3.5.2 Rapid Service/Prediction Centre

Processing Techniques

The algorithm used by the IERS Rapid Service/Prediction Center (RS/PC) for the determination of the quick-look Earth orientation parameters (EOP) is based on a weighted cubic spline with adjustable smoothing fit to contributed observational data (McCarthy and Luzum, 1991a). Contributed data are corrected for possible systematic differences. Biases or offsets and rates with respect to the 05 C04 (1–31 January 2011) and 08 C04 (1 February–31 December 2011) systems of the IERS Earth Orientation Centre (EOC) at the Paris Observatory are determined using a robust linear estimator (Matlab function 'regstats'). Statistical weighting used in the spline is proportional to the inverse square of the estimated accuracy of the individual techniques. Minimal smoothing is applied, consistent with the estimated accuracy of the observational data.

Weights in the algorithm may be either *a priori* values estimated by the standard deviation of the residual of the techniques or values based on the internal precision reported by contributors. Estimated accuracies of data contributed to the IERS Rapid Ser-

Table 1: Estimated accuracies of the contributors in 2011. Units are milliseconds of arc for x, y, dψ, dε, dX, and dY and milliseconds of time for UT1–UTC. Note that EMR discontinued its UT series on 2 June 2011.

Contributor Information	Estimated Accuracy				
Name, Type	x	y	UT1	dψ (dX)	dε (dY)
ILRS SLR	0.21	0.22			
IAA SLR	0.22	0.21			
MCC SLR	0.18	0.23			
GSFC VLBI Intensives			0.020		
USNO VLBI Intensives			0.022		
GSI Intensives			0.018		
GSFC VLBI	0.13	0.15	0.006	0.40	0.16
IAA[1] VLBI	0.23	0.26	0.008	(0.07)	(0.06)
IVS[1] VLBI	0.20	0.19	0.004	(0.06)	(0.06)
USNO VLBI	0.17	0.16	0.004	0.20	0.08
IGS Final	0.01	0.02			
IGS Rapid*	0.08	0.10	0.014		
IGS Ultra*	0.09	0.10	0.004		
USNO GPS UT*			0.017*		
EMR GPS UT*[2]			0.048*		

*All satellite techniques provide information on the rate of change of Universal Time contaminated by effects due to unmodeled orbit node motion. VLBI-based results have been used to correct for LOD biases and to minimize drifts in UT estimates.

[1] IAA and IVS VLBI nutation values are in terms of dX/dY using IAU 2000A Nutation Theory (see Petit and Luzum, 2010).

[2] Input series discontinued on 2 June 2011.

Table 2: Mean and standard deviation of the differences between the Rapid Service/Prediction Center combination solutions and the 05/08 C04 EOP solutions for 2011. Polar motion x and y values are in milliseconds of arc and UT1–UTC values are in units of milliseconds of time.

	Bulletin A – C04	
	Mean	Std. Deviation
Bulletin A Rapid Solution (finals.data)[2]		
x	0.01/0.00	0.07/0.04
y	0.00	0.05
UT1-UTC	-0.001	0.013
Bulletin A Weekly Solution (finals. data)[1]		
x	0.04	0.09
y	0.02	0.06
UT1-UTC	-0.001	0.020
Bulletin A Daily Solution (finals.daily)[2]		
x	0.00/0.02	0.04/0.05
y	-0.04/0.03	0.03/0.05
UT1-UTC	0.003/-0.002	0.029/0.029

[1] Statistics computed over the 7-day combination solution period prior to solution epoch.

[2] The first set of statistics refers to values computed from 1 – 31 Jan 2011 with respect to the 05 C04. The second set of statistics refers to values computed from 1 Feb – 31 Dec 2011 with respect to 08 C04.

vice/Prediction Center are given in Table 1. These estimates are based on the residuals between the series and the combined RS/PC EOP solution for 2011.

