3.5.2 Rapid Service/Prediction Centre

Introduction

This section provides a discussion and summary of the Earth orientation parameter (EOP) results produced by the IERS Rapid Service/Prediction Center (RS/PC) for the calendar year 2018. The accuracies of both the inputs used and the subsequent EOP combination and prediction results produced by the IERS RS/PC are provided. The combination and prediction comprise the Bulletin A results and are published in several human and machine readable formats. In addition, a plot of the polar motion path for the year, a summary of the expected times during each day at which inputs are provided to the IERS RS/PC solution, a low precision table of predictions of TT–UT1, and a comprehensive list of the inputs to the IERS RS/PC combination and prediction process are provided. This section also contains an overview of the combination processing techniques, the prediction processing techniques, the center activities that include developmental work to improve EOP results, and the web and FTP locations available to users for obtaining results. Lastly, detailed analyses and discussions regarding results may not, in general, be discussed in this section, but may be presented at upcoming conferences and meetings.

Combination Processing Techniques and Results

In combining the contributed observational data to generate the quick-look EOP results, the IERS RS/PC employs a smoothing cubic spline that weights each of the input data series based on its reported observational errors, which is referred to as a “weighted smoothing cubic spline” (WSCS) (McCarthy and Luzum, 1991a). Observational data contributions are corrected for possible systematic differences in the form of offsets and rates computed with respect to the C04 series of the IERS Earth Orientation Centre (EOC) at the Paris Observatory; to this end, a robust linear estimator is employed which ameliorates the effect of outliers on the computed offsets and rates. The statistical weights used in the spline are proportional to the inverse square of the estimated accuracy of the individual techniques computed over the past several years. Minimal smoothing is applied, consistent with the estimated accuracy of the observational data.

Weights for each contributor in the algorithm may be either a priori values estimated by determining the standard deviation of a long history of residuals or values based on the internal precision reported by contributors. The estimated accuracies for each of the IERS RS/PC contributors to the EOP combination solutions for 2018 are provided in Table 1. The estimates are based on the residuals between the contributor series and the IERS RS/PC (USNO) EOP solution (contained in the file finals.data) for all the epochs in 2018.

On 29 March 2018, the RS/PC EOP series for UT1–UTC, Polar Motion, and Celestial Pole Offsets (CPOs) was transitioned to be consistent with the newly computed and corrected 14 C04 EOP series. Two adjustments were made to implement this transition; 1) a small offset and slope (systematic corrections) were applied to the entire RS/PC EOP time series going back to 1972 to diminish any long-term drift between the two series and 2) the combination was re-solved going back approximately one year from 29 March 2018, with each input contributor having a revised systematic correction applied. Just before the transition, revised systematic corrections applied to each series had previously been computed based on the residuals of the observational inputs versus the 14 C04 series. (Note that a complete list of the input contributors to the combination software are listed in Table 7a.)

Some of the EOPs are measured directly while others are a hybrid of direct measurements and related quantities. For polar motion (x and y) and the CPOs, all the contributors provide direct measurements of these quantities. As mentioned in the previous report for 2017, starting in March 2018, all the CPO contributor inputs have been in terms of dX and dY, and are consistent with the IERS Conventions 2010 and IAU 2006 precession and 2000A nutation models. For UT1–UTC, some contributors provide direct measurements and others provide estimates based on the derivative of UT1.

All of the Very Long Baseline Interferometry (VLBI) contributors provide direct measurements of UT1; the International GNSS Service (IGS) ultra-rapid observations (IGS ultras) provide a length-of-day (LOD) type input, which is a derivative of UT1; and the USNO GPS UT provides a UT1-like estimate based on GPS orbit modeling. The VLBI-based results have been used to correct for the LOD bias in the IGS ultras and to minimize drifts in UT estimates in both the IGS ultras and USNO GPS UT ("UTGPS"). The corresponding statistics shown for the IGS ultras and UTGPS are computed after the bias corrections are applied. Although the Atmospheric Angular Momentum (AAM) inputs may be added to the EOP combination in the future, currently the AAM inputs do not contribute to the EOP combination solution, but provide inputs to the EOP UT1–UTC predictions out to seven days into the future; therefore, there is no mention of AAM results in Table 1. The combination refers to solutions of past EOP results; whereas, predictions refer to the current and future EOP look-ahead solutions, which are discussed later in the chapter.

Each day at approximately 17:00 UTC, input data spanning one year into the past are provided to the WSCS software to update EOP solutions. The data consists of the following: the epoch of observation, the observed EOP value, and the corresponding weight. The software computes the spline coefficients for every unique input data point, which are then used to interpolate the Earth orientation parameter time series so that x, y, UT1–UTC, dX, and dY values are computed for the midnight (00:00) UTC epoch for each day.

Table 1: *Estimated accuracies of the contributions to the IERS RS/PC combination results for 2018 with respect to the IERS RS/PC EOP series. Units are milliseconds of arc (mas) for x, y, dX, and dY and milliseconds of time for UT1–UTC. (All acronyms used in this table are defined in the Acronyms section – Appendix 5 – of this IERS Annual Report 2018.)*

	Estimated accuracy				
Contributor	**x**	**y**	**UT1–UTC**	**dX**	**dY**
ILRS SLR	0.22	0.22	–	–	–
IAA SLR	0.19	0.23	–	–	–
MCC SLR	0.13	0.18	–	–	–
GSFC VLBI Intensive	–	–	0.018	–	–
USNO VLBI Intensives	–	–	0.018	–	–
GSI Intensives	–	–	0.016	–	–
GSFC$^+$ VLBI	0.06	0.08	0.003	0.07	0.05
IAA$^+$ VLBI	0.20	0.25	0.008	0.06	0.07
IVS$^+$ VLBI	0.08	0.09	0.004	0.06	0.06
USNO$^+$ VLBI	0.08	0.07	0.004	0.05	0.07
IGS Final	0.02	0.01	–	–	–
IGS Rapid	0.03	0.03	–	–	–
IGS Ultra*	0.05	0.04	0.034*	–	–
USNO GPS UT*	–	–	0.050*	–	–

$^+$ GSFC, USNO, IAA, and IVS VLBI nutation values are in terms of dX/dY using IAU 2000A Nutation Theory (see Petit and Luzum, 2010).

* All satellite techniques provide information on the rate of change of Universal Time contaminated by effects due to un-modeled orbit node motion. VLBI-based results have been used to correct for LOD biases and to minimize drifts in UT estimates.

Additionally, LOD and estimated error results are published along with the EOP combination results. The LOD results for the combination are derived directly from the UT1–UTC data. The analytical expression for the first derivative of a cubic spline passing through the UT1–UTC data (after leap second discontinuities are removed) is used to estimate the LOD at the epoch of the UT1–UTC data. The uncertainties in the daily values (listed in Bulletin A) are derived from the quality of the spline fit in the neighborhood of the day in question.

Two groups of data points are excluded from the combination process. One group are those EOP inputs that have contributor reported errors (sometimes called formal errors) greater than three times their average reported precision. The other data excluded are those inputs that have a residual that is more than four times the associated a priori error estimate. Also, note that since all of the observations are reported to the IERS RS/PC with the effects of sub-daily variations already removed, the input data do not need to be corrected for these effects (see IERS Gazette No. 13, 30 January 1997).

