EPN2020-RI

EUROPLANET2020 Research Infrastructure

H2020-INFRAIA-2014-2015

Grant agreement no: 654208

Deliverable D5.13
LMSU contribution to PSWS Validation Report

Due date of deliverable: 31/08/2019
Actual submission date: 27/08/2019

Start date of project: 01 September 2015 Duration: 48 months

Responsible WP Leader: IRAP Toulouse, Nicolas André.

Project funded by the European Union's Horizon 2020 research and innovation programme		
Dissemination level		
PU	Public	x
PP	Restricted to other programme participants (including the Commission Service)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (excluding the Commission Services)	

Project Number	654208
Project Title	EPN2020 - RI
Project Duration	48 months: 01 September 2015 – 31 August 2019

Deliverable Number	D5.13
Contractual Delivery date	31.08.2019
Actual delivery date	27.08.2019
Title of Deliverable	LMSU contribution to PSWS Validation Report
Contributing Work package (s)	WP5
Dissemination level	Public
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Abstract: Planetary Magnetospheres Space Weather Service at SINP MSU http://www.magnetosphere.ru is intended to describe the magnetic field structure and dynamics in the magnetospheres of magnetized planets (Mercury, Earth, Jupiter and Saturn). The magnetic field in the Earth's magnetosphere can be obtained in the real-time mode using concurrent measurements of the solar wind monitoring satellites. Solar wind measurements in the L1 Lagrange point give possibility to predict Earth's magnetosphere's state approximately in 1 hour. Continuous monitoring of solar wind by near-Earth's spacecraft gives possibility to extend information on the solar wind parameters to the orbits of Mercury, Jupiter and Saturn using Europlanet's Propagation Tool. The main aim of future work is to create the algorithm that allows to predict the magnetic field inside the magnetospheres of Mercury, Earth, Jupiter, and Saturn.

1. Introduction and goals

The magnetic field in the terrestrial magnetosphere results from currents flowing in the Earth's core (the internal current system) and joint action of large-scale magnetospheric current systems (the external current systems). The latter are under continuous external driving and are responsible for magnetospheric dynamics during quiet and disturbed conditions. Solar activity is the main source of changes in the solar wind that impact the magnetosphere in several ways. Geomagnetic response is caused by the solar wind variations due to the high speed streams (HSSs) or coronal mass ejections (CMEs) propagation. Geoeffective (southward) interplanetary magnetic field (IMF) direction and solar wind pressure pulse can lead to the magnetic storm. The level of geomagnetic disturbances depends on the relationship between the solar wind parameters and IMF in the near-Earth vicinity. Continuous observations of solar FUV images allow the middle term forecasting of the solar wind velocity in the Earth's environment with prediction time about 3 days ahead. On the other hand, spacecraft measurements in the solar wind flow at L1 point give possibility of the short term (about 1 hour) forecasting of plasma/magnetic field parameters at the Earth's orbit, as well as of geomagnetic conditions in the Earth's magnetosphere. A real-time processing of observational data gives possibility to provide forecasting of solar wind parameters at the Earth's orbit.

The main goal of this study is to predict the Earth's magnetospheric state in approximately 1 hour based on the solar wind data from operational services of Space Monitoring Data Center (SMDC) of MSU (http://swx.sinp.msu.ru/index.php?lang=en).

2. Implementation

2.1 Earth's magnetosphere description by http://www.magnetosphere.ru/en/about

The paraboloid model of the Earth's magnetosphere A2000 (Alexeev et al. 2001; Alexeev et al. 2003) is implemented at SMDC to describe magnetic field structure and dynamics in the Earth's environment depending on the empirical data (solar wind parameters and geomagnetic indices, see (Alexeev et al. 2003)). The storm-time dynamics of the magnetosphere can be reproduced through the temporal variations of the solar wind and IMF upstream of the Earth's bow shock. The model of the Earth's magnetosphere represents magnetic field as a sum of internal planetary magnetic field, given by the IGRF2015 model, and the external one (B_m) represented by a superposition of the magnetic fields of the ring current, B_r, the tail current system including the currents across a tail and their closure currents on the magnetopause, B_t, the Region 1 field-aligned currents, B_{fac}, the magnetopause currents screening the dipole field, B_{sd}, and the magnetopause currents screening the ring current magnetic field, B_{sr} :

$$B_m = B_{sd}(\psi, R_1) + B_t(\psi, R_1, R_2, \Phi_\infty) + B_r(\psi, b_r) + B_{sr}(\psi, R_1, b_r) + B_{IMF}.$$

