The IERS Rapid Service / Prediction Center Mission, Challenges, and Developments

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Abstract The IERS Rapid Service / Prediction Center (RS/PC) is responsible for producing Earth Orientation Parameters (EOPs) from a combination of observation techniques that include Very Long Baseline Interferometry (VLBI), Global Navigation Satellite System (GNSS), Satellite Laser Ranging (SLR), Atmospheric Angular Momentum (AAM), and a UT1-like quantity (UTGPS) determined from Earth-referenced GPS satellite orbits. One of the most critical contributors to the combination is VLBI, as it is the only technique that can measure all five Earth orientation parameters, namely, Polar Motion (PM x,y), UT1–UTC, and Celestial Pole Offsets (dX and dY). The RS/PC significantly benefits from direct VLBI measurements of UT1–UTC. Maintaining access to robust time series that contain regular, accurate, and precise observations enables the RS/PC to produce a more accurate EOP combination. As EOPs relate the terrestrial and celestial reference frames, a more accurate RS/PC combination can in turn improve spacecraft navigation and pointing systems.

The RS/PC is committed to producing high-quality EOPs in a low-latency environment to support international geodesy. In this effort the RS/PC continues to develop quality standards to evaluate current and potential combination contributors and to investigate additional data sources that can provide increased redundancy, reliability, and accuracy to the combination.

Keywords EOPs, combination

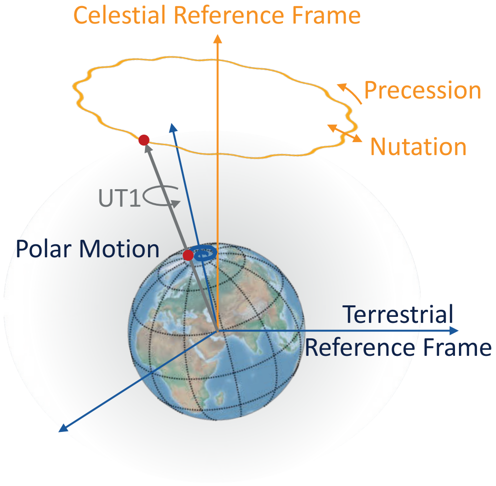

Fig. 1 Sketch of the five Earth Orientation Parameters (EOPs) with respect to the Terrestrial and Celestial Reference Frames (TRF and CRF, respectively).

1 The Importance of Earth Orientation Parameters

Earth Orientation Parameters (EOPs) provide a rotational relationship between the Terrestrial Reference Frame (TRF) of the Earth and the Celestial Reference Frame (CRF), where the CRF is considered a fixed-frame and the TRF is updated in regular intervals to re-align to the CRF. Given the variability of EOPs, it is critical to continuously make VLBI, GNSS, and SLR observations to maintain accurate and precise EOPs (Figure 1) required to support our modern society. Industries such as personal and space navigation, shipping, airlines, and farming all depend on an accurate representation of where their equipment

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is located with respect to the terrestrial reference frame and ultimately the celestial reference frame.

UT1–UTC can be particularly mercurial—at the minimum requiring daily observations to provide users with the highest quality “0-day” UT1–UTC value, where a “0-day” EOP value refers to the midnight epoch of a given combination day. As an example, Table 1 provides a rough estimate of the expected error in UT1–UTC at a given spacecraft altitude if updated values are not provided over a designated period of time. It also compares the difference in error if the spacecraft is able to use stored UT1–UTC predictions from the RS/PC versus length of day (LOD) values that must be integrated and extrapolated into the future. Table 1 demonstrates that stored RS/PC predictions on a given spacecraft provide a significantly lower UT1–UTC error for Low Earth Orbit (LEO) and Geostationary Equatorial Orbit (GEO) than using extrapolated LOD values during an update outage for one and ten days.

Table 1 A rough calculation of how errors in UT1–UTC at a given altitude (LEO and GEO) can increase over time using stored predictions or extrapolated LOD values. Errors in UT1–UTC at spacecraft altitudes can increase quickly when daily updates are not available, indicating the importance of daily EOP updates.

