Calc 10 Implementation

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Abstract

Calc 10 has been updated to comply with the IAU 2000 Resolutions and the IERS Conventions (2003). Comparisons with Calc 9 of the solved-for EOP parameters and the TRF are discussed.

1. Introduction

Calc version 10 has been updated to comply with the IAU 2000 Resolutions and the IERS Conventions (2003). Among other changes, Calc now uses the "non-rotating origin", or CIO-based (Celestial Intermediate Origin) method to compute the transformation from the terrestrial reference frame to the celestial reference frame (TRF-to-CRF). Much of the new code was taken from the IERS Conventions web site and modified to include time derivatives and various partial derivatives. [These are SOFA-based routines (the IAU's 'Standards of Fundamental Astronomy' software). See http://www.iau-sofa.rl.ac.uk.]

2. Summary of Changes in Calc 10

2.1. Nutation/Precession

Calc 10 makes two nutation/precession computations. First, X and Y [coordinates of the Celestial Intermediate Pole (CIP) in the Geocentric Celestial Reference System (GCRS)], and s (which locates the CIO on the equator of the CIP) are computed (using a modified version of subroutine XYS2000A). Second, classical nutation offsets ($\Delta\psi$, $\Delta\epsilon$) are computed based on the IAU2000A nutation model (using a modified version of subroutine NU2000A). Partial derivatives of the delays and rates with respect to X and Y are computed from the CIO-based formulation; and with respect to the classical nutation offsets $\Delta\psi$ and $\Delta\epsilon$ from the classical formulation. This allows solving for either observed corrections to X and Y or classical nutation corrections with respect to IAU2000A.

2.2. Polar Motion

The polar motion rotation matrix now has a small rotation about the Z-axis through the angle -*s'*, where *s'* locates the Terrestrial Ephemeris Origin (TEO) on the equator of the CIP. *s'* is approximated as linear with time (-47*Cent μarcsec, where Cent is the epoch in fractional centuries from 2000.0).

Short period ocean tide and nutation contributions to polar motion are now computed, as directed by the 2003 Conventions. The short period nutation contributions are computed using the terms of Table 5.1, and the short period ocean tide contributions are computed using subroutine Ortho_EOP. They should be added after interpolation of the X-pole and Y-pole tabular points. They will be optional in Calc/Solve (i.e., not included in the default delays and rates), available via the Lcodes 'WOBNUTAT' and 'WOBORTHO', which can be applied using the Solve CORFXX file. If used, the current Solve high frequency EOP model, jmg96.hf, should be turned off.

2.3. UT1

UT1 is now used to compute an Earth rotation angle for the CIO-based transformations. And the computation of Greenwich Siderial Time for the classical transformations was modified. The complementary terms in the equation of the equinoxes are more complicated and are computed using a modified form of subroutine EECT2000. Also, some structural changes were made in the UT1 interpolation. Smoothing of the tabular UT1 points is no longer done, and a 1.0 day interval EOP series must be used (5 day intervals no longer accepted). Subroutine Ortho_EOP also computes short period UT1 corrections for ocean tide effects. They are stored as Lcode 'UT1ORTHO' and can be applied using the Solve CORFXX file.

2.4. Fundamental Arguments

The fundamental arguments were modified to match the IERS Conventions (2003) and expanded to include the 9 planetary terms, for the CIO-based computations. Calc 10 has two other sets of fundamental arguments - for the IAU2000A nutation model and for the IAU1980 (Wahr) nutation model, each with small differences in some of the components. As a further complication, it seems there have been two different sets of fundamental arguments used in the past for computing Wahr nutations. One is the original set used with the 1976/1980 IAU Precession/Nutation models (used in Calc 8 and earlier versions). The second is a set specified in the IERS Conventions (1996) for use with both the IERS 1996 Nutation model (Herring code) and the 1976/1980 IAU Precession/Nutation (Wahr) model (used in Calc 9). It is not clear which set should really be used, but after some discussions here and with other colleagues, we decided to return to the original set.

2.5. Planetary Ephemeris

The JPL DE/LE405 ephemeris is now used. Two binary versions will be distributed with Calc 10. One is a 100-year file (1950-2050, 9.3 Mbytes) for use on Unix (Big Endian) systems. The other is an 80-year file (1960-2040, 7.5 Mbytes) for PC Linux (Little Endian) systems.