Here B_{IMF} is the partially penetrated into the magnetosphere interplanetary magnetic field. The model input values are the key parameters of the magnetospheric current systems, which represent their location and intensity:

- the geomagnetic dipole tilt angle ψ;
- the magnetopause stand-off distance R_1;
- the distance to the inner edge of the tail current sheet R_2;
- the magnetic flux through the tail lobes Φ_∞;
- the ring current magnetic field at the Earth's center b_r.

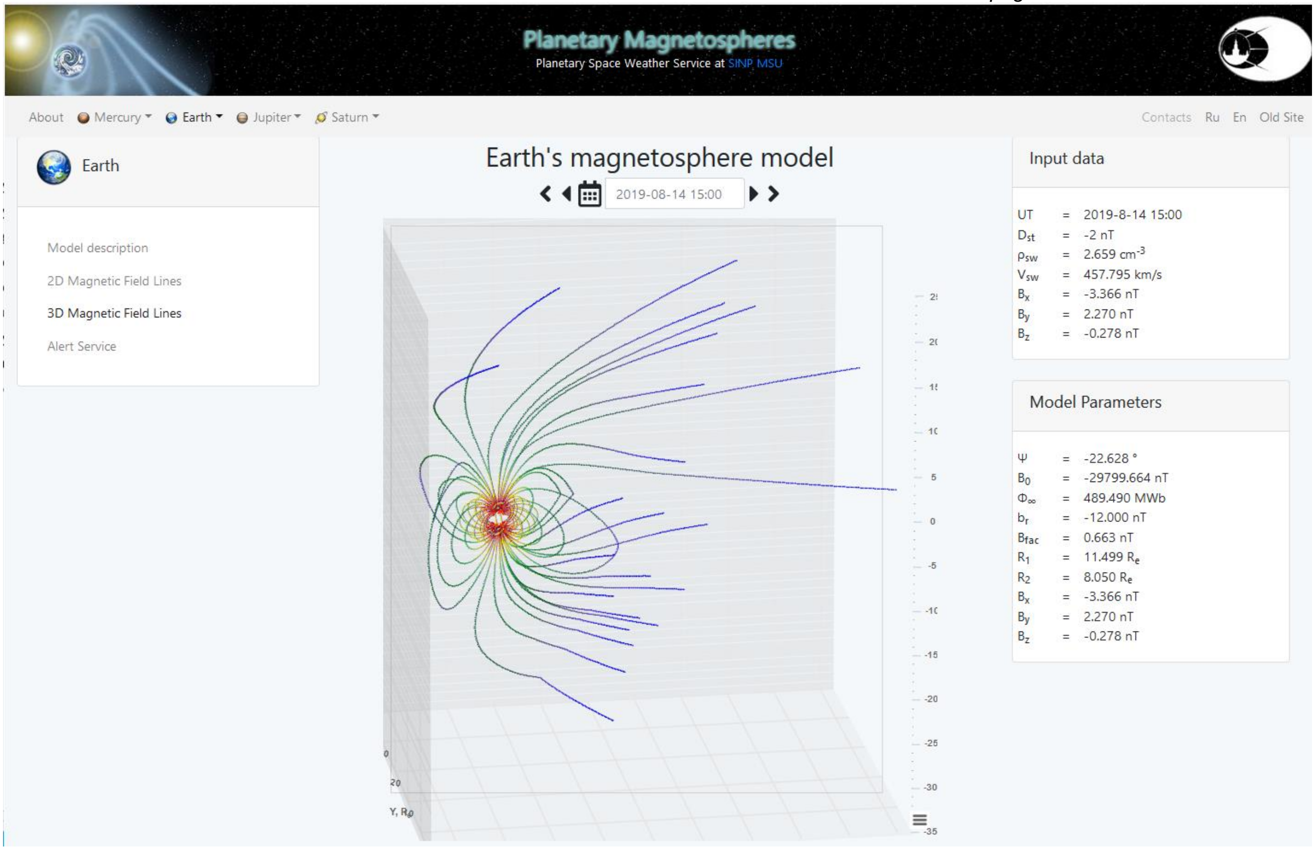
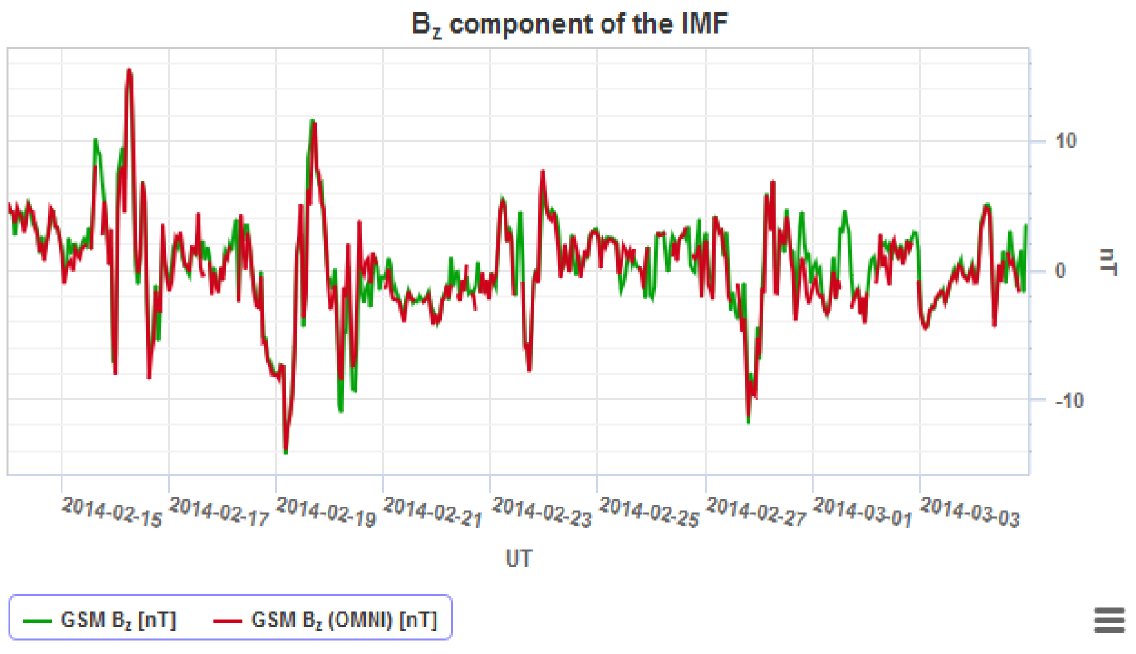


