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## RESEARCH ARTICLE

10.1002/2015SW001355

## One year in the Earth's magnetosphere: A global MHD simulation and spacecraft measurements

## Key Points:

- One full year Earth's magnetosphere is simulated using the GUMICS-4 global magnetohydrodynamic code
- The Cluster SC3 footprints determined from the simulations and the T96 model are in good agreement
- The footprints agree better in the Northern Hemisphere during quiet conditions

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**Abstract** The response of the Earth's magnetosphere to changing solar wind conditions is studied with a 3-D Magnetohydrodynamic (MHD) model. One full year (155 Cluster orbits) of the Earth's magnetosphere is simulated using Grand Unified Magnetosphere Ionosphere Coupling simulation (GUMICS-4) magnetohydrodynamic code. Real solar wind measurements are given to the code as input to create the longest lasting global magnetohydrodynamics simulation to date. The applicability of the results of the simulation depends critically on the input parameters used in the model. Therefore, the validity and the variance of the OMNIWeb data are first investigated thoroughly using Cluster measurement close to the bow shock. The OMNIWeb and the Cluster data were found to correlate very well before the bow shock. The solar wind magnetic field and plasma parameters are not changed significantly from the  $L_1$  Lagrange point to the foreshock; therefore, the OMNIWeb data are appropriate input to the GUMICS-4. The Cluster SC3 footprints are determined by magnetic field mapping from the simulation results and the Tsyganenko (T96) model in order to compare two methods. The determined footprints are in rather good agreement with the T96. However, it was found that the footprints agree better in the Northern Hemisphere than the Southern one during quiet conditions. If the  $B_y$  is not zero, the agreement of the GUMICS-4 and T96 footprint is worse in longitude in the Southern Hemisphere. Overall, the study implies that a 3-D MHD model can increase our insight of the response of the magnetosphere to solar wind conditions.

## 1. Introduction

Multispacecraft measurements provide very limited information about the near-space environment of the Earth. Satellites collect information along their orbit, in a very small region compared to the terrestrial magnetosphere with a characteristic size of several hundred thousand kilometers. Therefore, a model is necessary to understand physical processes occurring in the region that we cannot reach by observations. From a mathematical perspective, global simulations of the solar-terrestrial interactions are described by quite a complex system of partial differential equations. Different modeling approaches exist, one of them is the full fluid or magnetohydrodynamics (MHD) description of the magnetized fluids. Various global computer simulations have been developed which use a MHD description of plasma, for example, the Lyon-Fedder-Mobarry, LFM [Lyon *et al.*, 2004] code, the Open Geospace General Circulation Model, OpenGGCM [Raeder *et al.*, 2008], the Block-Adaptive-Tree-Solarwind-Roe-Upwind-Scheme, BATS-R-US [Powell *et al.*, 1999; Tóth *et al.*, 2012] and the Grand Unified Magnetosphere Ionosphere Coupling simulation, GUMICS [Janhunen *et al.*, 2012], and the only global Magnetosphere-Ionosphere MHD model in Europe. These four simulations are available at the Community Coordinated Modeling Center (CCMC; <http://ccmc.gsfc.nasa.gov/>) hosted by the NASA Goddard Space Flight Center (GSFC). These simulations have been developed by different teams, and all of them have their own strengths and weaknesses. However, every simulation faces the same challenge, namely, how realistic the results are. Therefore, all simulation modes have to be verified and validated by comparing the simulations to spacecraft and to ground-based measurements, as well as to results obtained from other simulations.

The Geospace Environment Modeling (GEM) "Metric and validation" Focus Group has been central in coordinating this activity, and it has suggested performing different simulation models on selected several hour long intervals for comparison with the ground-based and spacecraft measurements. The 2008–2009 GEM Metrics Challenge requested various simulation groups to submit results for four geomagnetic storm events and five different types of observations that can be modeled using the magnetosphere-ionosphere system. To compare each of the models with the observations, 1 h of averaged model data was used with the *Dst* index, and direct comparison 1 min model data with the 1 min *Dst* index was made. Generally speaking, the empirical models provided realistic results. It has been proposed by *Glocer et al.* [2013] that MHD models of the magnetosphere could produce more realistic results if the inner magnetosphere region contained a ring current model such as the Rice Convection Model (RCM) or the Comprehensive Ring Current Model (CRCM) as they exist in SWMF, LFM, and OpenGGCM. The capability of the models to reproduce observed ground magnetic field fluctuations and geomagnetically induced current (GIC) phenomenon is also an important question regarding the MHD models [*Pulkkinen et al.*, 2011, 2013], as is the validity of the models in the magnetosphere domain. The magnetic field near the geosynchronous orbit was also compared in various models. *Rastätter et al.* [2011] found that the empirical models perform well during weak storms, while the MHD models gave more realistic results during strong storms. If the inner magnetosphere module of the code coupled to the MHD code contained kinetic physics, the result was even closer to reality [*Rastätter et al.*, 2011].

Also, other results obtained from MHD models have been investigated. For example, *Tanskanen et al.* [2005] compared energy input and ionospheric energy dissipation from the GUMICS-4 simulation and data. About an order of magnitude difference was found in the energy dissipation. However, the time variation of the joule dissipation was similar in the data and in the simulation.

More recently, in *Honkonen et al.* [2013] the predictions of the BATS-R-US, the GUMICS, the LFM, and the OpenGGCM were compared with the measurements of the Cluster [*Escoubet et al.*, 2001], the WIND [*Acuña et al.*, 1995], and the GEOTAIL [*Nishida*, 1994] missions, as well as the Super Dual Auroral Radar Network (SuperDARN) [*Greenwald et al.*, 1995] cross polar cap potential (CPCP). The most realistic simulation result near the geosynchronous orbit was found on the dayside for all models outside the geosynchronous orbit. In the magnetotail, at  $-130R_E$ , simulations succeeded in reproducing well the  $B_z$  component but not the  $B_y$  component. The LFM magnetopause was found to be well in agreement with the empirical models. Furthermore, the BATS-R-US and the GUMICS produce a similar magnetopause, but their magnetopauses were shifted in respect to the empirical models. It was also found that the OpenGGCM magnetopause varied significantly and its deviation from the empirical model was the highest [*Honkonen et al.*, 2013]. Overall, the magnetopause determination in MHD models was found to be a challenging task [*Palmroth et al.*, 2003].

Moreover, also long-duration runs have been compared with observations. *Guild et al.* [2008] provided a two month long simulation to compare its average properties to 6 years of Geotail (<http://www.stp.isas.jaxa.jp/geotail/>) observations using the Lyon-Fedder-Mobarry global simulation model. The CPCP, the field-aligned current (FAC), downward Poynting flux, and the vorticity of ionospheric convection were compared with observed statistical averages. It was shown that the LFM model produces reasonably accurate average distributions of the currents. However, the CPCP was found to be greater than the observed results. The ionospheric convection pattern was instead realistic. Furthermore, the ionospheric field-aligned vorticity average was found to agree well with the measurements on the dayside. On the other hand, the LFM model simulation used unrealistically small ionospheric conductance on the nightside, and the nightside vorticity was higher than observed [*Zhang et al.*, 2011].

In this paper a global MHD simulation lasting approximately 1 year is performed using the GUMICS-4 code with about 1 year of OMNIWeb data from 29 January 2002 to 2 February 2003 given as input. The structure of this paper is as follows. Section 2 presents how the year-long simulation was launched. Section 3 gives comparisons between the simulations and observations. Results of the comparison are discussed in section 4. Finally, section 5 contains the conclusions.

## 2. Simulations

### 2.1. GUMICS-4 Model

The Grand Unified Magnetosphere Ionosphere Coupling simulation (GUMICS, version 4) is a global simulation of the terrestrial plasma environment. The only time-dependent input parameters are the properties of the solar wind. The simulation box is  $+32R_E$  to  $-224R_E$  in the GSE (Geocentric Solar Ecliptic)  $X$  direction and  $\pm 64R_E$  in the  $Y$  and  $Z$  directions. Outflow conditions are applied at all boundaries of the simulation box

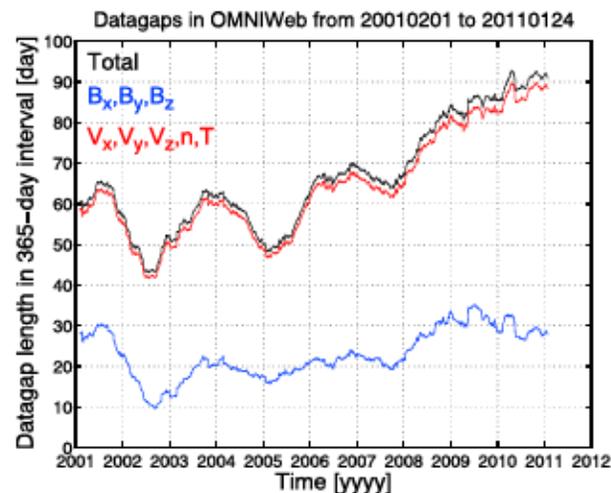
except at the sunward wall, where the values are solar wind parameters. There are two simulation domains: the ionospheric domain at 110 km altitude and the magnetospheric domain with an inner boundary at  $3.7R_E$ . These domains are coupled to each other, and the ionospheric potential is updated every 4 s in the simulation. The field-aligned currents (FAC) are derived from currents at the inner boundary at  $3.7R_E$  and mapped along dipole field lines to the ionosphere. In the electrostatic ionospheric domain the Pedersen and Hall conductivities are computed from the electron precipitation and solar EUV radiation. The electrostatic potential is calculated from the conductivities and the field-aligned currents and mapped back to the magnetosphere. The electrostatic potential is mapped back along dipole field lines to the ( $3.7R_E$ ) inner boundary and applied as a convection pattern [see *Janhunen et al.*, 2012, and references therein]. The GUMICS-4 grid is adaptively refined where interesting physical features occur in the simulation. The finest resolution of  $1/4R_E$  occurs along the dayside magnetopause and near the  $3.7R_E$  inner boundary, and the coarsest resolution of  $2R_E$  is found in the solar wind and in far down-tail regions.

