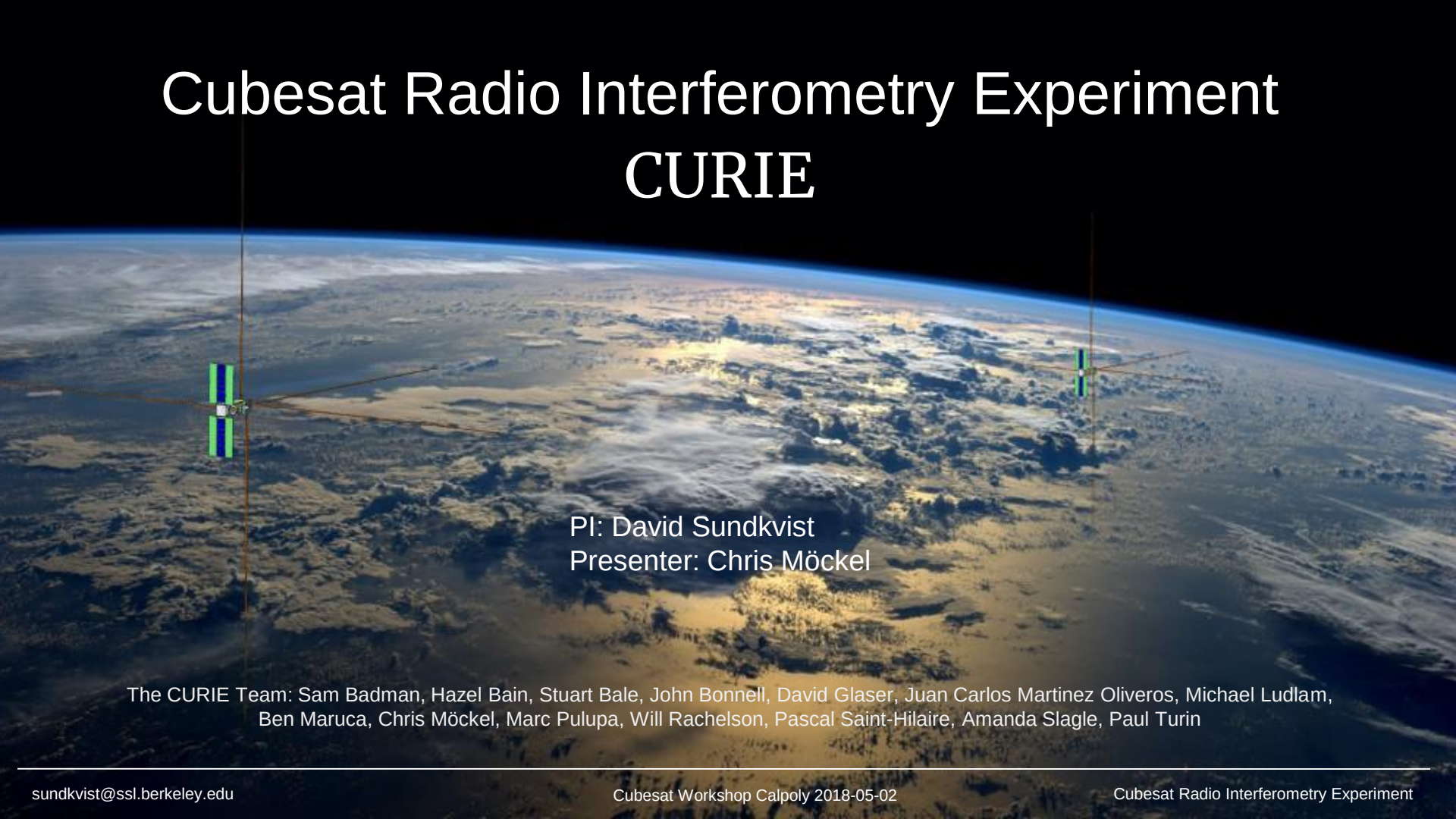
Cubesat Radio Interferometry Experiment
CURIE



