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 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 $a=0.735 \text{ s} \dots$ " 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 τ 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 \rightarrow 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 \rightarrow crosses

We have revised manuscript according to the referee's suggestions.

1 A new method to identify flux ropes in space plasmas

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5

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12

13 Abstract

14 Flux ropes are frequently observed in the space plasmas, such as solar wind, planetary 15 magnetosphere and magnetosheath etc., and play an important role in the 16 reconnection process and mass and flux transportation. One usually used bipolar 17 signature and strong core field to identify the flux ropes. We propose here one new 18 method to identify flux ropes based on the correlations between the variables of the 19 data from in-situ spacecraft observations and the target-function-to-be-correlated 20 (TFC) from the ideal flux rope model. Through comparing the correlation coefficients 21 of different variables at different time and scales, and performing weighted average 22 technique, this method can derive the scales and locations of the flux ropes. We 23 compare it with other methods and also discuss the limitation of our method.

24

25 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 31 the reconnection rate at a single X-line (e.g. Nakamura and Scholer, 2000; Wang et 32 al., 2010; Fu et al., 2013), multiple X-line reconnection (e.g. Lee et al., 1985; Deng et 33 al., 2004). Flux ropes play important roles in dissipating magnetic energy and 34 controlling the microscale dynamics of magnetic reconnection (e.g., Drake et al., 35 2006; Daughton et al., 2007; Wang et al., 2016; Fu et al., 2017). These structures are 36 frequently observed and widely studied recently in the magnetosphere, magnetosheath 37 and solar wind (e.g. Hu and Sonnerup, 2001; Slavin et al., 2003; Zong et al., 2004; 38 Zhang et al., 2010; Huang et al., 2012, 2014a, 2014b, 2015, 2016a, 2016b; Rong et al., 39 2013). Many works have tried to model flux rope from *in-situ* measurements based on 40 the force-free constant-alpha flux rope (e.g., Lepping et al., 1990), non-force-free 41 model (e.g., Hidalgo et al., 2002), or the Grad-Shafranov equilibrium (e.g., Hu and 42 *Sonnerup*, 2002).

43

44 Flux ropes embedded in current sheet are characterized by the bipolar signature of the 45 normal component of magnetic field, strong core field in the axis direction, and 46 enhancement in magnetic field strength. Therefore, one used negative-positive 47 (positive-negative) bipolar signature of the south-north magnetic field component in 48 the earthward (tailward) flow with an enhancement in the cross-tail component and 49 strength of magnetic field to identify flux ropes in the magnetotail (e.g., Slavin et al., 50 2003; Huang et al., 2012). At the magnetopause, the bipolar variation is usually along 51 the Sun-Earth direction, and the core field is typically along the dawn-dusk direction 52 (e.g., Zhang et al., 2010). However, flux ropes in the magnetosheath, which has been 53 reported recently by MMS (Huang et al., 2016b), can move in any directions due to 54 the large fluctuations of the shocked solar wind. This leads to difficultly in identifying 55 the flux ropes there.

56

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

61 bipolar field deflections (e.g., Kawano and Russell, 1996; Vogt et al., 2010; Jackman 62 et al., 2014; Smith et al., 2016). Karimabadi et al. (2009) have applied data mining 63 technique (MineTool) to search FTEs using magnetic field and plasma data. Recently, 64 Smith et al. (2017) developed a method to automatically detect cylindrically 65 symmetric force-free flux ropes in the magnetotail only using magnetic field data. 66 That method first locates the significant deflections in the north-south magnetic field 67 component with peaks in the dawn-dusk component or total field. Then, the 68 candidates are using Minimum Variance Analysis (MVA) to determine a local 69 coordinate system. Finally, the candidates are fitted by a fore-free model to determine 70 whether they belong to flux ropes or not.

71

72 For some flux ropes with short duration, the plasma data have not enough high time 73 resolution or even worse are not available. Thus the identification of flux ropes relies 74 heavily on the magnetic field data. All aforementioned automatical methods are a bit 75 complex, or require plasma data. Therefore, to identify flux rope only using the 76 magnetic field data from single spacecraft, we propose a new and simple method 77 based on the correlation coefficients between the signal and the ideal model of flux 78 rope to identify flux ropes in space plasmas. The paper will be presented as follows: 79 an introduction of the method in section 2; the test of the method on artificial data 80 from the model in section 3; the applications of the method on the Cluster and MMS 81 data in section 4; summary is given in section 5.