Previously, a large number of synthetic simulations (the so-called GUMICS run library) were used to verify the capability of the GUMICS-4 global MHD simulation [*Gordeev et al.*, 2013]. These simulations, based on typical solar wind parameters, can be used as a library. These results are useful when the upstream solar wind parameters are not known. Moreover, synthetic runs are also important because they give a possibility to study the response of the magnetosphere to constant upstream parameters. It is important to note several issues considering challenges related to the year-long simulation. GUMICS-4 cannot simulate time-dependent  $B_x$  on the solar wind boundary. Hence, the observed interplanetary magnetic field (IMF)  $B_x$  cannot be used in the simulation; otherwise, the simulation produces magnetic divergence and the solution becomes non-physical. There are two general ways to avoid introducing divergence of magnetic field into the simulation at the solar wind boundary. One is to set  $B_x$  from the input to zero and to add a constant background value to the magnetosphere and the dipole field. When a discontinuity is present, it is possible to determine the appropriate reference frame of the discontinuity, when the magnetic field divergence is zero across the boundary layer [*Raeder*, 2003]. However, this minimum variance method is applicable only for short intervals; thus, only some other method could be applied for a massive number of simulations.

## 2.2. Inputs to the Model: OMNI Data

The 1-year simulation was launched using OMNI (<http://omniweb.gsfc.nasa.gov/>) solar wind data as input to the GUMICS simulation, whose assimilation was a part of the European Cluster Assimilation Techniques (ECLAT) project. To achieve the maximum amount of dynamic simulation, the maximum amount of input data is necessary. The OMNI data contain data gaps; therefore, the minimum total data gap for 1 year shows the optimal interval of input files for simulations. In Figure 1 the total length of data gaps is plotted using OMNI data from the start of the Cluster mission to 365 days before the mission ended. The lengths of the data gaps are determined in each 365 day intervals starting from a given day. This calculation is made for plasma data (density, temperature, and solar wind velocity; see Figure 1, red curve) and magnetometer measurements (Figure 1, blue curve). The length of data gap in either instrument is plotted in black. When the plasma data are missing, the magnetic field data could be useful, but when the magnetic field measurements are disturbed, the plasma data are almost always also corrupted (or the data gaps in the B and the particle data often coincide briefly). After a year-long calibration period, the total length of data gaps slowly increases. The data quality of the plasma instrument decreases faster than the magnetic field data. Indeed, the total length of data gaps in the magnetic field measurements is almost constant between 2003 and 2008. The total data gap has three local minimums following the three visible minimums of plasma data gaps, but the OMNI data have the shortest data gap length in 2002 and 2003. It should be noted that both the ion plasma and magnetic field data are necessary for the simulations as input parameters. Based on the analysis above, the interval from 1 February 2002 to 31 January 2003 is selected to be simulated.

As mentioned before, the GUMICS-4 is the only 3-D MHD model in Europe which contains magnetosphere-ionosphere coupling. In this study the GUMICS-4 results are compared and validated with the Cluster mission. The Cluster-II mission was launched in July and August 2000, and it consists of four similar spacecraft, equipped with 11 instruments aboard [*Escoubet et al.*, 2001]. The four probe forms a tetrahedron, and their orbit is an almost polar 57 h long elliptical orbit with 19,000 km perigee and 119,000 km apogee. The orbit crosses the magnetosphere, the magnetosheath, the foreshock, the bow shock, and the magnetotail. The special formation of the four spacecraft allows the study of these plasma regions using multispacecraft methods. In this study we use FluxGate Magnetometer (FGM) magnetic field data [*Balogh et al.*, 2001] and Cluster Ion Spectrometry (CIS) ion plasma data [*Rème et al.*, 2001] for comparison.



**Figure 1.** The length of total data gap time in 365 days long sliding window using the OMNI 1 min averaged solar wind magnetic field and ion plasma data from 1 February 2001 to 24 January 2011. Red: solar wind plasma measurements ( $V_x$ ,  $V_y$ , and  $V_z$ : solar wind velocities,  $n$ : solar wind density,  $T$ : solar wind temperature). Blue: interplanetary magnetic field ( $B_x$ ,  $B_y$ , and  $B_z$ ). Black: the length of data gap in plasma and/or field measurements the total length of data gap in all data sets. The studied interval is the Cluster mission operation time.

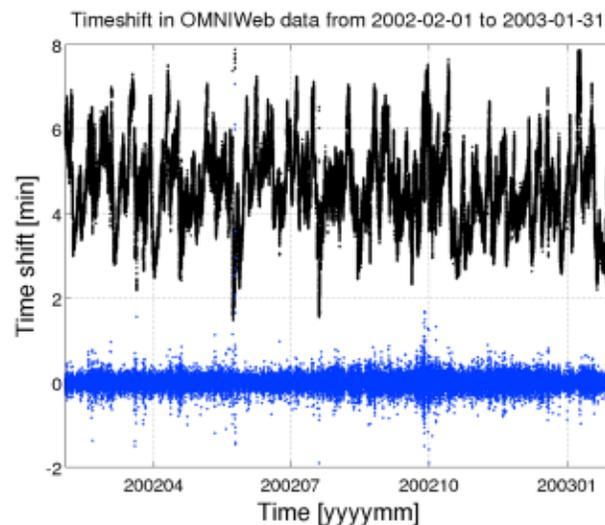
It is worth noting the following challenges associated with the computational performance of the used simulation model. The GUMICS-4 model has not yet been parallelized and runs much slower than real time at the resolution required for this study. Hence, a 1 year simulation would take decades to complete. Therefore, the 1 year time interval was broken up into 57 h intervals to coincide with full Cluster orbits. This method enabled easy comparison between the simulated results and the observations made by Cluster. In practice, the simulated time period had to be longer than 57 h because the GUMICS-4 needs at least 1 h input data as initialization.

It is also important to note the following practical issue concerning the simulations presented in this study. Approximately 1 year (368 days, 155 Cluster orbits) was selected and given as input to the GUMICS-4. The simulation of 57 h long orbits would have completed within a half year, because the GUMICS is 72 times slower than real time on the Cray supercomputer of the Finnish Meteorological Institute (FMI). Subdividing each orbit into 12 segments allowed us to complete each orbit in as little as 18 days and to start implementing postprocessing and analysis procedures. Up to 480 segments (out of the total of 1860) were run in parallel, allowing us to complete all calculations in less than 5 months (including computer down time and other operational delays). Each Cluster orbit was divided into twelve 4.75 h long slices with 1 h initialization period to parallelize the simulation. The initialization was done using 1 h constants of solar wind input values. One minute resolution OMNI data were used as solar wind input. As it could have been seen in Figure 1, the OMNI contained significant amount of data gaps. The data gaps were filled using linear interpolation between the last valid data before the data gap and the first valid data after the data gap. The magnetic field is treated in the following way: the  $B_x$  component of the OMNI magnetic field was not used and replaced with its average added to the background magnetic field during each interval. Moreover, the average dipole tilt angle was used for each slice. The magnetospheric and ionospheric results were always saved once in every 5 min.

### 2.3. Timeshift

As already mentioned, the solar wind input files of the GUMICS-4 simulation were 1 min of resolution OMNI solar wind data. The OMNI shifted its data to the subsolar point of the terrestrial bow shock (<http://omniweb.gsfc.nasa.gov/html/HROdocum.html#3>). However, the inbound wall of the GUMICS-4 simulation was at  $+32R_E$  in the GSE  $X$  direction. Thus, the OMNI input files should have been shifted to the  $+32R_E$  boundary. Applying the reverse delay from the bow shock to the  $+32R_E$  GSE  $X$ , the time shift should have been done on a case-by-case basis using the method we describe below.

