Determining and Predicting UT1-UTC to Support China's Interplanetary Spacecraft Navigation

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Abstract: *UT1-UTC is essential for interplanetary spacecraft navigation mission. Firstly, This paper introduces the method of UT1-UTC determination based on VLBI and UT1-UTC prediction in Beijing Aerospace Control Center(BACC). Then, The UT1-UTC determination and prediction results are compared with IERS, USNO and EOP_PCC. The compared results shows that BACC UT1-UTC products with high precision could effectively meet the requirement of interplanetary spacecraft navigation mission. Finally, UT1-UTC prediction products were successfully applied on China's first reentry return flight test mission to support spacecraft's orbit determination.*

Keywords: *UT1-UTC Determination, UT1-UTC Prediction, VLBI, China reentry return flight test mission*

1. Introduction

Earth orientation parameters (EOP), consists of polar motion, UT1-UTC, precession, nutation, is essential for the transformation of the international terrestrial reference system (ITRS) and the international celestial reference system (ICRS), thus, it is necessary for interplanetary spacecraft navigation missions[1,2]. EOP affects the transformations, with UT1-UTC being the most important contributor. Since UT1-UTC is the fastest varied parameter in EOP, which is also the most difficult parameter for determination and prediction[3]. Thus, the accuracy of UT1-UTC determination and prediction directly affects the accuracy of the interplanetary spacecrafts' orbit measurement and determination. For example, Error in UT1-UTC of 0.1 ms produces an error of 7 nrad in spacecraft right ascension, corresponding to a position error at Mars of 1.6 km[4]. Meanwhile, high precision determination and prediction of UT1-UTC plays a very important role in real-time or quasi-realtime navigation.

Very Long Baseline Interferometry (VLBI) is the only technique able to provide long-period variations in UT1-UTC[2], by mean of observing quasars, correlating the received quasar signals, and estimating UT1-UTC observations. On the one hand, this paper introduces determining UT1-UTC based on VLBI observations in Beijing Aerospace Control Center (BACC), utilizing VieVS VLBI analysis software, which is developed by Vienna University of Technology. On the other hand, this paper introduces a prediction method of UT1-UTC by dual differential least-squares (DDLS) and autoregressive (AR) model (DDLS+AR)[5,6]. Then, the determining and prediction results of UT1-UTC are compared with International Earth Rotation and Reference Systems Service (IERS) and United States Naval Observatory (USNO) results. Finally, the determination and prediction products of UT1-UTC were successfully applied on China's first reentry return flight test of lunar exploration (CE-5T1) mission, to support CE-5T1 spacecraft high precision orbit determination. Thus, this validates that BACC can provide high precision UT1-UTC products to support China's future deep space exploration mission.

2. The Theory of UT1-UTC Determining and Predicting

2.1 UT1-UTC Determining Method Based on VLBI

The basic process of UT1-UTC determining based on VLBI observation is as follows, the observation error equation is set up utilizing VLBI delay observation, then this observation error equation is calculated by Least-squares method, to obtain UT1-UTC estimating result.

The VLBI observation equation is shown in Formula (1).

$$O_t = C(X,t) + N_t \tag{1}$$

Where O_t is the obtained delay observation at the time of t, X is the parameter vector related to delay observation. $C(X,t)$ is mathematical model of X, which is also called the theoretical value. N_t is the noise vector. It assumes that X consists of prior value x_0 and correction value x. Thus, the linearization of Formula (1) is shown in Formula (2).

$$O_t = C(x_0,t) + \frac{\partial(X,t)}{\partial X}|_{x_0} \cdot x + N_t \tag{2}$$

Then,

$$y_t = A_t x_t + N_t \tag{3}$$

Where $y_t = O_t - C(x_0,t)$, it means the difference of observation value and theoretical value at the time t. A_t is partial derivative matrix.

Then, Formula (3) is expressed in the way of vector, shown in Formula (4).

$$Y = Ax + N \tag{4}$$

It assumes that the observation weight matrix is P, then the correction value x, obtained by Least-squares method, is shown in Formula (5).

$$x = (A^T PA)^{-1} PA^T Y \tag{5}$$

When UT1-UTC is estimated, the above process is also applicable.