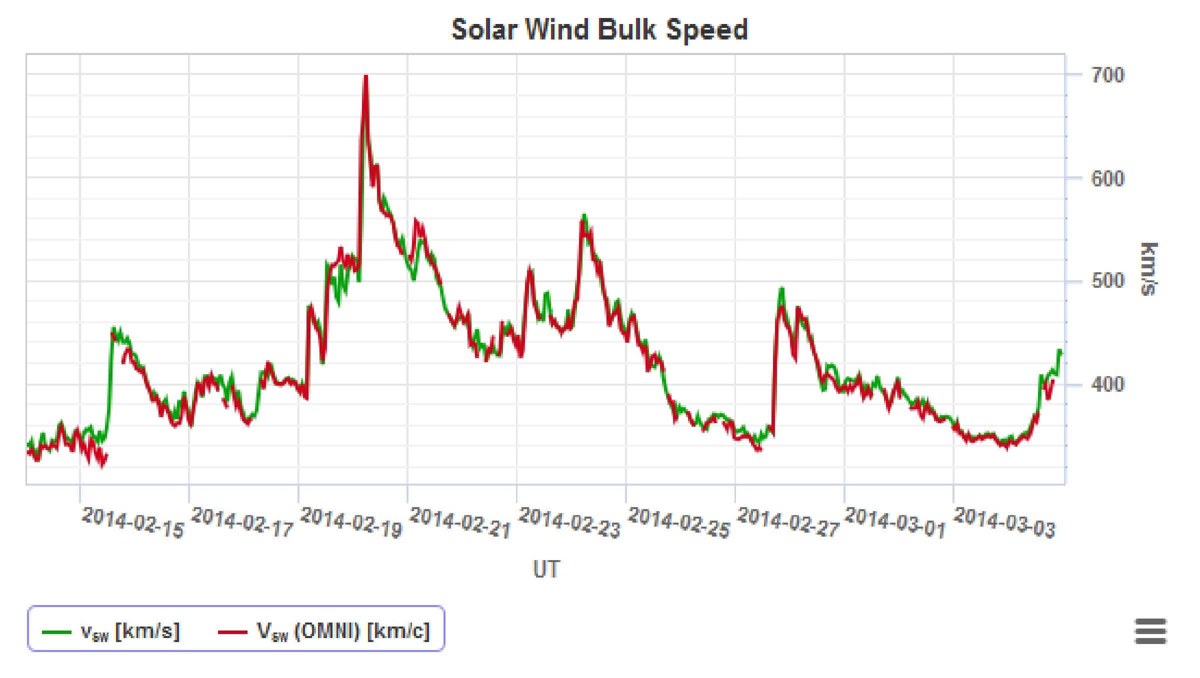
Figure 1 Magnetospheric magnetic field 3D structure calculated by PMM for soalr wind conditions on 14 August 2019 at 15:00 UT

