Analysis of Galileo Clock Products of MGEX-ACs

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***Abstract*—Compared with the positioning and timing results of each analysis center (AC), international GNSS service (IGS) combined products benefit in stability, reliability, completeness, and robustness. IGS initiated the multi-GNSS experiment (MGEX) to promote the engineering and science applications of multi-GNSS since 2011. Within MGEX, currently there are seven ACs provide satellite orbit and clock products of multi-GNSS, and the timing is right to start investigating combined products of multi-GNSS. At the IGS workshop 2018, a proposal has been made to combine the satellite orbit and clock products for multi-GNSS. In this paper, analysis of Galileo clock products of the MGEX-ACs has been performed from the view of clock combination. Galileo orbit and clock products of three ACs (COD, GFZ and CNES/CLS) in the first week of 2019 are analyzed. Results show that, day boundary discontinuities of COD clocks is within 1ns and same level can be found for CNES/CLS, while that of GFZ is a little large. Consistency between COD and GFZ is better than that of COD and CNES/CLS, and narrow-lane uncalibrated phase delay absorbed by clocks should be considered when combining the CNES/CLS clocks. Inter-category clock consistency can be found between Galileo in-orbit validation (IOV) and full operational capability (FOC) satellites. Pronounced bump in the clock Allan deviation is visible from the stability analysis result of MGEX AC Galileo clock products. It is because orbit errors are mapped to the apparent clock, and the harmonics should be considered in the modeling of Galileo satellite clock to account for the residual orbit errors.**

Keywords—Galileo, Clock analysis, MGEX

I. INTRODUCTION

Since the beginning of International GNSS Service (IGS), coordinators have combined the satellite orbit and clock products provided by each analysis center (AC). The orbit combination [1], the first and well known IGS combination, has played a major part in the improvement of the IGS products and has been the overall success of the IGS. Based on its success, clock, EOP and other combinations have been performed. The IGS combinations are consistently more accurate and reliable than the AC solutions with the most navigation positions epochs.

Three phases can be found in the development of IGS clock combination algorithm. In the first phase, weighted average algorithm was used for the combination of satellite clock, and in order to weaken the influences of the outliers, a robust estimator based on L1-norm was adopted. Each AC clock solutions were first aligned to GPS time (GPST) by L1-norm estimation of clock offset and drift and then combined by means of a weighted average [2]. In order to improve the consistency between the combined IGS orbits and the combined IGS clocks, one modification was made to the clock combination algorithm. Before the combination, AC clocks should be corrected based on the difference in the radial component between the AC orbit and the IGS combined orbit [3].

Following the setting up of "IGS/BIPM pilot project", IGS operational products were expanded to include the combined clocks for the tracking receivers to realize the accurate time and frequency comparisons between BIPM timing laboratory using GPS phase and code measurements. And IGS would prefer to link its clock products to the international UTC timescale rather than GPS broadcast time for improved stability and accuracy [4]. In order to realize the goals of the IGS/BIPM timing project, IGS clock combination program version was updated for the inclusion of a subset of the fiducial timing station clocks to facilitate a precise and consistent IGS UTC realization for both station and satellite combined clock solutions [5]. However, due to the daily linear alignment to broadcast GPST, clock estimate of the IGS combined product would have a large offsets in time and frequency between days, in order to minimizing the discontinuities at day boundaries, a filter package has been developed to produce an internally realized IGS timescale (IGST), formed as a weighted ensemble of the station and satellite clocks [6]. In the second phase, minimum norm robust estimation algorithm has been replaced by the Kalman filter with a two state polynomial model driven by white noise processes for each clock, and an internally realized frequency ensemble (i.e., IGST) with improved stability has been developed. Besides, determination of clock weights has changed to be based on the clock observed instabilities over sub-daily intervals. Frequency stability is related to the characteristic of clock, and this makes weights of clock more reasonable. IGST can be accurately relatable to UTC. These enhance the value of IGS clock products for applications other than pure geodesy, especially for timing operations [7].

