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RECONSTRUCTION OF NIGHTSIDE FLUX TRANSFER EVENTS USING CLUSTER DATA

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Abstract. A Petschek-type model of magnetic reconnection is used to describe the behaviour of nightside flux transfer events (NFTEs). Based on the Cagniard-deHoop method we calculate the magnetic field and plasma flow time series observed by a satellite. The reconstruction of the reconnection electric field is an ill-posed inverse problem, which we treat with the method of regularisation, since the solution of the Cagniard-deHoop method is given in the form of a convolution integral, which is a well-known problem in the theory of inverse problems. This method is applied to Cluster measurements from September 8th, 2002, and from August, 13th, 2002, where a series of Earth-ward propagating 1-minute scale magnetic field and plasma flow variations are observed which are consistent with the theoretical picture of NFTEs. Methods to estimate the satellite position with respect to the reconnection site as well as the Alfven velocity are presented because they are necessary parameters used in the model. The reconnection electric field for the event on September 8th, 2002, is found to be about 2 mV/m with a time duration of 30 s. The reconnection site is found at about 29 R_e in the magnetotail. The event on August 13th, 2002, gives a reconnection electric field of 4 mV/m with a time duration of 40 s and a location at about 24 R_e in the magnetotail.

1. Introduction

From the analysis of magnetic field data from ISEE--1 and 2 spacecrafts, Russell and Elphic (1978) found that there appear localized, transient reconnection events, identified by an isolated bipolar variation of the magnetic field component normal to the magnetopause and a simultaneous deflection in the tangential components. They interpreted these features as disturbances caused by a moving flux tube passing by the satellite, which they called ``flux transfer events'' (FTEs).

After the observation of these FTE signatures, some attempts were made to reconstruct different features of the reconnection process involved in the generation of FTEs (Southwood, 1985; Farrugia et al., 1987). Walthour et al. (1994) used a method based on integral transforms for inferring the cross-sectional size, shape, and the speed of propagation of a thin, infinitely long obstacle corresponding to a flux tube in a deHoffmann-Teller frame. Another approach to this topic was used by several authors (Hau and Sonnerup, 1999; Hu and Sonnerup, 2003) who developed a method based on the Grad--Shafranov equation to reconstruct two-dimensional space plasma structures in magnetohydrostatic equilibrium. Sonnerup et al. (2004) used this method to give a rough estimation of the reconnection rate.

In order to describe the temporal evolution of FTEs, time--dependent Petschek--type models of reconnection were developed (e.g., Biernat et al.,1987; Semenov et al.,1992; Heyn and Semenov, 1996). Lawrence et al. (2000) analyzed a series of FTE-like events generated by a time--dependent model of reconnection. Recently, Semenov et al. (2005) developed a theoretical model to reconstruct the reconnection rate out of perturbations of the ambient magnetic field for an incompressible plasma. This method was also sucessfully applied to Cluster measurements in the magnetotail (Penz et al., 2005).

FTE--like structures appear also in the Earth magnetotail, which was investigated by Sergeev et al. (1992). They called them nightside flux transfer events (NFTEs) and described such events in the frame of impulsive transient reconnection. The appearance of reconnection structures in the magnetotail was also confirmed by several other satellite observations, like Cluster and Geotail.

Here, we present an application of the model developed by Semenov et al. (2005) to two NFTEs observed by Cluster.

2. The theoretical method and the inverse problem

We consider a geometry of antiparallel magnetic fields, which are separated by an infinitely thin current sheet. The background magnetic fields and the total pressure are assumed to be constant. Additionally, we consider a fixed plasma, meaning that the velocity is zero in the inflow region in lowest order. The problem can be separated in two different steps. First we can evaluate the tangential components of the magnetic field and the plasma flow from the non-linear system of MHD equations for the zero order by assuming that these quantities are constant. If they are constant, they can be found from the Rankine-Hugoniot relations directly. In a second step, we can determine the normal components from the linearized system of MHD equations in the first order approximation. This is the direct solution of the Petschek-type model of reconnection (e.g., Biernat et al., 1987).