Table 2: *Mean and standard deviation of the differences between the Rapid Service/Prediction Center combination solutions and the 14 C04 EOP solutions for 2018. Polar motion x and y values are in milliseconds of arc and UT1–UTC values are in units of milliseconds of time.*

	Bulletin A – C04	
	Mean	Std. Deviation
Bulletin A Rapid Solution (finals.data)		
x	0.07	0.06
y	-0.02	0.04
UT1–UTC	-0.015	0.052
Bulletin A Weekly Solution (finals.data)[1]		
x	0.05	0.08
y	-0.02	0.06
UT1–UTC	0.009	0.060
Bulletin A Daily Solution (finals.daily)		
x	0.02	0.07
y	-0.00	0.04
UT1–UTC	0.000	0.074

[1] Statistics computed over the 7-day combination solution period prior to solution epoch.

Comparing statistics provided in Table 1 versus the same table in the IERS RS/PC section of the IERS Annual Report 2017[1], one can see some noteworthy differences. The ILRS SLR estimated accuracy for 2018 was 0.22 versus 0.14 for Polar Motion X and 0.22 versus 0.17 for Polar Motion Y; the GSFC, IVS, and USNO VLBI Polar Motion X and Y accuracies all improved by at least 20%. CPOs in Table 1 above are

[1] The IERS Annual Report (AR) 2017 and previous ARs are found at https://www.iers.org/AnnualReports

reported only as dX and dY; whereas previous annual reports reported these quantities as either dψ and dϵ or dX and dY depending on the contributor CPO system being used or reported by the contributor.

When comparing the integrated IGS Ultra LODs (IIUL) RMS residual value provided in Table 1 to that shown in Table 1 in the AR 2017, one can see a substantial decrease (0.034 for 2018 vs 0.051 milliseconds (msec) for 2017). The RMS provided is computed using the first IIUL residual for that solution if any IIULs were used in the combination for that day. The exact causes for the change are being considered; however, reasons for the change could be affected by the manner in which the following were computed: a) the RMS statistics and b) the IIUL constants of integration for each day. A discussion of the computation of the RMS statistics and IIUL constants of integration for each day were provided in the IERS RS/PC section of the IERS AR 2017 and the reader is referred to that detailed discussion. The causes of any noteworthy differences between the values reported in Table 1 above to those reported in the IERS 2017 AR may be discussed in more detail at an upcoming conference to be held in 2019 or later.

Table 2 shows the accuracies of Rapid Service/Prediction Center's combination solution for the running, weekly, and daily products compared to the 14 C04 series maintained by the IERS EOC for 2018; the latter series uses somewhat different data inputs and a different combination algorithm, which makes it suitable for comparison. Nominally, each Thursday, the IERS RS/PC produces a weekly EOP solution in two general file formats – "finals.data" and the "ser7.dat" files. The finals.data solution contains EOP data in a tabular, machine-readable form, for each day from 1992 to one year into the future from the Thursday updated solution date. At the same time, the results are published in the ser7.dat file, which is more in a human readable format. Formats for each can be found at http://maia.usno.navy.mil/ser7/readme.finals and ser7/readme.bulla. In addition, each day, the IERS RS/PC computes and publishes an EOP solution in the file "finals.daily". This file has the same format as the finals.data file; however, it only contains the current day, three prior months, and three future months of EOP results.

Figure 1 contains plots of the 2018 residuals between the daily rapid and the 14 C04 solutions, and the corresponding statistical results are listed in Table 2 under "Bulletin A Daily Solution (finals.daily)." These daily rapid solutions are considered the last combination or 0-day prediction results. The statistics for the Daily Solution are the differences between the EOP solution, updated daily and at each corresponding daily epoch for 2018, versus the respective 14 C04 series solution for that epoch when it becomes available. (An example of the method used to compute the Bulletin A Daily solution (finals.daily) statistics is provided in the RS/PC section of the IERS Annual Report 2015 on pages 82 and 83.)

The absolute value of the mean of UT1-UTC decreased to 0.000 in 2018 compared to -0.027 milliseconds for 2017; however, the STD increased to 0.074 in 2018 compared to 0.058 milliseconds for 2017. However, if one were to compare the USNO finals.daily UT1–UTC results versus the JPL EOP SPACE series[2], one would obtain a mean of 0.000 and STD of 0.0524 milliseconds. As may be shown in more detail in a conference or meeting later in 2019, there was possibly an overweighting of the IVS VLBI intensives observations compared to the IVS 24-hour series within the C04 series from early May to early August 2018. This overweighting caused the comparison of the RS/PC finals.daily results to the C04 reference series to have larger residuals than it should have if the C04 did not have this issue.

The running solution statistics, shown under the label "Bulletin A Rapid Solution (finals.data)," are the residuals of the combination solution, contained in finals.data, versus the 14 C04 series over the 365-day period covering 2018. The finals.data file used in computing these statistics was computed on January 14, 2019 (and also archived). Nominally, the last observational input data for the year (in this case, 2018) is processed and provided to the IERS RS/PC by January 14 of the following year (in this case, 2019); the last observational data to become available are usually the 24-hour VLBI input series. Thus, the running solution includes the effects of any late-submitted, but highly accurate data.

As seen in Table 2 under the label "Bulletin A Rapid Solution (finals.data)", there were noteworthy differences in the comparison of the polar motion X mean and UT1–UTC STD between the 2018 and corresponding 2017 results. The polar motion X mean differences were 0.07 and 0.01 milliarcseconds, respectively; reasons for the differences are not yet known, but may be investigated. The increase in UT1–UTC STD from 2017 to 2018 was 0.018 to 0.052 milliseconds. The cause of the UT1–UTC STD difference is most likely an issue with the C04 as mentioned a few paragraphs above; it should be noted that the STD compared to the JPL EOP SPACE series was only 0.023 milliseconds.

The "Bulletin A Weekly Solution" results shown in Table 2 are the statistics of the residuals obtained from the Bulletin A combination values, contained in the ser7.dat format, for 2018 versus the 14 C04 series. These combination values for 2018 are the concatenation of all 52 Bulletin A, 7-day EOP combination results. For each Bulletin A, there is a set of 7-day EOP combination results listed prior to the solution epoch. (For example, the Bulletin A solution computed on January 11,

[2] https://keof.jpl.nasa.gov/predictions/latest_midnight.eop

2018 has EOP combination results from 5 through 11 January, 2018.)

Prediction Techniques and Results

In 2007, the algorithm for polar motion predictions was changed to incorporate the least-squares, autoregressive (LS+AR) method created by W. Kosek and improved by T. Johnson (personal communication, 2006). This method solves for a linear, annual, semiannual, 1/3 annual, 1/4 annual, and Chandler periods fit to the previous 400 days of observed values for x and y. This deterministic model is subtracted from the polar motion values to create residuals that are more stochastic in nature. The AR algorithm is then used to predict the stochastic process while a deterministic model consisting of the linear, annual, semiannual, and Chandler terms is used to predict the deterministic process. The polar motion prediction is the addition of the deterministic and stochastic predictions. The additional unused terms in the deterministic solution help to absorb errors in the deterministic model caused by the variable amplitude and phase of the deterministic components (T. Johnson, personal communication, 2006). For more information on the implementation of the LS+AR model, see Stamatakos *et al.* (2008). A deficiency with the current implementation of this algorithm occasionally may cause poor quality short-term polar motion predictions. It is anticipated that within a few years, an evaluation effort recently funded by USNO will yield improved prediction algorithms.

The UT1–UTC prediction makes use of a UT1-like data product derived from a combination of the operational National Centers for Environmental Prediction (NCEP) and U.S. Navy's Global Environmental Model (NAVGEM) Atmospheric Angular Momentum (AAM) analysis and forecast data (UTAAM). AAM-based predictions are used to determine the UT1 predictions out to a prediction length of 7.5 days (Johnson *et al.*, 2005). For longer predictions, the LOD excitations are combined smoothly with the longer-term UT1 predictions described below. For more information on the use of the UTAAM data, see Stamatakos *et al.* (2008).

