Jet Propulsion Laboratory
California Institute of Technology

Memorandum
IOM 392R-14-003
30 April 2014

To: New Horizons Project

From: W. M. Folkner

Subject: Planetary ephemeris DE432

1. Introduction

The planetary ephemeris DE432 is based on the ephemeris DE430 (Folkner et al. 2014). The main difference between DE432 and DE430 is an update of the estimated orbit of the Pluto system barycenter to support the New Horizons project. The change in the estimated orbit of Pluto is due primarily to the availability of data from Lowell Observatory from 1930-1950 that have been re-reduced using the recent UCAC4 star catalog (Zacharias *et al*. 2013). This re-reduction of the Lowell data removes uncertainty in the orientation of star catalogs used for previous data reduction, and includes updated star position and proper motion information which results in reduced uncertainty in the estimated Pluto orbit. The uncertainty in the orbit is assessed and a covariance matrix describing the uncertainty is given.

Other changes from DE430 include updated mass parameters (GM) of the Pluto, Jupiter, and Uranus systems, and small updates in measurements of the other planets. The mass parameter (GM) of the Pluto system has been adjusted to match the value on the Pluto satellite file PLU043; the mass parameter of the Jupiter system has been adjusted to match the value on the satellite ephemeris file JUP310; and the mass parameter of the Uranus system has been adjusted to match the value from the satellite ephemeris file URA111.

2. Pluto observations and orbit estimation

The estimated orbit of Pluto depends on the data and data weights used. All of the data used in this estimation are measurements of the direction to Pluto relative to stars from observatories on Earth. The only other known observations are those of Pluto by the Cassini spacecraft and by the ALMA submillimeter array. The Cassini measurements are limited by the relatively coarse angular resolution of the camera and so do not contribute significantly to the orbit estimate accuracy. The ALMA data are very recent and not yet calibrated properly for this ephemeris release.

The noise of the measurements used for this estimation is dominated by errors in the star catalogs used and by tropospheric fluctuations. The data used for the fit covers the time span from 1930 to 2013. Since the total observation span is less than half of the orbit period, the determination of the semi-major axis and eccentricity are relatively poorly determined.

Most of the data for Pluto for times before 1990 were made with respect to star catalogs based on the Earth mean equator and equinox of 1950. Data based on EME 1950 catalogs were made by many different observers with several different star catalogs, and most with data spans limited to a small fraction of the observing period. The various data sets were processed for DE418 (Folkner et al. 2007) with attempts to adjust for differences in star catalogs and for adjustment from EME 1950 to the current standard International Celestial Reference Frame (ICRF). Most of those data sets still showed systematic trends in residuals in excess of the scatter in the measurement residuals when compared with other data sets.

For this fit, only data reduced with respect to star catalogs based on Earth mean equator and equinox of 2000 have been used. The re-measured data from Lowell observatory provide a strong data set from 1930 to 1950. These data can be compared with, and combined with, observations from Pulkovo observatory from 1930 to 1992 (Rylkov et al. 1995). The Pulkovo measurements were reduced against the FK5 star catalog, and rotated here to the ICRF frame (Schwann 2001). Starting in 1995 a series of more modern observations are used, from the US Naval Observatory/Flagstaff (e.g. Stone et al. 2003), Table Mountain Observatory (Owen 2013), and Pico dos Dias Observatory (Benedetti-Rossi et al. 2014). Also included are determinations of the direction to Pluto from stellar occultation (Assafin et al. 2009). Several other observatories have also observed Pluto since 1990. Since the star catalog error is one of the dominant sources of measurement error, and most observations since 1995 use similar star catalogs, only the data sets mentioned have been used here to reduce the number of measurements over the same time span which could share similar errors.

Note that some of the Pulkovo observations have been re-reduced against the UCAC4 catalog (Khrutskaya et al. 2013). These re-reduced observations from Pulkovo show a slight bias in right ascensions compared with the older FK5-based reduction and with the Lowell observations. The possibility of a misinterpretation of measurements times is one possible cause of such an offset. An advantage of the Pulkovo data reduced against the FK5 catalog is that the measurements were reported as differences relative to a previous JPL ephemeris, DE200. These differences are insensitive to interpretations of measurement times, so the FK5-based reduction is used for this estimation.

The measurement uncertainties assigned to each data set strongly affect the final orbit estimation. The measurement uncertainties used here have been derived from examination of the measurement residuals and by comparing estimates and uncertainties for various data subsets as described in the next section. For the re-reduced data from Lowell observatory, the measurement uncertainties were based on the measurement error from fitting of the digitized plates combined in quadrature with 0.16” to account for star catalog error at epoch 1940.0 based on an assessment of the Tycho 2 star catalog (Figure 1). The Pulkovo measurement uncertainties of 0.2” in right ascension and 0.3” in declination were based on the root-mean-square (rms) of the measurement residuals. The USNO/Flagstaff measurement uncertainties were 0.1”, which is about the rms of their residuals.

The Pico dos Dias observers provided measurement uncertainties for each observation, taking into account instrument, atmospheric, and star catalog components. However, their data set includes many nights with large number of measurements in each night. The reported measurement uncertainties assume that the star catalog errors average down for multiple measurements in a given night. For this fit it is assumed that the star catalog errors do not average down for multiple measurements in a single night, since the stars closest to Pluto will be the same throughout the night and their position errors should eventually dominate. Therefore the Pico do Dias measurement uncertainties used in this fit are the error estimate supplied multiplied by the square-root of the number of measurements in the night each measurement was taken.

