



# A reconstruction method for the reconnection rate applied to Cluster magnetotail measurements

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## Abstract

We apply a theoretical model to describe the behavior of nightside flux transfer events (NFTEs) measured by Cluster satellites in the Earth magnetotail. Based on the Cagniard–deHoop method we calculate the magnetic field and plasma flow time series observed by a satellite. Our aim is to solve an inverse problem to obtain the reconnection rate from the measured plasma data. The ill-posed inverse problem is treated with the method of regularization, since the solution of the Cagniard–deHoop method is given in the form of a convolution integral, which is well known in the theory of inverse problems. This method is applied to Cluster measurements from September 8th, 2002, where a series of Earthward propagating 1-min scale magnetic field and plasma flow variations were observed outside of the plasma sheet, which are consistent with the theoretical picture of NFTEs. Estimations of the satellite position with respect to the reconnection site and of the Alfvén velocity are made because they are necessary parameters for the model. The reconnection rate is found to be in the range of 1–2 mV/m and the reconnection site at about 29  $R_e$  tailwards.

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## 1. Introduction

Russell and Elphic (1978) analyzed ISEE observations of the dayside magnetopause and found events which last several minutes and have a bipolar variation of the magnetic field component normal to the magnetopause. These events were interpreted as isolated tubes of magnetic flux, connecting magnetosheath field lines with magnetospheric ones, and are called flux transfer events

(FTEs). After the observation of these FTE signatures several attempts were made to reconstruct different features of the reconnection process involved. Southwood (1985) predicted that FTE signatures would be observed by a satellite regardless of whether or not it actually penetrates the FTE itself. Farrugia et al. (1987) verified Southwood's suggestion and showed that FTE-like signatures could be detected without the satellite is penetrating the obstacle. After that a method for inferring the cross-sectional size, shape, and the propagation speed of a thin, infinitely long obstacle was developed by Walthour et al. (1993, 1994), where the analysis is confined to perturbations appearing outside the obsta-

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cle. Lawrence et al. (2000) applied this method to a series of FTE-like events generated by a time-dependent model of magnetic reconnection. Hu and Sonnerup (2003) developed a method to reconstruct two-dimensional space plasma structures in magnetohydrodynamic equilibrium, which they applied to two magnetopause crossings of the AMPTE/IRM spacecraft. Additionally, this method was applied to Cluster measurements at the dayside magnetopause (Hasegawa et al., 2004; Sonnerup et al., 2004). 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.

In this work, we apply this method to so-called night-side flux transfer events (NFTEs). These are short-term events in the substorm-time plasma sheet, which can be described by impulsive variations of the reconnection rate in models of transient reconnection. Such structures noticed in the tail plasma sheet are often referred to as individual bursts of BBF, as transient plasma sheet expansions, as plasmoids or flux ropes, as well as NFTEs (e.g. Sergeev et al., 1992; Ieda et al., 1998; Slavin et al., 2003). Our approach is based on the Cagniard–deHoop method which was applied to magnetic reconnection in an incompressible plasma by Semenov et al. (2005). Using this method, the magnetic field and velocity components are found to be convolution integrals of the reconnection rate. The reconstruction of the reconnection rate out of these components is therefore an ill-posed inverse problem, which we treat by using Tikhonov regularization (Tikhonov and Arsenin, 1977). Additionally, we reconstruct the distance between the satellite and the reconnection site.

## 2. The theoretical model 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. If we perform an order-of-magnitude estimate, we can use the assumption for weak reconnection that quantities perpendicular to the current sheet are small compared with the tangential components. Now 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 Pet-

schek-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

$$B_z(x, z, t) = C \mathfrak{R} \int_0^t g(x, z, t) E(t - \tau) d\tau, \quad (1)$$

where  $C$  is a constant,  $g(x, z, t)$  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 (Semenov et al., 2005).