The time dependent model parameters are calculated by the empirical data (solar wind density (*n*), velocity (*v*), Dst and AL indices, interplanetary magnetic field B-components (IMF_B)) and by the current date/time using special submodels (*Alexeev et al., 2003*) optimizing parameter dependences on the specific sets of empirical data. Input model parameters could be specified by user or can be taken fully or partially from database for a given time moment. Space Monitoring Data Center of MSU (http://swx.sinp.msu.ru/index.php?lang=en) provides empirical input parameters of the model (solar wind density (*n*), velocity (*v*), Dst and AL indices, interplanetary magnetic field B-components (IMF_B)) using the solar wind and geomagnetic indices data stored in database. Magnetospheric magnetic field is calculated "On The Fly" after entering the PMM page (http://www.magnetosphere.ru/en/earth3d/) or after specifying the date and time (see Fig.1).

2.2 Empirical input parameters calculations by SMDC space weather services

Physical conditions on the Earth's orbit can be obtained propagating solar wind parameters from L1 point (where they are measured by ACE or other monitoring satellite) to the Earth's location. A simple convection delay or "phase front" method described by (*Pulkkinen & Rastätter 2009*) was used at SMDC as an operational service to describe the solar wind and IMF propagation from ACE position to the Earth environment. Figures 2a, b and c compare solar wind parameters (IMF Bz, density and velocity), calculated by SMDC model and those from OMNI database ([http://swx.sinp.msu.ru/apps/solar_wind.php?gcm=1&lang=en)](http://swx.sinp.msu.ru/apps/solar_wind.php?gcm=1&lang=en). Correlations for results are 0.93 for density, 0.88 for Bz and 0.98 for velocity. Solar wind parameters at the Earth's orbit appear in the OMNI datadase after a half of year. Unlike OMNI database, SMDC gives possibility to get solar wind data near the Earth in real time (*Kalegaev et al., 2019*).

