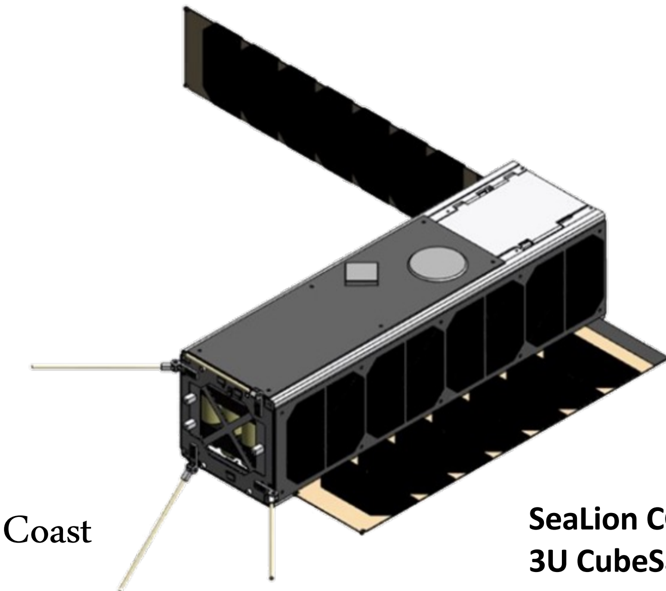
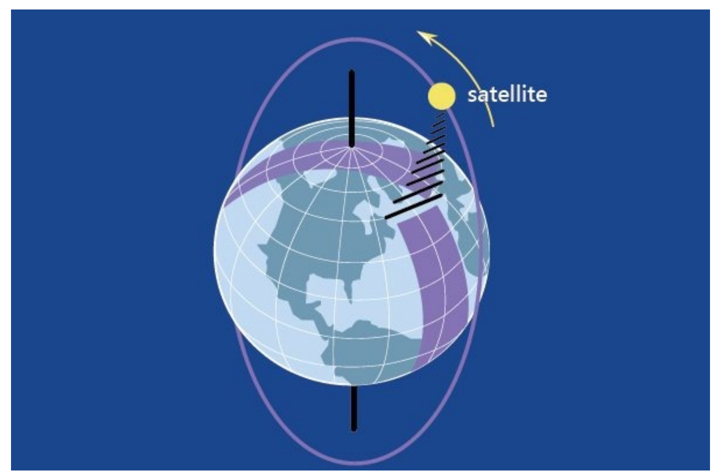
SeaLion 3U Impedance Probe
Space Plasma Measurement Investigations



SeaLion CGA-ODU
3U CubeSat

<u>Collaboration for Space & Energy (CSE)</u>

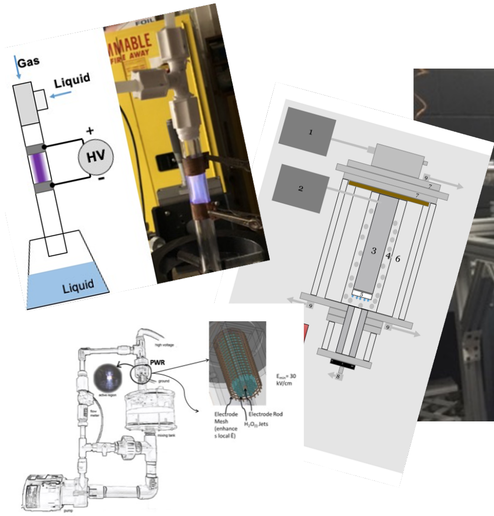
R. James, D. Burbank, L. Allen, C. Mehta, R. Hartnett, D. McGarry [U.S. Coast Guard Academy], E. Tejero [Naval Research Laboratory], S. Asundi, J. Abedrabbo, C. Schappi [Old Dominion University], C. Heckman, and B. Kay [Air Force Institute of Technology], Dr. C. Mehta [CGA Plasma Lab]

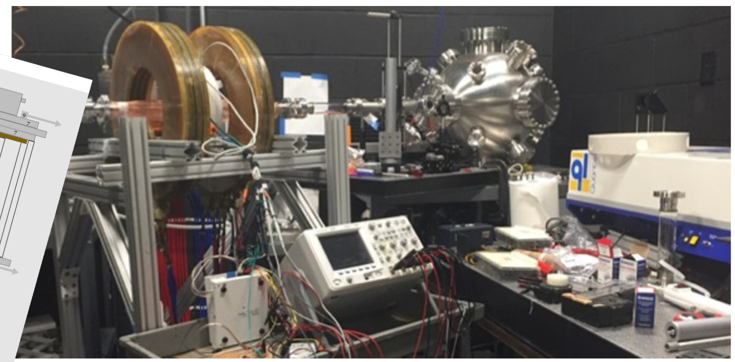


UNITED STATES COAST GUARD ACADEMY

COAST GUARD ACADEMY CGAPL PLASMA LABORATORY

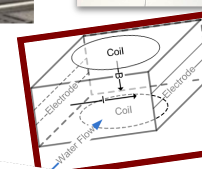
Coast Guard Academy
Collaboration for Space & Energy (CSE)

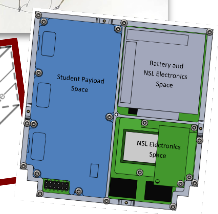




MHD Space

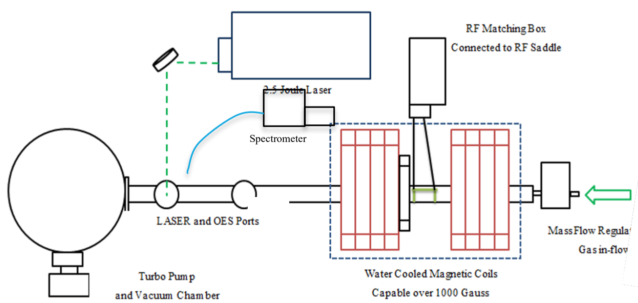
$$\rho \frac{d\vec{u}}{dt} = \frac{m}{V}\vec{u} = \frac{\vec{F}_A}{V}\hat{k} = -(\nabla p) + \vec{j} \times \vec{B}$$

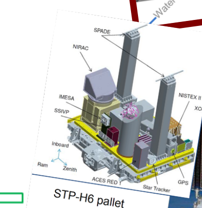


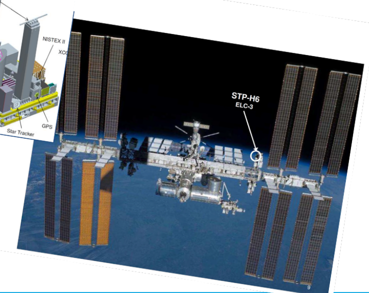


HPX

Plasma Water Treatment







Collaboration to Succeed

Academic

Mechanical, Electrical, Cyber Systems, Civil, Operations Research, Physics, Cyber Systems

Institutional

US Naval Academy
US Airforce Academy
US Military Academy
Air Force Institute of Tech
Naval Postgraduate School
Old Dominion University

Professional

CG R&D Center
CG C5ISC
CG C5PW
Naval Research Laboratory
Virginia Space
Virginia Institute for Spaceflight and Autonomy
Commercial Partners

Military Service Institutions of Higher Learning (MSIHL): Vital to USCGA-Space Program

Three MSIHL Principles

1.[**Equip**] Consolidate space/SmallSat effectiveness through unity MSIHL partners

   a. Capitalize on existing infrastructures/capacities via systems approach to scientific and engineering mission mandates: education, research, and national security / intel support plus home service missions
   b. Capitalize on platforms/hardware currently in use like the MC3 Network, SmallSat ideation/construction facilities, Data Processing/Cyber Programs, + Partnerships.

