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AERO: Auroral Emissions Radio Observer

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ABSTRACT

Earth's aurora has a deep complexity and richness that is of intense interest for our understanding of space physics, with many unknown or ill-defined features. Auroral radio emissions in the LF and HF frequency range allow radio remote sensing, leading to investigation of nonlinear wave processes and wave-particle interactions operating in a broad range of heliospheric, planetary and astrophysical plasmas. The Auroral Emission Radio Observer (AERO) is a one-year CubeSat mission in polar orbit that will significantly advance our knowledge by examining radio emissions from the auroral acceleration region in near-Earth space. AERO uses a unique electromagnetic vector sensor (VS) to study AKR at LF and HF frequencies (100 kHz – 5 MHz) with six orthogonal dipole and loop antennas giving angle of arrival and polarization information within a single unit. The mission will store many orbits of compressed data on board, then select download segments based either on summary spectrogram ground analysis or on automatic detection of bright auroral radio events. AERO is also a stepping stone to a novel spaceborne high capability remote sensing platform for diverse scientific targets such as radio emission from the solar corona and inner heliosphere, and anisotropic turbulence properties of interplanetary medium plasma.

Introduction

Earth's aurora has a complexity and richness in both energetics and spatial / temporal structure that is of intense interest for our understanding of space physics. Auroral radio emissions from the ionosphere in the LF to HF range are a powerful space physics tool because they provide a means to *remotely* sense auroral ionospheric plasma conditions and processes. Auroral kilometric radiation (AKR) is the most important energetic radio source in the aurora, radiating up to 1% of auroral energy input from solar and particle sources. One objective of AERO will be to answer the important question of whether AKR penetrates to low altitudes. Other AERO emission targets include auroral "roar," medium frequency bursts, and auroral hiss (Figure 1).

AERO's technical objective is to build and qualify the vector sensor (VS), first characterizing and validating it by measuring well known cyclotron harmonic phenomena, then applying it to AKR phenomena at LF to HF frequencies. The VS technique is a stepping stone to a novel remote sensing platform with direct applicability to broader classes of plasma waves and radiation in the heliosphere. A future application of particular importance is solar radio emission, for which detection and tracking can contribute to the prediction of terrestrial space weather.

AERO explores physical processes in the space environment, one of three heliophysics goals in the NASA Science Plan. Because radio emissions carry energy and information over long distances, they provide an effective means to remotely sense plasma conditions and processes and thus contribute to other overarching science goals, including detection and prediction of extreme space weather conditions, and advances in the understanding of connections linking the space environments of the sun, planets, and the outer solar system.

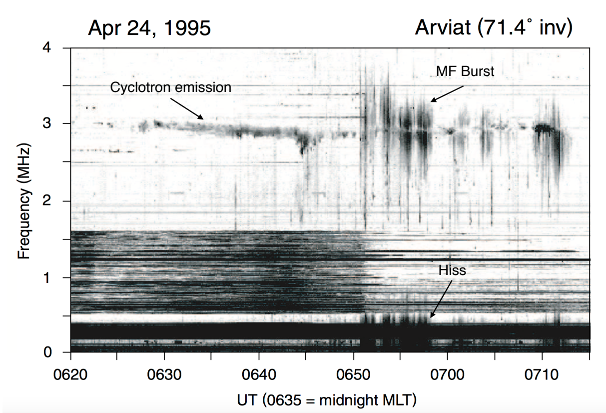

Figure 1: Ground-level radio spectrogram showing three types of auroral emissions: $2f_{ce}$ cyclotron emission (narrow bandwidth, 2.8-3.0 MHz), medium frequency burst (broadband, 1.6-4.3 MHz), and auroral hiss (broadband up to 800 kHz). The burst and hiss are strongly correlated. A polar substorm onset occurs at 0651 UT. From [1].

AERO Science

We describe selected AERO mission science targets below in more detail.

Science Question 1: Auroral Kilometric Radiation (AKR): Low Altitude Propagation

The auroral ionosphere is a source of multiple types of radio emissions [2]. AKR [3] is by far the most powerful naturally occurring radiation in Earth's environment, radiating up to 1 GW at peak intensity. AKR is caused by the cyclotron maser instability (CMI) which is one of the most ubiquitous radiation mechanisms in space plasmas ranging from planetary magnetospheres to blazars [4]. Not only is AKR significant energetically, but fine-scale AKR structure is an effective tool for remotely sensing the extent and dynamics of the auroral acceleration region [5-8]. Observation and theory show that X-mode AKR, the powerful radiating component, is beamed away from the Earth from sources in the auroral acceleration region at 5000-10000 km altitude [9-13]. The X-mode AKR originates in density cavities, as it needs low density for excitation, and should not be able to reach low altitudes because of the X-mode cutoff.

