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 2019. 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 centre 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 2019 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 2019.

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 Celestial Pole Offsets (CPOs), all the contributors provide direct measurements of these quantities. For all of 2019, the CPO contributor observational inputs used in the combination 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.

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

Table 1: *Estimated accuracies of the contributions to the IERS RS/PC combination results for 2019 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 (ms) for UT1−UTC. (All acronyms used in this table are defined in the Acronyms section of the Appendix of the IERS Annual Report 2019.)*

	Estimated accuracy				
Contributor	**x**	**y**	**UT1−UTC**	**dX**	**dY**
ILRS SLR	0.16	0.15	–	–	–
IAA SLR	0.24	0.20	–	–	–
MCC SLR	0.15	0.20	–	–	–
GSFC VLBI Intensive	–	–	0.018	–	–
USNO VLBI Intensives	–	–	0.014	–	–
GSI Intensives	–	–	0.016	–	–
GSFC$^+$ VLBI	0.13	0.09	0.005	0.06	0.06
IAA$^+$ VLBI	0.30	0.29	0.008	0.06	0.09
IVS$^+$ VLBI	0.11	0.12	0.004	0.05	0.06
USNO$^+$ VLBI	0.11	0.07	0.005	0.06	0.06
IGS Final	0.01	0.01	–	–	–
IGS Rapid	0.03	0.03	–	–	–
IGS Ultra*	0.04	0.04	0.028*	–	–
USNO GPS UT*	–	–	0.047*	–	–

$^+$ 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.

(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).

Comparing statistics provided in Table 1 versus the same table in the IERS RS/PC section of the IERS 2018 Annual Report[4], a few differences are worth mentioning. The 2019 versus 2018 Polar Motion x ILRS SLR estimated RMS accuracy was 0.16 versus 0.22 milliseconds

[4]The IERS Annual Report (AR) 2018 and previous ARs are found at https://www.iers.org/IERS/AnnualReports

Table 2: *Mean and standard deviation of the differences between the Rapid Service/Prediction Center combination solutions and the 14 C04 EOP solutions for 2019. Polar motion x and y values are in milliseconds of arc (mas) and UT1−UTC values are in units of milliseconds of time (ms).*

	Bulletin A – C04	
	Mean	Std. Deviation
Bulletin A Rapid Solution (finals.data)		
x	0.02	0.05
y	-0.01	0.05
UT1−UTC	0.001	0.016
Bulletin A Weekly Solution (finals.data)*		
x	0.01	0.07
y	-0.02	0.06
UT1−UTC	0.005	0.025
Bulletin A Daily Solution (finals.daily)		
x	-0.01	0.04
y	0.00	0.04
UT1−UTC	-0.001	0.042

* Statistics computed over the 7-day combination solution period prior to solution epoch.

of arc (mas), respectively; and for Polar Motion y, 0.15 versus 0.22. Comparing the 2019 versus 2018 GSFC, IVS, and USNO VLBI Polar Motion x RMS accuracies, all deteriorated by at least 30%, whereas the Polar Motion y were accuracies were very similar.

When comparing the integrated IGS Ultra LODs (IIUL) RMS residual value provided in Table 1 to that shown in Table 1 in the AR 2018, one can see an improvement (0.028 for 2019 vs 0.034 milliseconds (ms) for 2018). 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.

Table 2 shows the accuracies of RS/PC combination solution for the running, weekly, and daily products compared to the 14 C04 series maintained by the IERS EOC for 2019; 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 https://cddis.nasa.gov/archive/products/iers/readme.finals and 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 2019 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 2019, 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.)

Comparing the “Bulletin A Daily Solution (finals.daily)” UT1−UTC statistics between 2018 and 2019, the difference in mean was only 1 microsecond, however, the standard deviation (STD) improved to 0.042 in 2019 compared to 0.074 in 2018. The reasons for this welcome improvement are under investigation and may be provided at a conference or meeting later in 2020 or 2021. In addition, the PMx statistics between 2018 and 2019 showed a small improvement in mean and STD from 2018 to 2019; a mean of 0.05 and STD of 0.08 in 2018 compared to 0.01 and 0.07 mas in 2019. The PMy statistics between 2018 and 2019 were fairly similar.