The OMNI calculated the magnetopause position using the *Shue et al.* [1997] model. The bow shock position was calculated using the *Farris and Russell* [1994] bow shock model based on the above described magnetopause model. The GUMICS-4 inbound wall was always at  $+32R_E$ ; thus, using the solar wind speed GSE



**Figure 2.** Black: The time shift of the solar wind from the subsolar point of the terrestrial bow shock and the  $+32R_E$  (the ingoing wall of the GUMICS-4 simulation box) calculated using the OMNI 1 min averaged solar wind magnetic field and ion plasma data from 1 February 2001 to 31 January 2003. Blue: the difference of the time shift was computed every 5 min.

X component, the time shift relative to the subsolar point of the bow shock could have always been easily calculated (Figure 2, black dots). On the plotted time series it was visible that the time shift was roughly between +2 and +8min and the average was around +4–5 min. The dynamic simulation results were saved at every 5 min; thus, the time shift of the simulation parameters was only one input file value point or less. Note that Figure 2 showed 1 min of resolution values because it was derived from 1 min resolution OMNI data. The difference of the time shift of the saved data (every fifth time shifts) was mostly 0 min (Figure 2, blue dots).

#### 2.4. Quality of the Solar Wind Inputs

The quality of the simulation result depends on the quality of the input solar wind values, and therefore, it is important to note the following issues about the adopted inputs. As mentioned before, the OMNI data are created from various spacecraft measurements: ACE [Chiu *et al.*, 1998], Wind, and IMP 8 ([http://omniweb.gsfc.nasa.gov/html/omni\\_min\\_data.html#1a](http://omniweb.gsfc.nasa.gov/html/omni_min_data.html#1a)). The solar wind parameters are shifted to the subsolar point of the terrestrial bow shock. There are at least two uncertainties to this method: the position of the subsolar point and the quality of the data created. To test the quality of the input data, we selected time intervals of several hours durations in the magnetic field measurements of the Cluster reference spacecraft (SC3) when the SC3 were situated in the solar wind (Table 1 and Figure 3). The selection of the solar wind intervals was made manually. The bow shock crossings were visible as a large jump of the magnetic field magnitude from high ( $\sim 25$  nT) to lower ( $\sim 5$  nT) values and the solar wind speed increased from  $\sim 100$ – $200$  km/s to  $\sim 400$ – $800$  km/s. At the same time the density of the plasma also decreased. The same intervals are also selected in the OMNI magnetic field data. One minute averaged data are created from spin resolution Cluster SC3 magnetic field  $B_z$  component measurements. Data gaps are filled by linear interpolation. Cross correlations with and without time shifts are calculated between  $B_z$  observation data and model results. Time shifts that maximize correlations are listed in Table 1. The correlation is good between the different time series. The coefficient values are greater than 0.8; thus, the shape of the curves is quite alike. Note that 80% of the time shifts are less than 5 min (Figure 4) and two thirds of them are less than 2 min (not shown). For a comparison, the solar wind moves typically during that time only  $\sim 1R_E$ , which is not a significant distance in a global scale. Some of these large time shifts could be explained by very disturbed magnetic field (Cluster was at the quasi-parallel foreshock). Note that large time shifts are related to the long data gap.

#### 2.5. Continuity of Simulation Results

The 368 days are simulated in 1860 slices or subintervals. This approach could be considered as one large simulation if the jumps of the parameters at the boundary of the slices were not significant compared to the fluctuations of the same parameters inside the slices. In Figure 5, the magnetic field magnitude and the  $B_z$  component are plotted on the top in the GSE reference frame (this coordinate system is also used below).

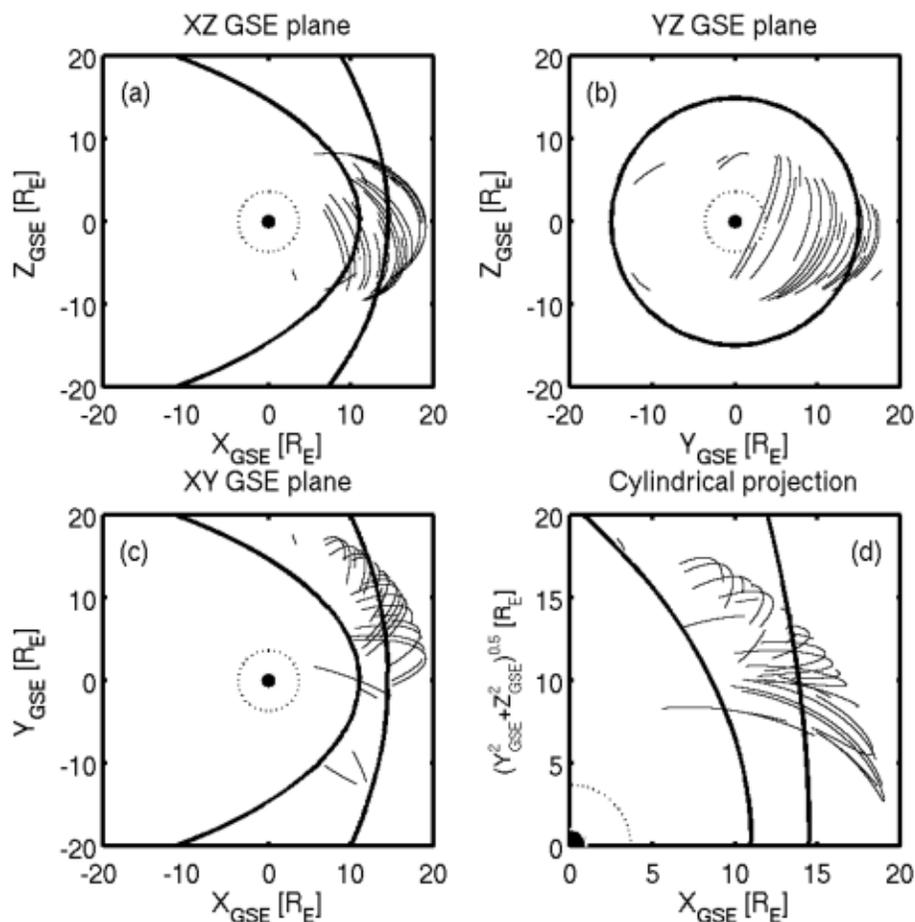
**Table 1.** Cross-correlation Calculation in the Solar Wind<sup>a</sup>

Start	Interval End	OMNI Versus Cluster SC3	
		Time Shift (min)	Correlation
2002/02/01 20:00	2002/02/03 04:00	-1	0.96
2002/02/09 01:00	2002/02/09 06:00	5	0.87
2002/02/11 13:00	2002/02/12 12:00	1	0.81
2002/02/13 16:00	2002/02/14 08:00	10	0.83
2002/02/18 09:00	2002/02/19 02:00	-1	0.93
2002/02/19 06:30	2002/02/19 15:00	-1	0.94
2002/02/20 18:30	2002/02/22 00:00	1	0.84
2002/03/18 17:30	2002/03/19 02:30	-1	0.88
2002/03/23 16:00	2002/03/23 18:30	-5	0.99
2002/04/12 20:30	2002/04/13 02:00	-2	0.93
2002/04/23 16:30	2002/04/23 22:00	-4	0.90
2002/12/06 15:30	2002/12/06 18:00	0	0.90
2002/12/29 20:00	2002/12/30 16:00	0	0.63
2003/01/01 16:00	2003/01/01 21:00	-27 <sup>b</sup>	0.83
2003/01/03 12:00	2003/01/04 02:00	2	0.69
2003/01/06 06:00	2003/01/06 19:00	2	0.76
2003/01/08 07:00	2003/01/09 03:30	4	0.59
2003/01/10 17:00	2003/01/10 20:30	1	0.94
2003/01/13 08:30	2003/01/13 18:00	0	0.91
2003/01/16 02:30	2003/01/16 05:30	25	0.57
2003/01/18 00:00	2003/01/18 18:00	3	0.74
2003/01/20 07:30	2003/01/20 13:00	1	0.80
2003/01/22 12:00	2003/01/23 14:00	1	0.79
2003/01/24 18:00	2003/01/26 00:00	2	0.70
2003/01/27 16:00	2003/01/28 06:00	-3	0.87
2003/01/29 12:00	2003/01/30 18:00	1	0.87
2003/02/03 06:00	2003/02/04 00:00	4	0.61

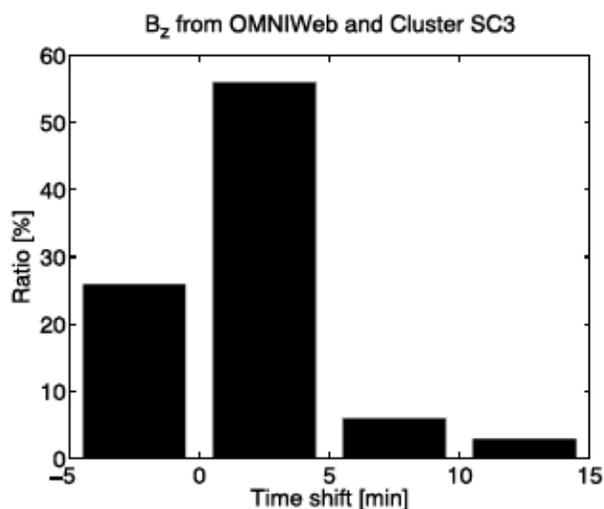
<sup>a</sup>The 27 selected intervals in the solar wind. From left to right: the beginning and end of the intervals, the calculated time shifts of the OMNI versus the Cluster SC3  $B_z$  magnetic field component cross-correlation calculation.

