SmallSat Constellations for Active and Passive Sensing in the Heliosphere

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Synopsis:
Constellations of spacecraft provide multi-point measurements that are particularly valuable to heliophysics. Small spacecraft (CubeSats/SmallSats) enable focused science investigations and are also the basis for larger, more distributed constellation missions at lower cost than traditional mission architectures. In this white paper, we describe the uniqueness of multi-spacecraft measurements enabled by these small, inexpensive spacecraft, present three case study missions to demonstrate the science value of CubeSat/SmallSat missions. We recommend:

- **NASA Heliophysics continue its strong support of SmallSat instrument development, mission concept development, and fast pace of flight mission selection and implementation**
- **Increasing the H-FORT cost cap in order to feasibly fund small constellation missions**
- **Strengthened collaboration between NSF and NASA to support ground-based support/enhancement of space-based observations**

1. Introduction

Constellations of spacecraft provide multi-point measurements that are particularly valuable to heliophysics. These measurements include ionospheric TEC via GPS, reconnection in the magnetosphere (MMS, [1]), or sensing turbulence in the solar wind (HelioSWARM [2]). Small spacecraft (CubeSats/SmallSats) enable focused science investigations and are also the basis for larger, more distributed constellation missions at lower cost than traditional mission architectures. In this white paper, we describe the uniqueness of multi-spacecraft measurements enabled by these small, inexpensive spacecraft, present three case study missions to demonstrate the science value of CubeSat/SmallSat missions, and provide recommendations to better support such missions in the next decade.

2. Uniqueness of multi-spacecraft measurements, enabled by small, inexpensive spacecraft

Over the last two decades, CubeSats [3] and SmallSats have evolved from purely educational tools to capable science instruments [4]. As the number of SmallSats has increased, the price and off-the-shelf availability of components, full spacecraft platforms, and support infrastructure has improved. the move to larger CubeSat platforms than the original 1U (10 cm x 10 cm x 10 cm) and 3U (10 cm x 10 cm x 30 cm) (6U, 12U, 16U+) have enabled more complex and capable science instruments.

2.1. In-situ measurements

The value of multi-point measurements and higher spatial sampling has been demonstrated by missions such as Cluster [5], MMS [1], and THEMIS [6]. These missions measured plasma and/or electric/magnetic fields at multiple points in space simultaneously in order to better understand phenomena with a range of scales, such as reconnection. We describe an augmentation to the multi-point in-situ measurements that have been successful and informative in the past by adding a remote-sensing component to the constellation architecture.

2.2. Heliospheric Remote Sensing

We focus here on radio observations, but also note that there are many remote sensing applications at other wavelengths that would benefit from multiple platforms. Auroral imaging is one such example.

2.2.1. Interferometry (passive)

Interferometry is a remote-sensing technique that combines data from multiple physically separated receivers via correlation in order to construct a "virtual" telescope with angular resolution proportional to the largest separation between receivers. Interferometry is used extensively on the ground at radio wavelengths to produce exquisitely high-resolution images of the sky. The Event Horizon Telescope uses nearly the full diameter of the Earth to form the highest resolution images of the sky in human history [7], [8]. Three interferometric CubeSat missions, AERO-VISTA [9], [10], SunRISE [11], and CURIE [12] are currently in development. These missions will form small interferometric constellations (6 spacecraft for SunRISE, 2 for AERO-VISTA and CURIE) that will collect data on solar radio bursts and Earth's auroral radio emission at frequencies not accessible from the ground due to ionospheric shielding.

Ground-based observatories such as the Low-Frequency Array (LOFAR) [13][14] and the Murchison Widefield Array (MWA) [15], [16] have been used for solar radio burst interferometry. The spot mapping technique, developed with MWA data [17], is used to produce spatially and temporally-resolved maps of solar radio . Earth-based arrays must operate in frequency bands well above the peak ionospheric plasma frequency, which largely limits studies to emission regions within 2 R_{sol} of the photosphere. Radio interferometry in space is challenging, however, due to the need for constellations of spacecraft with accurate position knowledge and large data bandwidths for cross-correlation between spacecraft pairs. Self-interference must be mitigated, and calibration difficulties that arise from limited sensor collecting area must be overcome. Space-based interferometry has long been proposed for a wide range of science cases from solar radio burst tracking and characterization to all-sky mapping and cosmology [18]–[22].