82

83 2. Approach

84 In this section, we simply introduce our method.

85

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.*, 2002; Zong et al., 2004; Zhang et al., 2010; Borg et al., 2012; Huang et al., 2012,
2016b). 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:

 $(B_{\nu} = B(r)\cos(\alpha(r)))$

$$\begin{cases} B_{\varphi} = B(r)\sin(\alpha(r)) \\ B(r) = B_0 \exp(-r^2/b^2) \end{cases}$$
(1)

96 Where α (r) = $\pi/2(1-\exp(-r^2/a^2))$, B_y is the core field component, B_0 , a, and b are the 97 constant, r is the radial distance to the flux rope center.

98

99 Figure 1 shows sketched diagram of the cylindrical flux rope from E-R model. For 100 convenience, the rectangular coordinate is used in our analyses (shown in Figure 1). Y 101 is the axis orientation of the flux rope, and the X-Z plane is the cross-section 102 perpendicular to the axis orientation. X can be treated as sun-earth orientation, Y is 103 the dawn-dusk orientation, and Z is similar to the south-north orientation in the 104 magnetotail. If one spacecraft crosses the flux rope following the red path in Figure 1, 105 B_z component will be characterized as bipolar signature, and B_y component and total 106 magnetic field B_t have strong peaks.

107

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 = 0.735units, $B_0 = 10$ 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.

115

116 Considering the previous observations, in which the B_z component during the crossing 117 of the flux rope usually does not reach zero like that shown in Figure 2a, we select 118 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).

125

126 Secondly, we calculate the Pearson correlation coefficients between the signal and the 127 TFC at different time and different scales (Hotelling et al. 1953). Before calculating 128 the correlation coefficients, the amplitude of the TFC will be estimated from the 129 signal. For example, the maximum value of B_t during the time interval is used as the 130 amplitude of B_t in the TFC. The sliding time window is used in the calculation of the 131 correlation coefficients. The calculated results of correlation coefficients are similar to 132 the power spectral densities by FFT that displays the power spectral density at 133 different time and different frequency. The higher values of the correlation 134 coefficients, the more suitable for the description of the model on the signal.

135

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.

142

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.

146

3. Model test

148 One test is performed on the artificial data from E-R model with the random noise.

149 Figure 4 presents the test results. The test artificial data is shown in Figure 4a where 150 the noise is 10% of the amplitude of the flux rope. A series of the calculations are 151 carried on B_z , B_y and B_t to obtain the correlation coefficients. One should point out 152 that the absolute values of the correlation coefficients of B_z and B_y are given in Figure 153 4b and 4c respectively, because the bipolar structure can be positive-negative or 154 negative-positive variation and the core field can be positive or negative. It can be 155 seen that the correlation coefficients are largest at the scale τ of 0.6 ~ 1.5 units during 156 the crossing of the flux rope (around *time* ~ 3.5 s).

157

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* ~ 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 τ .

163
$$\tau = \sum coef_i \times \tau_i / \sum coef_i$$
(2)

164 where *coef_i* is the correlation coefficient at scale τ_i .

165

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. Aforementioned sets, one can estimate the error of the scale as 3.9%, i.e., (1.039-1.0)/1.0 = 3.9%. Therefore, our method can successfully identify the flux rope, and estimate its scale, location and amplitude.

173

174 **4.** Application

175 In this section, we apply our new method to the spacecraft measurements in the176 magnetosheath and the magnetotail.

- 177
- 178 4.1 Flux rope in the magnetosheath

179 Flux ropes are successfully identified in the magnetosheath using the unprecedented 180 high resolution data from Magnetospheric Multiscale (MMS) (Burch et al., 2016) 181 mission (Huang et al., 2016b). Their observations have demonstrated that highly 182 dynamical, strong wave activities and electron-scale physics occur in the 183 magnetosheath ion-scale flux ropes. Figure 6 gives the observations of ~14 s from 184 MMS2 on 25 Oct 2015 and the test results of our method. The unit length of the TFC 185 is used the same unit of the real observations, i.e. second ('s'). The amplitude (B_0) of 186 the TFC is determined by the maximum value of B_t during the interval when calculate 187 correlation coefficients. Similar to the model test, we use the same variables to 188 present the components of the bipolar variation, core field and total magnetic field 189 after transformed to minimum variable analysis (MVA) analysis (Huang et al., 190 2016b). The threshold of the correlation coefficients is also set as 0.9 in Figure 6. We 191 can see that the correlation coefficients of the three variables (Figure 6b-6d) only have 192 high values at the same time around time = 5.5 s, implying that one flux rope is 193 identified by this method. Based on the weighted average method in equation (2), the 194 time scale of the flux rope is 1.11 s, and its central location is at 5.38 s. The amplitude 195 is estimated as 115 nT. All these results are consistent with previous findings from 196 multi-spacecraft data in Huang et al. (2016b).