<sup>b</sup>OMNI comments: Data gap in OMNI data.

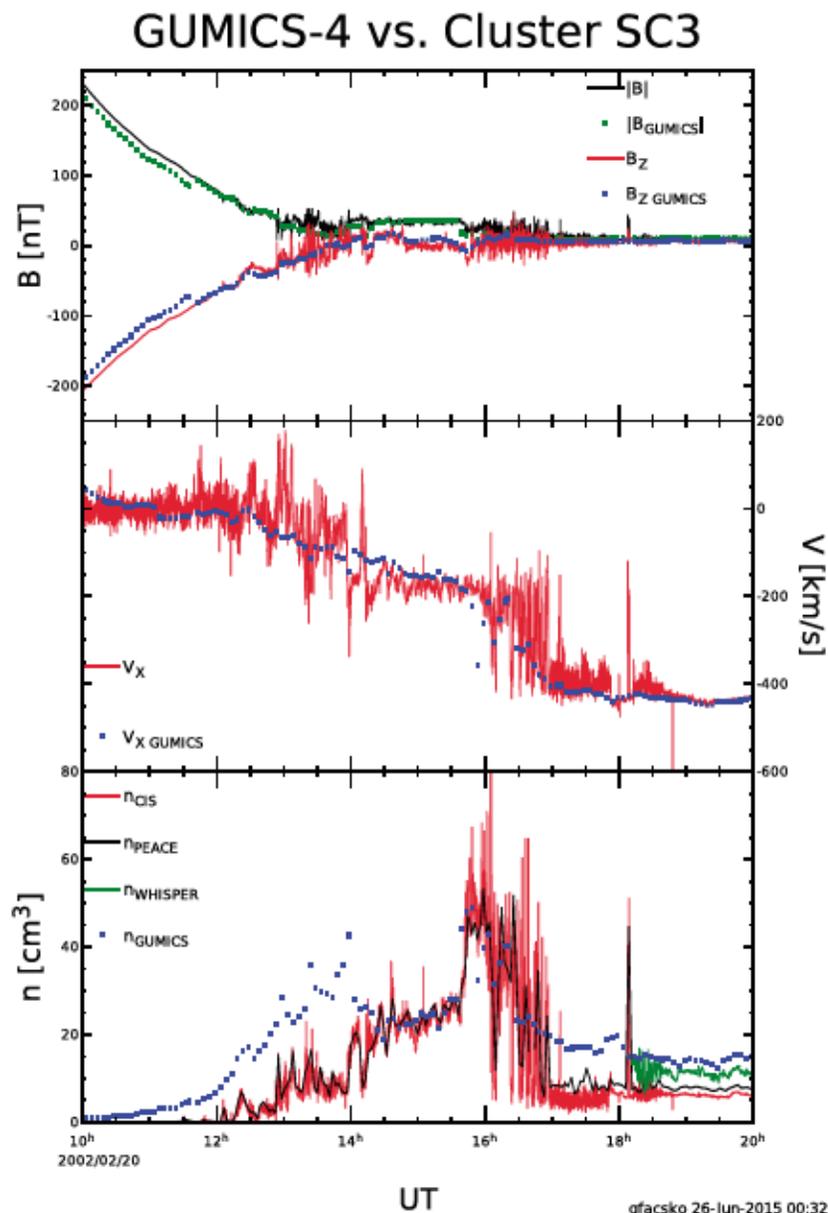
The simulation results are represented by dots and measurements by solid lines. The temporal resolution of the simulations is 5 min while in Figure 5 the original Cluster data has 4s resolution. Both the values and the shape of the curves correspond well for all magnetic field components. As can be seen in Figure 5 (middle), the simulated solar wind velocity  $X$  component is in good agreement with observations, as well as the velocity  $Y$  component. In Figure 5 (bottom), the simulated ion density is plotted together with the observed CIS HIA ion density [Rème et al., 2001] and the WHISPER [Décréau et al., 2001; Trotignon et al., 2010] and PEACE electron densities [Johnstone et al., 1997; Fazakerley et al., 2010a, 2010b]. Note that the simulated and observed plasma densities behave similarly although detailed values differ. Note also that the MHD simulation results are closer to the WHISPER electron density. The change of the orbit number, and sometimes the border of the simulated slices, makes nonphysical jumps in the parameters, because of the different tilt angles and  $B_x$  average given to the run. It should be noted that the magnetic field components correspond very well in values and shape, including the  $B_x$  component, that is changed to an average value for each slide. The plotted interval in Figure 5 contains two borders of slices at 11:38 and 16:23 on 20 February 2002. The border at 11:38 is visible in the magnetic field magnitude in Figure 5 (top); the other cannot be seen because of the short data gap at the boundary. The jump in the plasma density is usually smaller than the variance of the slices before and after the boundary (not shown here).



**Figure 3.** The Cluster reference spacecraft orbits plotted in the intervals which are listed in Table 1 in the GSE system. Average bow shock and magnetopause positions are drawn on all plots (Peredo et al. [1995] and Tsyganenko [1995], respectively). The black dots at  $3.7R_E$  show the boundary of the GUMICS-4 inner magnetospheric domain. The black circle in the origo of all plots shows the size of the Earth. The four panels show the same orbits presented in (a) the XY plane, (b) the YZ plane, (c) the XY plane, and (d) a cylindrical projection.

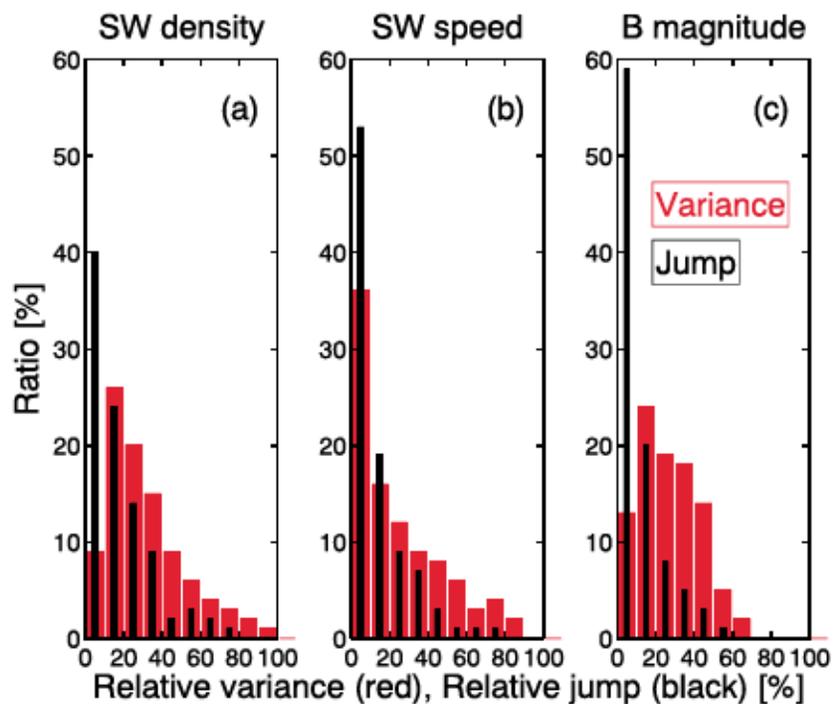


**Figure 4.** The histogram of the calculated timeshift using cross correlation of the 1 min resolution OMNI and 1 min averaged Cluster SC3 magnetic field  $B_z$  component data. The distributions of time shift in minutes from Table 1. Each column gives the relative ratio of the number of the time shift between the indicated lower and higher values of the bar.



**Figure 5.** Comparison of Cluster SC3 measurements and GUMICS-4 simulation results along the Cluster reference/SC3 orbit in the simulation space from 10:00 to 20:00 (UT) on 20 February 2002. (top) The magnitude and GSE Z component of the magnetic field. (middle) The GSE X component of the solar wind velocity. (bottom) The ion and electron densities. In the panels the simulated values are shown by dots and the measured values by solid lines. See text for details.