	Using RS/PC Stored Predictions		Using Extrapolated Historical LOD Values	
	1 day	**10 day**	**1 day**	**10 day**
LEO	∼4 cm	∼25 cm	∼8 cm	∼186 cm
GEO	∼24 cm	∼159 cm	∼48 cm	∼1158 cm

2 Overview of the IERS RS/PC EOP Combination

The IERS Rapid Service / Prediction Center (RS/PC) generates a low-latency, high-accuracy EOP time series by combining observational data collected from multiple techniques to support both industry and science in their Positioning, Navigation, and Timing (PNT) requirements [1, 2]. In this effort, the RS/PC disseminates a daily EOP solution using a combination of observed and modeled data from a variety of techniques (Table 2) to the international community. The RS/PC products contain a combined solution for Polar Motion (PM x,y), UT1–UTC, Celestial Pole Offsets (dX, dY or dψ, dε), and a calculated length of day (LOD) from the combined UT1–UTC solution. Each contributor in Table 2 is carefully curated to support the larger combined solution. For example, the primary contributor to the Polar Motion combination is the International GNSS Service (IGS). While the IGS Finals [3] has a latency of up to three weeks, these data also provide a highly accurate solution that strongly influences Polar Motion. Conversely, the IGS Ultra rapids [4] have a low latency of less than one day but in exchange provide a slightly less accurate estimate of Polar Motion. The UT1–UTC combined solution is primarily determined from the International

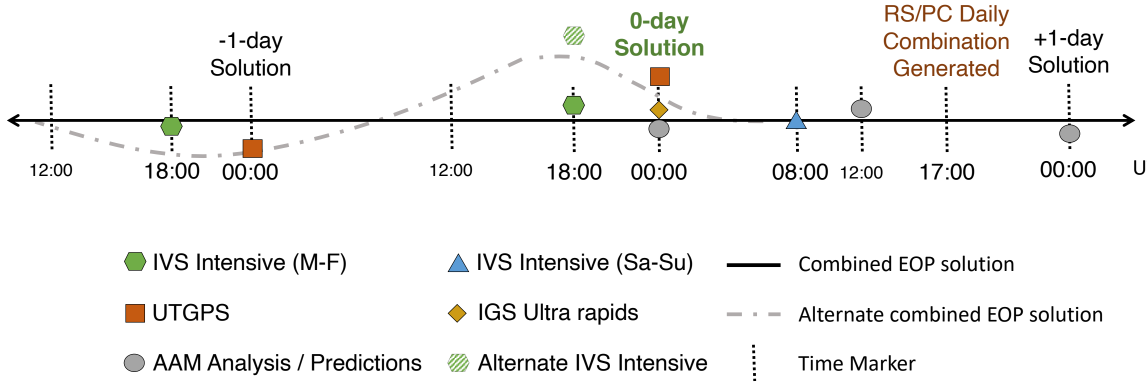

Fig. 2 Sketch of RS/PC data contributors for UT1–UTC combined 0-day solution. The alternate marker and alternate combined solution show a scenario where a low-latency observation (e.g., Alternate IVS Intensive) reports a significantly different UT1–UTC value; the local combined solution, including the UT1–UTC 0-day solution, would be reported in our daily products with a different UT1–UTC value.

Table 2 Techniques used in the RS/PC daily combination and Bulletin A EOP products, listed by Analysis Center (AC). Diversity in techniques, in addition to high-accuracy, low-latency observations, is critical to generating high-quality daily EOPs.