Similarly there are typically four measurements per night from Table Mountain, so the 0.1” measurement uncertainties used are about twice the observed rms of the measurement residuals to account for multiple measurements per night.

The occultation measurement uncertainties used were the rms of their residuals, which are 0.06" in right ascension and 0.03" in declination. The mean of the occultation measurement residuals is not quite zero, which affects the observed rms.

The residuals for the measurements compared with the DE432 ephemeris appear very similar to the residuals compared with the DE430 ephemeris (Folkner et al 2014) so they are not shown here. The residuals for the re-reduced Lowell observatory measurements are shown in Figure 2.

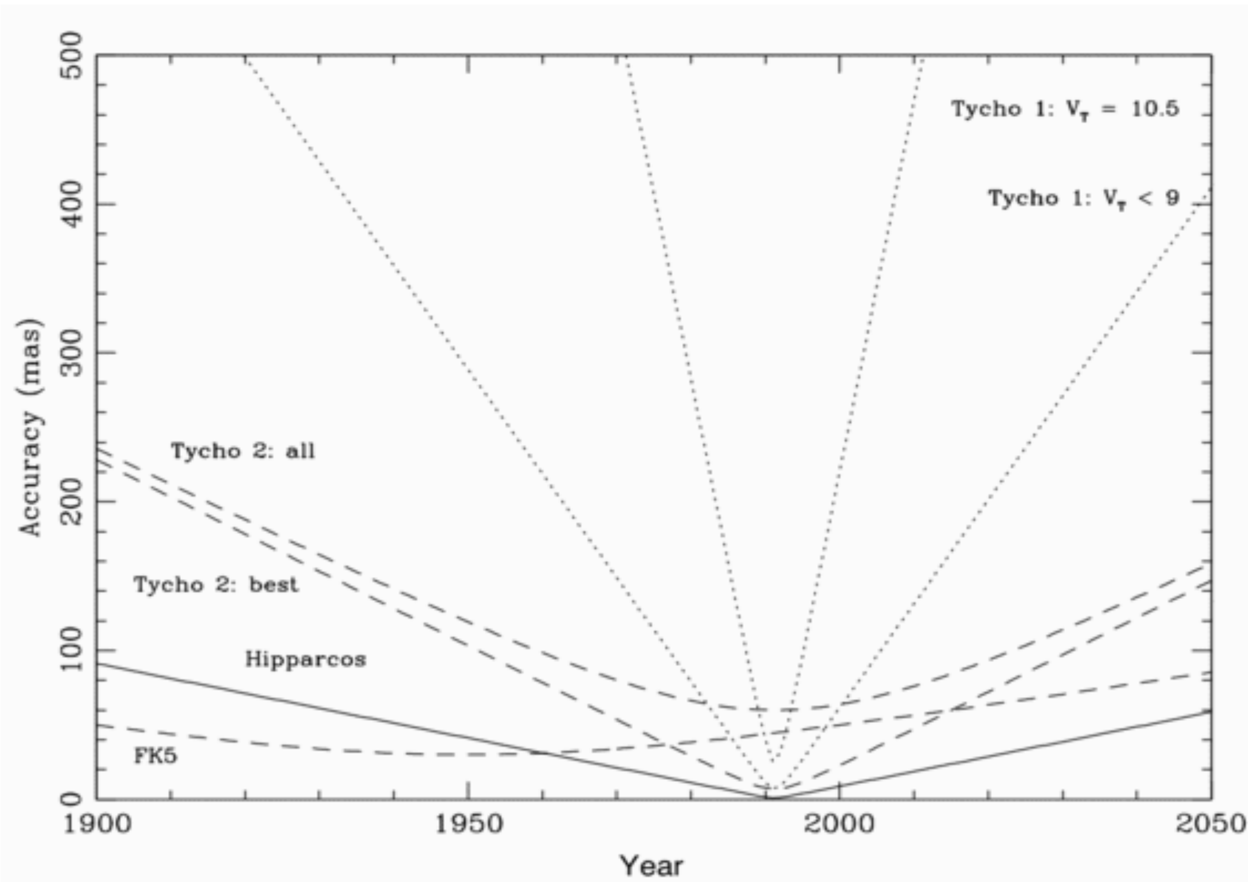

Figure 1: Estimated star catalog errors, including proper motion errors, as a function of time (M. Perryman, http://en.wikipedia.org/wiki/File:Hipparcos-accuracies.gif).

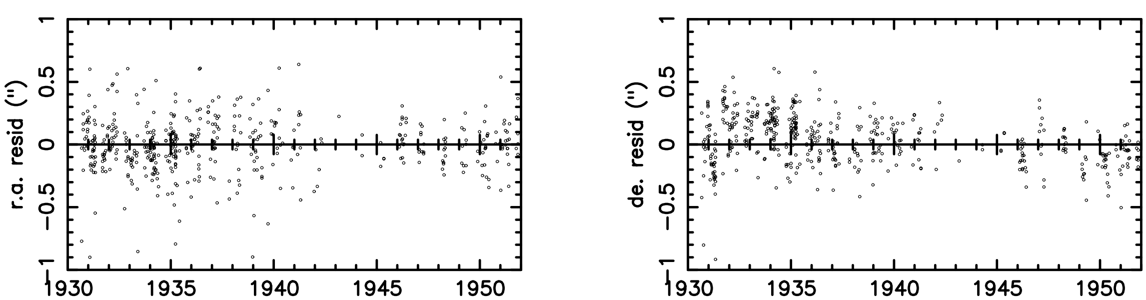

Figure 2: Residuals in right ascension and declination of re-reduced observations of Pluto from Lowell Observatory.