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 2019. The finals.data file used in computing these statistics was computed on January 14, 2020 (and also archived). Nominally, the last observational input data for the year (in this case, 2019) is processed and provided to the IERS RS/PC by January 14 of the following year (in this case, 2020); 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 some noteworthy improvements in the comparison of the polar motion x mean and UT1−UTC STD between the 2019 and corresponding 2018 results. The polar motion x mean differences were reduced from 0.07 in 2018 and 0.02 mas in 2019. There was a welcome improvement in UT1−UTC STD from 2018 to 2019, namely 0.052 to 0.016 ms. The cause of the improvement is under investigation and may be explained in more detail in a subsequent conference or meeting later in 2020 or 2021.

The “Bulletin A Weekly Solution” results shown in Table 2 are the statistics of the residuals obtained from the 2019 Bulletin A combination values, contained in the ser7.dat format, versus the 14 C04 series. These combination values for 2019 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 9 July 2020 has EOP combination results from 3 through 9 July, 2020.)

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*

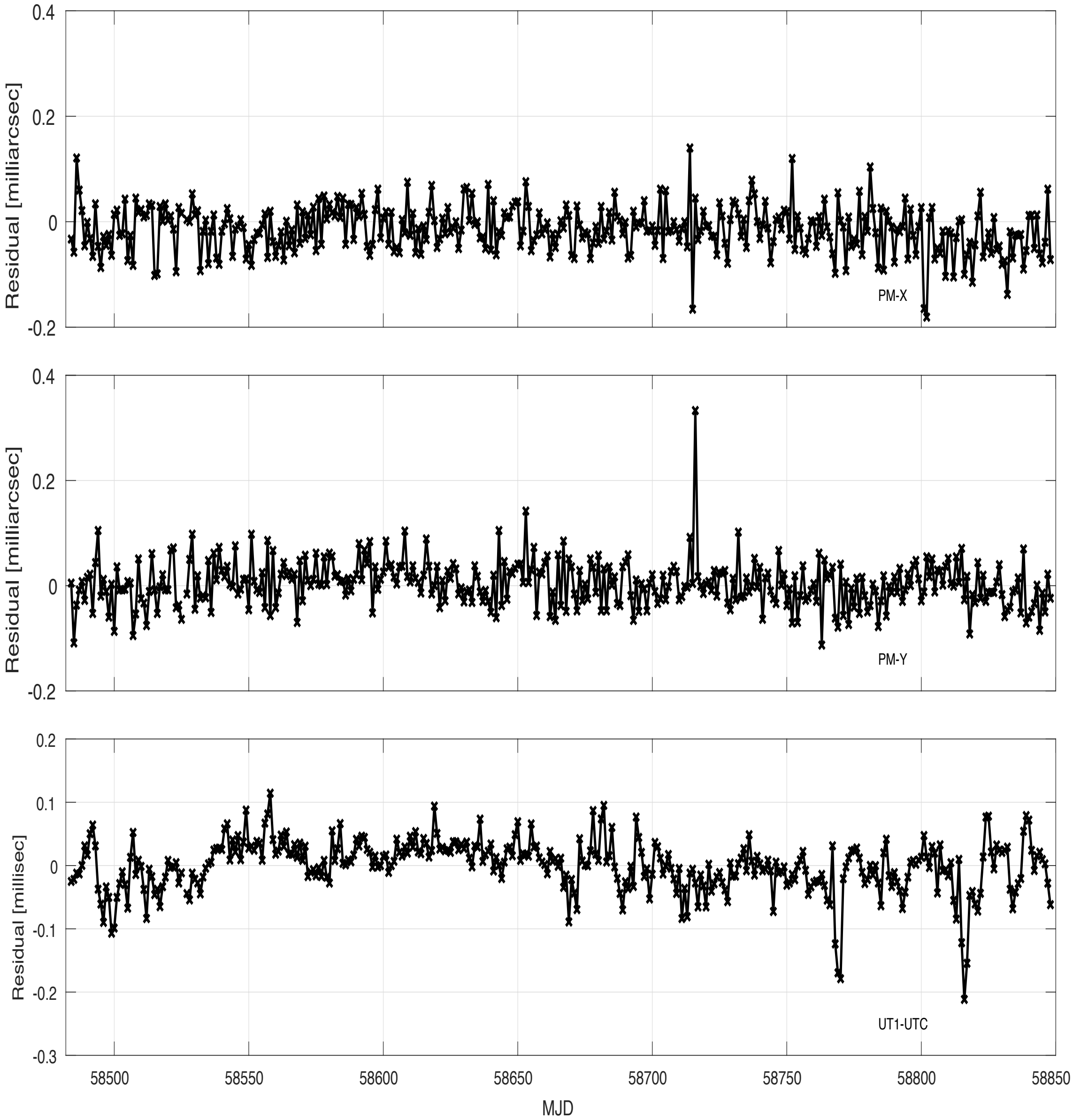

Fig. 1: *Differences for 2019 between the daily updated EOP solution at the day of the solution update and the 14 C04 series combination solution. (The day of the solution is also known as the last combination or 0-day prediction epoch.) Earth Orientation Parameters shown are: a) Polar Motion x; b) Polar Motion y; and c) UT1−UTC.*

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:

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

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 2019 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 0 for the EOP solution that was updated at 17:00 UTC on MJD 58757 (October 1, 2019) was at 00:00 UTC on MJD 58757 (i.e., 17 hours prior to the solution update time.) As a further example, prediction day 10 for the EOP solution that was updated at 17:00 UTC MJD 58757

