IERS RAPID SERVICE / PREDICTION CENTER PRODUCTS AND SERVICES: IMPROVEMENTS, CHANGES, AND CHALLENGES, 2017 TO 2019.

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ABSTRACT. The International Earth Rotation and Reference Systems Service (IERS) Rapid Service/Prediction Centre (RS/PC) has continued to make improvements to its products throughout the time period from 2017 to 2019. Several noteworthy improvements are as follows: a) the method of computing Celestial Pole Offsets (CPO) was updated; b) the Navy Global Environment Model (NAVGEM) atmospheric angular momentum (AAM) input was updated from version 1.4 to 1.4.3eop; c) a new version of the Earth Orientation (EO) matrix calculator using the IERS Conventions 2010 (v1.2.0) was made available; and d) updated VLBI 24-hour and intensive series solutions were incorporated.

In order to improve accuracy and increase robustness of the EO parameter (EOP) results, development work for future enhancements is being performed in the following areas: a) investigating the use of a new combination of Very Long Baseline Array (VLBA) and Very Long Baseline Interferometry (VLBI) intensives, named the w-series using a combination of Mauna Kea (Mk), Wettzell (Wz), and Wettzell-North (Wn) radio telescopes; b) improving polar motion and possibly UT1-UTC accuracy and robustness through the use of AAM and oceanic angular momentum (OAM) inputs; c) investigating the use of improved optimal estimation techniques to improve the accuracy and robustness of the EOP combination results; and d) investigating improving EOP prediction techniques.

A few anomalous EOP results that were reported, but not fully explained in the IERS RS/PC contribution to the IERS Annual Report 2018 (Stamatakos *et. al*, 2020), are further discussed. These are the larger than expected residuals in the Nxdaily/off-hours EOP solutions and the USNO versus IGS polar motion products reported in the weekly statistics (contained in the gpspol.asc file).

Between the time of the Journees 2019 conference[1] and the writing of this document, the U.S. Naval Observatory's IERS RS/PC web and FTP sites (maia.usno.navy.mil and toshi.nofs.navy) were ordered to be taken offline to undergo modernization, starting on 24 October 2019. The expected completion of work and return to service are estimated to be no earlier than June, 2020. The implications of this change are that a) the EO matrix calculator will not be available until the return-to-service work is completed and b) the RS/PC EOP results and the IERS Conventions will also be unavailable at `https://maia.usno.navy.mil` and `https://toshi.nofs.navy.mil`. However, both EOPs and Conventions are hosted at other servers – as discussed later in this report.

1. OVERVIEW OF RS/PC SOLUTION.

The operational, daily EOP combination and prediction (CP) solution (which includes finals.daily) is produced at approximately 17:00 UTC each day; the weekly version (Bulletin A) is produced on Thursdays just after 17:30 UTC. Both provide EOP values that include polar motion, UT1-UTC, and CPOs used to relate the terrestrial to celestial reference systems. Observations from VLBI, the Global Positioning System (GPS), Satellite Laser Ranging (SLR), and AAM are used to generate these solutions. Further details about inputs, processes, numbers of users, and

[1] Journées 2019, "Astronomy, Earth Rotation, and Reference Systems in the Gaia Era," Paris, France, 7-9 October 2019.

results are provided in Stamatakos *et al.*, (2011) and in Section 3.5.2 of the IERS Annual Report 2018 (Stamatakos *et al.*, 2020).

In addition to the operational, daily EOP CP solution, there are three additional EOP solutions (referred to as the *Nxdaily* solutions) that have been produced each day since 16 December 2011. The automated processes that generate the *Nxdaily* solutions begin at 03:10, 09:10, and 21:10 UTC and should be completed within 20 minutes after the initial start time. The only solution that is currently actively monitored by EOP RS/PC personnel is the operational, daily EOP solution that begins processing at 17:00 UTC. A discussion of the advantages, increased accuracy of results, and additional observations available at the 03:10, 09:10, and 21:10 EOP solution update times is provided in the Prediction Techniques and Results subsection within Section 3.5.2 of the IERS Annual Report 2018 (Stamatakos *et al.*, 2020).

