IERS Rapid Service / Prediction Center Products and Services:

Improvements, Changes and Challenges, 2017 to 2019

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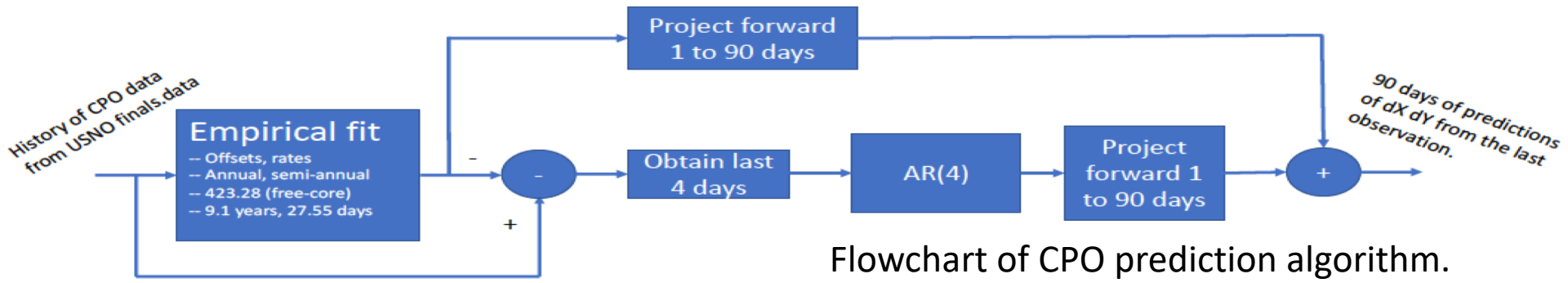
OUTLINE.

- Improvements since 2017.
- EO Matrix Calculator Update.
- Items from 2018 IERS Annual Report.
- Future Development Work.

Improvements since 2017: *Improved Celestial Pole Offset computations.*

Operational Celestial Pole Offset (CPO)

- Code prior to March 29, 2019:
  - Some contributors provided CPO in terms of $(d\psi, d\varepsilon)_{1976/1980}$ and some in terms of $(dX, dY)_{2006/2000}$.
  - All observations transformed to and combined in terms of $(d\psi, d\varepsilon)_{1976/1980}$.
  - Complex code; difficult to maintain; difficult to implement bias/system changes.
- Implemented starting March 29, 2019:
  - All VLBI contributions in terms of $(dX, dY)_{2006/2000.}$
  - Observations combined using $(dX, dY)_{2006/2000.}$
  - Reliable code; easier to maintain; easy to implement bias/system changes through configuration files.
  - Predictions method based on auto-regressive algorithm as shown in the flowchart below.



Flowchart of CPO prediction algorithm.

Improvements since 2017: *Improved Celestial Pole Offset computations since March 29, 2018.*

- Improvement in accuracy
  - Period 1: Jan. 1, 2016 to March 28, 2018 versus Period 2: March 29, 2018 to July 31, 2019

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

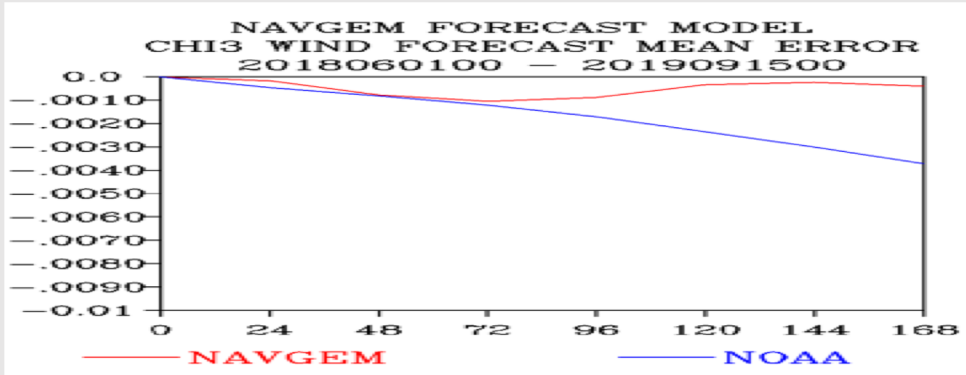
Prediction Day	Period 1: dY RMS (milliarcsec)	Period 2: dY RMS (milliarcsec)	% decrease
0-day	0.106	0.086	23
1-day	0.099	0.087	14