Operationally, the weighted spline uses as input the epoch of observation, the observed value, and the weight of each individual data point. The software computes the spline coefficients for every data point, which are then used to interpolate the Earth orientation parameter time series so that x, y, UT1–UTC, $d\psi$, and $d\varepsilon$ values are computed at the epoch of zero hours UTC for each day. While the celestial pole offset combination software can combine either $d\psi$ and $d\varepsilon$ or dX and dY, for historical reasons, it uses $d\psi$ and $d\varepsilon$. Therefore, IAA and IVS VLBI dX and dY values are converted to $d\psi$ and $d\varepsilon$ in the combination process. The LOD 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 is used to estimate the LOD at the epoch of the UT1–UTC data.

The only data points that are excluded from the combination process are the points whose errors, as reported by the contributors, are greater than three times their average reported precision, or those points that have a residual that is more than four times the associated *a priori* error estimate. Since all of the observations are reported with the effects of sub-daily variations removed, the input data are not corrected for these effects (see IERS Gazette No. 13, 30 January 1997).

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. Table 2 shows the accuracies of Rapid Service/Prediction Center's combination solution for the running, weekly, and daily products compared to the 05/08 C04 series maintained by the IERS EOC. The running solution is the combination solution over the past 365-day period. The statistics for the running solution at year's end show the agreement between the Bulletin A running combination solution and the C04 series. Two sets of statistics are computed for PM-x: a) one from 1 January 2011 through 31 January 2011 which compares the Bulletin A made at the end of January 2011 to the 05 C04 series and b) another from 1 February 2011 through 31 December 2011 which compares the Bulletin A made at the end of December 2011 to the 08 C04 series. The Bulletin A running solution was updated to be on the new 08 C04 series on 1 February 2011. It appears that the reason that the standard deviations for PM-x are larger for January than for February–December is that there are unusually large residuals between the IERS RS/PC and 05 C04 at the end of January. These large differences do not appear when comparing the IERS RS/PC solution to the JPL SPACE solution.

The comparison of the 52 weekly solutions to the 08 C04 series gives the statistics of the residuals computed over the new combination results for the 7-days prior to the solution epoch ("Bulletin A Weekly Solution" statistics). The statistics for the daily solution are determined from a series of differences spanning one year where each element of the series is the difference for the day of the solution epoch ("Bulletin A Daily Solution" statistics). EOP accuracies for the Bulletin A rapid weekly solution for the new combination for the day of the solution run and daily solution at the time of solution epoch are similar and, therefore, not included in the table.

Figure 1 shows the residuals between the daily rapid solution and the 08 C04 and presents the data used in Table 2 for the determination of the daily solution statistics. In 2011, the mean residuals between the daily solution and the 08 C04 were essentially the same as in 2010. The small bias differences in the polar motion components appear to be related to the use in the IERS RS/PC solution of the IGS Ultra series which is systematically biased with respect to the IGS Final series used in the 08 C04 solution. There has been a significant improvement in the UT1–UTC results due to the greater availability of the electronically transferred VLBI data in the IERS RS/PC solution.