To calculate time series of the magnetic field and plasma flow components, which correspond to satellite measurements, we use the Cagniard-deHoop method (Heyn and Semenov, 1996). The solution of the direct problem is obtained in terms of a displacement vector, from which the magnetic field and plasma flow parameters in Fourier-Laplace space can be derived. The Cagniard-deHoop method is used to perform the inverse Laplace transform analytically, which gives the normal component of the magnetic field in real space as the convolution integral

$$B(x,z,t)=\int_0^t \mathrm{G}(x,z,\tau)E(t-\tau)d\tau, \quad (1)$$

where *G(x,z,t)* is the integration kernel, which depends on the magnetic field configuration and the distance between the observation position and the reconnection site, and *E(t)* is the reconnection electric field. For the plasma flow and the tangential component of the magnetic field, similar expressions can be found.

The representation as convolution integrals in time is favorable, because it allows a convenient treatment of the inverse problem. If we consider the satellite as fixed in space, the magnetic field is a function of time only. In this case, the convolution integral in Laplace space can be written as

$$B(p)=G(p)E(p), \quad (2)$$

To reconstruct the reconnection electric field we introduce a regularization operator *M(p)* (Tikhonov and Arsenin, 1977) giving

$$E(p)=\frac{B(p)}{G(p)+M(p)}, \quad (3)$$

This operator is chosen in a way that it does not influence the electric field for small values of *p*, but when the functions *B(p)* and *G(p)* reach small values, the denominator is forced to go to infinity, so that the reconnection electric field is zero in Laplace space and large oscillations are suppressed.

3. The event on September 8th, 2002

On September 8th, 2002, an isolated substorm with a peak AE of about 400 nT occurred (Sergeev et al., 2005). A clear growth phase was observed after a phase of a southward-orientated IMF, which started at about 20:00 UT. The expansion phase onset took place at 21:18 UT in the 22-24 MLT sector. After 21:17 UT, a series of Earth-ward propagating 1 minute scale variations of the magnetic field and plasma flow components (Fig. 1) consistent with the picture of multiple NFTEs/flux ropes were observed by Cluster (Sergeev et al., 2005; Penz et al., 2005). The Cluster tetragon was located at [-16.7; 0.2; 4.5] R_e GSM. The satellites exited from the thinning plasma sheet shortly after 21:00 UT.

In the following we use the GSM magnetic field data obtained from the fluxgate magnetometer (FGM) experiment with 1 s time resolution and O^+ moments with 4 s time resolution by the Composition and Distribution Function Analyser (CODIF) of the Cluster Ion Spectrometry (CIS) experiment.

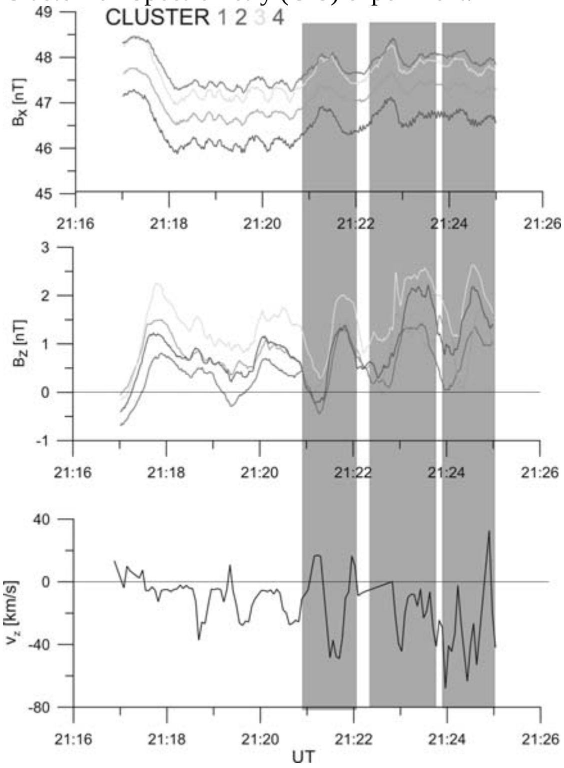

Fig. 1: The magnetic field and plasma flow components observed by the Cluster satellites. The shaded areas indicate the analysed NFTEs.