Nevertheless, there have been a steady stream of reports of AKR-like emissions observed with spacecraft in LEO

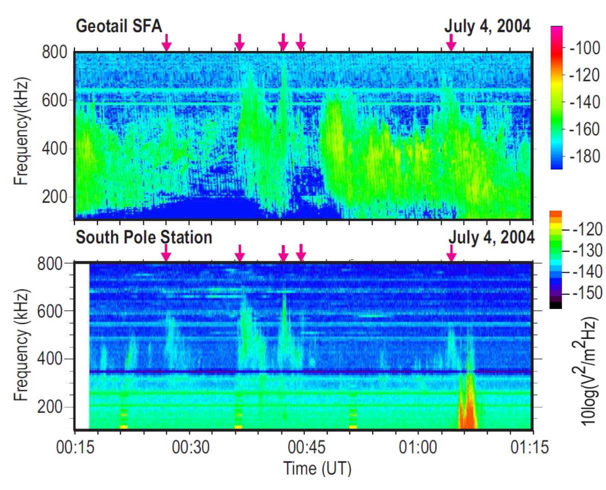

Figure 2: AKR observed from Geotail spacecraft (top) and from South Pole Station (bottom) [18].

[14,15] and rockets [16,17]. Recently these reports were

bolstered by measurements of AKR observed simultaneously at great distance from Earth and at ground level as shown e.g. in Figure 2 [18]. A follow-up study of many events established that those AKR-like signals are right-hand polarized, implying whistler modes (W mode) in the ionosphere, not X-mode [19]. Furthermore, the signals exhibit fine structure closely resembling that of AKR observed in space. The most likely source of AKR penetration to low altitudes lies in CMI mechanisms, as these have been shown to excite significant Z-mode emissions in regions adjacent to X-mode emission locations [10]. An inhomogeneous plasma can convert Z-mode waves to W-mode, which can propagate through dense plasma to low altitudes and, for appropriate wave normal angles, penetrate to ground level. Entirely different mechanisms have, however, been proposed [20].

Addressing the range of viable propagation mechanisms for AKR at low altitudes presents a compelling science target. Despite ground-level observations and existence of a plausible mechanism, the penetration of AKR to low altitudes remains controversial, and therefore determining the propagation mode is important. In particular, if AERO can verify that CMIs emit radiation into W-mode through mode-conversion of Z-mode waves, it would establish an additional mechanism by which the CMI can transmit energy to the ionosphere. It would also enable application of multi-faceted remote sensing of magnetospheric processes substituting inexpensive ground-based or LEO platforms for deep space observatories [7].

Science Question 2: Medium Frequency Burst: Source Characteristics

Years of ground-level observations show that the aurora emits broadband left-polarized (O-mode) emissions called Medium Frequency Burst (MFB) at 1.5-4.5 MHz, concentrated at onsets of polar substorms [21-25]. MFB, potentially significant as both a substorm onset marker and a new auroral beam emission mechanism, starts within seconds of the onset. It typically lasts for only a few minutes, when it is cut off due to substorm-induced absorption along the ground-source path. The duration in the ionosphere may be much longer. The generation mechanism is unknown, but two possibilities have been raised in the literature. First, fine structure observations [26] are consistent with mode-conversion of Langmuir waves distributed over a significant altitude range in the topside ionosphere [27]. Another possibility is raised by the temporal correlation between MFB and anomalous incoherent scatter radar features interpreted as Langmuir cavitons at specific altitudes in the ionosphere [28]; if the cavitation process produces the broadband emission, the source would be concentrated.

Understanding the nature of MFB source regions is also vital for space physics, as MFB may represent a new mechanism of emission from electron beams. Furthermore, its temporal association with substorm expansion makes it an effective marker of onset. Determining the generation mechanism and source location of AKR may enable the use of MFB to remotely sense polar substorm onsets. Substorm associated processes touch on every aspect of the coupled magnetosphere-ionosphere system.

AERO will distinguish two leading MFB theories by (a) spaceborne direction finding measurements, determining whether the source is in the topside or the bottomside of the ionosphere, and (b) measuring variation of the direction of arrival as AERO passes under or over the source, resolving whether it is extended over tens of kms or concentrated within 1-2 kms.