An example for the result of the calculations is shown in Fig. 1. The model predicts the bipolar variation of  $B_z$  which anticorrelates with the variation of the  $z$ -component of the plasma flow velocity. The beginning of the positive  $B_z$  pulse corresponds to the maximum of the variation in  $B_x$  (dashed–dotted line in Fig. 1). This behavior is considered to be the typical observational characteristic of an NFTE (Sergeev et al., 1992, 2005).

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,  $B_z(x, z, t) = B_z(t)$ . Now the convolution integral in Laplace space can be written as  $B_z(p) = G(p)E(p)$ . To reconstruct the reconnection electric field we introduce a regularization operator  $M(p)$  (Tikhonov and Arsenin, 1977) giving

$$E(p) = \frac{B_z(p)}{G(p) + M(p)}. \quad (2)$$

This operator is chosen in a way that it does not influence the electric field for small values of  $p$ , but when the functions  $B_z(p)$  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. Application to two events 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

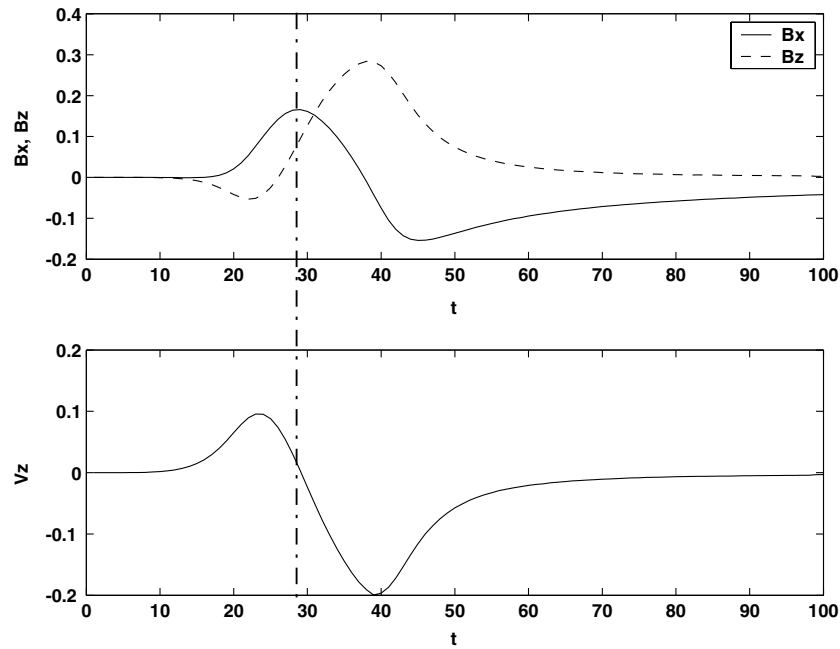


Fig. 1. The normal (dashed line) and the tangential (solid line) magnetic field (upper panel) and the normal flow velocity (lower panel). The dashed-dotted vertical line indicates the correspondence between the maximum of the variation in  $B_x$  and the change in sign of the other two components.

20:00 UT. The expansion phase onset took place at 21:18 UT in the 22–24 MLT sector. An auroral breakup, a westward auroral electrojet, and Pi2 pulsations were observed at different Earth-based stations and several satellites. After 21:17 UT, a series of Earth-ward propagating 1 min scale variations of the magnetic field and plasma flow components consistent with the picture of multiple NFTEs/flux ropes were observed by Cluster (Sergeev 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. Since the plasma sheet continued to be thin until the transient plasma sheet expansions start to be observed, the satellites were located outside of it. This is a favorable situation for our model, because if the plasma sheet is thin, the approximation of a tangential discontinuity is better fulfilled.

In the following, we use the GSM magnetic field data obtained from the fluxgate magnetometer (FGM) experiment (Balogh et al., 2001) with 1 s time resolution and  $O^+$  moments with 4 s time resolution by the composition and distribution function analyzer (CODIF) of the Cluster ion spectrometry (CIS) experiment (Rème et al., 2001) observed at the Cluster spacecraft C1. The  $O^+$  data were only used if the  $O^+$  density exceeded  $0.005 \text{ cm}^{-3}$ . As Sauvaud et al. (2004) showed, cold oxygen beams are an excellent tool for the measurement of the motion of lobe plasma tubes.

