# TC1 and Cluster observation of an FTE on 4 January 2005: A close conjunction

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[1] Observations of a Flux Transfer Event (FTE) signature at the dayside magnetopause are reported, which was consecutively observed on 4 January 2005 by both the Double Star/TC1 spacecraft and the Cluster quartet, while the spacecraft were traversing through the northern-dusk magnetopause. The event occurred as a magnetosheath FTE first at the Cluster spacecraft at about 07:13 UT on 4 January 2005 and crossed each of the others within 2 minutes. The spatial separations between the Cluster spacecraft were of the order of 200 km. The TC1 signature occurred about 108s after Cluster. All findings including magnetic fluxes, orientations and hot ion velocity distributions strongly suggest that Cluster and TC1 encountered the magnetosheath branch of the same flux tube at two different positions along its length and this is borne out by computation of the expected time delay. Four-spacecraft timing is used to obtain the velocity of FTE. **Citation:** Wang, J., et al. (2007), TC1 and Cluster observation of an FTE on 4 January 2005: A close conjunction, *Geophys. Res. Lett.*, *34*, L03106, doi:10.1029/2006GL028241.

## 1. Introduction

[2] Intermittent magnetic reconnection at the Earth's magnetopause (MP) can result in localized bundles of open flux ropes which carry distinct magnetic field signatures, when passing by adjacent to a spacecraft, known as FTEs [*Russell and Elphic*, 1978; *Haerendel et al.*, 1978]. The events are identified as the magnetosheath (magnetospheric) FTEs when they show a bipolar $B_N$ signature on the magnetosheath (magnetospheric) side of the MP. Newly opened flux tubes in FTEs provide channels for the solar wind plasma to access to the magnetosphere and for the magnetospheric particles to escape to the interplanetary space [*Owen and Cowley*, 1991; *Pu et al.*, 2005a]. There have been many papers on observed features of FTEs (see, for example, the review by *Elphic* [1995]), but there exist only a limited number of papers on the motion and configuration of FTEs [*Cooling et al.*, 2001; *Kawano and Russell*, 2005]. *Kawano and Russell* [2005] statistically analyzed the dual-satellite simultaneous observations of FTEs by ISEE 1 and ISEE 2. They found that longitudinally tailward motions of FTEs are significant and consistent with a longitudinally limited spatial size of the FTE structure at the merging line, rather than being longitudinally elongated.

[3] Until now there has been no direct measurement along the length of a flux tube moving across the magnetopause. Detection of such motions of FTEs is difficult with two-point observations, which do not completely resolve the problem. Recent coordinated measurements of Cluster and Double Star have made it possible to measure the motion of FTEs and flux rope configurations at large scales [*Liu et al.*, 2005]. *Dunlop et al.* [2005] investigated a Cluster-TC1 conjunction event on April 6, 2004 in which Cluster and TC1 observed a series of oppositely directed FTEs at the dawnside northern magnetopause and dawnside southern magnetopause, respectively. They showed that the flux ropes observed by Cluster were moving dawnward and northward, and the flux ropes observed by TC1 were moving dawnward and southward. This result is in agreement with the fact that these flux ropes were formed near the dayside equatorial MP, propagating in pairs from a common X-line. *Xiao et al.* [2005] compared the TC1 multiple FTEs on March 18, 2004 at the duskside southern MP and the Cluster multiple FTEs on January 26, 2001 at the dawnside northern MP. These two events occurred in almost the same IMF and solar wind conditions; the motions of flux rope possess the similar features as *Dunlop et al.* [2005] reported. *Fear et al.* [2005] also made a statistical study of FTE motion with Cluster data and presented a basically tailward motion of FTEs along the MP.

