Uncertainty in Curlometer Technique: Cluster Ring Current Observations

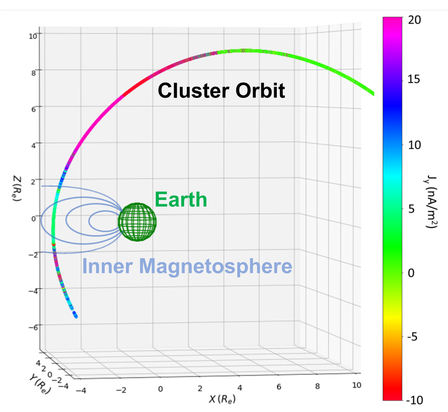
Timothy B. Keebler, Dr. Michael W. Liemohn

Department of Climate and Space Sciences and Engineering, University of Michigan

Abstract

- Significant discrepancy exists between ring current density calculated from plasma pressure and density using the curlometer technique and Cluster spacecraft data.
- The curlometer technique was applied to realistic simulated currents using actual spacecraft position data to assess uncertainty; these estimates greatly exceed prior studies.
- Climatologies of the ring current region were constructed using stringent data filtering measures and quality standards, but are insufficient to capture meaningful trends after filtering.

Background



- The ring current is a current torus with maximum density between 2-7 R_E with a dominant westward component.
- This current is thought to fluctuate dynamically during storm conditions due to plasma injections, bearing large correlation with Dst values.
- Previously, calculations of this current used single spacecraft magnetic field and plasma pressure data to find the perpendicular current density component.
- Publications using the four-spacecraft curlometer technique yield current densities much larger than accepted literature values.