a	
b	



c

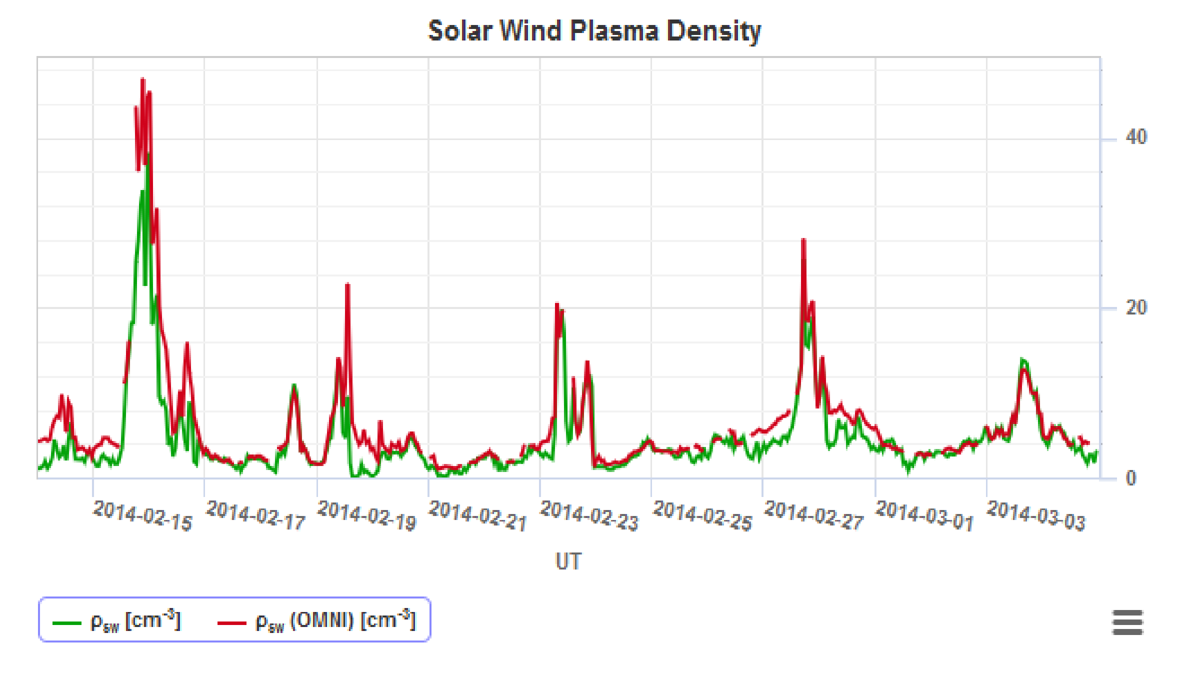


Fig. 2. Time profiles of the IMF Bz-component (a), solar wind density (b) and speed (c) calculated by SMDC model (green) and obtained from OMNI database (http://swx.sinp.msu.ru/apps/solar_wind.php?gcm=1&lang=en, red).

SMDC service (http://swx.sinp.msu.ru/apps/rss/index.php?gcm=1) makes it possible to calculate in real time the magnetopause stand-off distance on the base of some existing magnetopause model. Taking into account that solar wind has to spend about one hour (it depends on the solar wind speed value) to reach the Earth's magnetosphere from L1, the calculations by (*Shue et al. 1998*) model can provide a short-term forecast of the magnetopause stand-off distance. The time profile of the magnetopause stand-off distance calculated by (*Shue et al. 1998*) model during February 14 - March 5, 2014 is presented on Fig. 3.

Fig. 3. The time profile of the magnetopause stand-off distance (http://swx.sinp.msu.ru/tools/ida.php?gcm=1)

3. Upgrade the paraboloid magnetospheric models of the Solar system planets.

The LMSU team improved the paraboloid magnetospheric model and has continued working on a generalized magnetospheric model. This model can be calibrated to be used for analysis of the magnetosphere of any solar system planet possessing an intrinsic magnetic field. Consequently, we aim to develop a generalized approach for description of magnetospheric processes while using a paraboloid of revolution to define the magnetopause shape in all scenarios. Once successful, we can test the model using spacecraft data from European and US missions (MESSENGER, Cassini, Galileo, Juno); additionally, it may be used to investigate exoplanetary magnetospheres and to interpret the role of magnetic field in planetary atmosphere evolution and potential habitability. Continuous monitoring of solar wind by near-Earth's spacecraft gives possibility to extend information on the solar wind parameters to the orbits of Mercury, Jupiter and Saturn using Europlanet's Propagation Tool.

3.1 The combined model of Mercury's magnetosphere

The combined model (comprised of a numerical hybrid simulation and the empirical paraboloid model) of Mercury's magnetosphere has been constructed. It gives us the possibility to refine the global parameters of magnetosphere using MESSENGER's magnetometer data from each of over 4100 orbits of the spacecraft around Mercury (Parunakian et al., 2017).

We have performed calculation of the initial magnetospheric magnetic field of Mercury and the boundary conditions for subsequent hybrid modeling and defined the initial parameters of the global magnetospheric current systems in a way that allows us to minimize paraboloid magnetic field deviation along the trajectory of MESSENGER from the experimental data. We have modelled the magnetosheath magnetic field and calculated the portion of the interplanetary magnetic field penetrating the magnetosphere
(Alexeev et al., 2018).

