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Evolving plasma sensors for future measurements of Earth's magnetospheric cold plasma

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Routine measurements of Earth's magnetospheric cold plasma have not occurred on any recent space science mission. This hurdle to cold plasma science progress spans decades, root cause linked to space system and space environment interactions that compromise the conditions for acquiring cold plasma measurements. Focused efforts must still develop and mature techniques, methods, or technologies to overcome the complex sensor operating conditions that arise from these interactions. This Perspective article provides common and recent examples of observed experimental data artifacts caused by spacecraft- or sensor-environment interactions to remind us of the ensuing degradation in accuracy of magnetospheric cold plasma measurements. We then describe one angle of attack leveraging instrument technology development in progress today that can help improve measurement conditions for future sensors. Our Perspective can motivate parallel developments or application of such technologies to future science investigations.

KEYWORDS

magnetosphere, plasma, instruments, techniques, methods, sensors, proliferation

1 Introduction

Recent incremental advances understanding magnetospheric cold plasma leverage occasional measurements acquired by various scientific missions (e.g., Cluster: Escoubet et al., 2001; Time History of Events and Macroscale Interactions during Substorms (THEMIS): Angelopoulos 2008; and Magnetospheric Multiscale (MMS): Burch et al., 2016). For example, measurements by the NASA MMS mission consisting of four state-of-the-art, identically instrumented spacecraft motivated various studies on how magnetospheric cold (total energy below ~20 eV) plasma impacts magnetospheric physics (e.g., Fuselier et al., 2017; Alm et al., 2018; Lee et al., 2019, and references therein).

At the same time, investigations of complex on-orbit operating conditions for plasma sensors show the impacts of spacecraft electrostatic potential on precise plasma characterization (Toledo-Redondo et al., 2019; André et al., 2021). These efforts also showed that the latest accepted mitigation method using active spacecraft potential control (ASPOC) cannot sufficiently correct for a non-uniform spacecraft electrostatic potential and its effects on sensor operating conditions, therefore making accurate and routine plasma measurements impossible. Related past applied research has investigated why, even with methods to bias a frame-mounted plasma sensor, direct cold plasma ion measurements could not occur (Olsen et al., 1986). The spacecraft potential nonuniformity presents a complex research problem that sensor developers must maintain awareness of (Barrie et al., 2019). But practical awareness should flow the spacecraft potential problem into sensor engineering design. Such a design philosophy can consider the spacecraft bus vehicle, spacecraft end-use environment variability, and hosted payloads as setting a collective design requirement on the plasma sensor, although convention and tradition tends towards the opposite with the plasma sensor (or other payloads) specifying many of the accommodation requirements on the bus vehicle.

Even with these measurement difficulties induced by degraded sensor operating conditions that arise from spacecraft-environment interactions, some progress on magnetospheric cold plasma continues. Mining of cold plasma ion measurement data during plasma bulk flows (convection, ultralow frequency waves, or ionospheric outflows) provides a glimpse into the presence and properties of these seldom-measured cold plasma distributions (Hirahara et al., 2004; Chen and Moore, 2006; Lee and Angelopoulos, 2014; Yue et al., 2023). Some studies also leverage the formation of a spacecraft wake to make progress on cold ion occurrence (Engwall et al., 2009). Collective data see follow-on application to interpret localized growth of electromagnetic waves (Lee et al., 2019; Lee et al., 2021a; Toledo-Redondo et al., 2021b; Vines et al., 2019) or impacts on magnetic reconnection (André and Cully, 2012; Toledo-Redondo et al., 2021a). These studies contribute hints of magnetospheric plasma ion distributions, which remain unmeasured much of the time in the absence of acceleration to total energies exceeding the sum of the spacecraft potential and minimum energy of plasma sensors. A related hurdle limits plasma electron measurements: interactions of primary charged particles with spacecraft and sensor materials will generate secondary electrons, as does solar UV-photon bombardment of materials, creating artificial <30 eV cold plasma electron distributions attracted back towards a sunlit, positively charged spacecraft. The abundance of artificial electrons emitted competes with or overcrowds the natural cold plasma electrons most of the time. A way to fill the void on magnetospheric cold plasma characteristics required to determine roles in cross-energy or cross-scale interactions could utilize machine learning (ML) or artificial intelligence (AI) methods, using occasional direct measurements of cold plasma ions or electrons to inform the methods. Such methods show success utilizing electron density measurements derived from plasma wave data to produce 3-D models of inner magnetosphere electron density (e.g., Chu et al., 2017). Additional magnetospheric plasma parameters such as ion mass composition, partial ion densities, as well as plasma ion temperatures require future effort to adequately measure and then model. Taki et al. (2024) showed derivations of cold electron temperature from electron cyclotron wave emissions data based on linear dispersion theory, which combined with ML methods may allow for construction of a 3-D model of partial cold electron temperature in Earth's magnetosphere. Such models contribute to an overarching goal to run accurate global magnetospheric simulations to understand and predict sources, acceleration, and losses of magnetospheric plasmas. But deriving ion composition, partial ion density and temperatures from wave emissions for applications to modeling or simulations remains a difficult task. Even with progress understanding multiple magnetospheric ion populations and their contributions to plasma wave emissions like electromagnetic ion cyclotron waves (see: Lee et al., 2021b, for a review), the application of linear dispersion theory on these ion cyclotron wave emissions to derive magnetospheric plasma characteristics assumes a thorough understanding of why the waves occur. This understanding remains elusive in part because of infrequent direct measurements of cold plasma ion populations. An eagerness to apply new computing methods drives us to already think of ways to utilize these sparse cold plasma ion data in ML or AI applications. But when the guiding measurement data continue to suffer from space system-environmental effects that degrade accuracy, would ML or AI forward propagate these inaccuracies? From our Perspective, developing on-orbit experiment methods, techniques, or technologies to improve the accuracy of sensor measurements serves to improve future usefulness of such computational tools for advancing understanding of magnetospheric cold plasma.

