Comparing 1-year GUMICS−4 simulations of the Terrestrial Magnetosphere with Cluster Measurements

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Abstract

We compare the predictions of the GUMICS−4 global magnetohydrodynamic model for the interaction of the solar wind with the Earth's magnetosphere with Cluster SC3 measurements for over one year, from January 29, 2002, to February 2, 2003. In particular, we compare model predictions with the north/south component of the magnetic field (B_z) seen by the magnetometer, the component of the velocity along the Sun-Earth line (V_x), and the plasma density as determined from a top hat plasma spectrometer and the spacecraft's potential from the electric field instrument. We select intervals in the solar wind, the magnetosheath, and the magnetosphere where these instruments provided good quality data and the model correctly predicted the region in which the spacecraft is located. We determine the location of the bow shock, the magnetopause and, the neutral sheet from the spacecraft measurements and compare these locations to those predicted by the simulation.

The GUMICS−4 model agrees well with the measurements in the solar wind however its accuracy is worse in the magnetosheath. The simulation results are not realistic in the magnetosphere. The bow shock location is predicted well, however, the magnetopause location is less accurate. The neutral sheet positions are located quite accurately thanks to the special solar wind conditions when the B_y component of the interplanetary magnetic field is small.

1 Introduction

This paper compares the Cluster SC3 measurements directly to a previously made 1-year long GUMICS−4 simulation at locations in the solar wind, magnetosheath, and the magnetosphere along the Cluster SC3 orbit [10]. The structure of this paper is as follows. Section 2 describes the GUMICS−4 code, the 1-year simulation, and the Cluster spacecraft measurements. 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 The GUMICS−4 products and Cluster measurements

A 1-year global MHD simulation was produced with the GUMICS−4 code using the OMNI solar wind data from January 29, 2002, to February 2, 2003, as input [10]. The creation

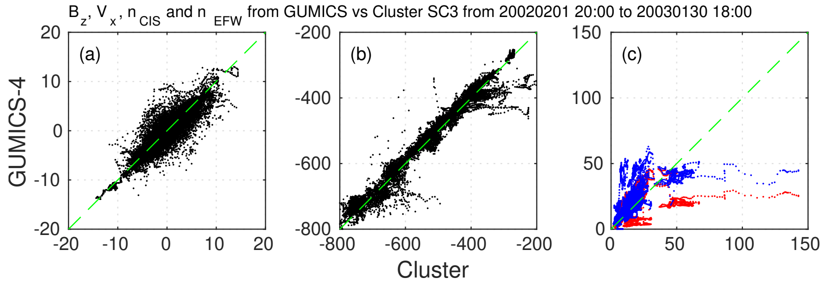

Figure 1: Scattered plots of the Cluster SC3 and GUMICS−4 simulations for all intervals in the solar wind. The dashed line is the y=x line. (a) Magnetic field Z component in GSE system. (b) Solar wind velocity X component in GSE system. (c) Solar wind density measured by the CIS HIA instrument (red) and calculated from the spacecraft potential (blue).

and analysis of the simulation were based on a work package of the European Cluster Assimilation Technology (ECLAT) project (https://cordis.europa.eu/result/rcn/165813_en.html; http://www.eclat–project.eu/).

The Cluster-II mission of the European Space Agency (ESA) was launched in 2000 to observe geospace [7, 9]. The four spacecraft form a tetrahedron in space however here we use only the measurements of the reference spacecraft, Cluster SC3.

We remove non-physical jumps from our results using a density determination based on different principles.

3 Comparison of measurements to simulation

The parameters saved from the GUMICS−4 simulations and the Cluster SC3 magnetic field, solar wind velocity and, density measurements are compared in different regions, namely the solar wind, magnetosheath, and magnetosphere via cross−correlation calculations.

For the correlation calculation, intervals are selected carefully in the solar wind (see Section **??**), the magnetosheath (see Section **??**), the dayside and the night side magnetosphere (see Section **??**). In these intervals, the parameters did not vary a lot and we exclude intervals when either Cluster or the virtual probe cross any boundaries. To compare the B_z magnetic field, V_x solar wind speed and the n_{CIS} and the n_{EFW} curves we cross–correlate selected intervals.

