Grotifer: A new electric field instrument design to address the need for highly accurate three-component electric field measurements

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Accurate knowledge of the full, three-dimensional electric field vector is of fundamental importance in understanding electrodynamics of a vast variety of space plasmas. However, heliophysics research still lacks access to the reliable parallel electric field measurements required to close many significant science questions. This uncertainty represents a significant barrier to progress in the field. The only way to close this major observational gap is a profound change in electric field instrument design. A new electric field instrument called Grotifer is now being designed to address the need for highly accurate three-dimensional electric field measurements while enabling lower cost missions and constellation missions in deep space. Grotifer (Giant rotifer) is a reference to the rotifer, also known as the "wheel animalcule." Similarly, Grotifer consists of mounting detectors on two rotating plates, orthogonal to each other, on a non-rotating central body. The two rotating plates provide continuous high-accuracy three-dimensional measurements of both electric fields and magnetic fields. The Grotifer design leverages more than 50 years of expertise in delivering highly accurate spin plane electric field measurements, while overcoming inaccuracies generated by spin axis electric field measurements. Our current efforts focus on designing Grotifer as a SmallSat (27U CubeSat). That said, Grotifer could also become part of the payload on a much larger platform. In the future, one could imagine fleets of Grotifers studying electrodynamics at many points, facilitating differentiation between spatial and temporal dynamics. Plasma detectors could also be added to the rotating plates to cover the full phase space better than is done on spinning spacecraft, leading to more complete correlation studies of the fields and plasmas.

KEYWORDS

electric fields, double probes, parallel electric field, instrument design, CubeSat

1 Motivation

Complete and accurate understanding of the electrodynamics of space plasmas requires a complete and accurate measurement of the three-dimensional electric and magnetic fields, as well as the velocity distribution functions of the charged particles that interact with those fields. While one can often infer the presence and magnitude of poorly measured components of the electromagnetic fields, such inference is model-dependent and can obscure the true physics that are active in a given region or phenomenon. In this paper, we describe the current state of the art in three-dimensional electric field measurements and make the case that current designs and methods are inadequate to achieve the accuracies required to solve the remaining fundamental questions of space plasma electrodynamics. We then describe a new design for electric field measurements, Grotifer, which easily addresses the current issues, and represents a path forward towards resolving these questions.

1.1 Current electric field instrument design limits measurement accuracy

Electric field (E-field) measurements in the heliosphere are usually made on spinning spacecraft equipped with two disparate types of double probe antennas: 1) long wire booms in the spin plane, and 2) ~10 times shorter rigid booms along the spin axis. These designs, with current-biased antennas, were invented and first flown on a sounding rocket 55 years ago (Mozer and Bruston, 1967). Since then, this detector design has flown on many missions, either with or without a rigid pair of booms along the spin axis, such as: S3-3 (Mozer et al., 1977), ISEE-1 (Mozer et al., 1978), CRRES (Wygant et al., 1992), Polar (Harvey et al., 1995), FAST (Ergun R. et al., 2001), the four Cluster spacecraft (Gustafsson et al., 1997), the five THEMIS satellites (Bonnell et al., 2009), the two Van Allen Probes (Wygant et al., 2013), and the four MMS satellites (Ergun et al., 2016a; Lindqvist et al., 2016).

On such systems, the potential difference (signal + noise) is divided by the boom length to produce a resultant E-field. Because the spacecraft-associated errors are larger nearer the spacecraft, the spin plane components of the E-field are well measured while the spin axis component is either not measured or poorly measured. This asymmetry in measurement quality is also due to the fact that measuring electric fields using spinning antennas rather than rigid booms presents additional advantages such as the possibility to use thin wire booms, thereby minimizing the detrimental aspect of support structures, and the possibility to remove DC offsets in the electronics via spin fits. As a result, the accuracy of 2D E-field measurements in the spin plane is routinely better than the larger of ±1% or a fraction of a mV/m (Mozer