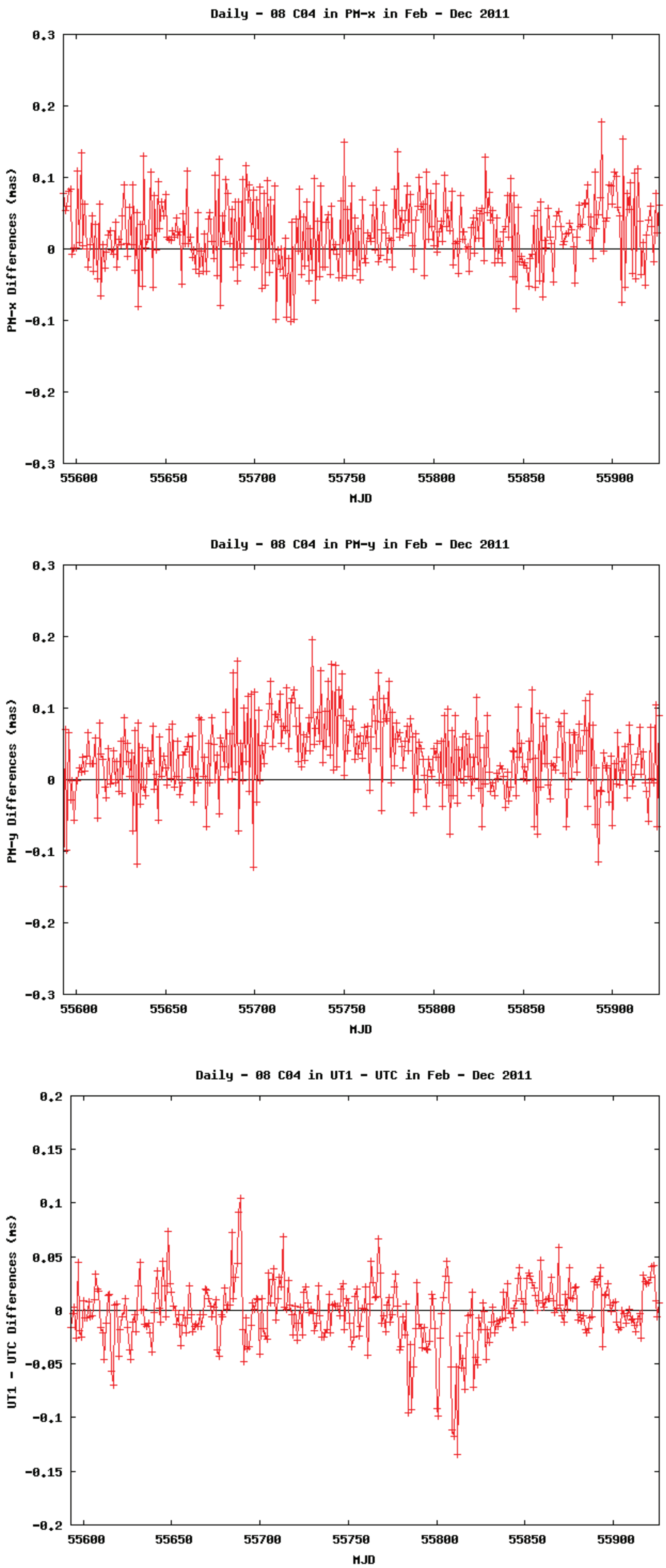

Fig. 1: Differences between the daily rapid solutions at each daily solution epoch for Feb–Dec 2011 and the Earth orientation parameters available in the 08 C04 series produced in September 2012.

Prediction Techniques

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).

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 Operational Global Atmospheric Prediction System (NOGAPS) model's AAM analysis and forecast data (UTAAM). AAM-based predictions are used to determine the UT1 predictions out to a prediction length of 7 days. 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 UT AAM data, see Stamatakos *et al.* (2008).

The procedure for UT1–UTC 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. Then, to determine a prediction of UT1–UTC n days into the future, $(UT2R–TAI)_n$, the smoothed time value from n days in the past, $\langle(UT2R–TAI)_{-n}\rangle$ is subtracted from the most recent value, $(UT2R–TAI)_0$

$$(UT2R–TAI)_n = 2(UT2R–TAI)_0 - \langle(UT2R–TAI)_{-n}\rangle.$$

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 strongly influenced by 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 GPS-based UT 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 tabular data, but predictions derived from these formulas are significantly less accurate than the tabular predictions. The predictions of $d\psi$ and $d\varepsilon$ are based on the IERS Conventions (McCarthy, 1996; McCarthy and Petit, 2004).

For 2011, the polar motion prediction errors were roughly the same accuracy as compared to the 2010 values. Figure 2 provides a plot of the prediction error as a function of polar motion value. The UT1–UTC prediction showed a significant improvement, especially over the latter part of the year. The improvement in UT1–UTC is due to the improved availability of rapid turnaround e-VLBI intensives. Table 3 shows the root mean square of the differences between the daily solution predictions and the 05/08 C04 solution for 2011.

