Calculating the Electron Diffusion Region Aspect Ratio with Magnetic Field Gradients

Steven V. Heuer[1], Kevin J. Genestreti[2], Takuma Nakamura[3], Roy B. Torbert[1,2], James L. Burch[4], Rumi Nakamura[3,5]

[1]*University of New Hampshire* [2]*Southwest Research Institute-EOS* [3]*IWF, Austrian Academy of Sciences* [4]*Southwest Research Institute* [5]*University of Graz*

Contact: Steven.Heuer@unh.edu

Citation: Heuer, S. V. et al., (2022). *Geophysical Research Letters*, 49, e2022GL100652

University of New Hampshire

SM45D-2256

1. Key Points

- New technique introduced to calculate aspect ratio of electron diffusion region (EDR) with magnetic field gradients. **Aspect ratio used to calculate normalized reconnection rate** (Section 2)
- EDR aspect ratio determined within 20% uncertainty for particle-in-cell simulation with added MMS-like errors (Section 3)
- For three MMS magnetotail EDRs normalized reconnection rates from the aspect ratio are within uncertainties of the measured reconnection electric field (Section 4)
- **Reconnection rate calculated using the EDR aspect ratio has fewer sources of error than previous methods which may enable future studies of the parameters controlling magnetic reconnection (Section 5)**

2. Deriving the reconnection rate from the aspect ratio

- Measurements of the reconnection rate typically have compounding sources of error from determination of coordinates, velocity frame, and upstream parameters for normalization.
- The EDR aspect ratio δ/ℓ (Fig 1) is already a normalized quantity, can be defined using the magnetic field gradient ∇B, which is well measured by MMS and is velocity frame independent

$$\frac{\delta}{\ell} \simeq \left[\left(\frac{\partial B_N}{\partial L} \right)^2 / \left(\frac{\partial B_L}{\partial N} \right)^2 \right]^{\frac{1}{4}} \qquad (1)$$

(*Hesse et al. 1999*) *L* and *N* directions are outflow and normal directions (Fig 1) *M* completes right-handed coordinate system.

- Liu et al. (2017) derived a relation between aspect ratio δ/ℓ and the normalized reconnection rate R_0

$$R_0 \simeq \frac{\delta}{\ell} \left(\frac{1-(\delta/\ell)^2}{1+(\delta/\ell)^2} \right)^2 \sqrt{1-\left(\frac{\delta}{\ell}\right)^2} \qquad (2)$$

- **Application to MMS data:** ∇B calculated from 4-pt MMS measurements of B. During EDR crossings, ∇B in Eq.(1) calculated 3 ways: with a time-independent coordinate system (Fig 1a/c), a time-dependent coordinate system (not pictured), and using the ratio of $(\nabla B)(\nabla B)^T$ eigenvalues assuming 2D, symmetric and anti-parallel EDR (Fig 1c/d)

3. Where/When is δ/ℓ Accurate?

- Errors in δ/ℓ calculation are characterized using a PIC simulation of the 11 July 2017 MMS EDR encounter (Nakamura et al., 2018).
- Accuracy of the technique is evaluated as function of location relative to the reconnection X-line (Fig 1a/b) and the error introduced in ∇B from MMS-like uncertainties in B (worst case shown in Fig 1c/d).