(October 1, 2019) is 00:00 UTC MJD 58767 (October 11, 2019). 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. (So, going back to the example of prediction day 0 for MJD 58757, if one can wait to obtain EOPs at update times of 21:10 UTC, or 03:10 or 09:10 on the MJD 58758, one generally can be assured of more observational data and obtain an improved estimate of EOPs at 00:00 UTC MJD 58757 over that obtained at the 17:00 UTC on MJD 58757 update time.)

As Table 3a shows, for most prediction days (although certainly not all) there were no noteworthy changes in the polar motion versus the same table in the AR 2018; however, there was a substantial improvement of UT1−UTC in 2019 compared to 2018 for the 0 and 1 day predictions. The 0- and 1-day changes from 2018 to 2019 were 0.074 ms versus 0.042 and 0.087 versus 0.063, respectively. This improvement occurred even with a missed update of the EOP solution on December 13, 2019 due to network issues. More detailed explanations for the improvements (including the effect of the missing update) 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. In general, the results are very similar since on most days an observation is made either on the solution day or the day before.

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 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

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 2019. 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	0.05	0.04	0.042
1	0.30	0.23	0.061
5	1.90	1.25	0.198
10	3.46	1.88	0.463
20	5.75	2.84	1.851
40	7.21	4.04	6.259
90	8.45	8.66	19.983

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 2019.*

Days in future	PMx (mas)	PMy (mas)	UT1−UTC (ms)
0	0.05	0.05	0.041
1	0.29	0.23	0.063
5	1.89	1.23	0.199
10	3.45	1.85	0.463
20	5.73	2.84	1.846
40	7.23	4.03	6.255
90	8.37	8.69	20.012

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 2019.*

Days in future	PMx (mas)	PMy (mas)	UT1−UTC (ms)
0	0.05	0.05	0.041
1	0.27	0.21	0.061
5	1.85	1.19	0.197
10	3.45	1.81	0.463
20	5.77	2.81	1.854
40	7.23	3.99	6.269
90	8.39	8.54	20.046

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 2019.*

Days in future	PMx (mas)	PMy (mas)	UT1−UTC (ms)
0	0.05	0.05	0.040
1	0.26	0.21	0.060
5	1.81	1.18	0.197
10	3.41	1.79	0.463
20	5.73	2.80	1.853
40	7.21	3.98	6.269
90	8.40	8.53	20.047