Technique	Contributor	Latency*	Product	EOP
GNSS (IGS)	IGS Finals	≤ 21.5 days	IGS Combination	PM x,y
	IGS Rapids	29 hrs		
	IGS Ultra rapids	17 hrs		PM x,y, UT1–UTC†
VLBI (IVS + 1 VLBA)	GSFC VLBI AC USNO VLBI AC	22 hrs	one hr Intensives	UT1–UTC
	GSI VLBI AC	9 hrs		
	GSFC VLBI AC USNO VLBI AC	∼2 weeks	24 hr R1/R4	PM x,y, UT1–UTC, dX, dY
	IAA VLBI AC	N/A		
	IVS Combination AC	2–3 weeks		
SLR	ILRS	2.5–7 days	Series A	PM x,y
UTGPS	USNO GPS AC	17 hrs	Derived from IGS Ultra rapid	UT1–UTC
AAM	NOAA U.S. Navy	17 hrs	Analysis + 7.5 days predictions	UT1–UTC†

* Latency is defined as from the observation mid-point to the time of RS/PC combination.

† Integrated LOD

VLBI Service for Geodesy and Astrometry (IVS). In the way that IGS creates an understanding of Polar Motion behavior from the low- to high-latency, the IVS also produces high-accuracy 24-hour "Rapid" observations that typically take two to three weeks to process and analyze [5]. The IVS also sponsors low-latency one-hour "Intensive" UT1–UTC observations that have a lower accuracy but can be processed and analyzed in less than one day [6].

While the IGS primarily supports Polar Motion and the IVS primarily UT1–UTC, other techniques also contribute to the respective EOP combination (Table 2). However, 24-hour VLBI observing sessions are the only technique able to observe the Celestial Pole Offsets (CPOs) dX and dY.

For each parameter, the available data are combined using a weighted smoothing cubic-spline. Only data present at the time of the RS/PC combined solution will determine the daily EOP solution. Therefore, high-quality, low-latency data are critical in determining a high-quality 0-day EOP solution. In other words, low-latency observations that are also low quality can significantly impact the 0-day solution, particularly for UT1–UTC. This concept is explained in Figure 2, where two versions of a combined UT1–UTC solution are shown. The solid, horizontal line represents the combined EOP solution for a given day, while the faded dashed line demonstrates how the combined EOP solution could be affected if a low-latency observation with low accuracy (faded hexagon) is included in the combination. An additional challenge with low-latency data is determining how close to "truth" a given input is. Typically, validation for low-latency observations cannot occur for up to two to three weeks, once higher-accuracy observations have been fully processed and integrated into the RS/PC combination. For UT1–UTC, "truth" cannot be determined until a 24-hour IVS Rapid

Table 3 The RS/PC publishes updated Earth Orientation Parameters daily and weekly, in addition to quarterly and annual updates to deltaT data and predictions. The presence of “2000A” in the title of a $*.data$ or $*.daily$ file indicates the Celestial Pole Offsets (CPOs) are calculated in dX and dY, while the absence of “2000A” indicates CPOs are calculated in $d\psi$ and $d\varepsilon$. All files in this table can be found on the RS/PC website, **https://maia.usno.navy.mil/ser7**.

File	Description	Publishing Schedule
finals[2000A].all	2 Jan 1973 (MJD 41684) → $\langle \text{day}_{BulletinA} \rangle$ + 373 days	Thursdays by 20:00 UTC (typically by 18:30 UTC)
finals[2000A].data	1 Jan 1992 (MJD 48622) → $\langle \text{day}_{BulletinA} \rangle$ + 373 days	
Bulletin A (ser7.dat)	$\langle \text{day}_{BulletinA} \rangle$ - 7 days & 365 days predictions (PM, UT1–UTC) - Latest updates to CPOs - Human readable + announcements	
mark3.out	$\langle \text{day}_{BulletinA} \rangle$ - 85 days → $\langle \text{day}_{BulletinA} \rangle$ + 90 days - Only PM-x, PM-y, and UT1–UTC	
gpsrapid.out	1 May 1992 → $\langle \text{day}_{BulletinA} \rangle$ + 15 days	
finals[2000A].daily.extended	2 Jan 1973 (MJD 41684) → $\langle \text{today} \rangle$ + 373 days	Daily by 17:30 UTC
finals[2000A].daily	$\langle \text{today} \rangle$ - 90 → $\langle \text{today} \rangle$ + 90 days	
gpsrapid.daily	$\langle \text{today} \rangle$ - 90 → $\langle \text{today} \rangle$ + 15 days	
deltat.data	deltaT values on first of each month since Feb 1973	Quarterly
deltat.preds	deltaT predictions on beginning of quarter for 10 years	Annually
historic_deltat.data	deltaT values every half year from 1657 to 1984.5	—

