A Compact Five-channel VLF Wave Receiver for CubeSat Missions

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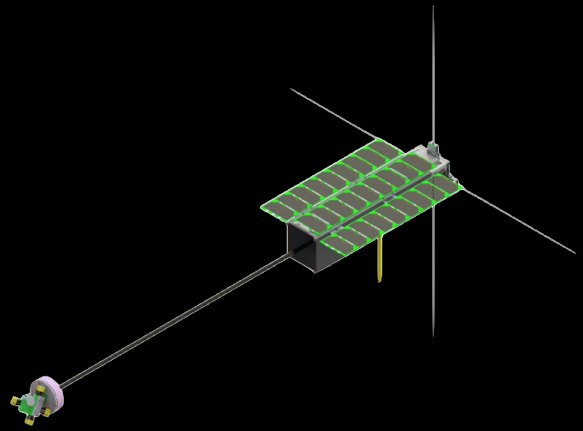
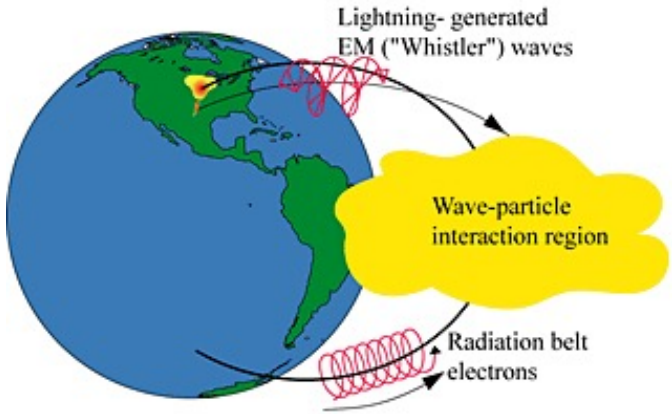
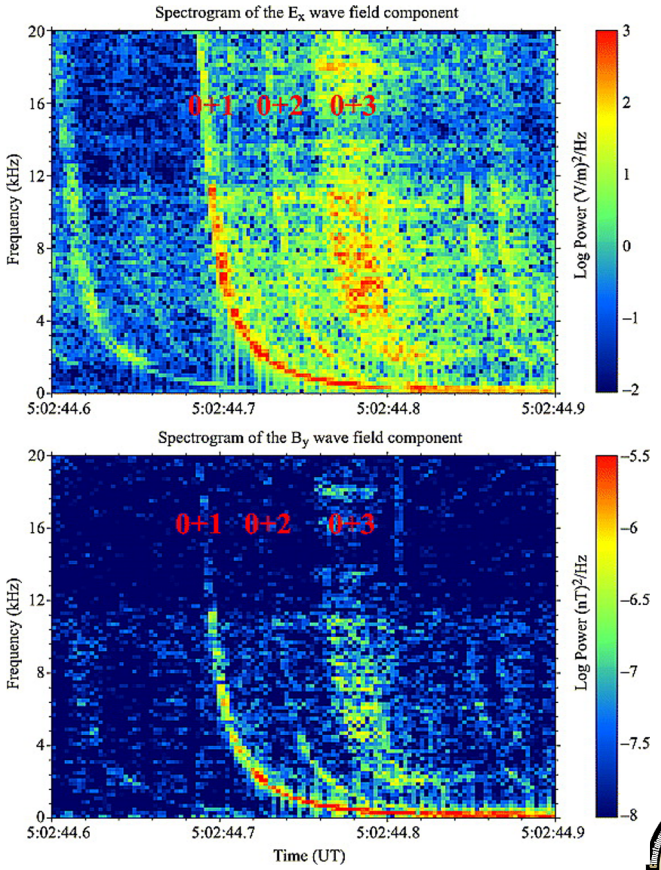


Background & Motivation

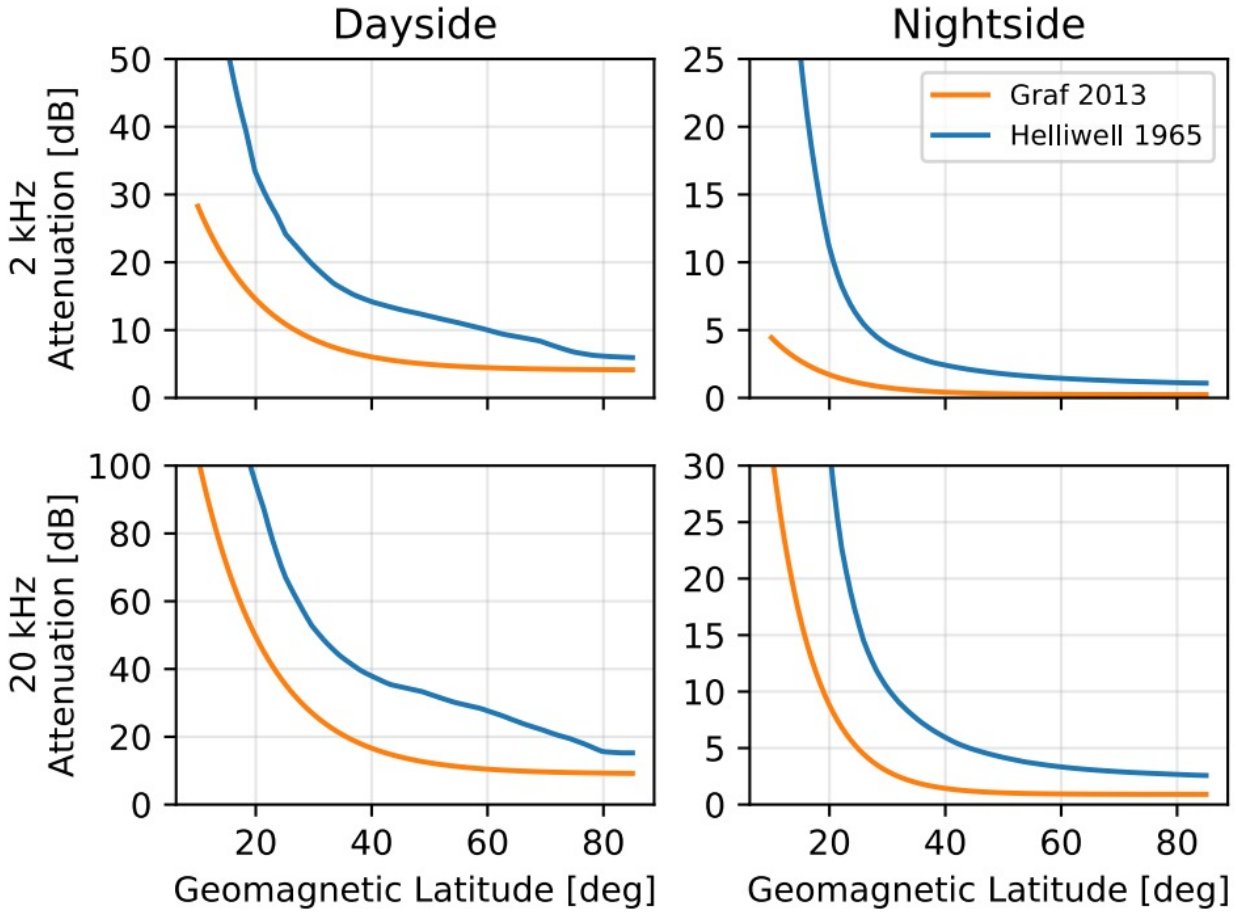
- Lightning releases EM energy that partially dissipates through the ionosphere and into the magnetosphere
- Energy propagates as whistler-mode waves & interacts with energetic electron populations (e.g. Thorne, 2010, Meredith 2009)



