# Rapid Service and Prediction

# U.S. Naval Observatory Center for Rapid Service and Predictions

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## 1 Introduction

The mission of the U.S. Naval Observatory (USNO) includes determining the positions and motions of the Earth, Sun, Moon, planets, stars and other celestial objects, providing precise time, measuring the Earth's rotation, and maintaining the master clock for the U.S. The Earth Orientation (EO) Department contributes to this mission by collecting suitable observations and performing data analyses to determine and predict the time-varying orientation of the terrestrial reference frame within the celestial reference frame. The key parameters determined and disseminated are polar motion coordinates, universal time (UT1), precession, and nutation. The user community includes the U.S. Department of Defense, other U.S. government agencies, scientific researchers, and the general public. The primary applications are for high-accuracy navigation and positioning with an emphasis on real-time uses.

In order to accomplish these objectives, USNO collaborates closely with a large number of other groups and organizations, and relies on a combination of results from a variety of techniques. Very long baseline interferometry (VLBI) is essential in order to maintain accurate knowledge of UT1, the celestial pole, and the celestial reference frame, which is realized by the positions of about 600 extragalactic radio sources. Increasingly, however, GPS is being used to satisfy important aspects of the USNO mission. This report summarizes the current status of USNO participation with the IGS and GPS, together with some recent results.

## 2 IERS Sub-Bureau for Rapid Service and Predictions

The IERS Sub-bureau for Rapid Service and Predictions of Earth orientation parameters (EOPs) is hosted by the EO Dept. at USNO. EOP results contributed by many analysis centers derived from observations by VLBI, satellite laser ranging (SLR) to LAGEOS, lunar laser ranging (LLR), or GPS are combined into a homogeneous daily time series which is updated and distributed twice each week as *IERS Bulletin A*. Combined EOP values for the recent past are published together with predictions extending a year into the future.

In recent years, the *Bulletin A* polar motion results have been dominated by the precise, daily determinations of the IGS combined Final products, with the Rapid series being used for the most recent measurements. The Rapid determinations are quite important for *Bulletin A* by providing timely (delivered within 22 hours after each UTC midnight), high-quality results which are most significant for the polar motion predictions needed by real-time users. The accuracy of these series during 1997 is estimated to be about 0.1 mas (per component) for the Finals and 0.2-0.3 mas for the Rapids. Implementation on 01 March 1998 of the much more robust and improved terrestrial reference frame realization proposed by Kouba *et al.* (1998), where the coordinates and velocities of 47 sites are constrained to their ITRF96 values, will surely produce significantly more stable polar motion results. Early indications are that the accuracy of the Rapid polar motion values has been improved to about 0.1 mas (Ray, 1998a). This, in turn, should improve the quality and reliability of near-term polar motion predictions.

In addition to polar motion, *IERS Bulletin A* has become increasingly reliant on IGS estimates of length of day (LOD). The IGS started producing an official LOD product on 02 March 1997 using a weighted combination of LOD results submitted by each IGS Analysis Center (AC). To calibrate for LOD biases, each series is compared with the most recent 21 days of non-predicted UT1 values from *Bulletin A* (Kouba and Mireault, 1997; Ray, 1996). Shortly after its advent, the IGS combined LOD results were introduced into the *Bulletin A* combination to extend the UT1 value of the most recent VLBI determination forward by integration. A few months later an independent set of GPS-based estimates of univeral time, derived at USNO and described below, were also included in *Bulletin A.* About two weeks of the most recent estimates are used, after calibration in offset and rate compared to overlapping UT1 results from VLBI. In April 1998, an analogous universal time series from the EMR AC (Natural Resources Canada) was added in a similar manner. The EMR analysis strategy differs from the other IGS groups in applying *a priori* orbit constraints that allow both universal time and LOD to be estimated simultaneously. These three series together have proven very successful in extending UT1 results forward from the latest VLBI determinations, which can have a latency of up to about a week. As a consequence, the last non-predicted UT1 value in *Bulletin A* is now generally more accurate than 100 :s, usually considerably more so.

Errors in predicted EOP values are a significant source of systematic error in the IGS Predicted orbits, although they rarely dominate the overall error budget. MartRn Mur *et al.* (1998) have stressed the need for improved EOP predictions for use in computing the IGS Predicted orbits. Partly to address this concern, refinements already under development were implemented in *Bulletin A* on 03 March 1998 (Ray and Luzum, 1998). The improvement is most significant for the shortest prediction intervals (53% for 1 day) with dimishing effect over longer spans. Research is continuing into further improvements, which are likely to be implemented later in 1998.

For real-time users, given two updates of *Bulletin A* each week, the longest prediction interval is 7 days (for Tuesday updates compared with the previous Thursday issue which normally contains most recent data from 2 days earlier). This means that real-time users can experience polar motion prediction errors up to ~2.4 mas (in an RMS sense per component) and UT1 errors as large as ~1 ms (15 mas). Predictions of UT1 variation are more problematic because the geophysical excitation is about an order of magnitude larger than for polar motion. To reduce these prediction errors significantly will require more frequent *Bulletin A* updates, preferably done daily shortly after the IGS Rapid products are released. Such a process is expected to be implemented during 1998 and will reduce the longest prediction interval from 7 days to ~58 hours, under normal circumstances. In that case, the maximum errors for real-time users should be less than ~0.7 mas (RMS per component) for polar motion and less than ~0.3 ms for UT1.