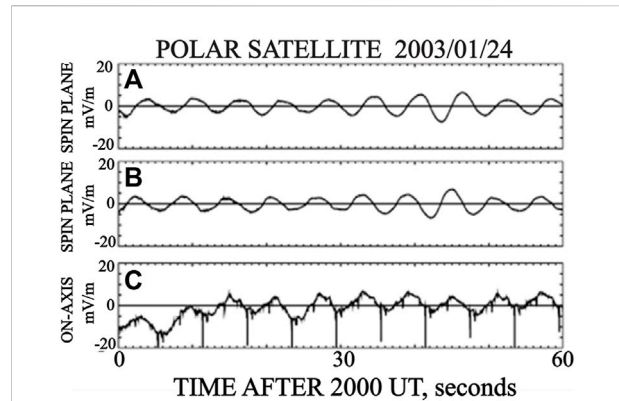**FIGURE 1**
(A,B) Spin plane and **(C)** Spin axis E-field components measured by Polar. While the signal in the spin plane corresponds to a geophysical signal, the signal along the spin axis presents a large error, leading to a large uncertainty in the 3D E-field measurement.

et al., 1978; Gustafsson et al., 2001; Mozer, 2016). On the other hand, the short axial antennas see offsets 1 to 2 orders of magnitude larger than the relevant field strengths (several to tens of mV/m). A similar situation exists for magnetic field (B-field) measurements, where stray B-fields from the spacecraft (~10 nT or larger) create offsets and noise that are larger nearer the spacecraft.

An example of the failure to make useful E-field measurements along the spin axis is provided in Figure 1, where 60 s of E-field components measured by the Polar satellite are displayed. The top two panels (Figures 1A,B) give the spin plane measurements of a 5 mV/m DC E-field, producing a sinusoidal signal at the satellite spin rate. The bottom plot (Figure 1C) presents the spin axis data: It should be a DC signal having no power at the spin frequency, yet spin dependent variations of the spacecraft potential are felt by the short on-axis sensors as different elements of the spacecraft rotate in and out of sunlight. Due to the non-rotating short antennas and spacecraft generated electrical signals, there is no useful data in this component of the measurement.

An example of the current state of the art is provided in Figure 2 (Adapted from (Øieroset et al., 2016)). It displays the estimated DC uncertainty in the parallel E-field measured by MMS during a 9 s crossing of the magnetopause reconnection region. The estimated error in the parallel E-field measurement is a data product of MMS E-field data. Figure 2 shows that the estimated DC uncertainty in the parallel E-field (in green) is usually greater than its measured value. This significant uncertainty in the parallel E-field restricts the analysis of the associated electrodynamics to the largest-amplitude events.

Because of these limitations, no existing instrument is capable of measuring all three components of the DC and low

FIGURE 2
MMS **(A)** perpendicular E-field, **(B)** parallel E-field **(C)** zoom-in. The estimated DC uncertainty in the parallel E-field (in green) is usually greater than its measured value. Adapted from (Øieroset et al., 2016).
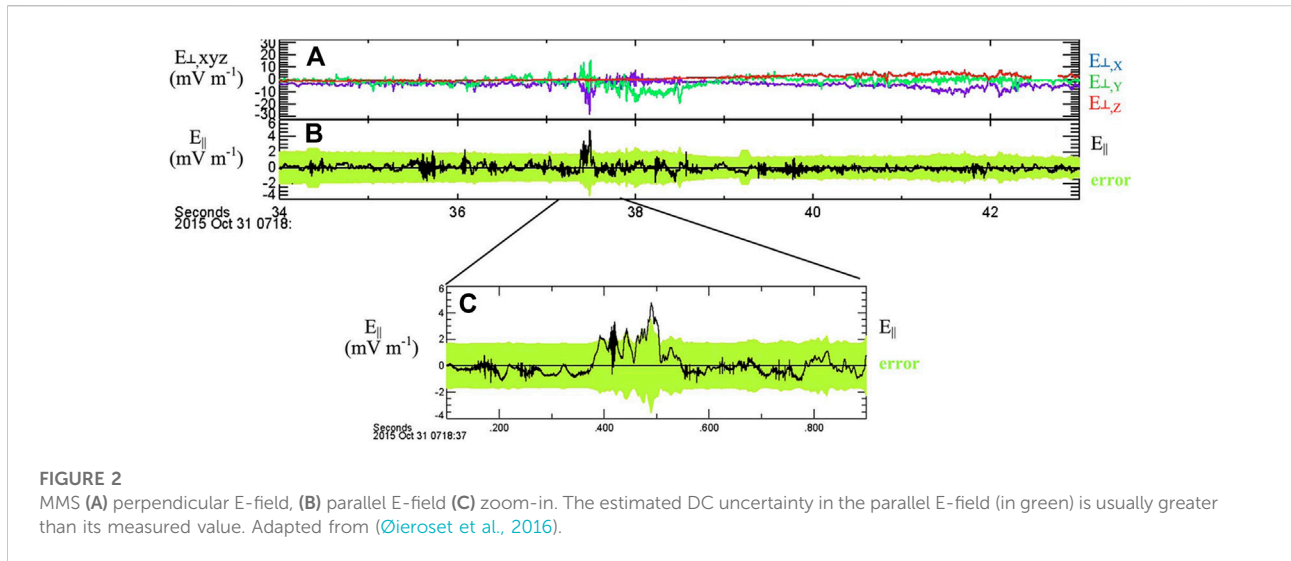
frequency E-field throughout the heliosphere with sufficient accuracy to determine the smallest and most consequential component: the E-field component parallel to the background B-field.