Adapted from O'Toole, 1999



Lefeuvre, et. al. 2009



Sousa, 2018

Background & Motivation

- Trans-ionospheric absorption curves
- Helliwell curves show significant disagreement with satellite observations and full wave modeling results (Starks, 2008, Tao 2010)

Previous VLF Missions

DEMETER satellite

Observing ionospheric perturbations from seismic activity

5-channel VLF observations up to 20 kHz

700 km Sun-synchronous orbit, 10:30/22:30 LT

~ 130kg

ZH-1 satellite

Similar scientific goals as DEMETER

6-channel VLF observations up to 20 kHz

500 km Sun-synchronous orbit, 02:00/14:00 LT

~ 500 kg

VPM CubeSat

6U CubeSat

2-channel VLF observations up to 40 kHz

LEO 500km circular orbit

< 6kg

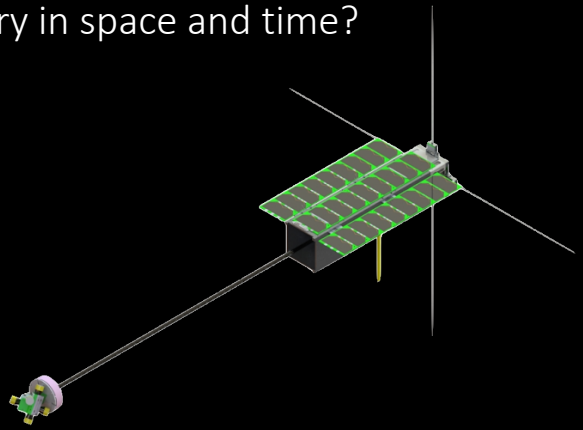
Kramer, 2002

Barbosa, 2018

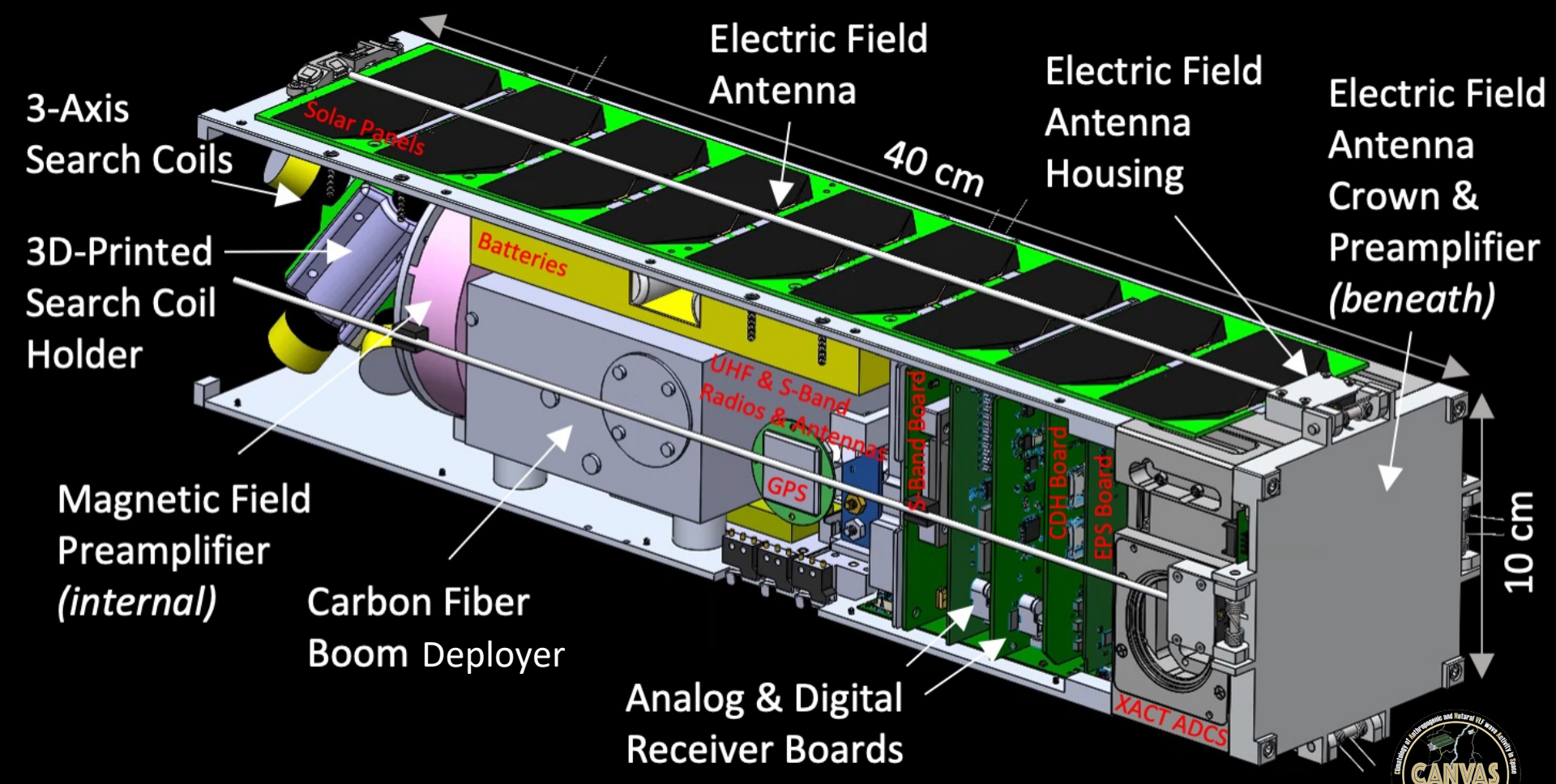
The CANVAS Mission

CANVAS (Climatology of Anthropogenic and Natural VLF-wave Activity in Space)

1. What is the electromagnetic energy input into the space environment by lightning and ground-based VLF transmitters?
2. What is the frequency spectrum of VLF wave energy above the ionosphere in the 0.3–40 kHz range?
3. What is the transmission transfer function of the ionosphere for VLF energy, and how does it vary in space and time?

