The EUREF Permanent Network: Ocean Tide Loading, Height and Troposphere Estimates

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Abstract

The processing of the data acquired by the EUREF permanent network as well as the estimation of the network kinematics are done with the Bernese GPS software. Up to the end of 1999 this software package did not provide the capability of modeling the periodic site displacements due to ocean tide loading. Considering that this mismodeling mainly affects the vertical position components and presumably the troposphere estimates, this simulation study analyzes the effect of neglecting the ocean tide loading on the heights and tropospheric zenith delays for a subset of the EUREF stations. This subnetwork of 21 stations comprises mainly highly affected sites at the Atlantic coast, sites in Greenland and Iceland as well as continental inland locations. The effects of neglecting the loading displacements on epoch solutions and time series adjustments are discussed, and a software development to account for the periodic vertical displacements in the absence of loading models is presented.

1. Introduction

The aim of the EUREF permanent GPS network is to determine and preserve the European Terrestrial Reference Frame (ETRF) as part of the International Terrestrial Reference Frame (ITRF) on the highest possible level of accuracy. Presently daily adjustments of such permanent GPS arrays demonstrate repeatabilities of a very few millimeters in the horizontal position components, whereas the vertical component is generally worse determined by a factor of about three. Considering the increasing importance of accurate heights, e.g. for monitoring sea level changes, the software systems used for processing the GPS data need to be capable of accounting for or modeling all phenomena affecting the height estimation. Among there are tropospheric delays, antenna phase center variations as well as direct and indirect effects of earth and ocean tides respectively.

In particular, the ocean tide loading is probably the most poorly modeled phenomenon in the processing of GPS networks, although a number of investigations on the subject were performed during the past years. An overview and a demonstration of the amplitudes of vertical displacements at sites on the British Isles are given by BAKER et al. (1995). Analyses of data sets from IGS stations around North America during a one year period (SCHENEWERK et al., 1995) and from a Canadian coastal site during four weeks (DRAGERT et al., 2000) showed in many cases promising agreement between sub-daily height estimates and tidal predictions. Recently SCHERNECK et al. (2000) were able to prove that ocean loading tides can be recovered from long time series of precise point positions.

The weekly solutions of the EUREF network and their combination for deriving the kinematic of the network are done with the Bernese GPS software package. Up to the end of 1999 the version 4.0 (ROTHACHER and MERVART, 1996) was used which did not provide the capability of modeling the periodic site displacements due to ocean loading. As the EUREF network includes a number of coastal stations exposed to very high tidal variations, neglecting the effect may cause biases in the weekly results and in the time series. Moreover, accurate height determinations for these stations are of utmost importance because they should be used to monitor vertical crustal movements of tide gauge benchmarks.

Therefore, a simulation study has been performed to analyze the effects of neglecting the vertical site displacement due to ocean tide loading on a representative sub-network of the EUREF permanent network and its time evolution. In the course of this study the capability of applying loading displacements to simulated observations and of recovering vertical periodic displacements in the adjustment was established in the Bernese software.

2. Software Developments

The software capabilities developed for this simulation study refer to the Bernese software version 4.0 (ROTHACHER and MERVART, 1996) the latest version available at the time of initiating this analysis in autumn 1999. Figure 1 displays the basic structure of the data simulation program GPSSIM and those modules which were added or modified. The file OTLFIL contains the amplitudes and phases of the main 11 tidal waves in local radial, west and south direction in the format specified in table 7.1 of the IERS Conventions 1996 (MCCARTHY, 1996). The subroutine GETOTL reads this file once per simulation run and carries all available data relevant to the actually simulated network through the entire simulation. The subroutine OTLOAD estimates the time dependent site displacement due to ocean tide loading and applies it to the generation of the simulated observations. Thus, as with true observations the simulated data include the loading effect. ARG is nothing else than a realization of the module ARG given in the IERS Conventions 1996.