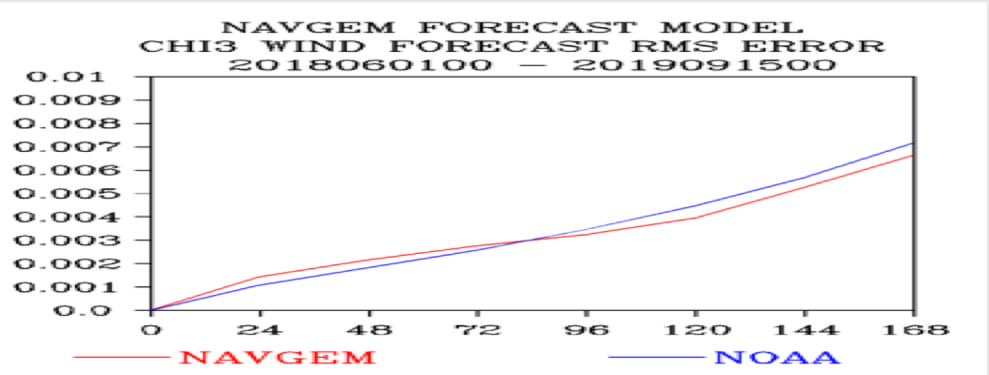
Improvements since 2017: Updates of inputs to the EOP C/P software.

- Updated VLBI 24-hour and intensives series solutions:
  - USNO updated 27 Sept 2017, 23 Aug 2018, and 01 Aug 2019; GSFC updated 29 Aug 2019.
- Updated Atmospheric Angular Momentum Inputs:
  - Navy Fleet Numerical Meteorology and Oceanography Center (FNMOC) Navy Global Environmental Model (NAVGEM) updated on 17 May 2018 to 1.4.3eop.
    - ~31 km grid spacing
    - Model top ~60 km
    - Hybrid 4D-Var Data Assimilation
    - Ozone Assimilation
    - Engineering fit to better model upper atmospheric (zonal) winds. Applies to above 500 mbars.

NAVGEM and NOAA Chi3 Wind Forecast Term; Mean and Root Mean Errors; June 1, 2018 – September 15, 2019