2.6. Solid Earth Tide

Some small changes were made to match the new Conventions, as described in Chapter 7, page 9. Step 1 is unchanged from Calc 9, except there is now no elastic/anelastic option. Step 2 uses different tables and additional terms. Also, the partial derivatives defined by John Gipson for Calc 9 were never used, so they were removed.

2.7. Pole Tide

Mean (secular) pole offsets (linear with time) are subtracted from the polar motion values, then these modified X-pole and Y-pole values are used to compute the pole tide corrections. The same was done in Calc 9, but with slightly different linear formula. Also as in Calc 9, we compute a delay and rate contribution ('PTOLDCON') that will remove this step. Adding the 'PTOLDCON' values to the delays and rates will be the same as computing the pole tide with X-pole and Y-pole values uncorrected for secular polar motion.

2.8. Antenna Fixed Axis Tilts and Axis Offsets

Calc 10 was updated to read an antenna fixed-axis tilt file. This file has a large set of tilts (E-W and N-S) for Pietown (from 1989-2004), and single tilts for the other 9 VLBA antennas (only SC-VLBA's is significant though). If anyone knows of other antennas that should be included here, please let me know. Calc 10 uses these tilts in the axis offset computations. For Pietown, the current tilt (~4 arc-minutes) can make a delay difference of ±8 psec maximum.

A small error was found in the axis offset computations. Apparently it was never quite correct. A small atmosphere term was incorrectly modified several versions ago, when it should have been replaced with a small relativity correction. It has finally been corrected. Very little change should be expected though, except at a few stations with large axis offsets.

3. Comparison of Calc 10 and Calc 9

The TRF-to-CRF transformation in Calc has changed for the first time in its ~30 year history, so a detailed study of its affect on the data solutions was made. We made matching Calc 9 and 10 globl solutions for 3785 VLBI sessions from 1979.6 through 2005.8, to compare differences in the solved-for parameters. To limit the differences as much as possible, the same apriori's (site positions, source positions, EOP's, and ocean loading coefficients) were used. Figures 1-3 and 5-6 show the unmodified differences (Calc 10 minus Calc 9) between the solved-for X-pole, Y-pole, UT1, and IAU1980 nutation. The data before 1984 is considerably noisier and has been excluded.

3.1. X-pole, Y-pole Differences

The polar motion differences of Figures 1 and 2 are small compared to their formal errors (typically ~35-100 μas), but some systematic effects are seen. X-pole has an ~13 μas offset. The reason has not yet been determined, but may be related to a reversal in the order of rotations in the polar motion matrix, or in the application of the pole tide correction.

3.2. UT1 Differences

The UT1 differences of Figure 3 show a semi-annual cycling, modulated in amplitude with a period of approximately half the lunar cycle. This is due to the effect of the quantity s in the CIO-based transformations. It can be seen more clearly in the equation of the equinoxes complementary terms in the equivalent equinox-based transformations. If we compute and remove the differences between the complementary terms used in Calc 10 and Calc 9, we get the 'corrected' differences shown in Figure 4. Most of the systematic effects are gone, but a small slope of ~-3.1 μsec/century, or ~-47 μarcsec/century remains. This slope is apparently due to the Z-axis rotation in the polar motion matrix of $-s'$, or +47*Cent μarcsec.

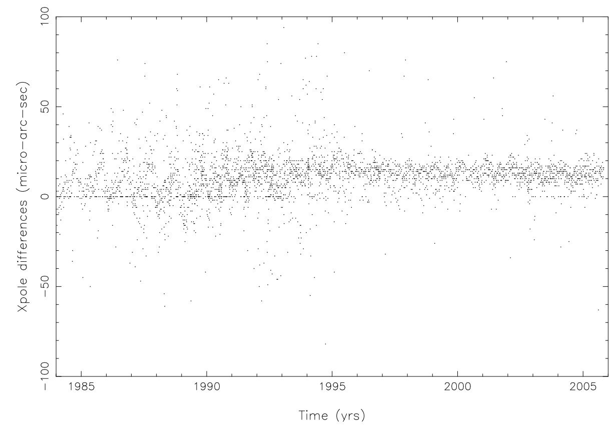

Figure 1. X-pole differences (μasec)

