solution, which is also the solution submitted to the IERS for the 1998 IERS Annual Report. The reference 1999-3 solution used 2,295,502 delay and rate observation pairs from 2695 observing sessions, with useful data on 652 sources from 1119 baselines and a total of 115 observing stations. The reference Navy 1999-3 solution has a Weighted Root Sum Square (wrms) delay residual scatter of 29.97 picoseconds, and a wrms phase delay rate scatter of 89.67 femtoseconds / second. The reference time adopted was January 1, 1997.

2.1. Differences Between the 1998-10 and 1999-3 Systems

The Navy 1999-3 reference system is intended for operational use by the U.S. Naval Observatory (USNO) VLBI program in the reduction of VLBI data for the determination of Earth orientation. It is in general very similar to the Navy 1998-6 system in its 1998-10 realization, which is described in the IERS Annual Report for 1997 [1]. The differences between the 1999-3 and the earlier 1998-10 system are:

- The ITRF-97 is used instead of the ITRF-96 to define the origin of the system. The system is tied to the *a priori* TRF by minimal constraints, such that there is no-net rotation, translation, rotation rate and translation rate between the *a priori* TRF and its VLBI realization. Further details on these constraints are provided below.
- The Niell Mapping Function (NMF) is used instead of the MTT mapping function.
- The constraints on the piecewise linear tropospheric gradient model were changed from 25 mm and 25 mm day^{-1} to 1.25 mm and 15.0 mm day^{-1}.

Note that the Celestial Reference Frame tie has **not** changed: both systems are tied to the International Celestial Reference Frame (ICRF) [5] through a no-net rotation constraint.

In a detailed analysis of the differences between the 1998-10 and 1999-3 systems [4], the parameterization changes are found to cause about 60-80 micro arc second (μas) scatter in the Earth Orientation Parameters (EOP), while the TRF change causes a rotation of order 200 μas and a rotation rate of as much as 40 $\mu\text{as yr}^{-1}$.

2.2. Models Used in the VLBI Reduction

The data used in the report are processed with models consistent with the *IERS Conventions*[6] to the maximum extent possible, with the CALC 8.2 software being used throughout in the data reduction process. The NMF dry tropospheric mapping function is used to relate line of sight tropospheric propagation delays to the tropospheric zenith delay, the NMF wet mapping function is used for the tropospheric zenith parameter partial, and an elevation angle lower limit of 7 degrees is used in all solutions. The IERS standard model for both horizontal and vertical deformations due to ocean tidal loading is applied, although neither atmospheric loading deformations of the ground nor thermally induced antenna deformations are modeled at present.

Unmodeled variations in the tropospheric propagation delays and the relative time offset between the station clocks are a significant source of error in geodetic VLBI. The surface pressure, temperature and relative humidity are recorded at each station and the pressure is used to estimate the variations in the hydrostatic zenith tropospheric propagation delay. Further variations in this quantity are treated by the estimation of piecewise continuous linear models directly in the least squares solutions. A new piecewise continuous linear function is introduced every 60 minutes for the zenith tropospheric propagation and every 90 minutes for the relative station clocks. In order to account for variations of atmospheric properties near each observing station, parameters of a linear gradient model for the tropospheric propagation delay are now estimated, with an East-West and North-South piecewise continuous linear gradient function being estimated for each station every 3 hours.

2.3. The Terrestrial Frame Tie

The USNO Navy 1999-3 Earth orientation reference frame is obtained directly in a solution for all terrestrial and celestial reference frame parameters, subject to minimal ties to *a priori* reference frames. This makes it possible to estimate the TRF, CRF and the Earth orientation parameters for all observing sessions simultaneously in one solution. The TRF tie is to the ITRF-97, and consists of no-net translation and rotation, together with translation rate and rotation rate constraints, to the positions and velocities of the 27 stations given in the technical description [3]. Only the horizontal components of position and velocity are used in these constraints, and the sum over each component is weighted by the corresponding diagonal element of the inverse covariance matrix. There is no constraint of any sort on the frame scale or scale rate. In general, collocated VLBI stations are used to derive independent velocity estimates. There are six collocated pairs of stations where this could not be usefully done for one of the two stations, or, in the case of Fort Ord, it was judged better to have one rate estimate. These close station pairs, also described in the technical description [3], were constrained to have the same velocities in the solution. For 26 stations, there was insufficient data to estimate a meaningful velocity, and so the data from these stations were only used to estimate the station positions, with their velocities being those given in ITRF-97. In addition, 14 stations suffered from discontinuous position shifts, either due to earthquakes or due to repair or other changes at the station, and for these stations a step-function in position was estimated together with one station velocity for the entire period of data. Further details on all of these special cases is given in [3].

2.4. The Celestial Frame Tie

The Celestial Reference Frame (CRF) is tied in rotation to the positions of 198 of the 212 defining sources of the IAU International Celestial Reference Frame (ICRF). Fourteen defining sources, as described in [3], were dropped from this constraint as they have not provided good data in recent observations. Again, the sum over each component used is weighted by the corresponding diagonal element of the inverse covariance matrix.