1.2 The closure of many significant science questions from various heliophysics research areas is hampered by the lack of accurate 3D E-Fields

Parallel E-fields exist in a multitude of plasma regimes in the heliosphere. These regions include such important loci of plasma acceleration and heating as reconnection sites (e.g., Egedal et al., 2012; Argall et al., 2015; Fox et al., 2018; Phan et al., 2018; Wilder et al., 2018), shocks (e.g., Goodrich and Scudder, 1984; Bale and Mozer, 2007; Mozer and Sundkvist, 2013; Schwartz et al., 2021), the auroral acceleration region (e.g., Mozer and Fahleson, 1970; Knight, 1973; Mozer et al., 1977; Gorney et al., 1985; Hultqvist and Lundin, 1987; Koskinen et al., 1996; Ergun R. E. et al., 2001; Andersson, 2002; Williams et al., 2006; Vedin and Ronnmark, 2007), the magnetosphere (e.g., Stark et al., 2011; Kropotkin, 2018; Arnold et al., 2019), the solar wind and corona (e.g., Hesse et al., 2005, Halekas et al., 2012, Mozer and Chen, 2013). Parallel E-fields have been observed at Earth and at other planets, including in the ionosphere of Mars (e.g., Dubinin et al., 2008; Akbari et al., 2019), and in the Jovian magnetosphere (e.g., Ergun et al., 2009; Underwood, 2017). They have been measured in standing waves (e.g., Damiano et al., 2019), in Alfvén waves and turbulence (e.g., Rankin et al., 1999; Ergun et al., 2005; Bian et al., 2010; Chaston, 2021), and in time domain structures (e.g, Mozer et al., 2015). Because parallel E-fields are essential components of the electrodynamics in all these regions,

their measurement is required for understanding the acceleration and heating of the plasma that occupies these regions and that plays a significant role in the coupling of momentum and transport of mass and energy between and within the heliosphere, magnetosphere and ionosphere. This demonstrates the urgent need to accurately measure the three-dimensional (3D) E-field that is vital to a complete understanding of plasma dynamics. Instances of science questions that illustrate the need for a profound change in E-field instrument design are provided in the following.

1.2.1 Shock studies—Terrestrial bow shock, interplanetary shocks

1. Do quasi-DC fields or fluctuations dominate the electrodynamics of energy conversion in shock acceleration, reflection, and heating of electrons and ions?
2. Do the two sorts of processes produce significant quantitative or qualitative differences in energy partition?
3. Under what conditions does each mechanism dominate?

Recent studies utilizing MMS have begun to address these questions, but they have also suffered from significant uncertainties in the cross-calibration of 3D E-fields (e.g., Mozer and Sundkvist, 2013; Mozer and Sundkvist, 2014; Schwartz, 2014; Goodrich et al., 2018; Cohen et al., 2019; Hanson et al., 2019; Schwartz et al., 2021).

1.2.2 Reconnection studies—Terrestrial magnetopause

1. What is the partition of energy conversion between processes that are perpendicular and parallel to the B-field?
2. What is the partition of acceleration, scattering, and heating between quasi-DC fields and fluctuations?

Various MMS studies have shown how E-field uncertainties obscure the science, or restrict detailed analysis to the largest-amplitude events (Ergun et al., 2016b; Torbert et al., 2016; Øieroset et al., 2016; Gao et al., 2021). Cluster's 2D ecliptic normal attitude allowed the inference of Electron Diffusion Regions (EDR) at the magnetopause, but not direct measurement of parallel vs. perpendicular electrodynamics. Similarly, the THEMIS E-field instrument allowed investigation of Ion Diffusion Region (IDR) scale electrodynamics (perpendicular E-field), but not the 3D electrodynamics of the EDR (Mozer et al., 2005; Mozer et al., 2008).