3.2 The upper limit of the ring current strength in the Earth's magnetosphere.

Størmer's particles' trapping regions for a planet with an intrinsic dipolar magnetic field are considered, taking into account the ring current which arises due to the trapped particles' drift for the case of the Earth. The influence of the ring current on the particle trapping regions' topology is investigated. It is shown that a critical strength of the ring current exists under which further expansion of the trapping region is no longer possible. Before reaching this limit, the dipole field, although deformed, retains two separated Størmer regions. After transition of critical magnitude, the trapping region opens up, and charged particles, which form the ring current, get the opportunity to leave it, thus decreasing the ring current strength. Numerical calculations have been performed for protons with typical energies of the Earth's radiation belt and ring current. For the Earth's case, the Dst index for the critical ring current strength is calculated (Lavrukhin et al., 2019)..

3.3 Optimal parameters of the Jovian magnetodisc

In the magnetospheres of the giant planets the significant magnetic field source is a magnetodisc, which is located near the equatorial plane. For this reason investigation of the disc is very important. This task was done for Jupiter in the frame of the project. Several Juno orbits from the dawn sector were studied for determination of the disc parameters using paraboloid model of the Jupiter's magnetosphere. It is a significant step in optimization of paraboloid model (Pensionerov et al., 2019a),. .

During the work on the project a new empirical model of the Jovian magnetodisc was developed. As magnetodisc is the main magnetic field source in the Jupiter's magnetosphere, its corrected model plays significant role for optimization of calculations in the magnetosphere of this giant planet. In the suggested model of magnetodisc the radial dependence of the disc's current varies with the distance from the planet. The curvature of the disc dependent on the distance is also included (Pensionerov et al., 2019b),.

3.4 An open and a partially closed models of the Saturn's magnetosphere

For the Saturn's magnetosphere the question about reconnection of the magnetospheric and interplanetary magnetic fields was studied using paraboloid magnetospheric magnetic field model. Comparison of the model calculations of the open-closed magnetic field lines boundary at the ionospheric level with the poleward edge of the auroral oval shows that for the measured by Cassini solar wind magnetic field the better result gives the model which takes into account the reconnection process. UV auroral images were obtained by the Hubble Space Telescope. The investigation of this problem is significant for optimization of the paraboloid Kronian magnetospheric model (Belenkaya et al., 2017).

3.5 Dynamics of the magnetospheric magnetic field under strong magnetic storms

Comparative analysis of the ring current dynamics during the geomagnetic storms on March 17–18, 2015 and June 22–23, 2015 with maximal amplitude of *Dst*-variation (|*Dst*max| ~ 200 nT) was completed. Explanations of the features of development of two similar magnetic storms that occurred under substantially different conditions in the interplanetary environment are given based on the calculations of the magnetic field using the A2000 paraboloid model of the magnetosphere and proton flux measurements in the near-equatorial magnetospheric region by two *Van Allen Probes* (Nazarkov et al., 2018).

4. Conclusion

Planetary Magnetospheres Space Weather Service at SINP MSU http://www.magnetosphere.ru allows us to describe the magnetic field in the Earth's magnetosphere in the real-time mode using concurrent measurements of the solar wind monitoring satellites. LMSU team improved the paraboloid magnetospheric model and has continued working on a generalized magnetospheric model. This model can be calibrated to be used for analysis of the magnetosphere of any solar system planet possessing an intrinsic magnetic field. Consequently, we aim to develop a generalized approach for description of magnetospheric processes while using a paraboloid of revolution to define the magnetopause shape in all scenarios. Once successful, we can test the model using spacecraft data from European and US missions (MESSENGER, Cassini, Galileo, Juno); additionally, it may be used to investigate exoplanetary magnetospheres and to interpret the role of magnetic field in planetary atmosphere evolution and potential habitability. Solar wind measurements in the L1 Lagrange point gives a possibility to predict the Earth's magnetosphere's state approximately in 1 hour. Continuous monitoring of the solar wind by near-Earth's spacecraft gives a possibility to extend information on the solar wind parameters to the orbits of Mercury, Jupiter and Saturn using Europlanet's Propagation Tool. The main aim of future work is to create the algorithm that allows to predict the magnetic field inside the magnetospheres of Mercury, Earth, Jupiter, and Saturn.

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