Plots provided by Dr. Tim Hogan of NRL Monterey

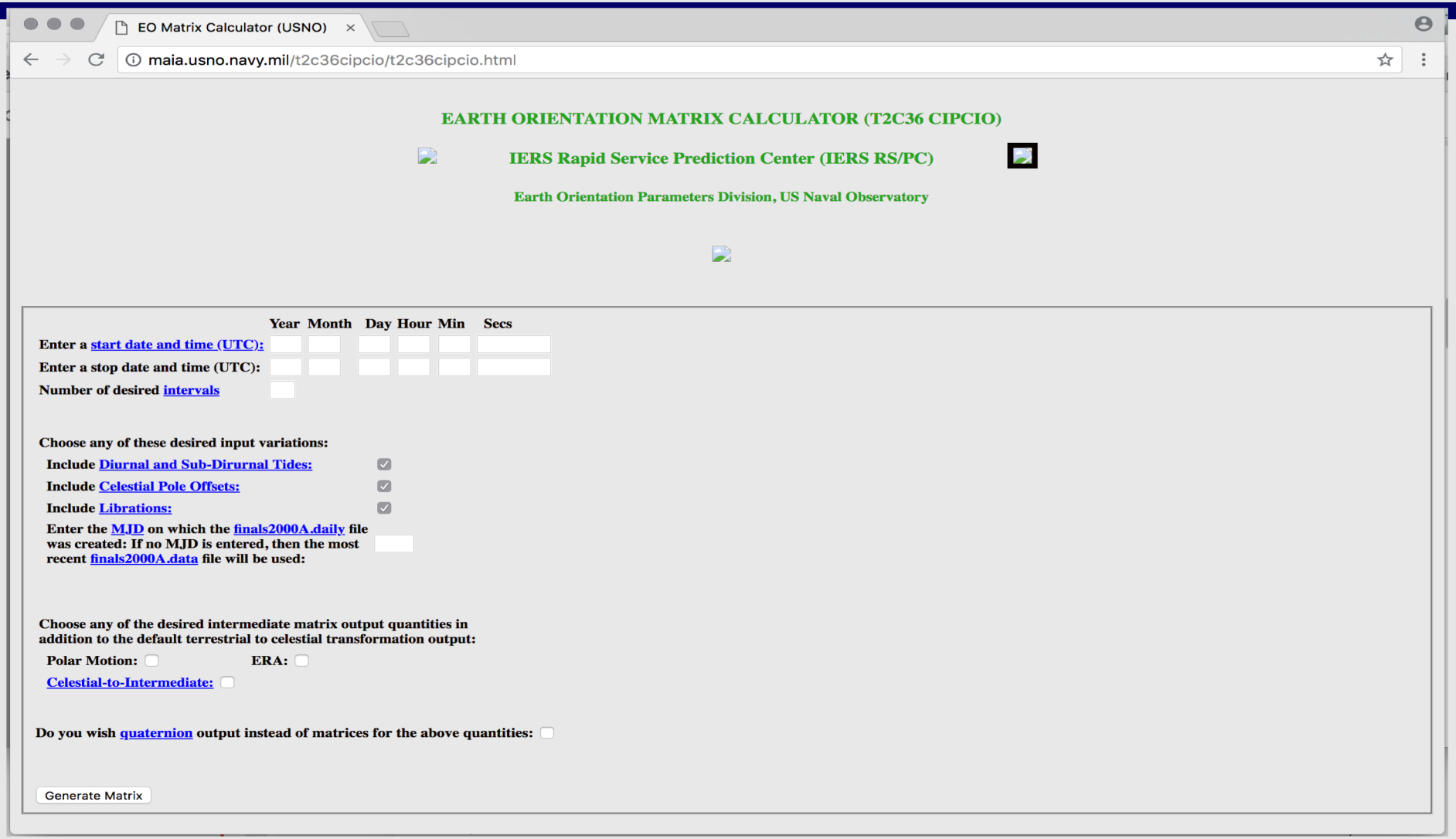




EO matrix On-line Calculator based on IERS Conventions 2010 CIP/CIO/TIO Paradigm: *Background*

- URL for new EO matrix calculator: http://maia.usno.navy.mil/t2c36cipcio/t2c36cipcio.html (URL may change in the near future for non-DoD customers. Backup at http://toshi.nofs.navy.mil...)
  - Based on the Chapter 5, IERS Conventions (2010) (Tech Note 36), Celestial Intermediate Pole and Origin and Terrestrial Intermediate Origin, non-equinox paradigm.
    - Written in FORTRAN with HTML and PHP web interface codes.
    - Relying heavily on code from http://maia.usno.navy.mil/conventions/2010/2010_update/chapter5/software/ and Standards of Fundamental Astronomy (SOFA) libraries.
  - Observable quantities are from a version of finals2000A.data or .daily
    - If necessary, the polar motion and UT1 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 and several intermediate transformations.

EO matrix On-line Calculator based on IERS Conventions 2010 CIP/CIO/TIO Paradigm: *User-Interface*



USNO ITRF to GCRS (EO matrix) On-line Calculator based on IERS Conventions 2010 CIP/CIO/TIO: ***Summary of Differences Between Equinox-Based and CIP/CIO/TIO TN36 Calculator:***

