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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.

Keywords: Reconnection; Flux transfer events; Cluster spacecraft; Inverse problem

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

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obstacle. 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 nightside 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 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

$$B_z(x,z,t) = C\Re\int_0^t g(x,z,t)E(t-\tau)\,\mathrm{d}\tau, \tag{1}$$

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

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

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