2.2.2. Tomography (active)

Tomography is an active technique where a signal is transmitted from one node and received by others after passing through a medium that alters the signal. Seismic tomography, which uses natural and human-produced seismic waves, has enabled mapping of underground structures such as aquifers and oil/gas deposits as well as imaging of oceanic crust slabs descending into the mantle. Tomography is used extensively in medical imaging.

In the heliophysics context, tomography is an extension of sounding, but doing so with many more nodes and receivers, which enables more detailed reconstruction of the three-dimensional plasma properties in a volume. To understand and ultimately predict the behavior of transient solar phenomena such as coronal mass ejections (CMEs) will require powerful remote-sensing techniques that sense complex and rapidly varying plasma conditions throughout vast volumes of space. Sensitive measurements of propagation effects between widely separated transmitters and receivers will usher in the ability to tomographically map electron density and magnetic fields within a large volume of CME plasma.

By measuring changes in RF emissions from known bright extragalactic sources with ground-based telescopes, interplanetary scintillation (IPS) has been used to determine the orthogonal velocity component of the solar wind along lines-of-sight [23], [24] and to trace small-scale density variations [25][26]. Using a solar wind model, these IPS measurements have been combined to perform heliospheric tomography [27] in order to probe stream interaction regions (SIRs) [28], CMEs [29], and other solar phenomena. Tomographic reconstructions have advanced to incorporate in situ measurements in addition to IPS [30], but the spatial and temporal resolution is still limited to 20° × 20° in solar latitude and longitude and 1 day in time by SNR and observational coverage of the extragalactic sources [31].

3. Case studies

3.1. Case study 1: Space Weather Impact on Planetary Emissions (SWIPE)

The SWIPE mission concept is a follow-on to the AERO-VISTA mission [9], [10]. SWIPE consists of four spacecraft equipped with vector sensors [32][33] that form a small interferometer in a geostationary graveyard orbit. The science goal of SWIPE is to monitor the auroral radio emission of Earth, Jupiter, and Saturn and observe changes in that emission as interplanetary CMEs and SIRs pass by each planet. SWIPE takes a remote-sensing approach to a field where previous studies relied upon a serendipitous arrangement of heterogeneous in-situ sensors at various planets.

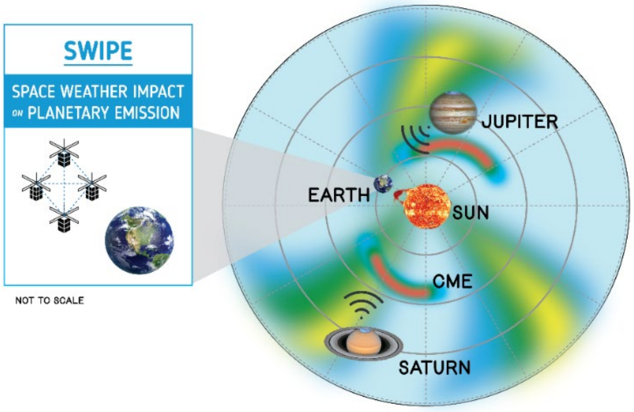

Figure 1. SWIPE mission concept; an interferometric constellation of 4 spacecraft observe auroral radio emission from Earth, Jupiter, and Saturn simultaneously and continuously in order to assess the effects of space weather (CMEs, SIRs, etc.) on their magnetospheres.

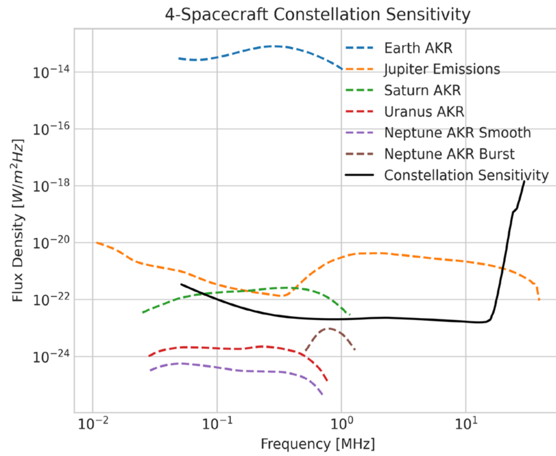

Figure 2. SWIPE sensitivity (black) for a 10-minute, 100 kHz bandwidth observation compared to averaged radio emission spectra from solar system planets [34]. *Adding more spacecraft to the constellation would allow for observation of radio emission from Uranus and Neptune as well.*