2.[**Staff**] Leverage MSIHL experts in their respective fields to better link resources, up and coming technologies, and hard-earned experience in specialty areas. Institutional leads/reps on steering/advisory board with external partners i.e. military/national research labs, NASA, *VaSpace*, and others.

3.[**Discover**] Sci/Eng discovery/development is integral to the formation & continuance of military science past, present, and future. *Preparing our future Officers, Technicians, and Civil Servants to carry the torch of discovery to meet our future missions*. MSIHL offers a unique opportunity to link our educational programs.

AFIT — Air Force Institute of Technology

NPS — Naval Postgraduate School

United States Air Force Academy

United States Coast Guard Academy

USNA — United States Naval Academy

United States Military Academy West Point

Mission SeaLion - USCGA/ODU 3U CubeSat

Scheduled to launch on a **Firefly Aerospace *Alpha*** rocket

from U.S. Space Force Base **Vandenburg**, CA

NET 19 SEP 2024

Mission SeaLion's Upgrade to a Multi-Year, Polar Orbit

Generates **New Coast Guard-Relevant Mission Objectives**

Primary Mission Objectives (PMO)

- Validate operation of Impedance Probe as primary payload
- Establish S-band communication link with the MC-3 network
- Transmit spacecraft and payload data to CGA and partner MC-3 ground stations
- Utilize CubeSat Design Standards for spacecraft design and build
- **Demonstrate RF application for Artic SAR localization**

Secondary Mission Objectives (SMO)

- Validate operation of the Ms.S as a secondary payload
- Validate operation of DeCS experiment as secondary payload

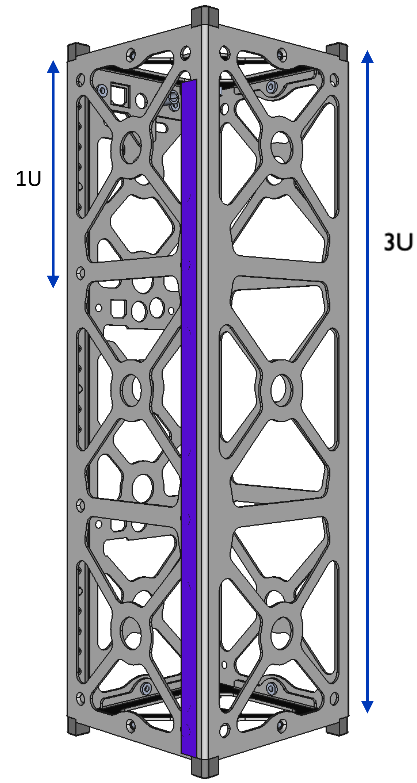
Tertiary Mission Objectives (TMO)

- **Demonstrate Comm Relay for CG Units operating in the Artic**
- Validate on-orbit deployment and functioning of custom developed UHF antenna system
- Gather DeCS experiment in-orbit performance data by capturing structural behavior through accelerometer and temperature sensor

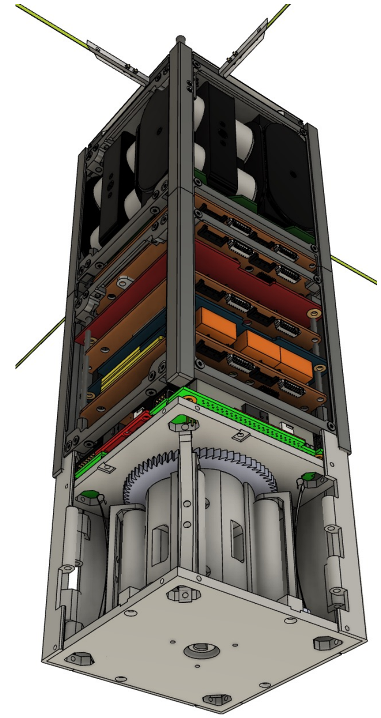
SeaLion Science Payloads Support Discovery & CG Missions

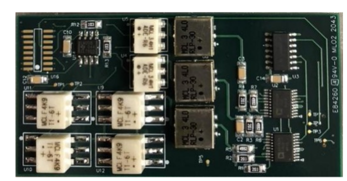
Impedance Probe (IP)

- Dual strap surface mounted dipole antenna
- 1st Designed for ThinSat mission w/ 5-7 days lifespan!
- Custom designed and developed
- Virginia Space ThinSat & CubeSat partnership