Although laboratory and simulation studies continue to assume the effective use of ASPOC to support future space science investigations, past and recent work both suggest the spacecraft electrostatic potential does not follow a uniform, symmetric structure around the spacecraft and deployed structures (Miyake and Usui, 2016; Toledo-Redondo et al., 2019). In addition, routine observations of small levels of positive charging remaining indicate insufficient ASPOC current to fully correct the spacecraft charging. ASPOC operation can also compromise measurements by other scientific instruments like electric field probes, which can further limit its use when mission goals require continuous precision field measurements. We describe an alternative sensor development perspective that assumes the spacecraft potential structure and nonuniformities of it will always compromise operation of a frame-mounted sensor. We then offer a complementary methodology for instrument developers seeking to improve the likelihood of measuring cold magnetospheric plasmas. By considering past and present observations, we believe future instruments must anticipate measurement complexities on all future scientific spacecraft, even those equipped with ASPOC.

2 Unwanted artifacts in on-orbit plasma measurement data

Unwanted artifacts litter on-orbit cold plasma measurement data. A presentation of measurements from recent spacecraft missions follows. These examples come from NASA's MMS and THEMIS missions due to the authors' familiarity analyzing datasets produced from measurements made by instruments hosted on the missions' spacecraft. Make no mistake: measurements made by other scientific spacecraft also have these problems.

Figure 1 shows samples of measurement data from the MMS-2 (panels 1a through d) and THEMIS-A (TH-A; panels 1e,f) spacecraft on 13 February 2024. These data help illustrate the effects of spacecraft charging, instrument interference, and secondary electrons on magnetospheric cold plasma science investigations. Although the figure contains plots of somewhat recent data, the observations resemble those already discussed