observation has been analyzed and integrated into the combination. If the original low-latency observation is more than 12 hours from the more precise IVS Rapid observations, the uncertainty of the local “truth” becomes increasingly difficult to determine.

2.1 Products Generated by the RS/PC

While the IERS Earth Orientation Center produces a more stable EOP product because it is delayed by 30 days (C04/Bulletin B) [7, 8], the IERS Rapid Service / Prediction Center (RS/PC) combination supports geodetic applications and research that require near real-time EOPs. These products are generated on a daily and weekly basis, and while the recent EOPs will fluctuate as more observational data become available, the RS/PC products are able to generate a dynamic, low-latency EOP combination to support daily requirements. The RS/PC generates a rapid EOP combination each day by 17:30 UTC and weekly EOP products each Thursday before 20:00 UTC (Table 3).

In March 2021 the RS/PC began publishing finals[2000A].daily.extended (Table 3), which provides the benefit of a long-term time series (beginning in 1973) along with daily updates to combined and predicted EOPs. This relatively new product can now replace ad-hoc files users were creating using finals[2000A].all and finals[2000A].daily to meet their needs.

For those interested in deltaT values, the RS/PC publishes an updated file, “deltat.data”, approximately every three months containing a deltaT value for the first of each month since 1973. A static “historic_deltat.data” file reports deltaT values for every six months from 1657 to 1984.5, and “deltat.preds” is published annually, providing 10 years of predictions.