Science Question 3: Auroral Hiss: Directional Morphology and Wave-Normal Angle Characteristics

Auroral hiss was the first auroral emission to be discovered [29,2]. Satellites encounter VLF (3-30 kHz) auroral hiss on virtually every pass through the auroral zone [30]. Of the two types, continuous and impulsive, the impulsive type commonly extends to LF and even as high as 1 MHz. At VLF, ground-level direction-of-arrival studies [31] and observed low-frequency cutoffs suggest that impulsive hiss is ducted from high altitude sources with exit points at altitudes of 1000-3000 km [32]. At 1 MHz, however, the source itself must be lower than 1000 km since $f<f_{ce}$ for whistler modes. In up to 1/3 of events, LF hiss is observed without a VLF hiss component, an effect attributed to characteristics of the LF waves in space not measurable from the ground [33].

Impulsive auroral hiss occurs at the onset of polar substorms, often correlated with MFB. It therefore has the same importance as MFB as an indicator of timing and location of substorm onsets. The outstanding mystery of auroral hiss [32] is its propagation to ground level. Transmission through the atmosphere-ionosphere boundary requires near vertical incidence, meaning near-parallel wave-normal vectors. On the other hand, resonant excitation by auroral electrons can only occur at substantial wave normal angles. Scattering from meter-scale irregularities may be the mechanism that produces vertical (near parallel) wave-normal angles [32], but this hypothesis has never been directly tested. Full characterization of the wave is required to determine what fraction of the auroral hiss reaches ground level and to elucidate the mechanism involved. Previous satellite experiments have observed upward-going VLF hiss organized into "saucer" features resulting from propagation at the resonance cone [34,35], and other features that have been related to off-resonance cone propagation [36].

Impulsive auroral hiss has an additional geophysical significance as it occurs at the onset of polar substorms, often correlated with MFB discussed above. It therefore has a similar importance as MFB as an indicator of timing and location of substorm onsets.

AERO addresses MFB questions by measuring the wave-vector composition and estimating the scattering location. This data will determine what fraction is near the resonance cone, what fraction has been scattered, and the efficiency of the scattering and transmission to ground-level. AERO measurements of directions of arrival along the satellite track will determine the morphology and approximate source height or duct exit height of LF auroral hiss, and will resolve differences between LF and VLF impulsive hiss.

Science Question 4: Auroral Emission Locations Relative to Auroral Current System and Auroral Arcs

Alongside VS measurements, AERO's Auxiliary Sensor Package (ASP) will make photometer and magnetometer measurements to localize radio emissions with respect to Birkeland Region 1 field-aligned currents and green line auroral arcs. The ASP's on-board magnetometer and photometer will provide contextual data to AERO auroral emission studies, aiding determination of the sources or ducts relative to auroral arcs or field aligned current regions. For example, AERO will use ASP information to probe low altitude AKR source or duct locations relative to upward / downward field aligned current, therefore testing association of low altitude AKR with powerful X mode emissions known to be generated in the upward current region. As another example, ground based observations point to MFB as possibly being associated with poleward arcs in substorm expansions, but they cannot determine whether the source is also associated with arcs that follow the leading expansion edge [24]. AERO's space based observation platform does not have these limitations and can help resolve this question, which is critical to constraining MFB generation theories.

Other AERO Science Opportunities

Based on previous satellite data, AERO should commonly encounter $3f_{ce}$ emissions. Akebono data [37] show these are sometimes right-hand polarized, contradicting ground-based observations and theory. AERO will further investigate this phenomenon, which may involve nonlinear wave-wave processes.

Electrostatic Langmuir-upper hybrid waves are seen on almost every suitably instrumented auroral sounding rocket, especially above about 600 km. These occupy the range between the plasma and upper hybrid frequency, from 1-10 MHz in the auroral ionosphere (AERO captures up to 5 MHz). In the presence of density structure with scales comparable to their wavelengths, ubiquitous in the auroral ionosphere, Langmuir waves become highly structured through the development of Langmuir eigenmodes, previously detected in the auroral environment [38] and in the solar wind [39]. AERO may be able to directly detect and confirm conversion of these structured electrostatic (ES) waves to electromagnetic (EM) as some observations suggest [40]. Other phenomena that fall within AERO's frequency range include dispersive features at 100s of kHz frequency [41]. Identifying this wave mode as ES or EM [42] would be of significance.