2.2 UT1-UTC Predicting Method

2.2.1 Least-squares

Least-squares model of UT1-UTC prediction is shown in Formula (6), it contains linear term and periodic term. The periodic term contains annual, half of a year, 9.3 year, 18.6 year, etc.

$$X(t)=A+Bt+Ct^2+D_1\cos\left(\frac{2\pi t}{p_1}\right)+D_2\sin\left(\frac{2\pi t}{p_1}\right)$$
$$+E_1\cos\left(\frac{2\pi t}{p_2}\right)+E_2\sin\left(\frac{2\pi t}{p_2}\right)+\cdots \tag{6}$$

Where, t is UTC time (unit is year). $A,B,C,D_1,D_2,E_1,E_2,\cdots$ are the fitting parameters, p_1, p_2, …are the fitting periods, which could be determined by prior experience.

2.2.2 AR model

For a stationary sequence x_t ($t=1,2,\ldots,N$), the AR model is expressed as follows[7]

$$x_t=\varphi_1 x_{t-1}+\varphi_2 x_{t-2}+\cdots+\varphi_p x_{t-p}+a_t=\sum_{i=1}^{P}\varphi_i x_{t-i}+a_t \tag{7}$$

where φ_1, φ_2, . . ., φ_p are model parameters, a_t is white noise, p is model order. Formula (7) is called p order AR model, denoted by AR(p). $a_t\sim N\left(0,\sigma_n^2\right)$, σ_n^2 is the variance of the white noise。

The key technique of AR model is determining model order parameter p. There are many criterions which can be utilized for determining the model order parameter p, such as Final Prediction Error Criterion (FPE), Akake Information Criterion (AIC), Singular Value Decomposition (SVD) criterion, etc.

This study utilizes FPE for determining AR model order. FPE criterion function is as follows.

$$FPE(p)=\frac{N+p}{N-p}\sigma_n^2 \tag{8}$$

2.2.3 Prediction Error Estimates

In order to evaluate prediction error, Mean absolute error (MAE) is utilized as the prediction accuracy index shown as follows.

$$MAE_i=\frac{1}{n}\sum_{j=1}^{n}\left(\left|p_j{}^i-o_j{}^i\right|\right) \tag{9}$$

Where o is the real observation, p is prediction value, i is prediction day, n is prediction number.

2.2.4 Dual differential LS+AR prediction process

The process of the dual differential LS+AR UT1-UTC prediction is shown in Figure 1.