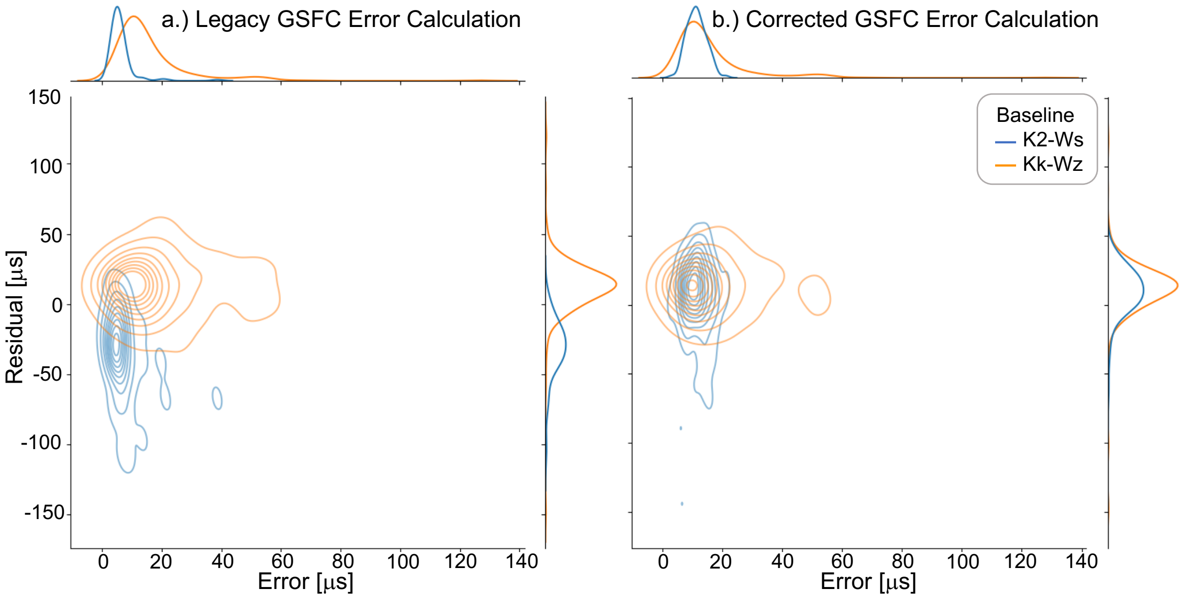

Fig. 3 The RS/PC initially found that a) the reported error of the VGOS baseline K2–Ws (Kokee to Wettzell-South) was significantly overestimating the accuracy of the observation. This relationship was corrected enough to use in the RS/PC combination after b) GSFC AC applied a model accounting for physical parameters such as atmospheric turbulence.

3 VLBI Contribution to the RS/PC Combination

The IVS VLBI 24-hour and one-hour observations are critical to producing a high-quality EOP combination. As discussed in Section 2, VLBI is the only technique that can measure all five EOPs. While Polar Motion is heavily influenced by the IGS Finals, Rapids, and Ultra-rapids in the RS/PC combined solution, it is essential to include VLBI EOPs in the combination to validate the accuracy of the IGS products. If the IGS EOP time series were the sole contributor to Polar Motion, there would be no other observations that could identify a systematic or other error in their data. Further, the RS/PC is dependent on the high-accuracy, low-latency one-hour Intensives curated by the IVS to provide a high-quality 0-day UT1–UTC value.

In this vein, accuracy, latency, redundancy, and diversity are all important aspects of a healthy Intensive "system." The accuracy of each Intensive series (e.g., "I", "Q", "V2") as determined in relation to our best understanding of "Truth" (i.e., C04 [7], Finals [9]) should be consistently maintained. Further, the reported formal error for any given observation should reflect the accuracy of that observation (discussed in further detail in Section 3.1), and no unexplained signals should be present in the time series.

The RS/PC defines latency as the mid-point of an observation to 17:00 UTC (i.e., the time when the EOP combination is executed) on the day when it is included in the combined solution. An observation is considered low-latency when its given latency is $<$ 24-hours. Redundancy includes multiple IVS Intensives that at the minimum all produce UT1–UTC values within 2σ of the "gold standard", where the *gold standard* is the Kk–Wz residuals w.r.t. the R1 and R4 UT1–UTC values. Redundancy also refers to having enough Intensive baselines that produce a UT1–UTC value within 1σ of the *gold standard at least* every day of the year (i.e., enough baselines so that intermittent station maintenance days or unexpected outages do not impact the observation of an Intensive for a given day). That is to say, a healthy, redundant Intensive *system* will have enough adequate baselines to produce a "quality" UT1–UTC value every day, so as not to leave gaps in the UT1–UTC time series.

This *system* also requires geographic diversity so that Intensive production is not solely dependent on a small number of sites in the event of large-scale events that would affect a region, such as a power outage or severe weather event. As stated in Section 1, UT1–UTC is highly variable and requires regular observation to maintain an accurate and precise estimate.

3.1 Challenges in Integrating VLBI Observations

The VGOS-INT-A series, analyzed by the NASA Goddard Space Flight Center (GSFC) AC, was recently integrated into the RS/PC combination, and it utilizes the VGOS Kokee and Wettzell (K2 and Ws) antennas. This Intensive series underwent more rigorous analysis prior to being integrated into the combination, as VGOS is a new observation methodology within the VLBI community. While the UT1–UTC observations generally behaved similarly to the S/X Kk–Wz Intensive series, the relationship between the series' residual ($\text{UT1–UTC}_{\text{K2–Ws}} - \text{UT1–UTC}_{\text{RS/PC Finals}}$) and reported error was skewed (Figure 3a). While Kk–Wz slightly overestimates the accuracy of its observations, K2–Ws significantly overestimates the accuracy of its observations (Figure 3). However, the GSFC Analysis Center (AC) was able to correct a large portion of the overestimation (Figure 3b) by applying an updated model to account for previously poorly modeled (or un-modeled) physical parameters, such as atmospheric turbulence [10]. While the error appears to continue to be overestimated, the discrepancy between the Intensive residual and the associated error is sufficiently small enough to use in the RS/PC combination. The additional VGOS Intensive on the K2–Ws baseline continues to add resiliency to the combined UT1–UTC solution.