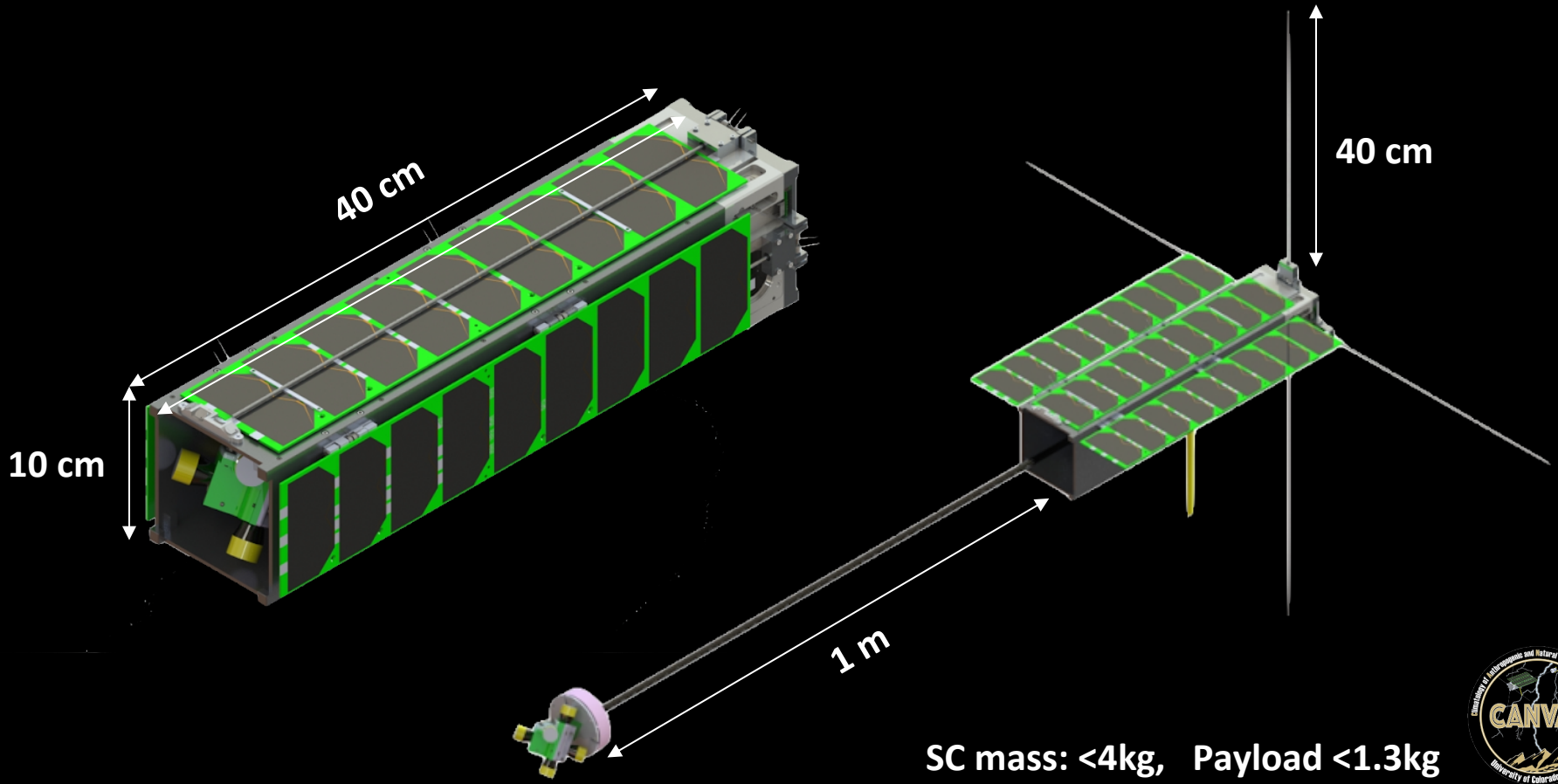


Mission Elements		
Duration	1 year	cover **seasonal variation**
Altitude	500 km	allows for 1-year mission
Inclination	51.6°	coverage of latitudes of **most lightning and most powerful VLF transmitters** also covers **all local times**
Deployment	ISS/Cygnus	ease of deployment from CubeSat Deployer



Blue Canyon Technologies XACT ADCS provides position knowledge better than 10km and pointing knowledge within 1 degree