The predictions of celestial pole offsets (both dX/dY and $d\psi/d\varepsilon$ representations) are produced through the use of the KSV1996 model (McCarthy, 1996). In addition, a bias between the model and the last 20 days of celestial pole offset observations is computed. Correcting for this bias allows for a seamless transition between the observed and predicted celestial pole offsets. This bias is tapered so that as the prediction length is extended, the bias becomes progressively smaller. Since celestial pole offsets 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

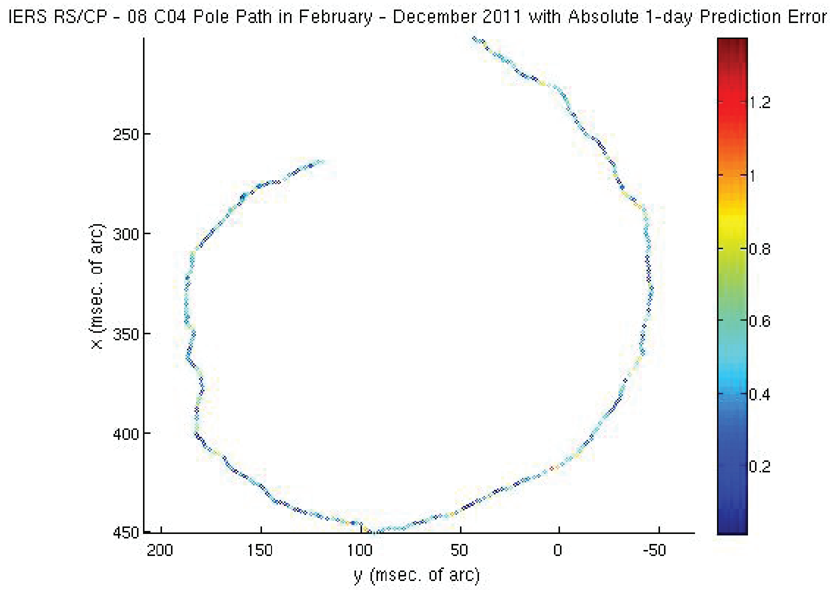

Fig. 2: Plot of the prediction error as a function of polar motion. The prediction error is in units of milliseconds of arc.

Table 3: Root mean square of the differences between the EOP time series predictions produced by the daily solutions and the 05/08 C04 combination solutions for 2011. Note that the prediction length starts counting from the day after the last available observation is made for polar motion or UT1–UTC (or UT-like data).

Days in Future	PM-x mas	PM-y mas	UT1-UTC ms
1[1]	.74	.30	.069
1[2]	.39	.28	.054
5	2.22	1.37	.305
10	4.01	2.49	.776
20	6.72	4.71	1.99
40	11.9	9.13	3.62
90	26.6	17.7	13.6

[1] Statistics computed for data from 1 – 31 January 2011 against the 05 C04.
[2] Statistics computed for data from 1 February – 31 December 2011 against the 08 C04.

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 differences between the daily predictions and the 05/08 C04 for 2011 are given in Table 4.

Predictions of TT–UT1, up to 1 January 2020, are given in Table 5. 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.

Table 4: Root mean square of the differences between the nutation prediction series produced by the daily solutions and the 05/08 C04 combination solutions for 2011.

Days in Future	dX mas	dY mas	dψ mas	dε mas
1	.16	.15	.44	.13
5	.17	.15	.46	.13
10	.18	.16	.48	.14
20	.20	.19	.53	.18
40	.25	.24	.65	.24

Table 5: Predicted values of TT–UT1, 2012–2020. Note that UT1–TAI can be obtained from this table using the expression UT1–TAI = 32.184s – (TT–UT1).

