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# Combinations of Earth Orientation Measurements: SPACE2009, COMB2009, and POLE2009

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# ABSTRACT

Independent Earth orientation measurements taken by the space-geodetic techniques of lunar and satellite laser ranging, very long baseline interferometry, and the Global Positioning System have been combined using a Kalman filter. The resulting combined Earth orientation series, SPACE2009, consists of values and uncertainties for Universal Time, polar motion, and their rates that span from September 28, 1976, to May 28, 2010, at daily intervals and is available in versions with epochs given at either midnight or noon. The space-geodetic measurements used to generate SPACE2009 have then been combined with optical astrometric measurements to form two additional combined Earth orientation series: (1) COMB2009, consisting of values and uncertainties for Universal Time, polar motion, and their rates that span from January 20, 1962, to May 28, 2010, at daily intervals and which are also available in versions with epochs given at either midnight or noon; and (2) POLE2009, consisting of values and uncertainties for polar motion and its rate that span from January 20, 1900, to May 22, 2010, at 30.4375-day intervals.

# ACKNOWLEDGMENTS

The authors would like to thank all those involved in acquiring and reducing the Earth orientation measurements that have been combined here to form SPACE2009, COMB2009, and POLE2009. This study would not have been possible without their considerable efforts.

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# INTRODUCTION

Reference series of Earth orientation parameters (EOPs) obtained by combining independent measurements of the Earth's orientation are generated annually at the Jet Propulsion Laboratory (JPL) in support of tracking and navigation of interplanetary spacecraft. This report describes the generation of the most recent such combined Earth orientation series: SPACE2009, COMB2009, and POLE2009. Since the procedures used to generate these most recent series are similar to those used to generate previous such combinations, only a brief description of their generation is given here. Further details regarding the approach used at JPL to annually combine independent measurements of the Earth's orientation can be found in Gross (1996, 2000) and Gross et al. (1998).

# SPACE2009

## Data Sets Combined to Form SPACE2009

SPACE2009 is a combination of independent space-geodetic measurements of the Earth's orientation. Table 1 lists the space-geodetic series used in generating SPACE2009, giving their identifiers, the number of measurements from each series that were actually incorporated into SPACE2009, and the time interval spanned by those measurements. Note that the University of Texas Center for Space Research (UTCSR) satellite laser ranging (SLR) Universal Time (UT) values were not used in generating SPACE2009 due to problems associated with separating this component of the Earth's orientation from the effects of unmodeled forces acting on the satellite that cause the node of its orbit to drift (see Gross et al. 1998, p. 217 for further discussion about this point). For similar reasons, the International Laser Ranging Service (ILRS) satellite laser ranging length-of-day (LOD) values have also not been used in generating SPACE2009.

Since it was desirable to combine only independent measurements of the Earth's orientation, only those series listed in Table 1 were used, even though other space-geodetic series are available from other analysis centers. When more than one series determined by the same measurement technique was used, care was taken to make sure that the measurements themselves were not included more than once. In particular, polar motion measurements from the JPL Global Positioning System (GPS) series were only used until the start of the International Global Navigation Satellite System (GNSS) Service (IGS) combined series EOP(IGS) 95 P 01 on January 1, 1995; polar motion measurements from the IGS combined series EOP(IGS) 95 P 01 were then used until the start of the IGS combined series EOP(IGS) 95 P 02 on June 30, 1996; polar motion measurements from the IGS combined series EOP(IGS) 95 P 02 were then used until the start of the accumulated IGS Solution Independent Exchange (SINEX) combined series EOP(IGS) 00 P 03 on February 27, 2000; and polar motion measurements from the accumulated IGS SINEX combined series EOP(IGS) 00 P 03 were used thereafter. Similarly, measurements from the National Oceanic and Atmospheric Administration (NOAA) International Radio Interferometric Surveying (IRIS) Intensive UT1 series were used until it ended on December 31, 1994; measurements from the United States Naval Observatory (USNO) National Earth Orientation Service (NEOS) Intensive UT1 series were then used until it ended on December 4, 2000; and measurements from the Goddard Spaceflight Center (GSFC) NEOS Intensive UT1 series were used thereafter. Finally, polar motion measurements from the UTCSR SLR series EOP(CSR) 96 L 01 were used until it ended on February 4, 1996 with measurements from the ILRS combined SLR series being used thereafter.

## Data Preprocessing and Treatment of Tide-Induced Rotational Variations

The Earth orientation series listed in Table 1 were first preprocessed by removing leap seconds from the Universal Time (UT1) values and, when necessary, by correcting the UT1 values to be consistent with the extended definition of Greenwich Sidereal Time (GST) as adopted by the International Earth Rotation Service (IERS; IERS 1997, p. I49). Since most of the series listed in Table 1 were already consistent with the extended definition of GST, this correction needed to be applied to only the NOAA IRIS Intensive UT1 series.

**Table 1.** Data Sets Combined to Form SPACE2009*

| Data Set Name | Data Type | Analysis Center | Reference | Data Span | Number |
|---|---|---|---|---|---|
| LLR (JPL10M01; VOL, UT0) | | | | | |
| McDonald Cluster | LLR | JPL | Williams et al. (2007) | Oct. 5, 1976, to Mar. 17, 2009 | 743 |
| OCA | LLR | JPL | Williams et al. (2007) | April 7, 1984, to July 30, 2005 | 1071 |
| Haleakala | LLR | JPL | Williams et al. (2007) | Feb. 10, 1985, to Aug. 11, 1990 | 70 |
| Apache Point | LLR | JPL | Williams et al. (2007) | June 4, 2006, to June 15, 2009 | 169 |
| UTCSR (CSR96L01) | | | | | |
| Lageos Polar Motion | SLR | UTCSR | Eanes & Watkins (1996) | Sep. 27, 1976, to Feb. 4, 1996 | 2218 |
| ILRSA (11JUN10; Polar motion) | | | | | |
| ILRS Primary Combination | SLR | ASI-CGS | Sciarretta et al. (2010) | Feb. 5, 1996, to May 27, 2010 | 5200 |
| DSN (JPL97R01; T, V) | | | | | |
| California-Spain Cluster | VLBI | JPL | Steppe et al. (1997) | Nov. 26, 1979, to May 17, 2010 | 956 |
| California-Australia Cluster | VLBI | JPL | Steppe et al. (1997) | Oct. 28, 1978, to Sep. 30, 1997 | 698 |
| NOAA (NOAA95R02) | | | | | |
| IRIS Intensive UT1 | VLBI | NOAA | Ray et al. (1995) | April 2, 1984, to Dec. 31, 1994 | 2394 |
| USNO (N9903) | | | | | |
| NEOS Intensive UT1 | VLBI | USNO | Eubanks et al. (1999) | Jan. 4, 1995, to Dec. 4, 2000 | 1496 |
| NASA/GSFC (GSFINT24) | | | | | |
| NEOS Intensive UT1 | VLBI | GSFC | NASA/GSFC VLBI Group (2010) | Dec. 6, 2000, to May 27, 2010 | 3227 |
| NASA/GSFC (GSF2009a) | | | | | |
| Multibaseline | VLBI | GSFC | NASA/GSFC VLBI Group (2010) | Aug. 4, 1979, to May 28, 2010 | 4116 |
| NASA/GSFC (GSFC1122) | | | | | |
| Westford-Fort Davis | VLBI | GSFC | Gordon et al. (1999) | June 25, 1981, to Jan. 1, 1984 | 105 |
| Westford-Mojave | VLBI | GSFC | Gordon et al. (1999) | March 21, 1985, to Aug. 6, 1990 | 18 |
| GPS (21APR04; Polar motion) | | | | | |
| Post-processed Flinn Analysis | GPS | JPL | Heflin et al. (2004) | June 10, 1992, to Dec. 31, 1994 | 817 |
| GPS (IGS95P01; Polar motion) | | | | | |
| IGS Final Combined (ITRF93) | GPS | NRCan | Kouba & Mireault (1997) | Jan. 1, 1995, to June 29, 1996 | 546 |
| GPS (IGS95P02; Polar motion) | | | | | |
| IGS Final Combined (IGS05) | GPS | CODE | Mireault & Kouba (2000) | June 30, 1996, to Feb. 26, 2000 | 1336 |
| GPS (IGS00P03; Polar motion) | | | | | |
| IGS SINEX Combined (IGS05) | GPS | NRCan | Ferland (2004) | Feb. 27, 2000, to May 27, 2010 | 3743 |
| GPS (IGS95P02; LOD) | | | | | |
| IGS Final Combined (IGS05) | GPS | CODE | Mireault & Kouba (2000) | Feb. 23, 1997, to Feb. 26, 2000 | 1099 |
| GPS (IGS00P03; LOD) | | | | | |
| IGS SINEX Combined (IGS05) | GPS | NRCan | Ferland (2004) | Feb. 27, 2000, to May 27, 2010 | 3743 |