We applied our model to the NFTEs at 21:21 and 21:23 UT (Fig. 2), since the main features and the 1 min time scale expected for NFTEs are well pro-

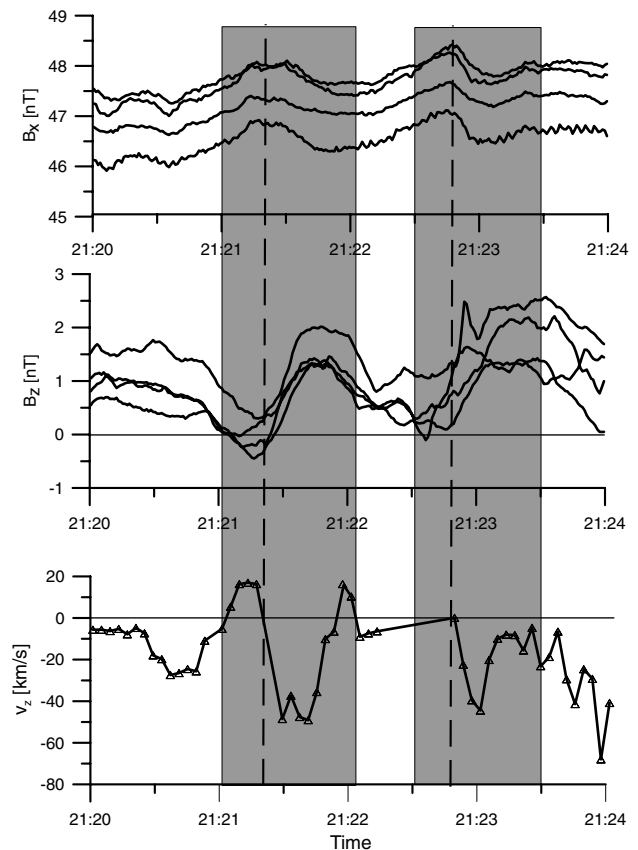


Fig. 2. The event on September 8th, 2002, observed by the four Cluster satellites. We analyze the NFTEs starting at 21:21 and 21:23 UT marked by the shaded areas. The dashed vertical line has the same meaning as in Fig. 1.

nounced for these events. The bipolar variation of  $B_z$ , a deflection of  $B_x$ , as well as a plasma flow  $v_z$  of cold  $O^+$  ions directed to the plasma sheet are clearly visible. Therefore, we suppose that the observed features can be treated in the frame of our theoretical model, which predicts exactly the same behavior.

To evaluate the integration kernel  $K(p)$  it is necessary to know the distance between the satellite and the reconnection site. The determination of the  $z$ -distance can be found by using a magnetotail model from which we can approximately find the shift of the plasma sheet compared with the GSM coordinate system (Sergeev et al., 2005). For the event we consider, the shift is about  $1 R_e$  in  $z$ -direction. Therefore, the  $z$ -distance between the satellite and the reconnection site is approximately  $3.5 R_e$ . The determination of the  $x$ -distance is done by using a global minimization routine. We use the measured  $B_z$  component as input data, calculate the electric field, which should be strictly positive, but since we do not know the  $x$ -distance it can be negative somewhere. Therefore, we take the module of the electric field and recalculate  $B_z^*$  out of it. This procedure can be summarized as

$$B_z(t) \Rightarrow B_z(p) \Rightarrow E(p) \Rightarrow E(t) \Rightarrow |E(t)| \Rightarrow B_z^*(t).$$

Then we minimize the difference between  $B_z(t)$  and  $B_z^*(t)$  with a least square approach in order to find the  $x$ -distance as the value of  $x$  where the difference between the initial and the reconstructed magnetic field has a minimum. We limit the search to distances less than  $30 R_e$ ,

which corresponds to the region of the near Earth neutral line (NENL), where reconnection most likely takes place. The local velocity of the disturbances is determined by using multipoint timing analysis (e.g. Harvey, 1998), giving about 700 km/s. We assume that this velocity is approximately the Alfvén velocity. Additionally, this analysis shows that the flow is directed mainly earthwards in  $x$ -direction with a small  $y$ -component, which is a preferable configuration for our 2D model.

