Reply to Referee #1 (RC1)

We greatly thank the reviewer for the valuable comments and suggestions that we tried to consider in the re-submission. We have revised and improved the manuscript in response to the reviewer’s comments. All revised parts are marked in red in the text. Detailed answers to the comments are listed below.

General Comments
This paper introduces a new method that can be used to search for flux ropes from in-situ observations. This method fits observation data into a flux rope model and uses the correlation coefficient between data and model to tell where the flux rope is. This method is important for making future studies on flux ropes easier. However, there is an important issue that needs to be clarified about this method (see the specific comments below).

Specific Comments
Line 182 and all the following parts: When the authors compare the model with real data, they did not mention how they determined the unit length for the model and the B0 to put in the model. These values must be related to the data and are crucial for applying the model to the data. Therefore, the authors should explain in detail how these values are determined.

Thanks for the referee’s reminding. We used the same unit of the real data as the unit length for the model, i.e. second (‘s’) in our test. We revised the caption of figures accordingly.

The amplitude ($B_0$) in the TFC is determined by the maximum value of $B_t$ during the interval when calculate correlation coefficients.

We included this in the Line 184-187.

Technical corrections
Line 109: unite/s -> unit/s
Line 109: “thus set a=0.735 s . . .” Here the authors use the ‘s’ for the unit of a and b, which are length quantities. In other parts of the text the authors use ‘s’ to mean ‘seconds’, a unit for time. In this line, ‘s’ actually means ‘units’. Please use a different letter for this unit.
Line 191: estimate -> estimated
Line 196: dynamic -> dynamics
Line 206: 6b-6d -> 7b-7d
Figure 4: please explain in the caption that the time scale on the vertical axes is the $r$ mentioned in the text.

According to the referee’s suggestions, we have revised the related parts in the new version of the manuscript.
Reply to Referee #2 (RC2)

We greatly thank the reviewer for the valuable comments and suggestions that we tried to consider in the re-submission. All revised parts are marked in red in the text.

Comments on the manuscript entitled “A new method to identify flux ropes in space plasmas” by Huang et al. Magnetic flux ropes have been regarded as an most important byproduct of magnetic field reconnection. They can raise the reconnection rate, generate energetic electrons, and change the magnetic topology. The typical signatures of a magnetic flux rope are a bipolar variation of magnetic field in the normal direction of the current sheet, and a significant enhancement of the core field as well as the total magnetic field strength. Generally, the flux ropes in the magnetopause and the magnetotail can be easily recognized from the spacecraft measurement by eyes. However, it becomes complicated while the flux ropes were located in the magnetosheath where the current distribution was turbulent. In this paper, the authors proposed a new method to identify the flux ropes in both the large-scale current sheet and the small-scale current sheet. Furthermore, this method was tested by the Cluster and MMS observations in the magnetosheath and magnetotail. The results indicates that the method can select the flux rope effectually. In my view, the result is new and interesting, and suitable to publish in Ann. Geophys. After the following issues are considered.

Line 26 flux ropes → magnetic flux ropes
Line 31 Wang et al., PRL 2010 reported the first evidence of magnetic flux rope or island generated during a single X-line, should be cited here. Line 34, Wang et al., Nat. Phys. 2016 shows a clear picture of the dissipation role that the magnetic flux ropes play on. Line 103 cross → crosses

We have revised manuscript according to the referee’s suggestions.
A new method to identify flux ropes in space plasmas

Shiyong Huang\textsuperscript{1}, Pufan Zhao\textsuperscript{1}, Jiansen He\textsuperscript{2}, Zhigang Yuan\textsuperscript{1}, Meng Zhou\textsuperscript{3}, Huishan Fu\textsuperscript{4}, Xiaohua Deng\textsuperscript{3}, Ye Pang\textsuperscript{3}, Dedong Wang\textsuperscript{1}, Xiongdong Yu\textsuperscript{1}, Haimeng Li\textsuperscript{4}, Roy Torbert\textsuperscript{5}, and James Burch\textsuperscript{6}