* LLR, lunar laser ranging; JPL, Jet Propulsion Laboratory; VOL, variation of latitude; UT, Universal Time; OCA, Observatoire de la Côte d'Azur; UTCSR, University of Texas Center for Space Research; SLR, satellite laser ranging; ILRS, International Laser Ranging Service; ASI, Agenzia Spaziale Italiana; CGS, Centro di Geodesia Spaziale; DSN, Deep Space Network; T, transverse; V, vertical; VLBI, very long baseline interferometry; NOAA, National Oceanic and Atmospheric Administration; IRIS, International Radio Interferometric Surveying; USNO, United States Naval Observatory; NEOS, National Earth Orientation Service; NASA, National Aeronautics and Space Administration; GSFC, Goddard Space Flight Center; GPS, Global Positioning System; IGS, International Global Navigation Satellite System (GNSS) Service; ITRF, International Terrestrial Reference Frame; NRCan, Natural Resources Canada; CODE, Center for Orbit Determination in Europe; SINEX, solution independent exchange; LOD, length of day.

Rotational variations caused by solid Earth and ocean tides were also removed from the UT1 values. The effect of the solid-Earth tides was removed by using the model of Yoder et al. (1981); the model of Kantha et al. (1998) was used to remove the effect upon UT1 of the ocean tides at the *Mf*, *Mf'*, and *Mm* tidal frequencies. Since the Yoder et al. (1981) model already includes a contribution from the equilibrium ocean tides, only the Kantha et al. (1998) oceanic corrections to the Yoder et al. (1981) model were actually removed. Also note that the Kantha et al. (1998) model was used to remove the effect of ocean tides on only UT1, not on polar motion. Ocean-tide-induced polar motion variations were not removed from any of the polar motion observations. Finally, the only Earth orientation series listed in Table 1 that includes the effects of semidiurnal and diurnal ocean tides on the Earth's orientation is the NOAA IRIS Intensive UT1 series. This series included these effects by adding to the released UT1 values the model of Herring (1993; also see Herring and Dong 1994). Hence, the same Herring (1993) model was used to remove them.

On June 30, 1996, the IGS reference frame changed from the International Terrestrial Reference Frame ITRF93 to ITRF94; on March 1, 1998, it changed from ITRF94 to ITRF96; on August 1, 1999, it changed from ITRF96 to ITRF97; on February 27, 2000, it changed from ITRF97 to the IGS realization of ITRF97 known as IGS97; on December 2, 2001, it changed from IGS97 to the IGS realization of ITRF2000 known as IGS00; on January 11, 2004, it changed from IGS00 to a new IGS realization of ITRF2000 known as IGb00; and on November 5, 2006 it changed from IGb00 to the IGS realization of ITRF2005 known as IGS05. These changes in reference frames potentially introduce discontinuities into the IGS combined Earth orientation series. However, the IGS Final combined series EOP(IGS) 95 P 02 and the accumulated IGS SINEX combined series EOP(IGS) 00 P 03 used here have had each of these segments aligned to the same IGS reference frame. Thus, to within the uncertainty in determining the corrections required to align each segment, the IGS combined series EOP(IGS) 95 P 02 and EOP(IGS) 00 P 03 used here should be reasonably consistent with each other. They were, therefore, concatenated with one common set of bias-rate corrections being determined for them, as described below.

## Adjustments Made to Space-Geodetic Series Prior to Combination

Prior to combining the series listed in Table 1 to form SPACE2009, series-specific corrections were applied for bias and rate, the stated uncertainties of the measurements were adjusted by multiplying them by series-specific scale factors, and outlying data points were deleted. Values for the bias-rate corrections and uncertainty scale factors were determined by an iterative procedure wherein each series was compared, in turn, to a combination of all others. In order to minimize interpolation error (see Gross et al. 1998, pp. 223–225), the comparison of each series to its reference combination was done at the epochs of the measurements of that series by generating its reference combination using a Kalman filter that interpolates to (and prints its EOP estimates at) the exact epochs of those measurements. Also, both the bias-rate corrections and the uncertainty scale factors for all components of a given series were determined simultaneously in a multivariate approach using nonlinear weighted least squares. Using a multivariate approach allows the correlations between the components to be taken into account when determining the bias-rate corrections and uncertainty scale factors (see Gross et al. 1998, pp. 225).

All the series listed in Table 1 were included in the iterative procedure. Details of the iterative procedure are described in Gross (1996, 2000) and Gross et al. (1998) and will not be repeated here. These details include:

(1) Use of a reference series, SPACE2008 (Ratcliff & Gross, 2010), for initial bias-rate alignment;

(2) Analysis of each data type in its natural reference frame;

(3) Clustering of the McDonald LLR stations and, separately, the DSN very long baseline interferometry (VLBI) stations in California, Australia, and Spain;

(4) Initial convergence on values for the series-specific bias-rate corrections and uncertainty scale factors prior to the start of outlier detection and deletion; and

(5) Final convergence on these values after detecting and deleting all data outliers.

At the end of the iterative procedure, relative bias-rate corrections have been determined that make the series agree with each other in bias and rate; uncertainty scale factors have been determined that make the residual of each series have a reduced chi-square near one when differenced with a combination of all others; and outlying data points (those with residual values greater than four times their adjusted uncertainties) have been deleted. A total of 89 data points, or about 0.26% of those combined, were thus deleted.

During the iterative procedure, the uncertainties of the JPL GPS polar motion, IGS GPS polar motion, and IGS GPS LOD series were adjusted in order to find and delete outlying data points. However, prior to combining these series with the others to form SPACE2009, their uncertainties were reset to their original values in order to avoid over-inflating them and hence overly smoothing the SPACE2009 series.

Finally, each series was placed within a particular IERS reference frame by applying to it an additional bias-rate correction that is common to all the series. This additional correction was determined by first combining all the series after applying to them the relative bias-rate corrections and uncertainty scale factors that had been determined for them as described above. This intermediate combination was then compared to the IERS combined Earth orientation series EOP(IERS) 05 C 04 (IERS 2009, Section 3.5.1) during the interval 1984–2009 in order to obtain the additional bias-rate correction required to make it, and therefore each individual series, agree in bias and rate with the IERS series.