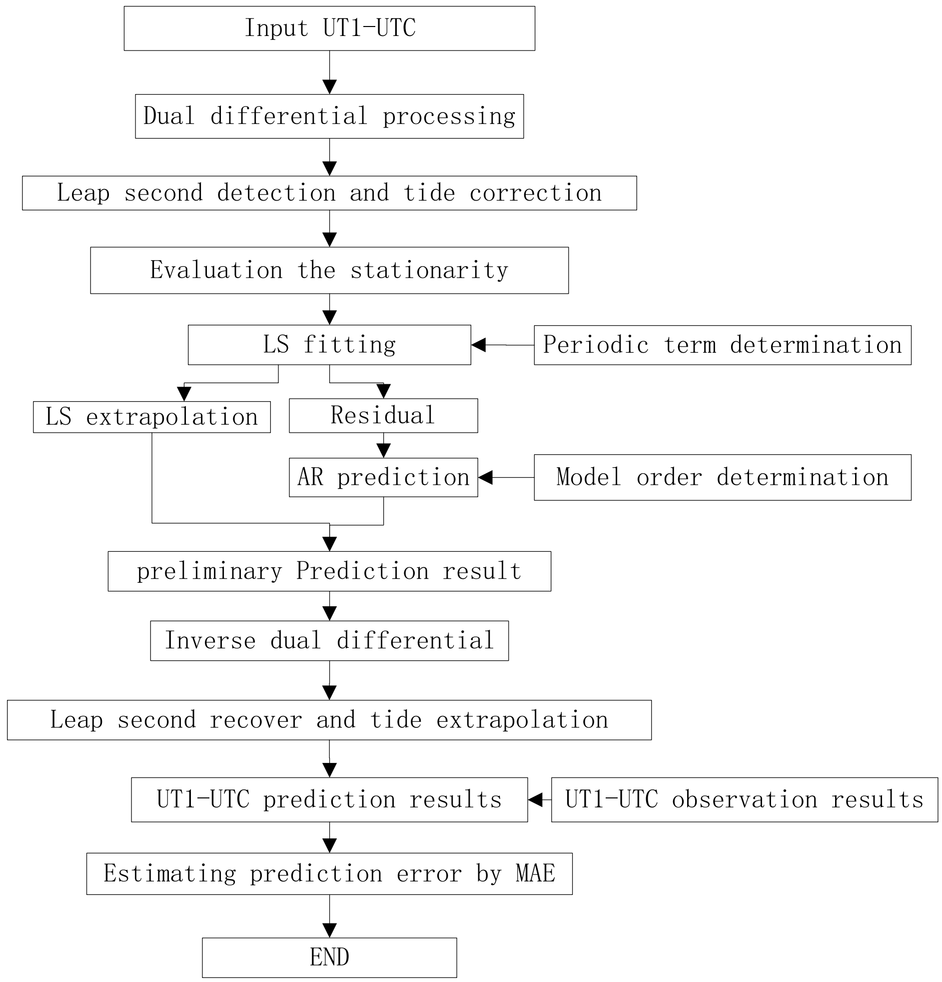


Figure. 1 Dual differential LS+AR prediction process of UT1-UTC

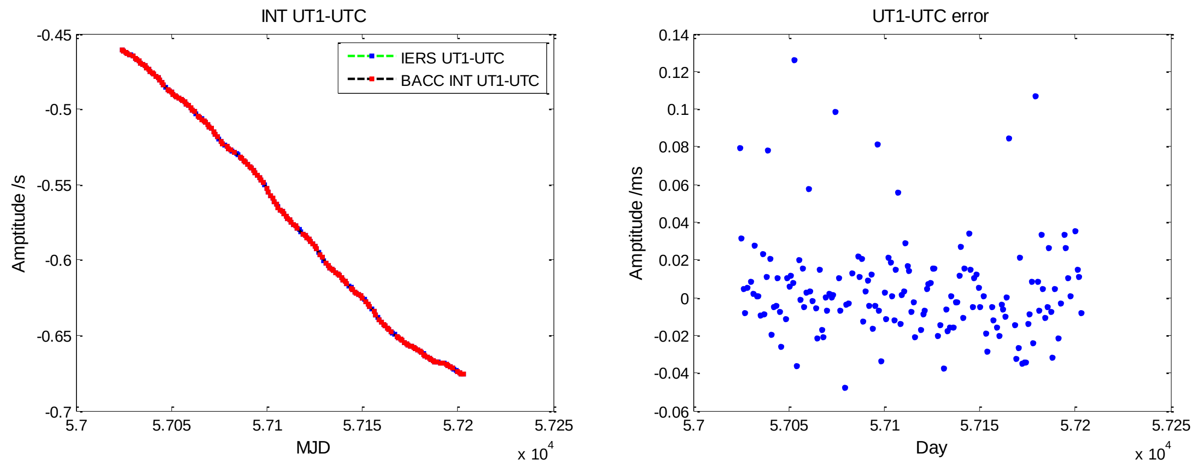
Firstly, leap seconds are removed in UT1-UTC observations, and Earth zonal harmonic tidal is corrected. Then, the corrected UT1-UTC is processed by dual differential method. In doing so, the stationary of UT1-UTC is improved. Then, least-squares and AR methods are utilized to analyze the dual differential UT1-UTC to obtain the preliminary prediction results. Finally, the preliminary prediction results are processed by inverse dual differential method, and tidal correction are extrapolated and leap seconds are recovered to obtain high precision UT1-UTC prediction results.

3. UT1-UTC Results Comparing

3.1 UT1-UTC Determination Results Comparing

In order to evaluate the performance of UT1-UTC determination, UT1-UTC products of BACC are compared with other international organization's UT1-UTC products. The Vienna VLBI Software (VieVS) is a new state of the art VLBI analysis software written in MATLAB, this software is utilized to determinate UT1-UTC based on VLBI observation in BACC. The raw VLBI observation results are get from international VLBI service for geodesy and astrometry (IVS) database, which is from Jan. 1, 2015 to Jun.30, 2015. UT1-UTC products calculated by

VieVS software are shown in Figure 2. Red points are BACC results, blue points are IERS results shown in Figure 2(a), IERS results is EOP 08 C04 final products. The difference value of UT1-UTC between BACC and IERS is shown in Figure 2(b), and the standard deviation of this difference is 2.01953e-05s, about 0.02ms.