\textsuperscript{1} School of Electronic Information, Wuhan University, Wuhan, China
\textsuperscript{2} School of Earth and Space Sciences, Peking University, Beijing, China
\textsuperscript{3} Institute of Space Science and Technology, Nanchang University, Nanchang, China
\textsuperscript{4} School of Space and Environment, Beihang University, Beijing, China
\textsuperscript{5} University of New Hampshire, Durham, New Hampshire, USA
\textsuperscript{6} Southwest Research Institute, San Antonio TX, USA

Abstract

Flux ropes are frequently observed in the space plasmas, such as solar wind, planetary magnetosphere and magnetosheath etc., and play an important role in the reconnection process and mass and flux transportation. One usually used bipolar signature and strong core field to identify the flux ropes. We propose here one new method to identify flux ropes based on the correlations between the variables of the data from in-situ spacecraft observations and the target-function-to-be-correlated (TFC) from the ideal flux rope model. Through comparing the correlation coefficients of different variables at different time and scales, and performing weighted average technique, this method can derive the scales and locations of the flux ropes. We compare it with other methods and also discuss the limitation of our method.

1. Introduction

Magnetic flux ropes, as one universal structure in the space plasma, are formed as a helical magnetic structure with magnetic field lines wrapping and rotating around a central axis (e.g., Hughes and Sibeck, 1987; Slavin et al., 2003; Zong et al., 2004; Zhang et al., 2010). It is generally believed that flux ropes can be generated by magnetic reconnection in the eruptive energy processes, such as rapid variations of
the reconnection rate at a single X-line (e.g. Nakamura and Scholer, 2000; Wang et al., 2010; Fu et al., 2013), multiple X-line reconnection (e.g. Lee et al., 1985; Deng et al., 2004). Flux ropes play important roles in dissipating magnetic energy and controlling the microscale dynamics of magnetic reconnection (e.g., Drake et al., 2006; Daughton et al., 2007; Wang et al., 2016; Fu et al., 2017). These structures are frequently observed and widely studied recently in the magnetosphere, magnetosheath and solar wind (e.g. Hu and Sonnerup, 2001; Slavin et al., 2003; Zong et al., 2004; Zhang et al., 2010; Huang et al., 2012, 2014a, 2014b, 2015, 2016a, 2016b; Rong et al., 2013). Many works have tried to model flux rope from in-situ measurements based on the force-free constant-alpha flux rope (e.g., Lepping et al., 1990), non-force-free model (e.g., Hidalgo et al., 2002), or the Grad-Shafranov equilibrium (e.g., Hu and Sonnerup, 2002).

Flux ropes embedded in current sheet are characterized by the bipolar signature of the normal component of magnetic field, strong core field in the axis direction, and enhancement in magnetic field strength. Therefore, one used negative-positive (positive-negative) bipolar signature of the south-north magnetic field component in the earthward (tailward) flow with an enhancement in the cross-tail component and strength of magnetic field to identify flux ropes in the magnetotail (e.g., Slavin et al., 2003; Huang et al., 2012). At the magnetopause, the bipolar variation is usually along the Sun-Earth direction, and the core field is typically along the dawn-dusk direction (e.g., Zhang et al., 2010). However, flux ropes in the magnetosheath, which has been reported recently by MMS (Huang et al., 2016b), can move in any directions due to the large fluctuations of the shocked solar wind. This leads to difficulty in identifying the flux ropes there.

Several attempts are tried to survey flux ropes in the Earth’s magnetotail by eyes based on their signatures, such as bipolar variation of north-south magnetic field (e.g., Richardson et al., 1987; Slavin et al., 2003). Also, some methods are proposed to automatically in some degrees survey flux ropes or flux transfer events (FTEs) via
bipolar field deflections (e.g., Kawano and Russell, 1996; Vogt et al., 2010; Jackman et al., 2014; Smith et al., 2016). Karimabadi et al. (2009) have applied data mining technique (MineTool) to search FTEs using magnetic field and plasma data. Recently, Smith et al. (2017) developed a method to automatically detect cylindrically symmetric force-free flux ropes in the magnetotail only using magnetic field data. That method first locates the significant deflections in the north-south magnetic field component with peaks in the dawn-dusk component or total field. Then, the candidates are using Minimum Variance Analysis (MVA) to determine a local coordinate system. Finally, the candidates are fitted by a fore-free model to determine whether they belong to flux ropes or not.