The total bias-rate corrections and uncertainty scale factors determined by the procedures outlined above are given in Table 2. The values of the bias-rate corrections given in Table 2 are the sum of: (1) all the incremental corrections applied during the iterative procedure, (2) the corrections applied to initially align the series with each other, and (3) the additional, common correction applied in order to place each series within that particular IERS reference frame defined by the IERS combined Earth orientation series EOP(IERS) 05 C 04. The values of the uncertainty scale factors given in Table 2 are the products of all the incremental scale factors determined during the iterative procedure. The uncertainties of the bias-rate corrections given in Table 2 are the 1σ standard errors of the incremental bias-rate corrections determined during the last iteration. There are no bias-rate entries in Table 2 for components that were either not used (e.g., the UTCSR SLR UT1 component) or not available (e.g., the NOAA IRIS Intensive polar motion components). Note that the same IERS rate correction is applied to all the data sets, including those such as the Westford-Mojave single baseline VLBI series, for which no relative rate correction could be determined. Therefore, the rate corrections given in Table 2 for those series for which no relative rate corrections could be determined are simply the IERS rate

**Table 2.** Adjustments to Space-Geodetic Series*

| Data Set Name | Bias, mas | | | Rate, mas/yr | | | Uncertainty Scale Factor | | |
|---|---|---|---|---|---|---|---|---|---|
| LLR (JPL10M01) | | VOL | UT0 | | VOL | UT0 | VOL | | UT0 |
| McDonald Cluster | | –0.023 ± 0.087 | 0.152 ± 0.089 | | 0.021 ± 0.020 | –0.021 ± 0.018 | 1.447 | | 1.364 |
| OCA | | 0.010 ± 0.045 | 0.014 ± 0.037 | | –0.002 ± 0.007 | –0.003 ± 0.005 | 2.300 | | 1.981 |
| Haleakala | | –1.783 ± 1.157 | –1.719 ± 0.701 | | –0.341 ± 0.225 | –0.330 ± 0.147 | 2.724 | | 2.336 |
| Apache Point | | 0.409 ± 1.121 | 2.676 ± 1.180 | | –0.042 ± 0.073 | –0.195 ± 0.079 | 3.053 | | 2.830 |
| DSN (JPL97R01) | | T | V | | T | V | T | | V |
| California-Spain Cluster | | –0.852 ± 0.024 | –0.285 ± 0.057 | | 0.182 ± 0.002 | 0.163 ± 0.005 | 1.844 | | 1.336 |
| California-Australia Cluster | | 0.639 ± 0.018 | 0.535 ± 0.053 | | 0.083 ± 0.008 | –0.022 ± 0.024 | 1.440 | | 1.168 |
| NASA GSFC (1122) | | T | V | | T | V | T | | V |
| Westford-Fort Davis | | 8.074 ± 3.654 | 2.232 ± 5.767 | | 0.772 ± 0.368 | 0.156 ± 0.578 | 1.317 | | 0.910 |
| Westford-Mojave | | 0.469 ± 1.007 | 0.172 ± 1.700 | | 0.002 | 0.000 | 2.222 | | 0.734 |
| GSFC (GSF2009a) | PMX | PMY | UT1 | PMX | PMY | UT1 | PMX | PMY | UT1 |
| Multibaseline | 0.011 ± 0.006 | 0.001 ± 0.005 | 0.016 ± 0.010 | 0.001 ± 0.001 | 0.000 ± 0.001 | 0.002 ± 0.001 | 1.714 | 1.429 | 1.623 |
| NOAA (95R02) | PMX | PMY | UT1 | PMX | PMY | UT1 | PMX | PMY | UT1 |
| IRIS Intensive | ----- | ----- | 0.191 ± 0.023 | ----- | ----- | –0.001 ± 0.007 | ----- | ----- | 1.047 |
| USNO (N9903) | PMX | PMY | UT1 | PMX | PMY | UT1 | PMX | PMY | UT1 |
| NEOS Intensive | ----- | ----- | –0.120 ± 0.040 | ----- | ----- | 0.031 ± 0.007 | ----- | ----- | 1.429 |
| GSFC (GSFINT24) | PMX | PMY | UT1 | PMX | PMY | UT1 | PMX | PMY | UT1 |
| NEOS Intensive | ----- | ----- | 0.058 ± 0.028 | ----- | ----- | –0.001 ± 0.002 | ----- | ----- | 1.623 |
| UTCSR (96L01) | PMX | PMY | UT1 | PMX | PMY | UT1 | PMX | PMY | UT1 |
| Lageos | –0.416 ± 0.010 | 0.762 ± 0.009 | ----- | 0.112 ± 0.004 | 0.139 ± 0.003 | ----- | 0.756 | 0.677 | ----- |
| ILRSA (11JUN10) | PMX | PMY | LOD | PMX | PMY | LOD | PMX | PMY | LOD |
| Primary Comb. | 0.004 ± 0.007 | 0.062 ± 0.006 | ----- | 0.002 ± 0.001 | –0.008 ± 0.001 | ----- | 3.025 | 2.988 | ----- |
| GPS (21APR04) | PMX | PMY | LOD | PMX | PMY | LOD | PMX | PMY | LOD |
| JPL Post-Flinn | –0.286 ± 0.016 | 0.174 ± 0.013 | ----- | 0.012 ± 0.015 | –0.035 ± 0.012 | ----- | 1.000 | 1.000 | ----- |
| GPS (IGS95P01) | PMX | PMY | LOD | PMX | PMY | LOD | PMX | PMY | LOD |
| Final Combined | –0.114 ± 0.056 | 0.247 ± 0.056 | ----- | 0.199 ± 0.019 | 0.319 ± 0.020 | ----- | 1.000 | 1.000 | ----- |
| GPS (IGS95P02) | PMX | PMY | LOD | PMX | PMY | LOD | PMX | PMY | LOD |
| Final Combined | 0.124 ± 0.005 | 0.035 ± 0.005 | –0.001 ± 0.018 | –0.012 ± 0.001 | 0.002 ± 0.001 | 0.000 ± 0.002 | 1.000 | 1.000 | 1.000 |
| GPS (IGS00P03) | PMX | PMY | LOD | PMX | PMY | LOD | PMX | PMY | LOD |
| SINEX Comb. | 0.124 ± 0.005 | 0.035 ± 0.005 | –0.001 ± 0.018 | –0.012 ± 0.001 | 0.002 ± 0.001 | 0.000 ± 0.002 | 1.000 | 1.000 | 1.000 |

*Reference date for bias-rate adjustment is 1993.0. See Table 1 footnotes. mas, milliarcseconds; PMX, polar motion X; PMY, polar motion Y.

correction, but given in the natural reference frame of that series. In these cases, uncertainties for the rate corrections are not given. Also note that the entries for the bias-rate corrections in Table 2 for the IGS combined series EOP(IGS) 95 P 02 and EOP(IGS) 00 P 03 are the same. Since these entries were initially given within the same IGS reference frame, they were merged and a common bias-rate correction was determined for them. The entries in Table 2 for the uncertainty scale factors of the JPL GPS polar motion series, all three IGS GPS polar motion series, and both IGS GPS LOD series are unity since, as discussed above, the uncertainties of these series have been reset to their original values prior to forming SPACE2009.

## Combined EOP Series: SPACE2009

A Kalman filter was used to combine the series listed in Table 1 after the bias-rate corrections and uncertainty scale factors listed in Table 2 had been applied to them. The resulting combined Earth orientation series, SPACE2009, consists of values (Figure 1) and 1σ standard errors (Figure 2) for polar motion, Universal Time, and their rates spanning September 28, 1976, to May 28, 2010, at daily intervals; and it is available in versions for which the epochs are given at either midnight or noon. Leap seconds have been restored to UT1, and the effects of the solid Earth and ocean tides have been added back to the UT1 values using the same models for these effects that were originally used to remove them from the raw series: namely, the Yoder et al. (1981) model for the solid Earth tides and the Kantha et al. (1998) model for the ocean tides. However, semidiurnal and diurnal ocean tidal terms have not been added to and are therefore not included in the SPACE2009 UT1 values.

Figure 3 is a plot of the difference between the SPACE2009 polar motion, UT1, and LOD values and those of the IERS combined Earth orientation series EOP(IERS) 05 C 04. These two series are very consistent with each other, especially after January 1, 2000 when the root-mean-square (rms) of their difference is only 0.036 milliarcseconds (mas) for the *x*-component of polar motion, 0.031 mas for the *y*-component, 0.023 milliseconds (ms) for UT1, and 0.017 ms for LOD. Prior to 2000, the difference between these two series exhibits greater variability and even some systematic behavior, particularly in the *x*-component of polar motion. This systematic behavior is due to differences in the approaches used here and by the IERS to correct the bias and rate of the individual series before they are combined.

