Independent generation of Earth Orientation Parameters

Executive Summary

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1 Introduction

Earth Orientation Parameters (EOPs) are fundamental geodetic parameters that describe the relative orientation of the Terrestrial Reference System w.r.t. the Celestial Reference System. Their knowledge and therewith their highly accurate determination is indispensable for various applications in science and practice. In particular, EOPs are required for the realization of reference systems and time systems, for precise orbit determination, for navigation on Earth and in space as well as for positioning and surveying. Dependent on the application, EOPs are required as final products (i.e. at the highest possible accuracy but with a latency of a few weeks), as rapid products (i.e. in (near) real-time with lower accuracy but with latencies between a few hours and minutes) or as predictions (with different accuracies for different prediction horizons). The basis for the determination of EOPs at best possible accuracy are observation data of the space geodetic observation techniques VLBI (Very Long Baseline Interferometry), SLR (Satellite Laser Ranging), GNSS (Global Navigation Satellite Systems) and DORIS (Doppler Orbithography and Radiopositioning Integrated by Satellite) along with sophisticated strategies for their combination. The meaningful prediction of EOPs requires comprehensive theoretical knowledge concerning physical and empirical Earth rotation modelling as well as forecasts of the relevant excitations by processes within the various components in the Earth system, in particular in atmosphere, ocean, hydrosphere and the Earth's interior.

In the frame of its responsibility to provide the geodetic reference for ESA missions, ESA's Navigation Support Office at ESOC is contributing to the realisation of the International Terrestrial Reference Frame (ITRF) and the combined Earth Orientation Parameters provided by the International Earth Rotation Service (IERS). In this context, ESA is providing individual contributions to different scientific services of the International Association of Geodesy (IAG), in particular to the International Laser Ranging Services (ILRS), the International GNSS Service (IGS), the International DORIS Service (IDS) and the IERS. Ongoing ESA activities aim at providing contributions to the International VLBI Service for Geodesy and Astrometry (IVS) in near future.

The overall objective of the project "Independent generation of Earth Orientation Parameters" was the prototype development of final, rapid and predicted Earth rotation parameters, generated independently from external Analysis Centres (ACs) on the basis of ESA products. The core part of the project was the development of a concept to optimally combine the ESA products into a single ERP (Earth Rotation Parameter) product comprising the parameters *polar motion* (i.e. the orientation of the Earth rotation axis with respect to the conventional terrestrial pole in x- and y-direction) and $\Delta UT1$ (i.e. the difference between observed Universal Time and Coordinated Universal (atomic) Time) (documented in Technical Note 3 [TN3]). The project was initiated by a review of existing algorithms, models and products for EOP generation (TN2), followed by a thorough assessment of ESA's up-to-date involvement in reference frame and EOP activities and the derivation of recommendations to optimize ESA's product portfolio (TN1). The developed concept for ERP determination was subsequently implemented into a prototype software to combine and predict ERPs. The project closed with a thorough demonstration of the software performance as well as with an external and internal quality assessment of the resulting ERPs (TN4). The work was carried out by a consortium led by the Deutsches Geodätisches Forschungsinstitut of the Technical University of Munich (DGFI-TUM), Germany, in collaboration with TUM's Chair of Satellite Geodesy, the Bundesamt für Kartographie und Geodäsie (BKG), Frankfurt a. M., Germany, the Deutsches GeoForschungsZentrum (GFZ), Potsdam, Germany, and the Technische Universität Wien, Vienna, Austria.

2 State of the art and opportunities for improvement

In order to develop an innovative ESA ERP product capable of exploiting the full potential of the available data, the existing products and available scientific literature were reviewed in order to identify weaknesses and opportunities for improvement. The international reference time series for ERPs are provided by two product centers within the *International Earth Rotation and Reference Systems Service* (IERS): The IERS Earth Orientation Center for final products and the IERS Rapid Service/Prediction Center for rapid products and predictions. The reference series for long-term final ERP is called "IERS C04" (Combined 04) and results from the combination of intra-technique ERP series, provided by the Technique Services IVS, ILRS, IGS and IDS as well as individual ACs. Since 2017, the series *IERS 14 C04*, re-aligned with the 2014 International Terrestrial Reference Frame solution (ITRF2014), is the official ERP solution (Bizouard et al., 2019). It is updated twice per week, has a daily resolution and a latency of 30 days. The comparison of the IERS 14 C04 series with other ERP products generated independently demonstrated that the accuracy level of the IERS 14 C04 series does not fulfil the requirements specified by ESA but needs to be improved by a factor of 2–3. The reference series for rapid ERPs at daily intervals and predictions for one year into the future is called *Bulletin A* (Stamatakos et al., 2017). Also the presently available IERS rapid ERP products, computed from a combination of VLBI Intensive and GNSS rapid solutions, do not fulfil ESA's accuracy requirements. Standard deviations of the Bulletin A series are larger by a factor of 2 for pole coordinates and 5-10 for $\Delta UT1$. Bulletin A predictions rely on a rapid combination of space geodetic observations and short-range forecasts of atmospheric Effective Angular Momentum (EAM) Functions. The predicted ERP series of the IERS do not fulfil ESA's accuracy requirements, in particular for the y-component of polar motion (y_{pole}) and $\Delta UT1$.