The procedure for generating UT1–UTC predictions after 7.5 days involves a simple technique of differencing (McCarthy and Luzum, 1991b). All known effects such as leap seconds, solid Earth zonal tides, and seasonal effects are first removed from the observed values of UT1–UTC, resulting in a quantity called UT2S – TAI. (UT2S is a smoothed version of UT1, removing periodic seasonal and long period variations due to tides, including the long-period tides up to 18.6 years.) Then, to create the prediction of $(UT2S - TAI)_N$ N days into the future, the smoothed time value from N days in the past, $(UT2S - TAI)_{-N}$, is subtracted from 2-times the most recent value, $2(UT2S - TAI)_0$ to yield:

$$(UT2S - TAI)_N = 2(UT2S - TAI)_0 - (UT2S - TAI)_{-N}.$$

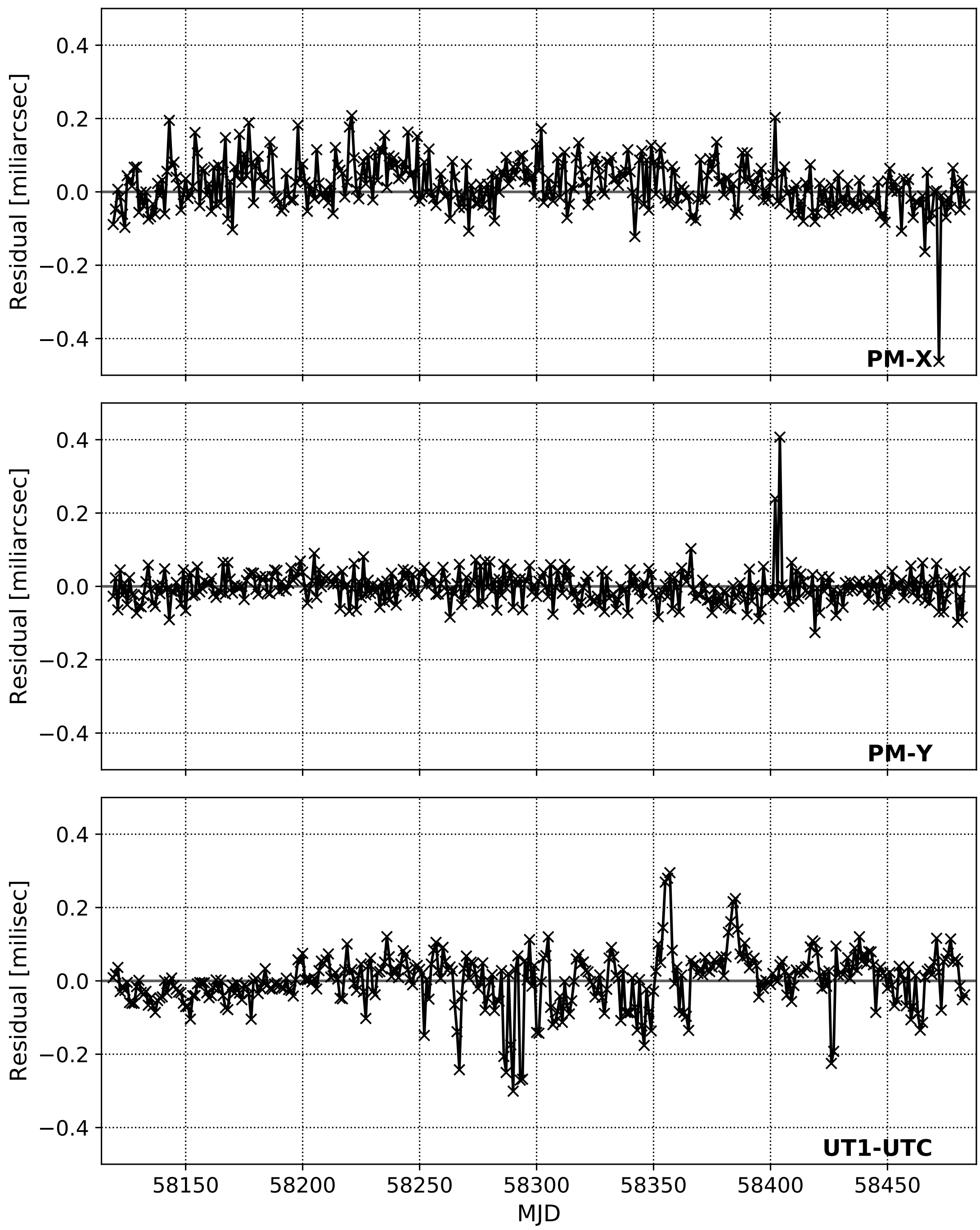

Fig. 1: *Differences for 2018 between the daily updated EOP solution at the day of the solution update and the 14 C04 series combination solution. (The day of the solution is also known as the last combination or 0-day prediction epoch.) Earth Orientation Parameters shown are: a) Polar Motion X; b) Polar Motion Y; and c) UT1–UTC.*

The amount of smoothing used in this procedure depends on the length of the forecast. Short-term predictions with small values of N make use of less smoothing than long-term predictions. Once this value is obtained, it is possible to restore the known effects in order to obtain the prediction of UT1–UTC. This process is repeated for each day's prediction.

The UT1–UTC prediction out to a few days is also influenced by UTGPS, the observed daily Universal Time estimates derived at USNO from the motions of the GPS orbit planes reported by the IGS Rapid service (Kammeyer, 2000). The IGS estimates for LOD are combined with the UTGPS estimates to constrain the UT1 rate of change for the most recent observation.

Errors of the prediction estimates are derived from analyses of the past differences between observations and the published predictions. Formulas published in Bulletin A can be used to extend the Bulletin A tabular data, but predictions derived from these formulas are significantly less accurate than the tabular predictions and are not recommended for operational use.

For several representative prediction days, the RMS of the residuals between USNO produced polar motion and UT1–UTC predictions and the 14 C04 series combination values for 2018 are shown in Tables 3a through 3d. Prediction day "N" is defined as "N" days into the future from the current day for which the EOP solution was updated. For example, prediction day 10 for the EOP solution that was updated on MJD 58392 (October 1, 2018) is MJD 58402 (October 11, 2018). Table 3a provides the RMS prediction errors for EOP solutions updated at 17:00 UTC; Tables 3b, 3c, and 3d provide RMS prediction errors for solutions updated at 21:10, 03:10, and 09:10 UTC, respectively.

As Table 3a shows, for most prediction days (although certainly not all) there were small improvements in the polar motion and UT1–UTC predictions compared to the same table in the AR 2017; one notable degradation is in the 0 day UT1–UTC prediction which went from 0.063 to 0.074 milliseconds. However, as was previously mentioned in the report, it should be noted that the C04 series had some known issues for UT1–UTC in 2018, thus affecting the residuals since the C04 is the baseline of the comparison. More detailed explanations of the comparisons may be provided at upcoming conferences.

In annual reports up through 2013, the prediction length (as shown in Tables 3a) was determined from the epoch of the last known VLBI or IGS observation, and not based on the date of the solution epoch. It has been determined that many EOP users base their inputs on the prediction from the date of the solution epoch, and also using this new paradigm simplifies the comparison of results among the 17:00 UTC EOP solution and the 21:10, 03:10 and 09:10 UTC solutions (which are discussed below). In general, the results are very similar since on most days an observation is made either on the solution day or the day before. The statistics based upon the older paradigm could be made available upon request from usn.ncr.navobsydc.mbx.eopcp@mail.mil.