The interactions between Earth's magnetosphere and solar transient events have been observed for decades via both ground- and space-based assets (e.g., [35]). Interactions between other solar system planets, especially the outer planets, and CMEs/SIRs have been historically less studied. Several studies have taken advantage of in-situ spacecraft measurements (e.g., from Cassini) as well as dedicated ground- and space-based remote observations to characterize the response of giant planet magnetospheres to the variable solar wind. For example, O'Donoghue et al., (2021) [37] used infrared spectroscopy to suggest that, during periods of enhanced activity, Jupiter's aurora drives heating throughout the planet's upper atmosphere. Cecconi et al., (2022) [38] studied in detail the response of Saturn's Kilometric Radiation (SKR) – the planet's primary radio emission, generated by auroral electrons – to the passage of a strong CME. Clarke et al., (2009) [39] used the Hubble Space Telescope (HST) and Cassini data to analyze the auroral response of both Jupiter and Saturn to the solar wind input, with their results indicating that Saturn's dependence on the upstream conditions is generally stronger than Jupiter's.

These studies and others demonstrate that the aurorae of Jupiter and Saturn can serve as 'sensors' for solar wind conditions in the outer heliosphere. However, these works have depended on multiple in-situ and remote-sensing instruments targeting the same objects at the same time – a relatively rare occurrence, which is reflected in the small number of relevant studies in the literature. The novelty of SWIPE, as well as its importance in unveiling the processes of solar wind interaction with giant magnetospheres, resides in SWIPE's capability for uninterrupted observations of three planets simultaneously (save for periods in which either Jupiter or Saturn are in superior conjunction with Earth). In fact, previous efforts have relied either on measurements from orbit (e.g., with Cassini for Saturn), with the limitation that a spacecraft can only detect a radio source when it is located in its beam [40] or on near-Earth-based campaigns (e.g., with HST), which have a restricted amount of observing time, thus limiting the potential for continuous, multi-planet tracking of impacting structures.

3.2. Case study 2: Top-side sounding

Top-side sounders have been used in the past to probe the ionosphere above the F-region peak [41]. Currently there are no active top-side sounders, so the community is missing a useful tool to better understand coupling between the magnetosphere and ionosphere. A new generation of topside sounder constellations could take advantage of new technologies that have become recently available. For example, by taking multi-input multi-output (MIMO) radar theory and recent developments with vector sensor antennas [42], a space-based sounder constellation could do volumetric reconstructions of the ionosphere as it moves along its orbit. A vector sensor antenna detects all six components of the electromagnetic field, which gives it the unique capability of extracting angle of arrival and polarization information with a single element. Experiments have shown that a single ground-based vector sensor antenna can resolve the angle of arrival of the signal to about 5 degrees [43]. Multiple vector sensor antennas, for example in a SmallSat constellation, can also be phased together and have an even finer angular resolution. This would provide an unprecedented view of the top-side ionosphere and its structure, which has not been studied in detail.

3.3. Case study 3: SHIELD

SHIELD is a mission architecture concept that combines beacon tomography and interferometry into a single instrument package. Each spacecraft in the constellation has a vector sensor for passive sensing as well as a beacon for tomography and a suite of in-situ measurement instruments. These identical units are deployed throughout a volume of space (e.g. magnetosphere, L1, inner heliosphere) to 1) detect and image radio bursts from the Sun and/or Earth aurora, 2) measure the plasma within the volume using radio propagation and tomography, and 3) provide point measurements of plasma properties at the location of each spacecraft to set boundary conditions.

Beacon propagation measurements between multiple spacecraft enables radio tomography. Such tomographic measurement has been extraordinarily successful in the ionosphere with GPS satellites providing the radio beacons and ground-based receivers providing a large number of distributed receivers. The SHIELD concept will actively probe interplanetary coronal mass ejections (ICMEs), measuring total electron content and magnetic field properties on propagation paths between spacecraft. Additionally, SHIELD’s vector sensor-based interferometric spot maps of type II solar radio bursts will be comparable to those that would be produced by twice as many conventional spacecraft [44].