PI: David Sundkvist
Presenter: Chris Möckel

The CURIE Team: Sam Badman, Hazel Bain, Stuart Bale, John Bonnell, David Glaser, Juan Carlos Martinez Oliveros, Michael Ludlam, Ben Maruca, Chris Möckel, Marc Pulupa, Will Rachelson, Pascal Saint-Hilaire, Amanda Slagle, Paul Turin

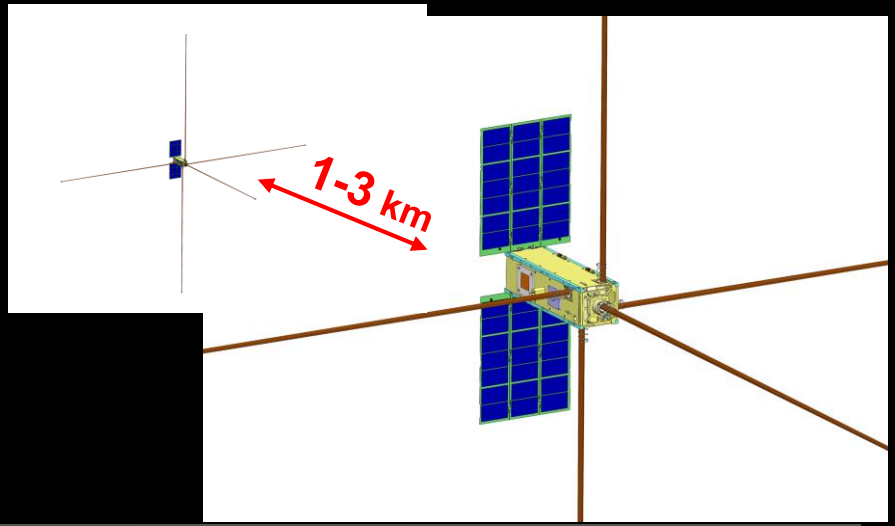
Key Points of the CURIE Mission

CUbesat **R**adio **I**nterferometry **E**xperiment - CURIE

- First path-finder mission for future low frequency interferometer observatory in space.
  - Low frequency observations (0.1 - 40 MHz).
  - Two Cubesats flying in formation in Low Earth Orbit, with a few km separation.

- Built and operated from Space Sciences Laboratory (SSL) / UC Berkeley.
  - Scientists, engineers, students.
  - Student participation at all stages of the mission.

- Funded by NASA (4 year program).
  - Heliophysics Technology and Instrument Development for Science (HTIDS/LCAS).

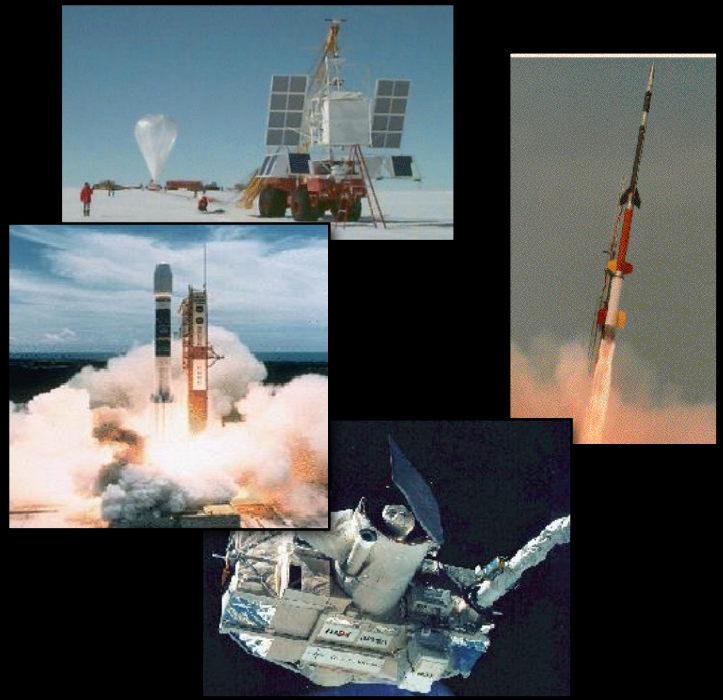


SPACE SCIENCES LABORATORY (SSL)
(UC Berkeley Organized Research Unit)

