frontiers | Frontiers in Astronomy and Space Sciences

TYPE Editorial
PUBLISHED 06 March 2025
DOI 10.3389/fspas.2025.1579994

OPEN ACCESS

EDITED AND REVIEWED BY
Julio Navarro,
University of Victoria, Canada

*CORRESPONDENCE
Katariina Nykyri,
katariina.nykyri@nasa.gov

RECEIVED 19 February 2025
ACCEPTED 21 February 2025
PUBLISHED 06 March 2025

CITATION
Nykyri K, Blanco-Cano X, Knudsen D, Sibeck DG and Borovsky JE (2025) Editorial: Past, present and future of multispacecraft measurements for space physics.
Front. Astron. Space Sci. 12:1579994.
doi: 10.3389/fspas.2025.1579994

Editorial: Past, present and future of multispacecraft measurements for space physics

Katariina Nykyri[1]*, Xochitl Blanco-Cano[2], David Knudsen[3], David Gary Sibeck[1] and Joseph E. Borovsky[4]

[1]Heliophysics Division, NASA Goddard Space Flight Center, Greenbelt, MD, United States, [2]Instituto de Geofísica Unam, National Autonomous University of Mexico México City, Mexico City, Mexico, [3]Department of Physics and Astronomy, University of Calgary Calgary, Calgary, AB, Canada, [4]Center for Space Plasma Physics, Space Science Institute (SSI), Boulder, CO, United States

KEYWORDS

space plasma physics, multi-spacecraft methods, imagers, gradient-based methods, vortex identification, energetic particle detectors, electric field measurements, soft-x ray (SXR) measurements

Editorial on the Research Topic
Past, present and future of multispacecraft measurements for space physics

Measurements of space plasmas have remained challenging as they must cover multiple species, a wide range of flux levels and energies, and time and spatial scales that range over orders of magnitude. Interactions between a wide variety of fundamental physical processes that occur both on both macroscopic and kinetic scales ultimately determine the modes and efficiency of the solar wind-magnetosphere coupling, including magnetic reconnection, particle energization, and ion-neutral interactions, as well as their corresponding ionospheric and ground signatures. During the last 25 years we have transitioned from single and two-point plasma and field measurements to constellation missions, e.g., Cluster, THEMIS and MMS. This has enabled the development of various multi-spacecraft techniques, e.g., using four-point tetrahedron measurement of magnetic field to determine boundary orientations and motion as well as current densities. This Research Topic has invited contributions to discuss the past, present and future of multi-spacecraft measurements as well as a new imaging mission and techniques for space physics. This editorial summarizes the nine articles submitted to this Research Topic: two review articles, three method articles, two original research articles, one opinion paper, and one perspective article.

The curlometer and spatial gradient based methods are comprehensively reviewed by Dunlop et al. These techniques are adaptable to a range of multi-point and multi-scale arrays, originally developed for ESA's Cluster mission, but later adapted for Swarm and MMS. The authors note that "multi-spacecraft estimates of current density and spatial gradients have provided key information on large and small magnetospheric current systems and related transient structures, resolving 3-D currents for a range of conditions in widely different geospace regions. The curlometer technique, in particular, has proved to be reliable and robust. The applicability of the method is limited by certain constraints, particularly those for relatively small structures compared to the spacecraft separation distances." The authors discuss the further adaptations of these techniques for future constellation missions such as Helioswarm and Plasma Observatory.

A thorough review of solar energetic particle measurements both from historical and current missions, together with the outlook for future missions are given by Reames. The author recommends that "advancing the physics of SEPs may require a return to the closer spacing of the Helios era with coverage mapped by a half-dozen spacecraft to help disentangle the distribution of the SEPs from the underlying structure of the magnetic field and the accelerating shock".

The Kelvin-Helmholtz Instability (KHI), arising from a velocity shear across a plasma boundary, plays a crucial role in plasma, momentum, and energy transfer, e.g., from the shocked solar wind into the planetary magnetospheres and at the boundaries of Coronal Mass Ejections (see, e.g., Nykyri et al. (2021); Nykyri (2024) and references therein). However, a robust vortex detection method by spacecraft has been missing. Here, Kelly et al. develop and validate a novel vortex identification method for ideal MHD, based on existing methods from hydrodynamics. Current techniques, both in hydrodynamics and space plasma physics, are summarized. Then this method is validated against MHD simulations. These techniques have the potential to become useful tools both in simulations and observations, enabling unambiguous detection of events and investigation of the physical effects behind vortex formation.

Tracing plasma, momentum, and energy flow through the geospace systems using *in-situ* data can be difficult due to the limited spatial coverage provided by isolated spacecraft, even when arrayed in formations. Just as in the Earth sciences, imaging missions can play an important role. Here, Murphy et al. review the Solar-Terrestrial Observer for the Response of the Magnetosphere (STORM) mission concept, a global solar wind-magnetosphere imaging mission. They determine how often STORM can observe and image three key science targets: the subsolar magnetopause, ring current, and auroral ovals. STORM's overarching science goal is to study the system science of and flow of energy through the solar wind-magnetosphere system. STORM achieves this by tracking boundary motion and emission intensity variations associated with the Dungey cycle and coupled solar wind-magnetosphere system. While a single spacecraft can readily accomplish these tasks on a case and statistical basis, the authors note that a dual spacecraft STORM mission would significantly enhance science and allow for tomography via stereographic imaging, e.g., Cucho-Padin et al. Such a dual spacecraft mission would however increase both complexity and costs.