In Figure 6 the distribution of the jumps between slices along the Cluster SC3 orbit, the last value of the previous and the first value of the following slice, is drawn. The status of the simulations is saved every 5 min; therefore, it is not useful to compare the mean of a short interval before and after the boundary and it does not provide very different results (not shown). The deviation (or difference) of the solar wind density, velocity, and magnetic field magnitude is divided with the mean value of the previous slice (Figure 6, black bars). This is what defines a jump in the following explanation. The variance of each quantity is normalized in respect to the mean density, velocity, and magnetic field, respectively (Figure 6, red). The distributions of the relative variance and the relative jump were normalized by the sum of the distribution. As can be seen in Figure 6, the relative jump distribution of all quantities tends toward the smaller values. 65-75-80% of the density, velocity, and magnetic field relative jump is less than 20%. Moreover, the relative variance has less steep distribution



**Figure 6.** Comparison of changes of plasma parameters between the simulation subintervals (black bars) and the variance (red) of (a) solar wind density, (b) velocity, and (c) magnetic field magnitude. Both the jump and the variance are relative; the quantities were divided by the mean value of the previous slice. The numbers of the distributions were normalized by the sum of the amounts. All quantities are unitless, given in percent.

on all plots; these values are higher than the relative jump on all plots—except the interval of the lesser values. Note also that the maxima of the density and the magnetic field relative variance distributions are at higher values than the relative jump. The relative jump is also usually smaller than the relative natural fluctuation of the previous subinterval or slice. Therefore, the slightly different values of the last and the first points cannot be considered as a serious break between the simulated intervals because these relative jumps are comparable to the normal variation of the slices.

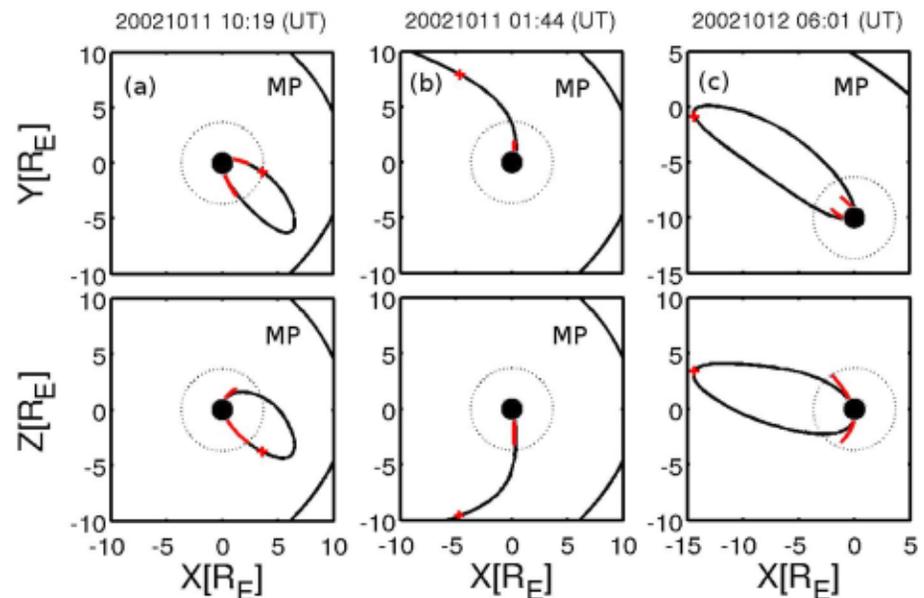
### 3. Comparison of Cluster C3 Footprints From the T96 (Tsyganenko) and GUMICS Models

In this section basic features of the output data to GUMICS and its results are presented. The simulated data made it possible to make numerous type of analysis, and only part of them are presented in this paper. More detailed analysis of various and different aspects of the results has already been published, for instance, in *Juusola et al.* [2014] and *Kallio and Facskó* [2015]. Here we provide a different analysis and its results.

The footprint determination is given in section 3.1. A comprehensive investigation of the GUMICS-4 magnetic field mapping capability is given in section 3.2. This gives a possibility to validate GUMICS-4 using empirical formulas as has been done previously in *Gordeev et al.* [2013]. Moreover, this model-model comparison is also a check of the magnetic field mapping based on T96, because the accuracy of the Tsyganenko method has never been studied previously.

#### 3.1. Magnetic Field Mapping in GUMICS-4 Global MHD Code

In the magnetic field mapping the spacecraft location is projected from the magnetosphere to the ionosphere along the magnetic field lines. Therefore, the footprint of the spacecraft is the magnetic conjugate to the spacecraft location through the same field line. Depending on whether the spacecraft is outside or inside the magnetosphere on an open (lobe field line) or a closed field line, there will be 0, 1, or 2 (one per hemisphere) footprints found, respectively. In Figure 7, black solid lines lead from the spacecraft location to the top of the ionosphere.



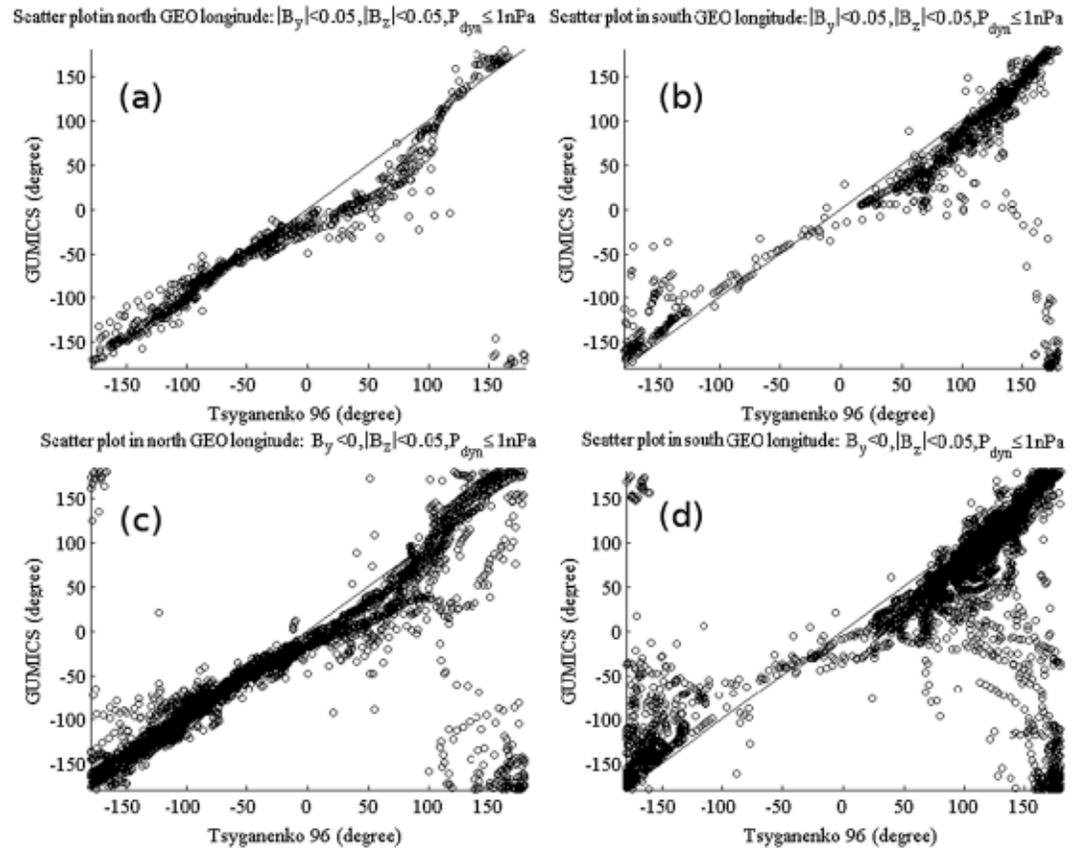
**Figure 7.** Comparison of Cluster SC3 (+) magnetic footprints determined from the GUMICS-4 simulations (red dots) and the T96 model (black line). The position of the magnetopause is based on the *Tsyganenko [1995]* model. (Only the first and the last positions of the GUMICS-4 magnetic field mapping are shown in the magnetospheric domain.) The red crosses mark the Cluster SC3 location. The magnetic field mapping method starts at the Cluster SC3 position in the magnetosphere domain of the simulation. The black dots at  $3.7R_E$  show the boundary of the GUMICS-4 ionospheric domain. The reference frame is GSE in all figures. The black circle in the origo of all plots depicts the Earth. (a) Example of a closed field line case when the virtual Cluster SC3 is in the terrestrial magnetosphere simulated by the GUMICS-4. (b) Example of an open-closed field line, when Cluster is magnetically connected to the magnetosphere. (c) Example of closed field lines, when the Cluster reference spacecraft is located in the nightside magnetosphere. Note that the difference between the GUMICS-4 and T96 is higher in Figure 7c than in Figures 7a and 7b.

Based on the geopack documentation the T96 model uses its own empirical magnetic field in the magnetosphere until a certain specific distance below which the International Geomagnetic Reference Field (IGRF) is used. The IGRF is the empirical representation of the Earth's magnetic field recommended for scientific use by the Working Group of the International Association of Geomagnetism and Aeronomy (IAGA). The IGRF model represents the main (core) field without external sources based on all the available data sources including geomagnetic measurements from observatories, ships, aircrafts, and satellites [*Tsyganenko, 1995; Tsyganenko and Stern, 1996, and references therein*]. The IGRF model is applied below  $3.7R_E$ , which is the GUMICS-4 domain boundary distance for comparison. *Tsyganenko's* geopack is used here for visualization and an approximate validation of the GUMICS-4 footprint determination results. The comparison is from the footprint data based on the T96 model created by the contributors of the St. Petersburg State University (Victor Sergeev, private communication).

