Second Earth Orientation Parameters Prediction Comparison Campaign (2nd EOP PCC) Workshop No. 2

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Abstracts

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Summary of the Second Earth Orientation Parameters Prediction Comparison Campaign (2nd EOP PCC)

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Real-time information on Earth Orientation Parameters (EOP) is needed for many advanced geodetic and astronomical tasks including positioning and navigation on Earth and in space. However, accurate determination of EOP requires post-processing of observational data collected from various space geodetic techniques, which causes delays in providing EOP solutions. Therefore, EOP short-term prediction has become a subject of increased attention within the international geodetic community.

Scientific progress in the prediction methods but also in the geodetic data processing, and modelling effective angular momentum functions raise the need to re-evaluate various EOP prediction approaches. This was the objective of the Second Earth Orientation Parameters Prediction Comparison Campaign (2nd EOP PCC), which operated between September 2021 and December 2023. The campaign was prepared by the EOP PCC office run by Centrum Badań Kosmicznych Polskiej Akademii Nauk (CBK PAN) in cooperation with GeoForschungsZentrum (GFZ) and under the auspices of the International Earth Rotation and Reference Systems Service (IERS). Thanks to international cooperation, the campaign was a great success of the geodetic community.

In this presentation, we provide a summary of the 2nd EOP PCC, focusing on both statistical information and qualitative assessment of the EOP prediction. We analyse the impact of eliminating outlier predictions on the overall accuracy of the EOP forecasts. We also present time evolution of the prediction quality obtained on the basis of the mean absolute error for the IERS EOP 14 C04 data as a reference. We end the presentation with initial conclusions on the most encouraging prediction methodologies together with plans for continuation of the campaign involving new release of IERS EOP 20 C04 solution.

The short-term prediction of Polar Motion using the combination of SSA and the Multivariate Multi-step 1D- Convolutional Neural Networks with Multioutput strategy

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Polar Motion is the movement of the Earth's rotational axis relative to its crust, reflecting the influence of the material exchange and mess redistribution of each layer of the Earth on the Earth's rotation axis. The real-time estimation of Polar Motion (PM) is needed for the navigation of Earth satellites and interplanetary spacecraft. However, it is impossible to have real-time information due to the complexity of the measurement model and data processing.

Various prediction methods have been developed. However, the accuracy of PM prediction is still not satisfactory even for a few days in the future. Therefore, a new technique or a combination of the existing methods needs to be investigated for improving the accuracy of the prediction PM.

In this study, we combine the 1D Convolutional Neural Network with the Singular Spectrum Analysis (SSA). The computational strategy follows multiple steps, first, we model the predominant trend of the PM time series using SSA. Then, the difference between the PM time series and its SSA estimation is modeled using the 1D Convolution Neural Network. However, we developed a Multivariate Multi step 1D-CNN Model with a Multi-output strategy to predict at the same time both components (Xp, Yp) of the PM. We introduce to the Model: the Ocean Angular Momentum, Atmospheric Angular Momentum, and Hydrological Angular Momentum (OAM+AAM+HAM) to improve the results. Multiple sets of PM predictions which range between 1 and 10 days have been performed based on an IERS 14 C04 time series to assess the capability of our hybrid Model. Our results illustrate that the proposed method can efficiently predict both (Xp, Yp) of PM.

Combining Evolutionary Computation with Machine Learning technique for improved prediction of Earth Rotation Parameters

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Prediction techniques of the highly variable motion of the Earth's rotation axis with respect to the Earth's surface (polar motion) and the angular velocity of the Earth (length of day) have been continuously improved over the past years. This is because many applications in astronomy, geosciences, and space missions require Earth Rotation Parameters (ERP) predictions. The polar motion coordinates and length of day are collectively known as ERP. Machine Learning (ML) algorithms are used to learn from data and make data-driven predictions. The approach in this study is to combine ML with efficient Evolutionary Computation (EC) algorithms to achieve reliable and improved predictions. The EC algorithm is used for feature selection and hyperparameter optimization in the ML algorithm. Gaussian Process Regression (GPR) is used as the ML technique with Genetic Algorithm (GA) as the EC algorithm. This improved the quality of the predicted model by ~5%. The ERP data used for the study are the multi-technique combinations (C04) generated by International Earth Rotation and Reference Systems Service (IERS). The combined excitations of atmosphere, oceans and hydrology (AAM+OAM+HAM) are used as predictors as they are highly corelated with the input ERP data. Then, EC combined with ML algorithm is used on the detrended and de-seasonalized time series to achieve improved predictions. The improvement in predictions is compared with the real estimates of IERS C04 for assessing the quality of predictions.