197

198 4.2 Flux rope in the magnetotail

199 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; 200 201 Zong et al., 2004; Chen et al., 2008; Huang et al., 2012, 2016a; Fu et al., 2015, 2016). 202 Chen et al. (2008) have identified several flux ropes filled with energetic electrons 203 during magnetic reconnection on 01 Oct 2001 by using the Cluster data. Figure 7 204 shows the magnetic field in GSM coordinates from the Cluster mission (Escoubet et 205 al., 1997) in the magnetotail and the application results of our method. There are 206 several bipolar variations in B_z during this time interval (Figure 7a). Figures 7b-7d 207 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 208

209 method only at short time scale. There are full of high correlation coefficients (grey 210 shadows) in Figures 7b-7d. After compare with the correlation coefficients at the 211 same time and same scale, our method resolves three possible flux ropes in Figure 7e. 212 The results are summarized in Table 1. The three structures are close to ideal flux 213 rope with bipolar signature in B_z , and peaks in core field B_y and total magnetic field B_t . 214 All three flux ropes identified by our method have been reported in *Chen et al.* 215 (2007).

216

217 We should point out that our method only can identify the flux rope and derive its 218 duration. If the plasma velocity data is available, then we can estimate the actual 219 spatial scale of the flux ropes. If multi-spacecraft data are available for the time 220 interval of interest, one can derive the size, the orientation, and the motion of the flux 221 rope using by the multi-spacecraft method such as Sonnerup et al. (2004), Shi et al. 222 (2005, 2006) and Zhou et al. (2006a, 2006b). However, the separation of the Cluster 223 was much lager than the size of the flux ropes on 01 October 2001, implying that one 224 cannot use multi-spacecraft method here.

225

226 5. Summary and Discussion

227 In summary, we developed a new method to identify flux ropes in the space plasmas. 228 This method is based on the correlation coefficients between the signal and the TFC 229 from non-force-free E-R model. If the correlation coefficients of three variables $(B_{z},$ 230 $B_{\rm v}$ and $B_{\rm t}$) of the signal have high values of correlation coefficients at the same time 231 and same scale, one can deduce the existence of one flux rope and estimate its 232 location and its time scale (i.e., the duration). The tests on the artificial data and the 233 in-situ realistic spacecraft data show that our method can successfully search out the 234 flux ropes and obtain their locations and time scales.

235

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.

245

246 Aforementioned attempts are used to identify flux ropes in the Earth's magnetotail by 247 eyes or half-automatically based on the bipolar variation of (e.g., Richardson et al., 248 1987; Slavin et al., 2003; Kawano and Russell, 1996; Vogt et al., 2010; Jackman et al., 249 2014; Smith et al., 2016). The identifications by eyes would miss a lots of flux ropes, 250 and spend too much time. Karimabadi et al. (2009) used data mining technique 251 (MineTool) to search flux ropes using both magnetic field and plasma data. That 252 method is too complex to apply in the data analysis. Smith et al. (2017) proposed one 253 method to automatically detect force-free flux ropes based on magnetic field data 254 from single spacecraft. In present study, we used the TFC derived from non-force-free 255 flux rope model to calculate the correlation coefficients with the signal, and then 256 compare the large correlation coefficients of different variables to identify the flux 257 rope. Our method is flexible, reliable and easy to apply in the in-situ spacecraft data 258 compared with other methods. We will quantitatively model the flux ropes identified 259 by our method and derive more information of the flux ropes. For example, we can 260 statistically survey and investigate the locations, the scales and global distributions of 261 flux ropes in the magnetosheath using MMS data.

262

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

264

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 $J \times B \neq 0$. Actually one can use other flux rope models to 269 replace E-R model, and extend our method to identify the flux ropes.

270

271 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.
- 273

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.

277

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.

282

283

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293

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Table 1. The location, sale and amplitude of the flux ropes identified by the method.

420 The amplitude is defined as the values of the bipolar variation from minimum to

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TL I	ппалтпипп.	

# of flux rope	1	2	3
Location [s]	37.91	113.79	127.93
Scale [s]	1.99	2.84	2.05
Amplitude [nT]	9.96	20.49	12.59

Λ	2	2
4	7	7

- 12,

444 Figure captions

445



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). 453



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455 Figure 2. The three variables B_z (a), B_y (b), and B_t (c) of the ideal cylindrical flux rope

456 described by E-R model.



459 Figure 3. The target-function-to-be-correlated (TFC) derived from E-R model. The460 amplitudes and scale are dimensionless.



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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 τ mentioned in the text, which is also can be thought as units.

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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 (≥ 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.



482 Figure 6. Testing the method on MMS data in the magnetosheath. The same format as

483 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 asin Figure 6.