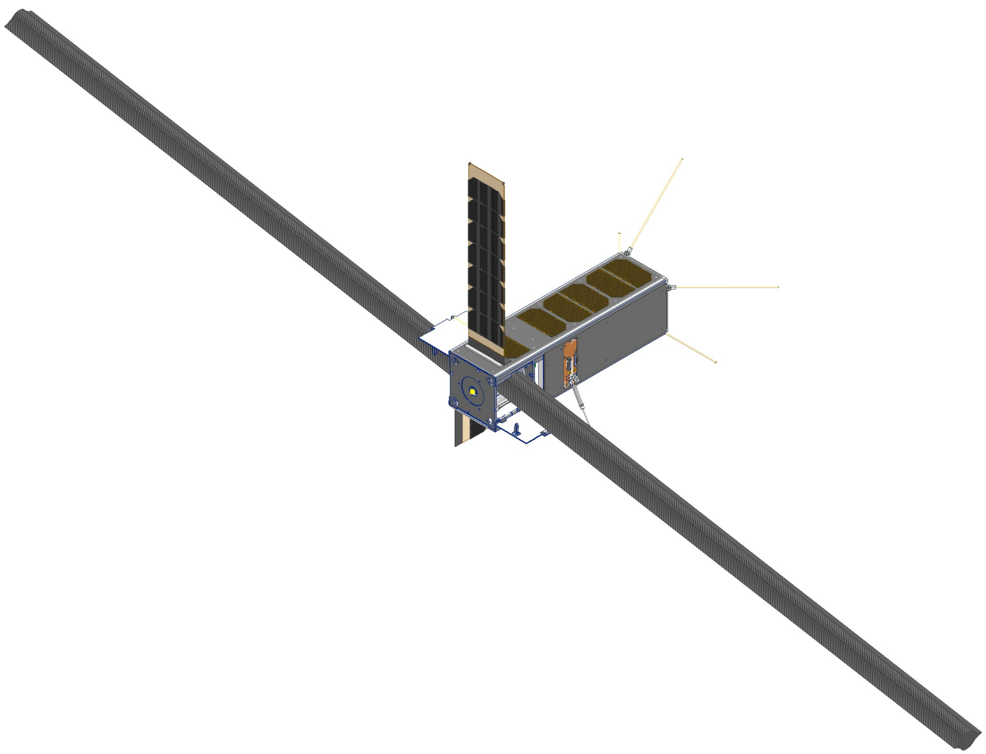
Surface Mounted Antennas for IP



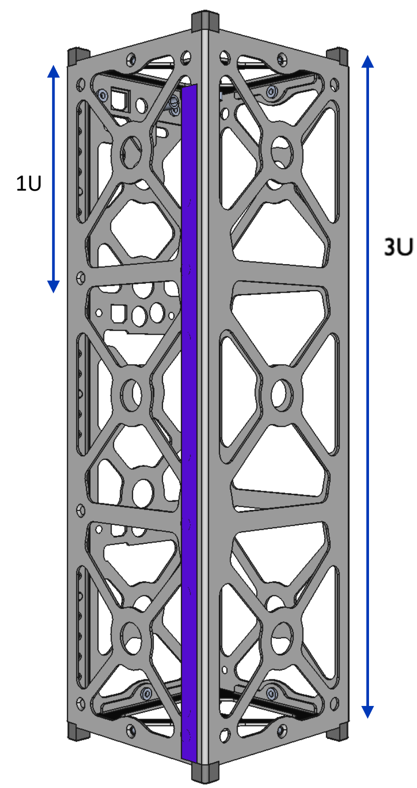


Impedance Probe (IP)

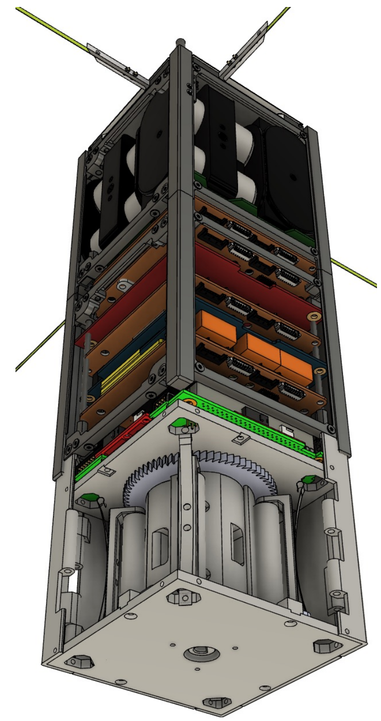
SeaLion Science Payloads Support Discovery & CG Missions

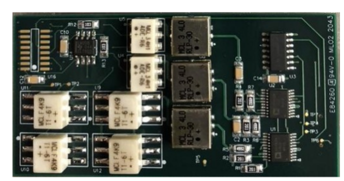


Deployed Booms



Surface Mounted
Antennas for IP



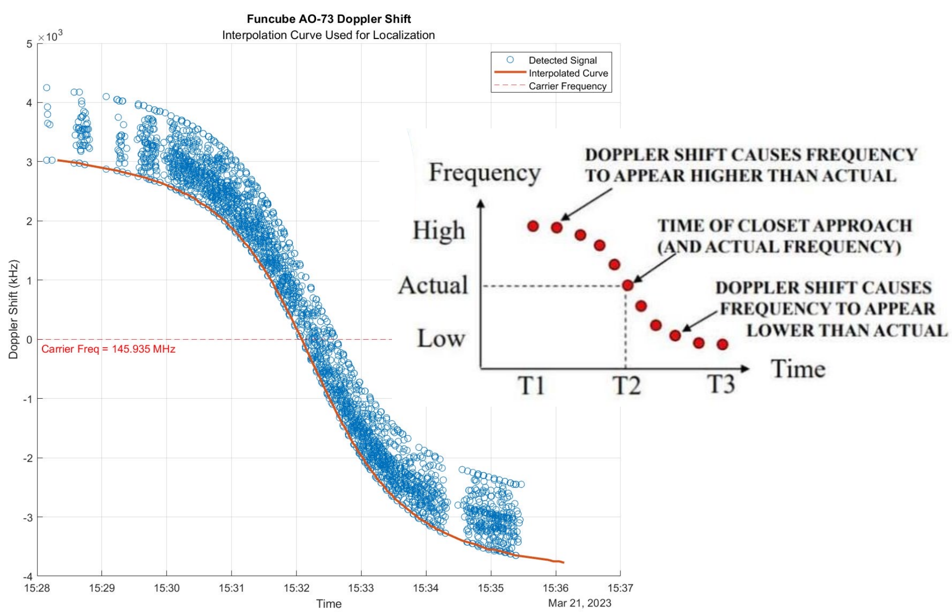


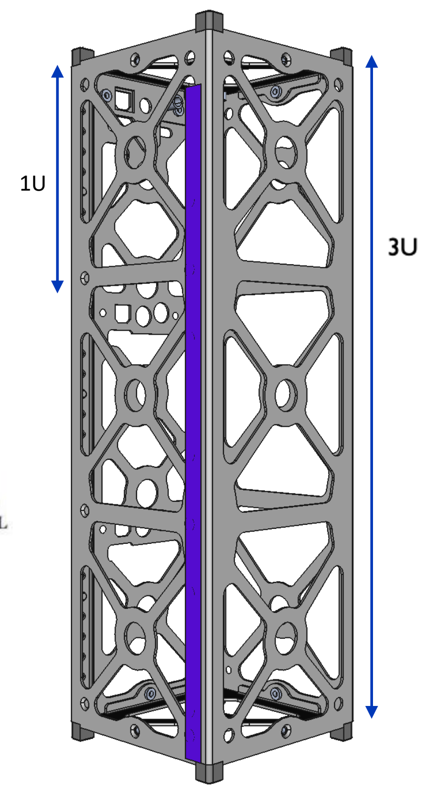
Impedance Probe (IP)

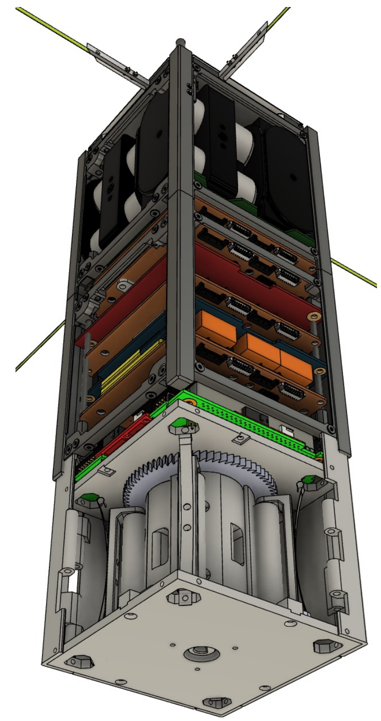
SeaLion Science Payloads Support Discovery & CG Missions