We use OMNI IMF and solar wind velocity, density, and temperature data as input to the simulation. Hence, there are only 17 solar wind intervals to study, as shown in Figure **??**.

The selected intervals occur for quiet solar wind conditions (Figure **??**). The GUMICS−4 simulation results have five–minute time resolution and the Cluster SC3 measurements have one–minute time resolution (Figure **??**). The measurements vary significantly. Despite the quiet conditions the observed solar wind density often changes and deviates from the simulation. Figure 1c shows that both densities deviate significantly. The CIS HIA density variations are even larger as expected given the complexity and a large number of working modes of the CIS instrument. The magnetic field and the solar wind velocity fit better. Figure **??**a shows that the correlation of the magnetic fields is very good; furthermore on Figure **??**c, **??**e, **??**g the correlation of the solar wind velocity and density is excellent (Table **??**). The time shift in Figure **??**b, Figure **??**d, Figure **??**f is about five–minutes for the magnetic field and the CIS data. In Figure **??**h for the EFW data,

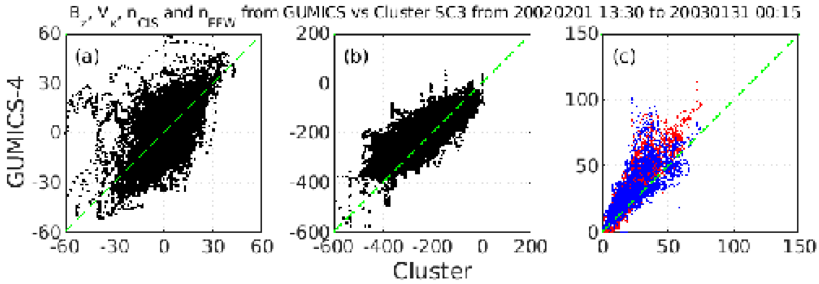

Figure 2: Scattered plots of the Cluster SC3 and GUMICS−4 simulations for all intervals in the magnetosheath in GSE system. The dashed line is the y=x line. (a) Magnetic field Z component. (b) Solar wind velocity X component. (c) Solar wind density measured by the CIS HIA instrument (red) and calculated from the spacecraft potential (blue).

the time–shift is less stable. It is not as well determined as in the case of the other parameters.

Cluster SC3 spent only a little time in the solar wind from December 2002 to May 2003. However, the spacecraft enters the magnetosheath in each orbit (Figure ??). Hence, 74 intervals considered in our final selection (Table ??).

All intervals have quiet upstream (or input) solar wind conditions (Figure ??). Despite our selected quiet magnetic field and plasma parameters, the calculated empirical density indicate that they vary significantly stronger than in the solar wind intervals (Figure ??). The deviation between the simulated and the observed data is also larger in this region than in the solar wind region. The scatter plots of the magnetic field, plasma flow speed, and the densities show that these parameters agree well, but with a greater variation than the scatter plots for the same parameters in the solar wind (Figure 2a, 2b, 2c). The correlation of the simulated and the observed data is good for the magnetic field (Figure ??a), very good for the ion plasma moments and the calculated density (Figure ??c, ??e, ??g). The timeshift of the magnetic field is within five minutes mostly (Figure ??b) however the timeshift of the ion plasma moments is scattered (Figure ??d, ??f). The timeshift of the calculated EFW density seems to be more stable (Figure ??h). Generally, the GUMICS−4 is less accurate in the magnetosheath than in the solar wind. The modeled magnetic field is better predicted than the modeled plasma parameters are. The calculated empirical EFW density (n_{EFW}) fits better than the CIS HIA density (n_{CIS}).

Here we show neither any correlation calculation nor comparison plot. In the magnetosphere, the GUMICS−4 does not work well. Neither the magnetic field nor the plasma moments nor the N_{EFW} fit well. The solar wind velocity does not reach zero in the simulation. Instead, the solar wind enters the night side magnetosphere. The solar wind CIS HIA ion plasma density and the calculated density from spacecraft potential increase closer to the Earth (plasmasphere). The GUMICS−4 density is low there. We calculated the dipole field in GSE using Tsyganenko Geotool box [43] and subtracted from both the observed and the simulated magnetic field B_z data. The correlation of these corrected magnetic field measurements and simulations is very low too.