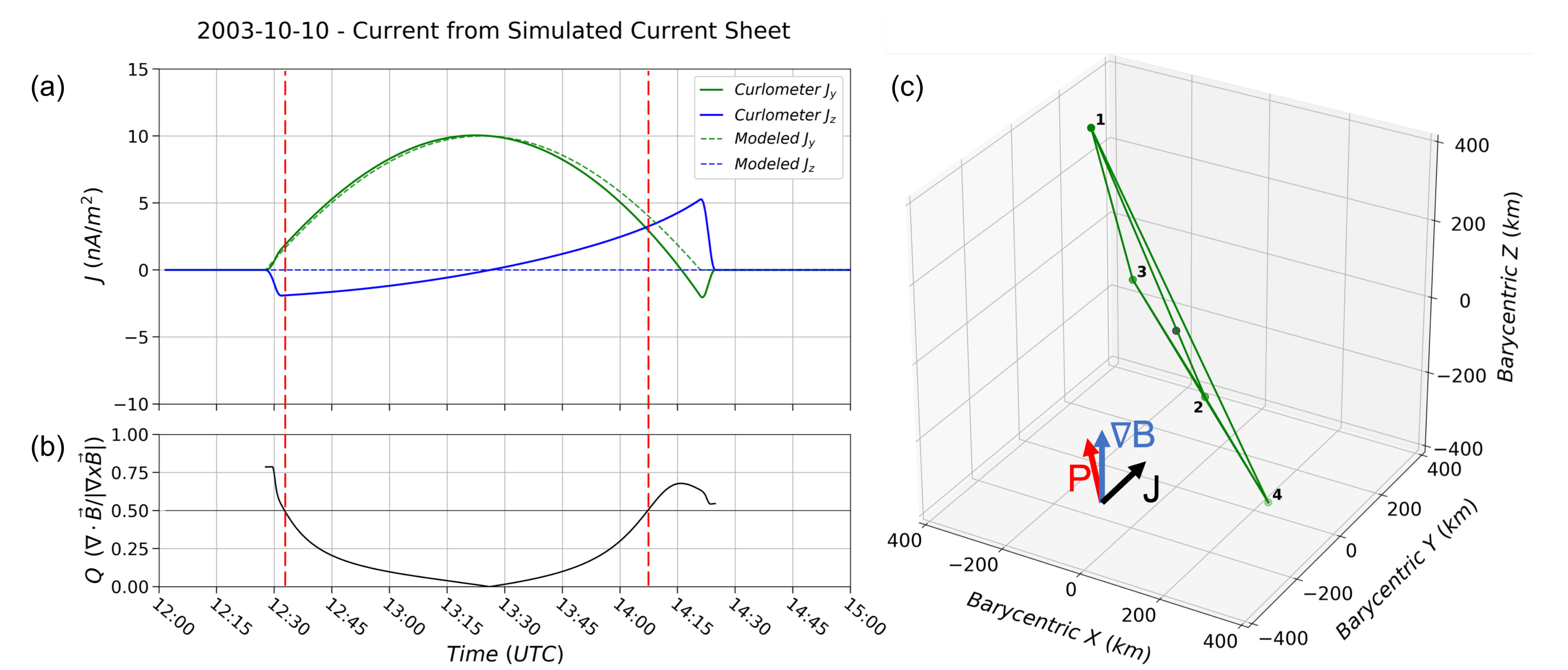
Methodology

- Compute ring current using Fluxgate Magnetometer (FGM) data and modified Python script provided by the Cluster Data Archive.
  - Cyclically integrate Ampere's Law over spacecraft tetrahedral volume.

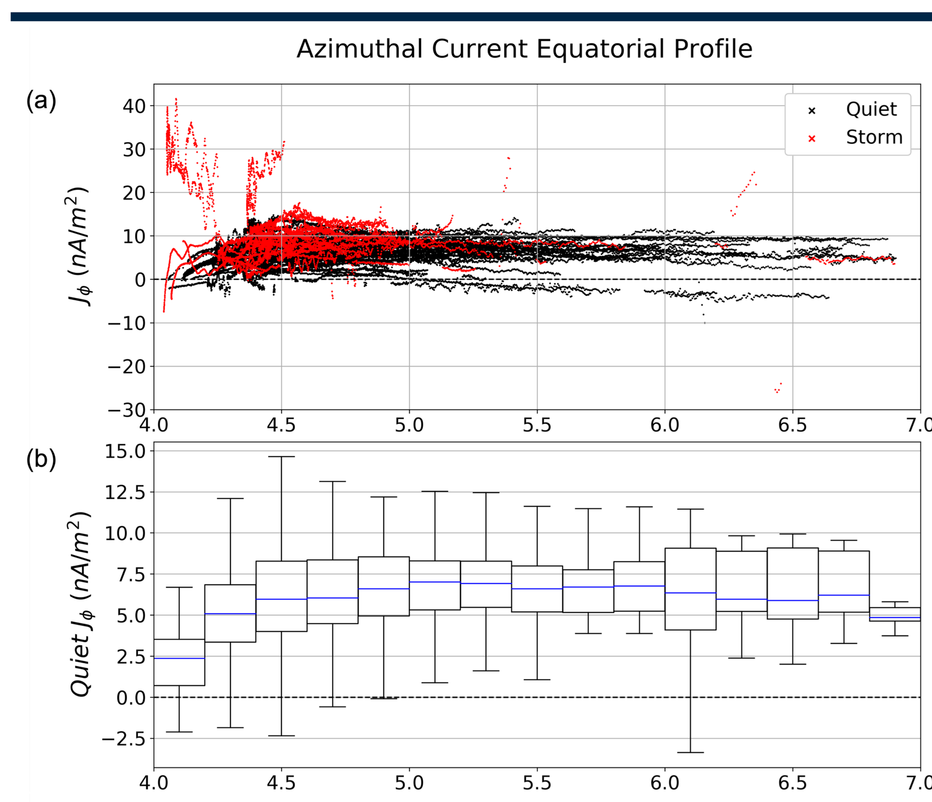
$$\mu_0 \boldsymbol{J}_{average}.(\Delta \boldsymbol{r}_i \times \Delta \boldsymbol{r}_j) = \Delta \boldsymbol{B}_i.\Delta \boldsymbol{r}_j - \Delta \boldsymbol{B}_j.\Delta \boldsymbol{r}_i$$

- Apply curlometry to simulated current sheets using actual spacecraft position data.
  - Simulate infinite slab currents in every plane and orientation
  - Design gradients representative of the space environment
  - Rotate tetrahedron about barycenter to examine the effect of elongation/planarity geometric factors
  - Compare simulations with historical quality thresholds
- Using increased scrutiny, construct new ring current climatologies from lower-uncertainty filtered datasets.
  - Look at radial current profile (L-shell) and as a function of local time
  - Assess climatological differences between perturbed and quiescent magnetospheric conditions
  - Compare filtered and unfiltered climatologies