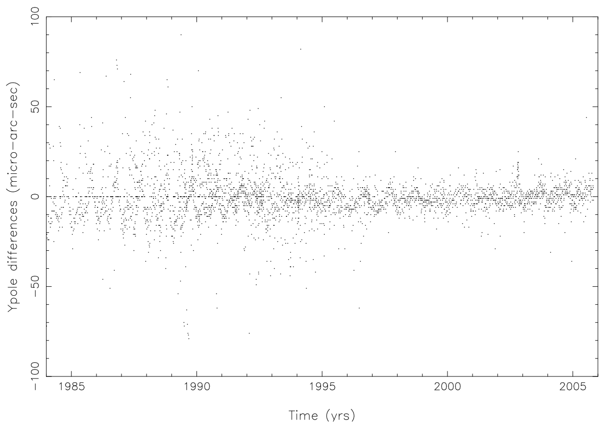

Figure 2. Y-pole differences (μasec)

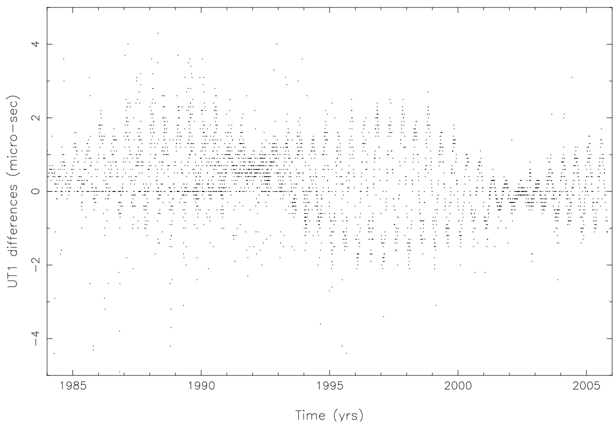

Figure 3. UT1 differences (μsec)

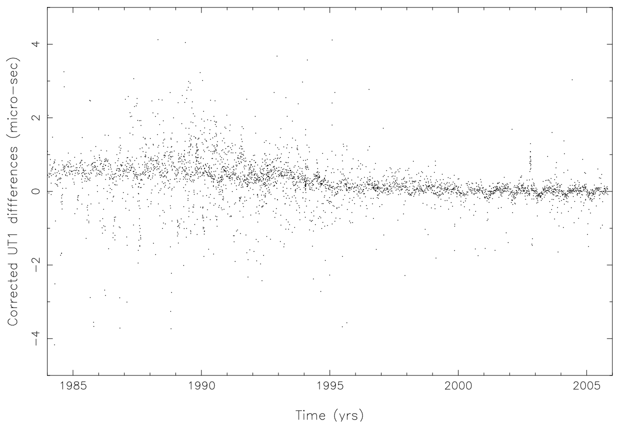

Figure 4. Corrected UT1 differences (μsec)

3.3. Nutation Differences

The Wahr nutation differences plotted in Figures 5 and 6 also show semi-annual cycles, with somewhat non-linear long term drifts. As mentioned earlier, the luni-solar fundamental arguments are slightly different for Calc's 9 and 10. If we compute and remove the effect of using different sets of fundamental arguments, we get Figures 7 and 8. The semi-annual cycling is gone, but nearly linear drifts remain, with nearly equal and opposite slopes (~-.45 and ~+.50 m-arc-sec/century for 1984-2005.8) for $\Delta\psi$ and $\Delta\epsilon$. In Solve, the IUA2000A nutation adjustments were converted to the IAU1976/1980 precession/nutation (Wahr) frame by adding the following terms for the frame offset and the difference in precession constants:

$$\Delta\psi\text{: -299.65*Cent - 41.775 (m-arc-sec)}$$
$$\Delta\epsilon\text{: -25.24*Cent - 6.8192 (m-arc-sec)}$$

It has since been pointed out by P. Wallace and N. Capitaine that this conversion is not quite correct. Solve will eventually estimate ΔX and ΔY for reporting to the IERS, so this conversion will not be necessary.