We selected 77 intervals when Cluster SC3 crossed the terrestrial bow shock once or multiple times (Table ??). All bow shock transitions of the virtual spacecraft are slower and smoother. Additionally, GUMICS-4 does not predict multiple bow shock transitions. The code reacts slowly to such sudden changes. The magnetic signatures fit better than the calculated plasma moments. The jump of the ion plasma parameters and the derived Cluster EFW density of the simulations are shifted to the measurements. Generally, the density and the velocity of the simulations seem to be less accurate than the magnetic

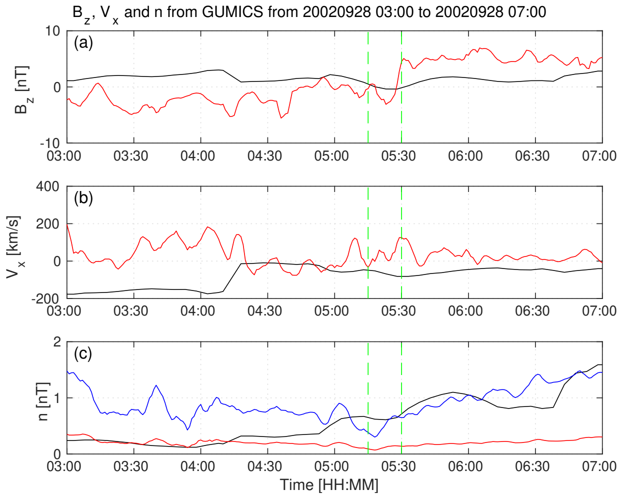

Figure 3: GUMICS-4 simulation results (black) and Cluster SC3 magnetic field Z component, ion plasma moments (red) and electron density calculated from spacecraft potential (blue) from September 28, 2002 from 3:00 to 7:00 (UT) in the tail in GSE system. (a) Magnetic field Z component. (b) Solar wind velocity X component (c) Solar wind density. From 05:15 to 05:30 between the green dashed vertical lines both the Cluster SC3 and the virtual spaceprobe of the GUMICS−4 simulation cross the neutral sheet multiple times.

field in the simulations.

54 intervals are selected around magnetopause crossings (Table ??). The location of the magnetopause is well determined by the Cluster SC3 measurements. However, it is very difficult to identify the magnetopause crossings in the simulation data. The magnetopause crossings usually (92 %) cannot be seen in the simulations. The magnetopause crossings are not visible in V_x and n. This observation is independent of the IMF orientation. Or when the magnetopause crossings are identified in both simulations and spacecraft measurements the events are shifted in time and location. The accuracy of the model is lower for the dayside magnetopause locations than the bow shock locations.

Nine intervals are chosen around Cluster SC3 neutral sheet crossings (Figure ??; Table ??). The neutral sheet crossings are visible in the GUMICS simulations (Figure 3; black curves). For five events (from nine Cluster SC3 crossings) the GUMICS−4 also provides similar smoothed parameters and change of sign of the B_z component. This is an outstanding result because the tail in the GUMICS−4 simulations is significantly smaller than observed in reality [14, 10]; furthermore the solar wind enters the tail in MHD simulations generally [23].

4 Discussion

The agreement of B_z, V_x and n_{EFW} in the solar wind with the similar GUMICS simulation predictions is very good (Figure 1a, 1b, 1c, blue). The agreement of n_{CIS} is worse (Figure 1c, red). It was expected because the n_{EFW} depends on the spacecraft potential provided by the EFW instrument. However, the CIS instrument has many modes for measuring the plasma parameters and it needs periodic calibration too. The correlation of the solar wind V_x, n_{CIS} and n_{EFW} with the similar GUMICS simulation parameters is greater than 0.9 (Figure ??c, ??e, ??g). The correlation of the B_z is also greater than 0.8 (Figure ??a). The upstream boundary of the GUMICS−4 code lies at $32\,R_E$ [19], the nose of the terrestrial bow shock is at about $20\,R_E$. If the solar wind speed is $400\,\mathrm{km/s}$, then this spatial distance means less than a 5 minutes delay, so it should not be visible in the time delays from the cross–correlations.