For some flux ropes with short duration, the plasma data have not enough high time resolution or even worse are not available. Thus the identification of flux ropes relies heavily on the magnetic field data. All aforementioned automatical methods are a bit complex, or require plasma data. Therefore, to identify flux rope only using the magnetic field data from single spacecraft, we propose a new and simple method based on the correlation coefficients between the signal and the ideal model of flux rope to identify flux ropes in space plasmas. The paper will be presented as follows: an introduction of the method in section 2; the test of the method on artificial data from the model in section 3; the applications of the method on the Cluster and MMS data in section 4; summary is given in section 5.

2. Approach

In this section, we simply introduce our method.

Firstly, we derive target-function-to-be-correlated (TFC) from the ideal model of flux rope. Considering the variable and complicated observed flux ropes, we use the ideal non-force-free model of flux rope proposed by Elphic and Russell (1983), named as Elphic and Russell (E-R) Model because most of flux ropes with nonnegligible perpendicular current are not consistent with the force-free model (e.g., Hidalgo et al.,
This model is constructed with an intense core field inside of flux rope, which is shown in Figure 1. The equation of this model in the cylindrical coordinate (Y is defined as the axis orientation of flux rope) can be modified as below:

\[
\begin{align*}
B_y &= B(r) \cos(\alpha(r)) \\
B_\phi &= B(r) \sin(\alpha(r)) \\
B(r) &= B_0 \exp\left(-r^2/b^2\right)
\end{align*}
\]  

(1)

Where \(\alpha(r) = \pi/2(1-\exp(-r^2/a^2))\), \(B_y\) is the core field component, \(B_0\), \(a\), and \(b\) are the constant, \(r\) is the radial distance to the flux rope center.

Figure 1 shows sketched diagram of the cylindrical flux rope from E-R model. For convenience, the rectangular coordinate is used in our analyses (shown in Figure 1). Y is the axis orientation of the flux rope, and the X-Z plane is the cross-section perpendicular to the axis orientation. X can be treated as sun-earth orientation, Y is the dawn-dusk orientation, and Z is similar to the south-north orientation in the magnetotail. If one spacecraft crosses the flux rope following the red path in Figure 1, \(B_z\) component will be characterized as bipolar signature, and \(B_y\) component and total magnetic field \(B_t\) have strong peaks.

Figure 2 shows the observations when one virtual spacecraft cross the ideal flux rope (see spacecraft path in Figure 1). Here we assume the scale of flux rope as one unit, and 1 unit/s of moving speed of the spacecraft, thus set \(a = 0.735\) units and \(b = 0.735\) units, \(B_0=10\) nT, and use the \(B_z\) as the bipolar variation component, \(B_y\) as the core field component, \(B_t\) as the total magnetic field. The center of the flux rope is located at 2.5 s. One can see the \(B_z\) bipolar signature, and the peaks of core field and total magnetic field inside the flux rope.

Considering the previous observations, in which the \(B_z\) component during the crossing of the flux rope usually does not reach zero like that shown in Figure 2a, we select one part of the ideal flux rope as the TFC which is shown in Figure 3. The TFC is
similar to the sinusoidal function when one performs Fast Fourier Transform (FFT) analysis. We only used two components ($B_y$ and $B_z$) and magnetic strength ($B_t$) as the TFC since only $B_z$ and $B_y$ components and $B_t$ have very obvious typical feature usually from in-situ measurements (i.e., $B_z$ has bipolar signature, $B_y$ is strong core field, and $B_t$ has peak inside flux ropes), and $B_x$ component has not common features from observation viewpoint (e.g., Slavin et al., 2003; Huang et al., 2014a).

Secondly, we calculate the Pearson correlation coefficients between the signal and the TFC at different time and different scales (Hotelling et al. 1953). Before calculating the correlation coefficients, the amplitude of the TFC will be estimated from the signal. For example, the maximum value of $B_t$ during the time interval is used as the amplitude of $B_t$ in the TFC. The sliding time window is used in the calculation of the correlation coefficients. The calculated results of correlation coefficients are similar to the power spectral densities by FFT that displays the power spectral density at different time and different frequency. The higher values of the correlation coefficients, the more suitable for the description of the model on the signal.