VHF Doppler Experiment

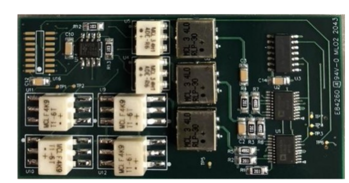
Augments Rescue-21 for SAR localization







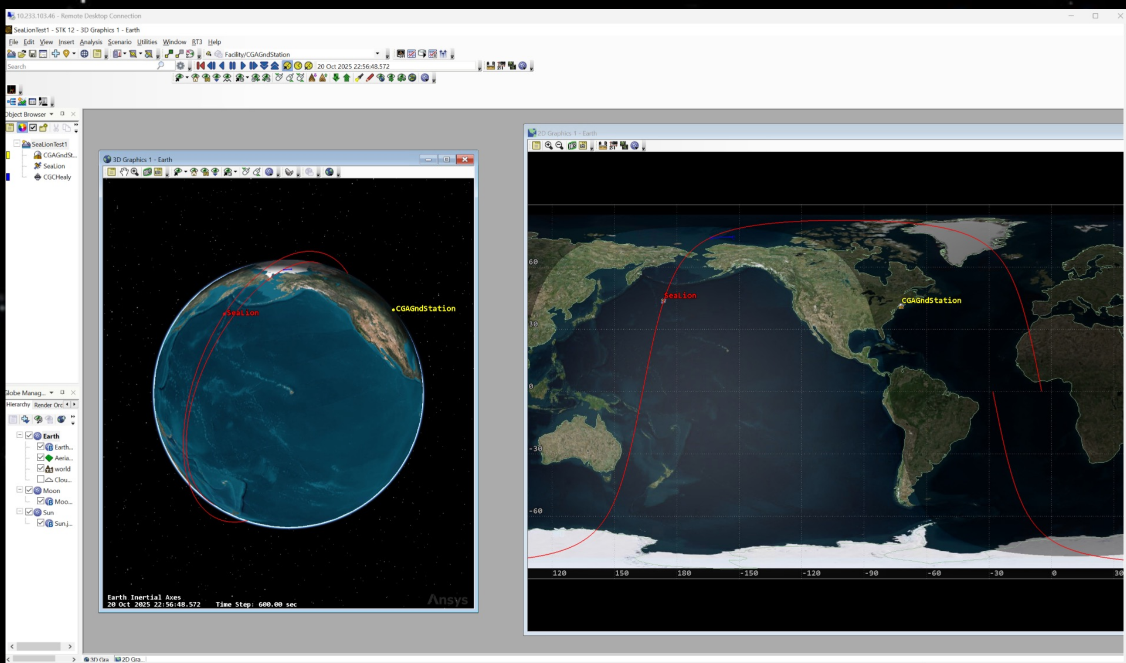
Surface Mounted Antennas for IP



Impedance Probe (IP)

FunCube Sat real Doppler reading - SeaLion Basis

SeaLion's sun-synchronous orbit provides 15x/day Arctic overflights



[High Altitude Cusp]

United States Coast Guard Academy

CUBESAT

SeaLion's sun-synchronous orbit provides 15x/day Arctic overflights

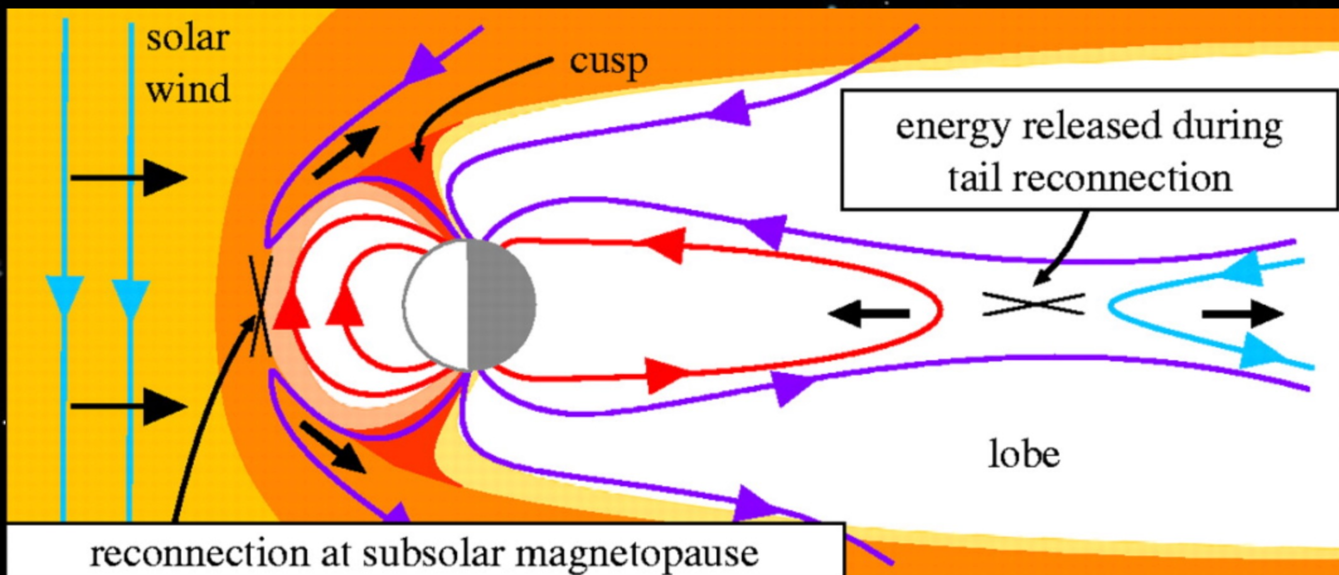
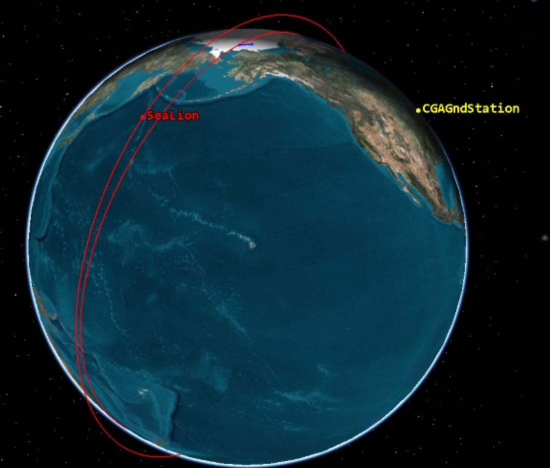


Image from: [Pathways for solar wind plasma and energy transfer to the earth's magnetosphere](#) – S. Wing



[Magnetic Reconnection](#)

