Accuracy of Earth Orientation Parameter Estimates and Short-Term Predictions Generated by the Kalman Earth Orientation Filter

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The Kalman Earth Orientation Filter (KEOF) software developed at the Jet Propulsion Laboratory (JPL) is used operationally to generate Earth orientation parameter (EOP) estimates and predictions of polar motion x (PMX), polar motion y (PMY), and Universal Time (UT1) in support of all JPL interplanetary flight projects. The estimates and predictions are made based on Earth orientation measurements obtained with very long baseline interferometry (VLBI) and satellite laser ranging (SLR), supplemented by atmospheric angular momentum (AAM) forecasts. KEOF uses empirically based stochastic models for the short-term behavior of Earth orientation to interpolate the data optimally and extrapolate the Earth orientation time series to generate near-real-time estimates and short-term predictions. Estimates and predictions made using incomplete raw data sets are evaluated for their accuracy by comparing them with Earth orientation series generated when complete data sets have become available for the time periods in question. The Deep Space Network (DSN) has a general requirement that the knowledge of the Earth's orientation should be accurate to within 30 cm (1σ) in each of the three EOP components. The root-mean-square (rms) accuracy of the KEOF EOP calibrations available to the navigation teams typically is better than 13 cm in PMX, 11 cm in PMY, and 17 cm in UT1. EOP estimates prior to a week before the day the calibrations are generated are accurate at the 3-cm-or-better level.

I. Introduction

Earth orientation parameter (EOP) estimates have been required by the Deep Space Network (DSN) for interplanetary spacecraft tracking since the early days of the space program. As tracking accuracy and navigation requirements have increased, so has the need for precise estimates of the Earth's position and orientation in space. In particular, the need for near-real-time estimates and short-term predictions of Earth orientation for spacecraft navigation has motivated the development of JPL support programs to provide accurate, timely estimates of Earth orientation for the tracking and navigation teams. The Time and Earth Motion Precision Observations (TEMPO) project and the Kalman Earth Orientation Filter (KEOF) software package are the cornerstones of these support programs.

Technically, there are five Earth orientation parameters (EOPs): polar motion x (PMX), polar motion y (PMY), Universal Time (UT1), a nutation correction in ecliptic longitude ($\Delta\Psi$), and a nutation correction in obliquity ($\Delta\varepsilon$). It is not difficult to model and predict the two nutation corrections to within 3 cm for periods up to about one year [1]. However, PMX, PMY, and especially UT1 vary rapidly and unpredictably in time; thus, estimating and predicting these three parameters is an ongoing challenge. PMX and PMY specify the coordinates of the point where the Earth's spin axis pierces its surface near the north pole. UT1 is a measure of the angular rotation of the Earth about its spin axis. PMX, PMY, and UT1 are collectively referred to as Universal Time and polar motion (UTPM). UT1 varies the most dramatically of the three UTPM parameters, thereby posing the greatest challenge to real-time estimation and prediction [2].

Kalman filtering of Earth orientation parameters, the operational use of KEOF Earth orientation estimates and predictions, general mission accuracy requirements, and the KEOF navigation file formats are discussed in Section II. The raw data sets used in the operational KEOF are explained in Section III. The method of monitoring the accuracy of the operational EOP predictions is explained in Section IV. It will be shown that the current navigational requirements are met and exceeded when KEOF receives the correct combination of timely, accurate raw data. New mission accuracy requirements and an anticipated change in KEOF are described in the final section.

II. The Operational Kalman Earth Orientation Filter

The Kalman Earth Orientation Filter, developed at JPL, is used to generate UTPM estimates and predictions. In operational use, KEOF combines Earth orientation raw data sets obtained with very long baseline interferometry (VLBI) and satellite laser ranging (SLR) supplemented by atmospheric angular momentum (AAM) forecasts. KEOF optimally interpolates the raw data and extrapolates the Earth orientation time series to generate UTPM estimates and short-term UTPM predictions.