(a) (b)

Figure 2. UT1-UTC determination results in BACC compared with IERS from Jan.1 to Jun.30, 2015

3.2 UT1-UTC Prediction Results Comparing

The Earth orientation parameters prediction comparison campaign (EOP_PCC) that started in 2005 was organized for the purpose of assessing the accuracy of EOP predictions[2]. Earth Orientation Parameters Prediction Comparison Campaign attracted 12 participants coming from 8 countries, who are the top professors or scholars in the time sequence analyzing filed. EOP_PCC referenced to more than 20 prediction methods[8]. EOP_PCC contains the ultra short term (predictions to 10 days into the future), short term (30 days), and medium term (500 days) predictions.

This paper compared BACC UT1-UTC results with EOP_PCC UT1-UTC results in ultra short term prediction and short term prediction, the same UT1-UTC input was utilized. Figure 3 shows the EOP_PCC results[1], Figure 4 shows the BACC results.

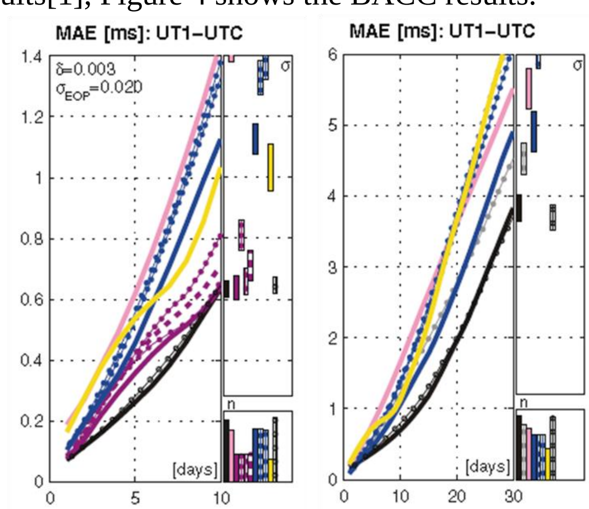


Figure 3. Short term prediction results of UT1-UTC in EOP_PCC

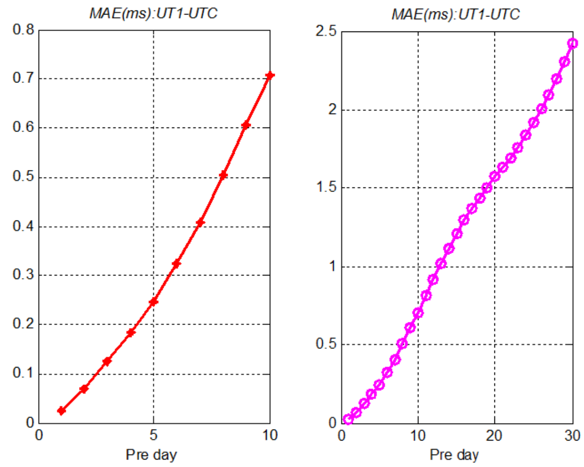


Figure 4. Short term prediction results of UT1-UTC in BACC

In general, BACC prediction results of UT1-UTC are at the same level as EOP_PCC by comparison. According to one day prediction accuracy, BACC one day UT1-UTC prediction accuracy is better than EOP_PCC. In BACC prediction, one day prediction error of UT1-UTC is at the level of 0.02ms. EOP_PCC polar motion minimum one day predictions error is at the level of 0.08 ms for UT1-UTC[1].

4. Application on CE-5T1 Mission

China successfully carried out the first reentry return flight test mission on Oct. 24, 2014 to Nov. 1, 2014, which was also called Chang E Five Test Mission (CE-5T1), for validating corresponding key technologies for China's lunar sample return mission[9]. BACC developed EOP prediction software, which is called EOPS, to produce EOP products for supporting CE-5T1 mission. The software interface of EOPS was shown in Figure 5, this software could provide daily EOP prediction products automatically, meanwhile, these prediction results could be compared with IERS and USNO.