Until 24 October 2019, all EOP results were located at `http://maia.usno.navy.mil/ser7` (*maia*) and `http://toshi.nofs.navy.mil/ser7` (*toshi*) and several other backup locations as listed in Table 8 of Section 3.5.2 of the IERS Annual Report 2018 (Stamatakos *et al.*, 2020). Until the restoration of *maia*, planned for June 2020, the 17:00 UTC, *operational daily*, EOP solutions are available only at Crustal Dynamics Data Information System (CDDIS)<[2]> and IERS<[3]> servers, with USNO uploading directly to each of those sites on a daily basis. As of the writing of this report, the Nxdaily solutions are only available at the CDDIS site. (Lastly, CDDIS does host RS/PC EOP results at an https site; contact CDDIS for details on how to access this site.)

2. IERS RS/PC IMPROVEMENTS AND CHANGES, 2017 TO 2019.

Beginning on 29 March 2018, an updated method for computing CPOs was integrated into the RS/PC EOP products. Prior to this date, some of the CPO inputs used in the combination were based on $(d\psi \ / \ d\epsilon)_{(1976/1980)}$ (based on the 1976 precession and 1980 nutation theory) and some inputs were based on $(dX \ / \ dY)_{2006/2000}$ (the 2006 precession and 2000 nutation theory, Wallace *et al.,* (2006)). With the updated software, all CPO inputs are based on $(dX \ / \ dY)_{2006/2000}$, thus making the combination algorithm much simpler to implement and making systematic correction adjustments more straightforward.

The algorithm to predict CPOs after the last combination value has also been updated and is illustrated in the flowchart in Figure 1. First, empirical fits are performed on two years of combination values to obtain offsets, rates, and annual, semi-annual, free-core, 9.1 year, and 27.55 day periodic signals, and then residuals are created by subtracting the empirical fits from the combination data. An auto-regressive model of order 4, AR(4), is fit to the residuals and then used to predict that portion of the signal forward 1 to 90 days. In addition, the empirical fit coefficients are used to project forward the same 1 to 90 day period and then added to the AR(4) signal; the results are dX and dY prediction values from 1 to 90 days into the future from the last observation day.

Following the implementation of the updated CPO methodology, there has been an improvement in accuracy in the 0-day and 1-day CPO predictions. A chart is shown in Figure 2 that compares the CPOs obtained during the period 29 March 2018 to 31 July 2019 (Period 2) with the period from 1 January 2016 to 28 March 2018 (Period 1). When compared to the C04 observational data, the Period 2 dX RMS 0-day prediction residuals were reduced by 11% when compared to Period 1 and 0-day dY prediction residuals were reduced by 23%. Similarly, the 1-day dX prediction residuals were reduced by 5% and the 1-day dY were reduced by 14%.

Several times between 2017 and 2019, the USNO and NASA Goddard (GSFC) VLBI input series were updated; USNO VLBI updated on 27 September 2017, 23 August 2018, and 01 August

[2] `ftp://cddis.gsfc.nasa.gov/pub/products/iers`

[3] `https://www.iers.org/IERS/EN/DataProducts/EarthOrientationData/eop.html`

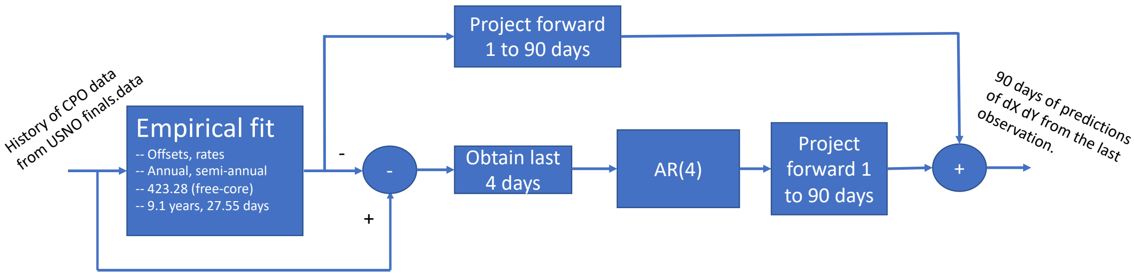

Figure 1: CPO Prediction Algorithm Flow Chart Used in RS/PC Software Since 29-March-2018.