A skewed relationship between reported error and the accuracy of the observation is also found in the R1 and R4 series. While this effect is minimized in UT1–UTC, PM x and y show the extent of how underestimated the EOP accuracy is. Given that VLBI is the only technique that directly observes UT1–UTC, it is difficult to discern the accuracy of observations. However, Polar Motion is predominantly determined by GNSS. Therefore, looking at the relationship between PM residuals (observation accuracy) to the reported error (reported accuracy) provides a better understanding of this relationship, where residuals are the observed PM with respect to a reference series (e.g., the RS/PC Finals). Figure 4 demonstrates this disproportionate relationship, where most errors are < 50 µas, whereas the bulk of the residuals generated from PM values produced at the GSFC AC and the IVS Combination AC extend up to ~ 200 µas.

To correct this issue, an accurate accounting of all equipment and observational errors must be correctly considered in analysis software. Without this, it is difficult to correctly identify the absolute accuracy of a given observation or the relative accuracy with

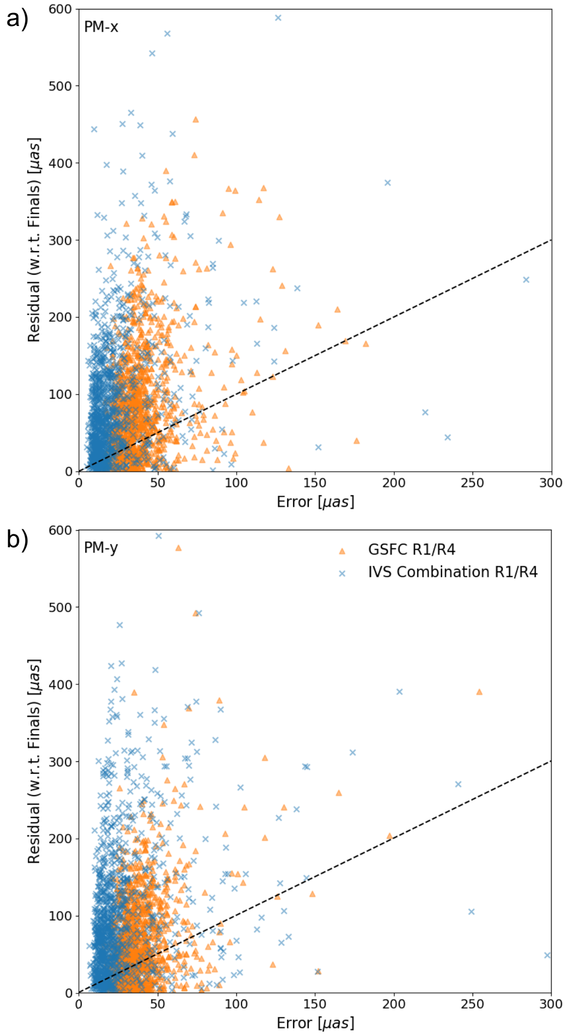

Fig. 4 The relationship between the observed accuracy (residuals) and the reported accuracy (error) for R1 and R4 Polar Motion analyzed at the GSFC and IVS Combination ACs.

respect to other types of EOP observations. The RS/PC expects that this will become an increasingly significant issue as VGOS sessions become more prominent in the RS/PC combined solution, as VGOS appears to overestimate observational accuracy more than S/X sessions.

4 Conclusions

The RS/PC continues to innovate our EOP combination software and combination methodology in an effort to improve the accuracy and increase the robustness of our low-latency EOP products, thereby better serving the international geodetic community. Any questions regarding our products may be directed toward the RS/PC group email address, eopcp@us.navy.mil.

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Large portions of this paper were taken from Davis et al. (2024) [11], as the topics are very similar while being presented to a different audience.

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