Background
- Initiated in 1958 by Struve, Teller and Seaborg
- Multi-disciplinary laboratory
- Space and suborbital research and ***training***
- Facility opened in 1966 (NASA CoE)
- New facilities added in 1998

Research Efforts Involving
- Balloons (GRIPS, NCT, etc)
- Sounding rockets (FOXSI, GREECE, TRICE-2)
- Cubesats (CINEMA, CURIE)
- Satellite instruments & science complements
- Complete satellites & multi-satellite missions
- Mission & Science Operations
- Education and Public Outreach

Agencies Involved
- NASA, NSF, NSBF, USAF, DOE, MBRSC
- ESA, JAXA, IKI, KARI, PSI, etc.
- $80-90M/yr (>90% NASA, <10% other.)



Long list of missions...

Some Previous Flight Systems
CHIPS (UNEX)
EUVE
FAST (SMEX)
Polar EFI
Image FUV, WIC,
Mars Global Surveyor ER
Lunar Prospector ER
ROCSAT 2 – ISUAL
Ulysses LAN, HUR
FUSE
KITSAT SPEAR

Operational Flight Systems
THEMIS (MIDEX)
RHESSI (SMEX)
Wind 3DP
Cluster II EFW, CIS
SOHO UVCS & SUMER
STEREO – IMPACT, S/WAVES
HUBBLE – COS
NuSTAR
RBSP EFW
MAVEN Particles and Fields Suite (2013)

Under Development
Solar Probe Plus (2018)
ICON (2017) and GOLD, Litebird MoO Phase A
Balloons and rockets and Cubesats (CURIE)

SSL Facilities

- Research & Design
  - ~400 Scientists (4 Nobelists), Engineers, Students, Staff
  - 55000 sq. ft. Office and Laboratory Space
- Machining & Production
  - On-site Machine shop
- Integration
  - Clean Room Facilities to Class 100
  - 4-story High Bay
- Testing facilities
  - Vibration table
  - Thermal Vacuum Facilities up to 3m diameter
  - Radiation Sources Laboratory
- Operation
  - Mission Operations Center
  - Science Operations Centers
  - 11 Meter S-Band / UHF Satellite Antenna
  - Secure Communications to NASA

Berkeley Ground Station

Office and Lab Space

THEMIS in SSL cleanroom

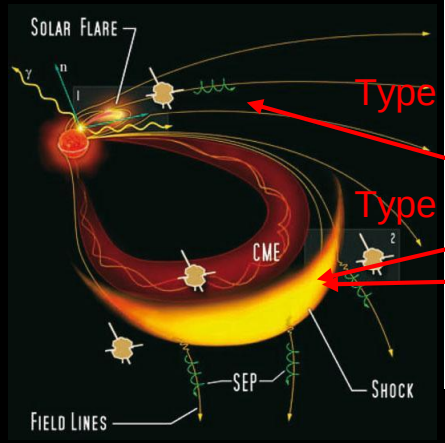
Missions Operations Center

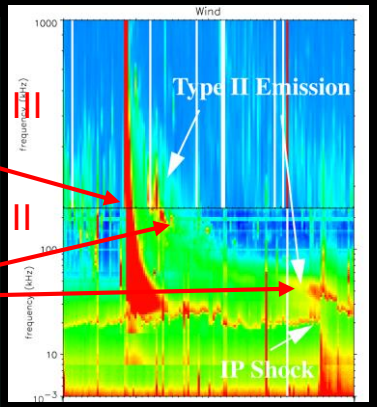
Science Objectives Overview

- (Primary)
  Radio interferometric observations of radio burst emissions from solar eruptive events.
  - Coronal mass ejections/shocks - Type II radio bursts.
  - Flares - Type III radio bursts.

- (Secondary)
  Ionospheric measurements (*in-situ*) of electron density and temperature.
  - Density gradients on the scale of a few km (spacecraft distance, 400-1100 km orbit).