One prerequisite for optimum results is the highest possible consistency of the input data with respect to applied standards, conventions and models and their rigorous combination. In the IERS procedure, ERP series are combined from individual technique-specific contributions of various IAG ACs for which highest consistency is not guaranteed. But as the generation of independent Earth rotation series by ESA will be based on its own product contributions, this important requirement can be fulfilled. For the improvement of ERP predictions it was recommended to make use of a deterministic component (derived from several years of past ERPs) and geophysical model forecast information about the future evolution of mass re-distribution in atmosphere, ocean, and the terrestrial hydrosphere as described by EAM function forecasts.

3 ESA's product contributions and recommendations

The review of ESA's product portfolio demonstrated that the ESA IAG service contributions of SLR, GNSS and DORIS are already of high quality and comparable to state-of-the-art single-technique solutions computed by other ACs. It was highlighted how essential these products are for the (geodetic) community, and that they are also used by other institutes to derive products with high relevance for society. With respect to VLBI, ESA is not an AC within the IVS yet, and at the moment, no official VLBI solution from ESA is available. But since VLBI is the only technique to estimate $\Delta UT1$ (and nutation), it was advised to establish a full VLBI analysis in ESA's product portfolio. Concerning SLR, the review resulted in the recommendation to include additional satellites into the routine ILRS processing, in particular LARES, Starlette and Stella which are especially beneficial for ERP as well as TRF and gravity key parameters. Further, it was recommended to include polar motion rates and $\Delta UT1$ into the ERP parameterization in order to be consistent with the other techniques and to allow SLR to benefit from UT estimation based on VLBI.

ESA's GNSS solutions exhibit a quality at the forefront among the IGS ACs. No relevant gaps were identified and no easy solutions for further improvement could be recommended. Results demonstrated the increased relevance of multi-GNSS products for ERP determination. ESA's GNSS solutions should ensure the inclusion of co-location sites, in particular for the GNSS rapid solutions, where at least Wettzell, Kokee Park and Ny-Ålesund need to be included as co-locations with VLBI Intensives sites. Also Ishioka should be included as soon as GNSS data becomes available. It was recommended to provide SINEX files for rapid analysis in order to perform a combination with VLBI Intensives with low latency. In the case of DORIS, it was recommended to provide estimates for length-of-day (LOD) changes which is feasible using improved satellite models. As a general recommendation, all technique-specific ESA contributions should be based on identical and up-to-date standards and conventions. Further particular recommendations were documented in TN1 along with estimates of the required effort for their implementation.

4 Scenario for the generation of independent ESA reference products

The identified scenario for ERP determination relies on the combination of the space geodetic observation techniques VLBI, SLR, GNSS and DORIS at normal equation (NEQ) level in order to create final (FIN), rapid (RAP), and FIN-RAP (continuous) ERP series. The combination at NEQ level has been selected as the best compromise between flexibility of the combination w.r.t. the input data sources and consistency of the combination. Prior to the combination, several pre-processing steps are performed. These comprise, among others, the reduction of non-target (technique-specific) parameters, the adaption of most recent TRF coordinates, the reduction of non-datum stations and the application of a GNSS LOD bias; see TN3 for details. Each final ERP solution covers one week of data and is realized with a latency of three weeks. This latency is caused by the latency of external geophysical models used within the analysis of space geodetic observations. Each rapid ERP solution, based on VLBI Intensive sessions and GNSS rapid solutions, covers one day. Its latency mainly depends on the availability of the Intensives data. Usually, a latency of 2-3 days can be achieved. The continuous ERP solution results from a combination of the last available weekly final ERP normal equation and a sequence of rapid ERP normal equations up to the recent date. This continuous solution is followed by a prediction of ERPs up to 90 days into the future, resulting in a continuous final, rapid and predicted ERP product fulfilling the project requirements.

The identified prediction scenario utilizes all information from EAM functions of the surface geophysical fluids (atmospheric, oceanic and hydrological angular momentum) and their forecasts (Dobslaw and Dill, 2018). Instead of predicting polar motion and $\Delta UT1$ directly, EAM predictions are integrated in time via the Liouville equation from initial values as given by the rapid solutions to obtain ERPs for future epochs. The basis for the ERP prediction is a combination of harmonic/stochastic extrapolation of the FIN-RAP ERPs with information from geophysical models given as EAM analysis and EAM forecasts.