VLBI measurements can determine all Earth orientation components. The SLR technique can reliably monitor PMX and PMY; however, because of drifts in the satellite orbit node, SLR cannot unambiguously monitor UT1. Therefore, only the PMX and PMY measurements from SLR are used in KEOF. The axial components of AAM data are used by KEOF to supplement knowledge of the UT1 component of Earth orientation. The axial component of AAM and the length of day (LOD) form a conserved system and are closely correlated; LOD is proportional to the negative time derivative of UT1.

Earth orientation data from rapid turnaround monitoring programs are of particular importance in predicting the highly variable UT1. Of all the monitoring programs, TEMPO VLBI from JPL and AAM forecasts from the National Centers for Environmental Prediction (NCEP)[1] have the most rapid turnaround times. These two data types are relied upon heavily for high-quality UT1 predictions.

KEOF explicitly models the idiosyncrasies of the various space–geodetic techniques used by the contributing EOP monitoring programs. It also takes into account the variable quality and temporal density of the raw data sets by varying the amount of smoothing according to the accuracy and density of the data and by providing uncertainties for the estimates of the smoothed time series consistent with the raw data accuracy and density [2,3].

KEOF uses empirically based stochastic models to characterize unpredictable changes in Earth orientation. These stochastic models are derived from power spectral analyses of both EOP and AAM time series [4]. Atmospheric angular momentum, a vector quantity, is composed of three components: two equatorial components and an axial (polar) component. The equatorial components excite or drive polar motion. The axial component is associated with length-of-day changes. All three AAM components are used to derive the KEOF stochastic models.

[1] Formerly the National Meteorological center (NMC).

Earth orientation parameter estimates and predictions produced by the operational Kalman Earth Orientation Filter are aligned with the International Terrestrial Reference Frame (ITRF) and the International Celestial Reference Frame (ICRF), both maintained by the International Earth Rotation Service (IERS) in Paris, France [5]. The alignment of the KEOF EOP series with the ITRF and the ICRF is accomplished by applying bias and rate corrections to each input raw data series to make it consistent with the ITRF and the ICRF. Hence, the output KEOF series also is consistent with the ITRF and the ICRF.

In order to meet general navigational needs, in 1988 the DSN adopted the following general Earth orientation prediction error requirements:[2,3]

(1) 30 cm (1σ) in each component (PMX, PMY, and UT1) for the days on which the calibrations are generated.

(2) 5 cm (1σ) in each component for periods greater than 14 days prior to the day on which the calibrations are generated.

Larger errors are allowed for periods prior to 1985, when the quantity of data was less and their quality much poorer than is now the case.

In this article, KEOF "final estimates" are defined to be those meeting Requirement (2). These estimates are produced by KEOF when all operational raw data for a particular time span have become available. This typically occurs in 10 to 14 days. "Provisional estimates" meet Requirement (1) and are generated when only a partial set of geodetic data are available. Ordinarily, some data become available near the time of the KEOF run. "Short-term predictions" also meet Requirement (1). They are made without geodetic data, using only AAM 5-day forecasts and the KEOF stochastic models.

KEOF-produced Earth orientation estimates and predictions are made available to the JPL spacecraft navigation teams in two file formats: the Earth orientation parameter (EOP) file format and the standby timing operation in contingencies (STOIC) file format. Both files include Earth orientation (UTPM) estimate and prediction calibrations. UTPM calibrations are used by the spacecraft navigation teams to rotate DSN station locations from the noninertial Earth-fixed reference frame to the inertial celestial reference frame.

The EOP file format was developed in 1993.[4] It currently is being posted twice weekly on both the OSCAR computer network and on the EOP files web page. In addition to the UTPM calibrations, the EOP file includes the two nutation corrections, $\Delta\Phi$ and $\Delta\varepsilon$. These corrections help determine the station locations in the celestial reference frame to the few-centimeter level. There is no limit on the number of calibrations that may be included in the EOP file.