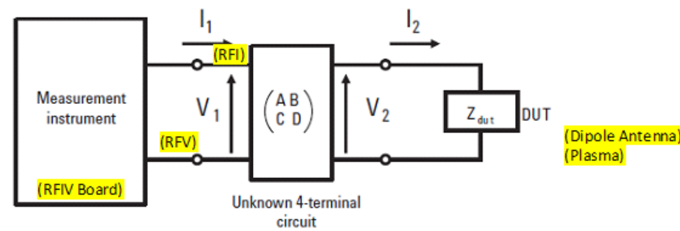
United States Coast Guard Academy

CUBESAT

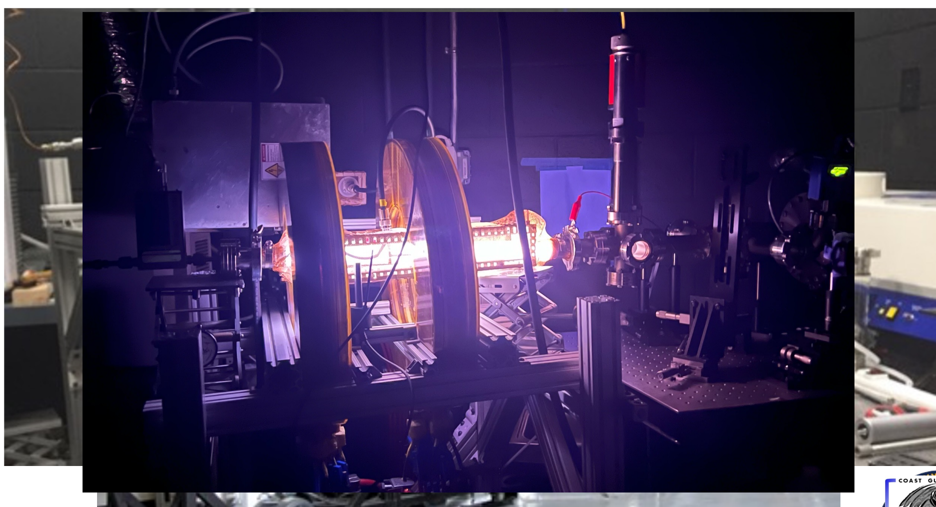
Impedance Probe (IP) – Test Plan

IP Verification w/ Measured Components

- RF transformers pick off the RFV & RFI in the circuit & route to mixers
- Onboard local oscillator (LO) and direct digital synthesizer (DDS) generates the RF signal and phase offset
- Mixer chip combines LO with the RFV or RFI signal
- Microcontroller sets a new frequency and process is repeated
- Generates the complex uncalibrated impedance spectrum



IP - Four terminal circuit used in calibration

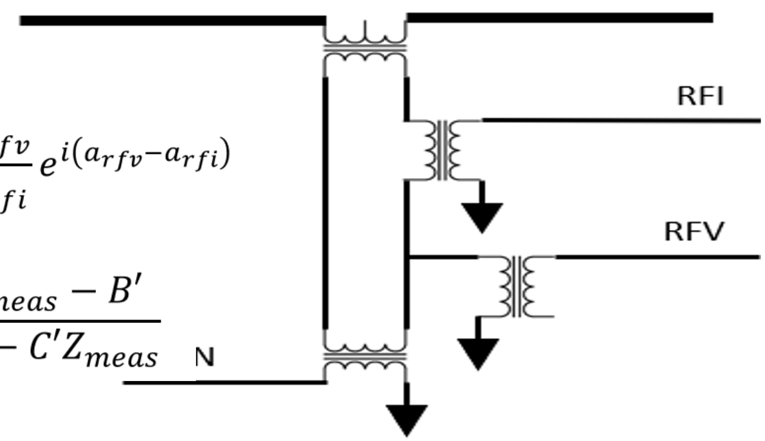


NRL Plasma Chamber

CGAPL Helicon Plasma Experiment

$$Z = \frac{RFV}{RFI} = \frac{A_{rfv}}{A_{rfi}} e^{i(a_{rfv} - a_{rfi})}$$

$$Z_{DUT} = \frac{Z_{meas} - B'}{A' - C' Z_{meas}}$$

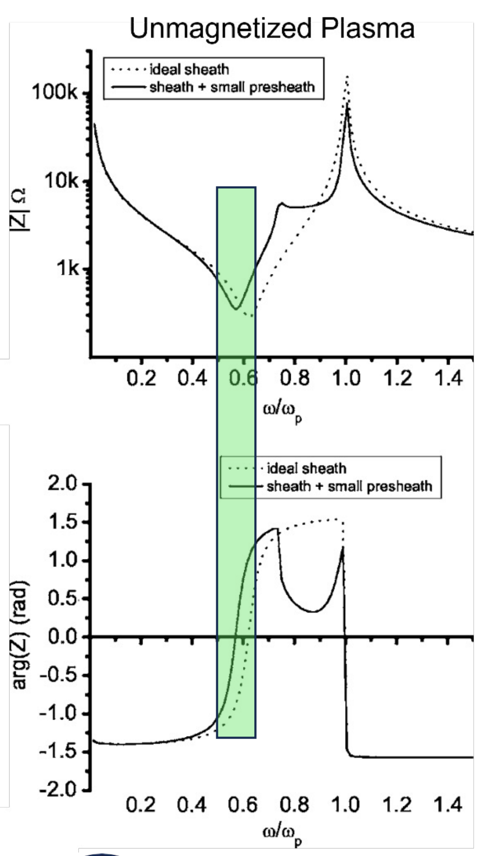


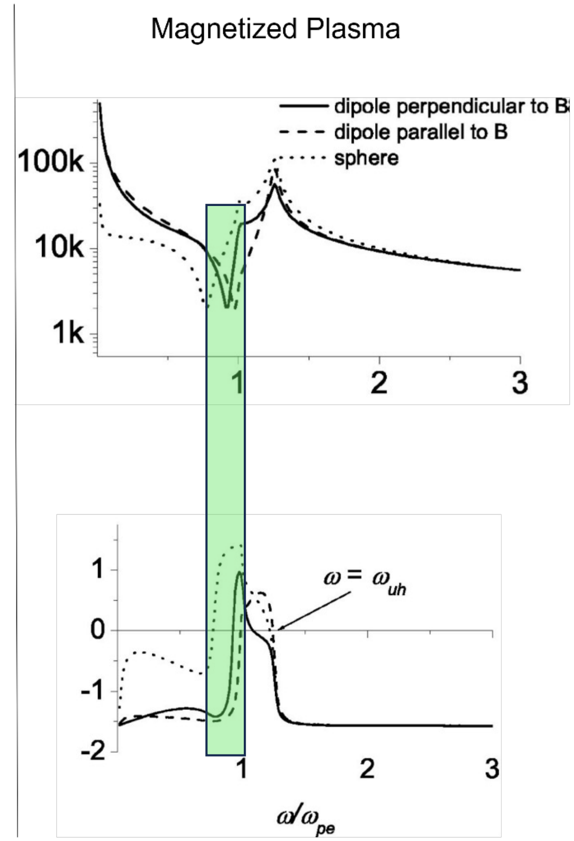
RF-IV antenna schematic

Blackwell Demonstrated Impedance Standards

- $\omega_1 = \omega_{pe}\sqrt{\frac{C_0}{C_{sh}+C_0}}$
  - Power Deposition at Maximum
  - Found below the plasma frequency (frequency of plasma sheath)

- $\omega_2 = \omega_{pe}$
  - Power deposition at minimum
  - Determines Plasma Frequency





LEFT: Total impedance and phase vs frequency in an unmagnetized plasma (Blackwell et al. 2005).

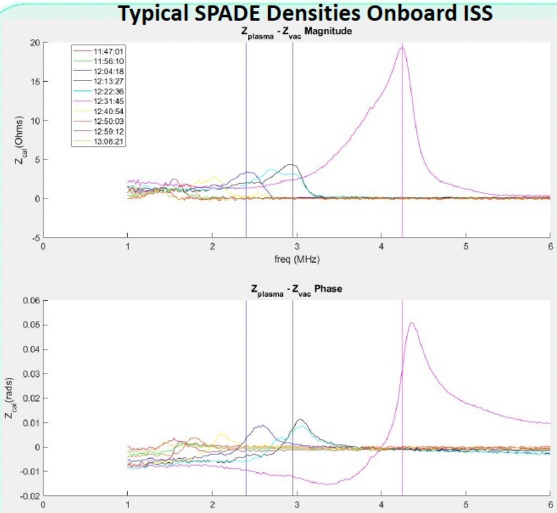
RIGHT: Magnetized plasma (Blackwell et al. 2007).