CANVAS Stowed & Deployed

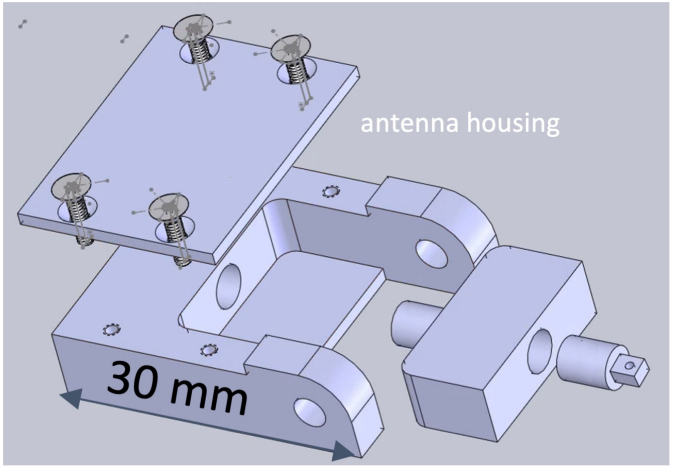


SC mass: <4kg, Payload <1.3kg

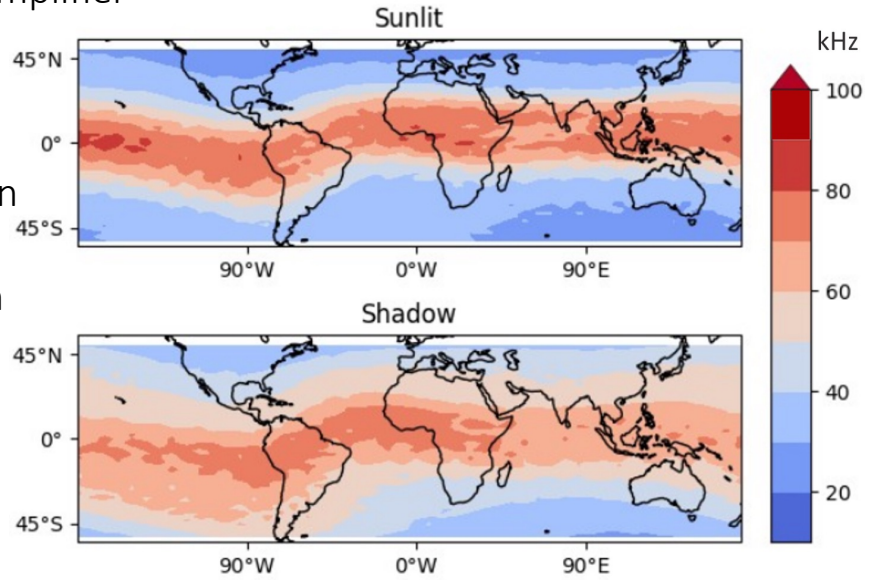
Instrument Hardware Overview

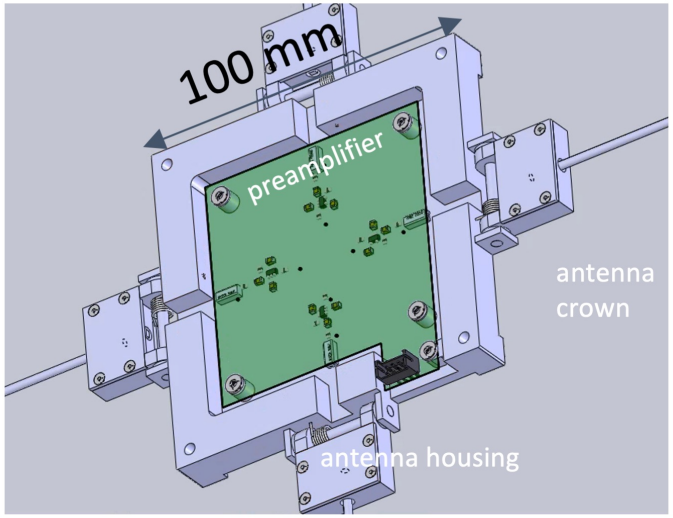
Two-Axis Electric Field Dipole

- 40 cm Al antenna and housing integrated into crown
- In-house manufacturing using press-fitting
- Antenna capacitance to spacecraft < 35pF
- Sensitivity better than $1\ \frac{\mu V}{m\sqrt{Hz}}$, signals conditioned in unity gain buffer preamplifier

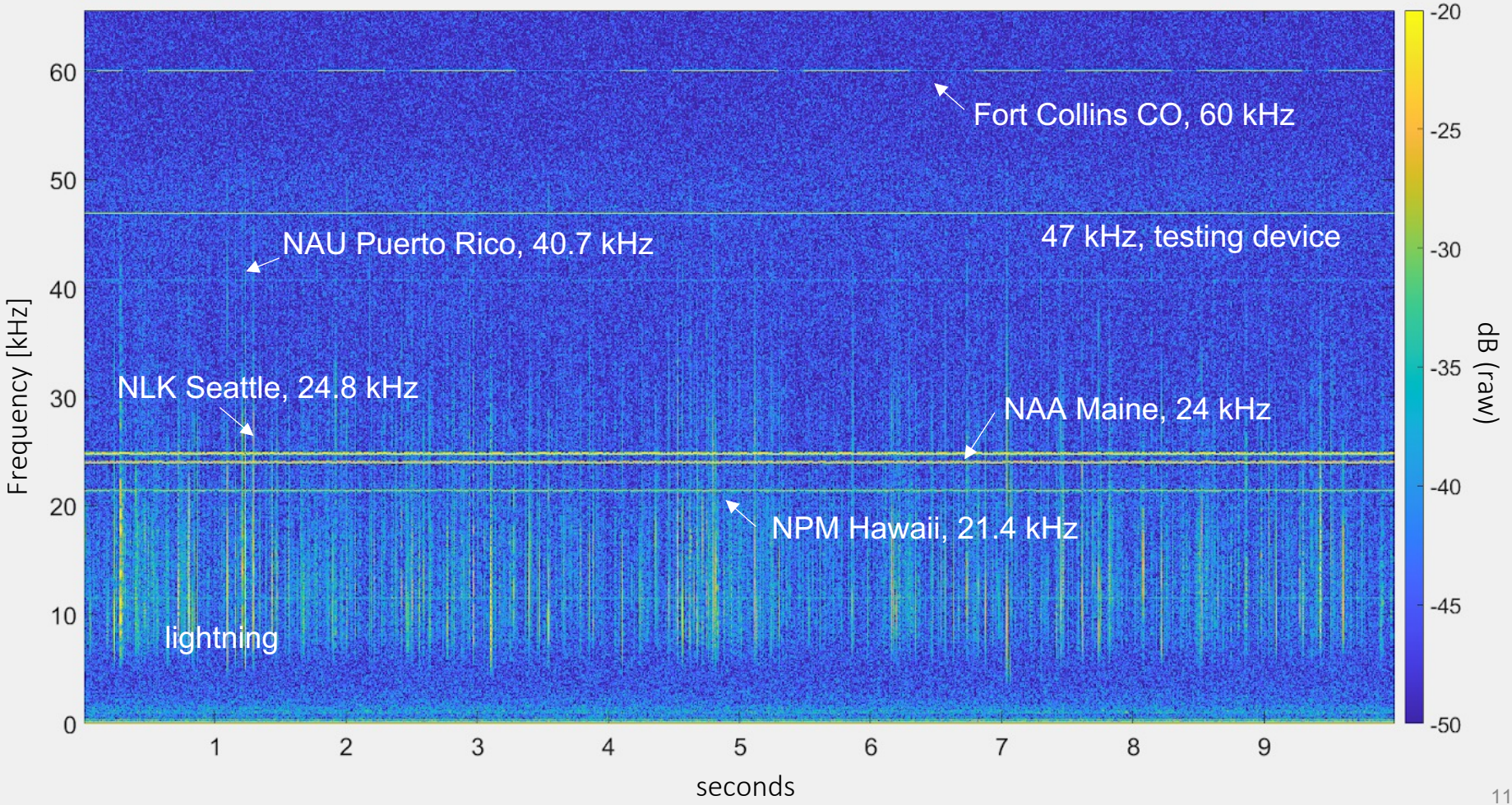


Frequency of transition between capacitive and resistive regime in antenna-plasma coupling using IRI densities



