ACTIVITIES OF THE IERS WORKING GROUP ON PREDICTION

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ABSTRACT. The International Earth Rotation and Reference Systems Service (IERS) established a Working Group on Prediction (WGP) to investigate what IERS prediction products are useful to the user community in addition to making a detailed examination of the fundamental properties of the different input data sets and algorithms. The major goals and objectives of the WGP are to determine the desired Earth orientation prediction products, the importance of observational accuracy, which types of input data provide an optimal prediction, the strengths and weaknesses of various prediction algorithms, and the interactions between series and algorithms that are beneficial or harmful. To focus the research efforts of the WGP, the user community was polled to ascertain what prediction products are needed and at what level of accuracy. The current status of WGP activities and the anticipated future directions are presented.

1. INTRODUCTION

Earth orientation parameters (EOP), which provide the time-varying alignment of the Earth's terrestrial reference frame with respect to the celestial reference frame, are critical to modern navigation and space applications. EOP predictions are a necessity for real-time space applications such as Global Navigation Satellite Systems. The current IERS EOP prediction products, which were implemented more than 15 years ago, are generated by the IERS Rapid Service/Prediction Center (RS/PC) to provide data to real-time users and others needing highest quality EOP information sooner than that available in the final series published by the IERS Earth Orientation Center.

The Working Group on Prediction (WGP) was established to determine what can be done to improve the IERS prediction of Earth orientation. Specifically, the WGP was tasked to determine what prediction products are needed by the user community and to examine the fundamental properties of the different input data sets and algorithms (see IERS website http://www.iers.org/MainDisp.csl?pid=167-1100082). There are two areas of investigation: the input data (geodetic and geophysical information) and the algorithms used to process the data. The WGP establishment grew out of RS/PC concerns about the continued relevance of current products, new accuracy requirements, the impact of new data sets, and viable new prediction methodologies and the desire to build on the interest generated by the EOP Prediction Comparison Campaign of the Technology University of Vienna [IERS (2005), Kalarus *et al.* (2007)], and the efforts of the IERS Combination Pilot Project [IERS (2004)]. Another expectation of the RS/PC was a definitive assessment of the current state-of-the-art in EOP prediction.

2. GOALS AND OBJECTIVES

The goals and objectives of the WGP are the following:

1. Determine the desired EOP products - What is needed by the user community?

2. Determine the importance of the input data - What new data sets are available? Are data sets interchangeable? Are some inherently better?

3. Determine which types of input data create an optimal prediction - What is the noise of the series? What smoothing is best? What geophysical phenomena are being measured?

4. Determine the strengths and weaknesses of the prediction algorithms - Which algorithms perform best under what circumstances? How can problems be mitigated?

5. Determine the interactions between series and algorithms that are beneficial or harmful - What qualities of certain data sets make them well suited or poorly suited for certain algorithms?

3. CURRENT EOP PREDICTION ACCURACY

The RS/PC produces IERS Bulletin A and its associated standard and the daily rapid EOP data files. Bulletin A reports the latest determinations for polar motion (x,y), universal time (UT1-UTC), and the celestial pole offsets ($\delta\psi$, $\delta\epsilon$ and dx, dy) at daily intervals based on a combination of contributed rapid and preliminary analysis results using data from Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR), and Global Positioning System (GPS) satellites. Predictions for variations a year into the future are also provided. Meteorological predictions of variations in Atmospheric Angular Momentum (AAM) are used to aid in the prediction of near-term UT1-UTC changes. The emphasis of the RS/PC is on near-term prediction (weeks) rather than long-term prediction (years) of EOP. Long-term stability and consistency with the other IERS products is achieved by aligning Bulletin A with the IERS final (Bulletin B) series, which is produced by the IERS Earth Orientation Center (EOC) at the Paris Observatory. Table 1 gives the prediction accuracies of the x- and y-components of polar motion and universal time from 2005 through the middle of 2007. Bulletin A values are compared with the final C04 results of the EOC. Additional information on the current IERS EOP prediction products is given by Stamatakos *et al.* (2007), Wooden *et al.* (2004), and the IERS Annual Reports [Dick and Richter,(2007)].