2.5. Details on the Changes in Atmospheric Parameterization

The Niell Mapping Function (NMF) was adopted for the first time in the Navy 1999-3 system. (The “dry” mapping function is used with the surface pressure and the Saastamoinen hydrostatic model [6] to calculate the *a priori* tropospheric delay, while the “wet” mapping function is used for the zenith delay partial.) Although this was done primarily because this mapping function is thought to produce a more reliable absolute VLBI frame scale, there is also internal evidence that the NMF is better than the MTT mapping function used previously [4].

In the Solve software used for VLBI data reduction at the USNO, the tropospheric gradients are estimated as piece-wise continuous linear functions, and both the 1998-10 and 1999-3 systems introduce a new gradient rate pair (North-South and East-West gradients) every 3 hours at each station, in order to capture the observed diurnal gradient variations. There is one constraint on the bias of each component of each station, averaged over the entire session, plus a constraint on each piece-wise linear rate parameter. The *a priori* values for these parameters are currently zero, so using any constraint will statistically bias the results towards zero. In the 1998-10 system the constraints were set to be “loose,” at 25 mm and 25 mm day^{-1}. This was found to cause problems with the VLBI data from before ~1986, which have very poor gradient determinations, and it seemed desirable to tighten these constraints. Adopting too strong a gradient constraint, however, also causes problems as most stations have a persistent bias of ~1/2 mm in the North-South gradients, due to the equatorial bulge of the troposphere, and there are also observed variations at seasonal, diurnal, and maybe other periods. The 1999-3 constraints were determined by adopting a criteria that neither the observed annual nor diurnal gradient oscillations should be attenuated by more than ~10% in the recent data, which yielded a gradient offset constraint of 1.25 mm, and a rate constraint of 15 mm day^{-1}.

2.6. EOP Parameterization

The USNO Earth orientation results are obtained from the long duration experiments in a multi-parameter least squares adjustment for UT1, polar motion and both components of nutation, together with the minimally constrained CRF and TRF, in addition to piecewise linear clock and troposphere models. Additional baseline-dependent clock offsets are added whenever the non-closure of the clock estimates around station triangles is judged to be significant. The operational USNO solutions also estimate the rate of change of the UT1 and polar motion for each observing session. These rate estimates, converted to the more geophysically useful "χ" excitation parameters, are provided routinely. The TRF and CRF are now updated in the course of each solution, and the updated reference frames are now routinely provided in addition to the Earth orientation parameters.

3. UT1 Intensive Data Reduction

The UT1 Intensive Series is derived from short-duration (~1 hour) single-baseline observations conducted solely to monitor daily changes in the UT1. One difference between the intensive solutions and the regular NEOS solutions lies in the treatment of nutation and polar motion, which are not estimated in the intensive solutions, but are instead held fixed to the values given in the IERS Bulletin A, linearly interpolated to the epoch of the data. The station coordinates and velocities, axis offsets, and the source positions are fixed at the *a priori* values given by the Navy 1999-3 reference frame, with the reporting epoch for each observing session being the mid-point of the session. The NEOS/IRIS UT1 Intensive files produced by the USNO now extend back to 1984 in one homogeneous solution.

3.1. High-Frequency EOP Variations and the Intensive Results

The current accuracy of VLBI Earth orientation results is sufficient to clearly detect tidally coherent diurnal and semi-diurnal variations in UT1 and polar motion, mostly due to the non-linear response of the oceans to the luni-solar gravitational tides. These variations can be a significant source of systematic error, and so have been removed from the 1999-3 solutions using the empirical hf966b model prepared by John Gipson and his colleagues in the Goddard Space Flight Center VLBI group. The model values are not added back into the UT1 and polar motion estimates, so that the orientation results provided in the operational Earth orientation solutions are close to the 24-hour average values for the Earth orientation centered on the epoch of observation. The same model is used in the reduction of the IRIS/NEOS Intensives. Again, the model values are not added back into the Intensive results; these short duration estimates thus do not reflect the true orientation at the reporting epoch, but are instead closer to the 24-hour average for the reporting epoch.

References

[1] The USNO Annual Report for 1997 is obtainable from `ftp://casa.usno.navy.mil/navnet/iers_report.97`.

[2] The availability of the Navy 1999-3 system is described in `ftp://casa.usno.navy.mil/navnet/README.n9903`.

[3] The USNO Technical Descriptions for the full Navy 1999-3 solution, and the Intensive solutions, are obtainable from `ftp://casa.usno.navy.mil/navnet/n9903.descript` and `ftp://casa.usno.navy.mil/navnet/n9903.int.descript`.

[4] A memo giving further details of the Navy 1999-3 system is currently available in draft form from `ftp://casa.usno.navy.mil/navnet/postscript/ivs_memo_1.ps`.

[5] Ma, C., et al., 1998, *AJ* **116** 516-546.

[6] McCarthy, D.D., (edt.), *IERS Conventions 1996*, IERS Technical Note 21, Observatoire de Paris, Paris, 1996.