Old

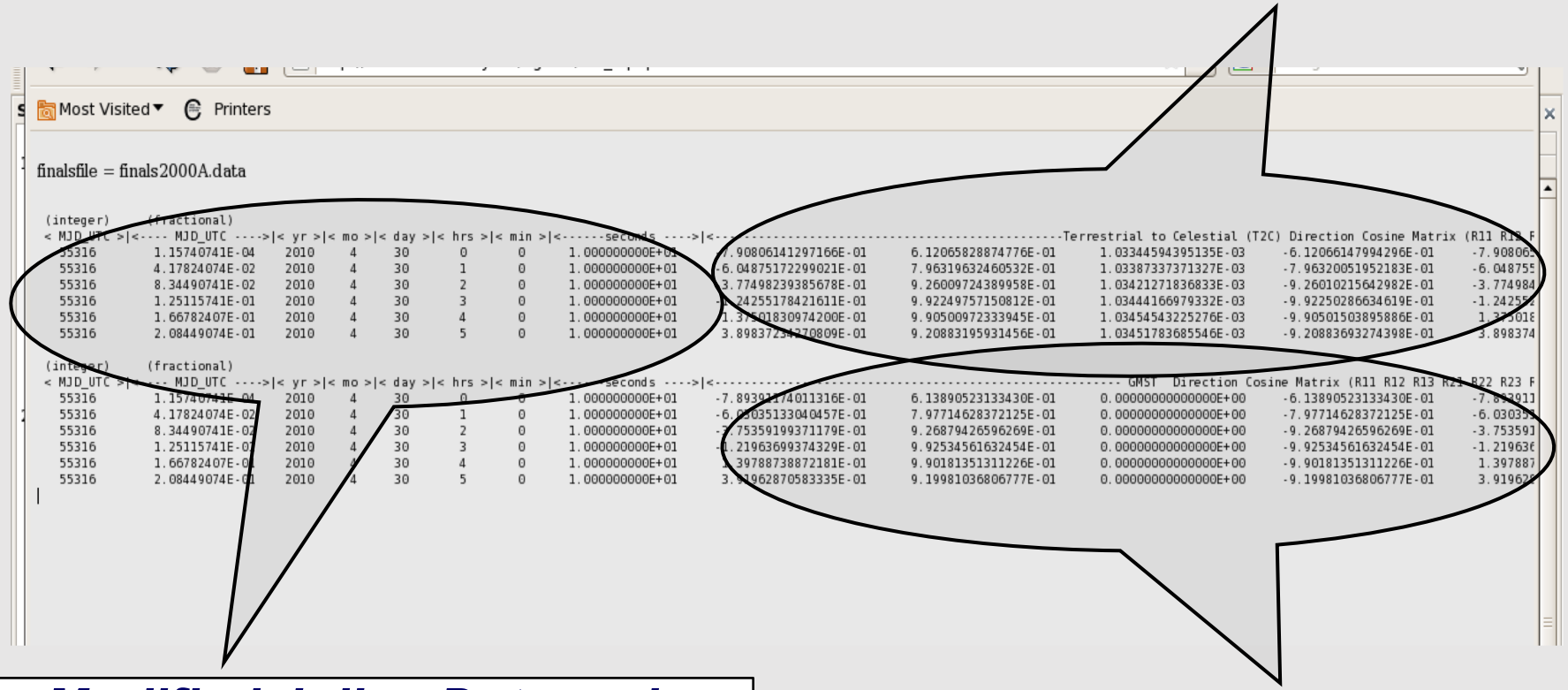
- *Observations (x, y, UT1-UTC, dX, dY) from finals2000A*
- *Equinox-based (Bias-Precession-Nutation): iau_c2teqx (IAU)*
  - *IAU 2006 precession & IAU2000A nutation: iau_*pnm*06a, iau_*bpn*2xy, iau_s06 (IAU)*
- *Polar Motion: iau_pom00 (IAU)*
  - *Earth Tides: RG_ZONT2(IERS Conventions 2010)*
  - *Diurnal & Sub-diurnal Tides: ORTHO_EOP & CNMTX (IERS)*
  - *"Sub-diurnal Nutation" quasi-diurnal terms: PMSDNUT2 (IERS)*
  - *TIO Locator (s') iau_sp00 (IERS)*
- *Sidereal Time: iau_GST06 (IAU)*
  - *Earth Tides: RG_ZONT2 (IERS Conventions 2010)*
  - *Diurnal & Sub-diurnal Tides: ORTHO_EOP & CNMTX (IERS)*

New

- Observations (x, y, UT1-UTC, dX, dY) from finals 2000A
- Celestial Intermediate Origin & Pole based: Matrix (USNO)
- Bias-Precession-Nutation: iau_C2IXYS (IAU)
  - IAU 2006 precession & IAU2000A nutation (X, Y): iau_xy06 (IAU); (CIO locator (s) iau_s06 (IAU)
- Polar Motion: iau_pom00 (IAU)
  - Earth Tides: RG_ZONT2 (IERS Conventions 2010)
  - Diurnal & Sub-diurnal Tides: ORTHO_EOP & CNMTX (IERS)
  - "Sub-diurnal Nutation" quasi-diurnal terms: PMSDNUT2 (IERS)
  - TIO Locator (s') iau_sp00 (IERS)
- Earth Rotation Angle: iau_era00 (IAU)
  - Earth Tides: RG_ZONT2 (IERS Conventions 2010)
  - Diurnal & Sub-diurnal Tides: ORTHO_EOP & CNMTX (IERS)
  - Sub-diurnal Libration: UT1LIBR (IERS)

USNO ITRF to GCRS (EO matrix) On-line Calculator based on IERS Conventions 2010 CIP/CIO/TIO: *User-Interface*

Terrestrial to celestial (T2C) Rotation matrix



Modified Julian Date and YMDHMS epochs.

