PRECISE ORBIT DETERMINATION OF LOW EARTH SATELLITES AT AIUB USING GPS AND SLR DATA

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ABSTRACT

An ever increasing number of low Earth orbiting (LEO) satellites is, or will be, equipped with retro-reflectors for Satellite Laser Ranging (SLR) and on-board receivers to collect observations from Global Navigation Satellite Systems (GNSS) such as the Global Positioning System (GPS) and the Russian GLONASS and the European Galileo systems in the future. At the Astronomical Institute of the University of Bern (AIUB) LEO precise orbit determination (POD) using either GPS or SLR data is performed for a wide range of applications for satellites at different altitudes. For this purpose the classical numerical integration techniques, as also used for dynamic orbit determination of satellites at high altitudes, are extended by pseudo-stochastic orbit modeling techniques to efficiently cope with potential force model deficiencies for satellites at low altitudes. Accuracies of better than 2 cm may be achieved by pseudo-stochastic orbit modeling for satellites at very low altitudes such as for the GPS-based POD of the Gravity field and steady-state Ocean Circulation Explorer (GOCE).

Key words: Low Earth orbiting (LEO) satellites; Precise orbit determination (POD); Pseudo-stochastic orbit modeling; GPS; SLR.

1. INTRODUCTION

The Astronomical Institute of the University of Bern (AIUB) has a well-documented record concerning the scientific analysis of Global Navigation Satellite System (GNSS) data with the Bernese GNSS Software [8]. The Center for Orbit Determination in Europe (CODE) [10], a global analysis center of the International GNSS Service (IGS) [11], generates the full IGS product line such as GNSS orbits and high-rate satellite clock corrections, which are used as input for spaceborne applications relying on GNSS data. Spaceborne measurements of the Global Positioning System (GPS) are used at AIUB to determine precise kinematic and reduced-dynamic orbits for a variety of low Earth orbiting (LEO) satellites. For this purpose the classical dynamic orbit determination techniques are extended by so-called pseudo-stochastic orbit modeling, which is extensively used for satellites at very low orbital altitudes to efficiently cope with potential force model deficiencies. The procedures described in this article are applied to different LEO satellites and are operationally used by AIUB to derive the precise science orbits (PSO) for the GOCE mission in the frame of the GOCE High-level Processing Facility (HPF) [18].

The Bernese GNSS Software has recently also been extended from a pure GNSS processing software to a package offering full capabilities for processing Satellite Laser Ranging (SLR) data to spherical satellites [28]. Identical orbit modeling techniques as used for GPS-based LEO precise orbit determination (POD) are applied when processing SLR data to solve for orbital parameters together with non-orbit parameters of interest, e.g., SLR station coordinates, Earth rotation parameters, SLR range biases, and geopotential coefficients.

2. ORBIT DETERMINATION

The equation of motion of an Earth orbiting satellite including all perturbations reads in the inertial frame as

$$\ddot{\boldsymbol{r}} = -GM\frac{\boldsymbol{r}}{r^3} + \boldsymbol{f}_1(t, \boldsymbol{r}, \dot{\boldsymbol{r}}, q_1, ..., q_d, s_1, ..., s_s) \doteq \boldsymbol{f} \ , \tag{1}$$

where GM denotes the gravity parameter of the Earth, $\boldsymbol{r}$ and $\dot{\boldsymbol{r}}$ represent the satellite position and velocity, and $\boldsymbol{f}_1$ denotes the perturbing acceleration. The initial conditions $\boldsymbol{r}(t_0) = \boldsymbol{r}(a, e, i, \Omega, \omega, T_0; t_0)$ and $\dot{\boldsymbol{r}}(t_0) = \dot{\boldsymbol{r}}(a, e, i, \Omega, \omega, T_0; t_0)$ at epoch t_0 are defined by six Keplerian osculating elements, e.g., $a, e, i, \Omega, \omega, T_0$. The parameters $q_1, ..., q_d$ in Eq. (1) denote additional dynamical orbit parameters considered as unknowns, e.g., spherical harmonic (SH) coefficients of the Earth's gravity field. The parameters $s_1, ..., s_s$ denote additional empirical parameters, e.g., once-per-revolution periodic accelerations or pseudo-stochastic parameters (discussed in Sect. 2.2).