Since 2004, IGS Rapid and Final clock products have been aligned to IGST. IGST is driven mostly by Hydrogen Maser clocks, though GPS satellite clocks also have non-negligible weight, resulting in a time scale with stability of 1e-15/day. However, in the first version of IGST algorithm, relatively simple weighting scheme were used, and IGST was loosely steered to GPST over intervals longer than about a day, the stability over shorter intervals and beyond several days suffers. In the third phase, IGST algorithm (version 2.0) has been developed. The basic clock model used in the IGST (version 2.0) for each clock, ground and satellite clocks, have changed to four state Kalman filter, which includes clock phase, frequency, drift and also an additional phase state [8]. The additional phase state is included to model the pure white phase noise, which present in the interval within one thousand seconds, and also the harmonic signals of GPS

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satellite clocks [9]. Besides, clock parameters can be adaptively estimated using filters, influences of clocks number changes in the ensemble are also minimized on the time scale, and the drift of timescale is adjusted to align to an average of UTC. IGST (version 2.0) algorithm has been transitioned to the Rapid/Final clock products since 2011. Compared with previous IGST, its stabilities is improved for intervals from one day to several days periods, better than 1e-15 [10].

With the modernization of GPS and GLONASS, and also the build-up of Beidou, Galileo and QZSS constellations, IGS initiated the Multi-GNSS Experiment (MGEX) in 2011 to preparing generating products for all GNSS available [11]. Within MGEX, currently there are seven ACs provide satellite orbit and clock products of multi-GNSS. General consistency of Galileo orbits of MGEX ACs was reported at 5-30 cm level [12], while for Galileo clocks, the consistency at 200ps-400ps [13]. Preliminary results of Galileo clock combination of MGEX ACs show that ACs exhibit standard deviation of clock differences w.r.t. the combined solution of about 100ps [14]. Independent work in multi-GNSS clock combination can also be found in the frame of the international GNSS continuous Monitoring and Assessment System (iGMAS). The average RMS of iGMAS AC clock and combined clock for a two week period in 2014 is about 500 ps [15].

At the IGS workshop 2018, it is recommended that the IGS Real-Time Service should prepare for the transition to a true multi-GNSS service [16]. In order to accomplish this, satellite and clock products for multi-GNSS should be combined, and firstly the characteristics of the products of each MGEX AC should be analyzed.

This manuscript starts with an overview of the MGEX precise clock products. Following a brief introduction of the clock combination procedure, characteristics of Galileo clock products of MGEX-ACs are analyzed and discussed, before presenting our summary and conclusions.

II. MGEX AC Clock Product

Precise orbit and clock products for multi-GNSS (GPS, GLONASS, BeiDou, Galileo and QZSS) are computed based on the observations of IGS Multi-GNSS tracking network. Up to seven MEGX ACs are contributing dedicated multi-GNSS products for MGEX on a routine basis:

(1) Centre National d'Etudes Spatiales (CNES) and Collecte Localisation Satellites (CLS), France

(2) Center for Orbit Determination in Europe (CODE), Switzerland

(3) GeoForschungsZentrum Potsdam (GFZ), Germany

(4) Japan Aerospace Exploration Agency (JAXA), Japan

(5) Shanghai Astronomical Observatory (SHAO), China

(6) Technische Universitat Munchen (TUM), Germany

(7) Wuhan University (WHU), China

A. Galileo precise clock products availability

Table 1 lists the Galileo precise clock products provided by various ACs. The products are publicly available at the MGEX product archive (ftp://cddis.gsfc.nasa.gov/pub/gps/products/mgex/) as well as mirror sites hosted by IGN (ftp://igs.ign.fr/pub/igs/products/mgex/) and ENSG (ftp://igs.ensg.eu/pub/igs/products/mgex/). The products are stored in weekly directories (identified by the 4-digit GPS week) and identified by a three letter AC ID (column two in Table 1) identifying the contributing agency. In the interest of brevity, three letter AC ID denotes precise orbit/clock products from certain MGEX AC, throughout the rest of this article, if there is no additional explanation given.

MGEX products over a long time span for more than six years can be publicly available from MGEX product archive, however, the continuity and latency of MGEX products are major concerns. In this paper, Galileo precise clock product of MGEX ACs in the first week of 2019 are analyzed. Until the paper was written, five ACs provided the Galileo precise clock. Among them, data of some days are lost for two ACs. Therefore, Galileo precise clock products of three ACs (GRG, GOD, and GFZ) are used for the characteristic analysis.