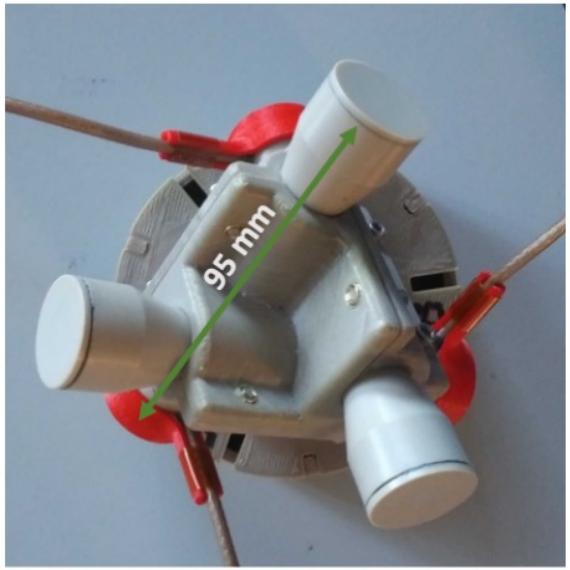


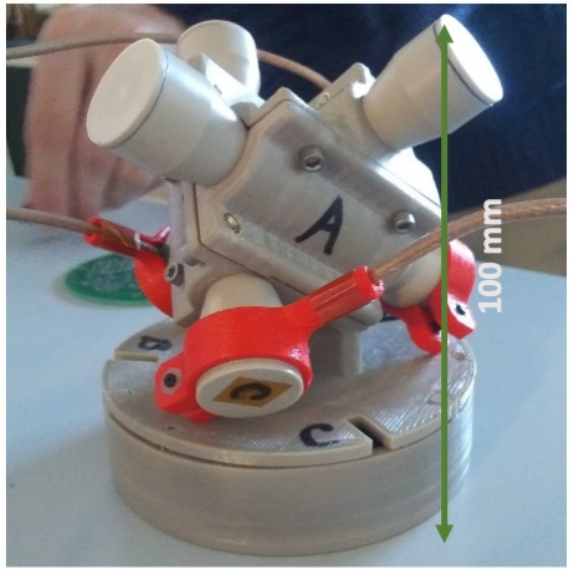
CANVAS E-field Antenna Ground Testing with Analog Receiver

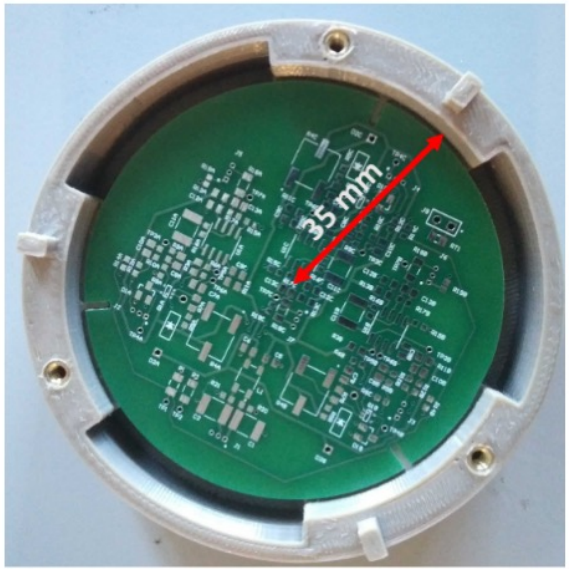


Three-Axis Magnetic Field Search Coils

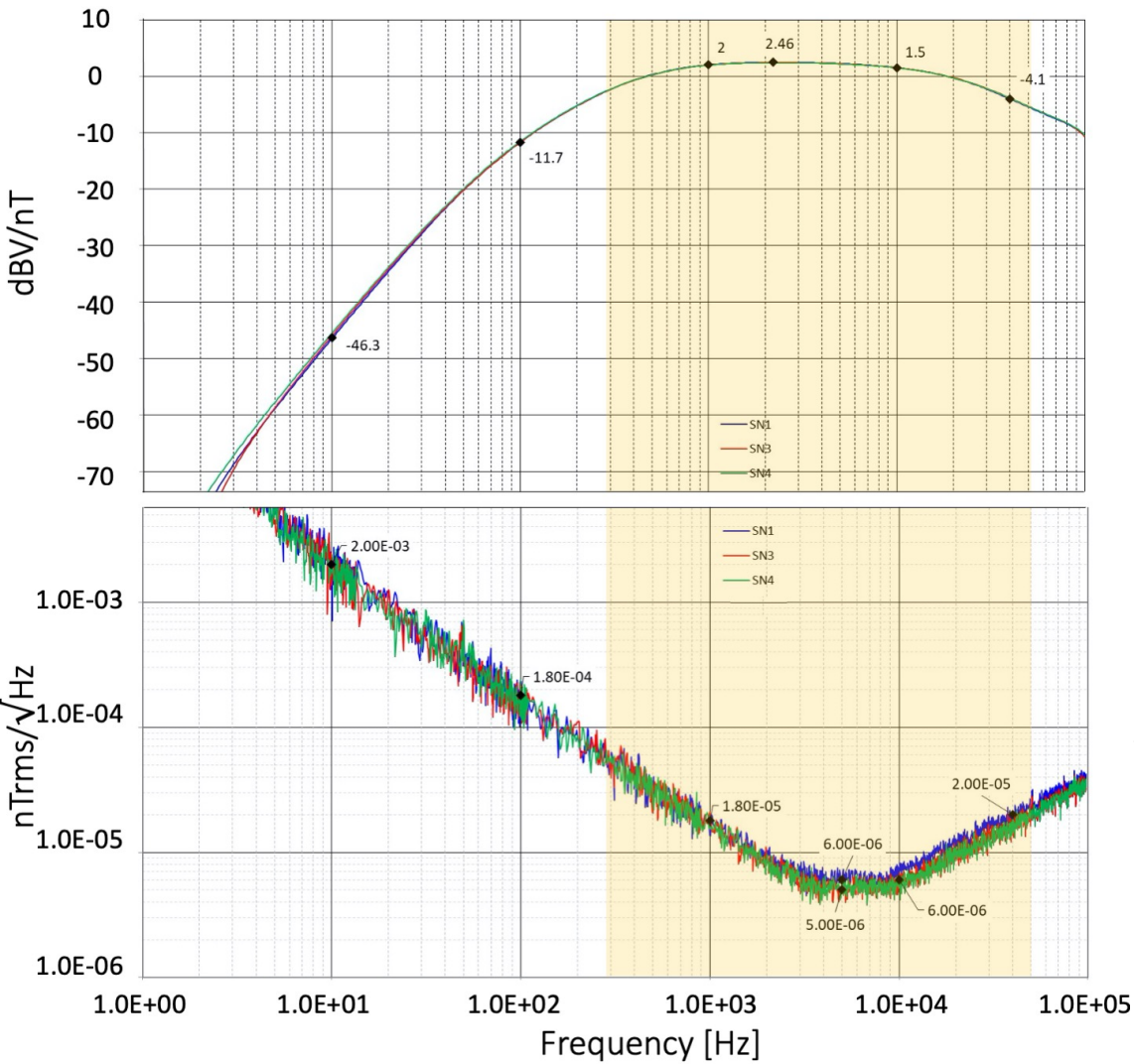
- Ferrite core in PEEK dumbbell-shaped casing
- LPC2E in Orléans, France, DEMETER heritage
- Low power preamplifier with 80dB of gain and bandpass filter
- Search coils + holder+ preamp. < 375g
- Custom 3D-printed PEEK holder by Roboze
- PEEK chosen as optimal lightweight, nonmagnetic thermoplastic that meets thermal, UV-damage depth, tensile strength, and outgassing requirements
- Ease of manufacturing and assembly of uniquely shaped pieces