Figures 3-5 show the differences in the estimated orbit of Pluto from DE432 with the earlier ephemerides DE430 and DE418. The difference between DE432 and DE430 is primarily due to the addition of the re-reduced data from Lowell Observatory. The earlier DE418 estimate included a number of data sets reduced against EME 1950-based star catalogs which were not used for the estimates of DE430 or DE432. The differences in right ascension and distance to Pluto are consistent with the estimated uncertainty in the Pluto orbit from DE418. The differences in declination are larger than the estimated uncertainty from DE418. The declination estimate is more sensitive to tropospheric effects than are right ascension and distance estimates. It is possible that some systematic effect from the troposphere, such as differential color refraction of the troposphere, is not accounted for by the rms of the measurement residuals.

Other estimates of the Pluto orbit (e.g. Fienga et al., 2011; Beauvalet et al., 2013; Pitjeva and Pitjev 2013) differ from the DE432 estimate by much more than DE418 and DE430 do, even though all estimates are based on much of the same data. The Pluto orbit estimate is very sensitive to the data selection and assumption on measurement uncertainties. The estimated orbit for DE432 is considered stable and repeatable, and agrees well with estimates based on independent data subsets (described in section 3). Also, importantly, the re-reduced data from Lowell observatory provide good consistency with orbit estimates made without those data included. But since the Pluto orbit estimate is based only on astrometric data which may be subject to unknown systematic errors, such as zone errors in star catalogs, it will be very helpful to confirm or correct the orbit estimate with data from ALMA when available.

3. Pluto orbit uncertainty estimation

In order to assess the appropriate measurement uncertainties and the accuracy of the estimated orbit of Pluto, the data were divided into four subsets. The re-reduced Lowell data data (L), covering 1930-1950, and the Pulkovo data (p), covering 1930-1992, were the two data sets used with measurements prior to 1995. The data from USNO/Flagstaff combined with Table Mountain and stellar occultation data were used as one set (N) of data since 1995 while the measurements from Pico dos Dias (B, for Brazil) were used as a second post-1995 data set. Four combinations of one pre-1995 data set and one post-1995 data set were used to generate four estimates of the orbit of Pluto. These allowed taking the differences for two pairs of estimated orbits with independent data: Lowell combined with USNO/TMO/occultation (LN) compared with Pulkovo combined with Pico dos Dias (PB); and Lowell combined with Pico dos Dias (LB) compared with Pulkovo combined with USNO/TMO/occultation (PN).

Figures 6-8 show the differences in estimated orbits of Pluto between those two pairs of independent data sets. Figures 9-11 show the estimated uncertainties in each of the four orbit estimates based on the measurement uncertainties used. The estimated uncertainties shown are a factor of two times the formal estimated uncertainties. The factor of two was applied so that the differences in estimated right ascension and distance to Pluto were comparable with the uncertainties. It is common for formal uncertainties to underestimate actual uncertainty since measurements are usually assumed to be uncorrelated in the orbit estimation process when in fact many measurements may share common unmodeled errors, such as star catalog zone errors.

It can be seen in Figures 9 and 11 that the Lowell data, with the assumed measurement uncertainties, provide the strongest information on the long-term right-ascension estimate and on estimated distance. The two combinations including the Lowell data, with either the USNO/TMO/occultations or with the Pico Dos Dias data, provide uncertainties in right ascension and distance that are similar to each other and with lower estimated uncertainty than the combinations including the Pulkovo data. The uncertainties shown in Figure 9-11 at twice the formal uncertainties agree fairly well with the differences in right ascension and distance between independent subsets as shown in Figure 6 and 8 but not with the differences in declination shown in Figure 7.

In order to provide an estimated uncertainty in the Pluto orbit consistent with the differences in estimated declination based on independent data sets (shown in Figure 7), an uncertainty estimate was made with all of the data considered above with significantly increased declination measurement uncertainties. The resulting uncertainties in right ascension, declination, and distance are shown in Figures 12-14. These estimated uncertainties are very similar in right ascension and distance to the uncertainty from the Lowell+USNO (LN) data shown in Figures 9 and 11. The uncertainty in declination shown in Figure 13 is about the same as the largest difference in declination shown in Figure 7. This might be somewhat conservative, since the differences in estimated declination for each of the four data combinations used differs from the combined DE432 solution by less than the maximum shown in Figure 7, with the orbit estimates of two subsets being about half the maximum value but with opposite signs. However, since the cause of the variation in declination estimates is unknown, and since the resulting estimated uncertainty in declination for the time of the New Horizons encounter is comparable with estimated uncertainty in distance, including a conservative estimate of declination uncertainty is considered appropriate.

Tables 1 and 2 give covariance (uncertainty) estimates for the orbital elements of Pluto and the Earth-Moon barycenter (EMB) in format suitable for the New Horizons navigation team. The uncertainty in the EMB orbit is taken from an earlier study for the Mars Science Laboratory project (Folkner 2010). Since the EMB uncertainty is small compared with the uncertainty in the Pluto orbital elements, it is recommended that the uncertainties in the EMB and Pluto orbits be treated as uncorrelated.