The GUMICS-4 uses the GSE reference frame. Its own magnetic field line trace tool [see *Janhunen et al., 2012*] determines the coordinate in GSE where the magnetic field line starts from where the spacecraft location crosses the boundary of the magnetospheric and ionospheric domains at  $3.7R_E$  (Figure 7). The red dots in Figure 7 show the spacecraft locations and, on the domain boundary, are the start and the end of the field line tracing. The tool does not share the steps of the magnetic field mapping. The magnetic field from the inner magnetosphere boundary to the ionosphere is mapped along a dipole field. First, all locations are transformed to the Solar Magnetic (SM) system because the SM system is the reference frame of the tilted terrestrial magnetic field; thus, it is easier to continue the field line mapping in the SM system. The magnetic field was assumed to be dipolar:

$$B_x = \frac{-3k_0xz}{(x^2 + y^2 + z^2)^{\frac{5}{2}}} \quad (1)$$

$$B_y = \frac{-3k_0yz}{(x^2 + y^2 + z^2)^{\frac{5}{2}}} \quad (2)$$



**Figure 8.** Scatter plot of the position of the magnetic footprint in longitude for quiet conditions: (a) Northern Hemisphere and (b) Southern Hemisphere. Scatter plot of the position of the magnetic footprints in longitude when  $B_y < 0$ : (c) Northern Hemisphere and (d) Southern Hemisphere.

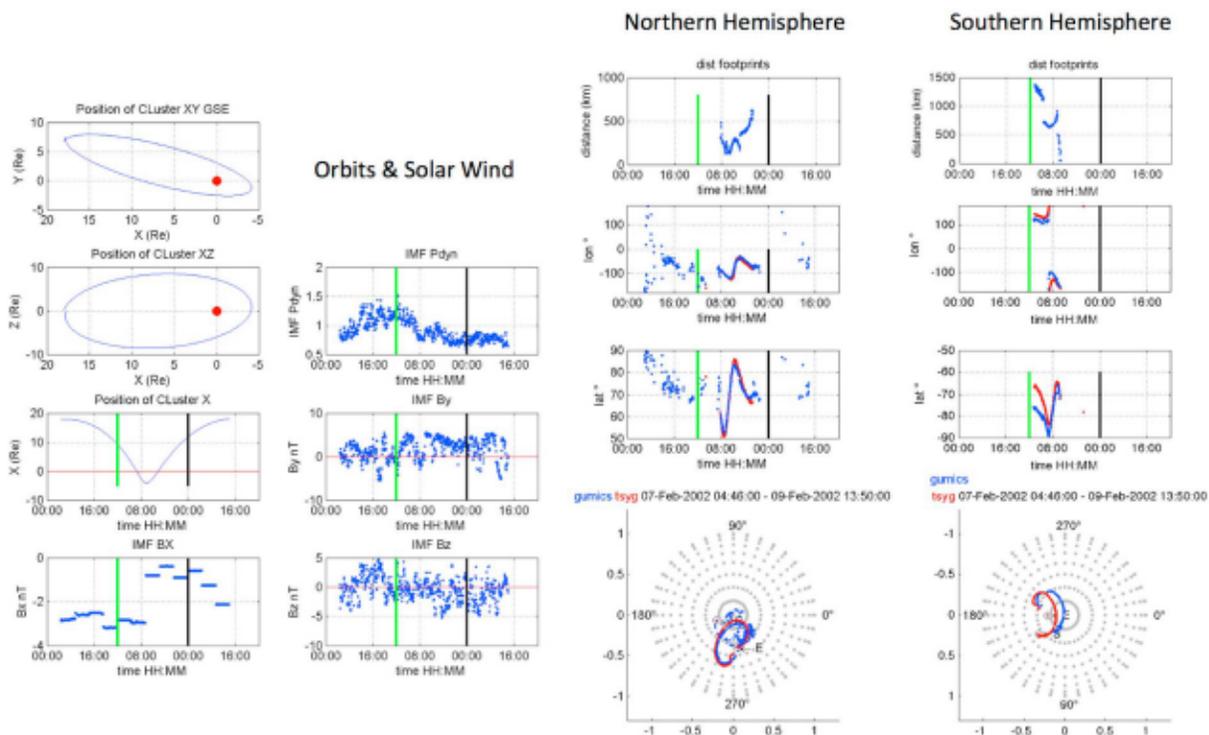
$$B_z = \frac{-3k_0 \left( z^2 - \frac{(x^2 + y^2 + z^2)}{3} \right)}{(x^2 + y^2 + z^2)^{\frac{5}{2}}} \quad (3)$$

$$l_s = \frac{\text{step\_size}}{\left( B_x^2 + B_y^2 + B_z^2 \right)^{\frac{1}{2}}}, \quad (4)$$

where  $B_x$ ,  $B_y$ , and  $B_z$  are the component of the dipole field and  $k_0 = 8 \times 10^{15} \text{ Tm}^3$ . The *step\_size* parameter is an initial selected spatial distance based on stability and accuracy considerations. In this study the step size was 100 km. On a closed field line, the field line tracing algorithm follows the field line in the direction of both hemisphere using the  $l_s$  step. The algorithm stops at 100 km altitude in the Earth ionosphere (see Figure 7, red dots in the ionosphere domain). On an open field line, the field line tracing is stopped at the boundary of the magnetospheric simulation box (see section 2). The results are converted to the GSE system and saved. These coordinates are compared to the T96 footprint coordinates in section 3.2.

### 3.2. Results

The correlation between the GUMICS-4 and T96 models has been investigated at different IMF magnetic field and solar wind dynamic pressure conditions. Investigations are made for each combinations of  $B_y < 0 \text{ nT}$ ,  $B_y > 0 \text{ nT}$  and  $|B_y| < 0.05 \text{ nT}$ ,  $B_z < 0 \text{ nT}$ ,  $B_z > 0 \text{ nT}$  and  $|B_z| < 0.05 \text{ nT}$ ,  $P_{dyn} < 1 \text{ nPa}$  and  $P_{dyn} > 1 \text{ nPa}$ . Figures 8a and 8b show GUMICS-4 versus T96 footprints in geographical coordinates for the Northern (a) and Southern (b) Hemispheres during quiet conditions, when  $|B_y| < 0.05 \text{ nT}$  and  $|B_z| < 0.05 \text{ nT}$  and when  $P_{dyn} < 1 \text{ nPa}$ . In the Northern Hemisphere below  $0^\circ$  longitude, the models are in good agreement. In the region between  $0^\circ$  and  $100^\circ$  both hemispheres display a deviation between the models, although the Southern Hemisphere footprints show a slightly better agreement between the models. In the cases when  $B_y < 0 \text{ nT}$ , the correlation