Thirdly, we compare the correlation coefficients of the bipolar variation component $B_z$, core field component $B_y$, and total magnetic field $B_t$, and find out the high correlations (larger than the given threshold) at the same time and the same scale. This is due to that the bipolar signature in $B_z$, the enhancements of core field $B_y$ and magnetic strength $B_t$ should appear simultaneously with the same duration when one spacecraft cross the flux ropes.

Fourthly, we infer the location and the scale of the flux ropes based on the weighed average (it will be shown later), and the amplitude from minimum to maximum values of the bipolar variation.

3. Model test

One test is performed on the artificial data from E-R model with the random noise.
Figure 4 presents the test results. The test artificial data is shown in Figure 4a where
the noise is 10% of the amplitude of the flux rope. A series of the calculations are
carried on $B_z$, $B_y$ and $B_t$ to obtain the correlation coefficients. One should point out
that the absolute values of the correlation coefficients of $B_z$ and $B_y$ are given in Figure
4b and 4c respectively, because the bipolar structure can be positive-negative or
negative-positive variation and the core field can be positive or negative. It can be
seen that the correlation coefficients are largest at the scale $\tau$ of $0.6 \sim 1.5$ units during
the crossing of the flux rope (around time $\sim 3.5$ s).

We set the threshold as 0.9 to represent the results in Figure 5 where only the
correlation coefficients with $> 0.9$ are displayed with black shadows. All correlation
coefficients of the three variables have peaks at the time $\sim 3.5$ s with the scale $\tau \sim 1$
units. We use the weighted average technique (shown below) to identify the flux rope
and estimate its scale $\tau$.

$$\tau = \frac{\sum \text{coef}_i \times \tau_i}{\sum \text{coef}_i}$$

where $\text{coef}_i$ is the correlation coefficient at scale $\tau_i$.

Figure 5e shows the estimated results. The crossing of the flux rope is marked with “1”
and the duration is its scale, the center of the flux rope is at the center of the line. In
this test, the scale is estimated as 1.039 units, the location is 3.496 s. The amplitude is
estimate as 4.43 nT from minimum to maximum values of the bipolar variation.
Aforesaid sets, one can estimate the error of the scale as 3.9%, i.e.,

$$\frac{(1.039-1.0)}{1.0} = 3.9\%.$$ 

Therefore, our method can successfully identify the flux rope, and estimate its scale, location and amplitude.

4. Application

In this section, we apply our new method to the spacecraft measurements in the
magnetosheath and the magnetotail.

4.1 Flux rope in the magnetosheath
Flux ropes are successfully identified in the magnetosheath using the unprecedented high resolution data from Magnetospheric Multiscale (MMS) (Burch et al., 2016) mission (Huang et al., 2016b). Their observations have demonstrated that highly dynamical, strong wave activities and electron-scale physics occur in the magnetosheath ion-scale flux ropes. Figure 6 gives the observations of ~14 s from MMS2 on 25 Oct 2015 and the test results of our method. The unit length of the TFC is used the same unit of the real observations, i.e. second (‘s’). The amplitude ($B_0$) of the TFC is determined by the maximum value of $B_t$ during the interval when calculate correlation coefficients. Similar to the model test, we use the same variables to present the components of the bipolar variation, core field and total magnetic field after transformed to minimum variable analysis (MVA) analysis (Huang et al., 2016b). The threshold of the correlation coefficients is also set as 0.9 in Figure 6. We can see that the correlation coefficients of the three variables (Figure 6b-6d) only have high values at the same time around time = 5.5 s, implying that one flux rope is identified by this method. Based on the weighted average method in equation (2), the time scale of the flux rope is 1.11 s, and its central location is at 5.38 s. The amplitude is estimated as 115 nT. All these results are consistent with previous findings from multi-spacecraft data in Huang et al. (2016b).