	2005				2006				2007		
Days in Future	PM-X (mas)	PM-Y (mas)	UT1-UTC (ms)	Days in Future	PM-X (mas)	PM-Y (mas)	UT1-UTC (ms)	Days in Future	PM-X (mas)	PM-Y (mas)	UT1-UTC (ms)
1	0.44	0.37	0.127	1	0.42	0.36	0.147	1	0.45	0.38	0.141
5	2.44	1.70	0.380	5	2.33	1.51	0.518	5	2.18	1.31	0.439
10	4.13	2.77	0.935	10	4.44	2.55	1.06	10	3.96	1.91	1.07
20	6.82	4.56	3.30	20	8.25	4.72	3.11	20	7.39	2.62	4.00
40	11.9	8.32	5.98	40	16.3	9.14	6.88	40	14.0	4.88	9.38
90	25.2	18.9	7.61	90	33.5	18.7	22.1	90	16.9	12.7	12.1

Table 1. Bulletin A prediction accuracies for polar motion (x-, y-components) and universal time (UT1-UTC).

4. EOP USER SURVEY

Given the variety of high-precision applications which need EOP predictions, the first task of the WGP was to determine whether the current products are adequate or whether modifications and/or improvements are necessary to meet more stringent requirements. Therefore, an easy-to-complete EOP user survey was developed by the WGP and posted on the IERS RS/PC website in order to address WGP goal #1. The IERS invited participation from those on the IERS mailing lists, those who receive RS/PC products, and any others thought to have an interest in EOP predictions. The first data call was issued in December 2006 and a second call went out in January 2007. The intent was to solicit information from current and potential users of EOP predictions to address the following questions and focus the WGP research effort:

1. Are the current IERS EOP prediction products, which were implemented more than 15 years ago, meeting the needs of the EOP user community.

2. Given the multitude of modern high accuracy applications, what characteristics of EOP predictions (type, accuracy, data spacing, data span, form, etc.) are required.

The survey form was designed to enable the WGP to determine who the major users of EOP information were. Specifically, were there different groups of users that had unique requirements or did all users have the same basic requirements? The survey began by asking some general information about the individual completing the survey. The intent was that if the individual had some specific recommendations that needed additional discussion, it would be easy to follow-up. Secondly, does the individual have a use for,

or anticipate a future use of IERS predictions? If the answer is positive, what information is needed to satisfy his/her requirements? We can then determine whether additional research is necessary to achieve the accuracies or timeliness needed. In addition we were interested in any specific improvements that might be recommended. Finally, the individual was asked to characterize the applications that utilize our predictions, *e.g.*, academic, engineering, operational, scientific, or other. The survey consisted of 10 questions that involved mostly checking boxes for a limited number of options. It was intended to be easy to complete and still provide enough characteristics to help the WGP determine where to focus its effort. The following figures summarize the results from the 71 surveys completed prior to 1 March 2007. Figure 1 shows the required accuracies for polar motion and universal time categorized by user application (indicated by different colors). The vertical axis represents the percentage of users in a given category and the horizontal axis shows the accuracy bins. Figure 2 shows the characteristics (prediction length, data spacing, update frequency, and formulation) of the predictions categorized by user application. Again, the vertical axis is the percentage of users categorized by application and the horizontal axis shows the options available for a given characteristic.