Comparison of machine-learning-based predictions of Earth orientation parameters using different input data

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Earth orientation parameters (EOP) are needed for precise navigation on Earth and in space and to connect the terrestrial to the celestial reference frame, and for several real-time applications. EOP are typically determined from the observations of different space-geodetic techniques. In order to overcome latencies in the processing and combination of these observations, accurate predictions of EOP are essential. To improve the modeling and prediction of EOP, effective angular momentum (EAM) functions, covering the domains of the atmosphere, ocean, and land hydrology, are typically incorporated to achieve the best performance.

The Space Geodesy group at ETH Zurich provides operational predictions of EOP and EAM via its Geodetic Prediction Center (GPC; https://gpc.ethz.ch). We have developed machine learning approaches to predict EOP over different time horizons based on existing EOP and EAM times series provided by other institutions.

In this contribution, we analyze the quality of our operational predictions with a focus on comparing the results based on different input time series. In particular, we use different rapid EOP products (IERS, SYRTE, and JPL) and EAM forecasts (GFZ and ETH). In terms of EAM, we study the impact of using only atmospheric angular momentum compared to the sum of all different EAM components. Preliminary findings indicate that rapid EOP data from SYRTE or JPL in combination with a full set of EAM functions leads to the best accuracy when considering IERS final products as reference.

Gaussian Process Regression for Celestial Pole Offsets Prediction

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Knowledge of the Earth's rotation is one of the most challenging problems in geosciences, astronomy, and space missions. Moreover, it has a high societal impact: Our ordinary life depends on accurate prediction of the Earth Orientation Parameters (EOP) (i.e. polar motion, dUT1 and celestial pole offsets [CPO]) for precise timing, navigation and positioning objects in space and our planet (e.g. satellite operation, precise farming and fleet management, sea level change, GNSS apps, etc.).

The proposed main goal of this study is to develop new and more accurate CPO predictions introducing new analysis procedures by combining astrogeodetic observations and conventional algorithms with versatile machine learning methods. Among the multiple machine learning approaches, we pay special attention in the Gaussian processes regression (GPR). GPR carries out a non-parametric modeling developed in a Bayesian framework and provides uncertainty intervals along with the mean estimates. This distinct feature, which is not shared by other machine learning algorithms, can open a unique source of information to assess the robustness of the predictions at various temporal scales. The statistical analysis of the residuals w.r.t. other methods and the conventional EOP 14 C04 series clearly evidences high accuracy and stability for ultra-short, short-, mid- and long-term predictions. It clearly proves that GPR is a very feasible tool to predict the variations in CPO.

Revisited the deconvolution and convolution methods for the Earth's polar motion prediction

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Combining the polar motion (PM) equation with predictions of the geophysical excitation functions, the accuracy of the Earth's PM prediction can be significantly improved (Dobslaw and Dill, 2017; Dill et al., 2019). This prediction method uses the deconvolution method of PM series and the convolution method of excitation function, that is, using the PM series to calculate the geodesic excitation function and using the geophysical excitation function tocalculate the PM series. We have compared and analyzed various deconvolution methods and found that the commonly used deconvolution method is flawed because the high-frequency component of the derived geodesic excitation function has a significant systematic bias and its PM prediction results are also systematically biased to some extent. In order to solve this problem, we try to adopt the higher precision deconvolution methods, and establish a new convolution method called convolution and least squares (Conv-LS) method. We demonstrate that these improved methods can eliminate the systematic bias mentioned above, which establishes the basis for further improving the accuracy of PM prediction.

Application of Kalman filter to operational C04 ERP series

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Last Earth Rotation Parameters (ERP) are generally of lower quality than their final values, and can be spoilt by errors up to 200 µas. In order to mitigate such errors on the operational ERP (pole coordinates, UT1, LOD) provided by Earth Orientation Center to the CNES, we design a Kalman filter integrating the modelled hydro-atmospheric excitation as reconstructed by GFZ. From the corrected values of the current days at 12hUTC, the transfer matrix of the Kalman filter is applied for predicting the EOP on the 6 following days by using the forecasts of the hydroatmospheric angular momentum as calculated by GFZ. After a description of our method, we shall eventually tell you if such a procedure allows to significantly improve the quality of EOP data and of their short term prediction.

Towards the improvement of EOP prediction: Final results of our contribution to the 2nd EOP PCC

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Real-time prediction of Earth orientation parameters is essential for various purposes, such as tracking and navigating interplanetary spacecraft, predicting weather patterns, and preventing disasters. In spite of efforts being made to improve EOP prediction, there is still a challenge in predicting the future with accuracy high enough, especially when it comes to short-term prediction.