TABLE I. Overview of the MGEX Galileo precise clock

Institution	*ID*	*Clock*	*Remarks*
CNES/CLS	GRG	30 s	
CODE	COD	30 s/5min	Satellite 30s, Station 5min
GFZ	GFZ	30 s/5min	Satellite 30s, Station 5min
JAXA	JAX	30 s	No Galileo products
SHAO	SHA	5 min	
TUM	TUM	5 min	
WHU	WUM	5 min	

B. Processing stategies

CNES/CLS use 1-day data for the orbit estimation, and additional 3 h of data from the neighboring days (3 h + 24 h + 3 h) is included to get smaller discontinuities at the day boundaries [12]. Starting with GPS week 2022, Galileo products provided by CNES/CLS are computed with un-differenced ambiguities fixed [17].

CODE uses double differenced data for the computation of the satellite orbits. These orbits are kept fixed when solving for receiver and satellite clock offsets based on un-differenced observations. CODE generate new ambiguity-fixed clock products for Galileo, and since GPS week 2006, they submit the new clock for MGEX [18]. CODE new clock and bias products has to be used together and they are conditioned in a way that maximum consistency may be ensured for ambiguity-float, ambiguity-fixed, and pseudorange supported PPP applications.

For GFZ, the integer carrier-phase ambiguities are fixed according to the paper [19] for the systems GPS and Galileo separately.

III. Clock Combination Procedure

The combined clock product is of very high quality, and should in general be more reliable and at least as accurate (if not more so) than the solutions obtained by the individual ACs. In order to obtain accurate and reliable combined products, the optimal data processing algorithms and robust estimation methods should be used in the product combination.

IGS station/satellite clock combination can be divided into four steps. In order to enforce and maintain the consistency between combined orbit/clock as well as SINEX/clock products, geo-center and station/satellite orbit corrections have to be applied in the first step. Different ACs use different reference clocks, therefore, in the second step, individual AC clocks should be aligned to correct for the differences between difference reference clocks. This procedure would speed up the convergence of the clock combination. The weighted average clock combination is performed in the third step, using a robust iterative outlier detection and rejection scheme. In the third step, reference clock jumps in individual AC solutions should be detected and corrected, and satellite/station biases should be handled [5]. The third step can also be used for generating an internally realized IGS timescale using weighted ensemble algorithm [6]. The last step is the alignment of the combined clocks to a chosen reference time scale. In order to minimize the discontinuities at day boundaries and deal with clock discontinuities, modelling of station/satellite clock should also be studied.

IV. Results and Discussion

In order to promote the clock combination of multi-GNSS, we analyze the characteristics of Galileo clock products of MGEX ACs in the first week of 2019. Just as previously mentioned, clock products of three ACs (GRG, GOD, and GFZ) are chosen for analysis.

A. Reference clock comparison of MGEX ACs

Different ACs use different reference clocks, therefore, individual AC clocks should be aligned to one common time reference frame. IGST is chosen as the common time reference. IGS final clock products of GPS week 2034 are used for the comparison of MGEX ACs reference clock. In GPS week 2034, reference clocks of three MGEX ACs (GRG, GOD, and GFZ) are shown in the Table 2.

TABLE II. Reference clock of MGEX ACs

MJD	*GFZ*	*COD*	*GRG*
58482	KOKV	MDVJ	BRUX
58483	KOKV	PTBB	BRUX
58484	KOKV	YEL2	GODE
58485	KOKV	MDVJ	BRUX
58486	KOKV	MGUE	GODE
58487	KOKV	OHI3	BRUX
58488	KOKV	BADG	BRUX

The clock estimations of reference clock for individual MGEX AC product are compared with that of IGS final clock product. In order for better comparison, GPST is also shown in Fig.1. From Fig. 1, it can be seen that reference clock of CNES/CLS product is more consistent with the GPST except the last day of the analysis period. While for CODE, there would be a constant offsets within one day interval, but the constant offsets would change from one day to another. No obvious trend can be found for GFZ clock products. These may be related with the processing strategies of precise clocks estimation.

