High Frequency (HF) Radio Astronomy from a Small Satellite

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The Last Unexplored Spectral Window

Gamma rays, X-rays and ultraviolet light blocked by the upper atmosphere (best observed from space).

Visible light observable from Earth, with some atmospheric distortion.

Most of the infrared spectrum absorbed by atmospheric gasses (best observed from space).

Radio waves observable from Earth.

Long-wavelength radio waves blocked.

Ionosphere is opaque below ~10 MHz.
Science at Low Frequencies

• Low frequency observations probe
  – Non-thermal processes (plasma, magnetic fields)
  – High redshift (early universe)

• Key science cases:
  – Heliospheric radio emission (solar bursts, CMEs)
  – Planetary and exoplanetary radio emission
  – Galactic synchrotron emission and cosmic rays
  – High energy objects (supernovae, pulsars, black holes, AGN)
  – Cosmic dawn (Epoch of Reionization (EoR), first stars and galaxies)
Outline

- Introduction
- Vector sensor for Radio Astronomy
- Maximum Likelihood Imaging with a Vector Sensor
- Radio astronomy small satellite
- Summary and Conclusion
Cubesat HF Radio Astronomy Approach

HF Radio astronomy from Cubesat orbiting above ionosphere peak

Data collected on satellites for down-link to ground:
- Raw data
- Statistics

Ionospheric path potentially aids imaging

Data down-link to ground station:
- Calibration and galactic reference
- Integrated mapping

Ionosphere peak (F2 layer) ~300 km
How can we minimize the number of spacecraft while still achieving required sensitivity?

What capabilities can a single spacecraft provide?
Electromagnetic Vector Sensing

- 3 dipoles + 3 loops (electrically small)
- Measures full E and B field vectors, $\mathbf{E} \times \mathbf{B} = \mathbf{S}$ (Poynting vector)
- Determines sources’ intensity, direction and polarization in single snapshot
- Typically used for finding direction of strong sources
- Additional degrees of freedom when compared to triad/tripole
- More sensitive ($\geq 2x$), capable element than tripole for interferometric arrays

A more complex single spacecraft to simplify full system and reduce overall cost
Vector Sensor Measurements

- Measurements are time dependent voltages from vector sensor elements

\[ z[t] = \sum_{k} \beta_k a_k + n[t] \]

\( \beta \): amplitude
\( n \): noise
\( a_k \): array response
\( k = \# \) of discrete signals incident

- Angle of Arrival \((\theta_k, \phi_k)\), Amplitude, and Polarization state \((\gamma_k, \eta_k)\) are embedded in measurements

- Variation in antenna patterns allows estimation of waveform parameters
  - “Curvature of the array manifold”

- Spatial mapping, often called spectral estimation, or inversion is necessary to estimate parameters for multiple sources

See e.g. K. Wong, IEEE T. A&P, Closed-Form Direction Finding...
Sensitivity Comparison
Tripole vs. Vector Sensor

- Comparison of Signal-to-interference plus noise (SINR)
- Interfering signal is at the center of the map, vertically polarized
- Direction-dependent increase in sensitivity with strong interfering source
- 3 dB (2x) sensitivity gain with no interfering source
- Conditions for SINR gain:
  - Full vector sensor
  - Noise is uncorrelated from element to element
  - Sensor elements do not interact
    - Antenna design challenge
    - Verified in prototype by
Vector Sensor Inversion Processing

Measurements \rightarrow \text{Spatial Mapping} \rightarrow \text{Application Specific Post Processing}

**Linear projection:**

\[
\hat{P}(\theta_i, \phi_i, \gamma_i, \eta_i) = \sum_t |z^H(t)a(\theta_i, \phi_i, \gamma_i, \eta_i)|^2
\]

**Super-resolution Maximum-Likelihood:**

\[
\hat{\Sigma}^{p+1} = \text{diag}(\hat{\Sigma}^p + \hat{\Sigma}^p A^H (\hat{R}^{p-1} S \hat{R}^{p-1} - \hat{R}^{p-1}) A \hat{\Sigma}^p)
\]

\[
\hat{R}^{p+1} = A \hat{\Sigma}^{p+1} A^H + \sigma^2 I
\]

\[
S = \frac{1}{M} \sum_{i=1}^{M} z[i]z^H[i]
\]

columns of A are the \(a(\theta_i, \phi_i, \gamma_i, \eta_i)\)
diagonal terms of \(\hat{\Sigma}\) are estimates of \(\hat{P}(\theta_i, \phi_i, \gamma_i, \eta_i)\)

- Invert measurements to spatial map
  - Intensity and polarization as a function of angle of arrival, frequency, and time
  - Sources are a combination of discrete and diffuse signals

- Algorithm development challenges
  - Extremely ill conditioned
  - Computationally intensive
  - Diffuse signals have low SNR

Algorithm development is ongoing

See e.g. F. Robey, MIT-LL TR-918
Imaging Algorithms

• Initial study is development of imaging algorithms for single vector sensor/single CubeSat
  – Imaging of distributed sources
  – Resolution of discrete sources

• Initial results with distributed sources illustrate ambiguity of ML estimator

• Continuing to develop algorithms
  – Higher order statistics: increase number of detectable sources
  – ‘Pixel’ estimation vs. spherical harmonic coefficient estimation
Source-finding Demonstration

- 18 impulsive sources
- Random location, intensity, polarization (either horizontal or vertical)
- Using second order statistics as input to ML algorithm

Truth

Algorithm Result: Horizontal Polarization

Algorithm Result: Vertical Polarization
CubeSat Deployable Vector Sensor

- **Stowed**
  - Upper Tape Hub
  - Lower Tape Hub
  - Stowed Diagonal Tape
  - Stowed Perimeter Loops
  - Stowed Corner Tape
  - Corner Fittings

- **Telescoped**
Deployable Vector Antenna Prototype
Technology Maturation

• Tracking and telemetry payloads
  – 900 MHz radios
  – Iridium transponder

• Antenna/Receiving payload
  – 1.8 m diagonal vector sensor
  – GPS / INS

• A/V payload
  – High Definition Video (all sides)
  – Low-frequency audio recording
  – INS and GPS

• Auxiliary Tracking payload
• Good agreement between measurements and truth
  – 3° bias plus RMS error

• Plan to re-run experiment with form-factored electronics
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Alan Fenn    Sara Seager  Ryan Volz
Alex Morris  Mike Hecht  Will Rogers
Mark Silver  Kerry Johnson  Tom Brown
Sarah Klein  Farshid Neylon-Azad
The unexplored radio sky below ~ 10 MHz offers insight into:
- Heliophysics
- Planetary and exoplanetary magnetospheres
- Galactic magnetic fields and high energy objects
- The early universe

Large-scale space-based interferometry is necessary to probe this regime

A new approach has the potential to provide results at much reduced cost
- CubeSat vector sensing in Earth orbit
- New processing algorithms (polarimetric maximum likelihood imaging)
- Ground-based validation in progress

Critical next step: in space demonstration of multi-spacecraft interferometry

Great potential for future scalable low frequency observatory enabled by CubeSats and vector sensing