Based on a numerically integrated a priori orbit $\boldsymbol{r}_0(t)$ solving Eq. (1), dynamic orbit determination may be formulated as an orbit improvement process. The actual orbit $\boldsymbol{r}(t)$ is expressed as a truncated Taylor series with re-

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spect to n unknown orbit parameters p_i about the a priori orbit, which is represented by the parameter values p_{i0}:

$$\boldsymbol{r}(t) = \boldsymbol{r}_0(t) + \sum_{i=1}^{n} \frac{\partial \boldsymbol{r}_0}{\partial p_i}(t) \cdot (p_i - p_{0,i}) \, . \tag{2}$$

Provided that the partial derivatives of the a priori orbit with respect to the unknown parameters are known, corrections to the a priori orbit parameters p_{i0} may be computed in a standard least-squares adjustment of the used tracking data together with corrections to measurement-specific parameters, e.g., ambiguity parameters for GPS carrier phase data or range biases for SLR data, and other non-orbit parameters of interest. The improved orbit may eventually be obtained by either using Eq. (2) or by propagating the improved state vector by numerical integration and by taking into account the improved dynamical and empirical orbit parameters.

2.1. Variational equations

The initial value problem associated with the partial derivative $\boldsymbol{z}_{p_i} \doteq \partial \boldsymbol{r}_0 / \partial p_i$ of the a priori orbit $\boldsymbol{r}_0(t)$ with respect to the orbit parameter p_i is referred as the system of variational equations [1] and is obtained by taking the partial derivative of Eq. (1). The variational equations for parameter p_i read as

$$\ddot{\boldsymbol{z}}_{p_i} = \boldsymbol{A}_0 \cdot \boldsymbol{z}_{p_i} + \boldsymbol{A}_1 \cdot \dot{\boldsymbol{z}}_{p_i} + \frac{\partial \boldsymbol{f}_1}{\partial p_i} \, , \tag{3}$$

where the 3×3 matrices $\boldsymbol{A}_0$ and $\boldsymbol{A}_1$ are defined by

$$A_{0[i;k]} \doteq \frac{\partial f_i}{\partial r_{0,k}} \qquad \text{and} \qquad A_{1[i;k]} \doteq \frac{\partial f_i}{\partial \dot{r}_{0,k}} \, , \tag{4}$$

where f_i denotes the i-th component of the total acceleration $\boldsymbol{f}$ in Eq. (1). For $p_i \in \{a, e, i, \Omega, \omega, T_0\}$ Eq. (3) is a linear, homogeneous, second-order differential equation system with initial values $\boldsymbol{z}_{p_i}(t_0) \neq \boldsymbol{0}$ and $\dot{\boldsymbol{z}}_{p_i}(t_0) \neq \boldsymbol{0}$, which may be solved by numerical integration techniques. For $p_i \in \{q_1, ..., q_d, s_1, ..., s_s\}$ Eq. (3) is inhomogeneous with zero initial values. As the homogeneous part of Eq. (3) is the same as for the parameters p_i defining the initial values, the inhomogeneous system may be solved by the method of variation of constants, which reduces the problem from numerical integration to numerical quadrature [1].

2.2. Pseudo-stochastic orbit modeling

Purely dynamic LEO POD is a challenge for satellites at low orbital altitudes due to unavoidable deficiencies in the non-gravitational force models such as atmospheric drag models [30]. If dense tracking data are available, however, use may be made of their geometric strength by adopting reduced-dynamic orbit determination techniques [31]. At AIUB, so-called pseudo-stochastic parameters, e.g., realized as instantaneous velocity changes, piecewise constant accelerations, or piecewise linear accelerations with a user-specified spacing in the radial, along-track, and cross-track direction, are added to the deterministic equation of motion (1). They may be efficiently set up, because the solution of Eq. (3) may be obtained as a linear combination of a few independent variational equations only. The number of independent variational equations (six, nine, or twelve) depends on the particular parametrization of the pseudo-stochastic parameters (pulses, piecewise constant accelerations, or piecewise linear accelerations) [13]. This is of importance because even thousands of pseudo-stochastic parameters may still be set up efficiently. Efficient methods are also available to solve the underlying system of normal equations [2].