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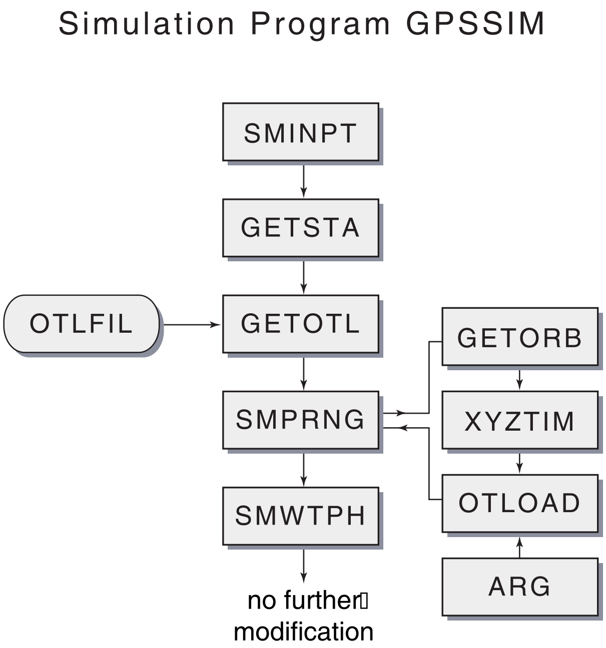

Fig. 1: Extension of the Bernese simulation program to apply site displacements due to ocean loading.

Figure 2 displays similar information on the modifications of the Bernese adjustment program GPSEST. The modules OTLFIL, GETOTL and OTLOAD are identical with those in the simulation program. The subroutines PRIAPR, PRIEST and PRIOTL are modified or added to print all information and results referring to the ocean tide loading. PRCMOD is a modified version of the original Bernese subroutine PRCEPO including several new options.

In the course of this study the idea appeared to go one step further and to estimate, in the absence of a model, the vertical loading effect in the adjustment. As the periods of the dominant tides are rather close to 12 and 24 hours respectively the vertical displacement ΔZ_{load} during a one day session can be approximated by simple harmonic functions:

$$\Delta Z_{load} = A_d \sin\frac{2\pi}{24}\Delta t + B_d \cos\frac{2\pi}{24}\Delta t + A_s \sin\frac{2\pi}{12}\Delta t + B_s \cos\frac{2\pi}{12}\Delta t$$

Δt = hours since 0:00 UT

However, the question arises whether station height, vertical site displacement caused by ocean loading and tropospheric delays can be estimated simultaneously. Figure 3 displays the geometrical configuration regarding the radial loading displacement ΔZ_{load} and the tropospheric zenith delay ΔZ_{trop} and shows that the separation of these parameters is indeed feasible because they are almost uncorrelated. Therefore, the amplitudes A_d, B_d, A_s and B_s of the diurnal and semi-diurnal accumulated tidal waves were defined as a new estimable parameter type in the adjustment program GPSEST. This extension implies mainly modifications of the subroutines SEQPAR defining the set of parameters to be solved for and SNDIFF creating the single difference observation equations. The results of this simulation study and of the extended adjustment model are given in the next chapter.

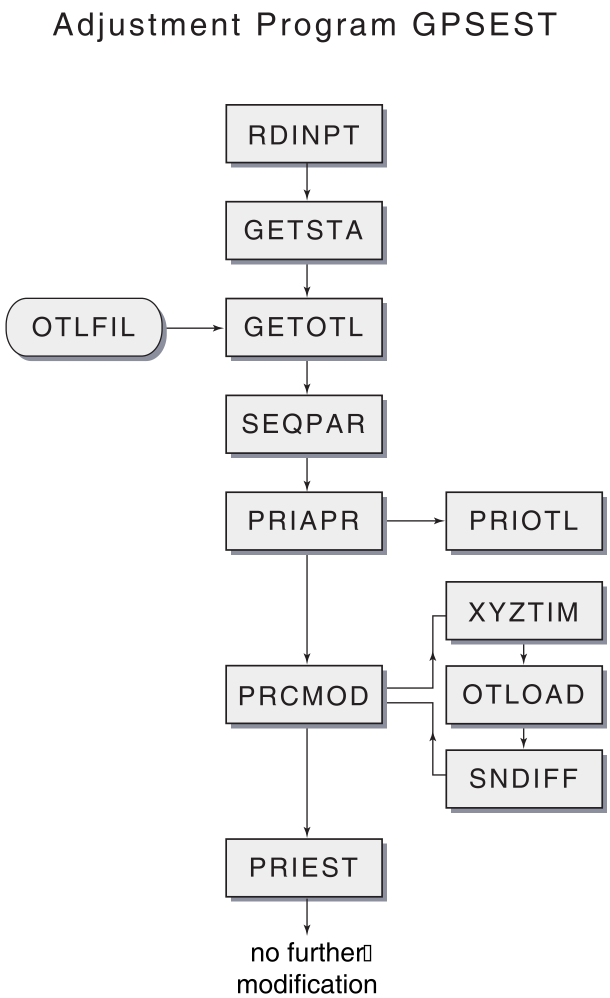

Fig. 2: Modification of the Bernese adjustment program to apply site displacements due to ocean loading and/or to model it by harmonic functions.