“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

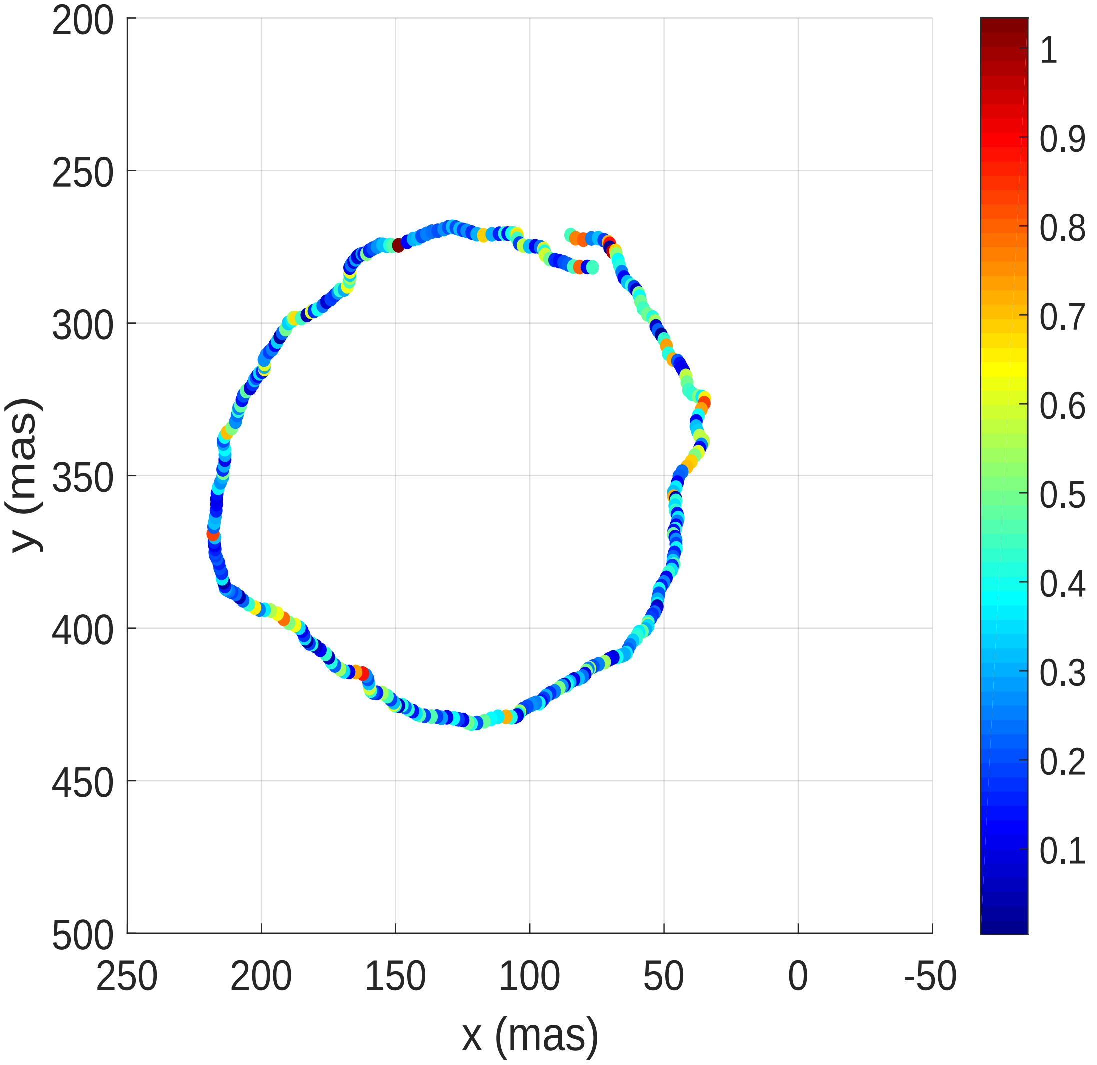

Fig. 2: *Plot of the polar motion path for 2019 with corresponding 1-day prediction residual values. The residuals are the RMS of the combined polar motion x and y residual values and are in units of milliseconds of arc (mas) and correspond to the color-coded vertical bar at the right ranging from less than 0.1 (dark blue) to greater than 1.0 (dark red) mas.*

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, Zhu, & Boboltz (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.