Because magnetic fields cannot be reliably measured remotely in the corona and interplanetary space, everything we know about the magnetic structure of ICME ejecta is from in situ measurements. ICMEs strongly alter the heliospheric plasma density and local magnetic field geometry. Magnetosonic shocks often develop when a CME exceeds the local Alfvén speed.

When the shocks accelerate already-energized electrons in the ambient plasma, the resulting type II radio burst reflects the morphology and motion of the shock front as well as the geometry of the local magnetic field. As the disturbance propagates outward into lower density plasma, the emission drifts from higher to lower frequency [14], with typical timescales of minutes to hours. Type II emission at modest coronal heights of up to ~2 solar radii (R_{sol}) can be well-modeled [45], [46] but detailed observational constraints and associated modeling is generally unavailable farther from the Sun. Understanding the evolution of ICME shocks therefore requires observations from space at frequencies <10 MHz, which are shielded from ground-based telescopes by the Earth's ionosphere.

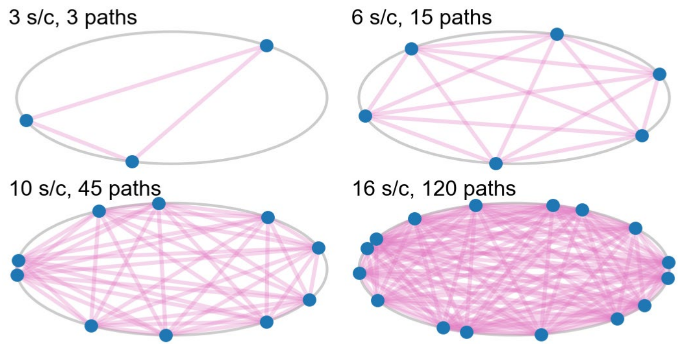

Figure 3. Propagation paths for constellations with 3, 6, 10, and 16 spacecraft. The tomographic resolution within the orbital plane is determined by the number of paths and increases quadratically with the number of spacecraft.

Beacon tomography offers a densely sampled volumetric view of the spatial and temporal structure of ICMEs approaching the Earth. Over sufficiently long propagation paths, this technique could revolutionize space weather forecasting. In beacon tomography mode, SHIELD measures total electron content (TEC) and magnetic field properties on propagation paths between spacecraft.

Each spacecraft transmits phase-coherent linearly polarized signals at dual frequencies and simultaneously receives the signals from all other spacecraft. TEC, the integrated electron density along a propagation path, is derived from the phase difference due to dispersion as a function of frequency. The beacon signals also experience a frequency-dependent change in the linear polarization electric field vector position angle due to Faraday rotation (FR) in the magnetized plasma (see [47] for review of FR in heliophysics). These FR measurements, when combined with the electron density distribution and constrained by in-situ magnetometer data from each spacecraft, can also be tomographically inverted to yield information on the magnetic field direction and strength. The level of detail in both electron density and magnetic field tomographic inversions is determined by the measurement precision and the number of propagation paths, which increase quadratically with the number of spacecraft (Figure 3).

A SMEX-scale mission might tomographically capture ICMEs passing through the volume of space bounded by an L1 halo orbit; a MIDEX-scale mission could expand this to include a global view of plasma processes throughout the Earth's magnetosphere; and a Flagship-class mission with high-power beacons seeded across ~0.72 AU interior to Earth's orbit and at the L4 and L5 Lagrange points might provide unprecedented early warning for potentially geo-effective space weather events (Figure 4).