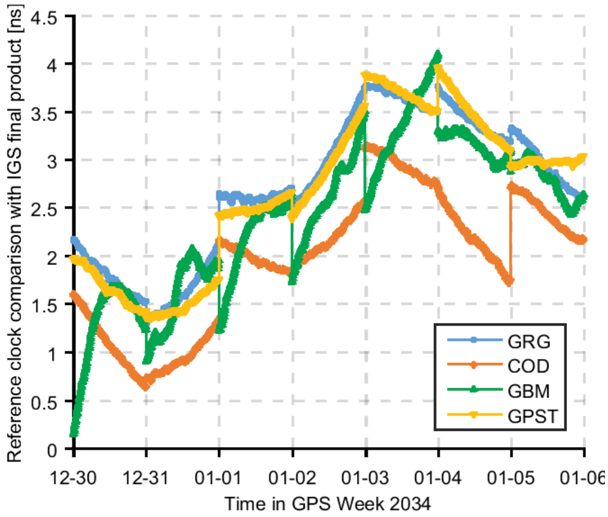

Fig. 1. Reference clock comparison of MGEX ACs, CNES/CLS, CODE and GFZ.

B. Galileo clock alignment to IGST and DBD analysis

IGST is a continuous time scale, and we align the clock product of each AC to IGST to perform day boundary discontinuities (DBD) analysis. The alignment is performed as follows:

$$\mathrm{Clock}_{AC} - \mathrm{Ref.\ Clock}_{AC} + \mathrm{Ref.\ Clock}_{IGST} = \mathrm{Clock}_{IGST} \quad (1)$$

where, Clock_{AC} and $\mathrm{Ref.\ Clock}_{AC}$ are the clock estimation of each AC, and Clock_{IGST} is the reference clock estimation of IGS final product. After alignment, we chose E01 as the reference satellite, and to compute the day boundary discontinuities. The results are shown in Table 3.

TABLE III. Day boundary discontinuities of MGEX ACs

MJD	*GFZ* [ns]	*COD* [ns]	*GRG* [ns]
58483	0.134	0.557	-0.183
58484	-12.845	0.012	-0.287
58485	13.351	0.076	-0.411
58486	-14.623	0.471	-1.414
58487	13.985	-1.088	-0.856
58488	-12.811	-0.158	3.253

From above table, it can be seen that DBD of CODE and CNES/CLS is commonly at the level of 1 ns, except the last day for CNES/CLS. While for GFZ, DBD value is a little large about of 15 ns.

C. Clock Consistency of MGEX ACs

After alignment to IGST, consistency between clocks of each MGEX AC is analyzed. Consistency between the clock of CNES/CLS and CODE AC is shown in Fig. 2. We find that differences between CNES/CLS and CODE AC is at the level of 1 ns, except for two Galileo In-orbit Validation (IOV) satellite, E11 and E12.

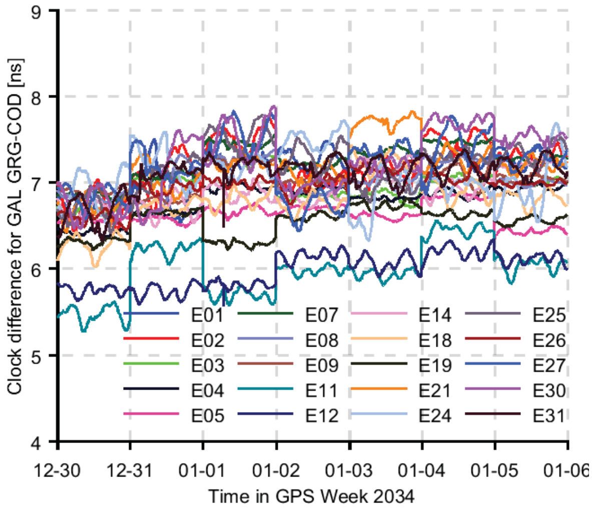

Fig. 2. Clock consistency between MGEX AC CNES/CLS and CODE after aligned to IGST

Compared with the consistency results between CNES/CLS and CODE AC, the consistency between CNES/CLS and GFZ AC is more regular (Fig. 3), and again Galileo IOV satellites show outlier feature.