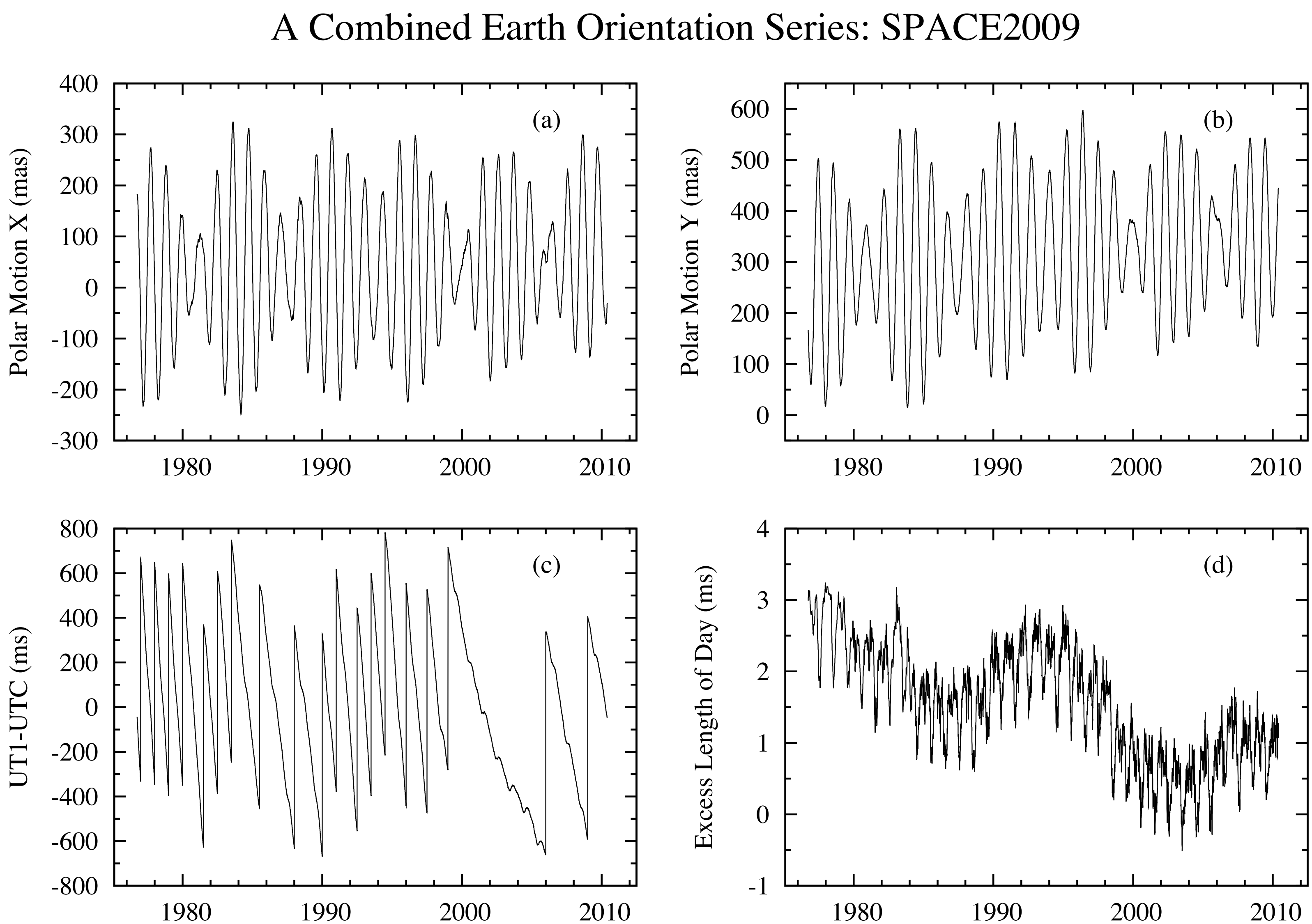


**Figure 1.** Plots of the *x*-component of polar motion (1a), *y*-component of polar motion (1b), UT1–UTC (1c), and excess length-of-day (1d) as given by the combined Earth orientation series SPACE2009. The discontinuous changes in the plot of UT1–UTC are caused by the presence of leap seconds. Note that the UT1–UTC values displayed in 1c include the tidal variations, whereas the excess length-of-day values shown in (1d) do not.

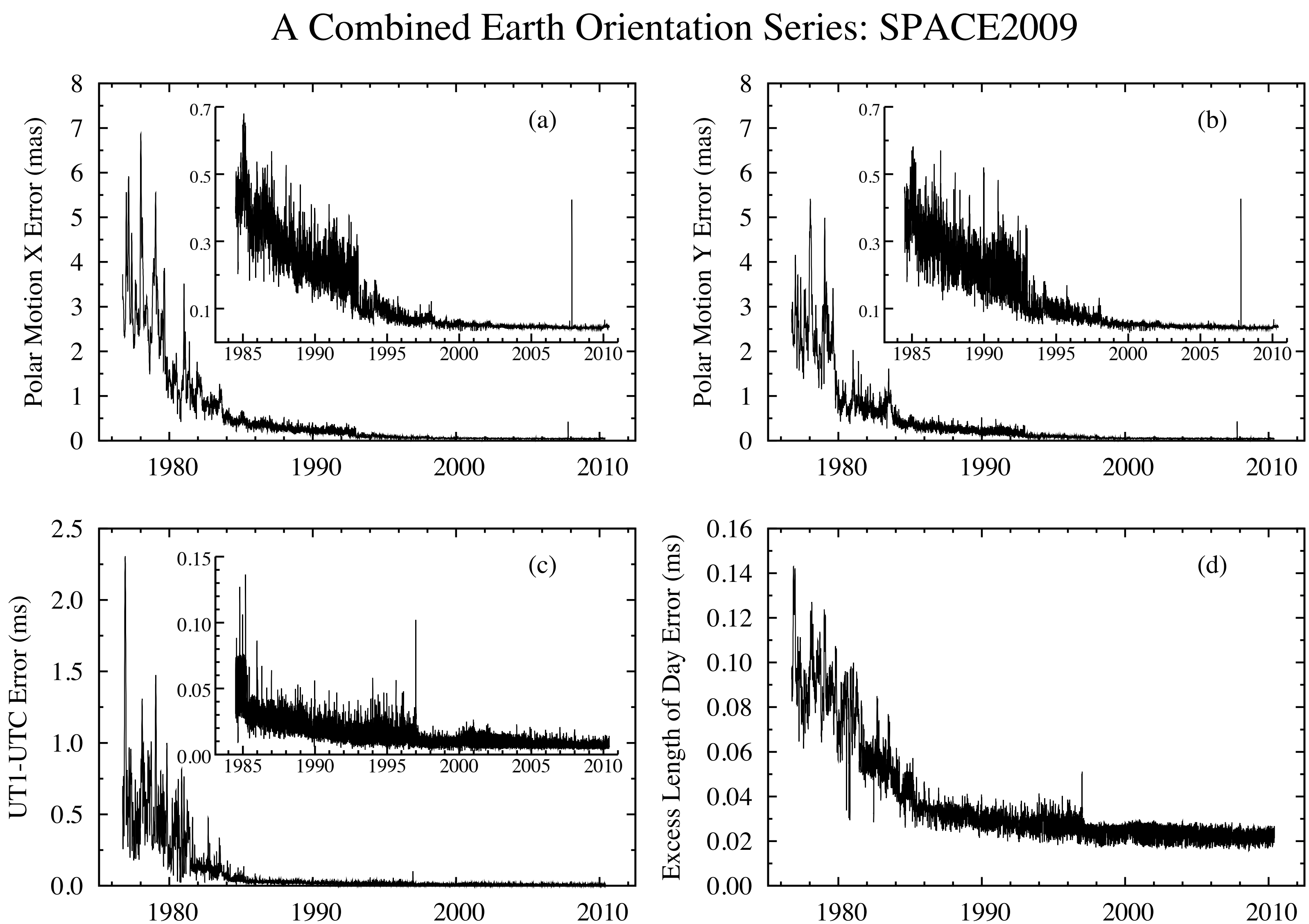


**Figure 2.** Plots of the 1σ formal errors of the *x*-component of polar motion (2a), *y*-component of polar motion (2b), UT1–UTC (2c), and excess length-of-day (2d) as given by the combined Earth orientation series SPACE2009. The inserts within panels (2a), (2b), and (2c) show that component's post-1984 uncertainties on an expanded scale with the same units: milliarcseconds (mas) for polar motion, milliseconds (ms) for UT1-UTC.