The STOIC file format has long been the standard navigation Earth-orientation calibration file. It is posted weekly on the OSCAR computer network. Unlike the EOP file, the STOIC file does not include the two nutation corrections. Also, the STOIC file size is limited to 37 UTPM calibrations. The STOIC file posted weekly on OSCAR spans about one and one-half years of UTPM estimates and about 2 months

[2] *Network Operations Control Center Subsystem Functional Requirements: Navigation Subsystem (1988 Through 1993)*, JPL 822-18, Rev. A (internal document), Jet Propulsion Laboratory, Pasadena, California, pp. 3-7–3-8, May 15, 1988.

[3] Although centimeters (cm) are the units of measure used here, milliarcseconds (mas), milliseconds (ms), and nanoradians (nrad) often are used when referring to Earth orientation. A displacement at the Earth's (equatorial) surface of 30 cm corresponds to an angular displacement of 9.70 mas or 47.0 nrad, which equals 0.645 ms of time for UT1.

[4] W. M. Folkner, J. A. Steppe, and S. H. Oliveau, "Earth Orientation Parameter (EOP) File Description and Usage," JPL Interoffice Memorandum 335.1-11-93 (internal document), Jet Propulsion Laboratory, Pasadena, California, May 21, 1993.

of predictions. In order to accommodate the 37 calibration limitation, the spacing between the UTPM values in the STOIC file must be 18 days. This spacing severely compromises interpolation accuracy.

The limitations of the STOIC file format led to the development of the EOP file. The JPL Working Group on Reference Frame Standards recommends the use of the EOP file format for all navigational purposes.[5]

III. Raw Data Sets

For operational estimates of UTPM, only high-precision data types that are available in a timely fashion are used in KEOF. Table 1 summarizes the characteristics of these various data sets, which are described more fully below. Additional information may be found in [5–7].

Table 1. Data types used in the operational KEOF.

Project	Center	Technique	Measurements used in KEOF	Frequency of data	Frequency of delivery, FY 1996 (usual day)	Usual age at time of semiweekly KEOF runs, days	Median adjusted uncertainties, FY 1996, cm
TEMPO	JPL	Single-baseline VLBI	Transverse and vertical baseline rotation components	2/week, 1 from each of 2 baselines: Australia-to-California and Spain-to-California	Semiweekly	2–3	Error ellipse axes: minor = 1.5 major = 5.1
IRIS intensive	USNO	Single-baseline VLBI	UT1–UTC	Nominally 5/week	Semiweekly	4–7	UT1 = 1.5
NAVNET	USNO	Multi-baseline VLBI	PMX PMY UT1–UTC	1/week, but also includes NAVNET analyses of raw data from other multi-baseline VLBI services	Weekly (Wed.)	9–13	PMX = 1.2 PMY = 0.8 UT1 = 1.1
SLR	University of Texas	SLR	PMX PMY	Every 2–3 days	Weekly (Tues.)	4–8	PMX = 1.3 PMY = 1.4
NCEP ϕ hour	NCEP	AAM	AAM forecasts ϕ hour	1/day	Daily	1	2.3
NCEP 5 day	NCEP	AAM	AAM forecasts 5 day	1/day	Daily	1	2.3

[5] R. J. Dewey, "Report of the Working Group on Reference Frame Standards," JPL Interoffice Memorandum 314.5-1754 (internal document), Jet Propulsion Laboratory, Pasadena, California, April 18, 1994.

The reported uncertainties of the geodetic measurements differ considerably among the various techniques. There is evidence that some of these uncertainties may be overly optimistic [5]. Since the Kalman filter requires accurate error uncertainties when assimilating the raw data, the reported uncertainties are adjusted in operational KEOF processing to a level consistent with the rms scatter over the last several years of the measurement residuals.