DATE	TT-UT1	Uncertainty
	(s)	(s)
2012 Jul 1	66.771	0.000
2012 Oct 1	66.810	0.000
2013 Jan 1	66.910	0.003
2013 Apr 1	67.02	0.01
2013 Jul 1	67.10	0.02
2013 Oct 1	67.13	0.02
2014 Jan 1	67.2	0.4
2014 Apr 1	67.3	0.5
2014 Jul 1	67.4	0.7
2014 Oct 1	67.5	0.8
2015 Jan 1	67.6	0.9
2015 Apr 1	68.	1.
2015 Jul 1	68.	1.
2015 Oct 1	68.	1.
2016 Jan 1	69.	1.
2016 Apr 1	69.	2.
2016 Jul 1	69.	2.
2016 Oct 1	69.	2.
2017 Jan 1	69.	2.
2017 Apr 1	69.	2.
2017 Jul 1	69.	2.
2017 Oct 1	69.	2.
2018 Jan 1	69.	3.
2018 Apr 1	70.	3.
2018 Jul 1	70.	3.
2018 Oct 1	70.	3.
2019 Jan 1	70.	3.
2019 Apr 1	70.	3.
2019 Jul 1	70.	3.
2019 Oct 1	70.	4.
2020 Jan 1	70.	4.
2020 Apr 1	71.	4.
2020 Jul 1	71.	4.
2020 Oct 1	71.	4.
2021 Jan 1	71.	4.

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.*, 2010).

Center Activities in 2011

During 2011, a number of significant changes occurred in the RS/PC products. On 1 February 2011, the EOP system was changed from 05 C04 to 08 C04 in coordination with the IERS EOC. This change was made in order to improve the consistency between EOP data and the underlying ITRF2008.

Starting in September 2011, the IERS RS/PC began the operational generation of two solutions per day: the original solution at 1700 UTC and a new solution at 0310 UTC. The additional solution is part of an ongoing progression to improve the accuracy of the EOP solutions by reducing their latency. Ultimately, the goal is achieve the generation of real-time EOP estimates. These twice-daily solutions take advantage of additional input data that have become available since the previous solution, such as eVLBI intensives and additional IGS Ultra data. The accuracy of these solutions is similar to the 1700 UTC daily solutions, but the 1-day predictions for UT1–UTC, as indicated in Table 3b and shown in Stamatakos *et al.* (2012) do show an improvement of 10% or greater. Revised versions of Table 2, 3, and 4, labeled Table 2b, 3b, and 4b, respectively, are shown below. These tables provide the relevant statistics for the last third of a year, 1 September 2011 – 31 December 2011, for the 0310 UTC solution.

On 21 April 2011, the IERS RS/PC procedures were modified to utilize the IGS Ultra LOD information in the operational combination and prediction procedures instead of the IGS Rapid LOD. The data are used in a fashion similar to how the IGS Rapid LOD were; the LODs are integrated to form UT-like data, calibrated and incorporated into the cubic spline. Like the IGS Rapids, only data extending beyond the last VLBI data are used.

Table 2b: Mean and standard deviation of the differences between the Rapid Service/Prediction Center 0310 UTC combination solutions and the 08 C04 EOP solutions for 2011. Polar motion x and y values are in milliseconds of arc and UT1–UTC values are in units of milliseconds of time.

	Bulletin A – C04	
	Mean	Std. Deviation
Bulletin A Daily Solution (finals.daily)[1]		
x	0.02	0.05
y	0.03	0.06
UT1–UTC	–0.000	0.030

[1] The statistics were computed from 1 Sep – 31 Dec 2011 with respect to the 08 C04.

Table 3b: Root mean square of the differences between the EOP time series predictions produced by the 0310 UTC daily solutions and the 08 C04 combination solutions for 2011. Note that the prediction length starts counting from the day after the last available observation is made for polar motion or UT1–UTC/LOD.

Days in Future	PM-x mas	PM-y mas	UT1-UTC ms
1	.36	.26	.049
5	1.85	1.52	.245
10	3.55	2.93	.608
20	6.08	6.30	2.21

The statistics were computed from 1 Sep – 31 Dec 2011 with respect to the 08 C04.

Table 4b: Root mean square of the differences between the nutation prediction series produced by the 0310 UTC daily solutions and the 08 C04 combination solutions for 2011.

Days in Future	dX mas	dY mas	$d\psi$ mas	$d\varepsilon$ mas
1	.17	.10	.48	.12
5	.19	.10	.53	.12
10	.21	.11	.56	.14
20	.23	.15	.62	.19

The statistics were computed from 1 Sep – 31 Dec 2011 with respect to the 08 C04.