[4] This paper presents a close conjunction of Cluster and Double Star/TC1 observed on 04 January 2005 [*Pu et al.*, 2005b] using spin averaged (4s resolution) data in which a

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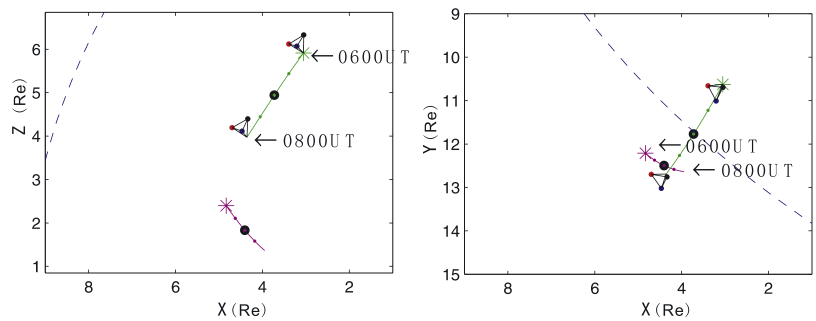


**Figure 1.** The orbits of Cluster and TC1. The black dots show the positions of the spacecraft where they meet the FTE, with the blue dashed lines indicating the magnetopause, based on Shue model [*Shue et al.*, 1998].

newly formed flux tube moving duskward on the MP is sampled along its length.

## 2. Observations

### 2.1. Instruments and Context

[5] This study is based on magnetic field data from Fluxgate Magnetometer (FGM)(0.2s resolution for Cluster and 4s for TC1) and plasma data from Cluster Ion Spectrometry (CIS), Plasma Electron and Current Experiment (PEACE) and TC1/Hot Ion Analyzer (HIA)[*Balogh et al.*, 2001; *Carr et al.*, 2005; *Rème et al.*, 2001, 2005; *Johnstone et al.*, 1997; *Fazakerley et al.*, 2005]. The events occurred on 4 January, 2005, when Cluster and TC1 crossed the MP consecutively at around 07:09UT, both outwards in the interested time interval, as shown in Figure 1. Cluster was located at ~(3.91, 12.11, 4.82) $R_E$(GSM), while TC1 at ~(4.33, 12.53, 1.73)$R_E$(GSM). The MP on the Y = 0 and Z = 0 planes are also shown with blue dashed lines, based on the Shue model [*Shue et al.*, 1998] and the positions of spacecraft during crossing. The IMF $B_z$ remains positive from ~06:30 to ~07:00UT, as detected by Geotail at ~ (19.6, 2.8, 3.8) $R_E$ (GSE). At ~07:00UT, the IMF $B_z$ suddenly became negative. This reversal arrived at the MP shortly after and was observed by Cluster at ~07:08UT, and about 1 minute later by TC1, shown in Figure 2. The onset of southward IMF and notable $B_y$ are expected to be favourable for the onset of reconnection.

### 2.2. TC1 and Cluster Observations

[6] Figure 2 shows the plasma and magnetic field data for the interval of interest. Both Cluster and TC1 were initially in MP boundary layer and magnetosheath before the arrival of the IMF reversal (at 07:08 UT), mentioned above. The MP appeared to move forth in ~3 minutes, resulting in the spacecraft re-entering the magnetosphere. The main crossing into the magnetosheath then occurred at 07:09 UT. Walen test analysis indicated that the MP at this time is an open boundary (not shown in this paper). This sequence was also observed in the energetic particle measurements, which showed field-aligned bi-directional energetic electrons (not shown in this paper).

[7] Figure 3a shows the magnetic field data in boundary normal coordinates. During 07:10–07:20UT, Cluster and TC1 encountered several FTEs. We focus our attention on the FTEs seen by Cluster at ~07:13UT and by TC1 at ~07:15UT, which is 108s later. It can be easily seen in Figure 2 that in both the Cluster and TC1 FTEs (marked by the vertical lines) the hot ion density and temperature were, respectively, lower and higher than the surrounding plasma, indicating that they were both magnetosheath events having similar properties. The PEACE energy spectrograms also show possible mixing of magnetospheric and magnetosheath plasma. The flow of background plasma was mainly tailward and duskward, reflecting that the spacecraft were located near the MP in the dusk sector. DeHoffman-Teller (HT) analysis [*Khrabrov and Sonnerup*, 1998] was applied to both events with very similar results in $V_{HT}$, consistent with background flows. Figure 3b also shows 3-dimensional distributions taken by HIA of thermal ions, detected by Cluster 1 at 07:13:15 and by TC1 at 07:15:05. It can be easily seen that both FTEs had extremely similar velocity distributions.