Currently, five services provide the data used in KEOF operationally:

(1) The JPL Time and Earth Motion Precision Observations (TEMPO) project provides two single-baseline VLBI Earth orientation measurements per week. Each measurement is based on VLBI observations of about 17 different compact extragalactic radio sources. One of the semiweekly sets of observations is made on the DSN Australia–California (AC) baseline, the other set on the Spain–California (SC) baseline. The data are telemetered back to JPL from the observing sites, allowing for very rapid turnaround and, thus, near-real-time UTPM information. The TEMPO data are reduced at JPL and are made available to KEOF as soon as processing is complete. When conditions are ideal, 24-hour turnaround can be achieved, although a 2-day delay is more typical. Each TEMPO measurement provides Earth orientation information in two dimensions: transverse and vertical with respect to the baseline. These are equivalent to changes in UT0 (an observatory-specific version of UT1) and variation of latitude of the baseline vector, which are linear combinations of UTPM. The TEMPO uncertainties are reported along the major and minor axes of the error ellipses in the UT0 variation of the latitude plane. The orientation of the error ellipse is determined mostly by the global station geometry. Over fiscal year (FY) 1996, the median of the adjusted uncertainty on the minor axis (the well-determined direction) was 1.5 cm; the median adjusted uncertainty on the major axis was 5.1 cm. The TEMPO data typically are 2 to 3 days old when the twice weekly KEOF is run.

(2) The United States Naval Observatory (USNO) nominally provides five single-baseline VLBI UT1–UTC (Universal Time–Coordinated Universal Time) measurements per week from the International Radio Interferometric Surveying (IRIS) INTENSIVE program. The IRIS INTENSIVE 1-hour observing sessions take place on the Wettzell, Germany–Green Bank, West Virginia transatlantic baseline. IRIS INTENSIVE UT1–UTC data usually are distributed twice weekly. Over fiscal year 1996, the median of the adjusted UT1–UTC uncertainty was 1.5 cm. The IRIS data typically are 4 to 7 days old when the twice weekly KEOF is run.

(3) The USNO also provides one new multibaseline VLBI UTPM estimate per week from its Navy VLBI Network (NAVNET) program. Five observation stations—Wettzell, Germany; Green Bank, West Virginia; Fairbanks, Alaska; Kokee, Kauai, Hawaii; and Fortaleza, Brazil—participate in each week's 24-hour observing session. The NAVNET VLBI data are distributed weekly. In addition to new NAVNET UTPM data, the weekly distribution file also includes the NAVNET reduction of sporadic multibaseline VLBI data available from other observing programs. Over fiscal year 1996, the median of the adjusted uncertainty was 1.2 cm in PMX, 0.8 cm in PMY, and 1.1 cm in UT1–UTC. The NAVNET data typically are 9 to 13 days old when the twice weekly KEOF is run.

(4) The Center for Space Research (CSR) of the University of Texas at Austin provides SLR measurements of polar motion at 2- to 3-day intervals. CSR SLR data are distributed weekly. Over fiscal year 1996, the median of the adjusted uncertainty was 1.3 cm in PMX and 1.4 cm in PMY. The SLR data typically are 4 to 8 days old when the twice weekly KEOF is run.

(5) The National Centers for Environmental Prediction (NCEP) provide AAM forecast values on a daily basis. Once each day, AAM is calculated for a forecast interval at the zero hour (midnight) and then at multiples of 12-hour intervals out to 10 days. The estimated value (what NCEP refers to as the zero-hour forecast) is based primarily on daily worldwide meteorological measurements. The predictions (multiples of the 12-hour intervals) are based on dynamical models of the atmosphere. AAM zero-hour and 120-hour (5-day) forecasts are used in the operational KEOF. AAM data routinely are available within 24 hours of the zero-hour measurement epoch. There is no uncertainty reported for the AAM data. Determining the adjusted uncertainty level for AAM is a challenging problem; in routine operation, a conservative estimate of 2.3 cm is used. The AAM data are almost always 1 day old when the twice weekly KEOF is run.