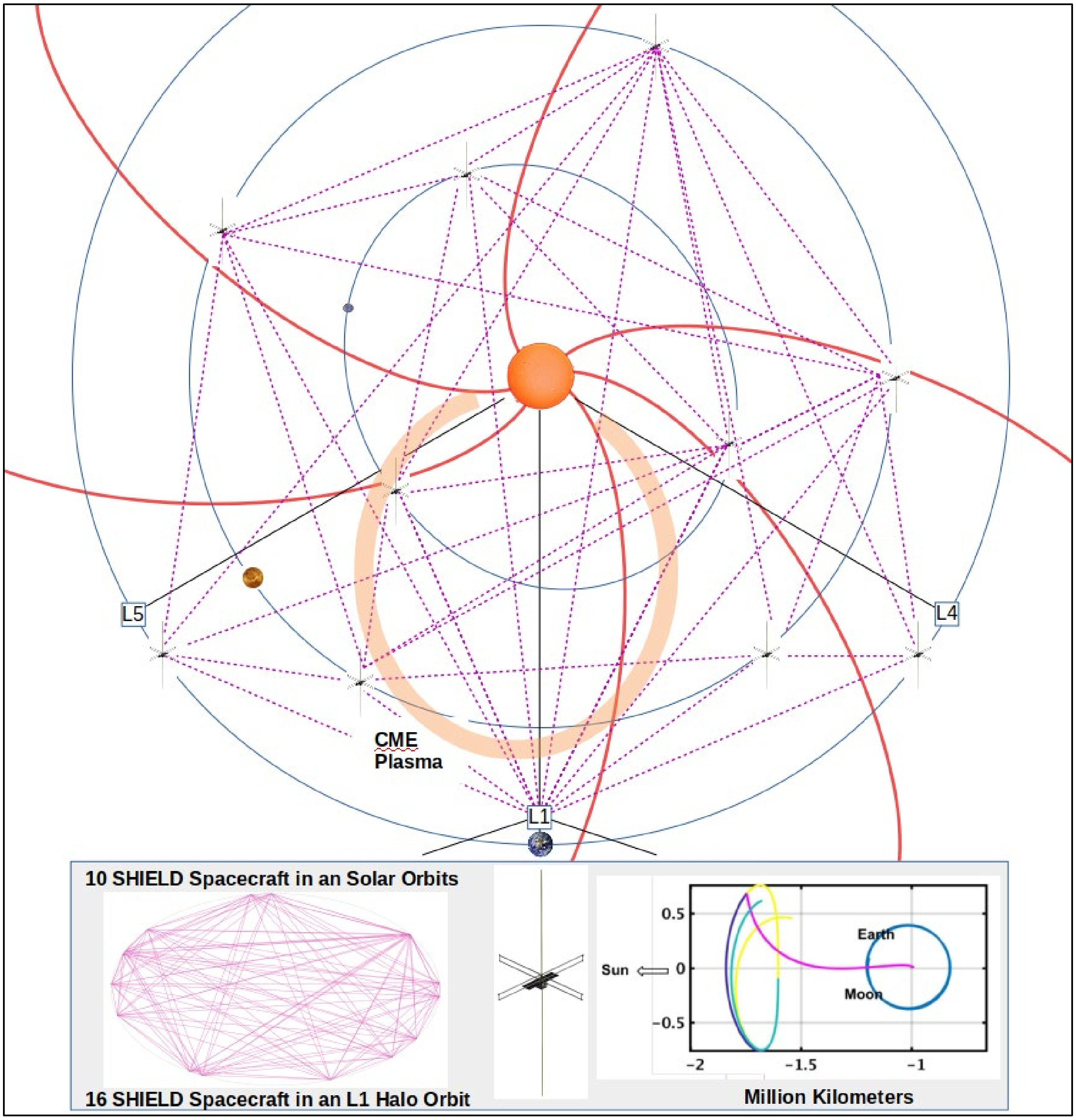

Figure 4. Conceptual depiction of "Big SHIELD," a notional flagship-class tomographic constellation that images ICME structure and magnetic field before the ICME reaches the Earth's magnetosphere. Radio paths are magenta, orbits blue, ICME plasma is orange. Not to scale.

In-situ sensors for particle measurement and magnetometers for magnetic field estimates provide time series point measurements of ICMEs as they travel through the heliosphere. These one-dimensional measurements hint at a complex plasma structure within the ICMEs as they travel by the spacecraft. However, since in-situ measurements can only probe a small fraction of the region of interest along a single trajectory, remote sensing is needed to unveil the physics of ICMEs and to monitor the vast space between Earth's orbit and the Sun. For ICMEs, radio waves offer a powerful remote probe. The large-volume, wide-field tomographic and interferometric measurements enabled by SHIELD will provide much-needed detail on the spatial and temporal structure of the solar ejecta.

4. Conclusion

Constellations composed of small but capable spacecraft have the potential to revolutionize our view of the Earth's ionosphere as well as the inner heliosphere while also probing the outer heliosphere via interferometric remote sensing. Robust and sustained development and flight opportunity funding is required to realize this potential.