To evaluate the integration kernel *G(p)* we need also to know the spacecraft location with respect to the reconnection site. Fortunately, the actual z-position of the neutral sheet is known from the modeling made in Sergeev et al. (2005). Therefore, the z-distance between the satellite and the reconnection site is approximately 3.5 R_e. The x-distance is estimated by using a minimization routine (Penz et al., 2005).

Application of our model to the NFTE starting at 21:21 UT leads to a reconnection rate between 1.5 and 2.1 mV/m determined from all 4 satellites, while the location of the reconnection site is between 29.2 and 30.9 Re in the magnetotail. The reconstructed electric field for the NFTE at 21:22:30 lies between 0.9 and 1.4 mV/m and is located between 29.2 and 30 R_e. The reconstructed reconnection rate for the NFTE starting at 21:24 UT is between 1.2 and 1.6

mV/m, and the reconnection site is at 28.6 to 29.7 Re in the magnetotail.

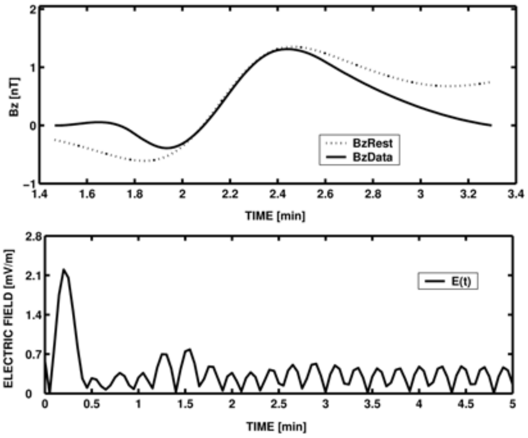

Fig. 2: The measured (solid line) and reconstructed magnetic field (dashed-dotted line) and the reconstructed reconnection electric field (lower panel) for the event on September 8th, 2002.

4. The event on August 13th, 2002

A substorm with a peak AE of about 400 nT occurred on August 13th, 2002, with electrojet intensification starting from about 22:52 UT. Cluster was located at postmidnight sector at [-17.2; -6.9; 2-4] R_e GSM and experienced thinning of the plasma sheet after 22:30 UT and exited into the lobe around 22:55 UT. Cluster then started to observe bursty flow enhancements with B_z fluctuations as the spacecraft reencountered the plasma sheet at 23:06 UT. A series of Earth-ward flows and variations of the B_z magnetic field similar to the September 8th events were detected except for the fact that Cluster was near the centre of the plasma sheet within the current sheet as shown in the small B_x values in Figure 3. In fact for this particular event, B_x of C3 was almost zero, indicating that C3 was located at the centre of the current sheet. For applying the analytical model we therefore use the z-distance from C3 as the location in z for each spacecraft, i.e., (Zc1, Zc2, Zc3, Zc4) = (0.4, 0.5, 0.0, 0.4) R_e. Note that if we simply fit the data into Harris current sheet assuming (1) lobe field value estimated from total pressure of C4 between 23:13:20 and 23:14:20 UT (2) C3 being at the center of the current sheet, the thickness of the current sheet will be 1.3 RE. Hence, all the four spacecraft are located quite inside the plasma sheet.

For this case, where the satellites are clearly located inside the plasma sheet, an reconnection electric field between 4 and 5 mV/m was found. The time duration of the pulse is in the range of 30 to 40 s, and the reconnection site is located 23.2 to 24.7 Re in the Earth magnetotail.