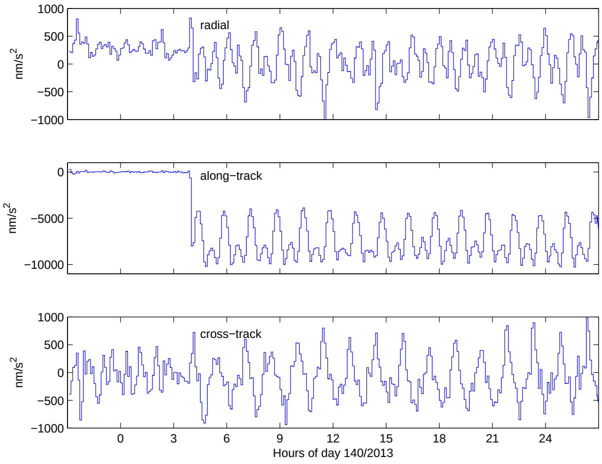

Figure 1. Piecewise constant accelerations estimated for GOCE on 20 May, 2013. Note the transition into non-drag-free flight and the different scale for the along-track component.

Since pseudo-stochastic parameters are primarily intended to compensate for force model deficiencies, they are characterized by a priori variances which constrain them to zero. If dense tracking data are available, pseudo-stochastic parameters may be set up frequently and may even replace deterministic force models to a certain extent by relaxing the a priori variances accordingly.

3. GOCE POD

AIUB is responsible for the generation of the PSO product of the GOCE mission, which consists of a kinematic and a reduced-dynamic solution [12, 6]. The 5 s GPS clock corrections [5] and the GPS final orbits from CODE [9] are used to process the full amount of 1 s GPS data for kinematic POD and 10 s GPS data for reduced-dynamic POD over an arclength of 30 hours. The parameters of the reduced-dynamic orbit of the PSO product are the six initial osculating elements, three constant empirical accelerations acting over the entire arc in the radial, along-track, and cross-track directions, and piecewise-constant

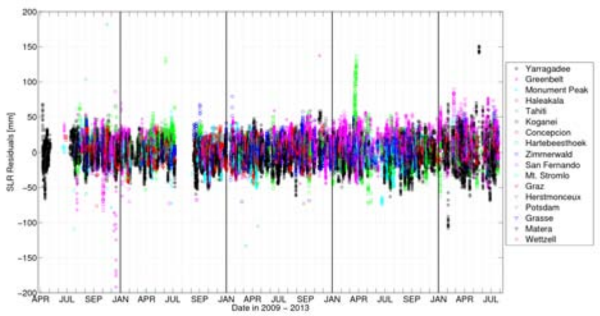

Figure 2. SLR residuals from 10 April 2009 until 31 July 2013 for the reduced-dynamic GOCE PSO solution.

accelerations over 6 min acting in the same directions. No use is made of the GOCE common-mode accelerometer data or non-gravitational force models for the official solution, which implies that the piecewise constant accelerations mainly compensate the not explicitly modeled non-gravitational accelerations. Due to the neglected accelerometer data and due to the low orbital altitude, only weak constraints are imposed on the piecewise constant accelerations.

Figure 1 shows the estimated piecewise constant accelerations on 20 May, 2013. On that day the drag-free mode was again interrupted by switching off the ion propulsion system at the altitude of 234 km to initiate the decay to the target altitude of 224 km of the extended mission phase. Figure 1 illustrates that the along-track drag is compensated to a large extent during drag-free flight and that large variations are observed again during the decay phase due to the very low orbital height and due to significant solar activity. It is worth mentioning that no adaption of the POD settings had to be made for processing the GPS data of that day.

Independent SLR measurements may be used to compare the computed ranges between the GPS-based GOCE orbit trajectories and the SLR ground stations with the directly observed ranges. Figure 2 shows the SLR validation for the reduced-dynamic PSO solutions since 10 April 2009 for the entire nominal mission period. The RMS of the SLR residuals is at a level of about 1.7 cm with negligible biases. It is important to emphasize that such an excellent agreement is not only achieved by properly modeling the phase center variations (PCVs) of the GOCE GPS helix antenna [15, 7], but also the phase center variations of the laser retro-reflector array [21]. The latter information explained small remaining biases between the two space-geodetic techniques.