In order to enable the exciting science described above, **we request that NASA Heliophysics continue its strong support of SmallSat instrument development, mission concept development, and fast pace of flight mission selection and implementation.** The low cost, commercial availability, and well-developed rideshare program for CubeSats and SmallSats are key factors that will enable larger, more capable constellations. Instruments developed for SmallSat missions are also relevant for larger missions, increasing the impact of instrument development funding. **Furthermore, we recommend increasing the H-FORT cost cap in order to feasibly fund small constellation missions**. Alternatively, another funding line could focus exclusively on constellation missions and their unique needs. Small constellation demonstrations may be pathfinders for larger constellations to be funded under other lines.

Ground-based observations will be a key supporting component of the constellation mission case studies describe here. For example, ground-based observations by existing radio observatories cover higher frequencies that can pass through the ionosphere, effectively extending the frequency coverage of the space-based instruments. Bottom-side ionospheric sounding complements and enhances the data returned from top-side sounding experiments to create a full picture of the ionosphere above and below the peak. **We ask for strengthened collaboration between NSF and NASA to support ground-based support/enhancement of space-based observations.** Ground-based observations that enhance space-based data should be seen as a strength in mission proposals, rather than a weakness or potential weakness.

References

[1] J. L. Burch, T. E. Moore, R. B. Torbert, and B. L. Giles, “Magnetospheric Multiscale Overview and Science Objectives,” *Space Science Reviews*, vol. 199, no. 1–4. Springer Netherlands, pp. 5–21, 01-Mar-2016.

[2] L. Plice, A. D. Perez, and S. West, “Helioswarm: Swarm mission design in high altitude orbit for heliophysics,” in *Advances in the Astronautical Sciences*, 2020, vol. 171, pp. 1787–1804.

[3] H. Heidt, J. Puig-Suari, A. S. Moor, S. Nakasuka, and R. J. Twiggs, “CubeSat: A new Generation of Picosatellite for Education and Industry Low-Cost Space Experimentation,” *14th Annual/USU Conference on Small Satellites*, 2000. [Online]. Available: http://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=2069&context=smallsat. [Accessed: 21-Apr-2014].

[4] E. L. Shkolnik, “On the verge of an astronomy CubeSat revolution,” *Nat. Astron.*, vol. 2, no. 5, pp. 374–378, May 2018.

[5] C. P. Escoubet, R. Schmidt, and M. L. Goldstein, “Cluster - Science and mission overview,” *Space Sci. Rev.*, vol. 79, no. 1–2, pp. 11–32, 1997.

[6] V. Angelopoulos, “The THEMIS Mission,” *THEMIS Mission*, pp. 5–34, 2009.

[7] K. Akiyama *et al.*, “First Sagittarius A* Event Horizon Telescope Results. I. The Shadow of the Supermassive Black Hole in the Center of the Milky Way,” *Astrophys. J. Lett.*, vol. 930, no. 2, p. L12, May 2022.

[8] K. Akiyama *et al.*, “First M87 Event Horizon Telescope Results. VI. The Shadow and Mass of the Central Black Hole,” *Astrophys. J. Lett.*, vol. 875, no. 1, p. L6, Apr. 2019.

[9] F. D. Lind *et al.*, “AERO & VISTA: Demonstrating HF Radio Interferometry with Vector Sensors,” in *33nd Annual AIAA/USU Conference on Small Satellites*, 2019.

[10] P. Erickson *et al.*, “AERO: Auroral Emissions Radio Observer,” in *32nd Annual AIAA/USU Conference on Small Satellites*, 2018.

[11] J. Kasper, J. Lazio, A. Romero-Wolf, J. Lux, and T. Neilsen, “The Sun Radio Interferometer Space Experiment (SunRISE) Mission,” *IEEE Aerosp. Conf. Proc.*, vol. 2021-March, pp. 1–13, 2021.

[12] D. J. Sundkvist *et al.*, “CURIE: Cubesat Radio Interferometry Experiment,” *Am. Geophys. Union, Fall Gen. Assem. 2016, Abstr. id.SH11C-2271*, 2016.

[13] M. De Vos, A. W. Gunst, and R. Nijboer, “The LOFAR telescope: System architecture and signal processing,” *Proc. IEEE*, vol. 97, pp. 1431–1437, 2009.