AERO Spacecraft and Launch Parameters

AERO will be a 3U size CubeSat and will use a spacecraft bus with flight heritage from either commercial or university sources. The selected system will have onboard star trackers (cf. Auxiliary Sensor Package) and a robust telemetry and command system. These will be adapted for the AERO science payload, with particular attention to electromagnetic self-compatibility and cleanliness. Control will be provided by the Mission Operation Center (MOC), where students will be engaged with all aspect of operations including telemetry and command, planning and scheduling, and anomaly resolution.

AERO is compatible with any CubeSat Launch Initiative (CSLI) launch that will place it in a polar orbit (inclination >70°) and altitude >400 km. The interface with AERO's launch vehicle is through the dispenser only, and the CubeSat requires no special handling or environments during integration and launch. AERO has no propulsion system, other pressurized gases, or other proscribed items that would compromise compatibility with the launch vehicle, and the slow spin rate associated with standard deployment from a commercial dispenser meets all AERO mission and science requirements. AERO will remain unpowered until deployed, with the possible exception of a compliant real-time clock circuit.

AERO Technology: Vector Sensor

The vector sensor is the main scientific sensor on the AERO platform. The VS consists of 3 orthogonal dipoles and 3 electromagnetic loop antennas that, through beamforming processing, provide angle-of-arrival and polarization information for HF signals from 50 kHz to 20 MHz [43,44,45], with a 5 MHz upper limit used for AERO. Figure 3 illustrates simple beamforming (i.e. identifying a localized source) with data collected from a vector antenna array [45] in response to a ground wave source.

To meet launch constraints, the antennas will be deployed with fiberglass “tape measure” technology. AERO has baselined 4-meter antennas (2 m in each direction), which are sufficient to ensure that the external signals dominate relative to internal noise despite being electrically short at the frequencies of interest. The antenna is extended in five directions from one end of the spacecraft and fits in 1U of payload space when stowed for launch. The loop antenna area is 0.8 m^2 for the crossed loops, and 8 m^2 for the perimeter loop.

An initial mechanical model of the VS used a boom to neutralize the force of gravity and to verify that the deployment system would work reliably. The design uses stored energy in the tape-measure type elements for deployment. For AERO, the steel tape measure elements will be replaced by LoadPath fiberglass tapes with embedded conductors, which have better electrical and mass properties than the steel tapes. Laboratory measurements have verified that the LoadPath elements will perform well both electrically and mechanically.

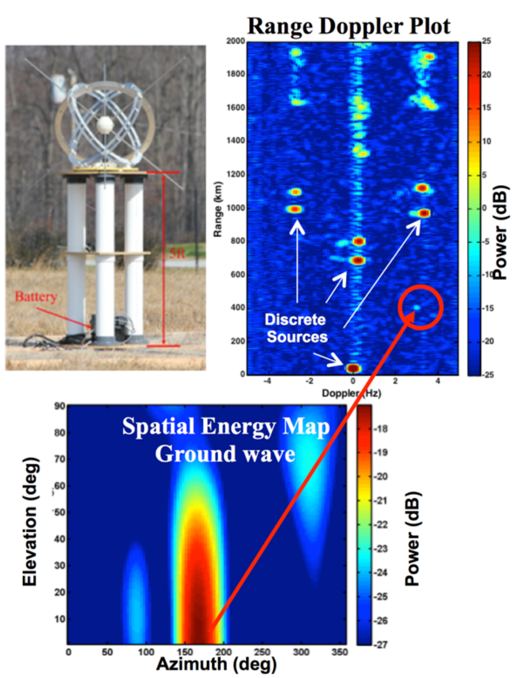

Figure 3. Beamforming result using VS techniques (bottom) [43]. The range-Doppler plot (upper right) shows a signal propagated to the VS by ionospheric and ground-wave multipath. A VS used for ground testing is in the upper left.

VS Calibration

Calibration of the vector antenna is important to perform beamforming, direction of arrival estimation, and/or determination of polarization. The Pattern Response Equalization for Spatial Symmetry (PRESS) algorithm is a maximum-likelihood technique for determining sensor calibration, and is our legacy approach to determining element gain and pattern responses [48,49]. This allows the calibration to factor in mutual coupling that is likely to be induced due to, for example, the solar panels and antenna elements. Accuracy of the vector sensor on the Shadow 200 using PRESS was reported in [48].