4. Conclusions

The availability of the re-reduced observations of Pluto from Lowell observatory have provided both a significant improvement in the estimated uncertainty in the distance of Pluto from the Sun (and from Earth), while also allowing a study of orbit estimates with strong yet independent data sets. The estimated orbit uncertainty given here meets the requirements for the New Horizons project, and is justified by comparison of orbits from independent data sets. However, the fact that other analysts using much of the same data produce significantly different estimates of the Pluto orbit, and that differences in the estimated declination of the Pluto orbit vary by more than the estimated uncertainties indicate that some caution is appropriate. Fortunately observations of Pluto from ALMA should be much less sensitive to the types of systematic effects that could affect the current estimate and so should improve the accuracy and confidence in the Pluto ephemeris prior to New Horizons arrival.

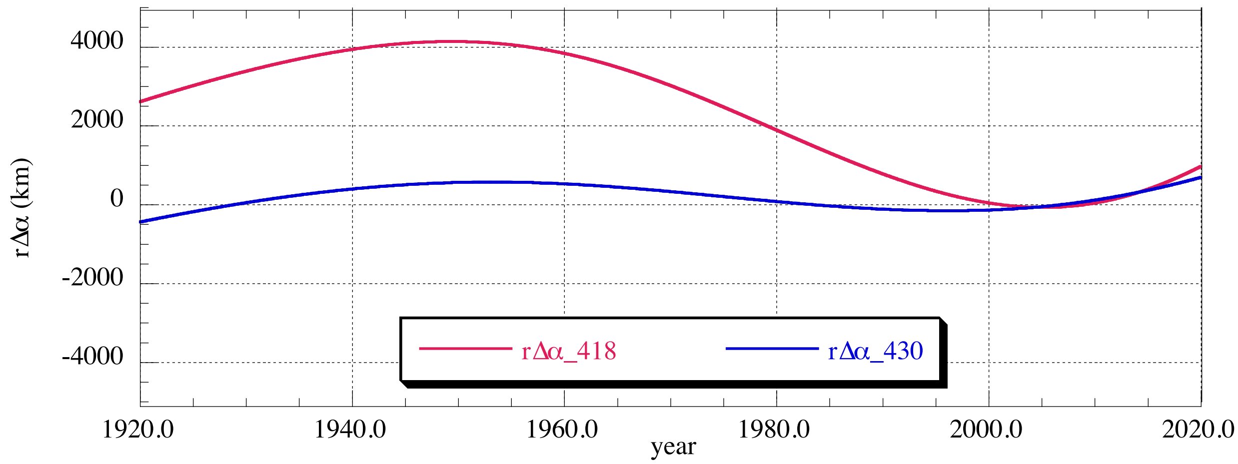

Figure 3: Difference in right ascension, multiplied by the distance from the Sun, of the estimated orbit of Pluto from DE418 and DE430 relative to DE432.

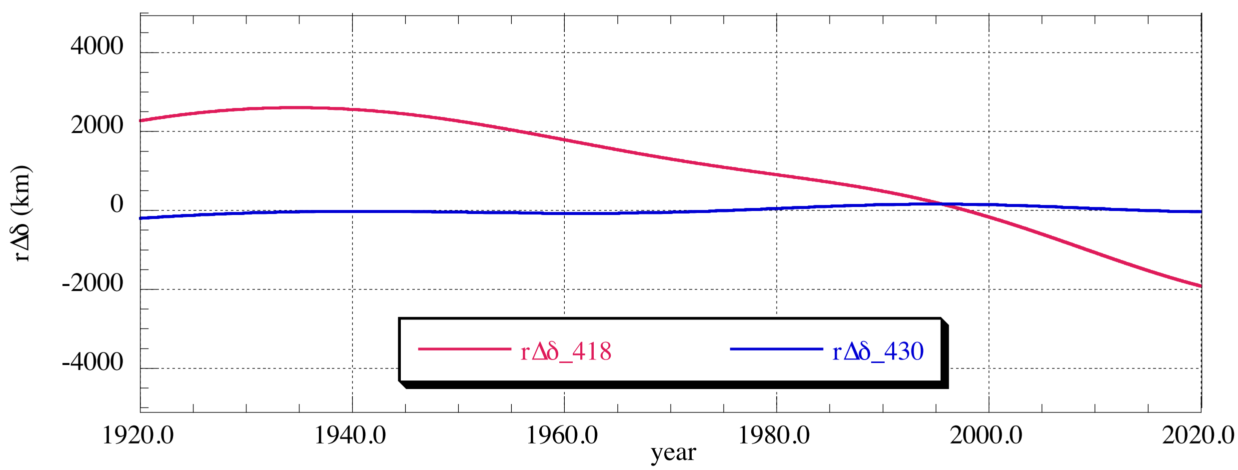

Figure 4: Difference in declination, multiplied by the distance from the Sun, of the estimated orbit of Pluto from DE418 and DE430 relative to DE432.