Application of our model to the NFTE starting at 21:21 UT in Fig. 2 leads to a reconnection electric field of 2.1 mV/m over a time period of about 30 s (Fig. 3). The location in  $x$ -direction was found to be  $29 R_e$  tailwards. The reconstructed electric field for the NFTE at 21:23 UT is 0.9 mV/m with a time duration of about 20 s (Fig. 4). Again the location of the reconnection site is at  $29 R_e$  tailwards. The smaller pulses which can be seen in Figs. 3 and 4 for times larger than 30 s are noise, resulting from the solution of the inverse problem. The amplitude of the noise mainly depends on the  $z$ -distance between the satellite and the reconnection structure (Semenov et al., 2005). If the  $z$ -distance decreases, the amplitude of the noise also decreases.

#### 4. Discussion and conclusions

To reconstruct the reconnection electric field, it is necessary to know crucial quantities like the distance be-

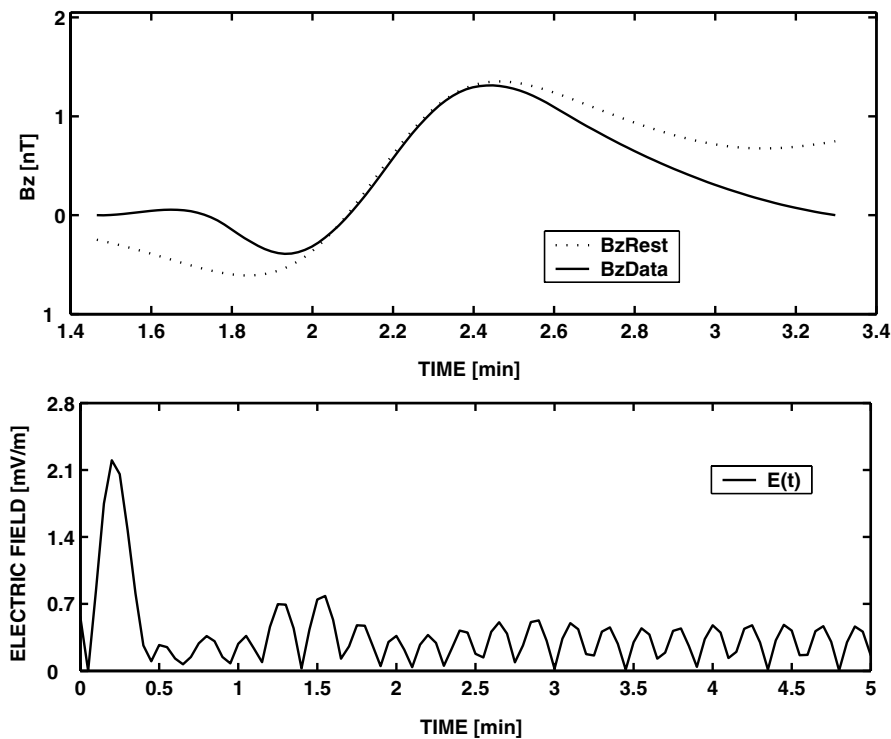


Fig. 3. The reconnection electric field for NFTE starting at 21:21 UT (lower panel), and initial (solid line) and reconstructed magnetic field (dashed line).