5 Results and validation

The concept was implemented into a newly developed Fortran prototype software for the determination of final, rapid and predicted ERP series. In order to demonstrate the software performance, the following input data were used in the combination: GNSS rapids/finals and SLR data from standard ESA IAG service products, DORIS data from GRGS (due to a gap in ESA's time series) as well as VLBI solutions from DGFI-TUM (24-h sessions) and BKG (Intensive sessions). The resulting ERP series were analysed with respect to their quality in three steps: (1) cross-comparison of final ERPs against the external final ERP series IERS 14 C04 and JPL-Comb2018 (Ratcliff and Gross, 2019), (2) comparison of final ERPs against independent numerical models of global geophysical fluids, and (3) comparison of the rapid and predicted ERPs against the related FIN ERP product (hindcast experiments). While creating the ERP series, different processing options of the software were evaluated. In particular the effects of the adaption/non-adaptation of most recent and consistent TRF coordinates (ITRF2014 instead of the pre-defined station coordinates in the SINEX files), the application/non-application of a GNSS LOD bias, and the application/non-application of a variance component estimation (VCE) for the weighting of the technique-specific NEQs were investigated. Best results were obtained using consistent station coordinates in ITRF2014 and applying a constellation-dependent GNSS LOD bias as well as constant technique-specific weighting. ERPs resulting from this processing setup showed the best performance in the quality assessment.

5.1 Performance of final ERP series against external products

In comparison with IERS 14 C04/JPL-Comb2018, the weighted root-mean-square (WRMS) deviations are 58/83 µas for x_{pole}, 49/72 µas for y_{pole}, and 18/12 µs for $\Delta UT1$. These values are in the range of the deviation of IERS 14 C04 and JPL-Comb2018 among each other (66 µas for x_{pole}, 50 µas for y_{pole},19 µs for $\Delta UT1$) and correspond well to the formal errors of the series. In view of the pair-wise differences, it can be noted that the best result from the newly developed software is closest to IERS 14 C04 for the pole coordinates, and closest to JPL-Comb2018 for $\Delta UT1$. Recalling the accuracy requirement (10 µas for pole coordinates, 4 µs for $\Delta UT1$), it can be concluded that neither IERS 14 C04 nor JPL-Comb2018 can be used as an error-free reference for the external accuracy assessment. The fits suggest, however, that the ERPs of the study are of a quality comparable to the two series that are typically considered as state-of-the-art.

5.2 Comparison against numerical models of global geophysical fluids

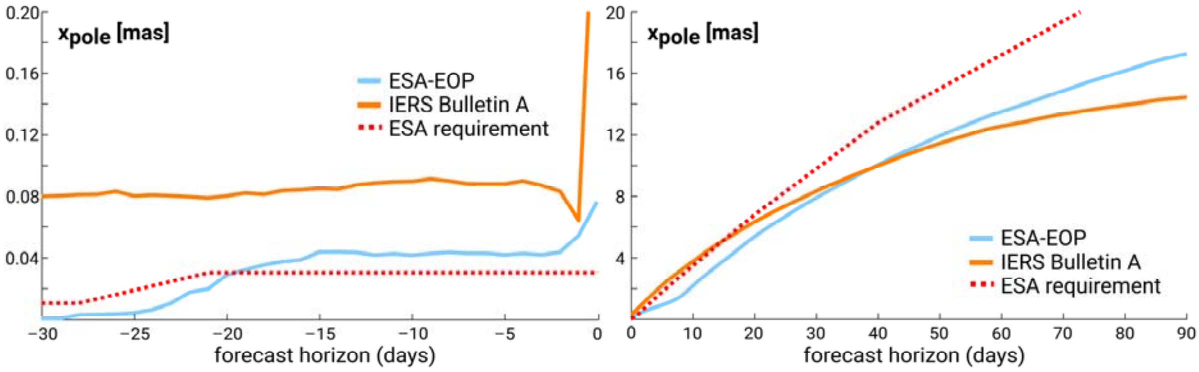
The obtained final ERPs were also assessed in terms of geodetic angular momentum functions, where the external benchmark is taken from a set of model-based EAMs (Dill et al., 2020). Variations in $\Delta UT1$ are largely dominated by zonal tropospheric winds whereas atmospheric surface pressure and ocean dynamics are rather equally important for the excitation of high-frequency polar motion variations. EAMs calculated from geophysical fluid models explain most of the observed variation in Earth rotation, especially for periods below 1 year. For the equatorial components (related to polar motion), good correspondence between the ERP series of the study and the modelled EAMs was obtained, in particular for periods longer than 8 days. For shorter periods, ERP series resulting from different processing options of the software show a larger spread. A consistent result was obtained for the axial component (related to $\Delta UT1$). Optimum agreement with EAMs was obtained for the processing setup described above. The comparison emphasised in particular the importance of introducing precise and consistent a priori TRF coordinates in the ERP determination which improved the agreement significantly. The final ERPs obtained from the optimal setup agree with the EAMs at a similar level as JPL-Comb2018 and outperform IERS 14 C04 substantially.