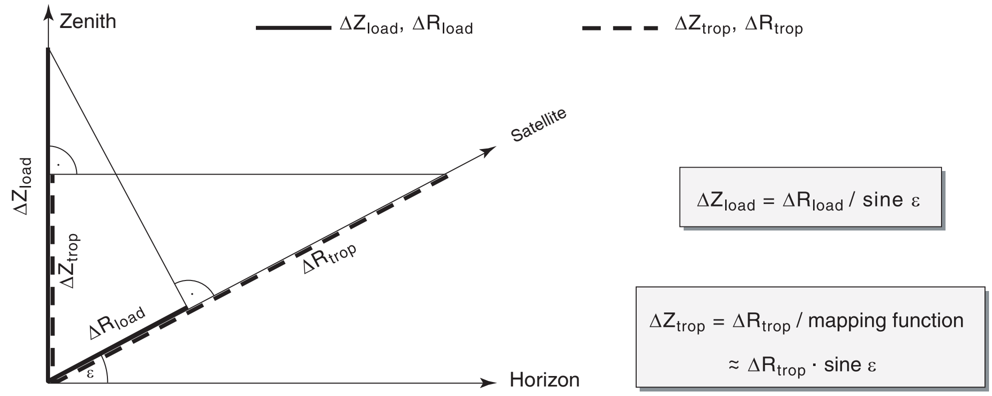

Fig. 3: Separation of vertical loading displacements and tropospheric delays.

3. Data Simulation and Processing

The modified simulation program GPSSIM was used to generate phase observations for a subset of 21 stations of the EUREF permanent network. These stations were selected such as to comprise a number of sites in central Europe and coastal sites on Greenland, Iceland and Svalbard, in Scandinavia as well as at the south western coast of Europe. In particular these latter stations at the Atlantic coast are exposed to high vertical loading effects, and the models available for that area may still not be sufficiently accurate (FRANCIS and MELCHIOR, 1996). The features of the data simulations can be summarized as follows:

- L1 and L2 phase observations generated for 21 stations and 25 one day sessions between 1995.4 and 1999.9;
- ITRF97 station positions and IGS orbits as well as earth orientation parameters fixed;
- No cycle slips and initial phase ambiguities introduced;
- No biases such as tropospheric delays applied, only white noise equivalent to 3 mm for a single difference observation at 30 seconds sampling put on the data;
- Site displacements due to ocean tide loading applied as available by anonymous ftp to

  gere.oso.chalmers.se/~pub/hgs/oload/README.

As a consequence, troposphere parameters solved for in the network adjustment and site velocities derived from all 25 sessions should be zero except for any loading effect.

Table 1 gives examples of the magnitude of the vertical amplitude for the 11 main tidal harmonics at some of the EUREF sites included in the analysis. As can be seen, the largest effects appear at ACOR, BRST and CASC where the accumulated amplitudes may reach 6 cm or even more. All 21 stations are listed in table 2 arranged according to the amplitude of the dominant semidiurnal wave M_2.

Tab. 1: Vertical amplitudes [mm] of main tidal harmonics at selected EUREF sites; h = solar hours, d = days.