Search Coil Response



- Oppositely-winded secondary coil on the same core as the primary coil to dampen the resonance response while retaining optimal sensitivity

- Sensitivity better than $10^{-4}\,\frac{\mathrm{nT}}{\sqrt{\mathrm{Hz}}}$ between 0.3-40 kHz

- Approximately 2.5 dBV/nT transfer function after preamplifier

Figure courtesy of LP2CE

Composite Carbon Fiber Boom

- Isolates the search coils from SC magnetic fields
- Deploys with known attitude within 1 degree
- Designed & manufactured by Composite Technology Development (CTD) in Lafayette, Colorado
- Flattened rolled up spool; upon deployment (CDH board enables power to the motor), flattened tape rolls up into a cylinder and locks to itself with teeth
- Motor encoder provides steps (translate to deployed distances) to confirm successful deployment
- Four shielded, twisted-pair cables in a slip ring integrated into hollow boom
- < 500 grams and 0.5 W to deploy

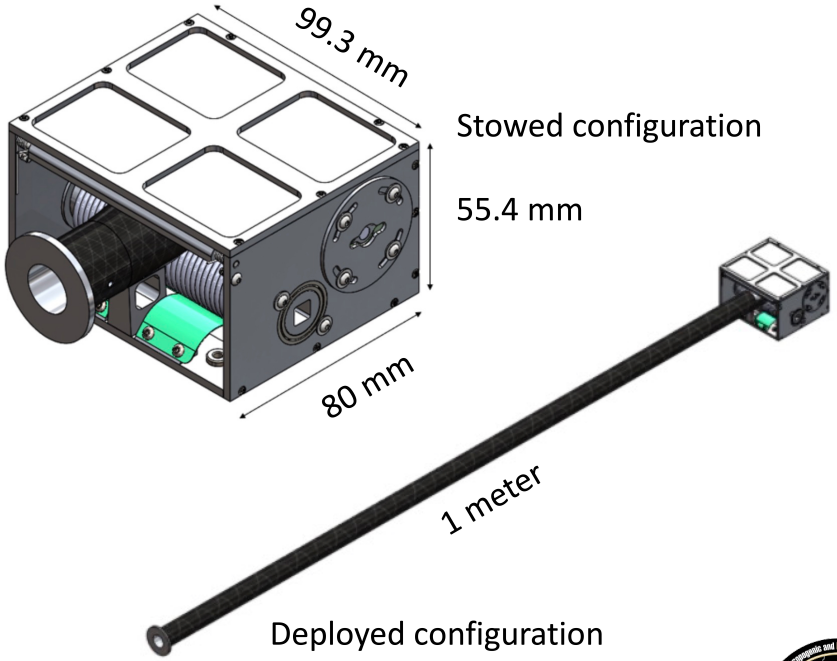
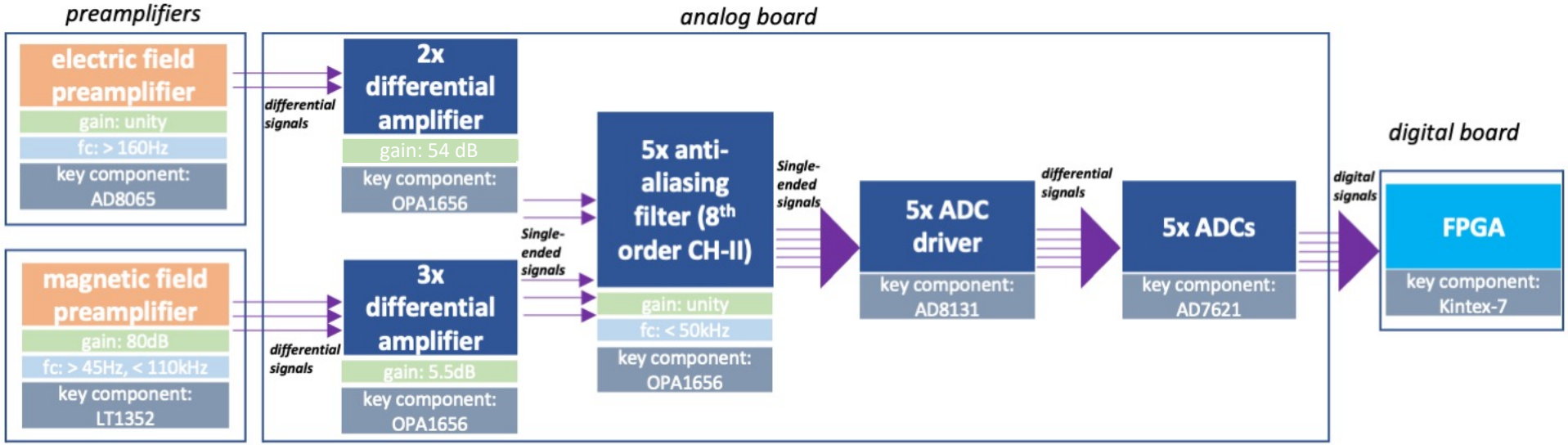