As part of its contribution to the IGS, USNO prepares regular reports and plots of the performance of each IGS Analysis Center compared with *Bulletin A*, which are available at http://maia.usno.navy.mil/bulletin-a.html. Additional analysis reports are prepared occasionally to assess changes in IGS performance (*e.g.*, Ray, 1998a) or to evaluate the geophysical implications (*e.g.*, Eubanks *et al*., 1998).

## 3 IGS Rapid Service Associate Analysis Center

Given the significance of the IGS results and our increasing reliance upon them, it is natural for USNO also to contribute actively as a data analysis center. Beginning 23 April 1997 USNO officially became a contributor to the IGS Rapid products. Originally we intented to eventually begin submitting Final and other products to become a full IGS AC. Since that time, however, other GPS-related activities have developed, particularly the IGS/BIPM timing project (Ray, 1998b), which are more closely tied to the USNO mission and therefore take higher priority. Given limited resources, USNO would, for the time being, prefer not to assume the additional responsibilities of a full AC and plan instead to maintain the status of a Rapid Service Associate Analysis Center (RSAAC) contributing to the IGS Rapid and (eventually) Prediction products. We hope to begin producing and contributing predicted GPS orbits by late 1998.

Basic features of the USNO Rapid analysis strategy are summarized in Table 1. The software used is GIPSY/OASIS II, developed and maintained by JPL.

Table 1. USNO Analysis Strategy.

| | |
|---|---|
| Software | GIPSY/OASIS II (vers. 4.8) |
| Observables | carrier phase & pseudo-range at 7.5 min. |
| Arc length | 3 + 24 hr. |
| Network | 30 global sites (usually) |
| Elevation cutoff | 15 deg. |
| Sat. parameters | initial position & velocity,<br>rad. pressure scale & Y-bias as constants,<br>X,Z rad. pressure scales as stochastic |
| Attitude | yaw rates for eclipsing sats. |

An emerging interest at USNO is improved GPS orbits for a variety of real-time applications, including precise time transfer. This requires the highest quality Rapid and Predicted orbits and EOPs. These interests mesh naturally with full participation in the IGS/BIPM timing project. In support of this effort, USNO deployed a TurboRogue

SNR12 receiver in Washington, DC connected to the USNO Master Clock (MC) as its frequency reference. Data were released to the IGS starting 01 May 1997. A second receiver was deployed at Falcon (recently renamed Schriever) Air Force Base in Colorado Springs on 25 March 1998. This is the site of the USNO Alternate Master Clock (AMC) and the operations center for GPS. The MC and AMC are kept closely synchronized by hourly two-way satellite time transfer (TWSTT) observations. These IGS sites can therefore serve as important comparison sites in the IGS/BIPM project.

A "timing solution" strategy is currently under development for the IGS/BIPM timing project. The approach is to adopt the IGS combined orbits (either Rapid or Final, as appropriate) without adjustment and to determine all the station and satellite clocks in a fully consistent way, relative to a reference station clock (normally, USNO). It is essential to use a global network of stations, preferably equipped with highly stable frequency standards, and to resolve as many phase cycle ambiguities as possible. Computational constraints limit the size of the tracking network to about 30 stations. In order to densify the clock network it will be necessary to supplement such an analysis with an adaptation of the precise point positioning technique (Zumberge *et al*., 1997).

## 4 GPS Determinations of Universal Time

Elsewhere Kammeyer (1998) has described his method to determine UT1-like variations from an analysis of GPS orbit planes as estimated for IGS Rapid submissions. Briefly, the Earth-fixed GPS ephemerides determined operationally at USNO are compared to orbit planes propagated using a modeled radiation pressure acceleration normal to each orbit plane. For each satellite, the modeled acceleration is expressed relative to the projection of the Sun direction on the orbit plane and depends only on the angle from the orbital angular momentum to the Sun. The models being used were obtained empirically from observed experience when this angle was greater than 90N during 1994-1995. For each satellite, there is a unique axial rotation angle which brings the observed Earth-fixed positions into alignment with the propagated orbit plane. Since the propagated orbit plane of each satellite is different from its osculating orbit plane in an inertial frame, offsets are added to the rotation angles to form single-satellite estimates of GPS-based universal time. The median of these values for the 13 satellites modeled gives the UT estimate reported to *IERS Bulletin A*.

Kammeyer's results show quite encouraging short-term performance. The relatively slow drifts allow sliding segments of these data to be included in the *Bulletin A* combination after calibration only for an offset and a rate. The residual scatter is about 75 :s over 3-week intervals. The procedure is described above and has proven very successful in extending more accurate but less timely VLBI measurements of UT1 to near real-time. Over longer spans these GPS-based determinations drift systematically, up to about 600 :s in six months.

Several improvements can be made and are being pursued. The long-term drifts reflect deficiencies in empirical models for the orbit plane motions. With the longer series of orbits now available, better models should be feasible. In particular, the present models are based on data collected before the current yaw bias was implemented. Models can be constructed for all satellites, not just the 13 currently being used. The procedure could be applied to the more precise and reliable IGS combined orbits rather using the USNO orbits.

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