4. GRACE POD

Undifferenced or doubly differenced GRACE GPS data have been extensively used at AIUB for various studies on reduced-dynamic and kinematic LEO POD, e.g., [14, 15], and on gravity field recovery, e.g., [4, 16]. Gravity field determination based on kinematic positions of both GRACE satellites and ultra-precise inter-satellite K-Band data may be treated in essence as a generalized orbit determination problem. Apart from the SH coefficients of monthly or multi-annual static Earth's gravity field models, arc-specific orbit parameters over 24 hours are simultaneously solved for by applying pre-elimination and back-substitution techniques [3]. The orbit parameters set up are the same as applied in Sect. 3 for GOCE POD, but more tight constraints are imposed on the piecewise constant accelerations due to the higher orbital altitude of the GRACE satellites and due to the use of accelerometer measurements for explicitly modeling the non-gravitational accelerations for orbit and gravity field determination. For a further stabilization of the gravity field recovery, the piecewise constant accelerations of GRACE-A and GRACE-B are tightly constrained relative to each other because the satellites are following each other with a separation of only 30 s on the same orbital trajectory.

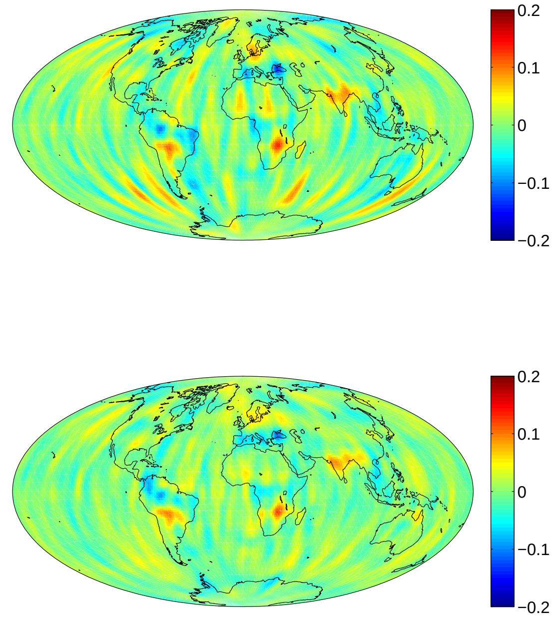

Figure 4. Difference of the monthly gravity field of March 2008 up to degree 60 with respect to the time variable signal of AIUB-GRACE03S (modeled by annual, semi-annual, and trend signals) when simultaneously (top) or separately (bottom) solving for orbit and gravity field parameters. The scale corresponds to ± 20 cm water height.

The SH coefficients and the arc-specific orbit parameters are simultaneously estimated for the nominal determination of monthly GRACE gravity field solutions at AIUB by pre-eliminating the arc-specific parameters before accumulating arc-wise normal equations to a monthly solution [20]. However, separating the estimation of arc-specific orbit parameters and global SH coefficients by fixing orbit parameters to estimates obtained before-hand in a separate orbit determination step by adopting a good a priori gravity field model including annual, semi-annual, and trend signals, considerably reduces the noise

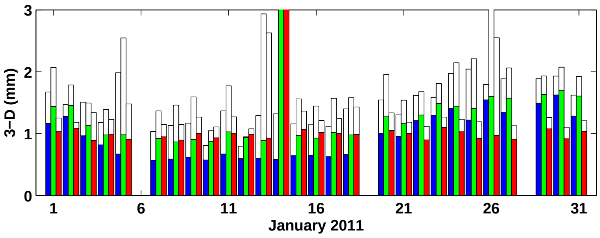

Figure 5. Daily standard deviations of inter-agency single-frequency 3-D baseline comparisons. Empty bars indicate the statistics for entire 24 h arcs, colored bars exclude maneuver periods (in blue: GFZ-DLR, in green: GFZ-AIUB, in red: AIUB-DLR).

(striping) of the monthly gravity field solutions as illustrated by Fig. 4. The consequences for the signal content are currently under investigation.