Intermediate rotation matrices Are below the T2C matrix

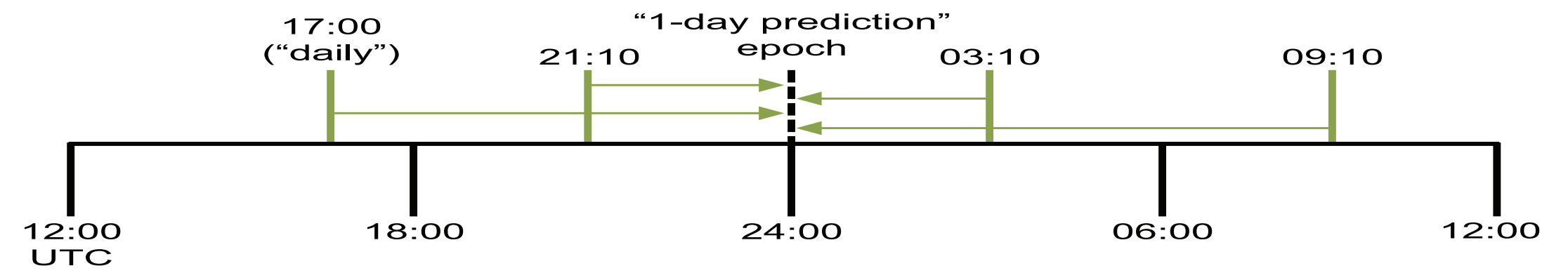
Items from 2018 IERS Annual Report: *Nxdaily/off-hours EOP solutions anomalous results.*

- Previous to 2018, the Nxdaily / off-hours USNO predictions had statistically shown improvement in at least Polar Motion (PM) predictions.
- Table below shows the improvement for Polar Motion <MJD> 1-day prediction RMS values. The solution generated on day <MJD> predicts Polar Motion at <MJD+1>. As more observations from the UGS ultra become available after the 17:00 UTC "daily" solution, at 21:10, 03:10, and 09:10, the estimate of PM at midnight <MJD+1> should improve.
  - Results for 2016 and 2017 show trend. Results for 2018 do not show trend.

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

Items from 2018 IERS Annual Report: *Nxdaily/off-hours EOP solutions anomalous results.*



Timeline of Nxdaily EOP 1-day prediction solutions in relation to the EOP "daily" solution produced at 17:00 UTC.

- Most likely reason for almost no improvement in waiting for more data at <MJD> 21:10, <MJD+1> 03:10 and <MJD+1> 17:10 was recently identified found as a code update issue.
  - New IGS ultras data was downloaded and new EOP solutions were updated; however, omission in code change did not always update final EOP results.
  - As of 15-Sept-2019, the code has been updated and should produce final EOP results with updated IGS ultra inputs.

Items from 2018 IERS Annual Report: Published Statistics Versus Weekly Reported Statistics.

- Polar Motion residuals for IGS products reported in IERS annual report and in weekly published statistics are seemingly inconsistent.
  - Weekly stats published at http://maia.usno.navy.mil/ser7/gpspol.asc

	RMS marcsec					
	IGS Finals		IGS Rapids		IGS Ultras	
	PMx	PMy	PMx	PMy	PMx	PMy
2018 IERS Annual Report	0.02	0.01	0.03	0.03	0.05	0.04
Weekly report 1st instance*	0.01	0.02	0.04	0.03	N/A	N/A
Weekly report 2nd instance*	0.02	0.04	0.04	0.04	0.04	0.04

* Statistics taken from IERS Bulletin A 25 April 2019. Note that RMS derived from mean and standard deviation which is reported in the file.

Weekly report, 1st instance:.