Darwin Symbol		Period	ACOR	BRST	CASC	KELY	MASP	REYK	SFER
Semidiurnal	M_2	12.42 h	34.8	39.8	32.3	11.2	22.7	22.1	22.5
	S_2	12.00 h	11.6	13.0	11.2	4.4	9.1	8.7	7.9
	N_2	12.66 h	7.4	8.0	6.8	2.2	4.9	4.4	4.8
	K_2	11.97 h	3.0	3.4	2.9	1.2	2.6	2.3	2.1
Diurnal	K_1	23.93 h	4.2	4.4	3.7	4.9	2.0	6.2	2.8
	O_1	25.82 h	1.1	1.5	0.9	2.4	1.5	3.3	0.4
	P_1	24.07 h	1.3	1.4	1.2	1.6	0.6	2.1	0.9
	Q_1	26.87 h	0.6	0.6	0.6	0.1	0.8	0.4	0.4
Long period	M_f	13.66 d	0.4	0.7	0.3	0.7	0.3	0.9	0.3
	M_m	27.55 d	0.2	0.4	0.2	0.3	0.2	0.4	0.3
	S_{sa}	182.62 d	0.1	0.9	0.1	0.3	0.7	0.6	0.2

Common features of all network solution performed with the modified program GPSEST are the application of a 5° elevation angle cutoff, a loose constraining of HERS to ITRF97 and the estimation of hourly troposphere parameters.

Each session was processed with and without applying the ocean tide loading models, and some sessions of high vertical displacements were adjusted solving for the amplitudes of the harmonic functions. The series of network adjustments aimed at addressing following aspects:

- The effect of neglecting the modeling of the loading displacement on the height estimates,
- the additional errors due to the occurrence of data gaps,
- the effect of not modeling ocean tide loading on time series of height estimates,
- the impact of neglecting the vertical loading effect on the tropospheric zenith delays, and
- the capability of the implemented harmonic functions of 12 and 24 hours periods for recovering the total vertical loading displacement.

Tab. 2: EUREF sites included in the simulations arranged according to their M_2 amplitudes

M_2 Amplitude	Sites
> = 3 cm	ACOR, BRST, CASC
> = 2 cm	MAS1, REYK, SFER
> = 1 cm	HOFN, KELY, TRO1, VILL
< 1 cm	CAGL, HERS, LAMP, MATE, METS, NOTO, NYA1, ONSA, STAV, THU1, WTZR

4. Results

It should be recalled that the simulated observations include the site displacements due to ocean loading. Thus, modeling the displacements in the network adjustment properly should yield results exactly matching the a priori coordinates applied to the simulation. The same holds for troposphere parameters solved for in the adjustment: they should be zero because no tropospheric biases were generated in the data simulation. It can be stated that this indeed applied to all 25 sessions. The deviation of any parameter estimate from its true value did never exceed the margins defined by the applied noise. Therefore, only the differences between solutions with and without modeling ocean tide loading are presented in the sequel. As these adjustments are otherwise identical, the appearing discrepancies can be completely assigned to the mismodeling of the loading effect.

Figure 4 compares the height estimates of these two adjustments for each of the 25 sessions by displaying the r.m.s. differences over all 21 stations and the largest difference. Possible small datum differences were removed by similarity transformation. As can be seen, the r.m.s. agreement is never worse than 2 mm but the height estimates of highly affected sites may become wrong by up to 6 mm.

In the case of data gaps the height errors may increase tremendously when neglecting the loading displacements because then the integrated effect of all diurnal and semi-diurnal tidal waves will not anymore be close to zero. Table 3 shows the height errors due to observation gaps supposed to be present at BRST and MAS1 for one of the sessions with large vertical displacements at the Atlantic coast. The example shows also that in the case of differencing software the neighbouring stations will be equally affected.

As data outages like this should only rarely occur in permanent networks, the impact on EUREF itself might be negligible but densification networks based on session lengths much less than 24 hours will be affected significantly.

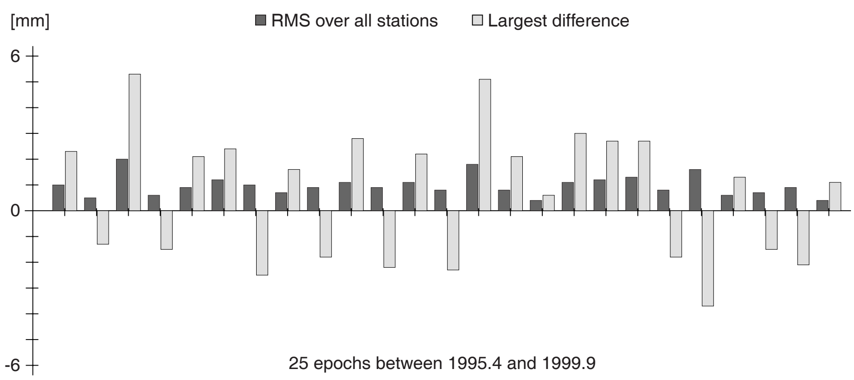

Fig. 4: Differences between height estimates from daily network adjustments with and without modeling ocean tide loading.