1.2.3 Auroral acceleration region studies—Parallel potential drops and small-scale perpendicular structures in the upward and downward current regions

1. What is the partition of parallel acceleration into localized and distributed structures (Debye-scale double layers vs. ambipolar fields)?
2. What is the local development and dynamics of small-scale perpendicular structure in parallel potential drops?

The need for particular spacecraft orientation has limited the depth and breadth of studies on the occurrence and properties of the quasi-DC parallel potential drops associated with auroral electron and ion acceleration (Hull et al., 2003a; Hull et al., 2003b; Ergun et al., 2004; Andersson and Ergun, 2006; Chaston et al., 2007). Large parallel E-fields have been measured at higher altitudes on auroral field lines (Mozer et al., 1977) but their extension to lower altitudes is unknown. Theoretical and observational studies (e.g., Chaston and Seki, 2010; Chaston et al., 2011) show that small-scale structures in the perpendicular component of the E-field and the development of a parallel E-field component and significant parallel potential drops are intimately linked, further demonstrating the need for simultaneous highly accurate 3D E-field measurements in the auroral acceleration region.

2 Solution: Grotifer, the future of electric field instruments

2.1 Proposed design

We propose a new E-field instrument design that addresses the need for highly accurate 3D E-field measurements while enabling lower cost missions and constellation missions in deep space. That is why we aim to develop a new E-field instrument that fits in a 27U ($0.3 \times 0.3 \times 0.3$ m³) CubeSat to provide accurate 3D E-field measurements in all environments of the heliosphere.

Grotifer (Giant rotifer) is a reference to the rotifer, also known as the "wheel animalcule," which has antenna-like cilia that appear to rotate in all directions. Grotifer's design consists of mounting detectors on two rotating plates, oriented at 90° with respect to
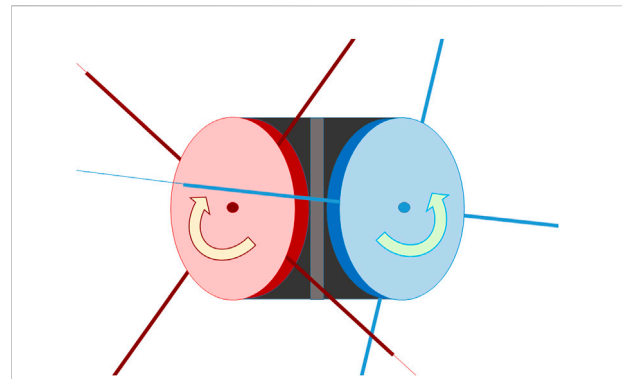

FIGURE 3
An illustration of the Twin Orthogonal Rotating Platforms (TORPs) on a non-rotating central body. The TORPs are oriented at 90° degrees with respect to each other, and they are both equipped with crossed double probes (only partially shown).
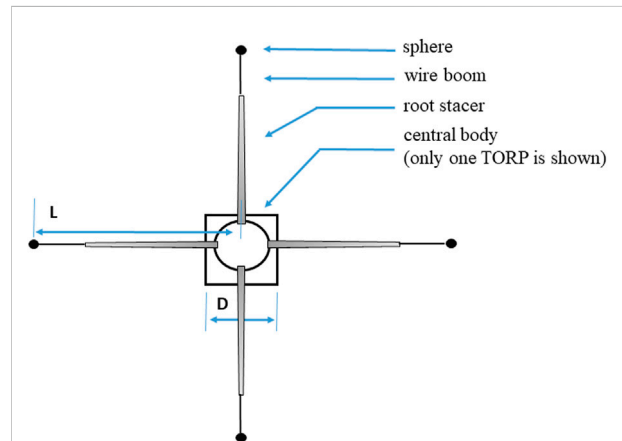

FIGURE 4
Definition of a single boom length, L, and spacecraft diameter, D. The components of each boom (root stacer, wire boom and sphere) are also defined.

each other, on a non-rotating central body. An illustration is provided in Figure 3. Each rotating plate has two component measurements of the E-field such that the Twin Orthogonal Rotating Platforms (TORPs) provide four instantaneous measurements of the E-field. That way, the three components are well-measured by the rotating detectors and redundant E-field measurements in the direction sampled by both TORPs can be used to estimate the time-varying measurement uncertainty. Grotifer's main requirements are described below, together with current design choices.