Table 3a: *RMS of the differences between the EOP time series predictions produced by the 17:00 UTC daily EOP solutions and the 14 C04 combination solutions for 2018. Note that the prediction length starts counting from the day after the date of the solution epoch.*

Days in future	PMx (mas)	PMy (mas)	UT1–UTC (ms)
0	0.07	0.04	0.074
1	0.31	0.23	0.087
5	1.75	1.32	0.198
10	3.29	2.29	0.537
20	5.89	3.80	2.347
40	10.24	5.78	5.118
90	17.25	9.28	9.748

Table 3b: *RMS of the differences between the EOP time series predictions produced by the 21:10 UTC daily EOP solutions and the 14 C04 combination solutions for 2018.*

Days in future	PMx (mas)	PMy (mas)	UT1–UTC (ms)
0	0.07	0.04	0.072
1	0.29	0.21	0.084
5	1.72	1.31	0.196
10	3.26	2.29	0.540
20	5.78	3.89	2.348
40	10.25	5.85	5.148
90	17.30	9.26	9.798

Table 3c: *RMS of the differences between the EOP time series predictions produced by the 03:10 UTC daily EOP solutions and the 14 C04 combination solutions for 2018.*

Days in future	PMx (mas)	PMy (mas)	UT1–UTC (ms)
0	0.07	0.04	0.072
1	0.29	0.28	0.083
5	1.86	1.60	0.196
10	3.25	2.62	0.537
20	5.62	4.27	2.349
40	10.03	6.33	5.158
90	17.36	9.26	9.815

Table 3d: *RMS of the differences between the EOP time series predictions produced by the 09:10 UTC daily EOP solutions and the 14 C04 combination solutions for 2018.*

Days in future	PMx (mas)	PMy (mas)	UT1–UTC (ms)
0	0.07	0.04	0.072
1	0.27	0.21	0.083
5	1.69	1.34	0.195
10	3.19	2.36	0.535
20	5.64	3.97	2.344
40	10.02	6.09	5.133
90	17.15	9.21	9.783

In addition to the 17:00 UTC EOP solution, three additional EOP solutions are computed each day – new solutions are computed at 21:10, 03:10, and 09:10 UTC. These four solutions are collectively referred to as the Nxdaily solutions. At these solution times, the EOP results

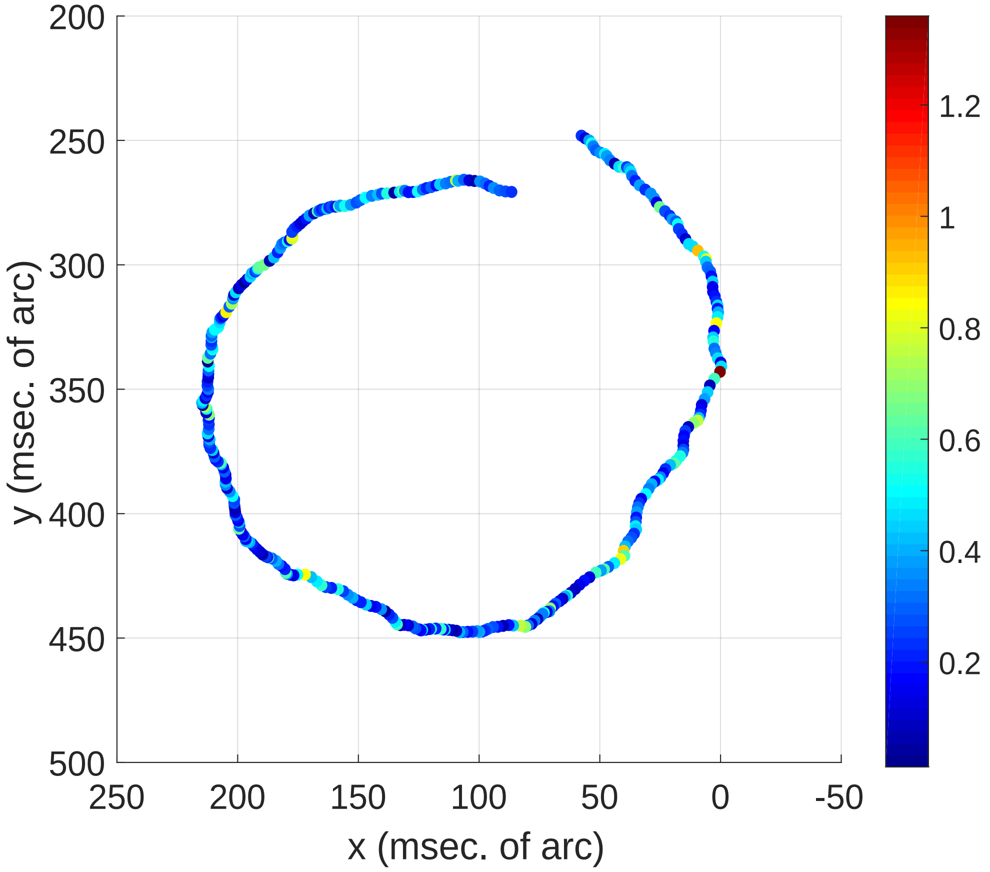

Fig. 2: *Plot of the polar motion path for 2018 with corresponding 1-day prediction residual values. The residuals are the RMS of the combined polar motion x and y residual values and are in units of milliseconds of arc (msec of arc) and correspond to the color-coded vertical bar at the right ranging from less than 0.1 (dark blue) to greater than 2.2 (dark red) msec of arc.*

are recomputed and made available to users. The original solution at 17:00 UTC has been produced by the IERS RS/PC each day for over 15 years. The additional solutions are part of an ongoing effort to improve the accuracy of the EOP results by updating EOP solutions soon after new observational data are available, thereby reducing the latency between observations and EOP solution updates. Examples of these new observational input data are e-VLBI intensives and the IGS ultras. Tables 4a and 4b illustrate the relationship between the EOP solution times and these input data.

At each Nxdaily UTC solution time listed in Tables 4a and 4b, major contributors, whose latencies between observations to availability for the EOP solution are under a few days, are listed with an associated "epoch at midpoint." IGS and VLBI solutions are determined from a span of observations and the EOP estimate is provided at the midpoint of this span. Typically IGS orbits are determined over a 24-hour period and VLBI intensives sessions span a 1-hour period. The “Contributor” column contains the most recently available input at the time of each UTC solution. Although major contributors, the 24-hr VLBI solutions are not shown in the table since the time between observations and availability to the EOP solutions is generally greater than 7 days. Table 4a lists the most recent major input contributors for each polar motion Nxdaily solution. For example, by the polar motion 17:00 UTC <MJD> solution time, the most recently computed IGS rapid observation solution (IGS rapid), which has an epoch at midpoint of 12:00 UTC noon from the previous day, <MJD-1>, is available. In addition, there are two IGS ultras available that contain an epoch at midpoint after the IGS rapid. By 21:10 UTC <MJD>, the IGS has produced an updated IGS ultra, the 18-hr solution, and the corresponding EOP solution will use this latest data. Similarly, the 03:10 UTC and 09:10 UTC solutions will have later IGS ultra data available as shown in the table. Finally, for the next day, <MJD+1>, the sequence of IGS Rapids and Ultras will repeat – the 17:00 UTC <MJD+1> solution will have the next IGS rapid solution whose midpoint was at 12:00 UTC <MJD> along with the next 6-hr and 12-hr Ultras.