[14] E. P. Kontar *et al.*, “Imaging spectroscopy of solar radio burst fine structures,” *Nat. Commun.*, vol. 8, no. 1, p. 1515, Dec. 2017.

[15] S. J. Tingay *et al.*, “The Murchison Widefield Array: solar science with the low frequency SKA Precursor,” *J. Phys. Conf. Ser.*, vol. 440, p. 012033, Jun. 2013.

[16] C. J. Lonsdale *et al.*, “The Murchison Widefield Array: Design Overview,” *Proc. IEEE*, vol. 97, no. 8, pp. 1497–1506, Aug. 2009.

[17] C. J. Eyles *et al.*, “The Heliospheric Imagers Onboard the STEREO Mission,” *Sol. Phys.*, vol. 254, no. 2, pp. 387–445, Feb. 2009.

[18] D. Jones *et al.*, “The Astronomical Low Frequency Array : Explorer Mission for Radio Astronomy A Proposed Explorer Mission for Radio Astronomy,” in *Radio Astronomy at Long Wavelengths*, R. G. Stone, K. W. Weiler, M. L. Goldstein, and J.-L. Bougeret, Eds. American Geophysical Union, 2000, pp. 339–349.

[19] R. J. MacDowall *et al.*, “Solar Imaging Radio Array (SIRA): A multi-spacecraft mission,”

in *Enabling Sensor and Platform Technologies for Spaceborne Remote Sensing*, vol. 5659, no. May 2012, G. J. Komar, J. Wang, and T. Kimura, Eds. 2005, pp. 284–292.
[20] D. Oberoi and J.-L. Pinçon, "A new design for a very low frequency space borne radio interferometer," in *American Geophysical Union Fall Meeting*, 2003, no. 1988, p. 17.
[21] M. Bentum and A. J. Boonstra, "OLFAR - Orbiting Low Frequency Antenna for Radio Astronomy," *20th Annu. Work. Circuits, Syst. Signal Process. ProRISC*, pp. 1–6, 2009.
[22] M. Knapp, A. Babuscia, R. Jensen-clem, and F. Martel, "SOLARA / SARA : Solar Observing Low-frequency Array for Radio Astronomy / Separated Antennas Reconfigurable Array," in *Innovative Ideas for Micro/Nano-Satellite Missions*, R. Sandau, S. Nakasuka, R. Kawashima, and J. Sellers, Eds. International Academy of Astronautics (IAA), 2013, pp. 2–15.
[23] W. A. Coles and J. J. Kaufman, "Solar wind velocity estimation from multi-station IPS," *Radio Sci.*, vol. 13, no. 3, pp. 591–597, May 1978.
[24] M. Kojima and T. Kakinuma, "Solar cycle evolution of solar wind speed structure between 1973 and 1985 observed with the interplanetary scintillation method," *J. Geophys. Res.*, vol. 92, no. A7, p. 7269, 1987.
[25] A. HEWISH, P. F. SCOTT, and D. WILLS, "Interplanetary Scintillation of Small Diameter Radio Sources," *Nature*, vol. 203, no. 4951, pp. 1214–1217, Sep. 1964.
[26] Z. HOUMINER, "Corotating Plasma Streams revealed by Interplanetary Scintillation," *Nat. Phys. Sci.*, vol. 231, no. 25, pp. 165–167, Jun. 1971.
[27] B. V. Jackson, P. L. Hick, M. Kojima, and A. Yokobe, "Heliospheric tomography using interplanetary scintillation observations: 1. Combined Nagoya and Cambridge data," *J. Geophys. Res. Sp. Phys.*, vol. 103, no. A6, pp. 12049–12067, Jun. 1998.
[28] M. M. Bisi, R. A. Fallows, A. R. Breen, and I. J. O'Neill, "Interplanetary scintillation observations of stream interaction regions in the solar wind," *Sol. Phys.*, vol. 261, no. 1, pp. 149–172, 2009.
[29] B. V. Jackson and P. P. Hick, "Three-Dimensional Tomography of Interplanetary Disturbances," in *Solar and Space Weather Radiophysics*, vol. 30, no. 11, Dordrecht: Springer Netherlands, 2004, pp. 355–386.
[30] B. V. Jackson, J. M. Clover, P. P. Hick, A. Buffington, M. M. Bisi, and M. Tokumaru, "Inclusion of Real-Time In-Situ Measurements into the UCSD Time-Dependent Tomography and Its Use as a Forecast Algorithm," *Sol. Phys.*, vol. 285, no. 1–2, pp. 151–165, Jul. 2013.
[31] B. V. Jackson, P. P. Hick, M. M. Bisi, J. M. Clover, and A. Buffington, "Inclusion of in-situ velocity measurements into the UCSD time-dependent tomography to constrain and better-forecast remote-sensing observations," *Sol. Phys.*, vol. 265, no. 1, pp. 245–256, Aug. 2010.
[32] A. Nehorai and E. Paldi, "Vector sensor processing for electromagnetic source localization," in *Conference Record - Asilomar Conference on Circuits, Systems & Computers*, 1991, vol. 1, pp. 566–572.
[33] M. Knapp *et al.*, "Vector antenna and maximum likelihood imaging for radio astronomy," in *IEEE Aerospace Conference Proceedings*, 2016, vol. 2016-June, pp. 1–17.
[34] P. Zarka *et al.*, "Planetary and exoplanetary low frequency radio observations from the Moon," *Planet. Space Sci.*, vol. 74, no. 1, pp. 156–166, Dec. 2012.
[35] T. Pulkkinen, "Space weather: Terrestrial perspective," *Living Rev. Sol. Phys.*, vol. 4, no. 1, pp. 1–60, May 2007.