2.1.1 Minimum boom length

The accuracy of the double probe E-field measurement increases with the boom length because the signal increases and the spacecraft

FIGURE 5
A deployed stacer.

noise decreases with distance. In addition, the spacecraft noise at a fixed distance from the spacecraft increases with spacecraft size. Thus, a reasonable starting point for the characterization of E-field measurement accuracy is the dimensionless ratio between the single boom length, L, and the spacecraft diameter, D, i.e., L/D (see Figure 4 for an illustration of these definitions). Even though E-field measurement accuracy is ultimately determined by a variety of factors, highly accurate E-field measurements are facilitated by the instrument design when L/D is large, as is the case for spin plane wire booms. On the other hand, when the ratio is small, as is the case for axial rigid booms, spacecraft noise likely dominates in most situations of interest. For instance, L/D for the E-field component along the spin axis of Polar is 2.5, while it is 27 in the spin plane (Figure 1). The minimum length requirement for each Grotifer antenna is determined by scaling the L/D of Grotifer to that of other spacecraft that made successful spin plane E-field measurements. We find that a single boom length of $L = 6.75$ m from the center of the TORP to the sphere, compared to Grotifer's 0.3 m diameter, provides antennas that are long enough to favor high-quality E-field measurements.

2.1.2 Boom design and deployment

The booms on the rotating platforms consist of 5 m stacers with spheres connected to wires that extend through the stacers in what is known as a wire boom plus root stacer design. The stacers are cold-formed from spring-grade metal strip material to produce a constant helix angle and free coil diameter. They are then stowed in a canister with no helix. When released the coils progressively stack on an attached tip piece to produce a slight taper. This stacking provides significant inter-coil friction such that this formed tube compares favorably in stiffness and strength to the equivalent (solid) thin wall tube. An important characteristic of the device is the observation that the boom forms one coil at a time, such that a fully formed tubular element emerges from the housing. A picture of a deployed stacer is provided in Figure 5.

Once the stowed stacer is released, it expands to its 5 m length along with the sphere. After the stacer has fully deployed, and the TORP is spun up to its initial spin rate, the wire boom is then played out with a motor another 1.75 m for a total deployed single boom length of 6.75 m. The wire booms are kept short enough that they cannot entangle under any circumstance. The spheres become the E-field sensor, held radially outward by the centrifugal force of the rotating platform.

An antenna system made from a boom plus wire has two important advantages over a boom alone: First, the antenna length is greater than with a boom alone. Second, the extended wire allows separation of the boom, at the spacecraft potential, from the spherical sensor, which greatly decreases its sensitivity to spacecraft noise.

2.1.3 Proposed boom mounting

The mounting of the boom systems on the rotating platforms is illustrated in Figure 6. Each rotating platform has two levels on which the boom systems are mounted, and each level holds two antennas. The stacers are mounted inside the cylinders and their wire spools and spheres are mounted at their ends. The rotating plates are nested at launch and they swing out and latch to make the angle between the plates equal to 90°. In Figure 6, the upper 2/3 of the bus is mostly occupied by the stowed TORPs while the lower third is reserved for bus avionics.

2.1.4 Angular momentum balance

Once the stacers are deployed on the rotors, the rotors are spun up using the motors between each rotor and the spacecraft bus. The torque required to spin up the rotors and maintain their spin rate against friction produces a counter-torque on the spacecraft bus. If uncompensated, the counter-torque would spin up the spacecraft bus to unacceptably large spin rates and complicate operations significantly. In order to counteract that spin up, the Grotifer bus will carry two orthogonal air core torque coils. The spin period for the TORPs is 5 s (12 RPM). The central body attitude control will maintain pointing towards the Sun for the side of the satellite with the primary solar array and with sufficient stability that the boom wires do not oscillate through more than a few degrees. It will also stabilize the platform against torques generated in the control of the rotating booms. The design and control problems for Grotifer are already under study: Mao et al. (2015) developed an initial model of the Grotifer attitude determination and control system; and a NASA Instrument Technology Development award supports the current development and testing of prototype versions of the root-stacer/wire-boom system and the TORP drive and control systems from a start TRL of 3 to an anticipated end TRL of 5. All this past and current work serves to mature our knowledge of the Grotifer design as a direct prelude to a flight test model within the next 5 years.