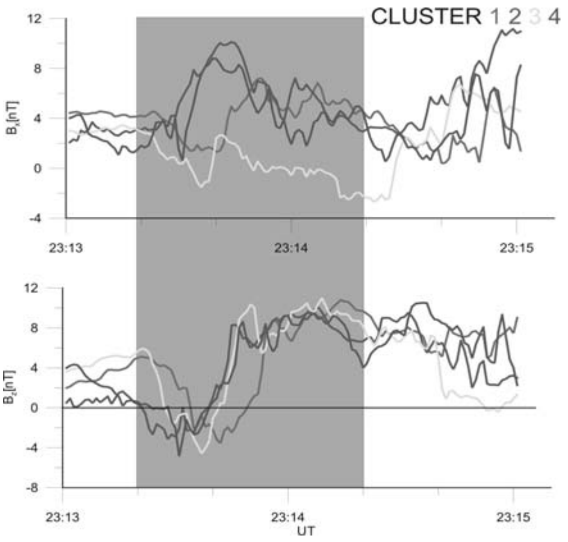

Fig. 3: The magnetic field components observed by the Cluster satellites on August 13th, 2002. The shaded area indicates the analysed NFTE.

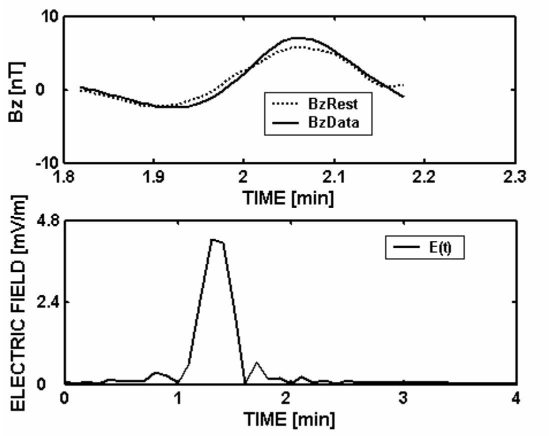

Fig. 4: The measured (solid line) and reconstructed magnetic field (dotted line) and the reconstructed reconnection electric field (lower panel) for the event on August 13th, 2002.

6. Conclusions

In this work we present a first attempt to reconstruct the reconnection electric field from satellite measurements in an incompressible plasma. However, the application of an analytical model requires to make some simplifications, which should be mentioned in the following.

The x-distance between the satellite and the reconnection site is determined by using a minimization routine. There exists the possibility that more that one minimum occurs, meaning that there is no single solution for the problem considered. In this case, the routine may give a wrong result. To avoid this problem, we applied our method only to the range of x-distances, where reconnection most likely takes place, namely the NENL to a distance less than 35 Re, and run it with different starting points.

We assume that the perturbations in the magnetic field are moving approximately with Alfvén velocity.

Additionally, we assume that there is a homogeneous background density in the magnetotail. If the density changes significantly between the point of observation and the starting point of the disturbances, the estimated Alfvén velocity may differ from the real one. Since the Alfvén velocity is used for the normalization of the length scales, a variation of the Alfvén velocity will also give a variation of the spatial distances.

Another simplification is the assumption of the incompressibility of the plasma. Future work on this topic will mainly deal with the extension of the model to compressible plasma. Direct models for compressible plasma exist (Heyn and Semenov, 1996), but it is necessary to rewrite the solution in form of a convolution integral over time in order to solve the inverse problem. Additionally, a comparison of the results with a numerical magnetotail model should clarify the influence of an inhomogeneous distribution of the plasma density and the finite thickness of the plasma sheet. This is of particular interest for the case on August 13th, 2002, since it is not clear if the location of the satellites inside the plasma sheet changes the result of our model. This should be investigated by a comparison with results of a numerical model.

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