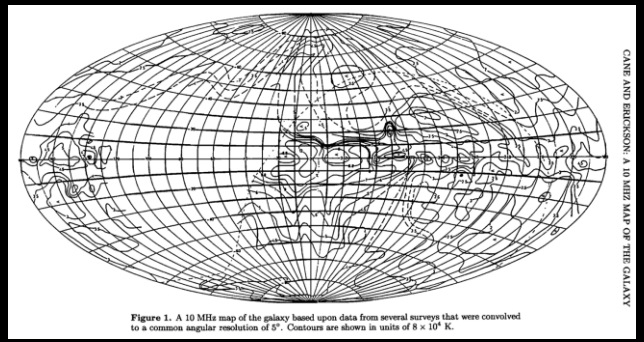
  Synthesis imaging
  - Create a map of the radio sky at frequencies below the ionospheric cut-off.

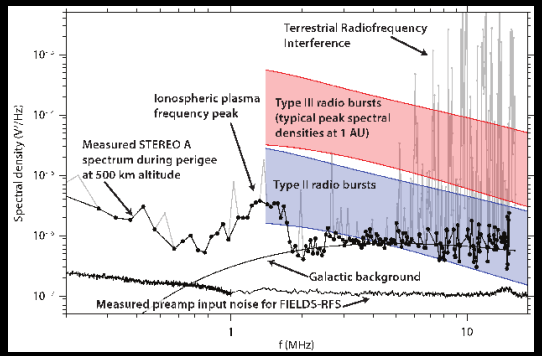


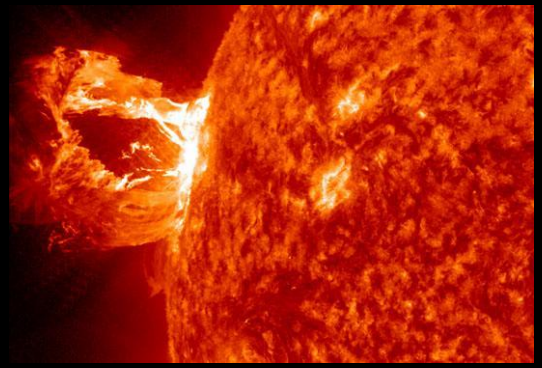


$$f_{pe}\,[kHz] \approx 9\sqrt{n_e\,[cm^{-3}]}$$

All science objectives addressed using the same data set.