As part of the 2nd Earth Orientation Parameters Prediction Comparison Campaign (2nd EOP PCC), our team has provided weekly full set of EOP predictions for the one year ahead period using the empirical free core nutation (FCN) model (B16) to predict celestial pole offsets and the Earth rotation parameter SSA+Copula method. In this workshop, we will present our latest findings and challenges from the continued application of the proposed techniques, demonstrating their efficiency and accuracy in predicting EOP at different terms.

Keywords: EOP, Prediction, Copula-based analysis, FCN

Strategies to realise highly precise Earth Rotation Parameter predictions

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Precise Earth rotation parameters (ERPs) are the fundamental requirement for a broad range of applications in the area of ground- and space-based navigation and Earth sciences. Applications in real time or at short latencies rely on predicted ERPs that can be based on the analysis of deterministic signals in combined ERP time series, the analysis and prediction of the Earth's Effective Angular Momentum (EAM), or the application of machine learning (ML) methods.

This investigation discusses two approaches to ERP prediction, namely (1) an approach based on EAM prediction and (2) an approach based on ML methods. By comparisons between the derived results as well as with external reference products provided by the International Earth Rotation and Reference Systems Service (IERS) and the NASA Jet Propulsion Laboratory (JPL), we demonstrate that both approaches yield ERP predictions at a quality level competing with state-of-the-art benchmark products in both the pole coordinates as well as ΔUT1.

Based on the results presented, we demonstrate advantages and deficiencies of both approaches, the importance of VLBI for an accurate estimation of ΔUT1, and whether ML-based methods might contribute to mitigating the impact of the technique-specific processing latency of VLBI at present.

Improved Prediction of Polar motion by combining effective angular momentum and IGS ultra rapid data

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Predictions of polar motion is required for real-time satellite orbit determination and deep space navigation. The ultra-rapid polar motion provided by IGS updates four times a day and has a time delay of about 15 hours. Thus, IGS ultra rapid polar motion are introduced to further improve the ultra-short term predictions using the approach proposed by Dill et al. (2019) which combines effective angular momentum functions (EAM) of Earth rotation excitation with LS+AR model. In this approch, we first use the latest ultra-rapid polar motion as the input data of LS+AR model to obtain an improved polar motion prediction on the first day. Then, the difference between this prediction and that from the approch of Dill et al., (2019) were caluculated and used to calibrate the predictions from approch of Dill et al., (2019) for the following days. Prediction results from July 24, 2020 to January 30, 2022 show that compared with Bulletin A, predictions of PMX and PMY on the first day can be respectively improved by 62.29% and 52.10%, and improved by 28.75% and 22.72% on the 10th days.

Improved ERPs prediction with different weights of EAM fitted residuals

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The 2nd EOP PCC has once again brought the study of Earth rotation parameters (ERPs) forecasting to the forefront. The ERPs, as necessary parameters for the interconversion of the celestial and earth reference frames, have been the focus of attention for users of autonomous satellite navigation and deep space exploration. In order to further improve user satisfaction, we have tried to improve a new method for forecasting ERPs based on IERS data and effective angular momentum (EAM) data. The EAM fitted residual series in the excitation domain is first transferred to the EOP domain, and then an empirical adjustment factor is added to construct a new EAM fitted residual series. Then the fitted residual series of ERP and the fitted residual series of the new EAM are subtracted to obtain the difference series. Using LS+AR models driven by final data and rapid data, experiments are performed for the difference series and the new EAM residual series, respectively, and finally forecasts for the target ERPs series are jointly introduced. Based on hindcast experiments from the beginning of 2012 to the beginning of 2021, it is shown that an overall better result can be obtained for the adjustment factor of 0.7 in both the x-pole and y-pole at forecast horizon of 1-365 days, with an average improvement of 31.86% and 21.00% over the traditional method, respectively; the average improvement over the traditional method was 15.01% when the adjustment factor of LoD was 1. This verifies the existing conclusion that about 70% of the high-frequency changes in the short time scale of polar motion are excited by EAM by means of numerical prediction, and provides a reference for ERPs prediction.

As of today, 2nd EOP PCC has been running continuously for 79 weeks and has achieved better statistical results. Next, in order to further upgrade the ERPs forecasting algorithm, future scholars will definitely add the 2nd EOP PCC results for comparison. However, the results of ERPs forecasts emphasize practical applications, so fairness in comparison needs attention. We propose to publish several sets of input data from candidate IDs, which need only include real-time rapid/ultra-rapid data for the last month of each input data period.