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 2019 (and for 2018), the resulting statistics do not follow this pattern in most cases. These results were caused by an error in the Nxdaily EOP software that prevented additional updated data from being used, and on September 15, 2019, the software problem was corrected.

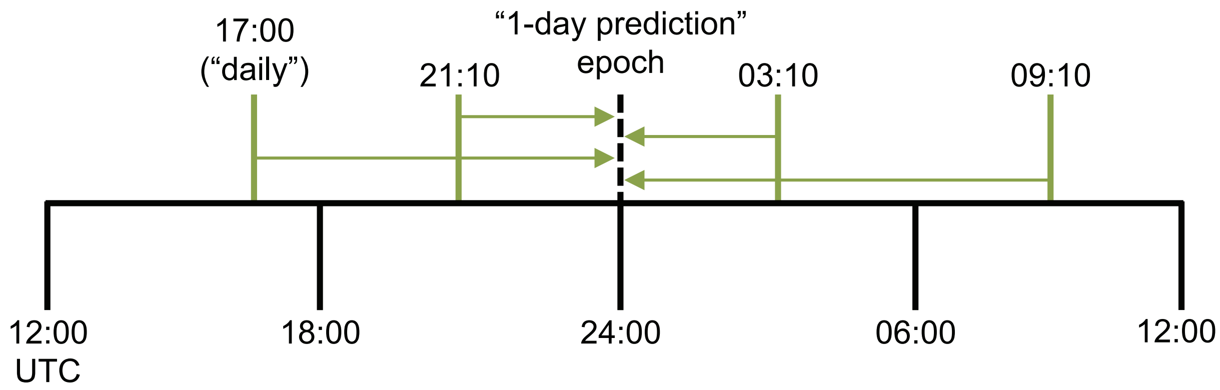

Fig. 3: *Timeline of Nxdaily EOP 1-day prediction solutions in relation to the EOP "daily" solution produced at 17:00 UTC. Each EOP solution update time is shown by the vertical green lines at 17:00, 21:10, 03:10 and 09:10 UTC, respectively. At each of these times, the latest observations are obtained. 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.*

To highlight the effect of this code correction, using only the period 15 September to 31 December 2019, the PMx and PMy statistics corresponding to those in the Table 3c were computed. The 1-day PMx and PMy residuals during this period were 0.172 and 0.133 mas (respectively), which are comparable to the 2017 statistics, namely, 0.13 and 0.092 mas; the 5-day PMx and PMy residuals were 1.70 and 1.04 for 2019 and 1.78 and 1.15 mas in 2017. Thus, with this correction implemented, it is anticipated that this trend will continue for the 2020 statistics; namely, that the Nxdaily residuals, especially for polar motion, will show noteworthy improvements as more input observations become available and used as indicated in Figure 3.

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 CPOs 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 2019 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 2019. For the dX residual prediction days, it was noticed that there were several outliers that were greater than 3σ . When the outliers are removed, the dX RMS residuals are reduced to 0.07, 0.07, and 0.09 mas for the 0-, 1-, and 40-day prediction days. Similarly, for the dψ residual prediction days, removal of outliers would result in 0.18, 0.20, 0.21, 0.21, and 0.22 mas for the 0-, 1-, 5-, 10-, and 20-day prediction days. If a reason is determined for the large outliers, this information may be presented at an upcoming conference or meeting.

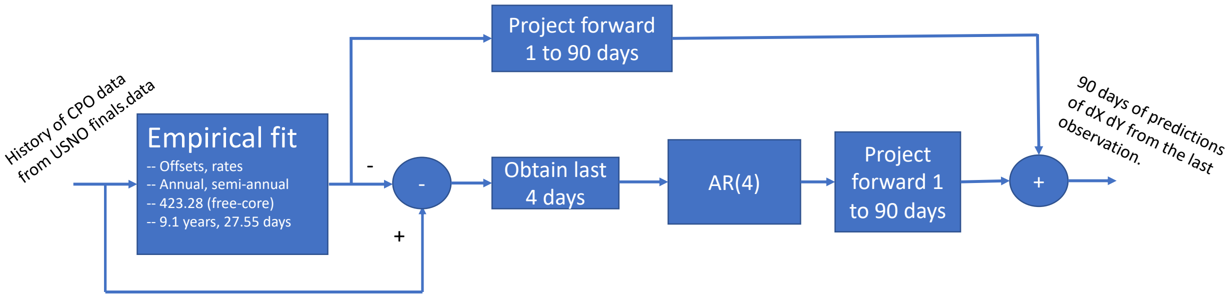

Fig. 4: *Flowchart of CPO prediction algorithm. Predictions out to 90 days are made from a) combining an extrapolated empirical model forward in time and b) an extrapolated autoregressive fit to residuals of past CPO observations minus an empirical fit.*