5. TERRASAR-X / TANDEM-X POD

Baseline vectors between the TerraSAR-X and the TanDEM-X satellites of the TanDEM-X interferometry mission have to be determined with an accuracy of 1 mm [27]. Doubly differenced GPS data from both spaceborne receivers have been used at AIUB to generate baseline solutions on a best effort basis and to compare them with solutions routinely generated by the German Research Centre for Geosciences (GFZ) and the German Space Operations Center (DLR/GSOC) [17]. Reduced-dynamic baseline solutions may be either based on dual- or single-frequency GPS data with carrier phase ambiguities fixed to their integer values. Single-frequency solutions benefit from a more robust ambiguity fixing, but are potentially affected by errors caused by an incomplete compensation of differential ionospheric path delays. The orbit parameters for both satellites are the same as applied in Sect. 4 for GRACE with the entire sets of empirical accelerations of TerraSAR-X and TanDEM-X tightly constrained with respect to each other. Since the TanDEM-X satellite performs daily pairs of thrusts, a series of instantaneous velocity changes at specified epochs need to be set up as additional parameters in the least-squares adjustment. Fig. 5 shows that the agreement of all solutions is very good outside maneuver periods, e.g., about 0.9 mm between AIUB and DLR, but a slight degradation is observed when including maneuver time periods in the solution comparison.

6. JASON-2 / METOP-A POD

Until recently the absolute phase center model for GNSS transmitter antennas was solely based on terrestrial GNSS data, which limited the estimation of GPS and GLONASS satellite antenna PCVs to a maximum nadir angle of 14°. This is not sufficient for the analysis of

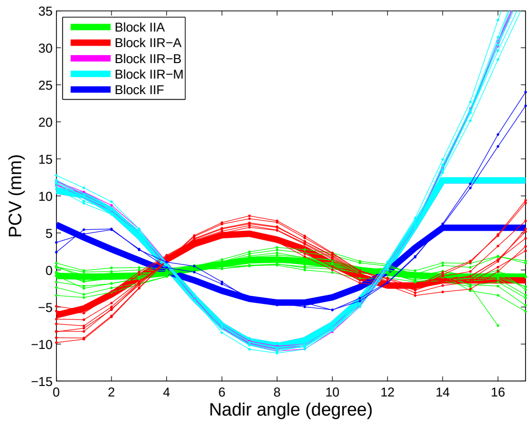

Figure 6. Estimated satellite-specific PCVs using LEO data (thin lines) and igs08.atx block-specific values used before the PCV extension beyond nadir angles of 14° (bold lines).

spaceborne GNSS data collected by LEO satellites that record, depending on the missions orbital altitude, observations at nadir angles of up to 17°. GPS tracking data from several LEO missions, e.g., Jason-2 and MetOp-A, were used to extend the GPS satellite antenna PCVs to nadir angles beyond 14° based on fixed reduced-dynamic orbits. Due to the higher orbital altitudes of the satellites, at which the dominating non-gravitational perturbation is no longer air-drag but solar radiation pressure, and due to a worse GPS tracking performance compared to GOCE and GRACE, a more dynamic orbit representation is needed. Apart from the six initial osculating elements, constant and once-per-revolution periodic accelerations acting over the entire arc are set up in the direction sun-satellite, in the perpendicular direction pointing along the solar panel axis, and in the direction complementing the right-handed orthogonal orbital frame. In order to cope with remaining model deficiencies (no a priori radiation pressure model is taken into account due to the complicated shape of the satellite), pulses are set up every 15 min in the radial, along-track, and cross-track direction. Based on these reduced-dynamic orbits which are kept fixed, satellite-specific GPS and LEO antenna PCVs (see Fig. 6) were simultaneously estimated to derive the recently published block-specific extension of the igs08.atx model beyond nadir angles of 14° [24, 25].

7. LAGEOS POD

The Bernese GNSS Software has been extended to become a full SLR analysis software for processing SLR data to spherical satellites, e.g., to the LAGEOS and Etalon satellites [28].

As opposed to the LEO satellites mentioned in the previous sections, the LAGEOS satellites are orbiting the Earth at a considerably higher orbital altitude. Therefore,

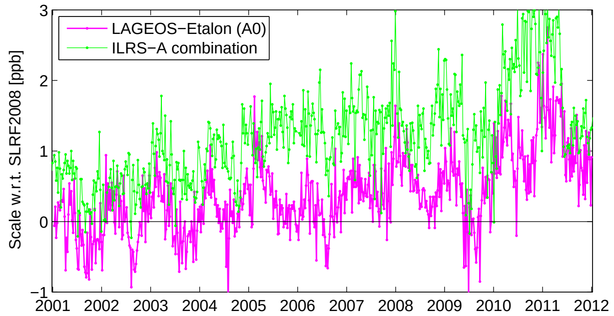

Figure 7. Scale differences with respect to SLRF2008 for the AIUB LAGEOS-Etalon solution and the official ILRS combined solution.