Impedance Probe (IP)

Used to monitor background space plasma condition to provide early warning of hazardous levels of spacecraft charging which affect spacecraft health and communication system performance

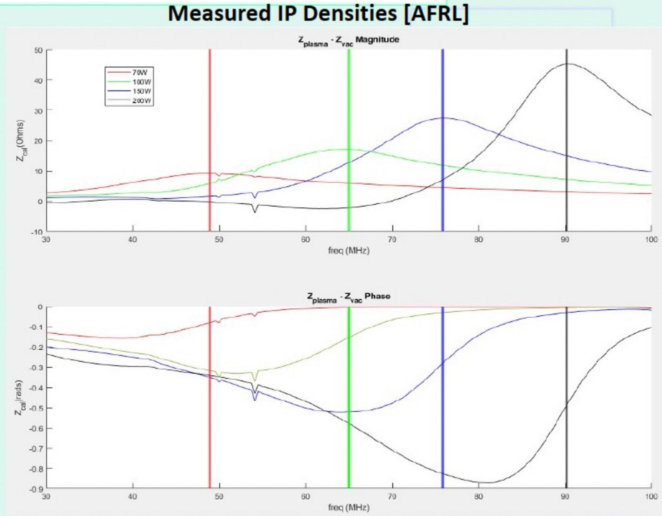
Improves our understanding of "space weather"

Typical SPADE Densities Onboard ISS



Calibrated magnitude & phase of plasma-SPADE impedance measured from the ISS on 15 September 2020. Time is in UTC and represents a roughly 90-minute period or one ISS orbit.

Measured IP Densities [AFRL]

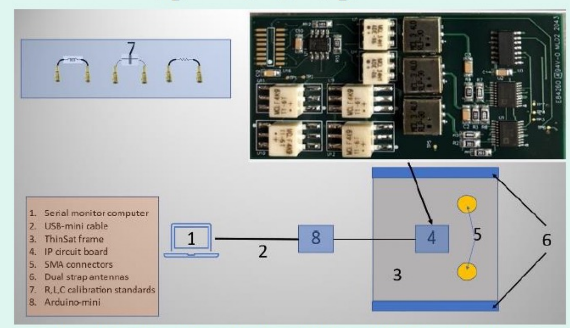


Magnitude and phase of antenna-plasma impedance after calibration with several different RF powers. Chamber pressure at 7.5 mTorr with increasing RF power, parallel resonant frequency increases.

$$Z^{+}(\beta, T) = \frac{T^2}{2\beta}\left[1 - \frac{\xi}{3}\left(1 - \frac{12S(\beta)}{\beta^3}\right)\right]\frac{(\upsilon_{e0} + \upsilon_e)}{4\pi\varepsilon_0\rho^2}$$

$$Z = \frac{RFV}{RFI} = \frac{A_{rfv}}{A_{rfi}} e^{i(a_{rfv} - a_{rfi})} \qquad Z_{DUT} = \frac{Z_{meas} - B'}{A' - C'Z_{meas}}$$

$$\begin{pmatrix} V_1 \\ I_1 \end{pmatrix} = \begin{pmatrix} A & B \\ C & D \end{pmatrix}\begin{pmatrix} V_2 \\ I_2 \end{pmatrix}$$



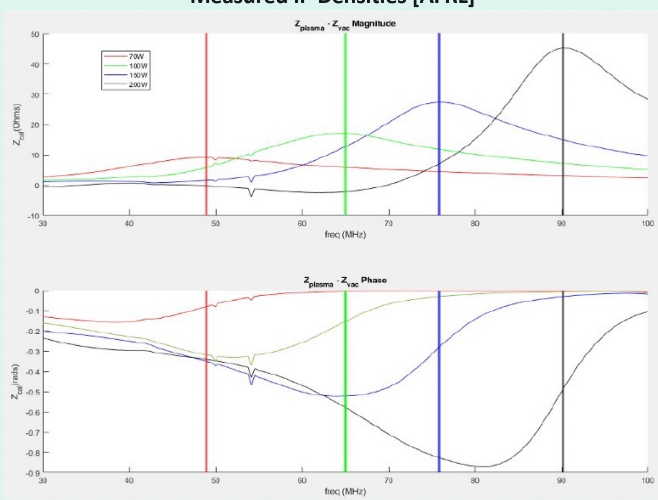
Onboard local oscillator (LO) and direct digital synthesizer (DDS) generates the RF signal and phase offset

Impedance Probe (IP)

Used to monitor background space plasma condition to provide early warning of hazardous levels of spacecraft charging which affect spacecraft health and communication system performance

Improves our understanding of "space weather"

Measured IP Densities [AFRL]

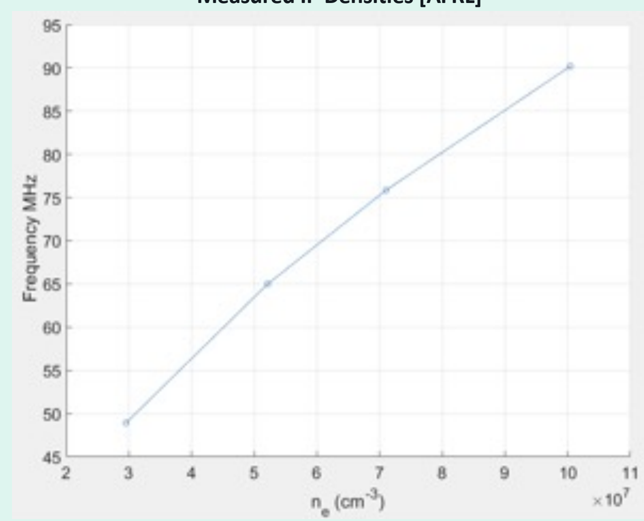


Magnitude and phase of antenna-plasma impedance after calibration with several different RF powers. Chamber pressure at 7.5 mTorr with increasing RF power, parallel resonant frequency increases.