Predictions of TT−UT1, up to 1 October 2030, 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 celestial pole offset predictions (also known as nutation offsets) produced by the daily solutions and the 14 C04 combination solution for 2019.*

Days in Future	**dX (mas)**	**dY (mas)**	**dψ (mas)**	**dϵ (mas)**
0	.10	.06	0.26	0.08
1	.11	.06	0.28	0.08
5	.09	.07	0.26	0.08
10	.10	.07	0.26	0.09
20	.09	.08	0.25	0.09
40	.10	.08	0.25	0.10

Center Activities for 2019

During 2019, several changes to the input data series, the usage of such data, or to output results were made.

A list of these upgrades is as follows:

a) On 01 August 2019, the USNO VLBI 24-hour and intensive data series were upgraded to the usno2019c series, and

b) On 29 August 2019, the NASA Goddard VLBI 24-hour and intensive data series were upgraded to the gsfc2019a series;

In addition, the method of computing statistics for the second instance of the IGS Final comparison in the file gpspol.asc during the last 30 days has been updated to use the more accurate smoothing cubic spline used in the EOP combination.

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 i) improve UT1−UTC derivative (or LOD) inputs, such as UTGPS, IGS LOD, USNO LOD, and AAM, to the EOP combination, and ii) better optimize the use of these inputs in the EOP solution;

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

d) Continuing efforts to test a greatly improved WSCS being developed to improve the EOP combination. One significant improvement that has been developed is that this greatly improved

Table 6: *Predicted values of TT−UT1, 2020–2030. Note that UT1−TAI can be obtained from this table using the expression UT−TAI = 32.184s−(TT−UT1).*

DATE		TT−UT1 (s)	Uncertainty (s)
2020	1 Jul	69.56	0.024
2020	1 Oct	69.4	0.600
2021	1 Jan	69.4	0.668
2021	1 Apr	69.4	0.736
2021	1 Jul	69.4	0.803
2021	1 Oct	70.1	0.870
2022	1 Jan	71.0	0.936
2022	1 Apr	71.1	1.000
2022	1 Jul	71.	1.064
2022	1 Oct	71.	1.126
2023	1 Jan	71.	1.186
2023	1 Apr	72.	1.245
2023	1 Jul	72.	1.302
2023	1 Oct	72.	1.358
2024	1 Jan	72.	1.411
2024	1 Apr	72.	1.463
2024	1 Jul	72.	1.514
2024	1 Oct	72.	1.562
2025	1 Jan	72.	1.609
2025	1 Apr	73.	1.654
2025	1 Jul	73.	1.697

Table 6 cont.

2025	1 Oct	73.	1.738
2026	1 Jan	73.	1.778
2026	1 Apr	73.	1.816
2026	1 Jul	73.	1.853
2026	1 Oct	73.	1.887
2027	1 Jan	73.	1.921
2027	1 Apr	74.	1.953
2027	1 Jul	74.	1.983
2027	1 Oct	74.	2.012
2028	1 Jan	74.	2.039
2028	1 Apr	74.	2.065
2028	1 Jul	74.	2.090
2028	1 Oct	74.	2.114
2029	1 Jan	74.	2.136
2029	1 Apr	75.	2.157
2029	1 Jul	75.	2.177
2029	1 Oct	75.	2.196
2030	1 Jan	75.	2.214
2030	1 Apr	75.	2.231
2030	1 Jul	75.	2.247

WSCS will accept derivative state inputs (such as LOD in combination with UT1);

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

f) Using new VLBI w-series intensive series (such as the Mauna Kea to Wettzell baseline) as an additional input series in the operational EOP solution;

g) Preparing to possibly use the Very Long Baseline Array (VLBA) estimates as additional UT1−UTC inputs to the EOP solution (Stamatakos, Luzum, Zhu, & Boboltz (2012));

h) Finalizing scripts to validate 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. 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.