Prediction Day	Period 1: dX RMS (milliarcsec)	Period 2: dX RMS (milliarcsec)	% decrease
0-day	0.110	0.099	11
1-day	0.111	0.106	5

Prediction Day	Period 1: dY RMS (milliarcsec)	Period 2: dY RMS (milliarcsec)	% decrease
0-day	0.106	0.086	23
1-day	0.099	0.087	14

Figure 2: CPO Prediction Statistics Before (Period 1) and After (Period 2) the Upgrade in Processing.

2019, while GSFC updated on 29 August 2019. Each time an update was included in the RS/PC combination, systematic adjustments for UT1-UTC, polar motion, and CPOs were re-computed and applied to each series to maintain a minimal residual between each new series and the IERS reference series (the C04).

Starting on 17 May 2019, the upgraded AAM model input, named the Navy Fleet Numerical Meteorology and Oceanography Center (FNMOC) Navy Global Environmental Model (NAVGEM) AAM version 1.4.3eop, was incorporated into the RS/PC combination and prediction software. This new model incorporated the following upgraded features: a) approximately 31 km grid spacing, b) an atmosphere up to a height of approximately 60 km, c) hybrid 4-D data assimilation, d) ozone assimilation, and e) an engineering fit to better model upper atmospheric (zonal) winds.

Using the NOAA AAM forecast results as a benchmark, one can see the improvement of the NAVGEM version 1.4.3eop to version 1.4. The top two plots are the mean and RMS errors of the NOAA and NAVGEM version 1.4 forecast results compared to the NOAA analysis data from 01 January 2016 through 15 May 2018; the bottom two plots are comparisons of the NOAA and NAVGEM version 1.4.3eop forecasts from 01 June 2018 through 15 September 2019. The x-axis in each plot is the prediction hour from the current day midnight hour, and the y-axis is the dimensionless effective angular momentum coefficients, χ_i. The top plots show the NAVGEM v1.4 mean and RMS residuals have higher residuals than the NOAA results; whereas, the v1.4.3eop has lower mean and comparable RMS residuals to NOAA.

A new on-line EO matrix calculator providing the direction cosine matrix (DCM) between the terrestrial (ITRF) and celestial (GCRS) reference frames was developed and made available to users in August 2018. It is based on the the Celestial Intermediate Pole and Origin (CIP and CIO, respectively) and Terrestrial Intermediate Origin (TIO), non-equinox algorithms presented in Chapter 5, IERS Conventions (2010, Tech Note 36.) However, as was stated in the Overview section, the U.S. Naval Observatory's IERS RS/PC web and FTP sites (maia.usno.navy.mil and toshi.nofs.navy) were taken offline to undergo modernization, starting on 24 October 2019; the expected completion of work and return to service are estimated to be no earlier than mid-June 2020, at which time it is anticipated that the EO matrix calculator will be made available to users again.

The matrix code is written in FORTRAN with HTML and web interface codes, and relies heavily on code from the IERS Conventions 2010 software and the Standards of Fundamental of Astronomy (SOFA) libraries. The observable quantities are from a version of finals2000A.data or finals2000A.daily, and, if necessary, the polar motion, UT1-UTC, and celestial pole observables are interpolated. Long period tidal terms are removed and then, long period tidal, diurnal, and sub-diurnal tidal terms are added back to these observables after interpolation. Sub-diurnal/diurnal tides, CPOs, and librations are used by default, but can be turned off. Outputs include the ITRF to GCRS direction cosine matrix at each requested epoch and several intermediate transformations. The EO matrix calculator user-interface is shown in Figure 4. In Figure 5, a comparison table of the Equinox-based and CIP/CIO/TIO-based calculators is provided.