Cucho-Padin et al. examined our ability to reconstruct the time-dependent three-dimensional structure of magnetospheric plasmas from observations by wide field-of-view soft X-ray imagers. To calculate emissivities along lines of sight from two imaging spacecraft in various configurations, they employed the OpenGGSM magnetohydrodynamic model for plasma densities and velocities in and near the magnetosphere and assumed a spherically-symmetric exospheric neutral density. This technique could be used in a two-spacecraft STORM mission to reveal three-dimensional dynamical processes in the Earth's magnetosphere.

Akbari et al. present a gradient calculation method for the upcoming, six-spacecraft Geospace Dynamics Constellation (GDC) mission, which will investigate dynamical processes in Earth's upper atmosphere. Achieving this goal will involve resolving and distinguishing spatial and temporal variability of ionospheric and thermospheric structures in a quantitative manner. Specifically, this paper implements the least-squares gradient calculation approach previously developed by J. De Keyser. The authors conclude that: "1) computation of the temporal gradients of neutral and plasma variables, while sensitive to the measurement noise level, are possible with GDC measurements; 2) The spatial gradients of the equatorial ionization anomaly can be reasonably resolved during phase 1 of the mission, while at the later phases the gradients are likely to be underestimated. On the other hand, in the presence of measurement noise, computing the gradients of the neutral temperature would likely be more difficult in the earliest phases of the mission due to the small gradients and large homogeneity lengths involved; 3) Gradients of the neutral wind can be well determined in the earliest phases of the mission even at the highest latitudes where the constellation skews in longitude."

Oberheide et al. discuss how the GDC mission can be used to resolve tidal weather. The GDC mission measures neutral temperatures and winds and thus likely enable significant progress towards resolving the tidal weather of the thermosphere and how it is driven by meteorological processes near the surface and *in situ* forcing in the ionosphere-thermosphere system. The authors demonstrate that GDC can resolve the day-to-day tidal variability (mean, diurnal and semidiurnal, migrating and nonmigrating) at orbit height during the mission. They note that the "mean state of thermosphere can also be recovered on a day-to-day basis throughout mission phases 3 and 4, including the mean meridional circulation".

In an opinion article, Weimer argue that the significance of the small-scale electric fields in the polar ionosphere may be overestimated. This somewhat contradicts earlier studies that highlight the importance of correctly capturing the variability of the electric fields in the models to accurately account for the total amount of Joule heating. The authors conclude that future multi-spacecraft measurements in the polar ionosphere, such as the future GDC mission, will be able to address this issue, "with some limitations due to missing double-probes".

In a perpective article Archer et al. discuss both new and improved observational directions for uncovering magnetopause, magnetospheric, and ionospheric dynamics and how these may aid our understanding of the magnetopause boundary's global importance to the geospace energy budget.

The science goals, methods, and open questions discussed in this Research Topic are well aligned with the Heliophysics Decadal Survey's 2024-2033 vision and strategy NAS (2024). The Decadal survey in Heliophysics "The Next Decade of Discovery in Solar and Space Physics: Exploring and Safeguarding Humanity's Home in Space" was published in December 2024. It sets forth a comprehensive science vision to advance and expand the frontiers of Heliophysics for the next decade. The report provides a prioritized research strategy and recommends both new and existing space missions, ground-based instruments and facilities, as well as modeling and simulation to achieve the identified science goals in the space and solar physics fields.

The extent, to which these can be accomplished in the next decade depends on the funding level of the associated agencies: NASA, NSF and NOAA as well as their international counterparts, and on the state of a healthy and educated workforce.

Author contributions

KN: Writing–original draft, Writing–review and editing. XB-C: Writing–review and editing. DK: Writing–review and editing. DS: Writing–review and editing. JB: Writing–review and editing.

Funding

The author(s) declare that financial support was received for the research, authorship, and/or publication of this article. KN was supported by NASA LWS grant #80NSSC23K0899 and ISFM grants. DS was supported by NASA's LWS and USPI programs.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The author(s) declared that they were an editorial board member of Frontiers, at the time of submission. This had no impact on the peer review process and the final decision.

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

Publisher's note

References

NAS (2024). *National academies of sciences: next decade of Discovery in solar and space physics: exploring and safeguarding humanityś Home in space*. Washington, DC: The National Academies Press. doi:10.17226/27938

Nykyri, K. (2024). Giant Kelvin-Helmholtz (KH) waves at the boundary layer of the coronal mass ejections (cmes) responsible for the largest geomagnetic storm in 20 years. *Geophys. Res. Lett.* 51, e2024GL110477. doi:10.1029/2024gl110477

Nykyri, K., Ma, X., Burkholder, B., Rice, R., Johnson, J. R., Kim, E.-K., et al. (2021). Mms observations of the multiscale wave structures and parallel electron heating in the vicinity of the southern exterior cusp. *J. Geophys. Res. Space Phys.* 126, e2019JA027698. doi:10.1029/2019JA027698