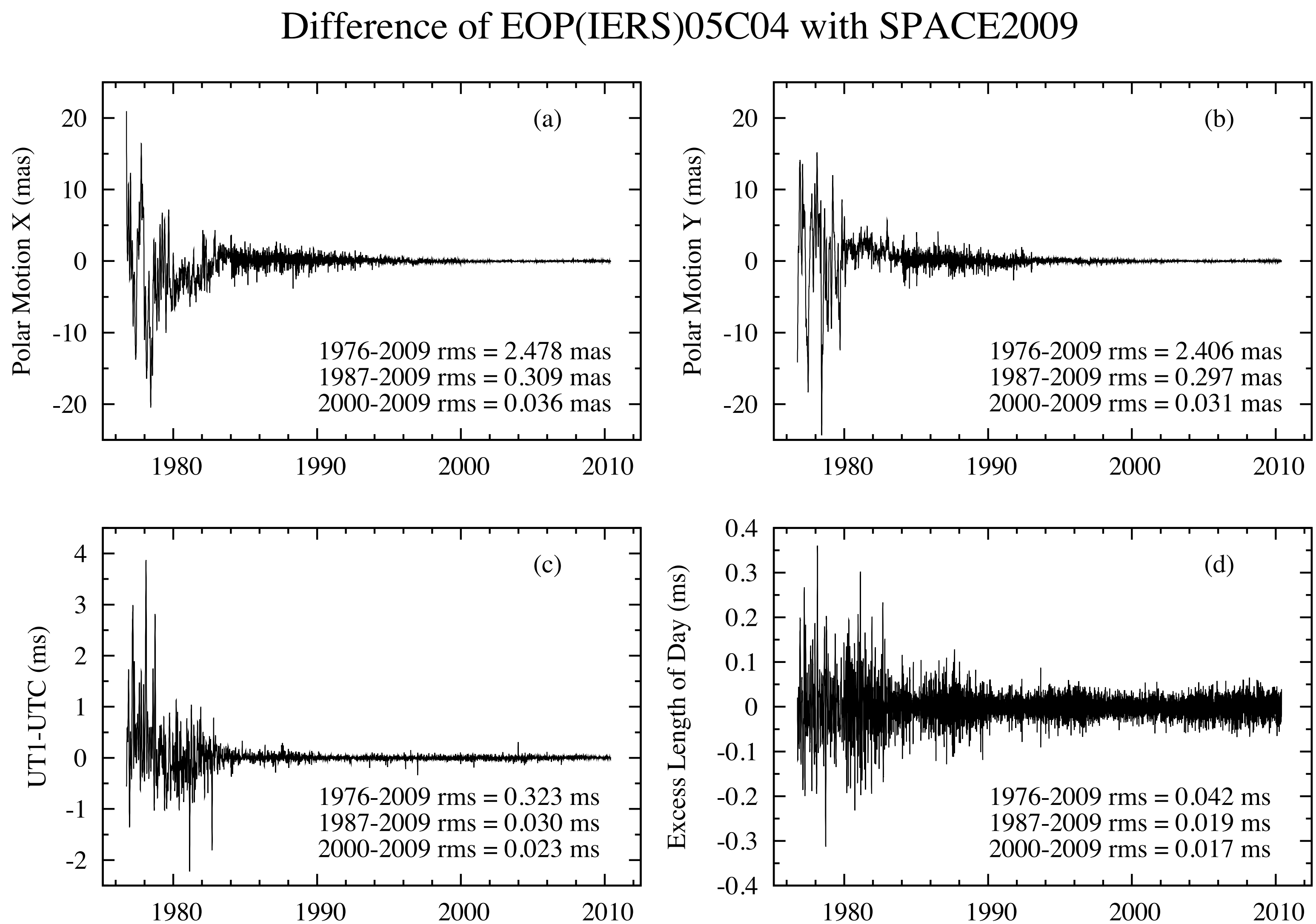


**Figure 3.** Plots of the difference between the IERS combined Earth orientation series EOP(IERS) 05 C 04 and SPACE2009 formed by subtracting the SPACE2009 values from those of the IERS series. The difference between the *x*-component of polar motion is shown in (3a), the difference between the *y*-component is shown in (3b), the difference between UT1–UTC is shown in (3c), and the difference between the excess length-of-day is shown in (3d).

# COMB2009

COMB2009 extends SPACE2009 by additionally incorporating the optical astrometric polar motion and UT1 series that was determined at the Bureau International de l'Heure (BIH) from an analysis of time and latitude observations by Li (1985; also see Li and Feissel 1986). This BIH optical astrometric series consists of values and uncertainties for polar motion and UT1 that span from January 5.0, 1962 to December 31.0, 1981 at 5-day intervals.

## Data Preprocessing and Treatment of Tide-Induced Rotational Variations

The BIH optical astrometric series was first preprocessed by removing leap seconds from the UT1 values and by correcting the UT1 values to be consistent with the extended definition of GST, as adopted by the IERS (IERS 1997, p. I49). Rotational variations caused by solid Earth and ocean tides were also removed from the UT1 values. The same models that were used to remove the tidal effects from the series combined to form SPACE2009 were also used to remove them from the BIH series: namely, the Yoder et al. (1981) model for the solid Earth tides and the Kantha et al. (1998) model for the *Mf*, *Mf'*, and *Mm* ocean tides. However, since the BIH UT1 measurements represent an average value over a 5-day-long observation window, and since 5 days is a substantial fraction of the monthly and shorter-period tides, the amplitudes of these solid Earth and ocean tidal terms were attenuated prior to their removal from the BIH UT1 measurements. (See Gross 1996, p. 8735 and Gross et al. 1998, pp. 226–227 for further discussion about this point.)

## Adjustments Made to BIH Series Prior to Combination

The preprocessed BIH optical astrometric series was combined with the space-geodetic series that comprise SPACE2009 after first: (1) correcting the BIH series to have the same bias, rate, annual terms, and semiannual terms as SPACE2009; (2) applying a constant multiplicative scale factor to the measurement uncertainties of the BIH series so that its residual, when differenced with SPACE2009, had a reduced chi-square of one; and (3) deleting those data points, if any, for which residual values were greater than four times their adjusted uncertainties. Due to software limitations associated with the need to correct the annual and semiannual terms of the BIH series, the above adjustments were determined separately for each component of the BIH series in a univariate approach rather than simultaneously in a multivariate approach as was done for the series combined to form SPACE2009. The procedure used to determine these bias-rate and seasonal term corrections, uncertainty scale factors, and outlying data points has been described before (Gross 1996, pp. 8735–8738) and will not be repeated here. The annual and semiannual terms of the BIH series were adjusted in order to correct for systematic, seasonally varying effects that are known to be present in optical astrometric measurements. Since the values of both the BIH series and the SPACE2009 series are given at midnight, interpolation error (see Gross et al. 1998, pp. 223–225) is automatically minimized when differencing these two series for the purpose of determining the adjustments to be made to the BIH series. Tables 3 and 4 give the resulting uncertainty scale factors and values and 1σ standard errors of the corrections to the bias, rate, annual, and semiannual terms thus determined for the BIH series. When determining these uncertainty scale factors and the corrections to the bias, rate, and seasonal terms, no outlying data points were detected.

## Combined EOP Series: COMB2009

A Kalman filter was used to combine the BIH series with the adjusted space-geodetic series that comprise SPACE2009 after first applying to the BIH series the uncertainty scale factors and corrections to the bias, rate, annual, and semiannual terms that are given in Tables 3 and 4. The resulting combined Earth orientation series, COMB2009, consists of values (Figure 4) and 1σ standard errors (Figure 5) for polar motion, Universal Time, and their rates that span from January 20, 1962, to May 28, 2010, at daily intervals and is available in versions with epochs given at either midnight or noon. Leap seconds have been restored to UT1, and the effects of the solid Earth and ocean tides have been added back to the UT1 values using the same models for these effects that were originally used to remove them: namely, the Yoder et al. (1981) model for the solid Earth tides and the Kantha et al. (1998) model for the ocean tides. The full amplitude (i.e., no tidal terms attenuated) of the effects of the solid Earth and ocean tides at the epoch of the time tag were added back to the UT1 values. Semidiurnal and diurnal ocean tidal terms have not been added to and are, therefore, not included in the COMB2009 UT1 values.