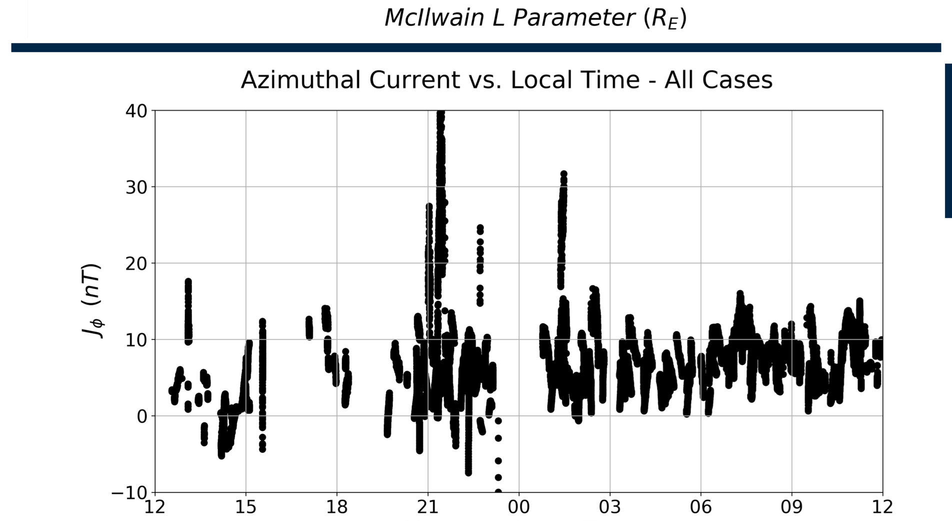
Analysis



- Magnetic field data replaced by a quadratically-varying infinite slab current in one direction produces false currents in other components in curlometry output.
- Passing a simulated pure J_y current through the curlometer (a) successfully captures the imposed current (green), but can produce a significant false current up to 100% of the imposed current (blue).
- These false currents can occur even at accepted thresholds of quality parameter Q (b), with the region where Q < 0.5 is denoted by dashed lines.
- Plotting tetrahedron orientation (c) suggests that false currents are created by large nonlinearity errors, when the magnetic field gradient (∇B) is most aligned with the largest plane of the tetrahedron (P).



- All ring current curlometer output subject to Q < 0.5, L < 7.0 was sorted by Dst index into "storm-time" and "quiet-time" data.
- The figure at left shows the azimuthal ring current component as a function of L-shell, sorted by Dst index, at ~4 second cadence (a).
- Storm-time data featured very diverse structures on each pass, seen as filamentary structures in (a).
- The spread of the quiet-time data is provided in (b) showing the majority of currents below 10 nA/m², with typical values below 7 nA/m².
- The ring current exhibits a distinct climatological structure, with steady magnitude at L > 4.5 and declining rapidly closer to Earth.
- Most samples are Earthward of L = 5.5 R_E, adding confidence to the climatology of this region.
- Most perigee passes also featured a strong southward field-aligned current, contrary to expected current systems.



- Azimuthal current density does not show clear dependence on local time, except for slight peaks in the post-dawn and pre-midnight sectors.
- The availability of good-quality curlometer output at all local times obscures climatological trends.

Conclusions

- Curlometer output is inconsistent with expected plasma structures, most likely due to linearization errors.
- Historical quality thresholds can still contain large non-physical currents.
  - Error in simulated calculation primarily stems from current gradients across the tetrahedron.
  - False current components can be as much as 100% of the simulated current, even with quality parameter Q < 0.5.
- Climatologies constructed using stricter quality controls provide too little data for strong conclusions; broader climatologies contain higher uncertainties.
  - Using all data, ring current densities are nearly always below 10 nA/m². However, they only show weak dependence on local time.
  - Quiet-time data shows radial structure, but storm-time data does not contain meaningful trends.

Future Work

- Use nonlinear magnetic gradients in conjunction with tetrahedron orientation to estimate false current magnitudes.
- Compare Cluster data to other multi-spacecraft missions (MMS, THEMIS) for better climatologies.

References

Liemohn et. al. (2016). Challenges associated with near-Earth nightside current. *Journal of Geophysical Research: Space Physics, 121*(7), 6763-6768. doi:10.1002/2016ja022948

Vallat et. al. (2005). First current density measurements in the ring current region using simultaneous multi-spacecraft CLUSTER-FGM data. *Annales Geophysicae, 23*(5), 1849-1865. doi:10.5194/angeo-23-1849-2005

Zhang et. al. (2011). The distribution of the ring current: Cluster observations. *Annales Geophysicae, 29*(9), 1655-1662. doi:10.5194/angeo-29-1655-2011

This project was funded through the National Science Foundation's Research Experience for Undergraduates Program (Grant #1659248), and by NASA Grant #NNX17AB876.