[36] J. O'Donoghue *et al.*, "Global upper-atmospheric heating on Jupiter by the polar aurorae," *Nat. 2021 5967870*, vol. 596, no. 7870, pp. 54–57, Aug. 2021.
[37] J. O'Donoghue *et al.*, "Global upper-atmospheric heating on Jupiter by the polar aurorae," *Nat. 2021 5967870*, vol. 596, no. 7870, pp. 54–57, Aug. 2021.
[38] B. Cecconi, O. Witasse, C. M. Jackman, B. Sánchez-Cano, and M. L. Mays, "Effect of an Interplanetary Coronal Mass Ejection on Saturn's Radio Emission," *Front. Astron. Sp. Sci.*, vol. 9, 2022.
[39] J. T. Clarke *et al.*, "Response of Jupiter's and Saturn's auroral activity to the solar wind," *J. Geophys. Res. Sp. Phys.*, vol. 114, no. A5, May 2009.
[40] B. Cecconi *et al.*, "Goniopolarimetric study of the revolution 29 perikrone using the Cassini Radio and Plasma Wave Science instrument high-frequency radio receiver," *JGRA*, vol. 114, no. A3, p. A03215, Mar. 2009.
[41] R. F. Benson and V. A. Osherovich, "Application of ionospheric topside-sounding results to magnetospheric physics and astrophysics," *Radio Sci.*, vol. 39, no. 1, pp. 453–458, Feb. 2004.
[42] K. T. Wong and M. D. Zoltowski, "Closed-form direction finding and polarization estimation with arbitrarily spaced electromagnetic vector-sensors at unknown locations," *IEEE Trans. Antennas Propag.*, vol. 48, no. 5, pp. 671–681, 2000.
[43] F. C. Robey, "High Frequency Geolocation and System Characterization (HFGeo) Phase 1B Proposers' Day Briefing: HFGeo Phase 0 and Phase 1B Test and Evaluation," 2012. [Online]. Available: http://www.iarpa.gov/images/files/programs/hfgeo/120710_Phase1B_Proposers_Day_Part2.pdf.
[44] M. Knapp *et al.*, "Vector Antenna and Maximum Likelihood Imaging for Radio Astronomy," in *IEEE Aerospace*, 2016.
[45] S. A. Knock and I. H. Cairns, "Type II radio emission predictions: Sources of coronal and interplanetary spectral structure," *J. Geophys. Res. Sp. Phys.*, vol. 110, no. A1, p. A01101, 2005.
[46] J. M. Schmidt and I. H. Cairns, "Type II solar radio bursts predicted by 3-D MHD CME and kinetic radio emission simulations," *J. Geophys. Res. Sp. Phys.*, vol. 119, no. 1, pp. 69–87, Jan. 2014.
[47] J. E. Kooi *et al.*, "Modern Faraday Rotation Studies to Probe the Solar Wind," *Front. Astron. Sp. Sci.*, vol. 9, p. 44, Apr. 2022.