Keywords: earth rotation parameters; adjustment factor; effective angular momentum; LS+AR; differencing between series; mean absolute error

Dynamic Mode Decomposition and bivariate autoregressive short-term prediction of ERP time series

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In this presentation we report preliminary results of short-term prediction (30-day forecast horizon) obtained via Dynamic Mode Decomposition (DMD) and bivariate autoregression (BA). DMD was employed to ERPs (polar motion and length of day) time series and BA to polar motion time series only. DMD is a new data-driven, equation free technique capable of reconstruction and forecast time series in one numerical procedure. BA, on the other hand, is a bivariate counterpart of AR model. DMD and BA performance was tested within five subsequent years (2017-2021) separately; namely 30-day predictions were done with 7-day shift giving 48 prediction within each year. We also tested the methods on a time span covering the 2nd EOPPCC under the same conditions. The quality of prediction was measured by mean absolute error. These offline tests showed that DMD and BA outperform kriging and ARIMA - the methods we used in the framework of 2nd EOPPCC. All methods kriging, ARIMA, DMD and BA were used without any external data in relation to analyzed time series, next step towards forecast accuracy improvement is to incorporate EAM information into the prediction procedures.

ESMGFZ EAM Products and EOP Prediction

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Since more than 10 years the Earth system modelling group at GFZ (ESMGFZ) provides Effective Angular Momentum Functions for Earth Rotation on a routinely daily basis. In addition to the individual Earth subsystems atmosphere, ocean, and hydrology, a global mass balance is calculated as barystatic sealevel variation by solving explicitly the sealevel equation. ESMGFZ provides also 6-day forecasts for all of these EAM products. EAM forecasts are naturally accompanied by forecast errors that typically grow with increasing forecast length, but they show also recurring patters with significantly higher errors at short forecast horizons. In order to identify the characteristics of such not randomly distributed errors, we tested an analytical and several neural network approaches. With a cascading forward neural network model we can reduce the forecast error by about 50% over the initial 3 forecast days. It is planned to provide in future also EAM forecast error estimates along with the EAM forecast products. From the purely model-based EAM analysis and 6-day forecast products we calculate also a 90-day EAM prediction that includes information from geodetic observations via the latest available final Earth Rotation Parameter (EOP) time series from The International Earth Rotation and Reference Systems Service (IERS). For the EOPPCC submission, we take the latest available EOP coordinates from USNO, made available via CDDIS, as initial values and integrate our 90-day EAM prediction forward in time to obtain the 90-day EOP prediction for polar motion, UT1-UTC, and dLOD.

NTSC Activities of UT1 Measurement and Services

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The universal time UT1, the time scale defined by the Earth rotation that links the terrestrial and celestial reference frame, is an essential components for the Coordinated Universal Time (UTC). UT1 and EOP services are widely used in satellite navigation, deep space exploration, VLBI astrometry, and geophysical applications. In this talk, we report our recent activities on UT1 measurements and Services, including Domestic VLBI observations, UT1 determination and combination, and EOP predictions.

A Sequential Estimation Approach to Determining Improved Reference EOP Series

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An approach, based upon the use of a Kalman filter, is used at JPL to combine independent measurements of the Earth's orientation and to predict their future evolution. Since changes in the Earth's orientation can be described as a randomly excited stochastic process, the uncertainty in our knowledge of the Earth's orientation grows rapidly in the absence of measurements. Consequently, it is important to analyze each measurement at its measurement epoch, rather than at some "nearby", regularized epoch as is commonly done in normal-point methods of combining data sets. The Kalman filter methodology allows for an objective accounting of this uncertainty growth between measurements since it contains a model for the process, and in the absence of measurements uses this model to propagate forward in time the state vector and its covariance matrix. Kalman filters are therefore an effective means of dealing with irregularly spaced data sets since the state vector and state covariance matrix can be propagated to the measurement epoch regardless of whether or not the measurements are equi-spaced, thereby facilitating the combination of measurements taken at different epochs (not necessarily uniformly spaced in time) and with different precision. However, care must be taken when generating such a combined series in order to account for differences in the underlying reference frames within which each individual series is determined (which can lead to differences in the bias and rate of the Earth orientation series). Traditionally, differences in the underlying reference frames are accounted for by applying a series-specific correction to the bias and rate of each individual series being combined with the goal of placing them within a common reference frame. But there is an uncertainty associated with estimating the bias and rate correction that needs to be applied to each series. In fact, this uncertainty is a major (if not the major) source of error in combined EOP series. At JPL, we are exploring the possibility of mitigating this source of error by jointly combining the EOP series with the terrestrial reference frame. The approach taken at JPL to determine combined and predicted EOP series using a Kalman filter will be reviewed and recent developments in using a square root information filter (SRIF) to jointly determine combined EOP series with a terrestrial reference frame will be presented.