[8] All results presented above strongly suggest that Cluster and TC1 encountered the same FTE. We therefore model this in terms of a single flux rope successively encountered by the Cluster spacecraft and TC1 at different locations along its length.

## 3. Discussion

[9] According to the model of FTEs, magnetic flux should remain constant in a specific flux rope. We reconstructed the flux rope based on solving the Grad-Shafranov (G-S) equation [*Hu and Sonnerup*, 2002] using FGM and CIS data. The magnetic fluxes contained in the FTEs of Cluster-1 and TC1, versus different magnitude of magnetic vector potential A, are listed in Table 1, which shows that these two FTEs apparently contain approximately equal flux, implying that they arise from the same flux rope. It can be seen that the deviation grows with magnetic flux, which may probably comes from the error increasing in solving the G-S equation with extrapolation. Other properties of the FTEs are also similar.

[10] For a quantitative analysis of this scenario we have analyzed the geometric properties (orientation and motion) of a tilted flux tube model, as described below. Diagrammatically, The flux tube should move along the MP surface in a manner consistent with the solar wind conditions for the event (and as confirmed in this case by the Cooling calculations [*Cooling et al.*, 2001]). As seen in Figure 1, in the X-Y plane, the distance from Cluster to TC1 is basically perpendicular to the MP, therefore, the velocity component in this plane does not affect the time delay much. But for the Z-Y plane the expected time delay will be