IGS Final	58579.50	30	0.00	0.00		0.01	0.02
IGS Rapid	58597.50	18	0.00	0.00		0.04	0.03
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IGS Ultra	58598.00	2	0.00	-0.01		0.02	0.04

Weekly report, 2nd instance:

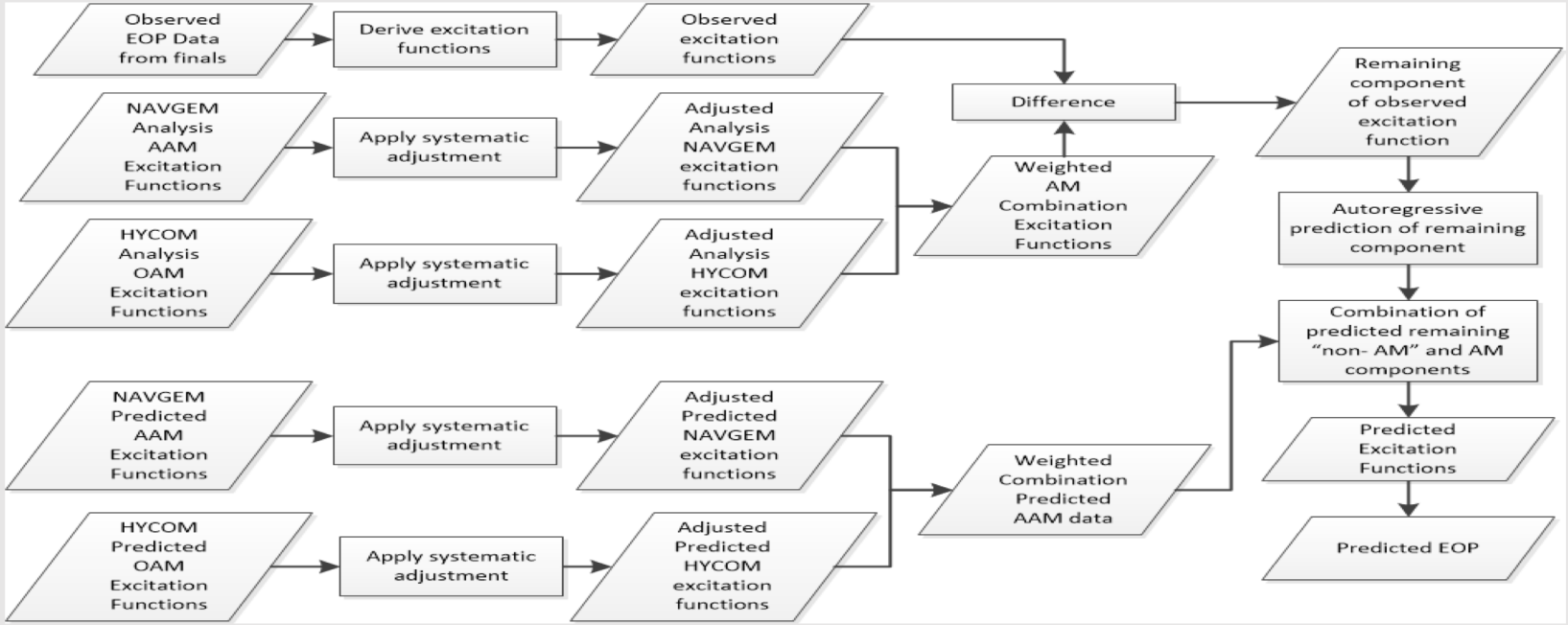
Series	Latest Day	#	Mean (series-BullA) x	y	UT	LOD	Standard Deviat. x	y	UT
IGS Final	58579.5	30	0.00	0.00	-0.001*	0.000*	0.02	0.04	0.016*
IGS Rapid	58596.5	30	0.00	0.00	-0.007*	0.002*	0.04	0.04	0.040*
IGS Ultra	58597.25	120	-0.01	-0.01	-0.003*	0.003*	0.04	0.04	0.037*

Items from 2018 IERS Annual Report: Published Statistic versus weekly reported statistics continued….

- Differences mostly to do with different interpolation methods used
  - IERS Conventions and Weekly report 1st instance Polar Motion results are computed using smoothing, weighted cubic spline coefficients.
  - Weekly report 2nd instanced Polar Motion results computed using simple cubic spline results.
- Since 11 July 2019, method for computing IGS finals Polar Motion residuals has been updated to use smoothing, weighted cubic spline.
  - More accurately reflects the residuals between the contributor and the combination.
  - Users currently only are provided smoothing spline results provided at each midnight epoch in reported EOP files (finals.daily, finals2000A.daily, etc) and not at each input epoch.