In Table 4b, there is a pattern for UT1–UTC that is similar to that described above for polar motion. In addition to the IGS contributions, the VLBI intensives series are included. While the IGS contributions have a consistent update time, the VLBI intensives updates are not as regular as the IGS updates. For example, new IGS ultra rapid observations are regularly provided every 6 hours with only a handful of missed or late solutions each year; whereas, a few VLBI intensives could be late or missing each month. So, the contributors shown for each solution are only an ideal case that occurs less than 100% of the time. There are 3 sets of VLBI intensives that are used in the EOP RS/PC UT1–UTC solution – called INT1, INT2, and INT3 intensives. The INT1 intensives are typically only observed on weekdays, the INT2 intensives on weekends, and the INT3 intensives on Mondays. For more information about the relation of the INT1, INT2, and INT3 VLBI intensives observation times to the EOP solution see Stamatakos, Luzum, Stetzler, & Shumate (2012).

Each Nxdaily EOP solution file (which are located in separate subdirectories) has an identical format to the original 17:00 UTC solution. As shown in Figure 3, the 1-day EOP prediction from the 17:00 UTC <MJD> EOP solution will make a prediction of the EOP for 00:00 UTC <MJD+1>; the 1-day EOP prediction from the 09:10 UTC <MJD+1> EOP solution will also make an estimate of the EOP value for the same 00:00 <MJD+1> epoch.

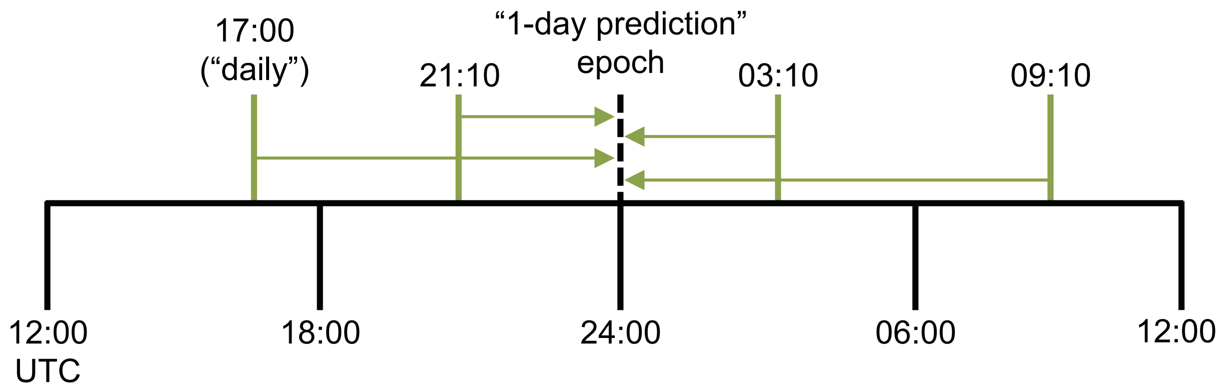

Fig. 3: *Timeline of Nxdaily EOP 1-day prediction solutions in relation to the EOP "daily" solution produced at 17:00 UTC. Each EOP solution update time is shown by the vertical green lines at 17:00, 21:10, 03:10 and 09:10 UTC, respectively. At each of these times, the latest observations are obtained. For example, at 03:10 UTC, the latest IGS ultra rapid observation, the 0-hour solution, is obtained (at the vertical black line labeled 24:00), and so the EOP solution for the "1-day prediction epoch" should be improved from that determined earlier at 17:00 and 21:10 UTC because of this additional, more recent, input observation.*

Unfortunately, unlike the AR 2017 Tables 3a, 3b, 3c, and 3d, the prediction days (especially the 0 and 1-day predictions) for polar motion and UT1–UTC RMS residuals, shown in Tables 3a, 3b, 3c, and 3d, do not follow an expected pattern. The expected pattern was that as more observations become available (as shown in Figure 3 and Table 4b), the RMS values would become smaller; however, for 2018, the resulting statistics do not follow this pattern in most cases. The exact causes for these surprising results are under investigation, and it is hoped that any findings could be presented at a future conference in 2019.

A flowchart that shows the algorithm used in determining the CPOs is shown in Figure 4. Celestial pole offsets are predicted for up to 90 days in advance using a combination of projected empirical models and autoregressive components. The empirical models are fit to past VLBI observations of dX and dY and the autoregressive [AR(4)] components are fit to the residuals between the past VLBI observations and models. The empirical models for dX and dY are composed of offsets, rates, annual and semiannual periodic terms as well as terms with periods of 423.28 days (free-core nutation), 9.1 years, and 27.55 days. In addition the residuals from the model starting with the observations of the four days preceding the date of prediction are used in autoregressive adjustments. Expected errors associated with the predictions are computed based on the past performance of the process. In addition, a bias, based on several years of past observations compared to the 14 C04 solution, is computed and applied to ensure consistency with the 14 C04 solution. Since celestial pole offsets are based solely on VLBI data, if no new VLBI 24-hour session observations are available, a new rapid combination/prediction of these angles is not determined. Therefore, the predictions of celestial pole offsets start before the solution epoch and the length of the prediction into the future can and does vary in the daily solution files. The RMS differences between the daily predictions and the 14 C04 for 2018 are provided in Table 5.

The results in Table 5 contain the RMS of the differences between CPO predictions produced by the daily EOP solutions (as described in the previous paragraph) and the 14 C04 combination solution for 2018. As anticipated with the improved prediction algorithm, there is an improvement in the Table 5 results for 2018 as compared to 2017. For all the dX and dY prediction days, there is at least a 10% improvement for 2018 versus 2017; and there is improvement for the dψ and dϵ derived predictions as well. While the dψ and dϵ improvements are less than 3% for the first few prediction days, the increase in accuracy becomes steadily larger for longer prediction days.

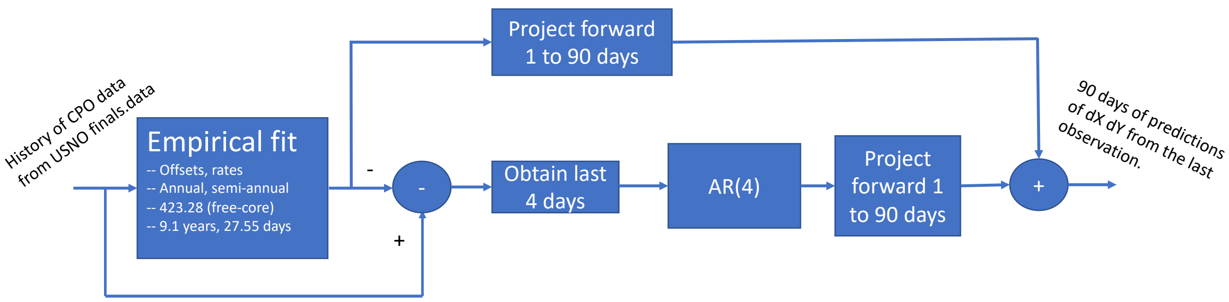

Fig. 4: *Flowchart of CPO prediction algorithm. Predictions out to 90 days are made from a) combining an extrapolated empirical model forward in time and b) an extrapolated autoregressive fit to residuals of past CPO observations minus an empirical fit.*

Predictions of TT–UT1, up to 1 October 2029, are given in Table 6. They are derived using a prediction algorithm similar to that employed in the Bulletin A predictions of UT1–UTC. Up to twenty years of past observations of TT–UT1 are used. Estimates of the expected one-sigma error for each of the predicted values are also given. These errors are based on analyses of the past performance of the model with respect to the observations.