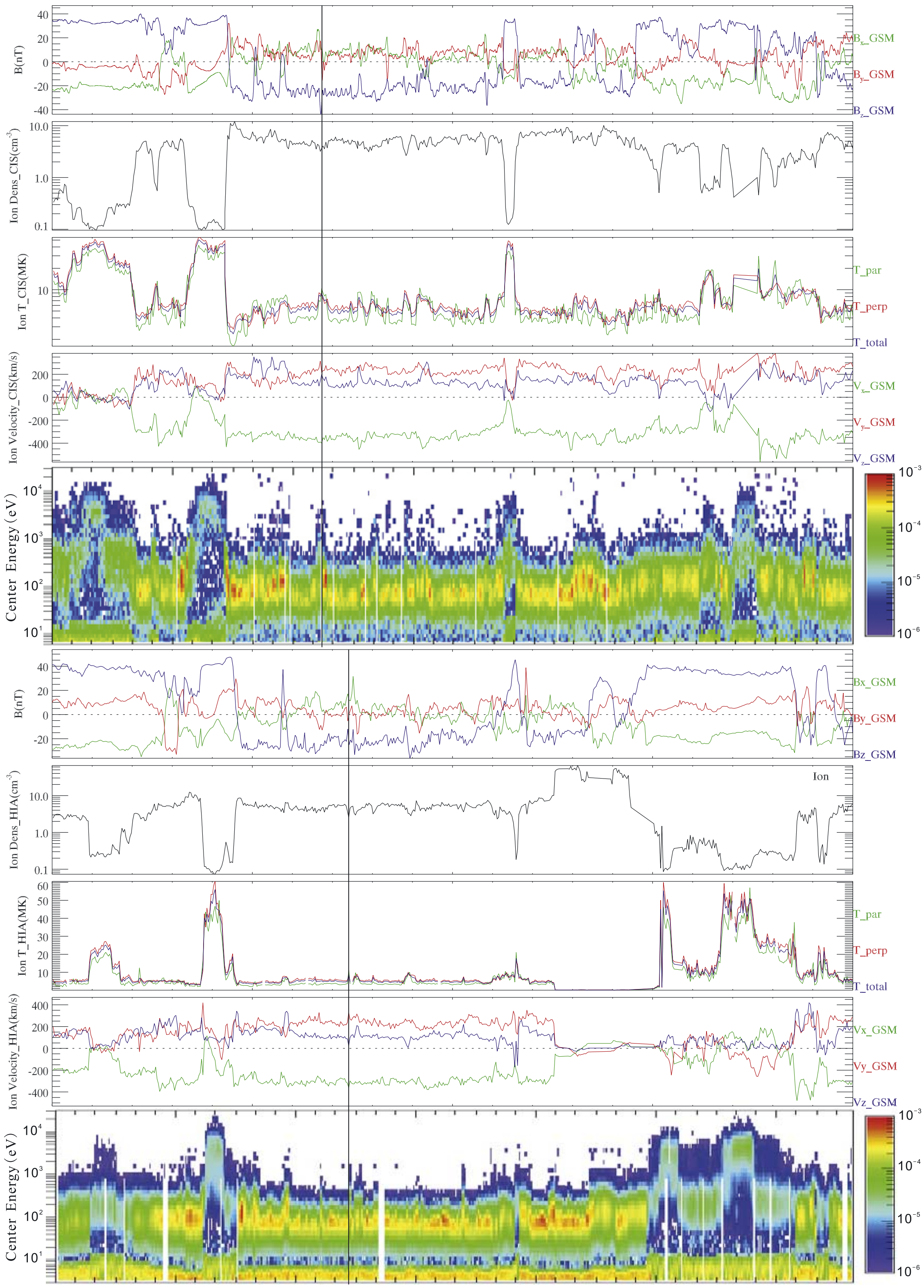


**Figure 2.** The observations of Cluster and TC1 from 07:00 to 07:40UT, 4 January 2005. The top 5 panels are magnetic field, hot ion density, temperature, velocity and PEACE energy spectrum by Cluster/SC1, while the bottom 5 are by TC1. The FTEs are shown by vertical gray lines.