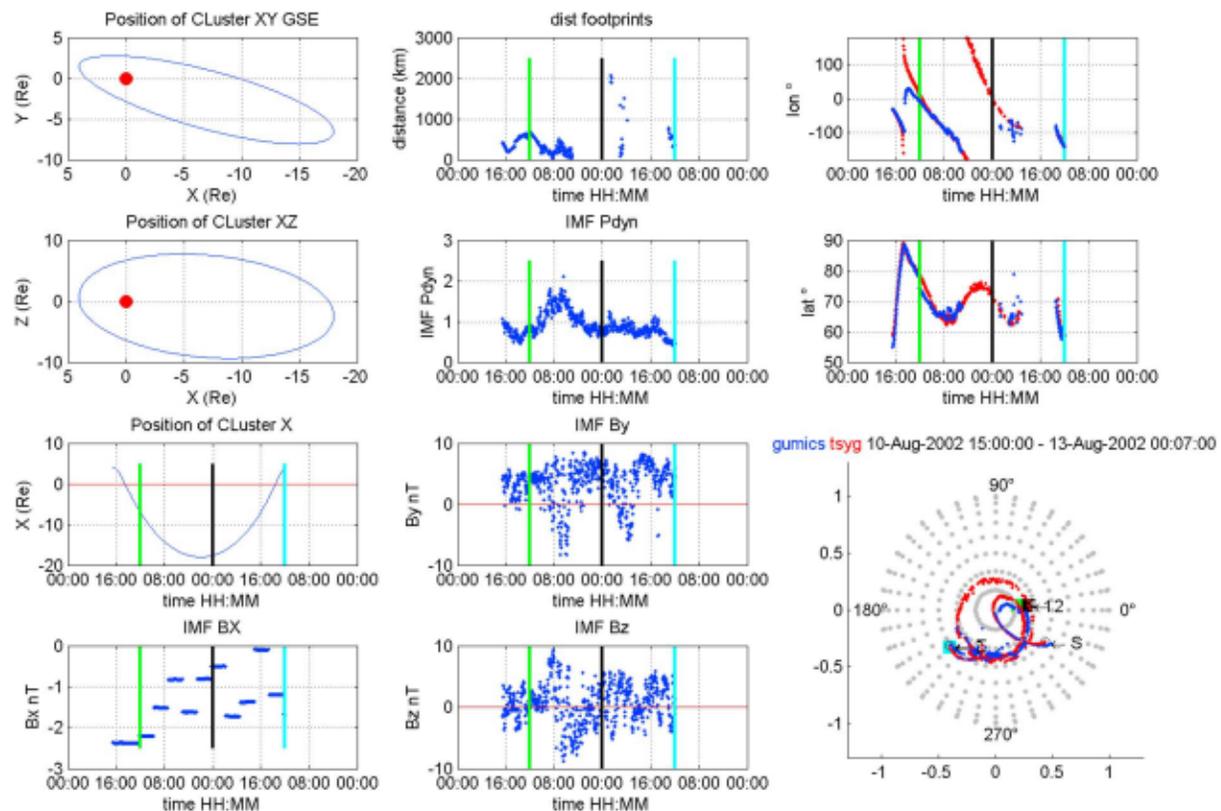
**Figure 9.** Example for magnetic footprints analysis on 7 February 2002, Northern and Southern Hemispheres. (first column) First row: the Cluster SC3 orbit in the XY GSE plane. Second row: the Cluster SC3 orbit in the XZ GSE plane. Third row: the Cluster SC3 X position. Fourth row: the  $B_x$  magnetic field GSE X component. (second column) Second row: the solar wind dynamic pressure. Third row: the interplanetary magnetic field (IMF) GSE Y component. Fourth row: the IMF GSE Z component. (third column) First row: the distance of footprints determined from the GUMICS-4 simulations and T96 model. Second row: the longitude of the T96 (red) and GUMICS-4 (blue) footprints in the SM system. Third row: the latitude of the T96 (red) and GUMICS-4 (blue) footprints in the SM system. Fourth to fifth rows: the T96 (red) and GUMICS-4 (blue) footprints in SM coordinates. (fourth column) First row: the distance of footprints determined from the GUMICS-4 simulations and T96 model. Second row: the longitude of the T96 (red) and GUMICS-4 (blue) footprints in the SM system. Third row: the latitude of the T96 (red) and GUMICS-4 (blue) footprints in the SM system. Fourth to fifth rows: the T96 (red) and GUMICS-4 (blue) footprints in SM coordinates.

between the models becomes worse particularly for the Southern Hemisphere, cf. Figures 8c and 8d. The same results are obtained for  $B_y > 0$  nT (here not shown).

The correlation in latitude does not seem to depend on magnetospheric conditions (not shown here). The footprints in the Southern Hemisphere, however, show less correlation. One possible explanation to this could be that GUMICS-4 assumes a simple dipole magnetic field for the inner magnetosphere within  $3.7R_E$  while T96 uses a more realistic intrinsic magnetic field model. For this reason, we mostly focus on the Northern Hemisphere on the plots.

Furthermore, we have compared GUMICS-4 and T96 footprints for two principal periods: February and March, and July and August 2002. In February and March, the perigee of the Cluster SC3 spacecraft occurred in the inner magnetosphere on the nightside, whereas the apogee did not reach the solar wind. Apart from intersections with the magnetic cusp, magnetospheric conditions were relatively quiet along the Cluster orbit, as Cluster spacecraft mainly was located in the inner magnetosphere. On the contrary, in July and August, the apogee occurred in the magnetotail, giving better opportunities for the Cluster spacecraft to be exposed to substorm-related magnetospheric disturbances.

Figure 9 gives an example from 7 February 2002. This quiet magnetospheric condition case provides an example of an event when the models give a relatively similar magnetic footprints in the Northern and the Southern Hemispheres. Figure 10, instead, shows an example from 10 August 2002, for the Northern Hemisphere, where  $B_y$  is mostly larger than zero. In this case the longitude of the footprints derived from GUMICS-4 differ substantially from the footprints derived from T96, as it has been seen in the scatterplot in Figures 8c and 8d, previously. Figure 11 shows an example for 24 August 2002 for the Northern Hemisphere, where the results of both models are in similar kind of footprints before the Cluster 3 spacecraft had reached apogee. However, at the apogee, presumably because the GUMICS-4 model has a shorter



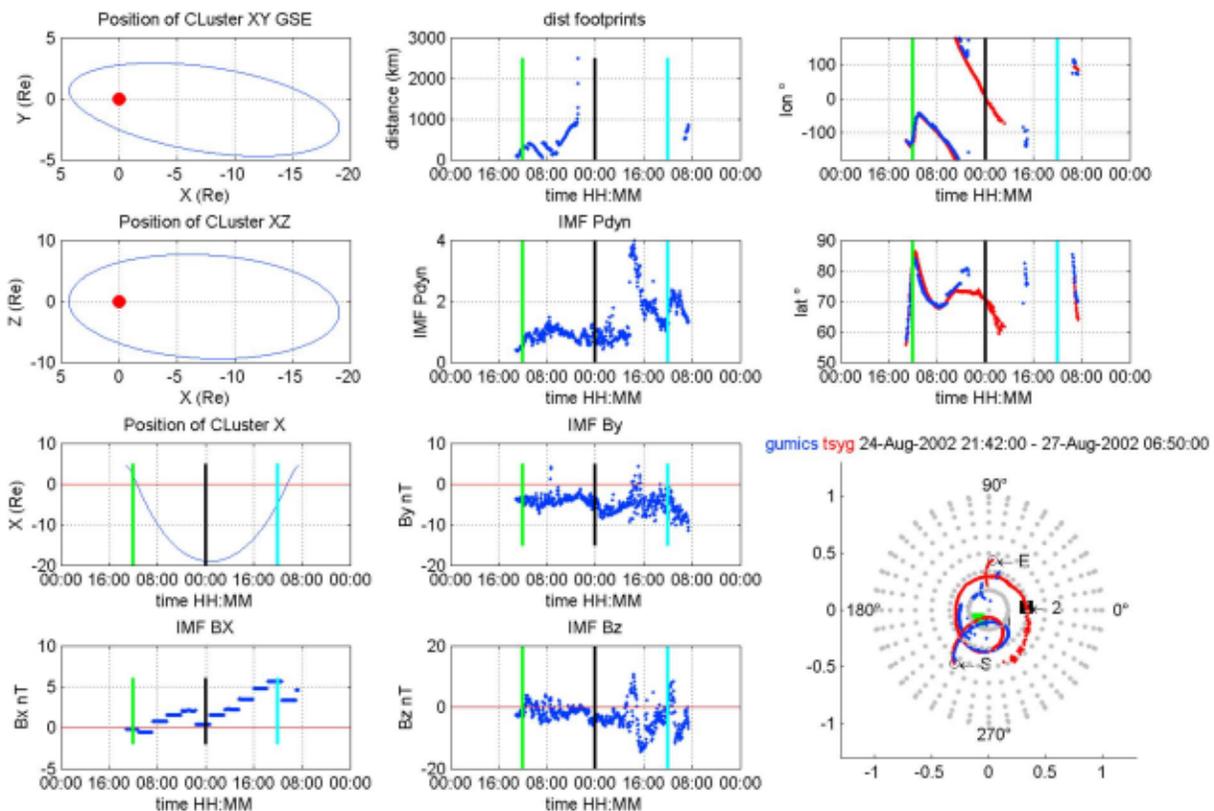
**Figure 10.** Example for 10 August 2002, Northern Hemisphere. (first column) First row: the Cluster SC3 orbit in the XY GSE plane. Second row: the Cluster SC3 orbit in the XZ GSE plane. Third row: the Cluster SC3 X position. Fourth row: the  $B_x$  magnetic field GSE X component. (second column) First row: the distance of footprints determined from the GUMICS-4 simulations and T96 model. Second row: the solar wind dynamic pressure. Third row: the Interplanetary Magnetic Field (IMF) GSE Y component. Fourth row: the IMF GSE Z component. (third column) First row: the longitude of the T96 (red) and GUMICS-4 (blue) footprints in the SM system. Second row: the latitude of the T96 (red) and GUMICS-4 (blue) footprints in the SM system. Third to fourth rows: the T96 (red) and GUMICS-4 (blue) footprints in SM coordinates.

magnetotail than T96, differences between the models become larger. Finally, Figure 12 shows an example of 27 August 2002 for the Northern Hemisphere, where there is a solar wind pressure pulse. In this case, GUMICS-4 results are substantially different footprint positions than T96. Furthermore, due to continuous pressure variations, the 4.75 h subrun interval in the GUMICS-4 year run is becoming obvious as clear steps, also in the ionospheric footprint. The same plots for the Southern Hemisphere show even less agreement between GUMICS-4 and T96, most probably because the GUMICS-4 model uses a tilted dipole magnetic field in the ionosphere (not shown).