**Table 3.** Adjustments to Bias, Rate, and Stated Uncertainty of Optical Astrometric Series*

| **Data Set** | **Bias, mas** | | | **Rate, mas/yr** | | | **Uncertainty Scale Factor** | | |
|---|---|---|---|---|---|---|---|---|---|
| | **PMX** | **PMY** | **UT1** | **PMX** | **PMY** | **UT1** | **PMX** | **PMY** | **UT1** |
| BIH | –2.172 ± 0.862 | –0.781 ± 0.709 | –7.890 ± 1.081 | 1.096 ± 0.532 | 1.166 ± 0.434 | 5.561 ± 0.677 | 1.831 | 1.703 | 1.952 |
| ILS | –50.737 ± 2.382 | –2.999 ± 1.697 | ----- | 0.460 ± 0.487 | –0.048 ± 0.346 | ----- | 2.182 | 1.530 | ----- |

*Reference date for bias-rate adjustment of BIH series is 1980.0. Reference date for bias-rate adjustment of ILS series is 1970.0.

**Table 4.** Adjustment to Annual and Semiannual Terms of Optical Astrometric Series*

| **Data Set** | **Coefficient of Sine Term, mas** | | | **Coefficient of Cosine Term, mas** | | |
|---|---|---|---|---|---|---|
| | **PMX** | **PMY** | **UT1** | **PMX** | **PMY** | **UT1** |
| BIH | | | | | | |
| annual | –5.702 ± 1.062 | –7.038 ± 0.894 | 5.288 ± 1.395 | –2.846 ± 1.133 | 9.743 ± 0.935 | –0.958 ± 1.450 |
| semiannual | 2.196 ± 1.084 | –0.263 ± 0.909 | –0.351 ± 1.421 | 1.031 ± 1.107 | 0.958 ± 0.916 | 1.721 ± 1.422 |
| ILS | | | | | | |
| annual | –2.427 ± 3.322 | 8.573 ± 2.359 | ----- | 8.057 ± 3.359 | –10.193 ± 2.389 | ----- |
| semiannual | 0.168 ± 3.331 | 9.022 ± 2.367 | ----- | 2.305 ± 3.347 | 1.684 ± 2.379 | ----- |

*Reference date for adjustment of annual and semiannual terms of BIH series is 1980.0.
Reference date for adjustment of annual and semiannual terms of ILS series is 1970.0.

# A Combined Earth Orientation Series: COMB2009

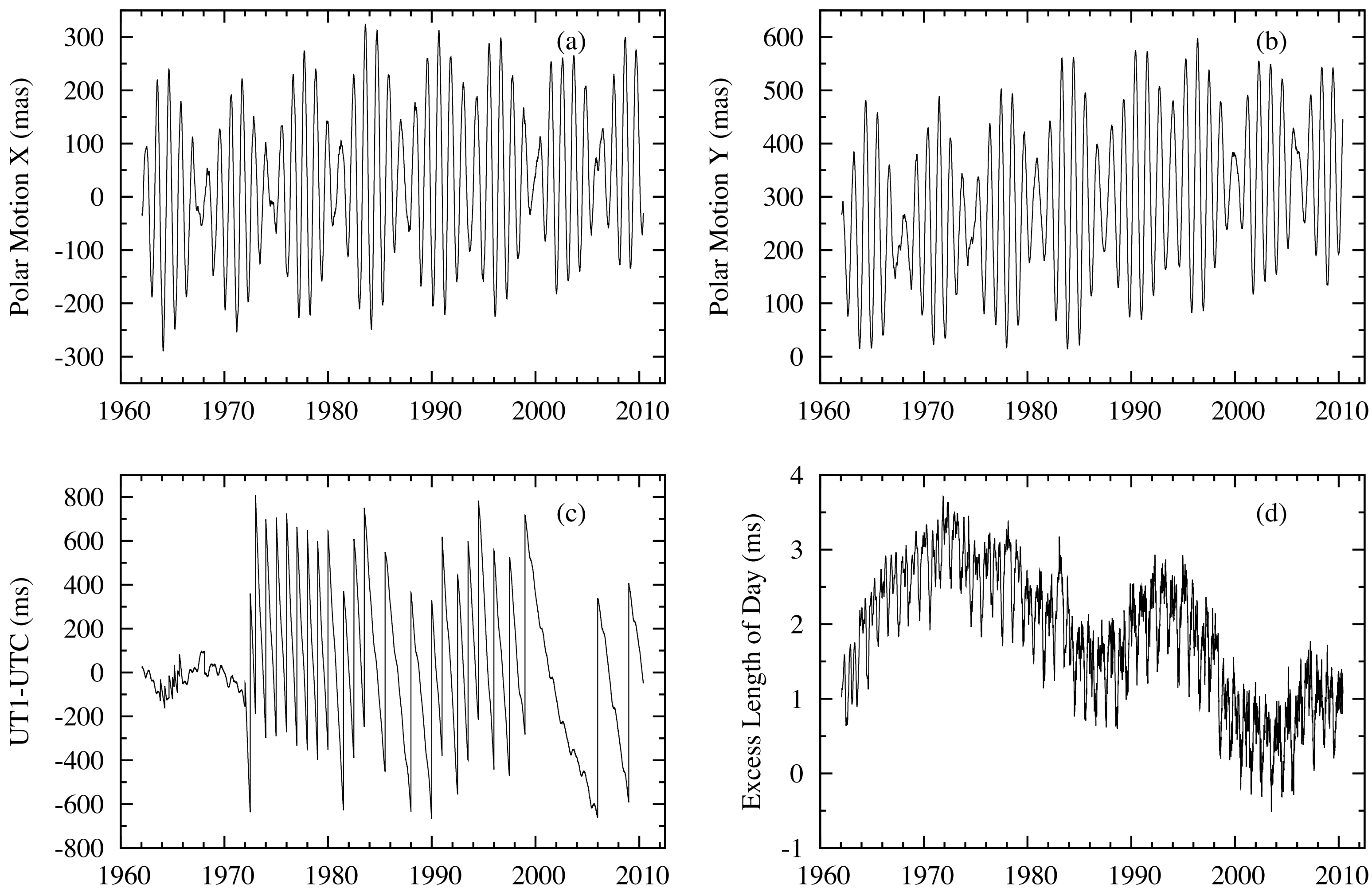


**Figure 4.** Plots of the *x*-component of polar motion (4a), *y*-component of polar motion (4b), UT1–UTC (4c), and excess length-of-day (4d) as given by the combined Earth orientation series, COMB2009. The discontinuous changes in the plot of UT1–UTC are caused by the presence of leap seconds. Prior to the introduction of leap seconds in 1972, Coordinated Universal Time (UTC) was adjusted by introducing step and rate changes designed to keep it close to UT1 (e.g., IERS 1997, Table II-3), the effect of which is also readily apparent in (4c). Note that the UT1–UTC values displayed in (4c) include the tidal variations, whereas the excess length-of-day values shown in (4d) do not.