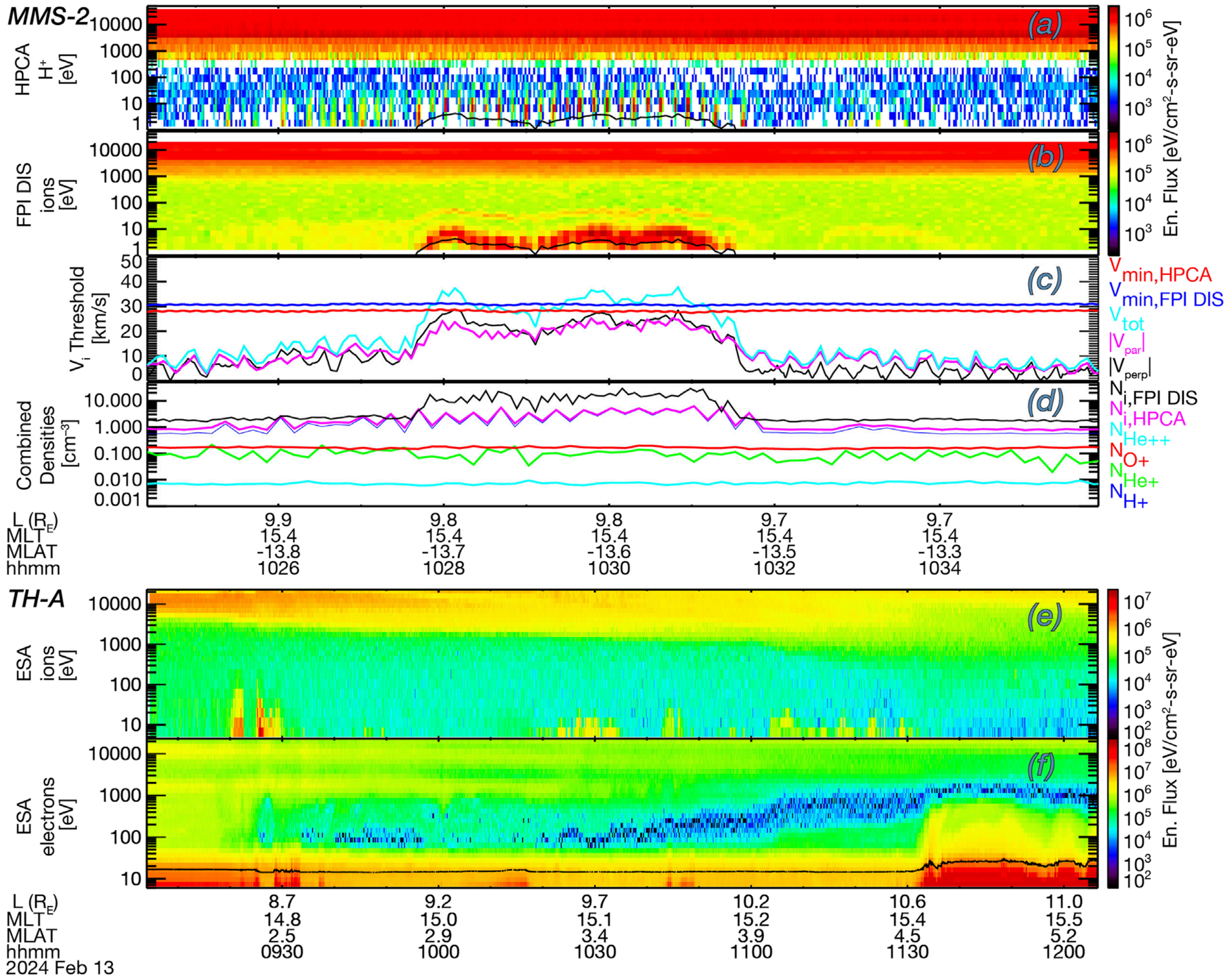

FIGURE 1
MMS and THEMIS observations of plasma ions and electrons in Earth's outer dayside magnetosphere on 13 February 2024. **(a,b)** Ion energy-time spectrograms from the MMS HPCA and FPI DIS plasma instruments, respectively, with an estimate of the E × B energy derived from the bulk velocity perpendicular to the mean magnetic field superposed on each panel (black); **(c)** magnitudes of plasma bulk velocity parallel and perpendicular to the mean magnetic field calculated from FPI DIS measurements alongside minimum velocity thresholds (Red: $V_{min,HPCA}$ and Blue: $V_{min,FPI\ DIS}$) calculated from the sum of the spacecraft potential energy and the midpoint of the minimum energy bin from the HPCA and FPI DIS instruments, and **(d)** partial ion densities derived from the HPCA (Blue: N_{H+}, Green: N_{He+}, Red: N_{O+}, Cyan: N_{He++} and Magenta: the summed partial ion density $N_{i,HPCA}$) and FPI DIS (Black: $N_{i,FPI\ DIS}$) instruments. **(e,f)** Ion and electron energy-time spectrograms from the THEMIS ion and electron ESA plasma instruments, respectively, with the derived spacecraft potential energy superposed (black) on panel **(f)**.

in earlier studies (cf. Anderson et al., 1996; Anderson and Fuselier, 1994; André and Cully, 2012; Lee and Angelopoulos, 2014; Walsh et al., 2020; Delzanno et al., 2021). We review these observations to remind the community of these problems and to support our Perspective.