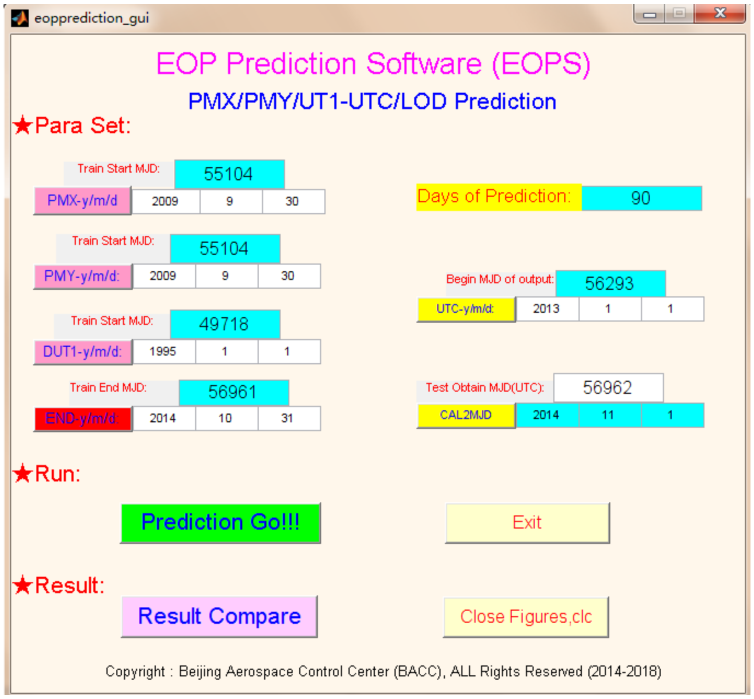


Figure 5. EOPS software interface in BACC

UT1-UTC prediction results were the important EOP products for CE-5T1 orbit determination system, thus, some of the UT1-UTC prediction results obtained by EOPS were shown in Figure 6 to Figure 7, corresponding to short-term (30 days) prediction results of Oct.24, Oct.26, Oct.28 and Oct.30, 2014.