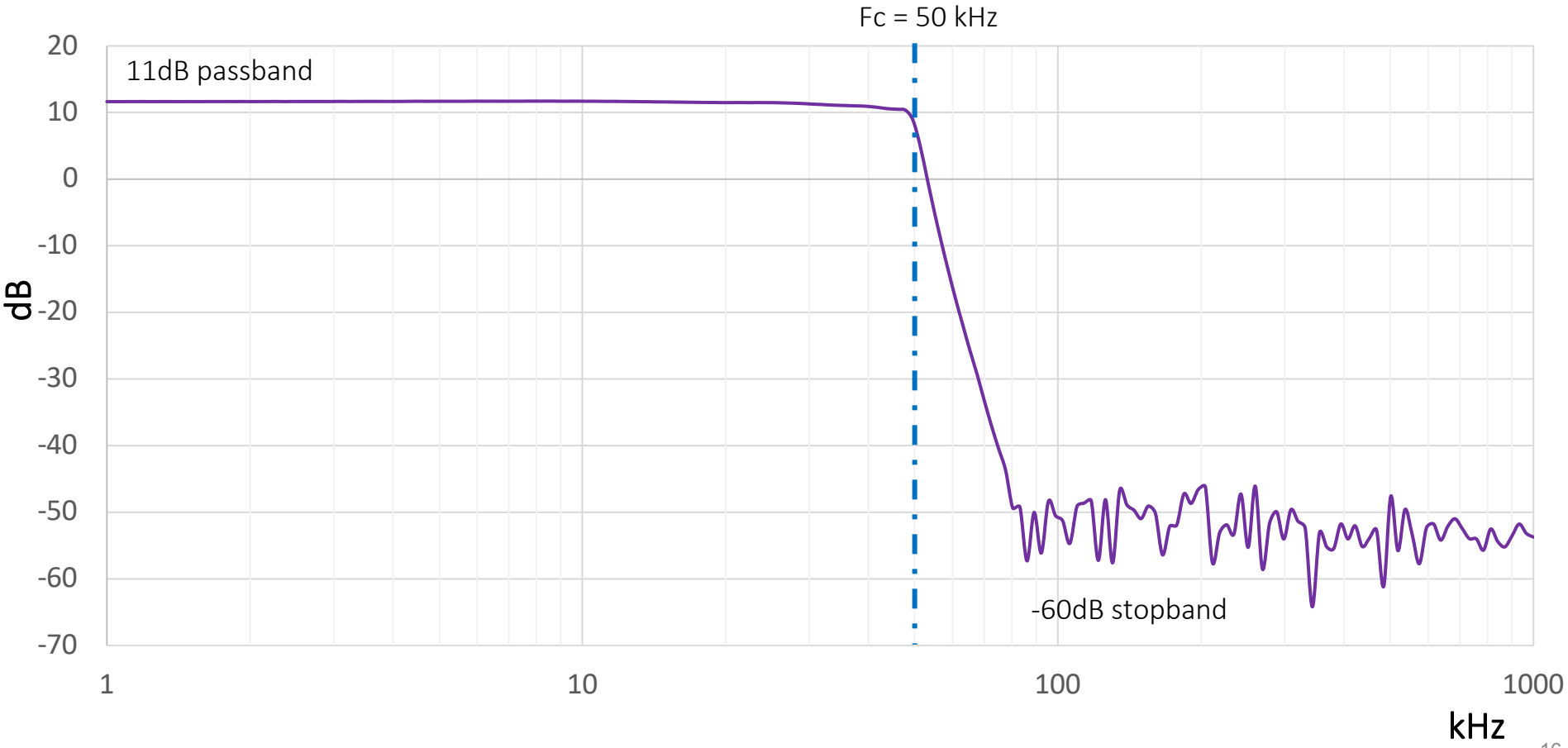
Figure courtesy of CTD

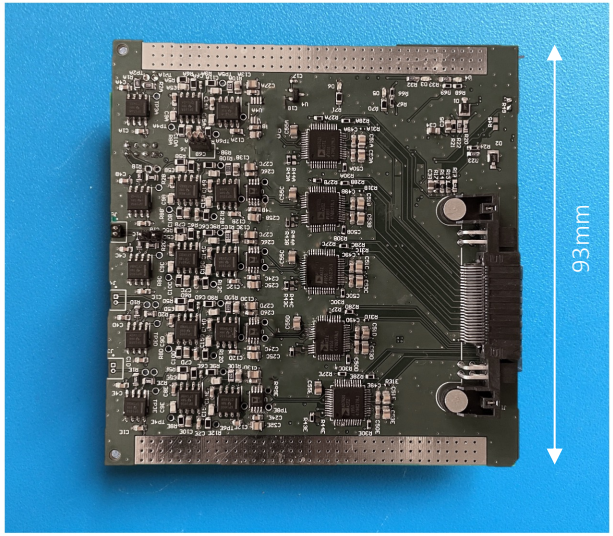
Analog Signal Processing

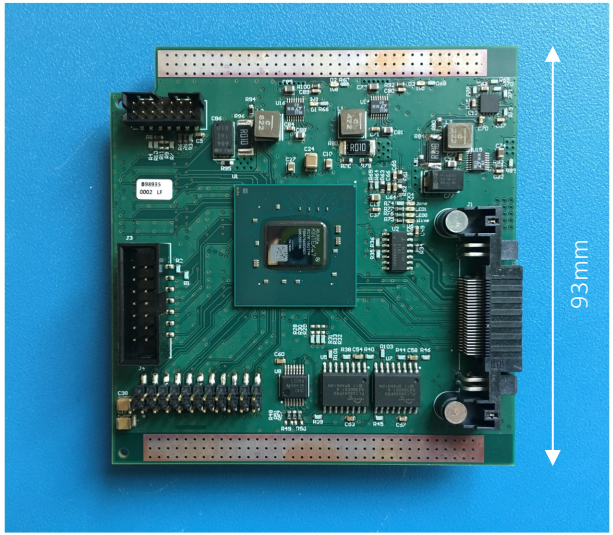


- 5 channels of VLF data through 4 processing stages
- Dynamic range estimated by processing large quantities DEMETER burst-mode data for daytime and night-time conditions
  - max E-field: 5mV/m and B-field: 0.5nT
- AAF 50 kHz cutoff frequency, < 1 dB of ripple in passband, and -60 dB attenuation at 88 kHz
- Provides regulated voltage supply to each preamplifier

Analog Receiver Response







Digital Signal Processing

- Onboard FPGA (Kintex-7) processes data in “fast survey” mode with 1-second time resolution sampling data at 2^{17} Hz:

1. Rotation module rotates B-field channels into E-field coordinate frame
2. FFT processor performs 1024-pt FFTs
3. Averaged into 57 log-spaced frequency bins and 10 VLF Tx bins, resolution better than 10%
4. 128 spectra and cross-spectra accumulated and averaged into 1-second data products
5. Pseudo-logarithmic compression & packetizing

- ~210 MB/day for downlink
- singular value decomposition methods (Santolik, 2003), determine wave power, Poynting vector, polarization, planarity of polarization, and fully defined k-vector