For both sets of observations, the respective NASA spacecraft sampled plasma in Earth's outer (>7 earth radii, R_E) dayside magnetosphere at afternoon magnetic local times (MLTs). MMS-2 had ASPOC (Torkar et al., 2016) in operation, controlling the spacecraft's potential to ~+2 V. Near the center of the interval shown, between 10:27:30 and 10:31:30 UT, enhancements in charged particle flux emerge at low energies below 100 eV in panels 1a, b. Based on the plasma bulk flow velocities derived and shown in panel 1c, the flux enhancements coincided with plasma flows from convection and ionospheric outflow. Similar enhancements appear in TH-A plasma ion data, panel 1e, also coinciding with plasma flows. Overplotted on panels 1a, b, the trace showing the E × B energy calculated using the velocity orthogonal to the dominant component of the average magnetic field (Vperp, the black trace in panel 1c) falls below the peak in ion energy fluxes observed in each panel, supporting our interpretation that observation of the enhancement occurred due to collective kinetic energy of bulk flow processes. These bulk flows likely then accelerated a dense (>~1 cm^{-3}, cf. panel 1d) distribution of cold ions—mostly protons, present but undetectable prior to 10:27:30, into the minimum energy ranges measurable by MMS plasma instruments (the Fast Plasma Investigation Dual Ion Spectrometers, or FPI DIS, Pollock et al., 2016; and the Hot Plasma Composition Analyzer, i.e., HPCA; Young et al., 2016). Although research has exploited similar observations to derive characteristics of the cold plasma, like the partial densities of multiple plasma ion species shown in panel 1d, panels 1a to d also show the limitations of ASPOC to fully correct for impacts of spacecraft charging on routine measurements of cold plasma distributions. These limitations result from both operational and payload driven requirements; ASPOC can impact operations of other scientific payloads (Toledo-Redondo et al., 2019). But even small positive potentials prevent routine measurements of the core of cold plasma distributions by plasma sensors, suggesting sensors themselves cannot rely solely on ASPOC. This awareness has existed for decades, yet present plasma sensors continue flight applications without the full spacecraft charging mitigation necessary to acquire routine cold plasma measurements. We define routine measurements as samples occurring during nominal science operations (sometimes termed as “survey”, “fast survey” or similar, depending on the mission, and occurring after station-keeping maneuvers or calibration activities) without the assistance of natural plasma physics processes (convection, ULF waves, or ionospheric outflows). At present, routine measurements of cold plasma do not occur. For example, Lee and Angelopoulos, (2014) conducted statistical analysis of cold ion presence in the outer dayside magnetosphere to show high occurrence (≥75%) of the cold ions but required the occurrence of plasma bulk flows to establish these occurrence statistics. Yue et al. (2023) investigated occurrence of cold ions and their properties in the inner (<7 R_E) magnetosphere using the Van Allen Probes dataset also leveraging the occurrence of plasma bulk flows.

In addition to the spacecraft charging problem, instrument interference degrades the accuracy of measurement data. We now discuss panels 1d,f. Comparisons of estimated total plasma ion density from the MMS sensors (black, FPI DIS, and magenta, HPCA, traces in panel 1d) during the flow interval show disagreement by a factor of 2 or more. Which value should apply for investigating contributions of cold ion presence on plasma wave instabilities? Toledo-Redondo et al. (2019) attributed such discrepancies at least in part to instrument interference resulting from a nonuniform electrostatic potential generated by charging of long wire booms used to deploy the electric field sensors away from the MMS frame. Short timescale discrepancies also appear: on the order of the MMS spacecraft’s spin period of 20 s, HPCA-derived density estimates fluctuate between ~1 and ~3 cm^{-3}. Boom-related interference likely contributed to these fluctuations (Toledo-Redondo et al., 2019). Finally, the charging of spacecraft and sensor surfaces in sunlight combined with secondary electron production by primary particles or solar UV photons presents severe problems characterizing natural cold plasma electrons. Panel 1f showing TH-A plasma electron data also displays a black trace indicating the spacecraft potential energy that varies between 10 and 30 eV. High (>few 1E6 electrons eV/cm^2-s-sr-eV) energy fluxes of cold plasma electrons track well with this spacecraft potential energy trace, consistent with a combination of space system-generated and natural cold plasma electrons attracted towards a positive charged spacecraft. Efforts can model the space system-generated electrons for a given spacecraft, allowing us to recover some information on natural plasma electrons for scientific studies (Gershman et al., 2017). These efforts must recur as a function of each new mission, since the empirical modeling must leverage on-orbit observations of the bus-specific offending fluxes to enable their removal from observational data during subsequent ground data processing. We next consider a potential remedy through instrument technology development.

3 Miniaturized and deployable plasma sensors

Spacecraft as well as spacecraft-hosted instruments continue to experience widespread reductions in size, weight, and often power at least partly leveraging miniaturization of electronics parts driven by the consumer electronics industry. At the same time, as commercialization of space continues and proliferated constellations experience rapid growth by the hundreds, plasma sensors remain a boutique “product.” Apart from the MMS FPI that employed commercial manufacturing to build up a total of 32 electron and 32 ion flight-model spectrometers, most plasma sensors continue development and production as one offs, each incrementally unique from its predecessor. To keep pace and best leverage new constellation types enabled by commercial space, future science investigations must also evolve new sensor production methods and do so on rapid timescales. The MMS FPI example may represent a new normal, though further simplification and miniaturization may yield even more production efficiency: Modular plasma sensors, straightforward to configure for overlapping science goals, and then built to print.