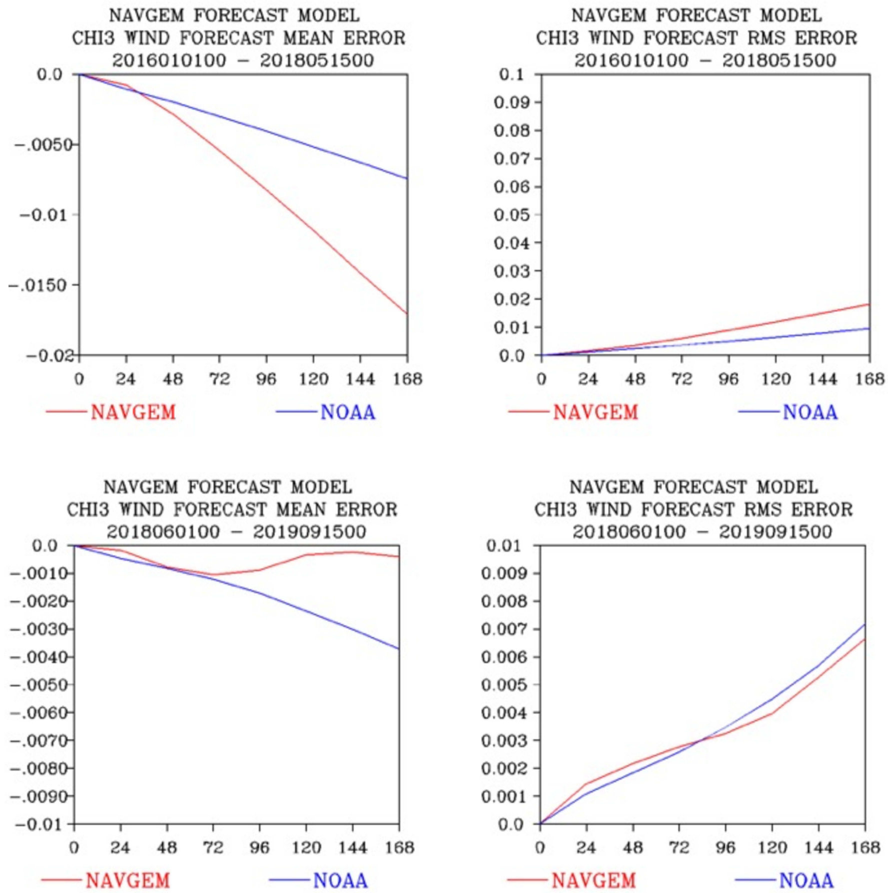

Figure 3: NAVGEM v1.4, NAVGEM v1.4.3eop, and NOAA CHI3 (χ_3) Wind Forecast Coefficient residuals versus NOAA analysis data. (Plots provided by Dr. Tim Hogan of NRL Monterey.) The X-axis of each plot has units of Days, and the Y-axis is the dimensionless effective angular momentum coefficient (χ_3).

As discussed in the IERS Annual Report 2018 (Stamatakos *et. al*, 2020), as more observational data becomes available, there should be an improvement in the polar motion predictions. The last IGS Ultra observation available for the operational solution made at 17:00 UTC is at 00:00 UTC of the current day (MJD); a prediction of the polar motion solution for 00:00 UTC of MJD+1 is created based on that last observation. At each of the later EOP Nxdaily solution updates begun

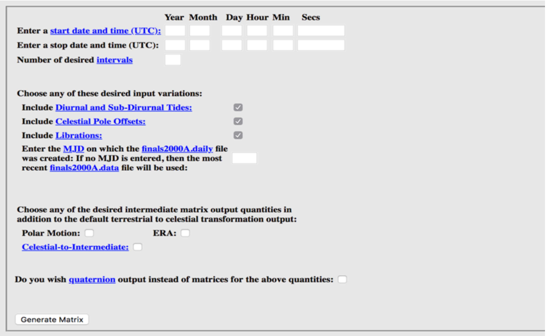

Figure 4: CIP/CIO/TIO-based EO matrix calculator user interface.