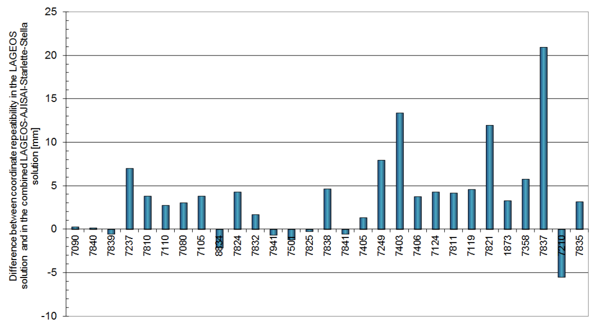

Figure 8. Difference of the repeatability of SLR station coordinates in the combined solution and in the LAGEOS-1/2 solution. Positive values denote a better repeatability in the combined solution.

and due to the sparse SLR tracking coverage, a purely dynamic orbit representation is needed. The strongest non-gravitational perturbations are caused by solar radiation pressure, but may be well described for spherical satellites and are thus taken into account by a priori models. As a consequence of the simple modeling, 7-day arcs are generated with only a few additional parameters estimated during orbit determination. Apart from the six initial osculating elements, only one constant acceleration in the along-track direction and once-per-revolution accelerations in the along-track and cross-track directions acting over the entire 7-day arc are set up. They are primarily intended to absorb unmodeled thermal forces [19].

Weekly solutions for the LAGEOS satellite orbits are estimated at AIUB together with Earth rotation parameters and station coordinates following the standards of the analysis centers of the International Laser Ranging Service (ILRS) [22]. Figure 7 shows the scale differences with respect to SLRF2008[1] for each weekly solution. The agreement is generally within 1 ppb, which is even better than for the routinely generated official ILRS-A combined solution. The different behavior is explained by checking for each weekly AIUB solution the set of stations used for the datum definition, whereas a fixed list of core sites is used for the ILRS-A solution [29].

8. STELLA / STARLETTE / AJISAI POD

Starlette, Stella, and AJISAI 7-day solutions are computed in close analogy to LAGEOS 7-day solutions, but with range biases estimated for all SLR stations because of a lack of precise Center-of-Mass corrections for these spherical satellites. Due to the much lower orbital altitudes the orbit parametrization has to account for airdrag as a relevant non-gravitational perturbation, which is modeled according to the NRLMSISE-00 model [23]. Scaling factors and once-per-rev accelerations are estimated in the along-track and cross-track directions on a daily basis. Pseudo-stochastic pulses are estimated every revolution period in the along-track direction only. The combination with weekly LAGEOS solutions is beneficial for estimating satellite orbits together with Earth rotation parameters, station coordinates, and SH geopotential coefficients due to a further decorrelation of the parameters thanks to the different orbital characteristics. The a priori sigmas of the individual normal equations are set to 25, 20, 20 and 10mm for AJISAI, Starlette, Stella, and LAGEOS, respectively, which reflect the residual levels of the individual solutions [26]. Figure 8 shows that station coordinates, e.g., generally show an improved repeatability when combining the LAGEOS solutions with the solutions for Starlette, Stella, and AJISAI.

9. CONCLUSIONS

LEO POD using either GPS or SLR data is performed at AIUB for satellites at very different altitudes and for a wide range of applications. Accuracies of better than 2 cm may be achieved by pseudo-stochastic orbit modeling for LEO satellites at low orbital altitudes such as GOCE. Provided that dense GPS tracking data are available, pseudo-stochastic parameters may be set up frequently and may even be used to replace deterministic force models to a certain extent. In the case of less favorable tracking conditions, more dynamic orbit determination strategies are preferable, but pseudo-stochastic modeling is still a valuable tool to compensate for unavoidable deficiencies in the available force models. Further extensions of the Bernese GNSS Software will also include combined LEO orbit determination from GPS and SLR data.

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