2.2 Proposed applications

Some of the benefits of the Grotifer development are the following:

1. Grotifer will measure the parallel E-field to an accuracy comparable to that of the perpendicular E-field, enabling a significant increase in science return (see also Section 1.2)
2. Fleets of Grotifers can study electrodynamics at many points, facilitating differentiation between spatial and temporal dynamics.

FIGURE 6
27U bus concept.
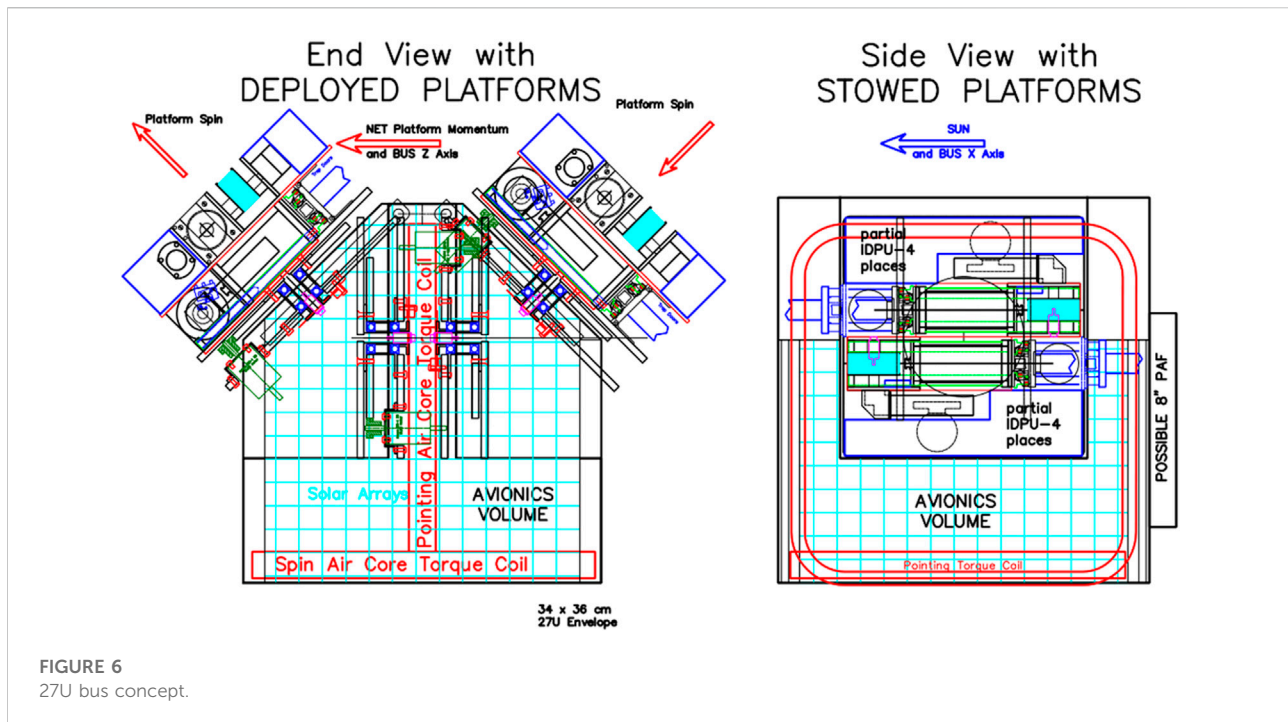
3. The current-biased, spherical, double probe E-field measurement is proven to work at reconnection sites, in the auroral acceleration region, at shocks, in the solar wind (see Section 1.2 and references therein) and at low L-values in the magnetosphere (e.g., Lejosne et al., 2022). Thus, Grotifer can become an important component of future space missions throughout the heliosphere.

4. TORPs easily allows accommodation of spinning and despun-preferring instrumentation on the same spacecraft (e.g., remote sensing limb/nadir/zenith looking imagers and charged particle detectors).

5. TORPs may also host plasma detectors so as to cover the full phase space more completely and continuously than on current spinning spacecraft. This would lead to more complete correlation studies of the fields and plasmas.

Data availability statement

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

Author contributions

We describe contributions to the paper using the CRediT (Contributor Roles Taxonomy) categories (Brand et al., 2015):

Conceptualization: FM, DP, DA, and JB. Funding acquisition: all authors. Project administration: SL. Visualization: FM, DP, JB, and SL. Writing—original draft: SL, FM, JB, and DP. Writing—review and edition: all authors.

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Conflict of interest

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