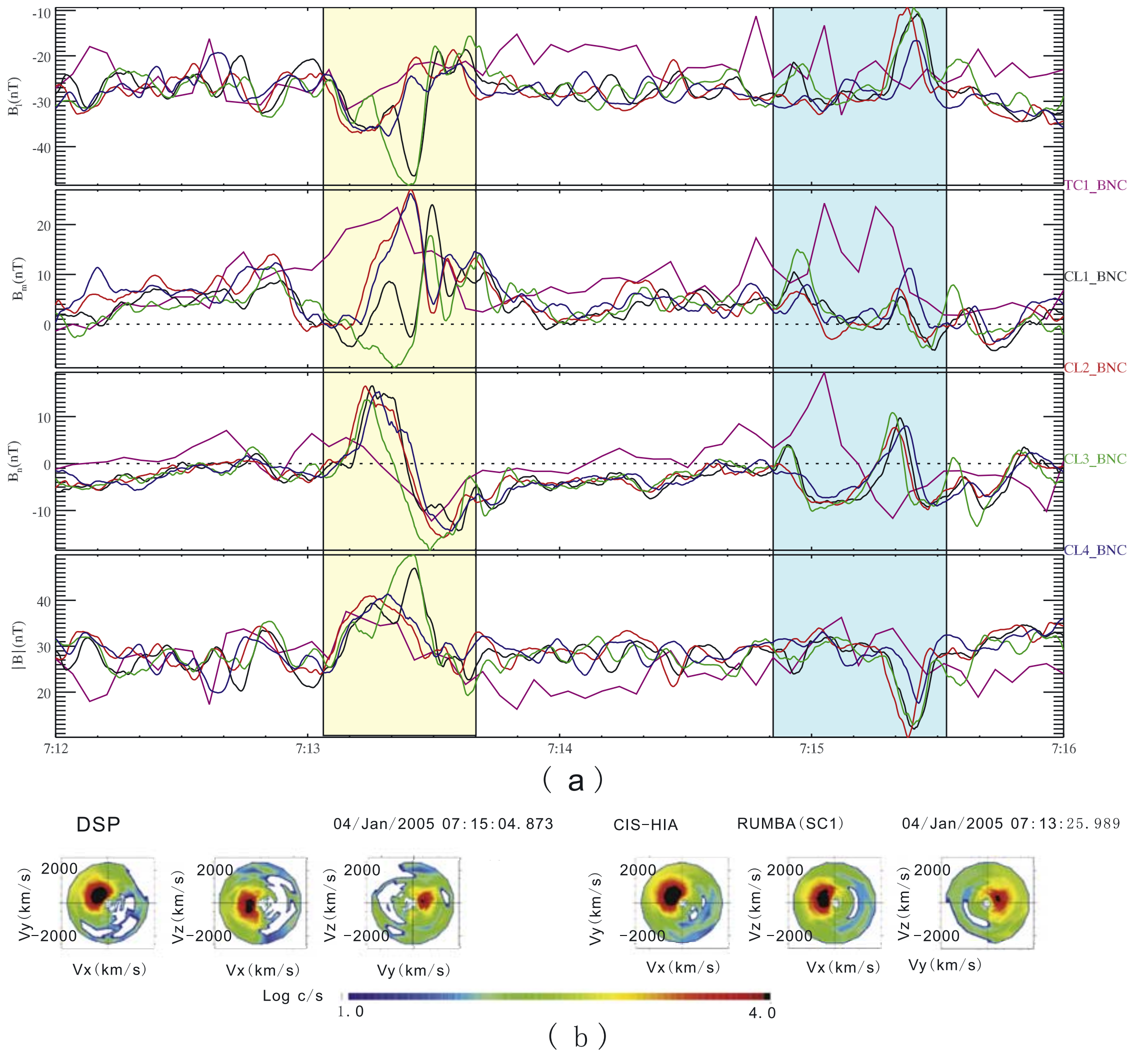


**Figure 3.** Detailed observation of the FTEs. (a) The magnetic field data in Boundary Normal Coordinates, where the $B_N$ bipolar signature is obvious. (b) The velocity distribution (produced by CESR) of hot ion around the center of the FTEs, by TC1 (left) and Cluster/SC1 (right).

highly dependent on the FTE orientation and velocity tilt angle. For the tube is mainly along the Z direction (see Table 2), the larger X component of orientation and Z component of velocity, compared with $V_x$, which makes the perpendicular velocity smaller, the longer will it take from Cluster to TC1.

[11] We have used several approaches to estimate the axis orientations of the flux ropes: The maximum and minimum variance analysis (MVA) based on the magnet field measurement of a single spacecraft (BMVA) [*Sonnerup and Scheible*, 1998], the MVA based on current density (CMVA) [*Pu et al.*, 2005a], the multiple triangulation analysis (MTA) [*Zhou et al.*, 2006] and reconstruction of the cross-section of the flux rope by using G-S reconstruction technique [*Hu and Sonnerup*, 2002] with FGM and CIS data. The inferred flux rope orientations are listed in Table 2. Although these estimated orientations are somehow different in details, the main component of the flux rope axis is clearly along Z direction. As the G-S analysis is less sensitive to the data interval than other methods like BMVA, we decided to take this result as the orientation of the FTE. What is more, it is consistent with the geometric estimation in last paragraph.

[12] A number of methods exist to estimate the velocity of FTEs. Here we have used deHoffmann-Teller analysis [*Khrabrov and Sonnerup*, 1998], multi-spacecraft timing analysis [*Russell et al.*, 1983] and the Spatio-Temporal Derivative method [*Shi et al.*, 2005]. There are numerous ways to characterize an FTE when carrying out inter-spacecraft timing, (i.e. maximum in $|B|$ associated with $B_n$ min). In this paper the time differences are determined

**Table 1.** Magnetic Flux Contained in the Flux Rope Based on G-S Reconstruction[a]

| Magnetic Vector Potential A, T*m | TC-1 | Cluster/SC1 | Relative Deviation, % |
|---|---|---|---|
| −0.05 | 15.41 | 12.76 | 17.2 |
| −0.06 | 11.56 | 10.71 | 7.35 |
| −0.07 | 8.916 | 8.869 | 0.53 |
| −0.08 | 6.196 | 6.244 | 0.77 |

[a]Magnetic flux is measured as $10^5$ *Wb*.