MIT-LL will calibrate the VS in terms of spatial angles, signal frequency, gain from free-space to digital data, amplitude, polarization, and frequency of the individual antennas. Receiver noise floor and dynamic range will be ground tested in the MIT-LL System Test Chamber, which as a Faraday cage provides >20 dB inherent shielding from external sources in this frequency range. The antenna element pattern and the effective height and loss of the electrically small loops and dipole responses will be measured in the MIT-LL RF Systems Test Facility. In flight, a stable NIST-traceable noise diode or comb generator, depending on the specific calibration, is injected into the six antenna inputs to determine channel-to-channel gain and phase differences as well as the absolute gain of the receiver system. The VS antenna element gains as a function of angle are measured by rotation of the spacecraft while observing a known reference such as a ground-based source.

AERO Technology: Auxiliary Science Package

To accompany VS measurements, the Auxiliary Science Package (ASP) provides photometry, for independent confirmation of auroral events, and magnetometry, to localize AERO observations with respect to the auroral oval through observations of Birkeland Region 1 currents.

Photometry is derived from the spacecraft star trackers, and requires only calibration, software to retrieve and utilize the information from the spacecraft bus, and operations protocols to fix the field of view for observations.

The magnetometer requirement is a modest 100 nT resolution to resolve Birkeland Region 1 auroral currents, which are of order 1 uA/m^2, corresponding to ΔB signatures of 100s of nT in low Earth orbit [46,47]. These signatures are of sufficient amplitude to allow the magnetometer to be integrated with the payload electronics, rather than requiring a separate boom. AERO has baselined the MicroMag3 magnetometer, which offers 15 nT resolution and was used by MIT in a similar configuration for the MicroMAS, MiRaTA, and MicroMAS 2 CubeSat missions.

The AERO CubeSat bus will be developed by Morehead State University (MSU). The VS payload will be developed by MIT Lincoln Laboratory (MIT-LL) and integrated by MIT Haystack Observatory (MIT-HO).

AERO Mission Profile and Data Processing

Sometime in 2022, AERO will be inserted into a high inclination, low-Earth orbit that crosses the auroral zone regularly above the ionospheric F region electron density maximum. Observations will be conducted during the two quarters of the orbit that span the auroral oval and polar regions. Following acquisition and initial checkout, the first few days will be used to calibrate the vector sensor against known HF sources. After that, AERO enters its survey phase. Each orbit, AERO will make 4 passes through or near the auroral oval where payload data is actively collected. Since the primary sensor is omnidirectional, attitude control and pointing is only required for solar cell charging and telemetry.

AERO telemetry consists of science thumbnail data, data products for selected sources of interest, attitude information from the star trackers, and housekeeping data. The VS provides 3-axis E and B signals in the spacecraft frame. At LEO, the International Geomagnetic Reference Field (IGRF) model is adequate to rotate into geomagnetic coordinates; the flight magnetometer provides a consistency check and will track magnetospheric distortions during active periods. The magnetometer is used to estimate auroral zone field-aligned Birkeland currents. Photometry from the star tracker will identify significant optical emissions.

Downlink of housekeeping and survey data including GPS positioning, followed by as much of the flagged science data as possible from spacecraft memory, will be collected in multiple daily passes at the Mission Operations Center (MOC) at MSU using their 21 m Deep Space Network antenna. Following downlink, mission data will be assessed for completeness, then processed through a data pipeline to produce low level data products as well as state of health summaries and memory management reports. These will be transferred from the MOC to the Science Operations Center (SOC) at MIT-HO. At the SOC, sources of interest (SoI), including AKR, LF Hiss, Roar and MFB events, will be identified from summary spectrograms. Twice daily, the spacecraft will be commanded with priorities for downlinking the raw data associated with those SoIs.

Data is stored on the spacecraft in the form of Cholesky factorization of the sample covariance in block floating point format, one fixed-point mantissa per element and a single multiplier for the block. These factors provide access to the electromagnetic character of the auroral emissions, and allow determination of the Poynting vector ($\boldsymbol{S} = \boldsymbol{E} \times \boldsymbol{B}$). In conjunction with a model magnetosphere and an estimate of plasma density (from resonance cutoffs), the emission will be ray-traced to probable source regions.