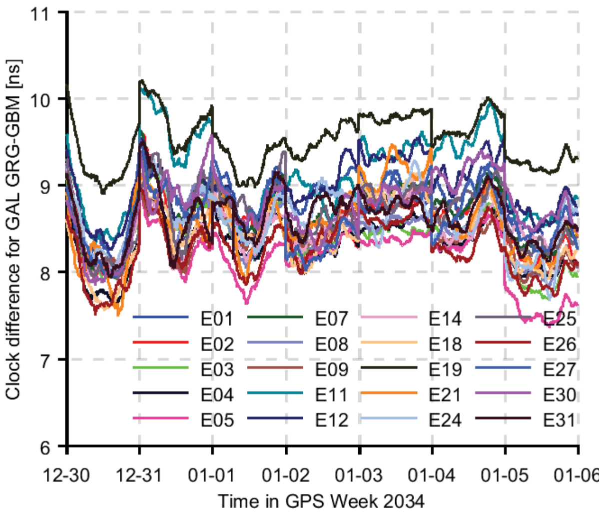

Fig. 3. Clock consistency between MGEX AC CNES/CLS and GFZ after aligned to IGST

Consistency between GFZ and CODE AC is the best, and at the level of about 500ps. There is constant offset between IOV satellites (E11, E12 and E19) and Full Operational Capability (FOC) satellites. The consistency between CNES/CLS and CODE, CNES/CLS and GBM is not good as the consistency between CODE and GBM, is related to the clock estimation strategy used by CNES/CLS [20]. Integer-recovery clocks produced by CNES/CLS AC absorb the zero-differenced narrow-lane un-calibrated phase delay. This makes them different from the clock products of other MGEX ACs. Wave length of Galileo E1/E5a narrow-lane would cause diversity of about 400 ps.

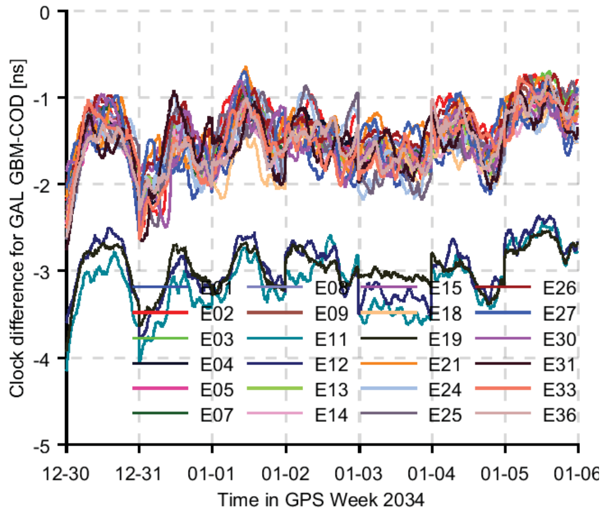

Fig. 4. Clock consistency between MGEX AC CNES/CLS and CODE after aligned to IGST

D. Stability analysis of MGEX ACs clock

Currently, IGS combined clock values are referenced to the IGST, formed as a weighted ensemble of station and satellite clocks. The ensemble algorithm is based on a Kalman filter. In order to design a Kalman filter, modeling of Galileo satellite clock should be studied, and also the noise processes present in the Galileo satellite clock. Besides, weights for individual clocks in the ensemble are determined iteratively and dynamically based on the frequency stability over sub-daily intervals. Therefore, in the following, frequency stability analysis of MGEX AC clock is performed, and modified allan variance is estimated in the time domain to distinguish the white phase noise and flicker phase noise .

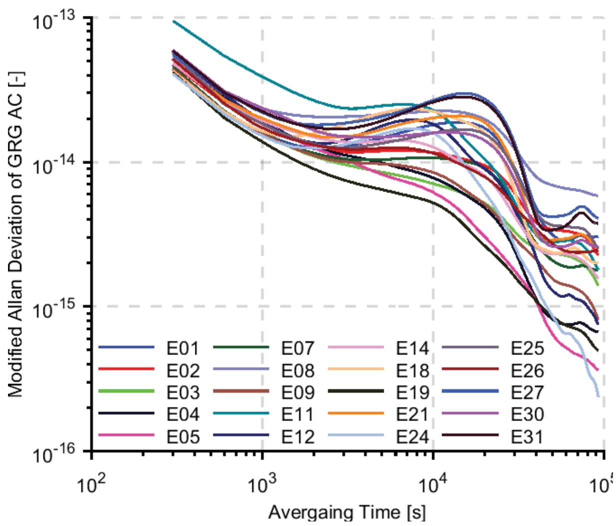

Fig. 5. Frequency stability analysis of CNES/CLS Galileo clock products

In Fig.5, a pronounced bump in the clock Allan deviation is visible from stability analysis result of CNES/CLS Galileo clock products. It is because the orbit errors are mapped to the apparent clock due to correlations of radial orbit and the clock estimates [12]. Besides, approximate power-law stochastic processes can be found on the sub-daily regime. An apparent white frequency process from 300s to several tens of thousands seconds can be found.