An example of miniature modular sensors that can be produced at scale and configured to satisfy different measurement ranges is Teledyne’s product line of micro-dosimeters, namely, the LoLET, MedLET, and HiLET (Linear Energy Transfer). The Aerospace Corporation designed these devices, then prototyped, and later licensed to Teledyne for commercial sale. Each type of dosimeter measures a different range of electrons and protons that contribute to ionizing dose. Development of a paired small silicon detector and custom application specific integrated circuit (ASIC) helped to reduce the size of the electronics by about several orders of magnitude. This also made the micro-dosimeter relatively straightforward to build as the number of parts was drastically reduced, and it made the dosimeter construction look more like a typical hybrid micro-electronic part, not unlike power converters and RF modules commonly seen on the market. The ability to produce the micro-dosimeter using the automated die attach and wire-bonding machines programmed with a high degree of reliability enabled a drastic reduction in dosimeter cost compared to hand made assemblies. Finally, the configurability for the three different energy ranges was straightforward as well, amounting to only selecting a different detector and ASIC for the build while the rest of the assembly process and overall dosimeter design remained the same. This experience with the micro-dosimeter translates precisely to the process envisaged for the modular plasma sensors. Of course, micro-dosimeters differ in complexity and measurement requirements when compared to an electrostatic analyzer (ESA) designed for plasma sensing. But even with increased complexity of ESAs, modularity and production efficiency strategies remain applicable, a topic we revisit later.

We now discuss new applications of such miniaturized sensors. Spacecraft operating in high density cold plasma environments like Earth's ionosphere experience less positive charging during nominal conditions. As discussed earlier, even small levels of positive charging (a few Volts) prevent accurate measurement of cold plasma distributions. Although ASPOC can help introduce current to partially mitigate surface charging of the spacecraft and frame-mounted sensors, a quasi-steady state positive spacecraft potential of at least a few Volts usually remains. To mitigate remnant charging effects on sensor measurements and operation, plasma sensors may operate on booms away from the spacecraft frame, a technique exploited on rockets but not recently on magnetospheric missions (Zurbuchen and Gershman, 2016) while also carrying the ability to control their surface potential independent of the spacecraft. A high density cold ionospheric plasma (e.g., 0.5 eV and >1E+10 m^{-3}) results in a Debye length λ_D (cf. Equation 1) on the order of a few cm. Similar calculations inform the boom lengths expected in other orbits such as GEO, where a GEO-like electron plasma (e.g., 100 eV and 50 cm^{-3} such that λ_D ~ 10 m) requires boom lengths >10 m to support operation of sensors outside the core spacecraft sheath plasma, possibly allowing future routine investigations of cold plasmaspheric plasma (cf. Jahn et al., 2017; Yue et al., 2023). A sensor deployed by a boom of necessary length, could operate beyond a spacecraft's Debye sheath. Yau et al. (2015) described a recent example of a boom-deployed plasma sensor called the Imaging and Rapid-Scanning Ion Mass Spectrometer (IRM) instrument on the Enhanced Polar Outflow Probe (e-POP) mission. The IRM, a small (cylindrical geometry with 64 cm^2 top and 353 cm^2 lateral surface areas) boom-deployed sensor, uses an electrical isolation scheme to isolate the sensor surfaces from the spacecraft by use of electrically insulating materials and coatings. The electrical isolation allows the IRM sensor surface to float at its own potential relative to the spacecraft and the ionosphere. Other small plasma sensors exist that might also apply to boom-deployed applications in Earth's magnetosphere. For example, Collinson et al. (2022a) described small ESA-type sensors of a hybrid variety that integrate an ESA with a retarding potential analyzer (RPA). Eight of these hybrid sensors deployed by booms during a sounding rocket flight to characterize naturally occurring photoelectron characteristics. Although hosted on a rocket flight, the small size of the dual electrostatic analyzer (DESA) sensors also supports hosting on spacecraft within the CubeSat specification (Collinson et al., 2022b). An electrical isolation scheme comparable to that devised for the IRM sensor might also allow a boom-deployed DESA to float at its own potential relative to the host platform. Although not developed for the IRM or DESA sensors, the capability of surface potential control of an electrically isolated, boom-deployed plasma sensor, achievable through current injection to compensate for excess secondary electron current leaving the sensor surface, could iteratively maintain the sensor potential at the ambient plasma potential to permit more frequent direct measurement of cold plasma distributions. Modern electric field instruments (e.g., Bonnell et al., 2008; Lindqvist et al., 2016) commonly leverage a similar mode of operation to guarantee high fidelity field measurements.