Additional information on improvements to IERS Bulletin A and the significance for predictions of GPS orbits for real-time users is available (Luzum *et al.*, 2001; Wooden *et al.*, 2005; Stamatakos *et al.*, 2008; Stamatakos *et al.*, 2009; Stamatakos *et al.*, 2011).

Table 4: *Available data for each Nxdaily solution is listed in Table 4a) for Polar Motion and Table 4b) for UT1–UTC. The 24-hr VLBI contributors are not included due to a $>$ 7 day latency between observation and EOP solution integration. (Note that 00:00 refers to midnight UTC; -06:00 refers to 18:00 UTC of the previous day; +06:00 refers to 06:00 UTC of the current day, etc.)*

(a) Major contributors to the Polar Motion EOP solution for each Nxdaily solution.

1700 UTC Solution		**2110 UTC Solution**		**0310 UTC Solution**		**0910 UTC Solution**	
Contributor	*Epoch at Midpoint**	*Contributor*	*Epoch at Midpoint**	*Contributor*	*Epoch at Midpoint**	*Contributor*	*Epoch at Midpoint**
IGS 12 hr Ultra	00:00	IGS 18 hr Ultra	+06:00	IGS 0 hr Ultra	+12:00	IGS 6 hr Ultra	+18:00
IGS 6 hr Ultra	-06:00	IGS 12 hr Ultra	00:00	IGS 18 hr Ultra	+06:00	IGS 0 hr Ultra	+12:00
IGS Rapid	-12:00	IGS 6 hr Ultra	-06:00	IGS 12 hr Ultra	00:00	IGS 18 hr Ultra	+06:00
		IGS Rapid	-12:00	IGS 6 hr Ultra	-06:00	IGS 12 hr Ultra	00:00
				IGS Rapid	-12:00	IGS 6 hr Ultra	-06:00
						IGS Rapid	-12:00

(b) Major contributors to the UT1–UTC EOP solution for each Nxdaily solution.

1700 UTC Solution		**2110 UTC Solution**		**0310 UTC Solution**		**0910 UTC Solution**	
Contributor	*Epoch at Midpoint**	*Contributor*	*Epoch at Midpoint**	*Contributor*	*Epoch at Midpoint**	*Contributor*	*Epoch at Midpoint**
AAM LOD[1]	—	AAM LOD[1]	—	AAM LOD[1]	—	AAM LOD[1]	—
INT2/3 VLBI[2]	+08:00	INT2/3 VLBI[2]	+08:00	IGS 0 hr Ultra	+12:00	IGS 6 hr Ultra	+18:00
IGS 12 hr Ultra	00:00	IGS 18 hr Ultra	+06:00	INT2/3 VLBI[2]	+08:00	IGS 0 hr Ultra	+12:00
UTGPS	00:00	IGS 12 hr Ultra	00:00	IGS 18 hr Ultra	+06:00	INT2/3 VLBI[2]	+08:00
INT1 VLBI[3]	-05:00	UTGPS	00:00	IGS 12 hr Ultra	00:00	IGS 18 hr Ultra	+06:00
IGS 6 hr Ultra	-06:00	INT1 VLBI[3]	-05:00	UTGPS	00:00	IGS 12 hr Ultra	00:00
IGS Rapid	-12:00	IGS 6 hr Ultra	-06:00	INT1 VLBI[3]	-05:00	UTGPS	00:00
		IGS Rapid	-12:00	IGS 6 hr Ultra	-06:00	INT1 VLBI[3]	-05:00
				IGS Rapid	-12:00	IGS 6 hr Ultra	-06:00
						IGS Rapid	-12:00

* IGS and VLBI solutions are determined by integrating a period of observation times. The reported EOP is the observation midpoint.
[1] The AAM LOD inputs contain 7.5 days of hourly forecast data from 00:00 to 18:00 hours.
[2] INT2 Intensives are observed Saturday and Sunday and INT3 Intensives are observed on Monday. Both sets of Intensives have an epoch midpoint of approximately 08:00 UTC.
[3] INT1 Intensives are observed Monday through Friday with a midpoint epoch of approximately 19:00 UTC. The “Epoch and Midpoint” value of -05:00 is an idealized scenario.

Table 5: *RMS of the differences between the nutation prediction (also known as celestial pole offset) series produced by the daily solutions and the 14 C04 combination solution for 2018.*

Days in Future	dX (mas)	dY (mas)	dψ (mas)	dϵ (mas)
0	.10	.10	.26	.10
1	.10	.10	.26	.10
5	.10	.10	.26	.10
10	.10	.10	.26	.11
20	.11	.11	.28	.11
40	.14	.13	.34	.13

Center Activities for 2017

On 29 March 2018, the IERS RS/PC Bulletin A solutions for UT1–UTC, Polar Motion, LOD, and CPO were transitioned to be consistent with the 14 C04 EOP series. In addition, the code that combined CPO observations was updated to use dX and dY inputs from all the VLBI contributions, and the CPO predictions were updated according to the algorithm shown in Figure 4.

During 2018, several changes to the input data series or the usage of such data were made. A list of these upgrades is as follows:

a) On 10 May 2018, the systematic corrections for the IAA VLBI 24-hour data series were updated to ensure better consistency with the 14 C04 series;

b) On 17 May 2018, the contribution of the US Navy Fleet Numerical Meteorology and Oceanography Center (FNMOC) to the Atmospheric Angular Momentum (AAM) inputs was upgraded to version 1.4.3eop of the Navy Global Environmental Model (NAVGEM);

c) In late July 2018, a new version of the EO matrix calculator (based on the IERS Conventions 2010 v_1.2.0 Celestial Intermediate Pole and Origin and the Terrestrial Intermediate Origin (CIP/CIO/TIO) paradigm) was made available at http://maia.usno.navy.mil/t2c36cipcio/t2c36cipcio.html;

d) On 16 August 2018, the method for identifying "duplicate" input epochs (epochs of observations within 0.01 days) to the EOP software was modified; and

e) On 23 August 2018, the USNO VLBI 24-hour and intensive data series were upgraded from the usno2017b to the usno2018b series.

Table 6: *Predicted values of TT–UT1, 2019–2029. Note that UT1–TAI can be obtained from this table using the expression UT1–TAI = 32.184s – (TT–UT1).*

DATE		TT-UT1 (s)	Uncertainty (s)
2019	Jul 1	69.358	0.000010
2019	Oct 1	69.5	0.162
2020	Jan 1	69.6	0.162
2020	Apr 1	69.8	0.215
2020	Jul 1	69.9	0.273
2020	Oct 1	70.0	0.335
2021	Jan 1	70.2	0.399
2021	Apr 1	70.3	0.465
2021	Jul 1	70.4	0.532
2021	Oct 1	70.5	0.600
2022	Jan 1	70.7	0.668
2022	Apr 1	70.8	0.736
2022	Jul 1	70.9	0.803
2022	Oct 1	71.0	0.870
2023	Jan 1	71.2	0.936
2023	Apr 1	71.	1.000
2023	Jul 1	71.	1.064
2023	Oct 1	72.	1.126
2024	Jan 1	72.	1.186
2024	Apr 1	72.	1.245
2024	Jul 1	72.	1.302

Table 6 cont.