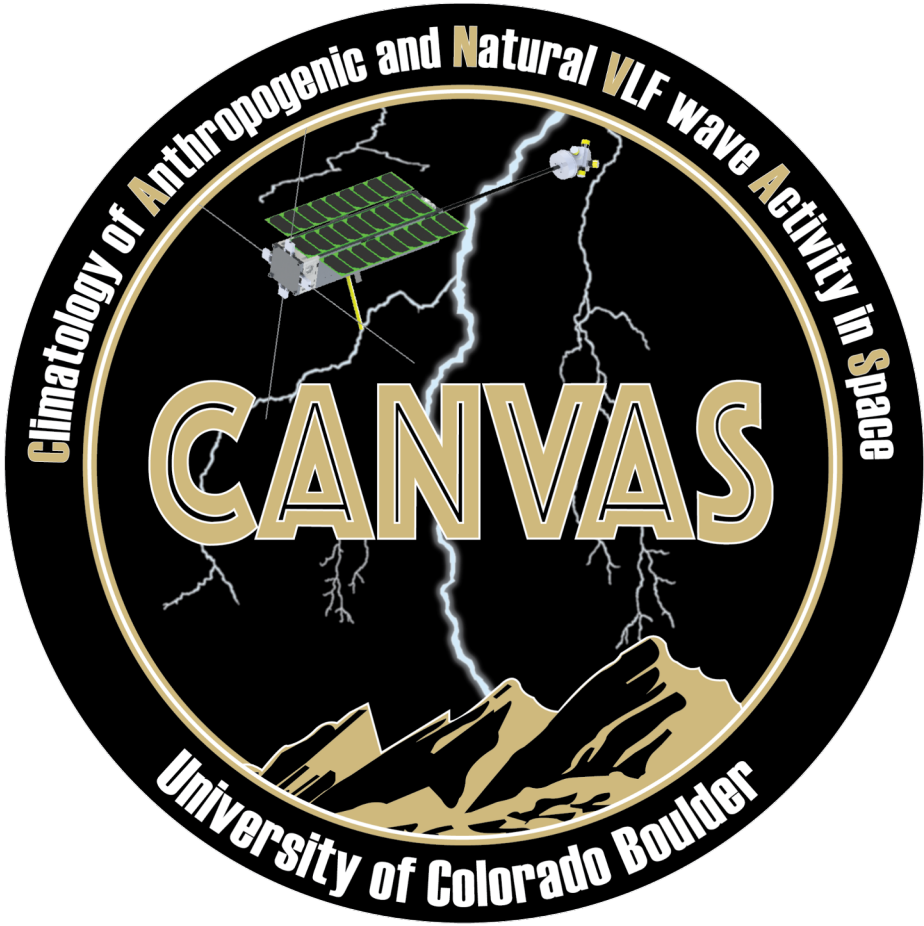
$$Q = \begin{bmatrix} c^2B_1^2 & c^2B_1B_2^* & c^2B_1B_3^* & cB_1E_1^* & cB_1E_2^* & cB_1E_3^* \\ c^2B_2B_1^* & c^2B^2 & c^2B_2B_3^* & cB_2E_1^* & cB_2E_2^* & cB_2E_3^* \\ c^2B_3B_1^* & c^2B_3B_2^* & c^2B_3^2 & cB_3E_1^* & cB_3E_2^* & cB_3E_3^* \\ cE_1B_1^* & cE_1B_2^* & cE_1B_3^* & E_1^2 & E_1E_2^* & E_1E_3^* \\ cE_2B_1^* & cE_2B_2^* & cE_2B_3^* & E_2E_1^* & E_2^2 & E_2E_3^* \\ cE_3B_1^* & cE_3B_2^* & cE_3B_3^* & E_3E_1^* & E_3E_2^* & E_3E_3^* \end{bmatrix}$$

- **Summer 2021 pre-integration review**

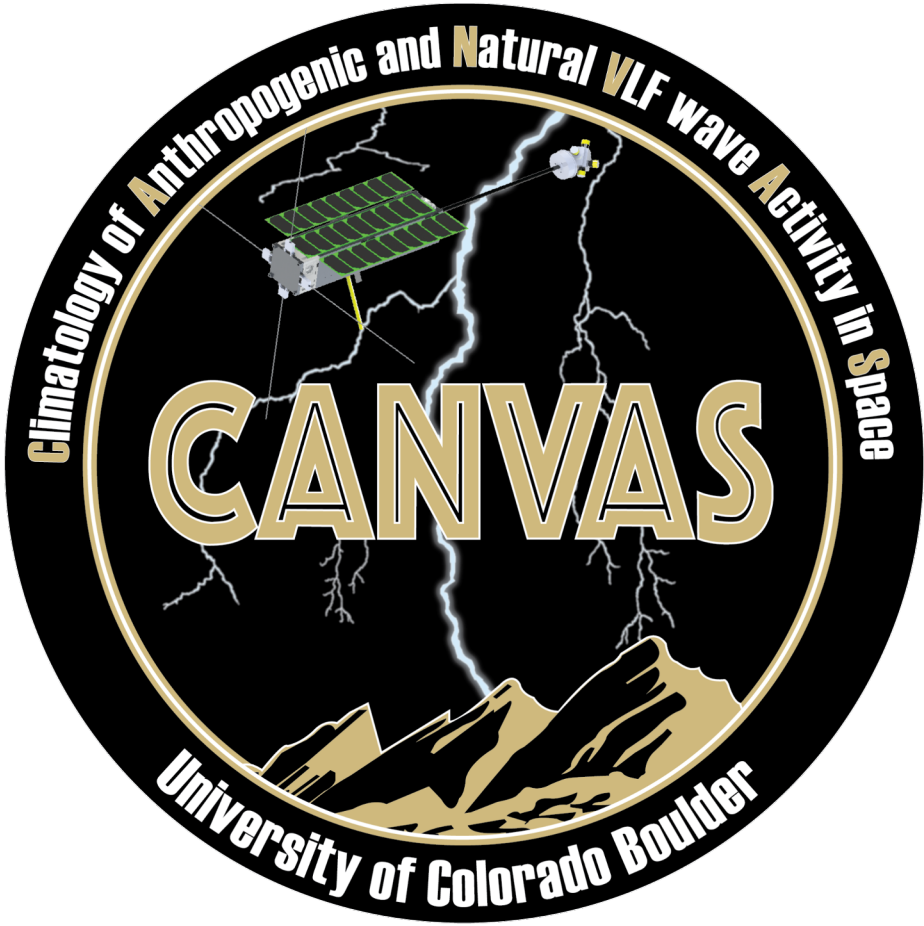
- PCBs nearing flight revisions
- Received flight versions of holder and boom June 2021
- Ground testing with VLF Tx and lightning signals on engineering models of dipole antennas
- Ground testing using mu metal chamber and Helmholtz coils with engineering model search coils

- **Payload integration into spacecraft Fall 2021**
- TVAC testing

- **Launch estimated for late 2022**



Thank You!



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Additional Figures from Slides

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