**Table 2.** Orientations of Flux Rope (GSM)

| Method | Cluster | DSP/TC1 |
|---|---|---|
| BMVA | −0.243, 0.425, 0.872(SC1)<br>0.140, 0.232, 0.972(SC2)<br>0.131, −0.356, 0.925(SC3)<br>0.062, 0.173, 0.983(SC4) | −0.410, 0.295, 0.907 |
| MTA | −0.197, −0.525, 0.827 | —[a] |
| CMVA | −0.209, 0.507, 0.836 | —[a] |
| G-S | −0.545, 0.184, 0.818 | −0.404, 0.234, 0.884 |

[a]Since TC1 has only one spacecraft, neither MTA nor CMVA is available to TC1 data.

by maximizing the cross-correlation function between the $B_N$ (B component along local MP normal direction) signature observed by all pairs of spacecraft and solving this over-determined equation set using the least square method. Applying this method to Cluster data we obtained a velocity for the FTE of (−44, 340, 178) km/s (GSM).

[13] Using the FTE velocity derived above, we made the following calculations. (1) The G-S reconstruction gives that at 07:13:15 the center of the flux rope cross-section of SC1 was located at (3.96, 12.11, 4.77) $R_E$ (GSM) and that at 07:15:05 the center of the flux rope cross-section of TC1 was located at (4.29, 12.54, 1.72) $R_E$ (GSM). (2) With the flux rope orientation of SC1 (given by GS technique) of ~(−0.545, 0.184, 0.818) and velocity of SC1 flux rope of ~(−44, 340, 178) km/s, we can shift the axis of Cluster along the velocity and get a plane containing the axis and the velocity of Cluster/SC1. From this we can show that the perpendicular distance from TC1 to the plane is ~1.22 Re. Considering the fact that the typical scale sizes of these FTEs are $1 \sim 2R_E$ [*Pu et al.*, 2005b] and that the orientations of the two flux ropes were somewhat close to each other, it is reasonable to expect that Cluster and TC1 in fact successively encountered with the same flux rope at two different positions.

[14] With the center positions, flux rope orientations and velocity of the structure, we can calculate the transmit time from Cluster to TC1 to be ~90.7s. Taking into account the estimating error from orientation, velocity and the bend of rope axis or the deceleration, this result is acceptable compared with the observed time of 108s.

[15] Thus this velocity can be used to verify that Cluster and TC1 encountered the same flux rope in different positions. It is worthy to emphasize that all the motion and polarity of the FTE signatures are in accordance with the predictions found by application of the Owen-Cowley-Cooling model [*Cooling et al.*, 2001].

## 4. Summary

[16] Observations of an FTE signature at the dayside magnetopause are reported, which is consecutively observed on 4 January 2005 by each of five spacecraft comprising the Double Star/TC1 spacecraft and the Cluster quartet, while the spacecraft were traversing through the northern-duskside magnetopause. Magnetosheath FTEs seen by Cluster and TC1 within two minutes are shown to manifest a single flux rope moving duskward and northward very close to the MP. Several features of the flux rope (the axis orientation, scale of the cross-section, H-T velocity, 3-D distribution of thermal ions, etc) have been investigated. The FTE motion direction and large-scale configuration of the flux rope are studied with the five point measurements.

[17] This study undoubtedly shows that the coordinated measurements of Double Star and Cluster have given the possibility to study flux tube evolution along the magnetopause with five-point measurements: First giving a quantitative estimate of the orientation, motion and characteristics of the open flux rope at Cluster and second relating this measurement to an adjacent location along the tube at TC1. We can see the structures of FTEs at small scales within the Cluster tetrahedron, as well as the large-scale evolution with Cluster and Double Star. A bended flux rope is observed and reconstructed for the first time by five-point measurement.

[18] What is more, different ways of estimating FTEs velocities have been applied during the study. The cross-correlation and timing analysis appears to be the most reliable and repeatable and the least sensitive to data collections and criterions.

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