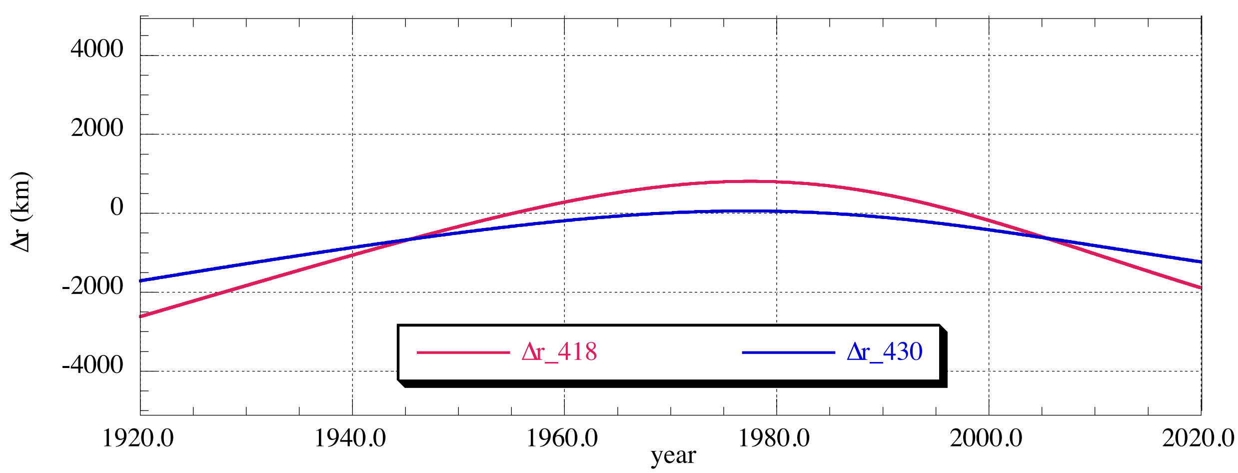

Figure 5: Difference in estimated distance to Pluto from DE418 and DE430 relative to DE432.

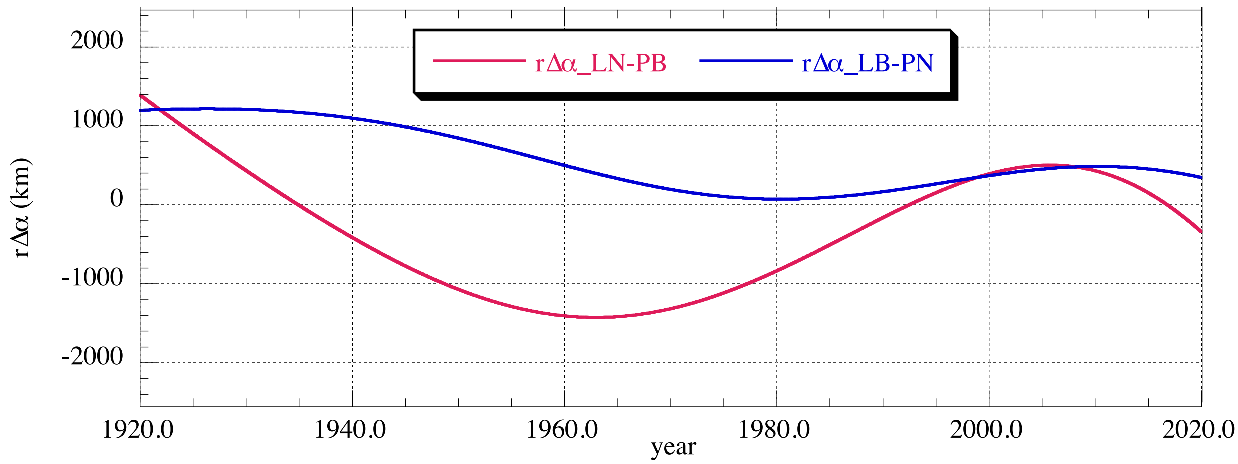

Figure 6: Differences in right ascension of Pluto, multiplied by the distance from the Sun, between estimates from independent data sets.

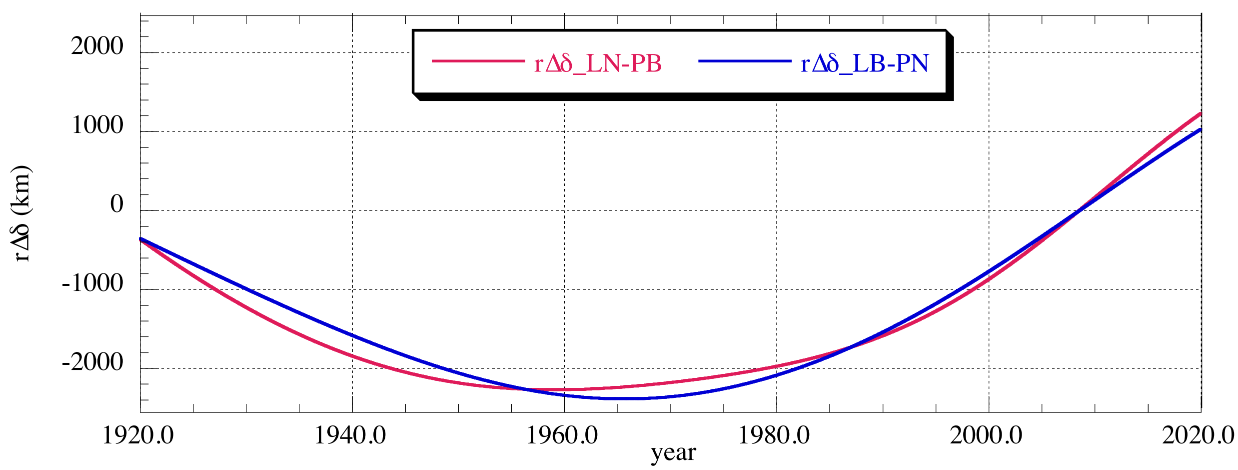

Figure 7: Differences in declination of Pluto, multiplied by the distance from the Sun, between estimates from independent data sets.