$$\omega_{pe} = \left(\frac{n_e e^2}{\epsilon_0 m}\right)^{1/2}$$

$$\frac{\omega_{pe}}{2\pi} = f_p \approx 9\sqrt{n_e}$$

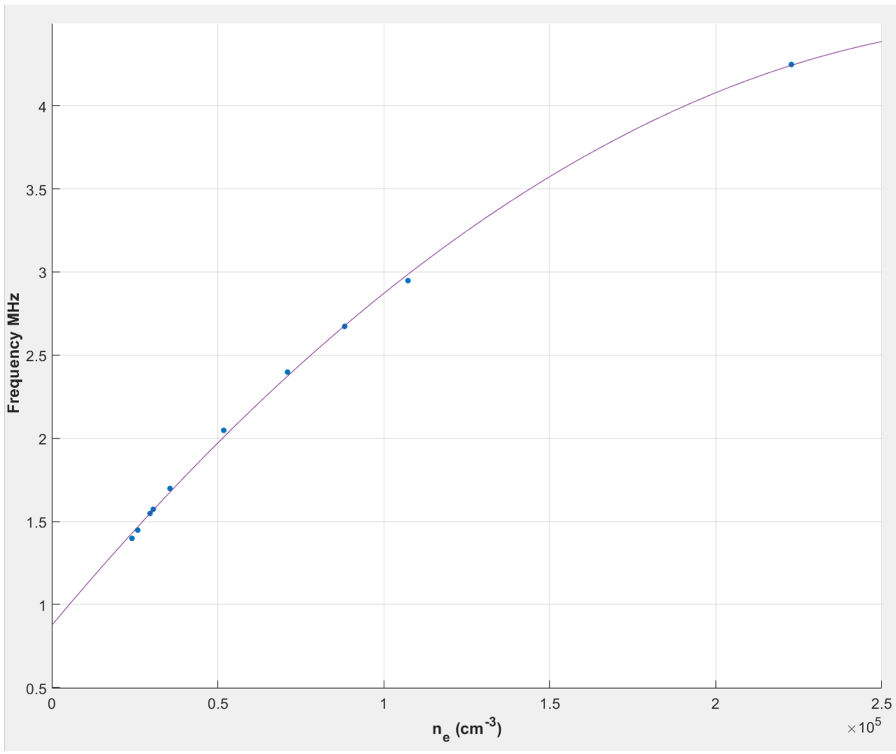
Measured IP Densities [AFRL]



Impedance Probe Density Measurements from associated matched frequencies.

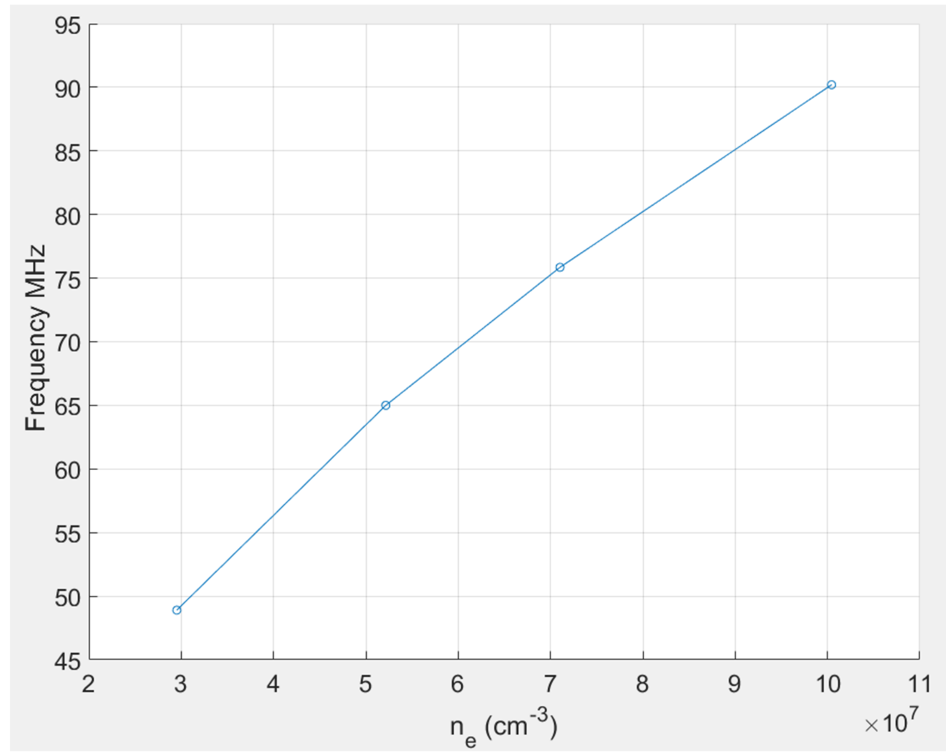
IP Comparison Tests – Contd...

Typical SPADE Densities Onboard ISS



SPADE Electron density measured from plasma frequency impedance measurements.

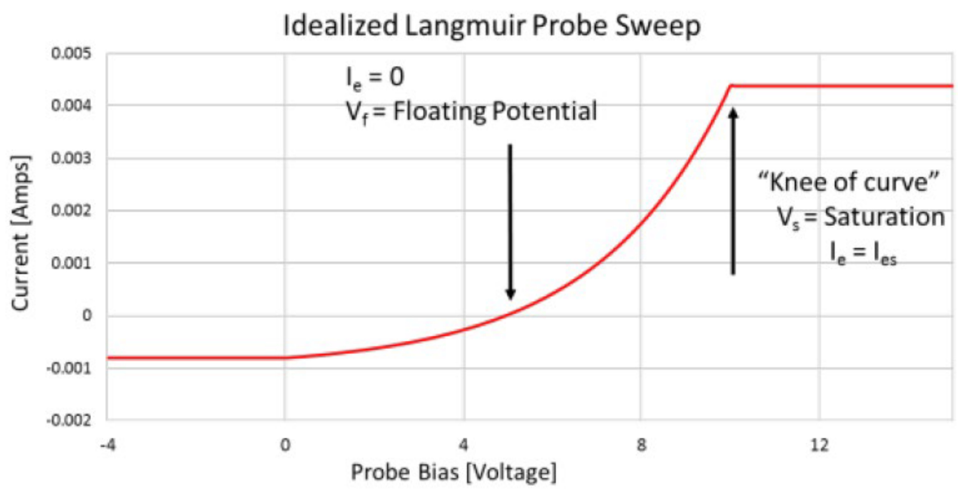
Measure IP Densities [AFRL]



Electron density obtained from plasma frequency impedance measurements

IP also Measures Plasma Temp

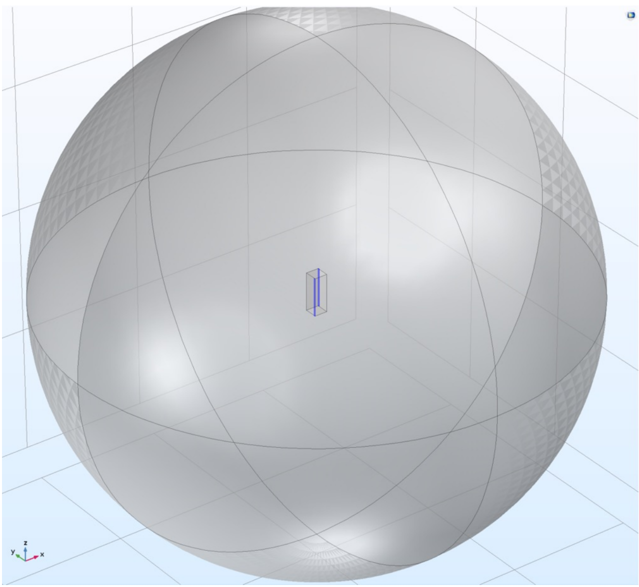
- Add a DC bias
  - Applied bias affects sheath thickness s(ϕ)
- Sweep bias from negative to positive
- Solve for temperature [T]