2024	Oct 1	72.	1.358
2025	Jan 1	72.	1.411
2025	Apr 1	72.	1.463
2025	Jul 1	72.	1.514
2025	Oct 1	72.	1.562
2026	Jan 1	73.	1.609
2026	Apr 1	73.	1.654
2026	Jul 1	73.	1.697
2026	Oct 1	73.	1.738
2027	Jan 1	73.	1.778
2027	Apr 1	73.	1.816
2027	Jul 1	73.	1.853
2027	Oct 1	73.	1.887
2028	Jan 1	74.	1.921
2028	Apr 1	74.	1.953
2028	Jul 1	74.	1.983
2028	Oct 1	74.	2.012
2029	Jan 1	74.	2.039
2029	Apr 1	74.	2.065
2029	Jul 1	74.	2.090

Efforts continued in the following areas as well:

a) Studying combined U.S. Navy AAM and OAM inputs to improve polar motion predictions (Stamatakos *et al.*, 2016a and 2016b; Stamatakos *et al.* 2017a, 2017b, 2018a, 2018b, and 2019);

b) Studying methods to better optimize the use of the UTGPS and IGS Ultra-rapid observations for LOD inputs to the EOP solution;

c) Upgrading the simulation environment algorithms used to test changes to codes, input data series, and configurations to the EOP software and processing;

d) Continuing efforts to test other optimal estimation techniques to replace the WSCS in the EOP combination. (These new optimal estimation techniques would stack and combine normal equations, which is the desired future methodology for combining EOPs as stated by the IERS.);

e) Continuing efforts to improve the EOP prediction algorithms. (These efforts would involve literature searches of advanced algorithms, prototyping, testing, and evaluation.);

f) Using the Very Long Baseline Array (VLBA) estimates as additional UT1–UTC inputs to the EOP solution (Stamatakos, Luzum, Zhu, & Boboltz (2012));

g) Planning for the use of a new VLBI w-series intensive series (using the Mauna Kea to Wettzell baseline) as an additional input series to a test EOP solution;

h) Investigating the publishing of a new version EOP solution file that has the following characteristics: i) updated daily, ii) contains EOP data going back to 1973, iii) re-solved combination results for one year in the past, and iv) re-computed polar motion and UT1–UTC prediction data for one year in the future.

Rapid Service Input Data Contributors and Products

A list of the observational and forecast inputs to the EOP combination and prediction solutions are provided in Table 7a (and Table 7b lists a few non-observational and non-forecast inputs); in addition, these tables indicate which EOPs are used from each contributor.

Other data sets are available and are listed below; however, they are not used in the EOP combination and prediction solutions. They include: UT from Natural Resources Canada GPS; UT0–UTC from University of Texas at Austin Lunar Laser Ranging (LLR); UT0–UTC from JPL LLR; UT0–UTC from the Centre de Recherches en Géodynamique et Astrométrie (CERGA) LLR; UT0–UTC from JPL VLBI; latitude and UT0–UTC from Washington, DC, Photographic Zenith Tubes (PZTs) 1,3,7; latitude and UT0–UTC from Richmond, Florida PZTs 2,6; LOD from ILRS 1-day SLR; x, y, UT1–UTC from Center for Space Research (CSR) UT at Austin LAGEOS 3-day SLR; x and y from CSR LAGEOS 5-day SLR; x and y from Delft, Netherlands 1-, 3- and 5-day SLR; and x, y, UT1–UTC, dψ and dϵ from International Radio Interferometric Surveying (IRIS) VLBI.

Daily and Bulletin A weekly EOP solutions can be obtained from the primary Earth Orientation (EO) server at http://maia.usno.navy.mil and ftp://maia.usno.navy.mil, and from the backup EO server at http://toshi.nofs.navy.mil and ftp://toshi.nofs.navy.mil. An additional backup mirror of the daily and Bulletin A EOP data is now hosted by NASA's

Archive of Space Geodesy Data server at ftp://cddis.gsfc.nasa.gov/pub/products/iers. Users may also request a weekly machine-readable version of the IERS Bulletin A containing the current 365 days' worth of predictions via the document request form at http://maia.usno.navy.mil/docrequest.html.

Table 7a: *Operational input data used in the IERS Bulletin A EOP combination and prediction software. All the observational and forecast data used in operations is listed in the Contributor Column. For each contributor, a check mark is provided under each EOP column if that particular EOP is used operationally. For example, the GSFC intensives (GSF Int) is used in the combination and prediction software, and the EOP that is used is UT1–UTC; no other EOPs from this contributor are used in the software.*

Contributor	**PM-x**	**PM-y**	**UT1–UTC**	**LOD**	**dψ**	**dϵ**	**dX**	**dY**
IAA VLBI	✓	✓	✓				✓	✓
GSFC VLBI	✓	✓	✓				✓	✓
USNO VLBI	✓	✓	✓				✓	✓
IVS VLBI	✓	✓	✓				✓	✓
GSFC Int.[a]			✓					
USNO Int.			✓					
GSI [b] Int.			✓					
ILRS [c]	✓	✓						
IAA [d] ILRS [e]	✓	✓						
MCC [f] SLR	✓	✓						
IGS	✓	✓		✓				
UTGPS			✓					
NCEP AAM [g]				✓				
NAVGEM AAM [g]				✓				

[a] The word "Int" is an abbreviation of the word Intensive.
[b, c, d, e, f] Defined in the Acronyms of the Appendix of this report.
[g] Both observational and forecast inputs are available.

Table 7b: *Miscellaneous input data available to the IERS Bulletin A EOP solution. The IERS EOC solution is used in diagnostic calculations and plots and is used in polar motion predictions. The IERS RS/PC solution is used in diagnostic calculations and plots and is used as the a prior solution to the WSCS.*

Contributor	**PM-x**	**PM-y**	**UT1–UTC**	**LOD**	**dψ**	**dϵ**	**dX**	**dY**
IERS EOC	✓	✓	✓	✓	✓	✓	✓	✓
IERS RS/PC	✓	✓	✓	✓	✓	✓	✓	✓

Table 8 lists the locations and update times of several of the EOP solutions discussed in this report. The first column lists the EOP solution time in UTC. These are the approximate times when an EOP result is computed; if a problem occurs, the solution may actually become available as much as one hour later than what is listed. The second column contains the subdirectory under each FTP or web address listed in the above paragraph where an EOP solution resides. For example, at http://maia.usno.navy.mil there exists a subdirectory called "ser7" (i.e., http://maia.usno.navy.mil/ser7) where the daily EOP solution computed at 17:00 UTC will be updated each day. Similarly, at ftp://cddis.gsfc.nasa.gov, there exists a subdirectory called "eop0300utc" (i.e., ftp://cddis.gsfc.nasa.gov/pub/products/iers/eop0300utc), where an EOP solution update computed at approximately 03:10 UTC will be uploaded each day.

Table 8: *EOP solution locations and update times.*

EOP solution Time (UTC)[1]	**Subdirectory location**	**Approximate time solution is posted** [2]
17:00	ser7	17:15
21:10	eop2100utc	21:15
03:10	eop0300utc	03:15
09:10	eop0900utc	09:15

[1] Solution times are the approximate times when an EOP result is computed; actual solution time may occur as much as one hour later than what is listed.

[2] At http://maia.usno.navy.mil, ftp://maia.usno.navy.mil, http://toshi.nofs.navy.mil, and ftp://toshi.nofs.navy.mil, this time represents the approximate time an updated EOP solution will be available. For ftp://cddis.gsfc.nasa.gov/pub/products/iers, the solution is posted shortly after 18:00 UTC, which is approximately 45 minutes after the "maia" and "toshi" servers have data posted. The additional time is needed to allow the EOP solution to finish at USNO and to be verified by EOP personnel before the mirroring is performed to post the solution to CDDIS.