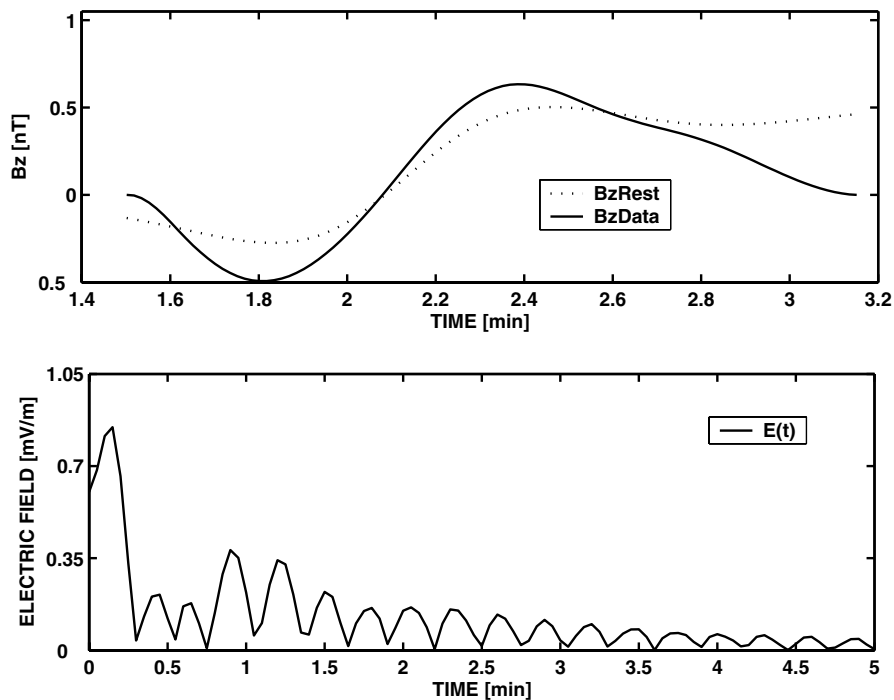


Fig. 4. The reconnection electric field for NFTE starting at 21:23 UT (lower panel), and initial (solid line) and reconstructed magnetic field (dashed line).

tween the satellite and the reconnection site and the Alfvén velocity. The distance in  $z$ -direction can be found with satisfactory precision by using a magnetotail model, which gives the location of the plasma sheet (Sergeev et al., 2005). The estimation of the  $x$ -distance is more problematic, because there is a possibility that more than one minimum occurs, meaning that there is no single solution. In this case the routine may give a wrong result. To avoid this problem, we apply our method only to the range of  $x$ -distances, where reconnection most likely takes place, namely the NENL to a distance less than  $30 R_e$ .

The Alfvén velocity is assumed to be approximately equal to the velocity of the magnetic disturbances found from multipoint timing analysis. But if the density changes significantly between the point of observation and the reconnection site, 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. If the Alfvén velocity decreases, the length scales will also decrease.

A weak feature of our model is the fact that the variation of the  $B_x$  component is overestimated. This is possibly a problem related with the assumed incompressibility of the plasma in our model. Implementation of the compressibility of the plasma leads to a smaller height of the outflow region. Since the variations of the  $B_x$  component depend mainly on the height of the outflow region and the reconnected flux, this overesti-

mation can be explained in that way. The  $B_z$  component depends on the inclination of the shock, which bounds the outflow region, and the inclination is very similar in both cases, therefore the model reproduces the  $B_z$  component satisfactory.

In this work, we present for the first time a method to reconstruct the reconnection rate out of magnetic field measurements outside the plasma sheet. We found that the variations observed by the Cluster spacecrafts are consistent with the impulsive model of magnetic reconnection used in this work. The amplitude of the reconnection electric field is found to be in the range of 1–2 mV/m. This amplitude is in good agreement with measurements of the magnetotail electric field (e.g. Cattell and Mozer, 1982). The time duration of the reconnection pulses is in the order of 20–30 s, while the reconnection site is located at about  $29 R_e$  tailwards.

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