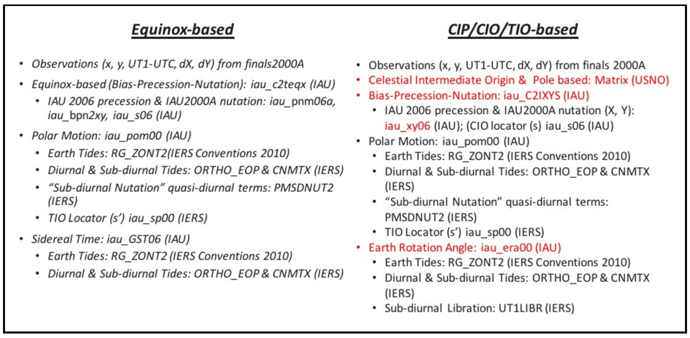

Figure 5: Comparison of CIP/CIO/TIO-based and Equinox-based EO matrix calculator algorithms.

at 21:10 UTC (4 hours after the 17:00 UTC update time), and at 03:10 UTC and 09:10 UTC of the following day, updated IGS Ultra observations are made available, and in theory, these later EOP solution updates should have improved predictions of polar motion at 00:00 UTC of MJD+1. As shown in Figure 7, the Nxdaily / off-hour 2016 and 2017 statistics show agreement with this theory – the RMS of the residual decreases from column 1 (17:00 UTC) to column 4 (09:10 UTC).

Unfortunately, as one can see in the last rows of the tables in Figure 7, for 2018, there was no such significant improvement as more observational data became available at 21:10, 03:10, and 09:10 UTC. After the 2018 Annual Report was published, the RS/PC performed an investigation and an improperly implemented code change was identified, namely, the updated IGS Ultra inputs were not being used. As of 15 Sept 2019, a code fix was implemented and final EOP results with updated IGS Ultra inputs are being generated. The forthcoming 2019 IERS Annual Report should demonstrate an improved polar motion as additional observational inputs become available throughout the day.

Another potential issue affecting the RS/PC results was identified in the 2018 Annual Report, namely, the polar motion residual statistics of the RS/PC versus the IGS finals reported in the Annual Report and that published weekly by the RS/PC (at the beginning of the file, gpspol.asc), both appear to be lower than that published in the weekly statistics at the end of the same file. After some analysis, the RS/PC determined that the method of interpolation used to compute the residuals was different among the cases. The IGS finals are produced for each noon epoch and the RS/PC results are produced for the midnight epoch. The IERS report and the beginning of the gpspol.asc use an interpolation method based on smoothing, weighted cubic spline (SWCS) coefficients; whereas, the reported statistics at the end of the gpspol.asc file use a simple cubic spline for interpolation. Since using the SWCS more accurately reflects the residuals between the contributor and the combination, as of July 11, 2019, the SWCS was chosen to replace the weekly statistics reported at the end of the gpspol.asc file – thus, more accurately reporting the accuracy of the RS/PC polar motion solution compared to the IGS finals.

3. FUTURE DEVELOPMENTS

Improvements in polar motion near-term prediction accuracies may be possible using combined AAM and OAM model data; AAM inputs used in these studies are based on the NAVGEM and the OAM based on the U.S. Navy Hybrid Coordinate Ocean Model (HYCOM). At the 2019 European Geophysical Union (EGU) meeting, a poster (Stamatakos *et al.*, 2019) was presented that explained the work in detail. As shown in the flowchart contained in that poster, excitation functions are derived from existing USNO EOP data and are differenced with combined and adjusted analysis AAM and OAM excitation functions to form residuals, from which a predictive AR model is determined. This AR model predicts the non-angular momentum part of the polar motion and is combined with the predicted (forecast) AAM and OAM data to form the polar motion near-term predictions.

As backup to the INT1, INT2, and INT3 intensives, USNO and the IVS have been developing new baselines combining VLBI and VLBA radio telescopes. One baseline that is being used is the Mauna-Kea (Mk) to Wettzell (Wz) pair, partly because of its similarity to the existing and well-characterized Kokee Park (Kk) Wz baseline. As shown in Figure 8, the two stations would share similar visibility to desired radio sources, yet they are far enough apart (>500 km) that adverse weather conditions may not affect both stations simultaneously. After USNO personnel had re-characterized the station position, which was significantly affected by seismic activity in mid-2018, the Mk-Wz baseline has been used in the operational RS/PC combination since December 2019, and continues to be a backup to the Ishioka (Is) to Wz baseline when Is is unable to observe. Another baseline being rapidly characterized is the Mk to Wettzell-North (Wn).