4.2 Flux rope in the magnetotail
Flux ropes are frequently observed in the magnetotail, and play an important role during magnetic reconnection and magnetotail dynamics (e.g., Slavin et al., 2003; Zong et al., 2004; Chen et al., 2008; Huang et al., 2012, 2016a; Fu et al., 2015, 2016). Chen et al. (2008) have identified several flux ropes filled with energetic electrons during magnetic reconnection on 01 Oct 2001 by using the Cluster data. Figure 7 shows the magnetic field in GSM coordinates from the Cluster mission (Escoubet et al., 1997) in the magnetotail and the application results of our method. There are several bipolar variations in $B_z$ during this time interval (Figure 7a). Figures 7b-7d present the correlation coefficients (larger than 0.9 of the threshold) of the three variables. Here we try to identify small-scale flux ropes, so that we perform the
method only at short time scale. There are full of high correlation coefficients (grey shadows) in Figures 7b-7d. After compare with the correlation coefficients at the same time and same scale, our method resolves three possible flux ropes in Figure 7e. The results are summarized in Table 1. The three structures are close to ideal flux rope with bipolar signature in $B_z$, and peaks in core field $B_y$ and total magnetic field $B_t$. All three flux ropes identified by our method have been reported in Chen et al. (2007).

We should point out that our method only can identify the flux rope and derive its duration. If the plasma velocity data is available, then we can estimate the actual spatial scale of the flux ropes. If multi-spacecraft data are available for the time interval of interest, one can derive the size, the orientation, and the motion of the flux rope using by the multi-spacecraft method such as Sonnerup et al. (2004), Shi et al. (2005, 2006) and Zhou et al. (2006a, 2006b). However, the separation of the Cluster was much lager than the size of the flux ropes on 01 October 2001, implying that one cannot use multi-spacecraft method here.

5. Summary and Discussion

In summary, we developed a new method to identify flux ropes in the space plasmas. This method is based on the correlation coefficients between the signal and the TFC from non-force-free E-R model. If the correlation coefficients of three variables ($B_z$, $B_y$ and $B_t$) of the signal have high values of correlation coefficients at the same time and same scale, one can deduce the existence of one flux rope and estimate its location and its time scale (i.e., the duration). The tests on the artificial data and the in-situ realistic spacecraft data show that our method can successfully search out the flux ropes and obtain their locations and time scales.

Bipolar variation in $B_z$ component and the enhancement in core field and magnetic field strength are the typical signatures for most of flux ropes. But it doesn’t mean that all observations from any crossing of the spacecraft would have those signatures.
which depends on the spacecraft trajectory (especially for bipolar component).

However, one only can select or identify the flux rope showing the typical signatures, and miss other flux rope not having the typical signatures. Some special field structures may induce the similar signatures along some special trajectories. But this opportunity is too few in the magnetotail. Moreover, one can use the plasma measurements to rule out this possibility.

Aforementioned attempts are used to identify flux ropes in the Earth’s magnetotail by eyes or half-automatically based on the bipolar variation of (e.g., Richardson et al., 1987; Slavin et al., 2003; Kawano and Russell, 1996; Vogt et al., 2010; Jackman et al., 2014; Smith et al., 2016). The identifications by eyes would miss a lots of flux ropes, and spend too much time. Karimabadi et al. (2009) used data mining technique (MineTool) to search flux ropes using both magnetic field and plasma data. That method is too complex to apply in the data analysis. Smith et al. (2017) proposed one method to automatically detect force-free flux ropes based on magnetic field data from single spacecraft. In present study, we used the TFC derived from non-force-free flux rope model to calculate the correlation coefficients with the signal, and then compare the large correlation coefficients of different variables to identify the flux rope. Our method is flexible, reliable and easy to apply in the in-situ spacecraft data compared with other methods. We will quantitatively model the flux ropes identified by our method and derive more information of the flux ropes. For example, we can statistically survey and investigate the locations, the scales and global distributions of flux ropes in the magnetosheath using MMS data.

We should point out that there are several limitations in our method.