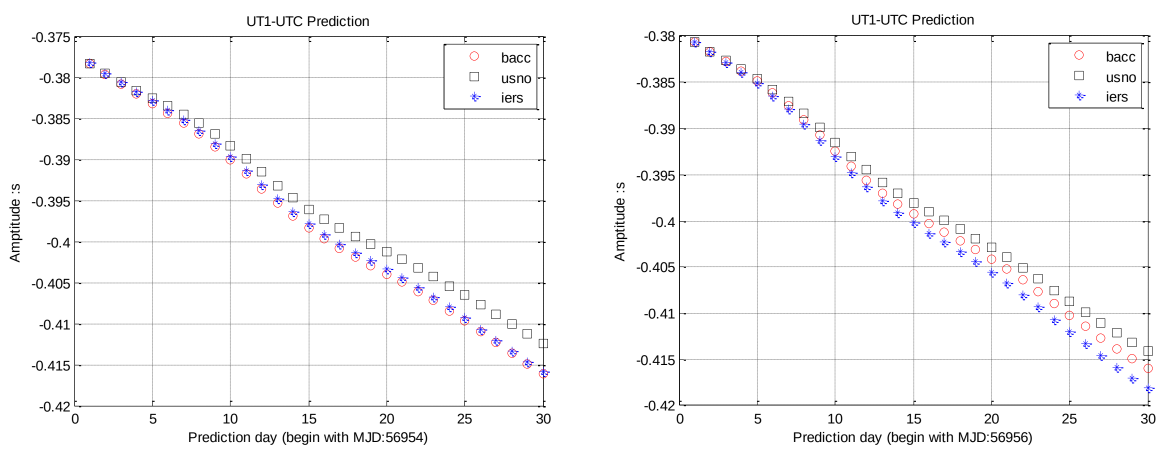


Figure 6. UT1-UTC prediction results of BACC/IERS/USNO on Oct.24 and Oct.26

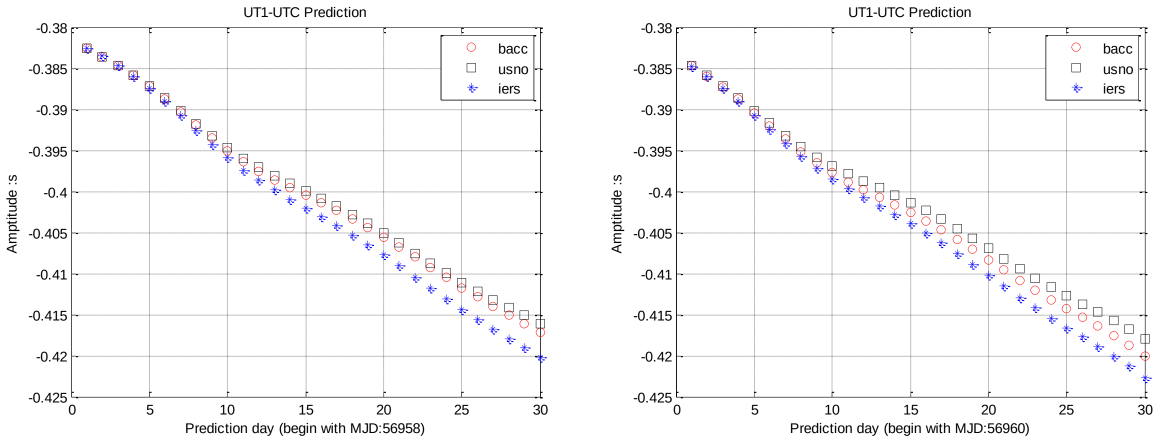


Figure 7. UT1-UTC prediction results of BACC/IERS/USNO on Oct.28 and Oct.30

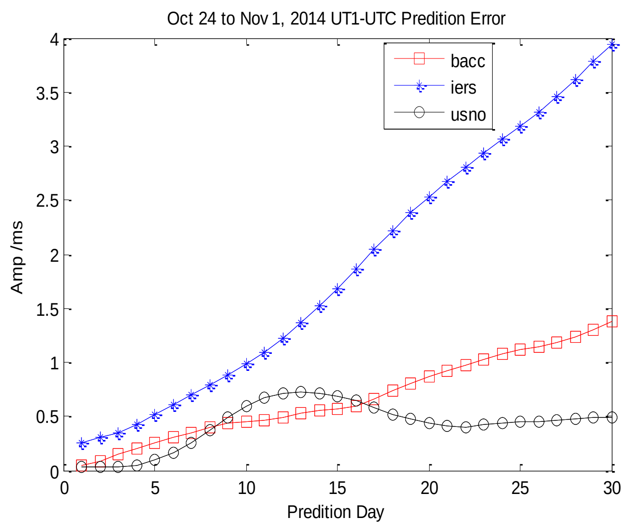


Figure 8. UT1-UTC prediction accuracy of BACC/IERS/USNO in China's reentry return flight test mission

It could be found that UT1-UTC prediction results in BACC were quite coincident with IERS and USNO. In order to quantificationally evaluate the prediction accuracy, MAE according to Formula (9) was utilized. The prediction accuracy was shown in Figure 8 and Table 1. The results shown that the UT1-UTC prediction results in BACC in China's reentry return flight test mission was very effective. And these UT1-UTC products were transmitted to orbit determination system according to standard data interface for supporting CE-5T1 spacecraft's orbit determination.

Table 1. MAE result of UT1-UTC in BACC/IERS/USNO

Prediction Days	BACC UT1-UTC(ms)	IERS UT1-UTC(ms)	USNO UT1-UTC(ms)
1	0.0303	0.2532	0.0304
5	0.2614	0.5152	0.1005
10	0.4542	0.9846	0.5927
15	0.5697	1.6835	0.6896
20	0.8693	2.5295	0.4380
25	1.1186	3.1790	0.4541
30	1.3755	3.9473	0.4949

5. Conclusion

This paper introduces the method of UT1-UTC determination based on VLBI, and introduces a prediction method of UT1-UTC by dual differential least-squares and autoregressive model (DDLS+AR). UT1-UTC determination results and prediction results are compared with IERS, USNO and EOP_PCC. The compared results shows that UT1-UTC determination results are quite coincident with IERS, the standard deviation is about 0.02ms. UT1-UTC short term prediction results are at the same level of EOP_PCC, one day UT1-UTC prediction accuracy is better than EOP_PCC. Finally, UT1-UTC prediction results, daily compared with IERS and USNO, were effectively applied on China's reentry return flight test mission.

6. Acknowledgements

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