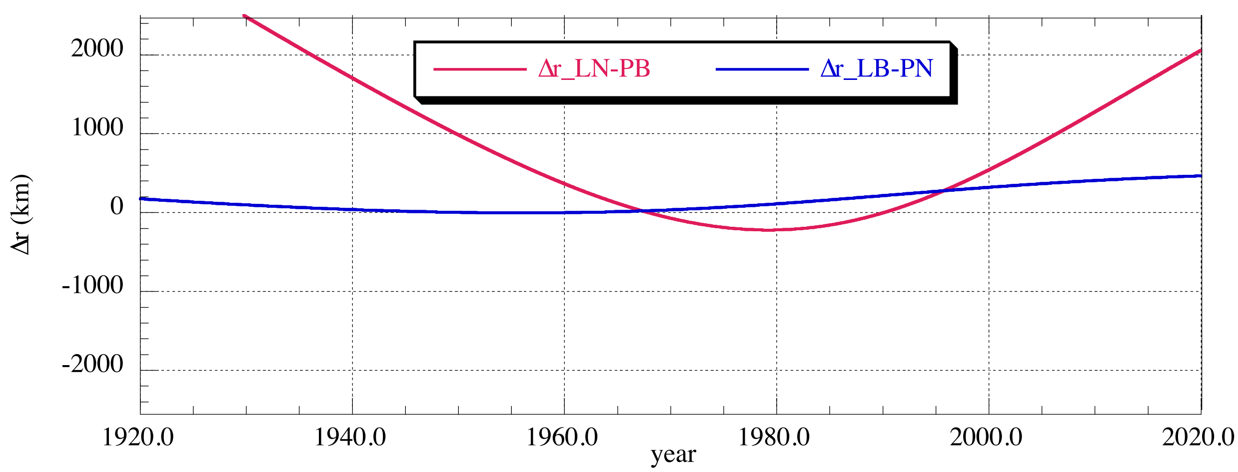

Figure 8: Differences in distance from the Sun to Pluto between estimates from independent data sets.

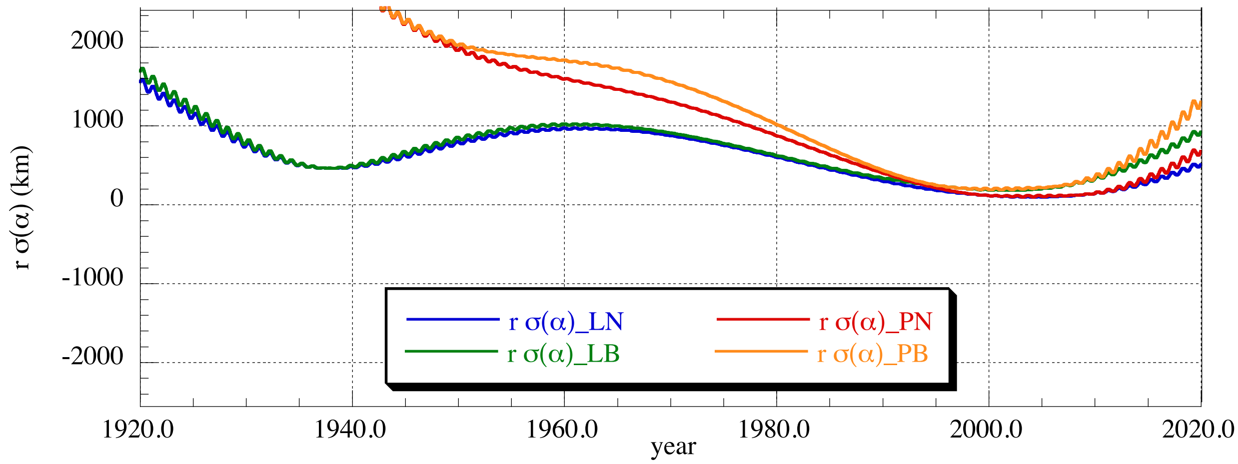

Figure 9: Estimated uncertainty in right ascension of Pluto, multiplied by the distance from the Sun, from four data combinations.

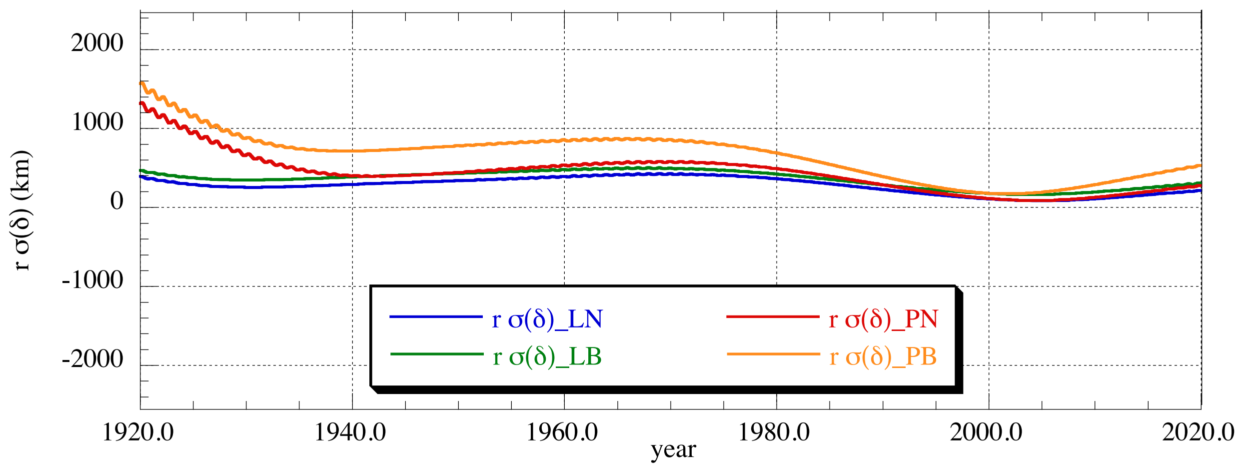

Figure 10: Estimated uncertainty in declination of Pluto, multiplied by the distance from the Sun, from four data combinations.