As indicated in each IERS Bulletin A since late October 2019, the US Naval Observatory's Rapid Service/Prediction Center web and FTP sites (at maia.usno.navy.mil and toshi.nofs.navy.mil) are undergoing modernization and have been offline since 24 October 2019. The expected completion of work and return of service is no earlier than Autumn of 2020. The official announcement from the U. S. Naval Observatory of this information is contained in Figure 5. One may visit https://www.usno.navy.mil and submit a Requirements Form to the USNO Public Affairs Official (PAO) if the information you are seeking is not accessible via another means. If the Requirements Form is not available, please contact the USNO PAO Geoff Chester directly at email address geoff.chester@navy.mil or phone number 202 762 1438.

This modernization has also lead to the indefinite cessation of IERS Bulletin A distribution emails. Alternative methods for email distribution were researched, however, given: a) the resources involved in using an approved email distribution method, b) more modern and reliable distribution methods available to users, and c) that no future plans for the creation agreed-upon, reliable email distribution have been made, it is doubtful that there will be restoration of the Bulletin A distribution email service.

Until 31 October 2020, the daily and Bulletin A EOP data will be hosted by NASA's Archive of Space Geodesy Data server at ftp://cddis.gsfc.nasa.gov/pub/products/iers. Daily EOP data is uploaded by 18:00 UTC and Bulletin A EOP weekly data are available by 20:00 UTC, nominally on Thursdays. Users should please verify results obtained from this site, as the RS/PC cannot guarantee the integrity or timeliness of files provided at this site. It is expected that as of 31 October 2020, all unencrypted ftp service will be permanently discontinued at CDDIS. For other download options from CDDIS, such as HTTPS or FTPS, please refer to the https://cddis.nasa.gov/About/CDDIS_File_Download_FAQ.html.

Lastly, updated EOPs may be available at IERS: https://datacenter.iers.org/eop.php. EOP data files are uploaded directly from USNO to this site each day. For further information, contact the IERS directly.

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IN REPLY REFER TO
5230
Ser N3-EO/072
19 Mar 2020

From: Superintendent, U. S. Naval Observatory
To: Internal Earth Rotation and Rapid System

Subj: NOTIFICATION OF USNO USER IERS RAPID SERVICE/PREDICTION WEBSITES

1. The U. S. Naval Observatory's IERS Rapid Service/Prediction web/FTP sites (maia.usno.navy.mil; toshi.nofs.navy.mil) and the IERS Conventions web site (maia.usno.navy.mil/conventions), are offline as they undergo modernization. These modernization efforts have been interrupted by current events and estimated return to service is no earlier than autumn of 2020.

2. Please visit https://www.usno.navy.mil and submit a Requirements Form to the USNO Public Affairs Official (PAO) if the information you are seeking is not accessible by another means. If the Requirements Form is not available, please contact the PAO Mr. Geoff Chester at email address Geoff.chester@navy.mil or telephone +1 (202) 762-1438.

D. R. KUEHN

Fig. 5: *Official notification from the U. S. Naval Observatory stating that the web and ftp servers, maia.usno.navy.mil and toshi.nofs.navy.mil, are offline as they undergo modernization.*

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 (GSFC 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 priori 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 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] The delay between solution time and posting time occurs for two reasons: a) the time it takes EOP personnel to verify and confirm the solution prior to its uploading to the CDDIS ingest server and b) an additional few minutes for transfer from ingest to publication servers at ftp://cddis.gsfc.nasa.gov /pub/products/iers (and the corresponding HTTPS and FTPS sites).

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
Mr. Nathan Shumate	Operational program manager, research, and software maintenance; Astronomer, EOP C/P Division
Ms. Merri Sue Carter	Assists in daily operations and support; Research Astronomer, EOP C/P Division
Ms. Maria Davis	Assists in daily operations and support, research, and software maintenance; Astronomer, EOP C/P Division

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