A Combined Earth Orientation Series: COMB2009

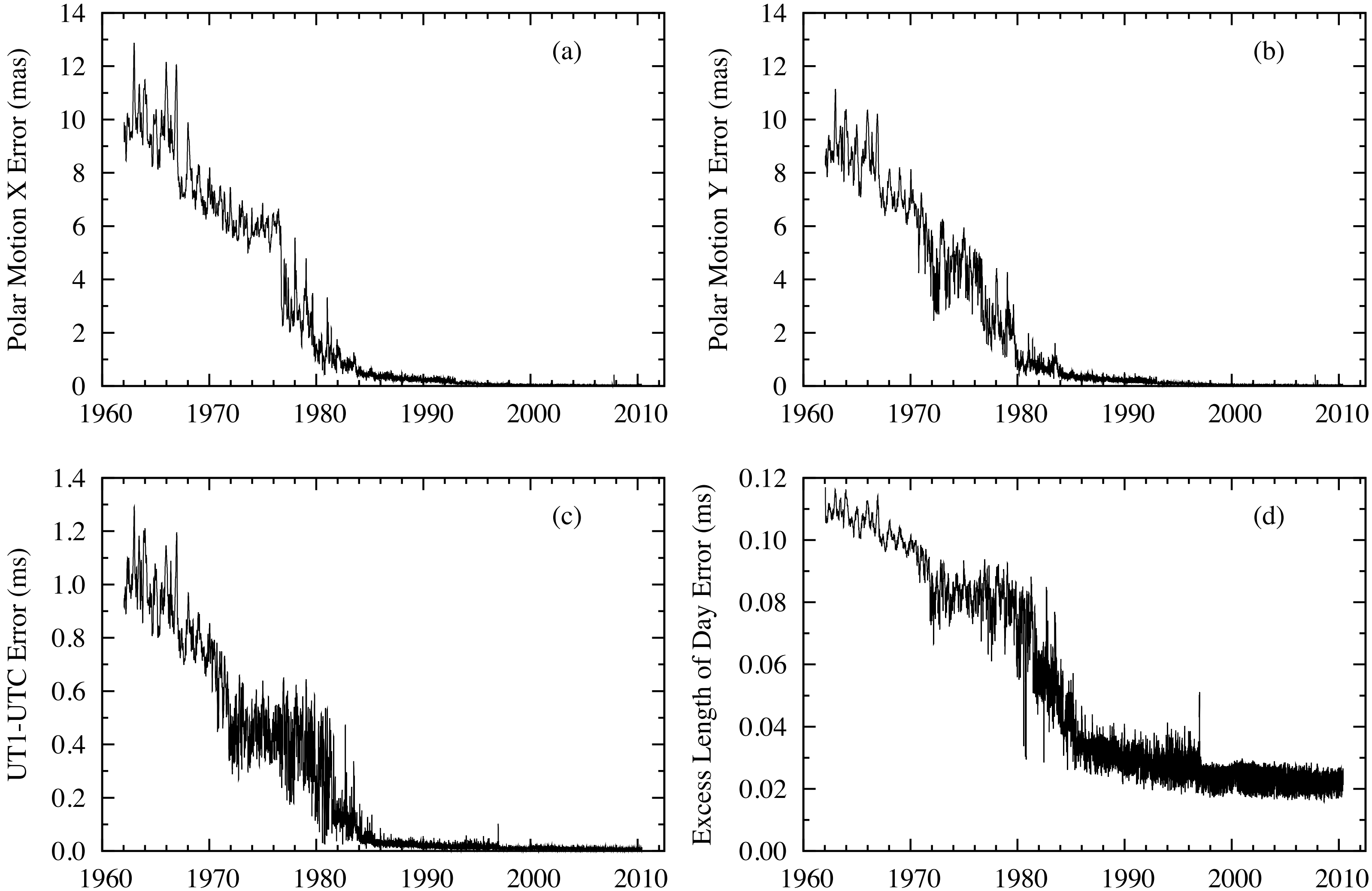


**Figure 5.** Plots of the 1σ formal errors of the *x*-component of polar motion (5a), *y*-component of polar motion (5b), UT1–UTC (5c), and excess length-of-day (5d) as given by the combined Earth orientation series COMB2009.

# POLE2009

No optical astrometric observations taken at the stations of the International Latitude Service (ILS) were used when creating the BIH optical astrometric series used in COMB2009 (Li 1985; Li and Feissel 1986). The ILS polar motion measurements (Yumi and Yokoyama 1980), which are based solely upon latitude observations made at the ILS stations are, therefore, independent of those comprising COMB2009 and have therefore been combined with them to form POLE2009. Being based solely upon latitude observations, the ILS series contains no UT1 measurements, but consists solely of polar motion measurements that span 1899.8–1979.0 at monthly intervals. Although no uncertainties are given with the individual polar motion values, the precision with which they have been determined is estimated to be 10–20 mas (Yumi and Yokoyama 1980, p. 27). An initial uncertainty of 15 mas was, therefore, assigned to each of the ILS polar motion values. Since this assigned measurement uncertainty will be adjusted later, its initial value is arbitrary as long as it is not zero and serves merely as an a priori estimate to be used in the series adjustment procedure described below.

The ILS series was combined with COMB2009 to form POLE2009 after: (1) correcting the ILS series to have the same bias, rate, annual, and semiannual terms as COMB2009; (2) applying a constant multiplicative scale factor to the measurement uncertainties of the ILS series so that its residual, when differenced with COMB2009, had a reduced chi-square of one; and (3) deleting those data points, if any, whose residual values were greater than four times their adjusted uncertainties. Again, due to software limitations associated with the need to correct the annual and semiannual terms, these adjustments were determined separately for the *x*- and *y*-components of the ILS polar motion series by fitting a bias, rate, and these seasonal terms to the difference of the ILS series with COMB2009 during 1962.0 to 1979.0. The measurement uncertainties of the ILS polar motion values were adjusted by determining and applying a scale factor that made the residual of this fit have a reduced chi-square of one. During this procedure to determine uncertainty scale factors and bias, rate, and seasonal term corrections, no outlying ILS data points were deleted since no data points had residual values greater than four times their adjusted uncertainties. Tables 3 and 4 (in the COMB2009 section) also give the resulting uncertainty scale factors and values and 1$\sigma$ standard errors of the corrections to the bias, rate, annual, and semiannual terms thus determined for the ILS series.

A Kalman filter was then used to combine the ILS series with the adjusted BIH and space-geodetic series that comprise COMB2009, after applying to the ILS series the uncertainty scale factors and corrections to the bias, rate, annual, and semiannual terms that are given in Tables 3 and 4. The resulting combined Earth orientation series, POLE2009, consists of values (Figure 6a and 6b) and 1$\sigma$ standard errors (Figure 6c and 6d) for polar motion and its rate that span from January 20, 1900, to May 22, 2010, at 30.4375-day intervals.