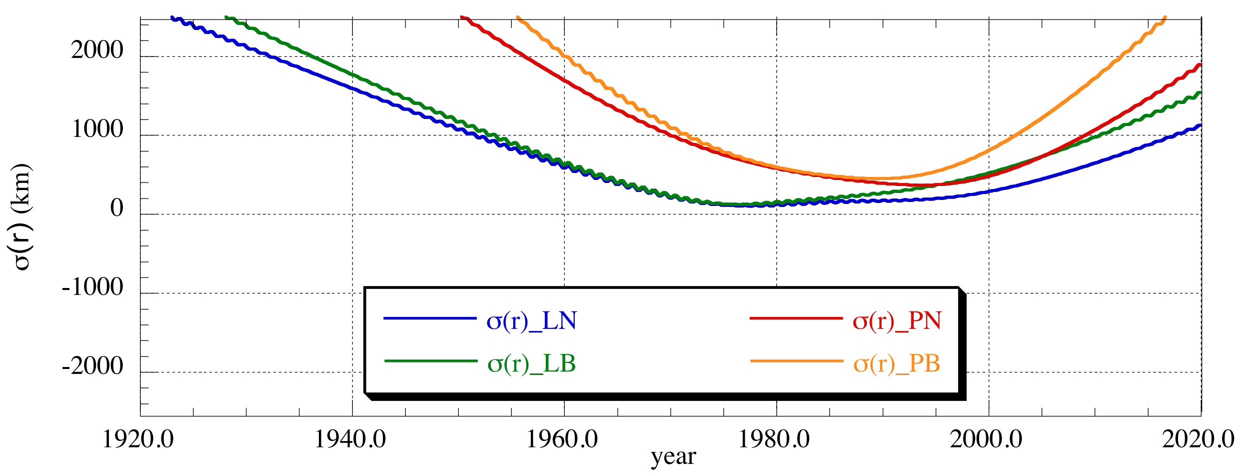

Figure 11: Estimated uncertainty in range to Pluto from four data combinations.

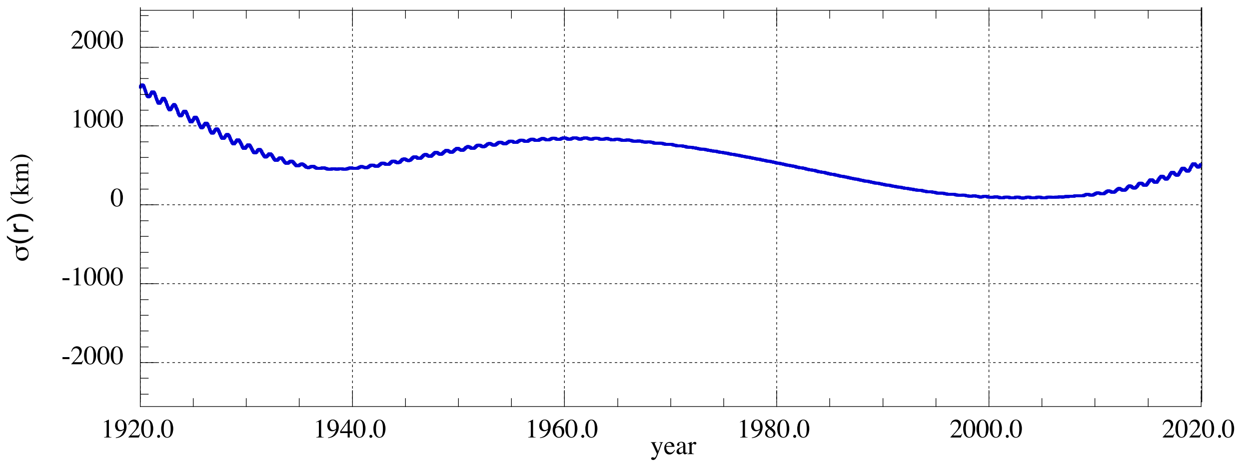

Figure 12: Estimated uncertainty in right ascension of Pluto, multiplied by the distance from the Sun, recommended for use with DE432.