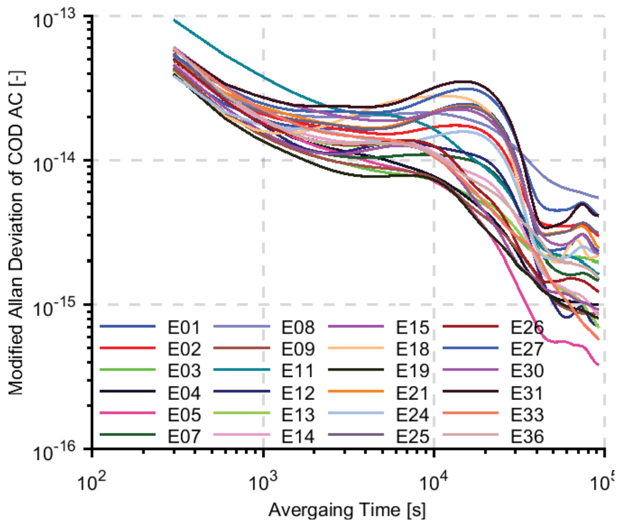

Fig. 6. Frequency stability analysis of CODE Galileo clock products

From Fig.6 and Fig. 7, it can be seen that analysis results of CODE and GFZ ACs are almost the same as that of CNES/CLS, but the variance of GFZ is a little larger than that of CNES/CLS and CODE especially for the time intervals within ten thousand seconds.

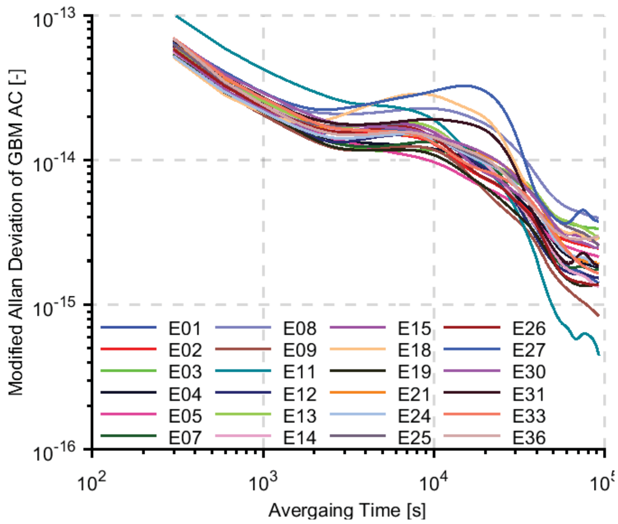

Fig. 7. Frequency stability analysis of GFZ Galileo clock products

V. Conclusions and Future Work

Analysis of Galileo clock products of the MGEX-ACs has been performed from the view of clock combinations. Reference clock of CNES/CLS product is more consistent with the GPST, and there is a constant offsets between reference clock of CODE product and GPST, and no obvious trend can be found for the reference clock of GFZ product. Day boundary discontinuities of CODE and CNES/CLS is commonly at the level of 1 ns, while that of GFZ is a little large, this maybe related with the alignment operation. Consistency between CODE and GFZ is better than that of CODE and CNES/CLS, GFZ and CNES/CLS, and this is related to the clock estimation strategy used by CNES/CLS. Integer-recovery clocks produced by CNES/CLS AC absorb the zero-differenced narrow-lane un-calibrated phase delay. Inter-category clock consistency can be found between Galileo IOV and FOC satellites, and this need further research. Pronounced bump in the clock Allan deviation is visible from the stability analysis result of MGEX AC Galileo clock products. It is because that the orbit errors are mapped to the apparent clock due to correlations of radial orbit and the clock estimates. Therefore, the harmonics should be considered in the modeling of Galileo satellite clock to account for the residual orbit errors.

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