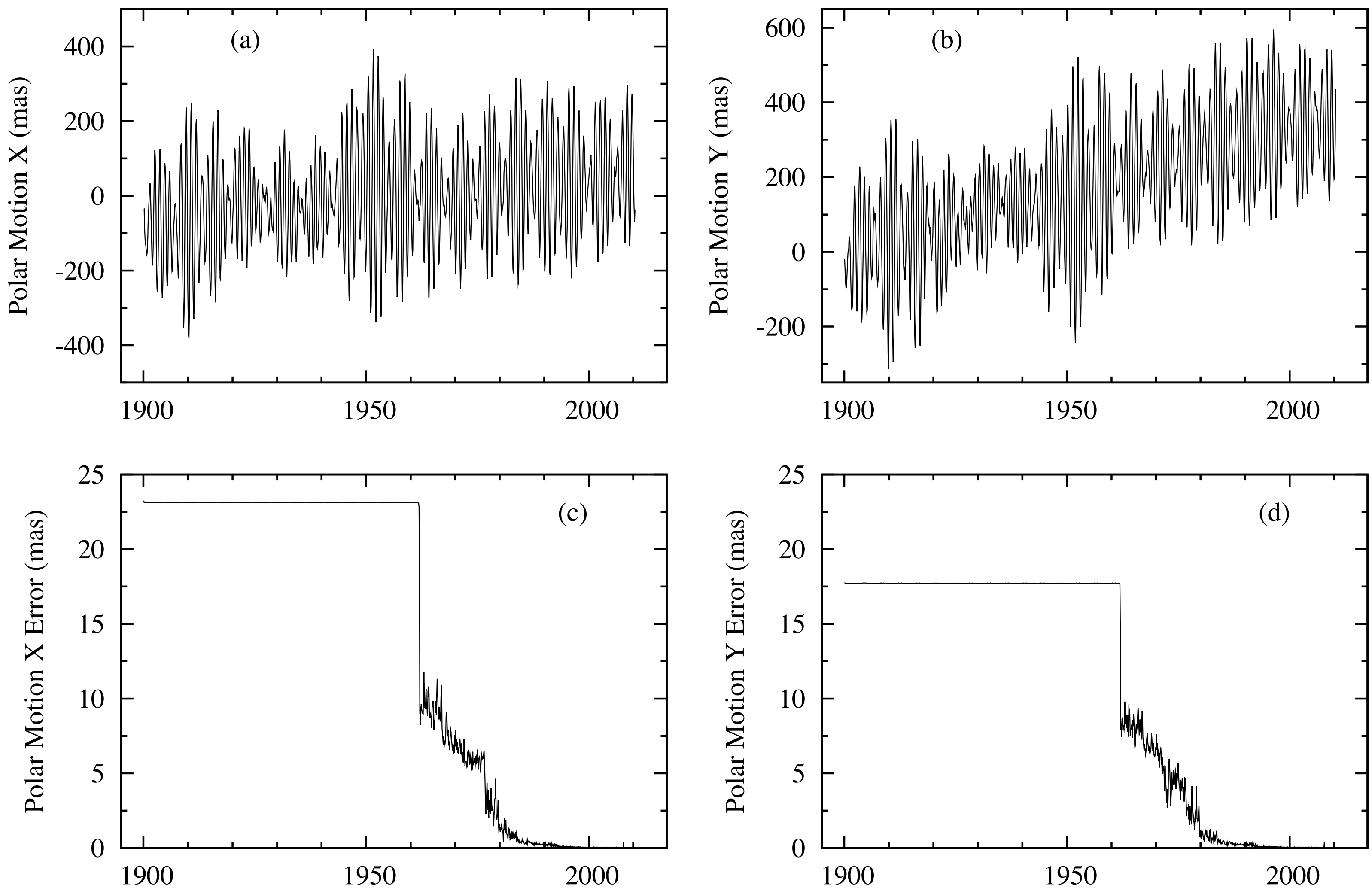


**Figure 6.** Plots of the *x*-component of polar motion (6a), the *y*-component of polar motion (6b), the 1σ formal errors of the *x*-component of polar motion (6c), and the 1σ formal errors of the *y*-component of polar motion (6d) as given by the combined polar motion series POLE2009.

# DISCUSSION

The Kalman filter that was used here to combine Earth-orientation measurements contains a stochastic model of the process that is used to propagate the state vector and its associated state covariance matrix forward in time to the epoch of the next measurement. For polar motion excitation, the stochastic model includes a random-walk term with equal noise forcing both the *x*- and *y*-components of excitation and having a white-noise power spectral density of 246.4 $mas^2$/day (Morabito et al. 1988). This level of polar motion excitation process noise in the Kalman filter was recently increased to 739.2 $mas^2$/day in order to better match the observed spectrum of polar motion excitation. Increasing the excitation process noise reduces the level of smoothing applied to the polar motion components of the propagated state vector and increases the covariance associated with those components. Thus, the SPACE2009, COMB2009, and POLE2009 polar motion and polar-motion excitation values are not as heavily smoothed as were those of SPACE2003, COMB2003, POLE2003 and earlier combinations produced at JPL; and the uncertainties assigned to the SPACE2009, COMB2009, and POLE2009 polar motion and polar-motion excitation values are somewhat larger.

The LOD components of the IGS Final combined EOP(IGS) 95 P 02 and EOP (IGS) 00 P 03 series were incorporated into JPL's combinations starting with SPACE2007 and COMB2007. In general, GPS LOD estimates are contaminated by orbital artifacts that must be removed prior to combination with other LOD or UT1 measurements (Chin et al., 2009). When determining the IGS Final combined LOD series, however, the IGS applies constraints that have the effect of removing these orbital artifacts. Therefore the IGS Final combined LOD series was incorporated into the Kalman filter as a true LOD measurement whose uncertainties are assumed to be "white" (i.e., random, uncorrelated in time, and with a flat power spectral density). Including the daily IGS Final combined LOD series in JPL's combinations helps to compensate for less frequent UT1 measurements and was found to improve the agreement of JPL's combined LOD estimates with independent atmospheric and oceanic angular momentum values, especially at the highest frequencies.

Since a Kalman filter has been used in generating SPACE2009, COMB2009, and POLE2009, the resulting polar motion and UT1 values are smoothed to a degree that depends upon both the spacing between the measurements being combined (which determines how far the state vector and state covariance matrix must be propagated forward in time) and the uncertainties that have been assigned to the measurements. Since improvements to the observing systems, both in the hardware and software and in the number of systems, have led to increasingly precise determinations of the Earth's orientation, and since the time resolution of the measurements has generally increased in concert with the measurement precision, the degree of smoothing applied to the SPACE2009, COMB2009, and POLE2009 values is a function of time, with the earlier values being more heavily smoothed than the more recent values.

Daily EOP values are reported in SPACE2009 since the NOAA IRIS and GSFC NEOS Intensive UT1 values are given at daily intervals, as are the GPS and ILRSA combined SLR values (although gaps exist in each of these data sets). However, prior to the start of these data sets, the measurements combined to form SPACE2009 are given less frequently; therefore, the Kalman filter used to combine these measurements also interpolates them in order to produce a series of equally spaced values. In order to be consistent with SPACE2009, daily EOP values are also reported in COMB2009 even though the BIH optical astrometric series used in COMB2009 is given at 5-day intervals. Thus, SPACE2009, COMB2009, and POLE2009 are equally spaced series of smoothed, interpolated Earth-orientation parameters.

The combined Earth-orientation series SPACE2009, COMB2009, and POLE2009 are available from JPL's Geodynamics and Space Geodesy Group via anonymous ftp:

<ftp://euler.jpl.nasa.gov/keof/combinations/2009>

and upon request from the authors: Todd.Ratcliff@jpl.nasa.gov or Richard.Gross@jpl.nasa.gov.

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## Acronyms and Terms

| | |
|---|---|
| ASI | Agenzia Spaziale Italiana |
| BIH | Bureau International de l'Heure |
| CGS | Centro di Geodesia Spaziale |
| CODE | Center for Orbit Determination in Europe |
| COMB | extends the SPACE series by additionally incorporating BIH optical astrometric measurements of polar motion and UT1 |
| DSN | Deep Space Network |
| EOP | Earth orientation parameters |
| GNSS | International Global Navigation Satellite System |
| GPS | Global Positioning System |
| GSFC | Goddard Space Flight Center |
| GST | Greenwich Sidereal Time |
| IERS | International Earth Rotation and Reference Systems Service |
| IGS | International Global Navigation Satellite System (GNSS) Service |
| ILRS | International Laser Ranging Service |
| ILS | International Latitude Service |
| IRIS | International Radio Interferometric Surveying |
| ITRF | International Terrestrial Reference Frame |
| JPL | Jet Propulsion Laboratory |
| LLR | lunar laser ranging |
| LOD | length-of-day |
| NASA | National Aeronautics and Space Administration |
| NEOS | National Earth Orientation Service |
| NOAA | National Oceanic and Atmospheric Administration |
| NRCan | Natural Resources Canada |
| OCA | Observatoire de la Côte d'Azur |
| POLE | extends the COMB series by additionally incorporating ILS optical astrometric measurements of polar motion |
| SINEX | Solution Independent Exchange |
| SLR | satellite laser ranging |
| SPACE | a combination of independent space-geodetic measurements of the Earth's orientation |

| | |
|---|---|
| T | transverse component of Earth orientation from single-baseline VLBI |
| USNO | United States Naval Observatory |
| UT | Universal Time |
| UT1 | the principle form of Universal Time; conceptually, it is mean solar time |
| UTC | Coordinated Universal Time |
| UTCSR | University of Texas Center for Space Research |
| V | vertical component of Earth orientation from single-baseline VLBI |
| VLBI | very long baseline interferometry |
| VOL | variation of latitude |