5.3 Internal validation by hindcast experiments

The accuracy of rapid and predicted ERPs was assessed by a comparison with the corresponding final ERPs in an ensemble of approximately 500 hindcast experiments between 2018 and 2019. The solutions show a smooth transition between final, rapid and predicted ERPs, which is in contrast to the quite discontinuous transition from rapid to predicted IERS products. The following table lists the required and obtained accuracies of the predicted ERPs for different prediction horizons:

Horizon [days]	$\sigma(x_{pole})$ [µas]		$\sigma(y_{pole})$ [µas]		$\sigma(\Delta UT1)$ [µs]	
	Requirement	Result	Requirement	Result	Requirement	Result
1	0.3	0.3	0.23	0.26	0.06	0.04
5	1.8	0.9	1.3	0.7	0.215	0.11
10	3.5	2.2	1.99	1.5	0.53	0.35
20	6.8	5.4	2.7	3.4	1.9	1.5
40	12.8	10.1	4.1	6.1	2.9	4.1
90	23.8	17.2	16.5	12.6	8.6	10.6

For a prediction of 1 day into the future, we note that the hindcast scenario meets the requirements well in both x_{pole} and $\Delta UT1$. For y_{pole}, the accuracy is even better than for x_{pole}, but the requirement is more demanding so that it is not met by a margin of 0.03 mas. For prediction horizons of 5 and 10 days, the requirements are all met. At those forecast horizons the accuracy is almost 50% better when compared to the official IERS products. For prediction horizons of 20 days, only the requirement for y_{pole} is missed. The requirements of 40 and 90 days into the future are met for x_{pole} and partly also for y_{pole}. A specific tuning of the prediction algorithm for those forecast horizons would be possible with the drawback of a reduced accuracy at shorter horizons. In comparison to IERS 14 C04 and IERS Bulletin A, the results achieved in this project are clearly superior for both the rapid estimates and predictions for all forecast horizons of up to 25 days. Results are shown exemplarily for the x-component of polar motion in the figure below. For more details and figures for other parameters, see TN5.



Result of the hindcast experiment for x_{pole}. Left: The blue curve shows the root mean square (RMS) difference between the continuous final-rapid ERP series (-30-0 days) and the respective final ERP series. Both series result from the optimal processing setup using ESA IAG service data as input. Right: The same for the predicted ERP series (0-90 days into the future). The red dotted curve shows the project requirement, and the orange curve shows for comparison the RMS difference between IERS Bulletin A and IERS 14 C04.

The following Table compares required accuracies with formal errors of the final ERP series and of the series IERS 14 C04 and JPL-Comb2018. Since the formal errors depend strongly on the assumed stochastic behaviour of the input data, they are only of limited significance to assess the performance of the underlying combination software but have to be viewed in combination with the applied input data:

	$\sigma(x_{pole})$ [µas]	$\sigma(y_{pole})$ [µas]	$\sigma(\Delta UT1)$ [µs]
Requirement for final ERP	10.0	10.0	4.0
Solution using ESA IAG service data	22.2	21.9	4.6
Experimental solution using reprocessed ESA data	4.7	5.1	0.9
IERS 14 C04	60.8	51.6	13.5
JPL-Comb2018	45.1	34.7	9.5

The combined solution based on standard ESA IAG service products has a formal error at a realistic level of accuracy. Especially for the pole coordinates, it does not yet fulfil the requirements, but it significantly outperforms IERS 14 C04 and JPL-Comb18. An experimental solution using specifically reprocessed ESA data apparently yields small formal errors, but investigations revealed that these are too optimistic since the applied preliminary GNSS Repro3 exhibits, compared to the actual results, unrealistically small standard deviations and dominates the solution. Nevertheless it is concluded that, at the level of formal errors, the final ERP time series derived from the software can fulfil the accuracy requirements in terms of formal errors once all homogeneously reprocessed input data are available.

6 Conclusion

The developed software combines space geodetic observations at normal equation level and delivers a consistent set of Earth Rotation Parameters. It offers a seamless processing, starting from archived observations extending back into the past for decades over rapid processing of the most recent data to EAM-based predictions for up to 90 days into the future. Based on different sets of hindcast experiments, it has been demonstrated that the final ERP series outperforms alternative final ERP solutions. ERP predictions for a few days into the future outperform the IERS official products by almost 50%. The software is designed in a way that new ERP estimates and the associated forecasts can be calculated as soon as new observation data becomes available. The software is thus well suited for an application in routine ERP computation at improved accuracy compared to what is provided as official ERP series by the International Earth Rotation and Reference Systems Service today.

7 References

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