In the magnetosheath we get worse agreement with the GUMICS simulation data (Figure 2a, 2b, 2c). While the parameters are correlated, the scatter is greater. The general reason for this larger uncertainty seems to be that the magnetosheath is turbulent. This phenomenon explains the higher variations of the B_z magnetic field on Figure 2a. The solar wind V_x, n_{CIS} and n_{EFW} agree better than the magnetic field component (Figure 2b, 2c). Here there is no deviation between the densities derived in different ways (n_{CIS} and n_{EFW}) on Figure 2c. Figure **??** seems to contradict these statements above. The larger uncertainty of the B_z is visible in Figure **??**a. However, that correlation is still good in Figure **??**b. The other parameters have larger (]0.9) correlation in Figure **??**c, **??**e, **??**g. However, the time shifts in Figure **??**d, **??**f, **??**h seem to be worse. Here the time shifts are worse because the shape of the time series in the magnetosheath looks very smooth and similar hence there are not enough points to get a sharp and large maximum correlation as the function of timeshift. The difference between the minimum and the maximum of the correlation is small compared with the uncertainty of the calculation. The maximum, the timeshift could be anywhere and the shape of the correlation vs. timeshift function is often neither symmetric nor does it have only one local maximum. Hence, the correlation calculation provides larger time shifts for the ion plasma parameters and the n_{EFW}.

In the magnetosphere, the GUMICS−4 does not work well. GUMICS−4 uses a tilted dipole to describe the terrestrial magnetic field [19]. After removing the magnetic dipole from the magnetic field measurements of the Cluster SC3 and the simulation we get very low correlations and unacceptable time shifts (not shown). The tilted dipole is an insufficient description of the inner magnetospheric magnetic field. The plasma moments and the n_{EFW} do not fit either. The single fluid, ideal MHD does not describe the inner magnetosphere well therefore V_x and n in the simulations do not agree with V_x, n_{CIS} and the n_{EFW} measured by the Cluster SC3. Within the $3.7\,R_E$ domain ring current physics must be added, as it has been in other global MHD codes [for example 40].

The bow shock positions agree in the GUMICS simulations and the Cluster SC3 measurements. However, the magnetopause locations do not match as well as the bow shock in simulations and observations. In simulations the location of the magnetopause is determined from peaks in currents density, particle density gradient, or changes in flow velocity [39, 13, 14, see references therein]. Here the previously saved simulation parameters along the virtual Cluster SC3 orbit are analyzed. This discrepancy of the magnetopause location agrees with the results of [14] and [10]. [14] compared synthetic GUMICS runs with an empirical formula for the magnetopause locations. [10] used OMNI solar wind data as input and got the same result as [14] and this paper. The neutral sheets are visible in both simulations and observations (Figure 3, Table **??**). This experience is exceptional because the night side magnetosphere of the GUMICS−4 simulations is small and twisted [14, 10]. However, in these cases, the IMF has no large B_y component. From [10] we know that the GUMICS has a normal long tail (or night side magnetosphere) if the B_y is small. The code can identify the bow shock transitions. For the magnetopause and the neutral sheet, the results are more complex.

5 Summary and conclusions

Based on the previously created 1-year long GUMICS−4 run global MHD simulation results are compared with Cluster SC3 magnetic field, solar wind velocity, and density measurements along the spacecraft orbit. Intervals are selected when the Cluster SC3 and the virtual space probe are situated in the solar wind, magnetosheath, and magnetosphere; firthermore their correlation is calculated. Bow shock, magnetopause, and neutral sheet crossings are selected and their visibility and relative position are compared. We achieved the following results:

1. In the solar wind the correlation coefficient of the B_z, the V_x, the n_{EFW} and the n_{CIS} are larger than 0.8, 0.9, 0.9 and 0.9, respectively. The agreement of the B_z, the V_x, and the n_{EFW} is very good, furthermore the agreement of the n_{CIS} is also good.
2. In the magnetosheath the correlation coefficient of the B_z, the V_x, the n_{EFW} and the n_{CIS} are larger than 0.6, 0.9, 0.9 and 0.9, respectively. The agreement of the magnetic field component, the ion plasma moments, and the calculated empirical density is a bit weaker than in the solar wind. The V_x, the n_{EFW} and the n_{CIS} fits better than the B_z component in the magnetosheath. Their agreement is still good. The reason for the deviation is the turbulent behavior of the slowed down and thermalized turbulent solar wind.
3. In neither the dayside nor the nightside magnetosphere can the GUMICS−4 provide realistic results. The simulation outputs and the spacecraft measurement disagree in this region. The reason for this deviation must be the missing coupled inner magnetosphere model. The applied tilted dipole approach is not satisfactory in the magnetosphere at all.
4. The position of the bow shock and the neutral sheet agrees well in the simulations and the Cluster SC3 magnetic field, ion plasma moments, and derived electron density measurements in this study. The position of the magnetopause does not fit that well.

The GUMICS−4 has scientific and strategic importance for the European Space Weather and Scientific community. This code developed in the Finnish Meteorological Institute is the most developed and tested, widely used tool for modeling the cosmic environment of the Earth in Europe. An inner magnetosphere model should be two–way coupled to the existing configuration of the simulation tool to improve the accuracy of the simulations.

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References

[1] Balogh, A., Carr, C. M., Acuña, M. H., et al. 2001, Annales Geophysicae, 19, 1207

[2] Balogh, A., Dunlop, M. W., Cowley, S. W. H., et al. 1997, Space Science Reviews, 79, 65

[3] Blagau, A., Dandouras, I., Barthe, A., et al. 2013, Geoscientific Instrumentation, Methods and Data Systems Discussions, 3, 407

[4] Blagau, A., Dandouras, I., Barthe, A., et al. 2014, Geoscientific Instrumentation, Methods and Data Systems, 3, 49

[5] Chittenden, J. P., Lebedev, S. V., Jennings, C. A., Bland , S. N., & Ciardi, A. 2004, Plasma Physics and Controlled Fusion, 46, B457

[6] Ciardi, A., Lebedev, S. V., Frank, A., et al. 2007, Physics of Plasmas, 14, 056501

[7] Credland, J., Mecke, G., & Ellwood, J. 1997, Space Science Reviews, 79, 33

[8] Décréau, P. M. E., Fergeau, P., Krasnoselskikh, V., et al. 2001, Annales Geophysicae, 19, 1241

[9] Escoubet, C. P., Fehringer, M., & Goldstein, M. 2001, Annales Geophysicae, 19, 1197

[10] Facskó, G., Honkonen, I., Živković, T., et al. 2016, Space Weather, 14, 351

[11] Fazakerley, A. N., Lahiff, A. D., Rozum, I., et al. 2010, Astrophysics and Space Science Proceedings, 11, 281

[12] Fazakerley, A. N., Lahiff, A. D., Wilson, R. J., et al. 2010, Astrophysics and Space Science Proceedings, 11, 129

[13] García, K. S. & Hughes, W. J. 2007, Journal of Geophysical Research (Space Physics), 112, A06229

[14] Gordeev, E., Facskó, G., Sergeev, V., et al. 2013, Journal of Geophysical Research (Space Physics), 118, 3138

[15] Greenwald, R. A., Baker, K. B., Dudeney, J. R., et al. 1995, Space Science Reviews, 71, 761

[16] Gustafsson, G., André, M., Carozzi, T., et al. 2001, Annales Geophysicae, 19, 1219

[17] Gustafsson, G., Bostrom, R., Holback, B., et al. 1997, Space Science Reviews, 79, 137

[18] Haiducek, J. D., Welling, D. T., Ganushkina, N. Y., Morley, S. K., & Ozturk, D. S. 2017, Space Weather, 15, 1567