$$\lambda_D = \left(\varepsilon_0 \mathrm{k} T_e / n_e q_e^2\right)^{1/2} \tag{1}$$

Challenges exist to realizing the deployed plasma sensor concept. Most modern plasma sensors require frame-hosting, due to size/weight and power (SWaP) and measurement requirements. Many of these large sensors, electrostatic analyzer or "top-hat" spectrometers, promise wide field-of-view (FOV) and fast sampling necessary to collect 3-dimensional plasma distribution functions at high energy and time resolution. Some efforts continue the assumption of frame-hosted operation, also assuming spacecraft potential control as well as additional aperture plane biasing requirements to ensure improved characterization of low-energy, cold plasma. Although this seems like a low-risk approach, past observations have shown aperture plane biasing has not sufficiently corrected for spacecraft potential (Olsen et al., 1986). Complex spacecraft potential structure generated by deployed sensors or spacecraft infrastructure may create further problems for biasing a frame-hosted plasma sensor (Miyake and Usui, 2016; Toledo-Redondo et al., 2019) and then interpreting measurement data (Barrie et al., 2019). Pursuit of new measurement strategies must occur in parallel with low-risk, incremental advances to improve measurement capabilities on cold plasma.

For example, whereas aspects of geometry and associated ratios can translate through miniaturization, dimensions will decrease. Smaller dimensions can impact the dynamic range achievable by miniaturized sensors. But if the goal of miniaturized sensors focuses on low-energy, cold plasma, achieving large dynamic range carries less priority. Miniaturized sensor FOV could suffer a similar trade-off, with potentially less anode collector area due to reduction in electronics printed circuit board area, thereby decreasing the angular resolution achievable. Proliferation or distribution of many sensors can mitigate the effects of trade-offs in measurement capability resulting from miniaturization. Like the distribution of Fast Plasma Investigation spectrometers around MMS's instrument deck, many boom-deployed sensors could provide a method to observe cold plasma distributions without common measurement interference effects known to exist near the spacecraft frame.

Figure 2 shows progress developing miniaturized electrostatic analyzers (Figures 2a,b: mini-ESA; Lee et al., 2024) and a deployable miniaturized instrument called the charging mitigation shell (Figures 2c–f: CMS; Lee et al., 2023) that will function as a companion instrument to deployable cold plasma sensors. The mini-ESA, shown in Figures 2a,b with a 360° FOV aperture and a 98 mm × 98 mm square base, leverages decades of sounding rocket heritage (e.g., Geoelectrodynamics and Electro-Optical Detection of Electron and Suprathermal Ion Currents (GEODESIC): Burchill et al., 2004; Lee et al., 2008; Knudsen et al., 2012; and VISualizing Ion Outflow via Neutral atom imaging during a Substorm (VISIONS): Collier et al., 2015), marrying successful sensor performance with more recent nanosatellite experience (e.g., Lee et al., 2020) to develop a modernized modular sensor architecture compatible with CubeSats. The mini-ESA design enables straightforward integration of mini-ESA module elements into the CMS. A mini-ESA module element consists of commercial off-the-shelf microchannel plates, a configurable segmented anode collector printed circuit board (PCB), and a pulse amplifier and discriminator PCB that performs conversion of analog current pulses into digital signals. The CMS design leverages a heritage instrument flown years ago on the Spacecraft Charging AT High Altitude (SCATHA) mission called the SC-2 payload (Fennell, 1982), consisting of two spherical 18-cm diameter boom-deployed probes that enclosed cylindrical ESAs designed to characterize