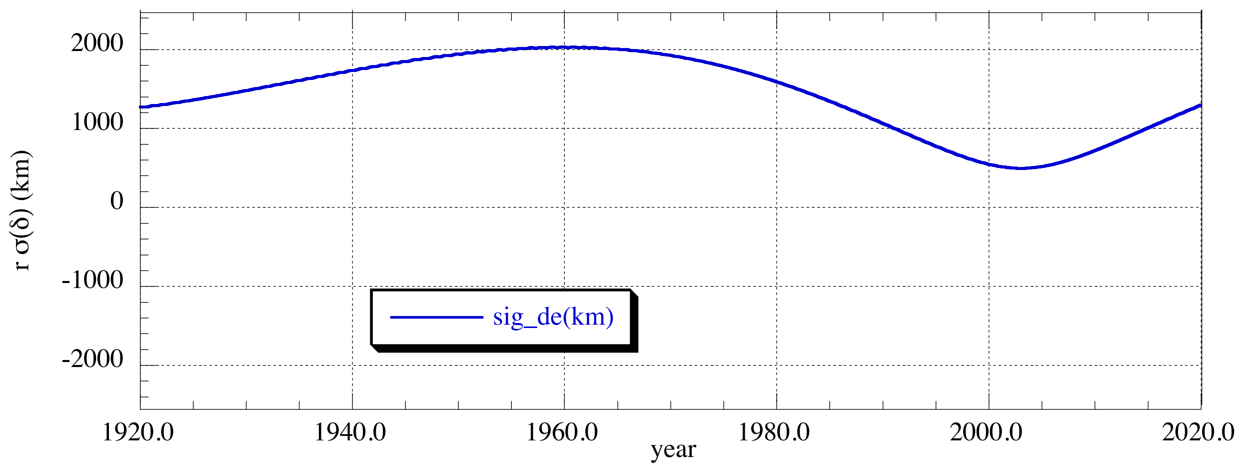

Figure 13: Estimated uncertainty in declination of Pluto, multiplied by the distance from the Sun, recommended for use with DE432.

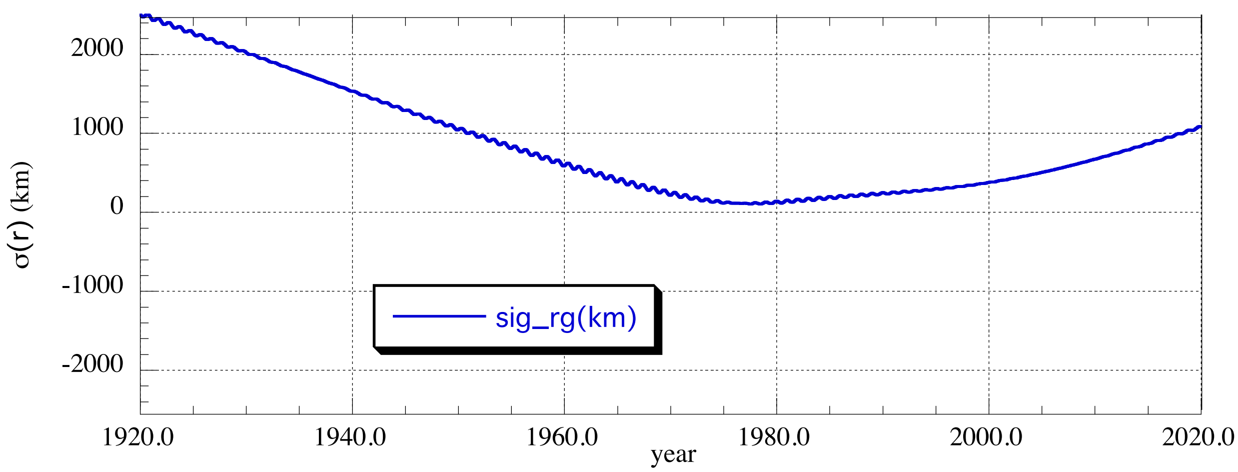

Figure 14: Estimated uncertainty in range to Pluto recommended for use with DE432.

Table 1: Covariance for Pluto orbital elements, in units of radian^2 stored in triangular input for ODP estimation program SIGMA.

```
APCSCALE1 =   6*1.D0
APCNAME1(1) =
'DMW9  ','DP9   ','DQ9   ','EDW9  ','DA9   ','DE9   ',
APCOV1( 1, 1) =   4.472674645667E-14,
APCOV1( 1, 2) =  -3.499240305635E-14,  1.144485244409E-13,
APCOV1( 1, 3) =  -1.903951262965E-14,  6.808801460715E-14,  5.500845785571E-14,
APCOV1( 1, 4) =  -6.159333864406E-15, -1.598481814331E-14, -1.352799860895E-14,
                  1.177967282433E-14,
APCOV1( 1, 5) =   8.444330449853E-14, -2.738958817550E-14, -9.190376814775E-15,
                 -3.225837048583E-14,  2.002567275630E-13,
APCOV1( 1, 6) =   6.748497640569E-14, -3.045018112510E-14, -1.345836556193E-14,
                 -2.241129341326E-14,  1.542756342925E-13,  1.202767415624E-13,
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Table 2 Covariance for Earth-Moon Barycenter orbital elements, in units of radian^2 stored in triangular input for ODP estimation program SIGMA..

```
APCSCALE2 =  6*1.D0
APCNAME2(1) =
'DMWB  ','DPB   ','DQB   ','EDWB  ','DAB   ','DEB   ',
APCOV2( 1, 1) =   2.832058214582E-18,
APCOV2( 1, 2) =  -1.681236820100E-19,  5.706531962594E-19,
APCOV2( 1, 3) =   1.082606892397E-19,  4.669780441564E-20,  3.425092483980E-19,
APCOV2( 1, 4) =  -1.553971291528E-20,  9.880928858052E-22,  3.106798459118E-22,
                  1.140857878977E-21,
APCOV2( 1, 5) =   7.883384872274E-21, -4.987731648854E-22,  2.699382297910E-22,
                 -4.704079208189E-23,  2.248570900464E-23,
APCOV2( 1, 6) =  -1.778126002926E-20,  1.672316981971E-21, -7.877141549562E-22,
                  1.096826445845E-22, -5.041109061923E-23,  1.063602022131E-21,
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