IV. KEOF Estimation and Prediction Accuracy

Formal uncertainties (1σ) of the operational KEOF estimates for fiscal year 1996 range between 0.5 and 1.0 cm for each UTPM component. Systematic errors also may exist in the raw data sets and, therefore, also exist in combinations of those raw data sets. These are unlikely to add more than 1 to 2 cm of error. Thus, realistic 1-σ errors in the KEOF estimates are probably under 3 cm.

Evaluating the true accuracy of the KEOF final estimates is difficult because no significantly better EOP reference series exists. The best that can be done is to compare KEOF output with other smoothed EOP estimates. Comparison between KEOF output and other EOP series has been made by the IERS [5] and indicates relative accuracies better than 1.5 cm in PMX and PMY and 2 cm in UT1, consistent with the formal errors. KEOF final estimates, therefore, meet the 5-cm accuracy requirements listed in Section II.

KEOF has consistently provided high-quality provisional estimates of UTPM as well as the best available short-term predictions of UTPM [2]. The accuracy of the UTPM provisional estimates and short-term predictions and their uncertainties are monitored by comparing them with a reference KEOF Earth orientation series generated when complete data sets are available for the time periods in question.

Figure 1 displays the prediction errors for the time span from October 1, 1995, to September 30, 1996 (fiscal year 1996). The figure is divided into three sections: one for PMX, one for PMY, and one for UT1–UTC. The lower case symbols “x,” “y,” and “t” (for PMX, PMY, and UT1–UTC, respectively) represent the differences between the short-term predictions and the final estimates for each day. The displayed error bars indicate the ± 2-σ uncertainty in centimeters for each value and are seen to grow between KEOF runs. The mean, the standard deviation, and the rms values for each set of prediction errors also are displayed.

Statistically, 95 percent of the x’s, y’s and t’s should fall within the error bars. This is seen to be so in Fig. 1. The overall rms prediction accuracies are better than 13 cm in PMX, 11 cm in PMY, and 17 cm in UT1–UTC. This is well within the general DSN Earth orientation accuracy requirement of 30 cm.

Figure 2 shows the rms errors of Fig. 1 broken down into those errors generated on the first 5 days following a KEOF run. PMX and PMY errors grow slowly, almost linearly over the 5 days, while UT1 errors exhibit more rapid growth. Day-1 rms prediction errors are better than 11 cm for all three components. By day 5, the rms prediction error has grown to 16.3 cm for PMX, 14.4 cm for PMY, and 26.0 cm for UT1. To maintain the UT1 error level below 30 cm, the filter must be rerun with new data by day 5. Current operational practice is to run KEOF twice a week.