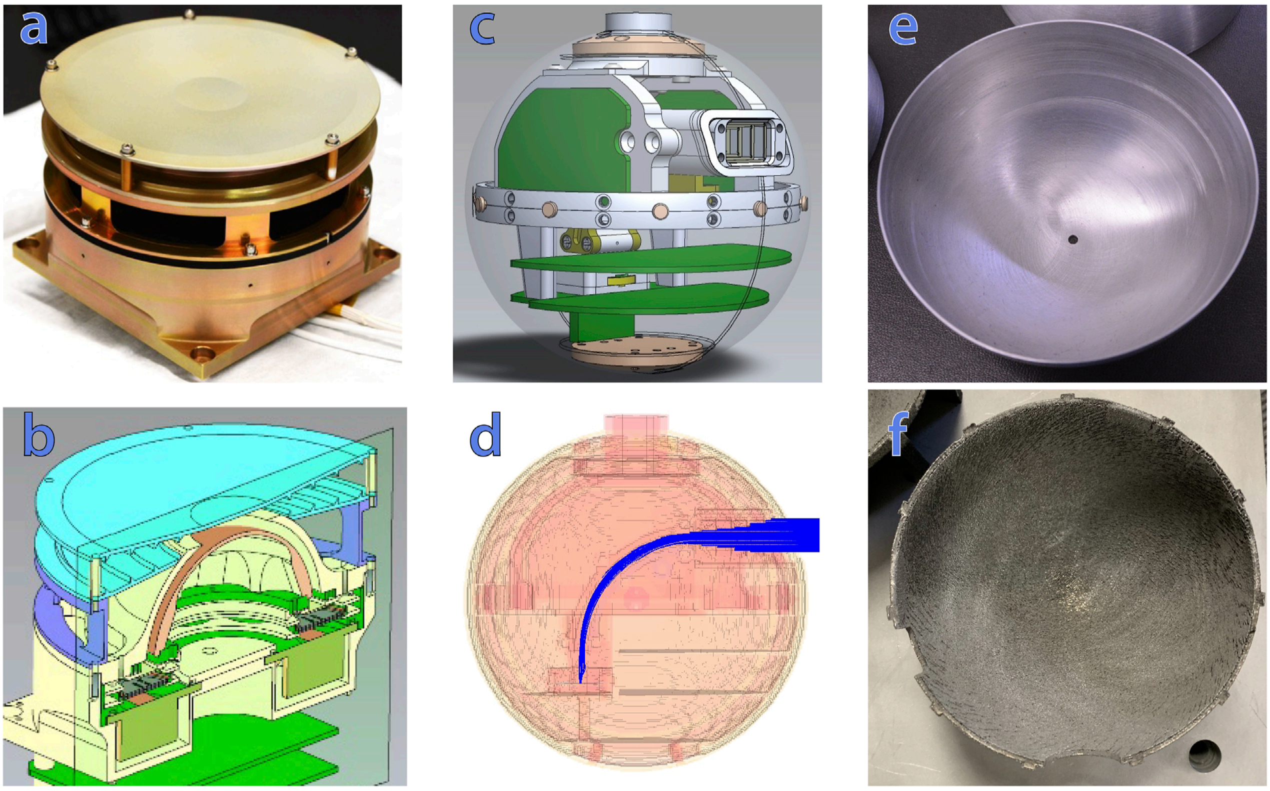

FIGURE 2
(a) A fully assembled CubeSat specification (Johnstone, 2022) compliant miniature electrostatic analyzer and **(b)** a cross-sectional slice of a CAD model cartoon of the same sensor. **(c)** CAD rendering and **(d)** transparent particle simulation of the CubeSat specification compliant miniaturized charging mitigation shell (CMS) instrument, and photos of an external hemisphere produced by **(e)** spin forming and **(f)** powder bed fusion additive manufacturing methods.

artificial plasma produced by SCATHA in addition to ambient magnetospheric plasma ions and electrons. SC-2 also contained instrumentation for regulating probe potential to support direct characterization of low-energy spacecraft sheath plasmas to improve understanding of their roles in spacecraft charging characteristics. The CMS, with a miniaturized 10-cm external diameter spherical shell structure (Figure 2c), encloses a small mini-ESA module in addition to its own measurement electronics. The CMS's outer shell will operate much like today's electric field probes, supporting bias voltage sweeps and current injection necessary to regulate shell potential in sunlight as necessary to operate at the plasma potential. To support low-energy plasma measurements, the electrically isolated outer shell surrounds an inner Faraday shell that then encloses the ESA and remaining infrastructure. The ESA's electronics and interior support structure share common ground with the Faraday shell. This configuration will help incoming cold ions experience no pre-acceleration upon passing through the outer shell that remains at the plasma potential to preserve the ambient state of the cold ions, improving their characterization. In Figure 2d, a partially transparent image of a simulation performed using the commercial SIMION software shows an example of a cold ion beam fully filling the CMS entrance aperture and the biased ESA electrode guiding an unattenuated portion of the beam towards the ESA detection electronics. The present ESA residing within the CMS provides high energy resolution cold ion measurement at <1,000 eV energies, carrying forward quasi-logarithmic stepped energy sweep and retrace architecture matured through many rocket flights. 32 or more discrete, configurable energy steps will cover the condensed energy range to support variable $\Delta E/E$ performance targets. Although the field-of-view provided by a single ESA enclosed within the CMS will not match that of the 360° FOV mini-ESA, deploying multiples of the low SWaP CMS that could each employ a segmented anode collector can provide the desired polar angle coverage and angular resolution. Present CMS development focuses on proving out the concept of controlling the miniaturized external shell potential while managing ESA electronics commonly used by today's plasma sensors. Therefore, performance of the ESA module does not presently drive overall CMS measurement requirements. But exploration of obvious additional desired measurement performance drivers such as angular resolution discussed above can proceed in the future.