New global solutions were received from the GSFC VLBI Analysis Center (gsf2011a and gsf2011b), the USNO VLBI Analysis Center (usno2011a), and the GSI Analysis Center (gsi2011a). These new solutions were examined and new slopes and biases were computed before being incorporated into operations.

The IERS RS/PC now runs EOP additional solutions off site at the Naval Observatory Flagstaff Station (NOFS). The solutions at the USNO DC and NOFS are checked on a daily basis to ensure that there are no discrepancies between the two. This redundancy provides an alternative location from which to obtain a solution should the primary facility at USNO DC be unable to deliver its EOP product due to internet outage, power outage, etc.

Additional capabilities for the EO transformation calculator were implemented. The calculator can now produce rotation matrix elements calculated using the IERS Technical Note 36 equinox-based algorithm (Petit and Luzum, 2010). This web-based product will provide both the transformation matrices as well as quaternion representations of the rotations between terrestrial and celestial reference frames.

Availability of Rapid Service

The data available from the IERS Rapid Service/Prediction Center consist mainly of the data used to derive the IERS Bulletin A combination solution. These data include: x, y, UT1–UTC, dX and dY from IAA VLBI; x, y, UT1–UTC, $d\psi$ and $d\varepsilon$ from GSFC VLBI; x, y, UT1–UTC, $d\psi$ and $d\varepsilon$ from USNO VLBI; x, y, UT1–UTC, dX and dY from IVS combination VLBI; UT1–UTC from GSFC 1-day Intensives; UT1–UTC from USNO 1-day Intensives; UT1–UTC from GSI 1-day Intensives; x, y from International Laser Ranging Service 1-day SLR; x, y from Institute of Applied Astronomy 1-day SLR; x, y from the Russian Mission Control Centre 1-day SLR; x, y, LOD from the International GNSS Service; UT from USNO GPS; UT from NRCanada (EMR) GPS; LOD from NCEP AAM; LOD from NAVY NOGAPS AAM; x, y, UT1–UTC, $d\psi$ and $d\varepsilon$, and dX and dY from the IERS Rapid Service/Prediction Center; x, y, UT1–UTC, $d\psi$ and $d\varepsilon$ from the IERS Earth Orientation Centre; and predictions of x, y, UT1–UTC, $d\psi$ and $d\varepsilon$, and dX and dY from the IERS Rapid Service/Prediction Center.

Other data sets are available that include: UT0–UTC from University of Texas as Austin LLR, UT0–UTC from JPL LLR; UT0–UTC from CERGA LLR; UT0–UTC from JPL VLBI; latitude and UT0–UTC from Washington PZTs 1,3,7; latitude and UT0–UTC from Richmond PZTs 2,6; LOD from ILRS 1-day SLR; x, y, UT1–UTC from CSR LAGEOS 3-day SLR; x and y from CSR LAGEOS 5-day SLR; x and y from Delft 1-, 3- and 5-day SLR; and x, y, UT1–UTC, $d\psi$ and $d\varepsilon$ from IRIS VLBI.

The data described above are available from the Center in a number of forms. You may request a weekly machine-readable version of the IERS Bulletin A containing the current 365 days' worth of predictions via electronic mail from

ser7@maia.usno.navy.mil or through
<http://www.usno.navy.mil/USNO/earth-orientation>.

Internet users can also direct an anonymous FTP to

<ftp://maia.usno.navy.mil/ser7> or
<ftp://toshi.nofs.navy.mil/ser7>.

where the IERS Bulletin A and more complete databases can be accessed including the daily solutions.

Center Staff

The Rapid Service/Prediction Center staff consisted of the following members:

Brian Luzum	Director
Nick Stamatakos	Operational program manager, research, and software maintenance
Merri Sue Carter	Assists in daily operations and support
Beth Stetzler	Assists in daily operations and support, research, and software maintenance
Nathan Shumate	Assists in daily operations and support, research, and software maintenance

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