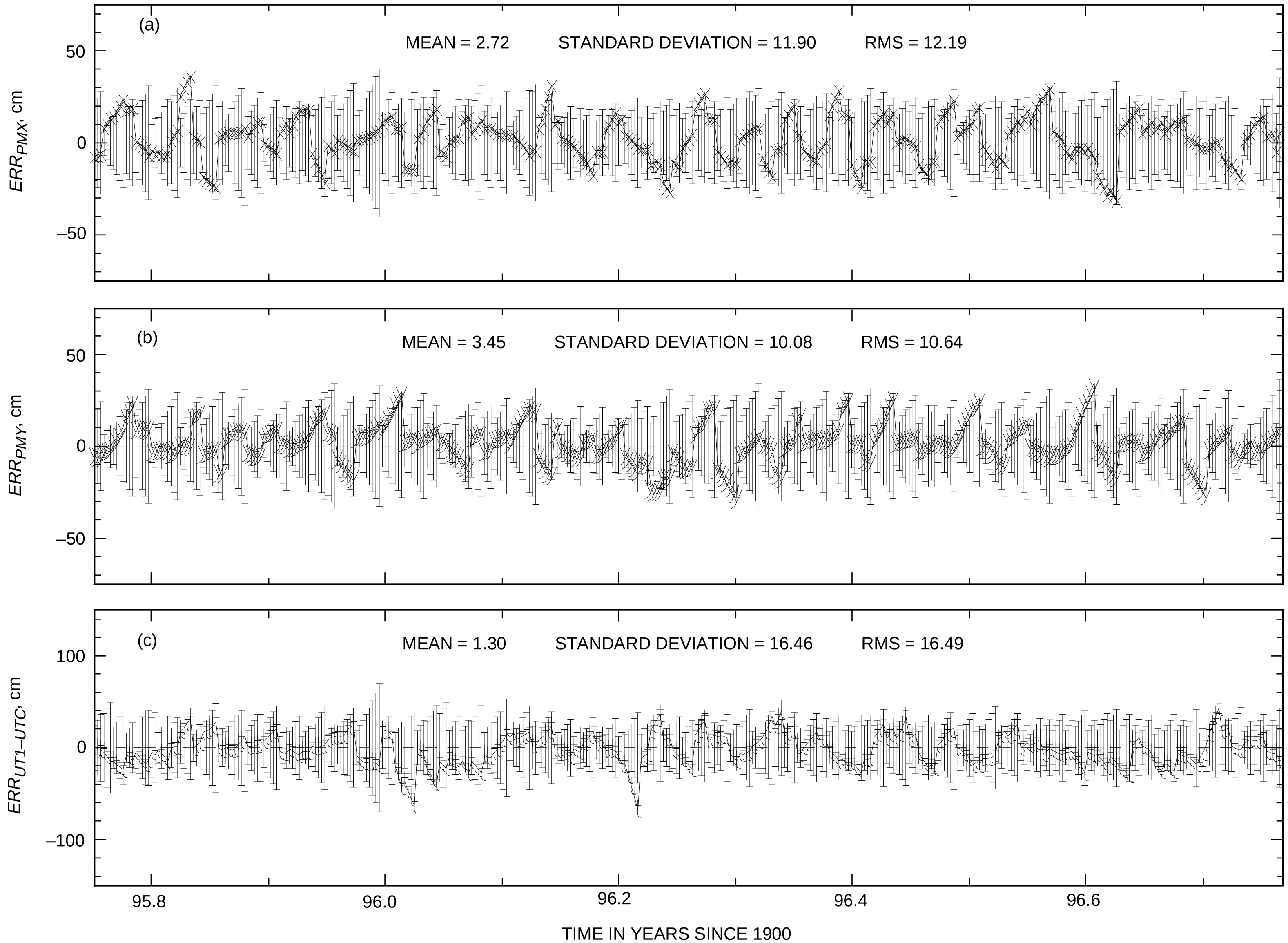

Fig. 1. Daily prediction errors from October 1, 1995, to September 30, 1996, for (a) PMX, (b) PMY, and (c) UT1–UTC.