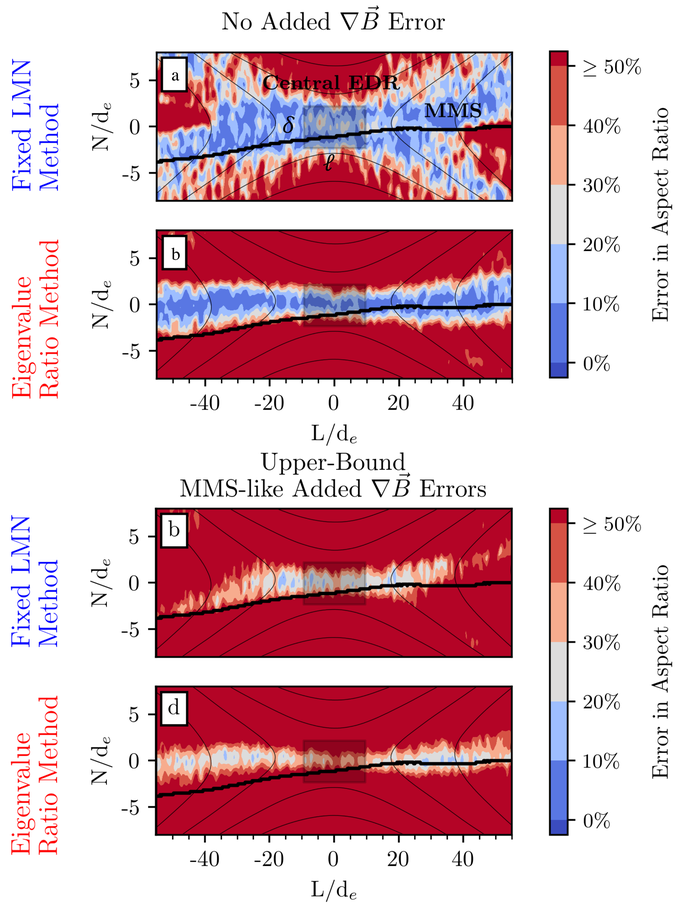

Figure 1. *Panels (a), (b) and (c), (d) show the uncertainty δ/ℓ calculated using the time independent coordinate system (Fixed LMN) and Eigenvalue Ratio with ∇B from the PIC simulation of the 11 July 2017 event. Panels (a) and (c) are displayed with no error, while (b) and (d) have MMS-like errors added to ∇B before calculating δ/ℓ.*

- **Error in δ/ℓ is smallest (< 10%) at center of the current sheet**
- **No significant difference from ideal case (Fig 1a/b) when nominal MMS uncertainties in B added to simulation (±0.01nT)**
- **Even for maximum MMS uncertainties in B (±0.1nT) error in δ/ℓ still < 20% at center of the current sheet**

4. Calculating δ/ℓ and $R_0(\delta/\ell)$ with MMS

- ∇B measured by MMS used to calculate EDR aspect ratio δ/ℓ and normalized reconnection rate $R_0(\delta/\ell)$ for three EDR encounters
- $R_0(\delta/\ell)$ compared to rate from normalized reconnection E field
- The different MMS trajectories (Fig 2) allowed us to test where δ/ℓ can be calculated accurately to confirm simulation analysis (Section 3)

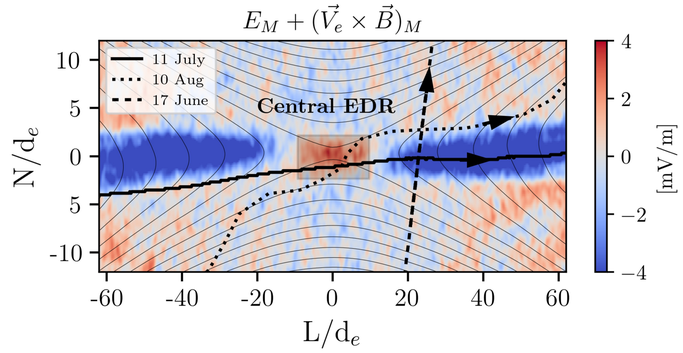

Figure 2. *Diagram showing the approximate trajectories for the three events used in this study relative to the central EDR, defined as the region surrounding the X-line with where the out-of-plane component of the non-ideal electric field is positive.*

- **At center of current sheets, normalized reconnection rates $R_0(\delta/\ell)$ calculated using Eq.(2) are within the (comparatively larger) error bars of the normalized reconnection E fields E_M/E_0 for all three EDRs.**

Event	δ/ℓ	$R_0(\delta/\ell)$	E_M/E_0
11 July 2017	0.210 ± 0.041	0.172 ± 0.020	0.18 ± 0.035^a
10 August 2017	0.202 ± 0.054	0.168 ± 0.028	0.19 ± 0.040^b
17 June 2017	0.119 ± 0.077	0.111 ± 0.063	0.077 ± 0.050^c

^{a}(Genestreti et al., 2018) ^{b}(Li et al., 2019) ^{c}(Farrugia et al., 2021)

5. Perceived Impact and Future Work

- The technique presented here has fewer sources of error than established methods, enabling accurate determination of the parameters controlling reconnection in future studies
- Further work will determine the accuracy/applicability of our methods over a broader parameter space (e.g., guide field/asymmetric reconnection, or when MMS separation exceeds EDR spatial scale)

References:
Hesse, M., et al., (1999) Physics of Plasmas, 6(5), 1781-1795
Liu, Y-H., et al., (2017), Phys. Rev. Lett., 118, 085101
Genestreti, K. J., et al. (2018), Journal of Geophysical Research: Space Physics, 123(11), 9130-9149
Farrugia, C.J., et al. (2021), Journal of Geophysical Research (Space Physics), 126(3), e28903
Li, X., et al. (2019), Geophysical Research Letters , 46 (24), 14263-14273.
Nakamura, TKM., et al. (2018), Journal of Geophysical Research: Space Physics, 123(11), 9150-9168