Tab. 3: Impact of data gaps [hours UT] at stations BRST and MAS1 on height estimates: differences [mm] to adjustments without gaps.

Data Gap	ACOR	BRST	CASC	KELY	MAS1	NYA1	SFER	TRO1	VILL
0 - 8	3.6	4.9	3.1	-0.4	2.1	-0.4	2.5	-0.3	2.7
0 - 8, 16 - 24	-7.9	9.4	-10.4	0.8	-21.1	0.8	-11.7	0.5	-10.8
0 - 15	8.4	-3.3	8.5	-0.5	17.6	-0.7	8.1	-0.5	7.6
0 - 18	26.7	22.7	25.0	-0.1	28.4	-0.2	23.7	-0.1	23.8
15 - 24	-2.2	4.2	-3.6	0.7	-8.3	0.7	-3.7	0.6	-3.3
16 - 24	-4.0	1.6	-5.6	0.9	-10.6	0.8	-5.7	0.7	-5.1

As regards any possible impact of neglecting the loading displacements on the kinematic of the EUREF network a number of baselines were analyzed.

Figure 5 shows as an example the time series of ellipsoidal height differences on the baseline BRST-MAS1. The height difference resulting from the positions applied in the data simulation has been subtracted, thus the displayed values reflect the mismodeling of the ocean tide loading. Fitting a straight line through these 25 epochs distributed over a period of 4.5 years would indicate a slope of 0.2 mm/year. All the other analyzed baselines showed effects less than that.

Finally, the impact of not modeling the ocean tide loading on estimates of tropospheric zenith delays and the capability of recovering the loading effect by harmonic functions in the adjustment are studied. The figures 6 and 7 display for stations BRST on day 270, 1995 and ACOR on day 231, 1997

- the vertical loading displacements applied to the simulated observations,
- the tropospheric zenith delays resulting from adjustments without recovering the loading effect, and
- the harmonic functions of 12 and 24 hours periods recovering the total vertical loading effect in the adjustments.

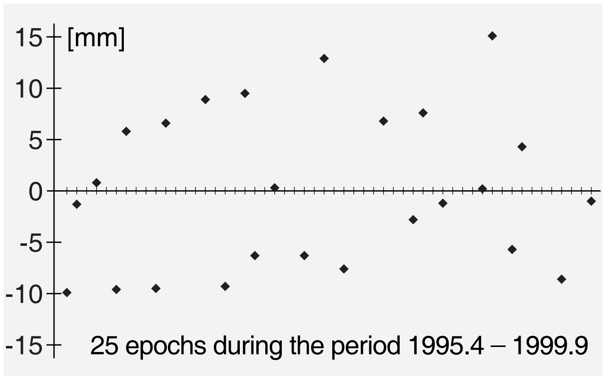

Fig. 5: Time series of the ellipsoidal height difference on baseline BRST-MAS1: errors due to not modeling ocean tide loading in the adjustment.

Figures 6 and 7 clearly demonstrate that the total accumulated vertical rite displacement from several tidal waves can be approximated rather well by simple harmonic functions. In addition, it appears, that tropospheric zenith delay estimates absorb only a very minor part of unmodeled vertical displacements caused by ocean tide loading.