Future Development Work: *Studying combined U.S. Navy AAM and OAM inputs to better prediction polar motion and UT1-UTC*

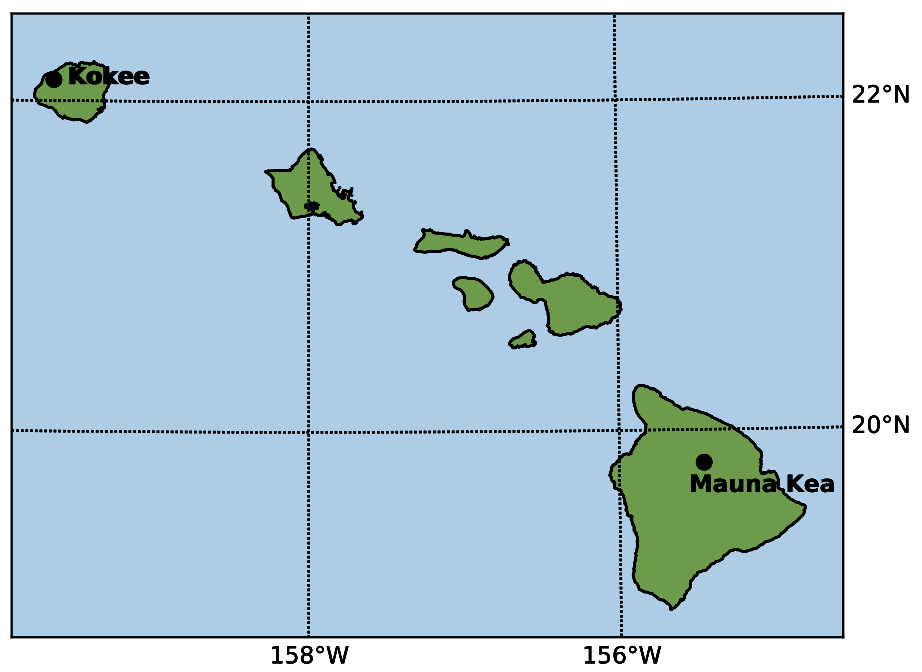
- Improvements in near-term prediction accuracy may be possible using Earth's AAM and OAM.
  - U.S. Navy Global Environmental Model (NAVGEM) AAM
  - U.S. Navy Hybrid Coordinate Ocean Model (HYCOM)



- Provides another data source which is only somewhat less accurate than IGS polar motion predictions.
- May be used operationally within a few years.

Future development work: W-series VLBI Intensives using combination of VLBA and VLBI radio telescopes.

- Interested in using VLBA Mauna Kea (Mk) antenna in IVS Intensives because of its geography and global proximity to Kokee
  - Yet, the two stations are far enough apart (> 500 km) that adverse weather conditions may not impact both stations simultaneously.
- Mauna Kea – Wettzell-North characterization observations will continue from October to January twice a week until 60 observations have been achieved
- Mauna Kea – Wettzell (MkWz) baseline has observed 60 sessions over 9 months as of July 2019
- To characterize any baseline with Mk, a new station-position must first be determined
  - Volcanic activity mid-2018 relocated station
- USNO is proposing to use MkWz as a backup to Ishioka – Wettzell INT2s on Saturdays from December 2019 to March 2020, while Ishioka is unable to participate in operational observations



Future Development Work: *Newer Optimal Estimation Techniques and Improving UTGPS*.

- Investigating the use a Kalman filter, improved smoothing cubic spline or other optimal estimation techniques to improve and increase robustness of EOP combination results.
  - Personnel also studying improved prediction techniques.
- Investigating how to improve the estimation of the UT1-like quantity derived from GPS orbits – UTGPS.
  - Since 30 March 2017, UTGPS influence on the combination has been de-weighted.
    - Degradation over the past few years in accuracy of results.
  - Ongoing studies to improve current UTGPS estimates.
    - Updating complementary filtering
    - Use of IIR only spacecraft in modeling.
    - Updating solar force modeling.

- BACKUP SLIDES

User-Interface Continued

- User chooses dates and time intervals.
  - Code produces a file containing the ITRF to GCRS transformation and desired intermediate quantities.
  - Number of intervals currently limited to 100.
    - Special exceptions can be arranged.
    - Dedicated server will lift this restriction.
- Standard output is the transformation matrix from terrestrial to celestial frames.
  - Optional quaternion / Euler parameter output.
- Intermediate options: polar motion, ERA, and celestial-to-intermediate matrix or quaternion outputs.
  - Useful for debugging purposes.
  - Useful to see motion of rotation axes relative to Earth fixed (ITRF) and celestial (GCRS).