The RS/PC is conducting a research and development project to investigate using improved optimal estimate techniques to better combine EOP inputs. First, code that uses an improved smoothing, weighted cubic spline (SWCS) that allows for state and derivative state inputs (such as UT1-UTC and length-of-day (LOD)) is being developed. Using this new spline should increase robustness and possibly accuracy of EOP solutions. Then, a development to broaden the improved SWCS to allow for covariance based inputs (such as from SINEX files) will be implemented. The use of a Kalman Filter or other type of filtering technique might also be investigated to determine if improvements in accuracy and robustness can be improved further. In addition, improved prediction techniques will be investigated in the later years of the project.

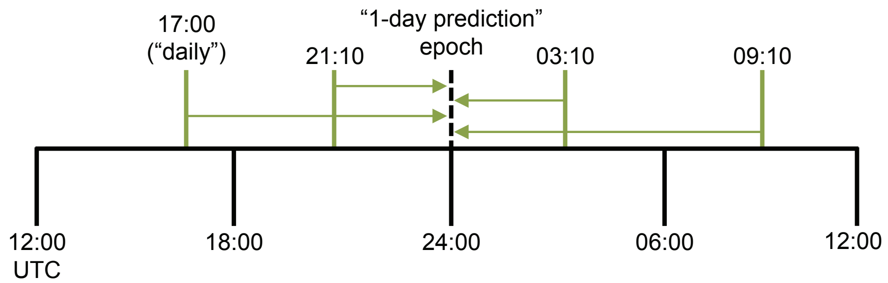

Figure 6: Timeline of Nxdaily EOP 1-day prediction solutions in relation to the EOP operational solution produced at 17:00 UTC. The 21:00 UTC solution is updated on the present day (MJD), while the 03:10 UTC and 09:10 UTC Nxdaily EOP solutions are updated at MJD+1.

PMx	Time of solution in UTC. Results in milliarcseconds			
Year	17:00 UTC	21:10	03:10	09:10
2016	0.34	0.29	0.16	0.08
2017	0.35	0.29	0.13	0.08
2018	0.31	0.29	0.29	0.27

PMy	Time of solution in UTC. Results in milliarcseconds			
Year	17:00 UTC	21:10	03:10	09:10
2016	0.25	0.22	0.08	0.09
2017	0.26	0.20	0.09	0.09
2018	0.23	0.21	0.28	0.21

Figure 7: Nxdaily EOP Solution Results. The 2016 and 2017 polar motion results are as expected; whereas, the 2018 results were anomalous.

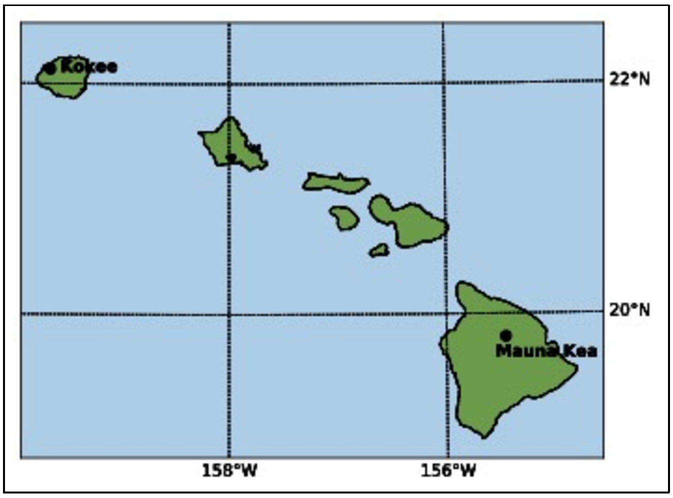

Figure 8: Proximity of Kokee Park and Mauna-Kea radio telescope locations.

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