[19] Janhunen, P., Palmroth, M., Laitinen, T., et al. 2012, Journal of Atmospheric and Solar-Terrestrial Physics, 80, 48

[20] Johnstone, A. D., Alsop, C., Burge, S., et al. 1997, Space Science Reviews, 79, 351

[21] Juusola, L., Amm, O., Kauristie, K., & Viljanen, A. 2007, Annales Geophysicae, 25, 721

[22] Juusola, L., Facskó, G., Honkonen, I., et al. 2014, Space Weather, 12, 582

[23] Kallio, E. & Facskó, G. 2015, Planetary and Space Science, 115, 69

[24] Lakka, A., Pulkkinen, T. I., Dimmock, A. P., et al. 2018, Annales Geophysicae Discussions, https://doi.org/10.5194/angeo-2018-81

[25] Lakka, A., Pulkkinen, T. I., Dimmock, A. P., et al. 2018, Journal of Geophysical Research (Space Physics), 123, 3320

[26] Lani, A., Sanna, A., Villedieu, N., & Panesi, M. 2012, in ESA Special Publication, Vol. 714, ESA Special Publication, 45

[27] Liemohn, M., Ganushkina, N. Y., De Zeeuw, D. L., et al. 2018, Space Weather, 16, 1583

[28] Lyon, J. G., Fedder, J. A., & Mobarry, C. M. 2004, Journal of Atmospheric and Solar-Terrestrial Physics, 66, 1333

[29] Mejnertsen, L., Eastwood, J. P., Chittenden, J. P., & Masters, A. 2016, Journal of Geophysical Research (Space Physics), 121, 7497

[30] Mejnertsen, L., Eastwood, J. P., Hietala, H., Schwartz, S. J., & Chittenden, J. P. 2018, Journal of Geophysical Research (Space Physics), 123, 259

[31] Peredo, M., Slavin, J. A., Mazur, E., & Curtis, S. A. 1995, Journal of Geophysical Research, 100, 7907

[32] Poedts, S., Kochanov, A., Lani, A., et al. 2020, Journal of Space Weather and Space Climate, 10, 14

[33] Powell, K. G., Roe, P. L., Linde, T. J., Gombosi, T. I., & De Zeeuw, D. L. 1999, Journal of Computational Physics, 154, 284

[34] Raeder, J., Larson, D., Li, W., Kepko, E. L., & Fuller-Rowell, T. 2008, Space Science Reviews, 141, 535

[35] Reigber, C., Lühr, H., & Schwintzer, P. 2002, Advances in Space Research, 30, 129

[36] Rème, H., Aoustin, C., Bosqued, J. M., et al. 2001, Annales Geophysicae, 19, 1303

[37] Reme, H., Bosqued, J. M., Sauvaud, J. A., et al. 1997, Space Science Reviews, 79, 303

[38] Ritter, P., Lühr, H., Viljanen, A., et al. 2004, Annales Geophysicae, 22, 417

[39] Siscoe, G. L., Erickson, G. M., Sonnerup, B. U., et al. 2001, in AGU Spring Meeting Abstracts, Vol. 2001, SM52D–02

[40] Tóth, G., van der Holst, B., Sokolov, I. V., et al. 2012, Journal of Computational Physics, 231, 870

[41] Trotignon, J. G., Décréau, P. M. E., Rauch, J. L., et al. 2010, Astrophysics and Space Science Proceedings, 11, 185

[42] Trotignon, J.-G., Valliéres, & the WHISPER team. 2011, Calibration Report of the WHISPER Measurements in the Cluster Active Archive (CAA), Tech. rep., LPC2E CNRS, caa-est-cr-whi

[43] Tsyganenko, N. A. 1995, Journal of Geophysical Research, 100, 5599

[44] Vörös, Z., Facskó, G., Khodachenko, M., et al. 2014, Journal of Geophysical Research (Space Physics), 119, 6273

[45] Wang, Z.-D. & Xu, R. L. 1994, Geophysical Research Letters, 21, 2087

[46] Zhang, B., Sorathia, K. A., Lyon, J. G., et al. 2019, The Astrophysical Journal Supplement Series, 244, 20