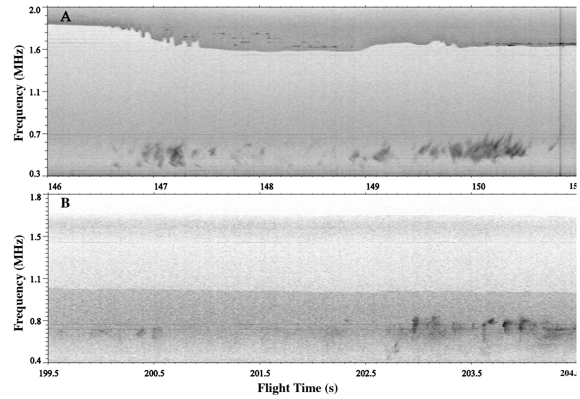

Figure 4: Radio spectrograms, typical of what AERO may encounter, measured with a sounding rocket in (a) overdense plasma ($f_{pe} > f_{ce}$) at 333 km, and (b) underdense plasma ($f_{pe} < f_{ce}$) at 475 km. Both panels show AKR-like emissions at 300-800 kHz. The plasma frequency appears as an upper cutoff of whistler-mode noise in underdense conditions and a lower cutoff in overdense conditions; electrostatic waves on the Langmuir/upper hybrid branch appear above f_{pe} in the overdense case [16].

AERO will obtain 3-axis electric and magnetic field spectral survey data with sufficient magnetometer and photometer data to put each datum into the auroral context (e.g. Birkeland current region, visible aurora present, IGRF magnetic coordinates). The 100 ms time resolution of survey spectrograms is optimized for identification of the emission types (AKR, LF Hiss, Roar, MFB), while remaining sufficiently compact so that the entire survey data product fits its telemetry budget. Figure 4 shows an example of a survey spectrogram.

When events are identified, the covariance data will be downlinked. Figure 5 shows AERO's VS instrument detection threshold with no integration and with 1 second integration (1 kHz bin size) for each SoI. AKR and LF hiss are sufficiently strong that they can in nearly all cases be accessed with minimal integration given expected noise levels. For MFB and some roar emissions, integration is likely required, but in nearly all cases a 1 s integration is more than sufficient to enable detection.

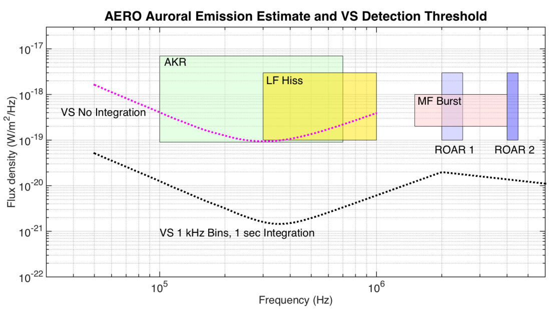

Figure 5: Auroral emission flux density range (colored boxes) compared to AERO VS detection threshold without integration (magenta), and at 1 kHz frequency resolution and 1 second integration (black).

Summary

The AERO mission's radio frequency remote sensing capabilities will unlock a deep and vital scientific investigation space for auroral processes in near-Earth space. In particular, AERO will attempt to settle the issue of whether auroral kilometric radiation indeed penetrates to low altitudes, a significant question given the power of AKR and its usefulness for remotely sensing the auroral acceleration region. Additionally, a host of other auroral emissions occur that will targeted by AERO observations, including auroral "roar" emissions which are closely analogous to magnetospheric continuum radiation, and medium frequency bursts which are poorly understood. Some of these bursts may be analogous to solar type III emissions, and auroral hiss, but even after years of study it is still not known how and where the waves are scattered to small wave normal angles that allow them to propagate to ground level. AERO aims to solve this last mystery and other related topics using thorough plasma wave characterization and direction finding.

AERO's technical approach using a unique electromagnetic vector sensor at LF and HF frequencies between 100 kHz and 5 MHz will provide a new on-orbit CubeSat capability for resolution of electromagnetic wave angle of arrival and polarization information within a single unit. The mission's data acquisition strategy will store many orbits of compressed data on board, then select segments for download based either on analysis of dynamic summary spectra on the ground, or on automatic detection of the extremely bright AKR events and other auroral radio emissions of opportunity.

From a heliophysics technology perspective, AERO also serves as an important stepping stone to a novel spaceborne high capability remote sensing platform that will provide new characterization opportunities for diverse scientific targets such as radio emission from the solar corona and inner heliosphere, and anisotropic turbulence properties of interplanetary medium plasma within the heliosphere. The wide ranging nature of these astrophysical applications will allow future space missions to more completely advance our understanding of the plasma universe and the role of propagating radio waves in facilitating energy exchange between its different regions.

Acknowledgments

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