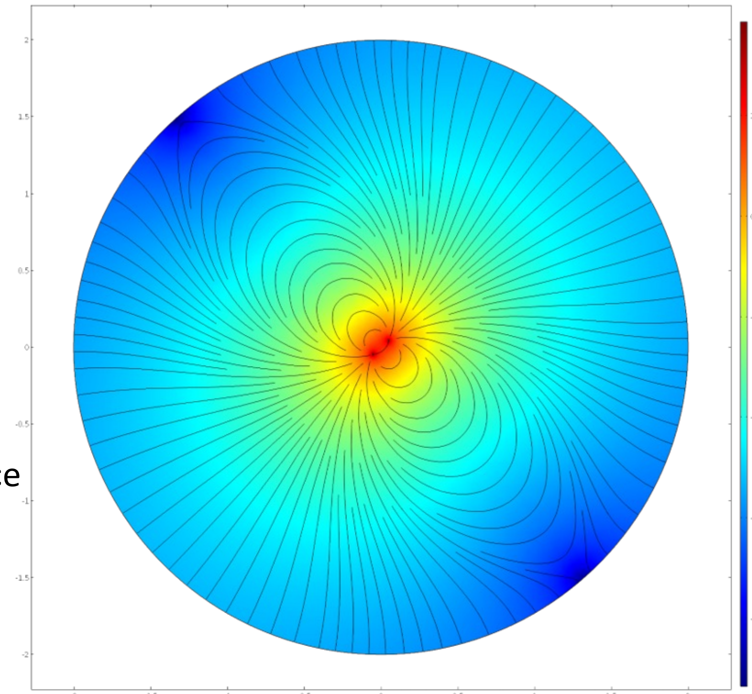
$$s(\phi) = \left(2.5 - 1.87e^{\left(-0.39\frac{\rho}{\lambda_d}\right)}\right)\left(\frac{e\phi}{kT_e}\right)^{2/5}\lambda_d$$

$$I_{es} = en_eA\left(\frac{KT_e}{2\pi m}\right)^{1/2} \;\&\; I_e = I_{es}\exp\left[\frac{e(V_p - V_s)}{KT_e}\right]$$

NRL Chamber Simulations Characterize Chamber Capacitance



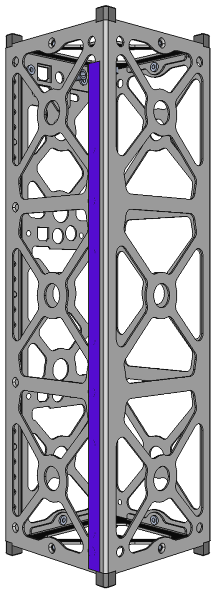
Dipole free space capacitance
$C_0 = 2.58\,pF$

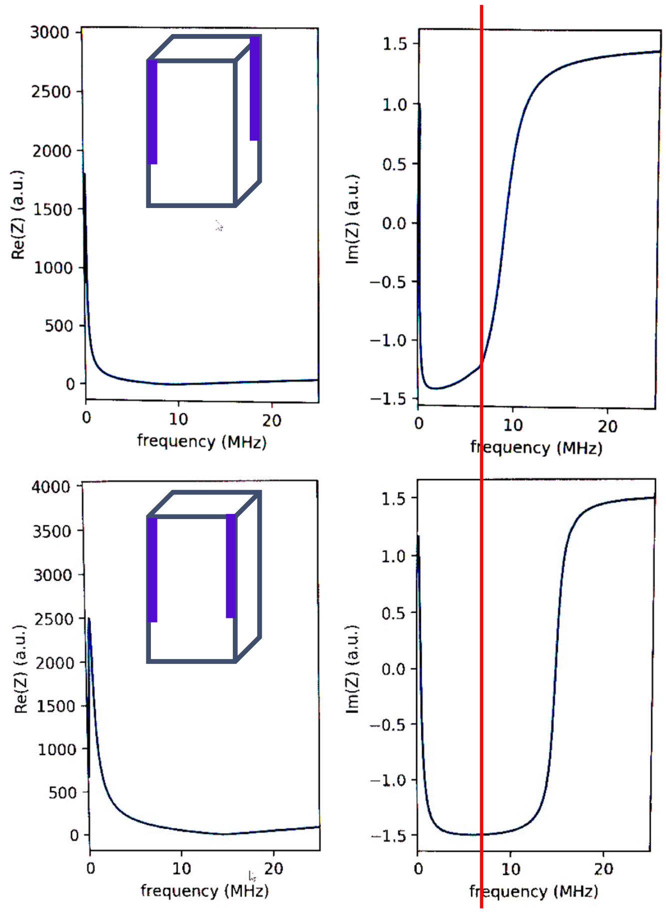


Simulation of spherical plasma filled chamber with volume matching the NRL plasma chamber, surrounding the dipole antenna

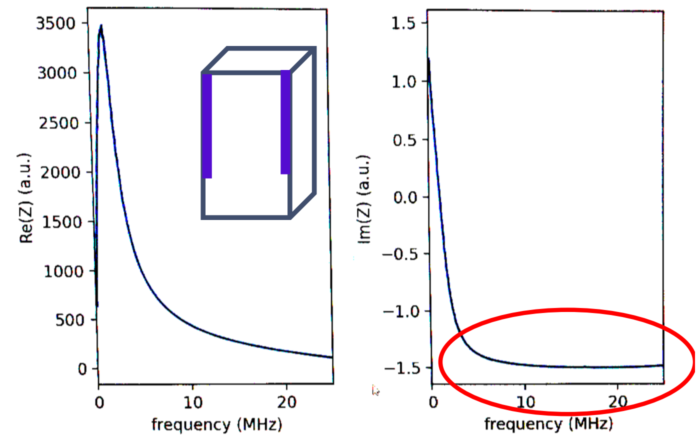
Simulation of electric field in a homogenous plasma surrounding our dipole antenna - length runs along the viewing axis

IP Development: NRL Plasma Chamber - Antenna Confirmed





Antenna Test 3 - with Kapton tape insulation between frame & Antenna



Capacitive loading highly reduced - a lab affect de-emphasized in space.

Test	Suspense
• IP PCB Delivery	- 03 MAY
• Chamber tests underway	- 22 MAY
• SeaLion Environmentals	- 25 JUN

Questions & Discussion

Backup Slides

Near-term Funding Required for 19 SEP 2024 *SeaLion* launch

Long-lead supplier items (batteries, solar cells, SDR) are putting **at risk the Aug '24 launch** date

One-time opportunity for CGA CubeSat launch at no cost (~250k typical launch cost)

Launches as a "rideshare" or secondary payload accept whatever altitude and inclination that the primary payload has – this polar orbit is ideal to demo CG-relevant technology in critical Arctic AOR

$30k for system upgrades necessitated by change in orbits

- Original launch was planned for Northrup Grumman Antares rocket from Wallops, VA
  - 185 km altitude
  - 51.5 deg inclination
  - short duration mission of ~4-8 days
- *New launch aboard Firefly from Vandenburg, CA*
  - 550 km altitude
  - 97.6 deg inclination (near-polar, sun synchronous)
  - Long duration mission of ~1 year
- Upgraded electrical power system (rechargeable batteries)
- Upgraded communication system
  - Demonstrate SAR localization in Arctic

Optional $280k for second vehicle

- Added redundancy
- *Demonstrate comm relay in UHF/VHF for CG patrolling aircraft and surface units in Arctic*, beyond line-of-sight of comm stations