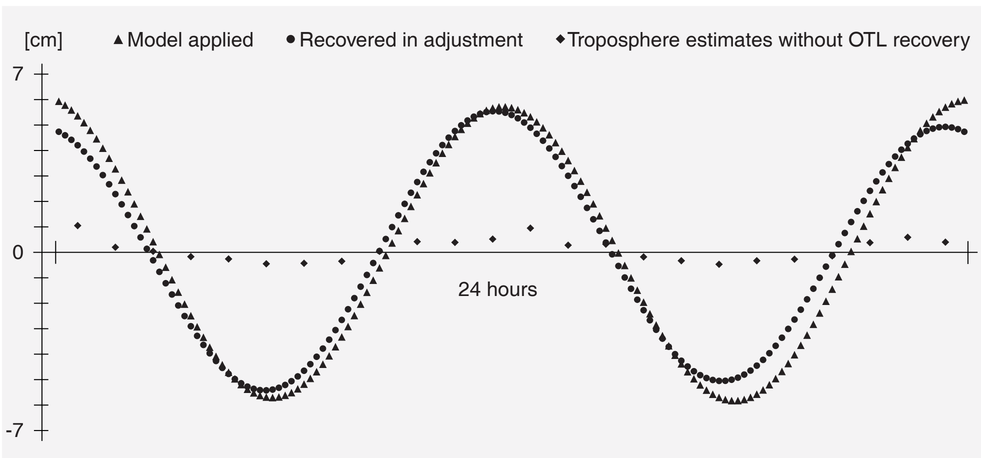

Fig. 6 Applied vertical ocean tide loading displacement at BRST on day 270, 1995 and recovery by harmonic functions

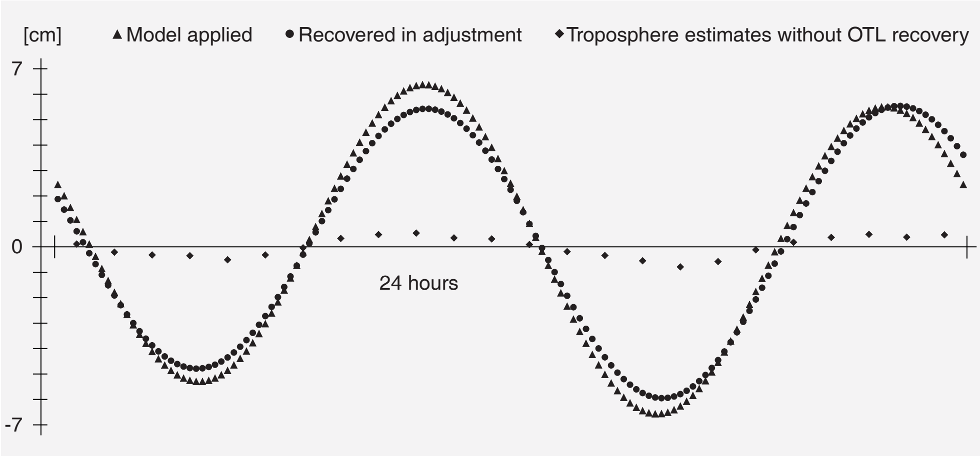

Fig. 7 Applied vertical ocean tide loading displacement at ACOR on day 231, 1997 and recovery by harmonic functions.

5. Conclusions

As the EUREF permanent network has been processed with the Bernese software without modeling the site displacements due to ocean tide loading at least up to the end of 1999, this simulation study aimed at identifying any resulting effects on the estimated heights and height velocities. The results of this analysis can be summarized as follows:

- On the average, the r.m.s. differences of the height estimates from daily network adjustments with and without modeling the loading displacements do not exceed 2 mm, but the largest discrepancies amount to 6 mm even in the case of 24 hours observations.
- Data gaps at coastal sites exposed to large vertical displacement variations may cause height errors in epoch adjustments of a few cm; in the case of differencing software also the adjacent stations will be affected.
- Although EUREF itself may not be affected significantly as long as data outages occur only rarely, densification networks based on observing sessions much shorter than 24 hours may be affected considerably because of the discrepancy between included EUREF fiducial data and reference coordinates.
- Fortunately, as long as the time series of EUREF position estimates is mainly based on 24 hours observations, in particular at the coastal sites exposed to high loading displacements, the effect on the kinematic of the network seems not to exceed 0.2 mm/year because the periods of the main tidal harmonics are approximately diurnal or semidiurnal.
- The tropospheric zenith delay estimates absorb about 1/10 of the unmodeled periodic vertical loading effect, and this should be considered when interpreting the estimated troposphere parameters.
- This study also demonstrates that the coefficients of a harmonic function can easily be implemented as a new parameter type in the adjustment program allowing to recover the periodic site displacements in the absence of a loading model.

Acknowledgement

Besides the models already available, Dr. Hans-Georg Scherneck, Onsala Space Observatory (Sweden), kindly provided the ocean tide loading displacement models for some of the sites included in this analysis.

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