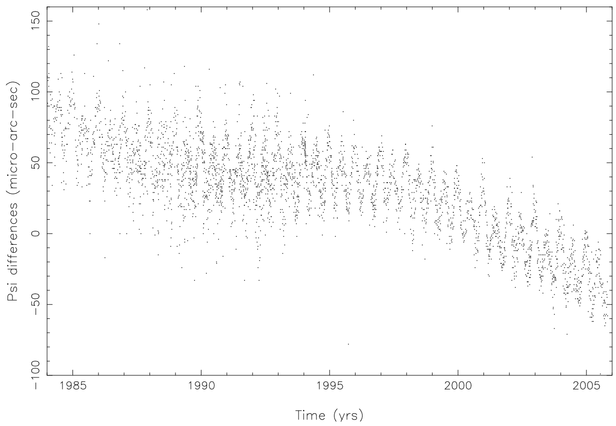

Figure 5. Psi differences (μasec)

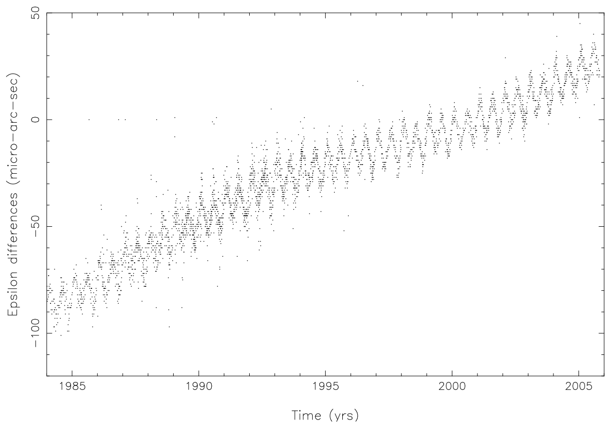

Figure 6. Epsilon differences (μasec)

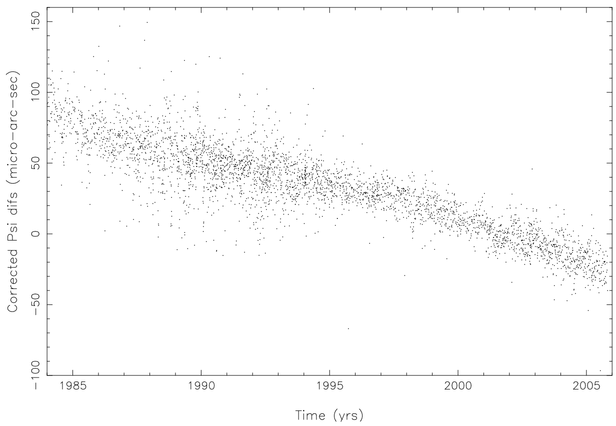

Figure 7. Corrected Psi differences (μasec)

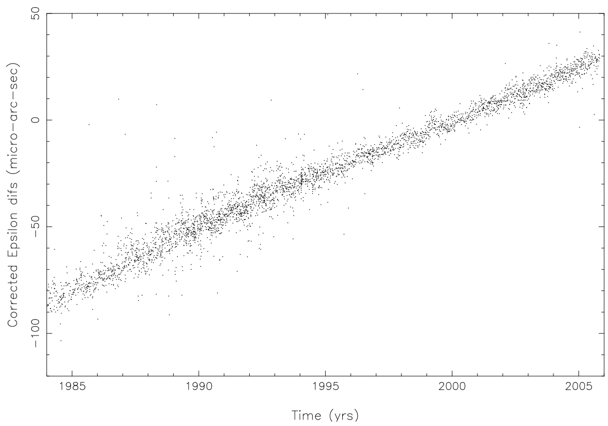

Figure 8. Corrected Epsilon differences (μasec)

3.4. Terrestrial Reference Frame and Axis Offset Differences

We solved for a simple translation/rotation between the terrestrial reference frames of the Calc 10 and Calc 9 solutions. We get a rotation of -3.2, -2.3, and +1.5 μasec; and a translation of 0.041, 0.075, and -0.036 mm in X, Y, and Z, respectively, with no significant scale factor (-0.0166 $\pm$.0152 ppb). Velocity differences show a rotation of -.13, -.31, and -.15 μasec/yr. These differences are essentially insignificant.

The Calc 10 vs. Calc 9 solved-for axis offsets were also compared. In all cases the formal errors were the same or slightly smaller in the Calc 10 solution. Differences of $\sim$.1% or less are seen for the larger axis offsets.

4. References

McCarthy, D.D. (ed.), IERS Technical Note 21, IERS Conventions (1996), 1996.

McCarthy, D.D., Petit, G. (ed.), IERS Technical Note 32, IERS Conventions (2003), 2003.