Before concluding this section, we revisit the modularity and production efficiency topic introduced earlier while discussing the micro-dosimeters and discuss how similar strategies can find implementation in more complex plasma sensors. We call out structural components because they present a significant difference between the mini-ESA and the micro-dosimeters. Most, if not all, present-day ESAs require precision machining and multiple post-processing steps to build up structural components such as the collimator "hat" and nested (hemispherical) electrodes. Part of

CMS research and development investigates production efficiency enabled by advances in additive manufacturing (AM), also known as 3-D printing. Figure 2e shows an interior face of a CMS external hemisphere produced using the well-known metal spinning or spin forming method and 2f shows the interior face of an external hemisphere produced by the AM powder bed fusion (PBF) method. At present, CMS hemispheres produced by spin forming must undergo multiple rounds of post-processing to apply additional cut-outs for the ESA aperture and accommodation of electrical isolation components as well as holes for fasteners. With AM, cut-outs occur as part of the build, visible at the left and bottom of Figure 2f, leaving sanding and polishing as the main post-processing efforts. The 360° FOV mini-ESA and the ESA module housed within the CMS can also leverage AM techniques. For example, part of machining the nested electrodes used by ESAs includes some degree of surface roughness applied to interior surfaces by applying fine serrations or other rough features to contribute to suppression of the undesirable effects of photons on measurements (cf. Gershman and Zurbuchen, 2010). In addition to the roughened surfaces, an additional coating procedure follows to support application of a black oxide finish (cf. Hooks et al., 2024), also to mitigate photon-induced measurement contamination. As seen in Figure 2f, surface roughness occurs organically through AM methods like PBF, though work remains to characterize the benefits of the roughness resulting from PBF build processes on charged particle detection. Finally, AM builds can proceed using specific materials already supportive of black oxide finishing, presenting yet another way to decrease production steps required for sensor manufacture. The AM build file(s) that include process parameters refined through our research can easily transfer to commercial AM vendors for production to benefit from economies of scale for future proliferated missions. Although we do not discuss how production efficiency can apply to the ESA electronics boards, it follows that methodology already explored and matured through the micro-dosimeters experience discussed earlier in this paper remain applicable to the modular circuits utilized for our ESA electronics architecture.

4 Discussion

Informed by mission experience and observations of common measurement problems still affecting progress on magnetospheric cold plasma science, we presented a Perspective on evolving low-energy cold plasma sensors for future missions. Development of this Perspective leverages experience conducting analyses on various on-orbit observations coupled with past or ongoing instrument development. Although frame-hosted, high-fidelity plasma sensors continue to prove their worth on many spacecraft missions, the assumption of sustained budget levels required to plan, procure, and execute similar spacecraft missions necessary to host such sensors in the future lacks pragmatism. We believe alternative proliferated spacecraft buses and rapid launch cadences increasingly employed for commercial purposes present new opportunities for fielding miniaturized plasma sensors that may also accelerate progress on magnetospheric cold plasma science. We provided a glimpse of new innovative techniques sensor developers might leverage to build plasma sensors for widespread deployment on such spacecraft constellations of the future. Miniaturized plasma sensors must quickly evolve to capitalize on these new avenues for executing space flight missions.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: https://lasp.colorado.edu/mms/sdc/public/datasets/ https://themis.igpp.ucla.edu/data_retrieval.shtml.

Author contributions

JHL: Conceptualization, Methodology, Writing – review and editing, Supervision, Writing – original draft, Investigation, Software, Project administration, Visualization, Funding acquisition, Formal Analysis, Data curation, Validation, Resources. JF: Investigation, Writing – review and editing, Conceptualization. CL: Methodology, Investigation, Conceptualization, Writing – review and editing. WC: Methodology, Investigation, Conceptualization, Writing – review and editing, Writing – original draft. SC: Investigation, Writing – review and editing, Methodology, Conceptualization. SB: Conceptualization, Writing – review and editing, Methodology, Investigation. GM: Investigation, Conceptualization, Writing – review and editing, Methodology. JRL: Methodology, Conceptualization, Investigation, Writing – review and editing.

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Conflict of interest

Authors JHL, JF, CL, WC, SC, SB, GM, and JRL were employed by The Aerospace Corporation.

Generative AI statement

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

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