1. Our method can only detect the nearly ideal cylindrical flux rope since we used non-force-free E-R model to describe the TFC, which limits the application of this method. The non-force-free model proposed by E-R is just one possible solution of all the flux rope that satisfies $\mathbf{J} \times \mathbf{B} \neq 0$. Actually one can use other flux rope models to
replace E-R model, and extend our method to identify the flux ropes.

2. If the flux ropes are not well regular, there are large time deviations between $B_z$, $B_y$ and $B_t$, which will lead to miss of some flux ropes when we apply the method.

3. The threshold value of correlation coefficients can affect the results. When the threshold value is too small that the method finds out some possible structures which do not belong to flux ropes, or too large that the method will miss some flux ropes.

4. The correlation coefficients at small scale (especially in $B_y$ and $B_t$) could be very large, which may affect our results. The method may find some possible structures related to such fluctuations. We will improve this method and apply it to detect the flux ropes in the turbulent magnetosheath in the future.

**Acknowledgement**

We thank the entire Cluster and MMS team and instrument leads for data access and support. This work was supported by the National Natural Science Foundation of China (41404132, 41574168, 41674161), and China Postdoctoral Science Foundation Funded Project (2015T80830). SYH acknowledges the support by Young Elite Scientists Sponsorship Program by CAST (2017QNRC001). MMS Data is publicly available from the MMS Science Data Center at http://lasp.colorado.edu/mms/sdc/. Cluster Data is publicly available from the Cluster Science Archive at http://www.cosmos.esa.int/web/csa.

**Reference**


Khrabrov, A. V., and B. U. O. Sonnerup, DeHoffmann-Teller Analysis, in Analysis Methods for Multi-Spacecraft Data, edited by G. Paschmann and P. W. Daly, chap. 9,


Table 1. The location, sale and amplitude of the flux ropes identified by the method.
The amplitude is defined as the values of the bipolar variation from minimum to maximum.

<table>
<thead>
<tr>
<th># of flux rope</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location [s]</td>
<td>37.91</td>
<td>113.79</td>
<td>127.93</td>
</tr>
<tr>
<td>Scale [s]</td>
<td>1.99</td>
<td>2.84</td>
<td>2.05</td>
</tr>
<tr>
<td>Amplitude [nT]</td>
<td>9.96</td>
<td>20.49</td>
<td>12.59</td>
</tr>
</tbody>
</table>
Figure 1. Sketched diagram of the cylindrical flux rope. The flux rope is right-hand handedness structure. The black circled lines are the magnetic field lines. The red arrow is the projection of spacecraft path. The rectangular coordinate is used in our analyses. Y is the axis orientation of the flux rope, and the X-Z plane is the cross-section perpendicular to the axis orientation. The core field is out-of-plane, and the color represents the relative strength of core field (yellow: large, blue: small).
Figure 2. The three variables $B_z$ (a), $B_y$ (b), and $B_t$ (c) of the ideal cylindrical flux rope described by E-R model.
Figure 3. The target-function-to-be-correlated (TFC) derived from E-R model. The amplitudes and scale are dimensionless.
Figure 4. The test results on E-R model. (a) three variables $B_z$, $B_y$, and $B_t$ from E-R model with 10% random noise; (b-d) the correlation coefficients between the variables of $B_z$, $B_y$, and $B_t$ and the TFC shown in Figure 3, respectively. The scale on the vertical axes of (b-d) is $\tau$ mentioned in the text, which is also can be thought as units.
Figure 5. The test results on E-R model with a threshold 0.9. (a) three variables $B_z$, $B_y$, and $B_t$ from E-R model with 10% random noise; (b-d) the correlation coefficients ($\geq 0.9$) between the variables of $B_z$, $B_y$, and $B_t$ and the TFC, respectively; (e) the index when the virtual spacecraft cross the flux rope (if the spacecraft cross the flux rope, the index is 1; if not, the index is 0). The duration of the index presents the time scale of the flux rope. The scale on the vertical axes of (b-d) is the same as in Figure 4.
Figure 6. Testing the method on MMS data in the magnetosheath. The same format as in Figure 5. The scale on the vertical axes of (b-d) is ‘second’.
Figure 7. Testing the method on Cluster data in the magnetotail. The same format as in Figure 6.