When the magnetic  $B_y$  component is different from zero, the longitudes of the footprints for GUMICS-4 and T96 deviate considerably from each other, particularly when  $B_y < 0$  nT. This might be due to the configuration of the magnetotail in the GUMICS-4 model. Furthermore, a mismatch between GUMICS-4 and T96 footprints arise when the apogee of the Cluster orbit is in the magnetotail, probably due to the shorter magnetotail in the GUMICS-4 model. Since GUMICS-4 runs are carried out in 12 slices per orbit, 4.75 h steps can be seen in the footprints as well. This is particularly obvious for varying magnetospheric conditions, e.g., when there is a pressure pulse close to the transition between the 4.75 h slots. However, well within the slots, GUMICS-4 responds relatively well to solar wind variability even under disturbed conditions.

#### 4. Discussion

In this study a 368 day time period global MHD simulation is launched and analyzed. The GUMICS-4 uses only a single processor; therefore, the 155 Cluster orbit long time period is divided into 1860 subintervals (slices) and 1860 GUMICS-4 simulations are launched. This mandatory technical decision is a potential source for inaccuracy in the GUMICS-4 simulation results. Moreover, another main source of possible inaccuracy is the input parameters. The OMNI solar wind data are derived from other spacecraft measurements.

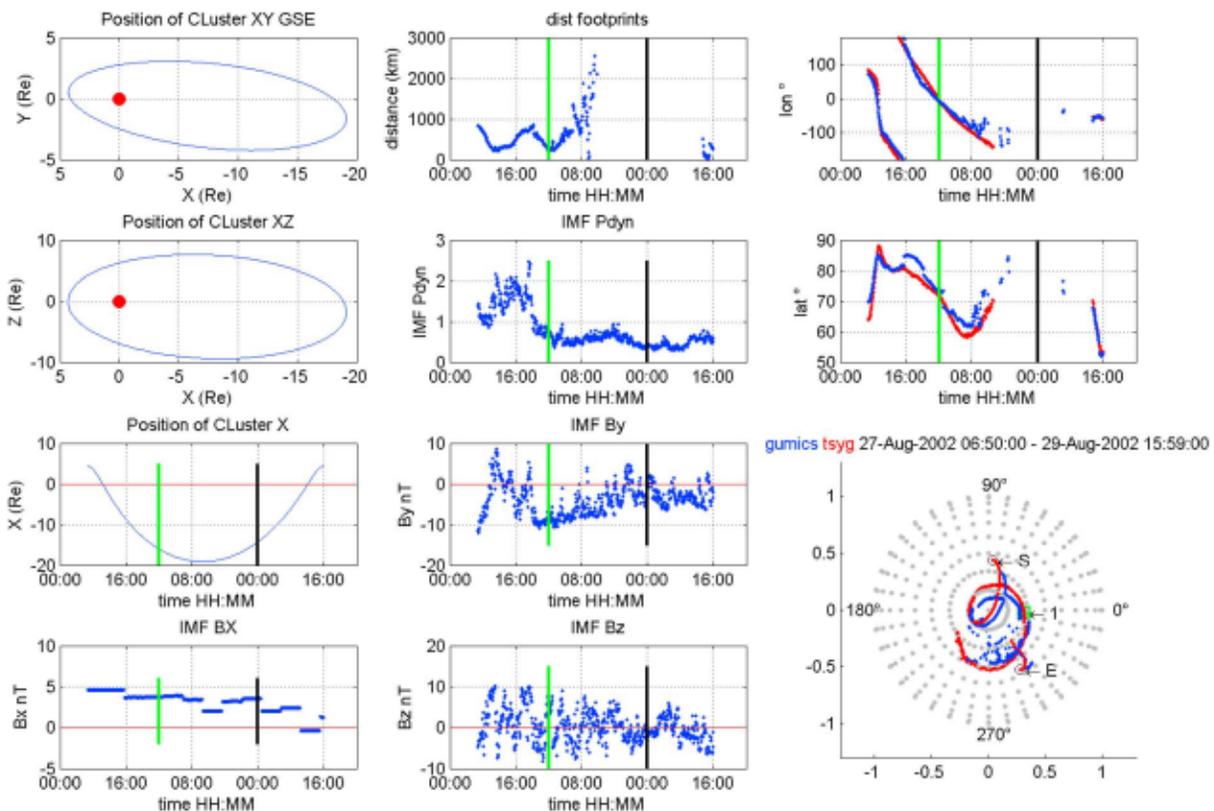


**Figure 11.** Example for 24 August 2002, Northern Hemisphere. See Figure 10 for the description of the panels.

These additional sources of input data inaccuracies—namely, the time shift to the subsolar point of the terrestrial bow shock— increase the risk of the failure of the simulations. It is therefore necessary to use the ACE measurement from the  $L_1$  inner Lagrange point. There are more data gaps; however, the only calculation is a 20–40 min time shift in the parameters.

From qualitative comparisons between the GUMICS-4 simulation and T96 during a year run, we can conclude that they give relatively similar footprints during quiet conditions for the Northern Hemisphere. Generally, the matching of the footprint latitude between the GUMICS-4 simulation and T96 is reasonably good for all magnetospheric conditions. However, the observed discrepancy is always worse for the Southern Hemisphere due to the assumed dipole magnetic field in the GUMICS-4 simulations. In the future, this hypothesis could be investigated by replacing the GUMICS-4 the simple dipole magnetic field with the IGRF magnetic field model. The step errors at the transition of the subrun intervals are more difficult to correct, as they arise from the assumption of 2 h of steady solar wind for the initialization of every GUMICS-4 subrun and a constant dipole tilt angle in that period. During disturbed solar wind conditions this assumption will introduce a bias to the system, as the real solar wind should be influencing the modeled magnetospheric configuration for the first few minutes of every subrun, while now there is a constant starting value assumed. Subsequent to the passage of the assumed constant solar wind region toward the deep tail, GUMICS-4 again develops a magnetosphere that corresponds to the measured solar wind. Depending on the solar wind speed this might give inaccuracies in the magnetospheric configuration on the dayside and the near-Earth region during the first 3 to 10 min of every subrun interval, as seen in the step of the footprint comparison.

The length of the data gaps is the shortest in the selected 368 day term period during 2001–2011 (Figure 1). This choice maximized the length of the simulations. However, the Cluster spacecraft were launched in July and August 2000, and the magnetometers and the plasma instruments were switched off or calibrated frequently in 2002. This produced many data gaps in the Cluster measurements on all spacecraft and limited the accuracy of the comparison of real measurements and simulations. An additional problem is the 5 min resolution of the simulation data. There was no data saving capacity to save the simulation status more frequently; however, the cross-calibration calculation and other methods cannot be applied that efficiently.



**Figure 12.** Example for 27 August 2002, Northern Hemisphere. See Figure 10 for the description of the panels.

A forthcoming paper will extend the comparison study for the main regions: the solar wind, the magnetosheath, the dayside magnetosphere, and the tail. In addition, it would be desirable to compare the magnetic field components and magnitude, the solar wind velocity components, and the density in each region. This will be addressed in the follow-up paper. Furthermore, in the future, the features of the bow shock, magnetopause, and neutral sheet will also be compared in simulations and in Cluster measurements in order to obtain deeper insight into the pros and cons of the MHD approach.

### 5. Summary and Conclusions

A long global MHD simulation lasting approximately 1 year (368 days) was launched using GUMICS-4 code and compared to satellite measurements. The authors knowledge, this is the longest 3-D MHD model simulation made so far to make a detailed comparison with observations. The simulation was made based on the previous experience of 162 stationary runs using the same global MHD code. Solar wind data derived from the OMNI was used as simulation input. The 365 day long interval that has the shortest data gap during the operation time of the Cluster fleet (2001–2012) was selected for input. Using correlation calculation, we proved that the OMNI can be applied to Cluster measurements because the IMF  $B_z$  variations are similar to those in the solar wind. The OMNI shifts its solar wind observations to the subsolar point of the terrestrial bow shock; however, this transformation does not overlap the different simulation results. The GUMICS-4 typically runs slower than real time; hence, we divided the interval of approximately 1 year into 1860 subintervals to complete the simulation faster. This method—simulation in subintervals or slices—has no significant influence on the quality of the simulation.

The Cluster SC3 magnetic footprints were determined in the GUMICS-4 simulations. The study showed that the determined footprints were relatively well in agreement with the T96 empirical model; however, the footprints agree better in the Northern Hemisphere than the Southern one during quiet conditions. The correlation in latitude does not depend on magnetospheric conditions. When  $B_y$  is nonzero, the correlation between models is worse in longitude in the Southern Hemisphere. When the Cluster SC3 was situated in

the dayside magnetosphere, the deviation between the footprints was small in the Northern Hemisphere during quiet conditions. In the magnetotail the deviation between the models became larger at the Cluster apogee, possibly because the GUMICS-4 magnetotail was shorter than the T96 tail. The study also suggests that GUMICS-4 could not model solar wind pressure pulses as realistically as T96. Overall, the study implies that a 3-D MHD model can increase our insight into the response of the magnetosphere to solar wind conditions, but the usage of the solar wind input parameters, the adopted technique to perform the runs, and analysis of the realism of the simulation results requires special attention.

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