Figure 1. Required polar motion (in arc seconds) and universal time (in seconds) accuracies as a function of user application.
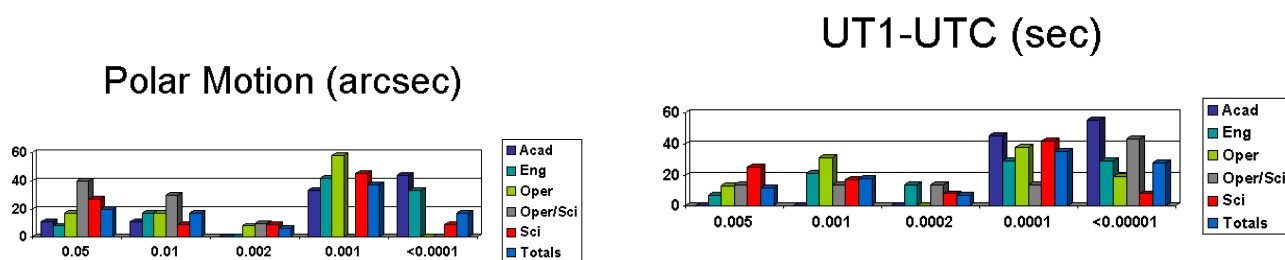
- Most users want accuracies of 1 milliarcsec or better
- Operational/Scientific users have the least stringent requirements

- Almost two/thirds of all users want accuracies of 0.1 millisecond or better
- A few scientific and operational users have low accuracy requirements
- Academic users have the most stringent accuracy requirements

The survey confirmed that there is a large group of operational users that need daily predictions, tabular data, one-day spacing, and predictions up to 30 days. Each category of user has different needs. Although some users would like to improve long term predictions, and while it is an interesting problem, the terms of reference under which the IERS RS/PC operates has been reconfirmed by the survey results. However, there is a need for increased accuracy and the efforts of the WGP to examine algorithms and incorporate potential new sources of data appears to address that need. In addition there seems to be a growing interest in daily and sub-daily predictions which require more timely measurements of EOP quantities and some increased processing capability.

5. PLANNING CONSIDERATIONS

The second task of the WGP is to examine the fundamental properties of the different input data sets and algorithms. To facilitate this task the WGP consists of two subgroups: one to examine the input data sets and another to examine the algorithms used for doing the prediction. Input data sets used for EOP determination come from geodetic sources such as VLBI, SLR, and GPS and also from geophysical sources such as AAM. Additional data sets are available as a result of recent geophysical research in the modeling of the oceans and the hydrological cycle. The earliest prediction algorithms for EOP were very simplistic but over the years have gotten more complex as measurements have become more precise.

Figure 2: Desired characteristics of the predictions as a function of user application.

Prediction Length
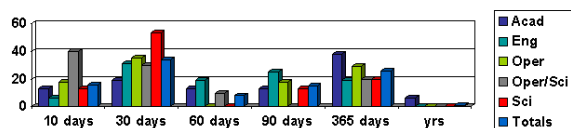
- Half of all users want predictions of 30 days or less
- There seem to be two classes of users: those who need predictions of less than 30 days and those who would like predictions of 1 year (~25%)
- Academic users are more interested in long term predictions

Update Frequency
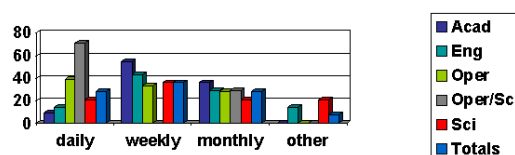
- Operational/Scientific users prefer predictions to be updated daily
- Academic users prefer weekly updates
- Almost two/thirds of all users would like daily or weekly updates

Data Spacing
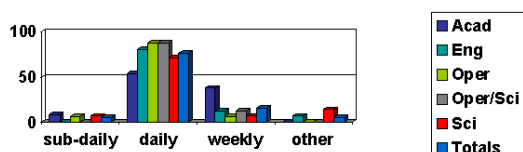
- Majority of users prefer data at 1-day intervals
- Some users have an emerging requirement for sub-daily prediction data

Data Formulation
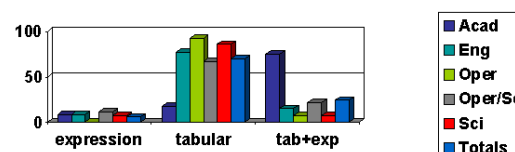
- Majority of users prefer tabular data
- Academic users desire analytical expression in addition to tabular data

Several different algorithms were used in the EOP Prediction Comparison Campaign. Because each participant in that campaign was able to choose what input data to use and also what algorithm to use, it is not possible to ascertain whether the best prediction was due to superior input data or a superior algorithm. Therefore, to determine the strengths and weaknesses of the various algorithms, a multitude of input data sets need to be processed. Additional considerations will be addressed in the next sections.