Center Staff

The Rapid Service/Prediction Center staff (at the USNO EO Department) consisted of the following members:

Dr. Christine Hackman	Director; Head, Earth Orientation (EO) Department
Mr. Nick Stamatakos	Project Director and Lead Scientist; Chief, EOP Combination and Prediction (EOP C/P) Division
Ms. Merri Sue Carter	Assists in daily operations and support; Research Astronomer, EOP C/P Division
Mr. Nathan Shumate	Assists in daily operations and support, research, and software maintenance; Astronomer, EOP C/P Division
Ms. Maria Davis	Assists in daily operations and support, research, and software maintenance; Astronomer, EOP C/P Division

Bibliography

Davis, M., Stamatakos, N., 2017, “Improving the IERS Rapid Service / Prediction Center UT1–UTC 0-day Solution,” Journèes 2017 des Systèmes de Référence et la Rotation Terestre, Alicante, Spain, 25–27 September, 2017.

Davis, M., Stamatakos, N., “Examining the Impact of New and Modified Techniques on the IERS RS/PC 0-day UT1–UTC Solution,” G31B-0661 POSTER at the American Geophysical Union Meeting, Washington D.C., December 2018.

Johnson, T.J., Luzum, B.J., and Ray, J.R., 2005, Improved Near-Term Earth Rotation Predictions Using Atmospheric Angular Momentum Analysis and Forecasts, J. Geodynamics, **39**(3), 209–221.

Kammeyer, P., 2000, A UT1-like Quantity from Analysis of GPS Orbit Planes, Celest. Mech. Dyn. Astr., **77**, 241–272.

Luzum, B.J., Ray, J.R., Carter, M.S., and Josties, F.J., 2001, Recent Improvements to IERS Bulletin A Combination and Prediction, GPS Solutions, **4**(3), 34–40.

McCarthy, D.D. and Luzum, B.J., 1991a, Combination of Precise Observations of the Orientation of the Earth, Bulletin Geodesique, **65**, 22–27.

McCarthy, D.D. and Luzum, B.J., 1991b, Prediction of Earth Orientation, Bulletin Geodesique, **65**, 18–21.

McCarthy, D.D. (ed.), 1996, IERS Conventions (1996), IERS Technical Note No. 21, Paris Observatory, France.

McCarthy, D.D. and G. Petit (eds.), 2004, IERS Conventions (2003), IERS Technical Note No. 32, Verlag des Bundesamts für Kartographie und Geodäsie, Frankfurt am Main, Germany.

McCarthy, D. and Stamatakos, N., “A Conventional Mean Pole,” G41A-1002 POSTER at the American Geophysical Union Meeting, San Francisco, California, December 2016.

Petit, G. and Luzum (eds.), 2010, IERS Conventions (2010), IERS Technical Note No. 36, Verlag des Bundesamts für Kartographie und Geodäsie, Frankfurt am Main, Germany.

Salstein, D., Stamatakos, N., “New Atmospheric and Oceanic Angular Momentum Datasets for Predictions of Earth Rotation/Polar Motion,” G13A-0521 POSTER at the American Geophysical Union Meeting, San Francisco, California, December 2014.

Stamatakos, N., Luzum, B., Wooden, W., 2008, “Recent Improvements in IERS Rapid Service/Prediction Center Products,” in Proc. Journées Systèmes de Référence Spatio-Temporels, Paris, 17–19 Sept. 2007, 163–166.

Stamatakos, N., Luzum, B., Stetzler, B., Wooden, W., and Schultz, E., 2009, “Recent Improvements in IERS Rapid Service/Prediction Center Products,” in Proc. Journées Systèmes de Référence Spatio-Temporels, Dresden, 22–24 Sept. 2008, 160–163.

Stamatakos, N., Luzum, B., Stetzler, B., Shumate, N., and Carter, M.S., 2011, “Recent Improvements in IERS Rapid Service/Prediction Center Products,” in Proc. Journées Systèmes de Référence Spatio-Temporels, Paris, 20–22 Sept. 2010, 184–187.

Stamatakos, N., Luzum, B., Stetzler, B., Shumate, N., Carter, M.S., and Tracey, J., 2012, “Recent Improvements in IERS Rapid Service/Prediction Center Products for 2010 and 2011,” in Proc. Journées Systèmes de Référence Spatio-Temporels, Vienna, 19–21 Sept. 2011, 125–129.

Stamatakos, N., Luzum, B., Zhu, S., and Boboltz, D., 2012, “Further Analysis of a New Geodetic VLBI Data Source and its Applications,” G51A-1084, AGU Fall Meeting, San Francisco, 3–7 Dec. 2012.

Stamatakos, N., Eubanks, T. M., McCarthy, D., Salstein, D., 2016a, “Using Atmospheric and Oceanic Angular Momentum to Improve Earth Orientation Products,” EGU2016-8556 POSTER at the European Geophysical Union Meeting, Vienna, Austria, April 2016.

Stamatakos, N., Eubanks, T. M., McCarthy, D., Salstein, D., 2016b, “Ongoing Efforts to Analyze and Use U.S. Navy provided Angular Momentum Datasets for Predictions of Earth Orientation,” G41A-1003 POSTER at the American Geophysical Union Meeting, San Francisco, California, December 2016.

Stamatakos, N., McCarthy, D., Salstein, D., 2017a, "Earth Orientation from the IERS Rapid Service / Prediction Center: Improvements with the Use of Atmospheric and Ocean Angular Momentum Data," EGU2018-10589 POSTER at the European Geophysical Union Meeting, Vienna, Austria, April 2017.

Stamatakos, N., McCarthy, D., Salstein, D., 2017b, "Earth Orientation Enhancement Efforts at the IERS Rapid Service / Prediction Center: Improvements, Changes, and Challenges," G11B-0409 POSTER at the American Geophysical Union Meeting, New Orleans, Louisiana, December 2017.

Stamatakos, N., 2017, "IERS Rapid Service / Prediction Center Products and Services: Improvements, Changes, and Challenges, 2012 to 2017," Journèes 2017, des Systèmes de Référence et la Rotation Terestre, Alicante, Spain, 25–27 Sept., 2017.

Stamatakos, N., McCarthy, D., Salstein, D., 2018a, "Enhancements and Improvements to USNO-produced Earth Orientation Results Using Navy or US-only Produced Atmospheric and Oceanic Angular Efforts," presented at the Institute of Navigation, Joint Navigation Conference, Long Beach, California, July 2018.

Stamatakos, N., McCarthy, D., Salstein, D., 2018b, "Updates on the use of Atmospheric and Ocean Angular Momentum for Earth Orientation within the IERS Rapid Service/Prediction Center." G31B-0659 POSTER at the American Geophysical Union Meeting, Washington D.C., December 2018.

Stamatakos, N., McCarthy, D., Salstein, D., 2019, "Investigating Possible Combinations of Atmospheric, Ocean, and other Geophysical Angular Momentum Data to Improve Operational Earth Orientation Information." EGU2019-3164 POSTER at the European Geophysical Union Meeting, Vienna, Austria, April 2019.

Wooden, W.H., Johnson, T.J., Kammeyer, P.C., Carter, M.S., and Myers, A.E., 2005, Determination and Prediction of UT1 at the IERS Rapid Service/Prediction Center, Proc. Journées Systèmes de Référence Spatio-Temporels, Paris, 20–22 Sept. 2004, 260–264.

Report contributors: Nick Stamatakos, Maria Davis, Nathan Shumate, Merri Sue Carter; Report reviewer: Christine Hackman