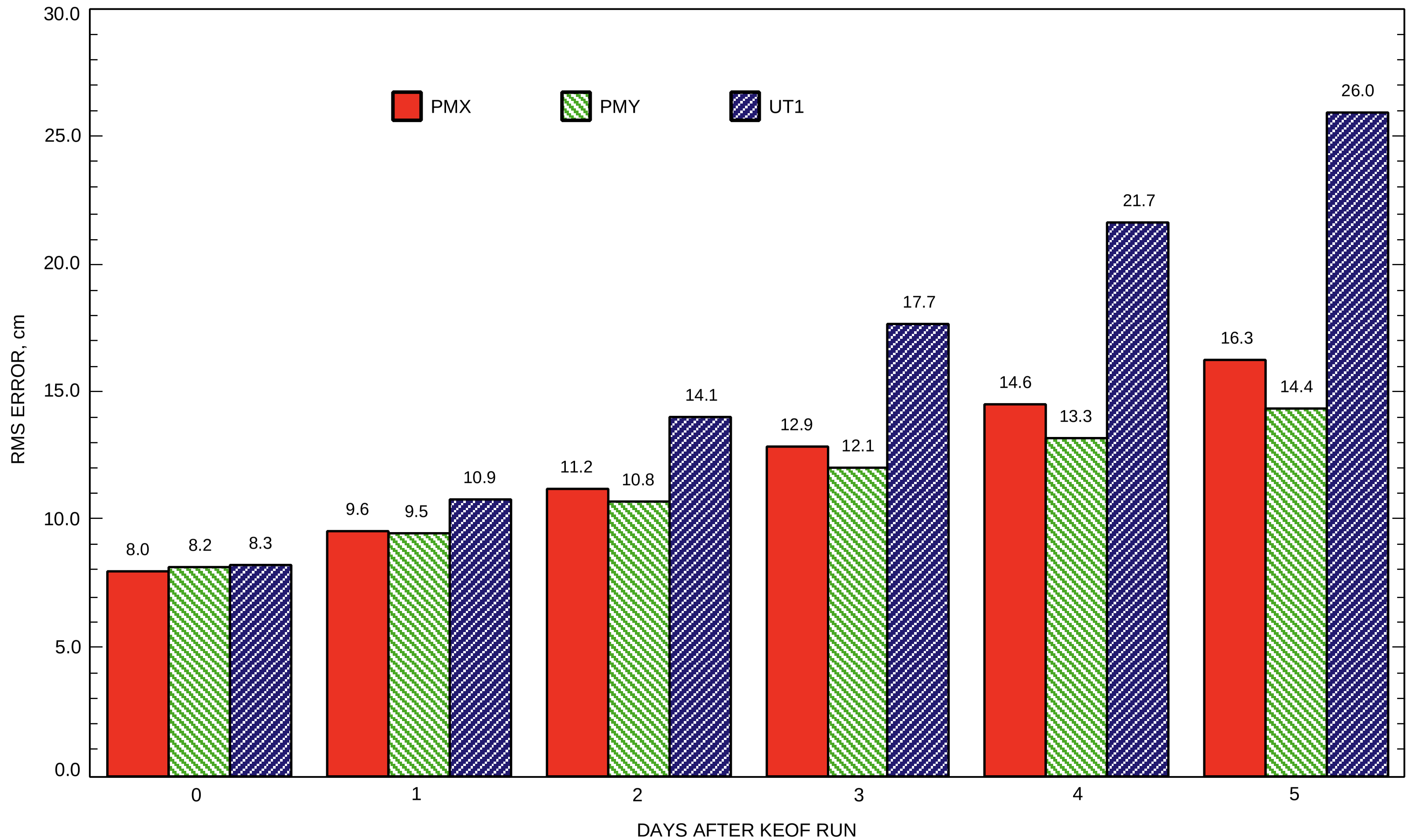

Fig. 2. The rms prediction error statistics of Fig. 1 broken down into those errors generated on each of the five days following a KEOF run.

V. Final Remarks

Although the operational performance of the present version of KEOF meets and even exceeds current DSN general navigational requirements for both final estimates and short-term predictions, Estefan and Folkner [1] recently have shown that uncertainty in Earth orientation is a significant, if not dominant, error source in spacecraft navigation. In addition to this, some missions require more precise Earth orientation accuracy than that of the general DSN accuracy requirements. Mars Pathfinder, for example, requires knowledge of the Earth's orientation to within 10 cm (1σ) in each component for the days on which the calibrations are generated.[6]

The JPL Earth orientation support groups continue to work on improving KEOF EOP estimation and prediction capabilities. A major change to be implemented in early 1997 is the use of Global Positioning System (GPS) Earth orientation data. GPS data will be incorporated into KEOF as a hybrid VLBI/GPS system. GPS will provide daily measurements of polar motion and length of day (LOD). VLBI will provide the benchmark UT0 measurements within which the GPS LOD data will be integrated to obtain the UT1 calibrations for delivery to the spacecraft navigation teams. This improvement is expected to substantially reduce the errors in both provisional estimates and short-term predictions, leading directly to improved spacecraft navigation.

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