6. INPUT DATA

WGP goals #2 and #3 will be answered by looking closely at the intrinsic properties of data sets available and how to maximize the geodetic and geophysical information content. The following input data issues need to be addressed:

1. Exploit methods to minimize data latency and reduce extrapolation to current time;
2. Determine loss of information if all data sets were reduced to common epochs;
3. Examine potential geophysical data sets from the IERS Global Geophysical Fluids Center;
4. Examine the geodetic technique services combination data sets resulting from the IERS Combination Pilot Project;
5. Determine sensitivities of missing data sets to the prediction process;
6. Examine pathological data sets from times when the Chandler and annual polar motion destructively interfere;
7. Determine the optimum combination of geophysical signals to create the best predictions;
8. Determine where research is needed to make future improvements in EOP prediction.

A password protected repository for retrieval and analysis has been established at the University of Luxembourg so that the test data sets and results can be tracked and readily available to the WGP. Test cases have been identified for polar motion loops, large amplitude Chandler/annual polar motion, radical UT1 changes, minimal UT1 changes, differences in smoothing, artificial noisier end points, and a general test case for 2000-2006. Input data sets include time series of geodetic data (GPS, SLR, GPS). Additional data sets are being identified in the geophysical fluids data area [AAM, Oceanic Angular Momentum (OAM), Hydrological Angular Momentum (HAM)].

7. ALGORITHMS

WGP goals #4 and #5 will be answered by understanding the intrinsic properties of each algorithm, how each handles the various pathological test cases, and what additional information content is beneficial. The following algorithm issues need to be addressed:

1. Maintain the integrity of effort, the group analyzing the predictions will be different from the group generating the predictions – each group checks the other groups' results;
2. Finalize the specific metric criteria for comparison;
3. Examine time dependency and/or frequency dependency issues with the results;
4. Provide definitive description of each algorithm – characterize the advantages and shortcomings;
5. Determine what the state-of-the-art is in prediction techniques;
6. Determine how robust the algorithms are;
7. Determine suitability for operational setting.

The EOP time series data generally consist of both deterministic and stochastic components. The deterministic component gives rise to trends, seasonal variations, and tidal variations, while the stochastic component causes statistical fluctuations which have a short-term correlation structure. The best prediction results of the EOP are obtained when the deterministic components are predicted by the deterministic method and a stochastic prediction technique is applied to forecast the stochastic component. Combination of deterministic and stochastic predictions improves the prediction accuracy in low and high frequency components.

Prediction methods to be considered include least-squares extrapolation, least-squares collocation, Kalman filter, autoregressive, autoregressive (integrated) moving-average, autocovariance, neural networks, fuzzy logic, and multidimensional. Unfortunately, there are problems associated with each of these methods. However, each has certain advantages under given conditions. The focus of the algorithm group is to characterize the strengths and weaknesses of each of the algorithms on the basis of the various test cases. A recent comparison of different techniques is given by Kosek *et al.* (2007).

8. FUTURE

The future activities of the WGP include adding more data sets to the repository at the University of Luxembourg, finalizing criteria for algorithm comparisons, determining the optimal parameters in combination prediction algorithms, investigating geophysical causes of prediction errors, and investigating new forecast techniques. The expectations of the WGP are to have definitive user requirements, a comprehensive look at prediction methods, a comprehensive look at new data sets, and to produce an IERS Technical Note describing current state-of-the-art EOP prediction including requirements, methods, and data set information content.

9. REFERENCES

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