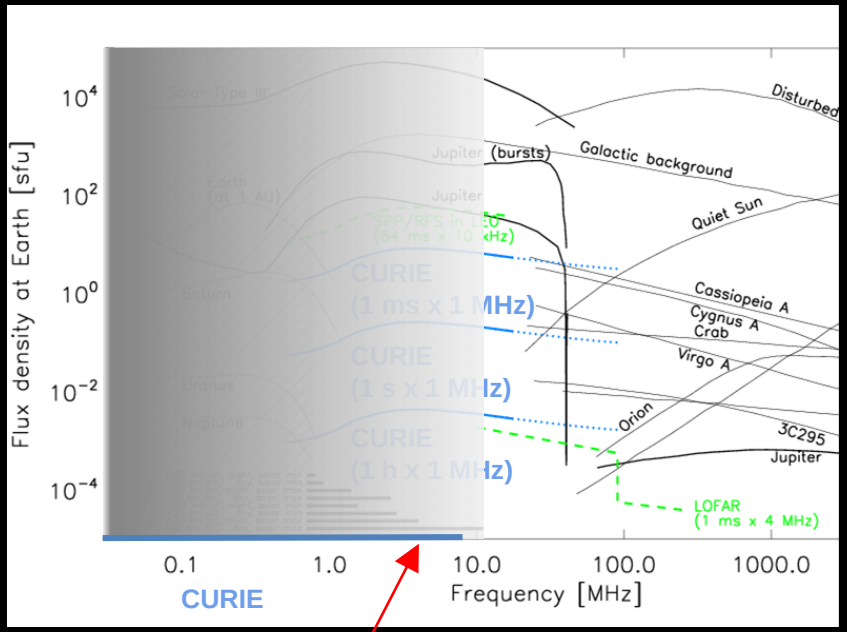






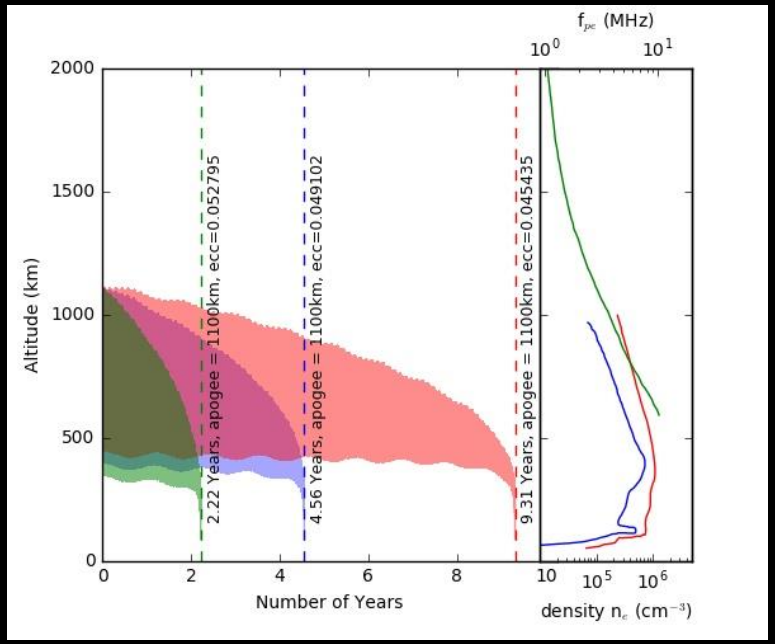
Radio Sources

- Lowest frequencies cut-off by the ionosphere.
  -> Need space based measurements.
- CURIE's primary frequency range: 0.1-40 MHz.



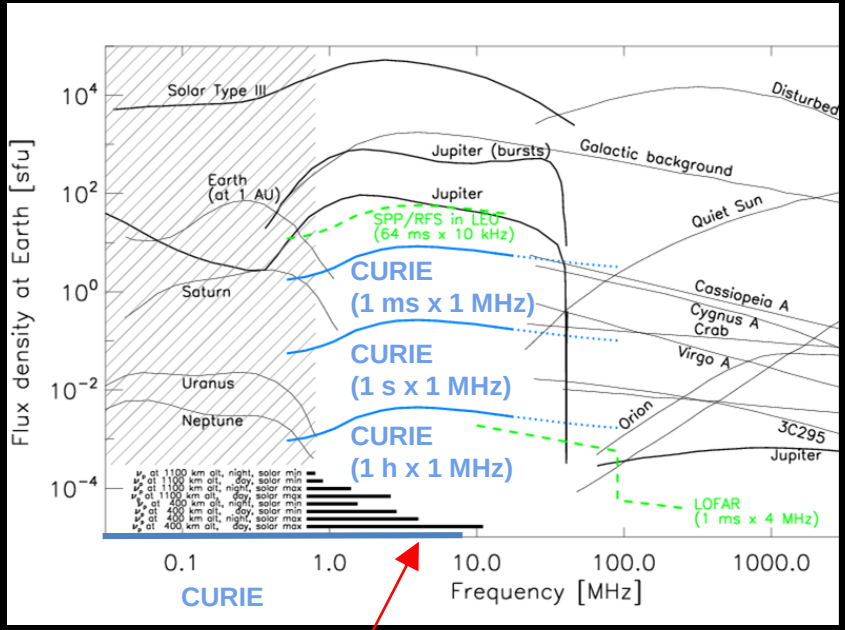
Ionospheric cut-off frequency $f_{pe}\,[kHz] \approx 9\sqrt{n_e\,[cm^{-3}]}$

- Low Earth Elliptical Orbit, compromise between
  - Science (high apogee)
  - Operations



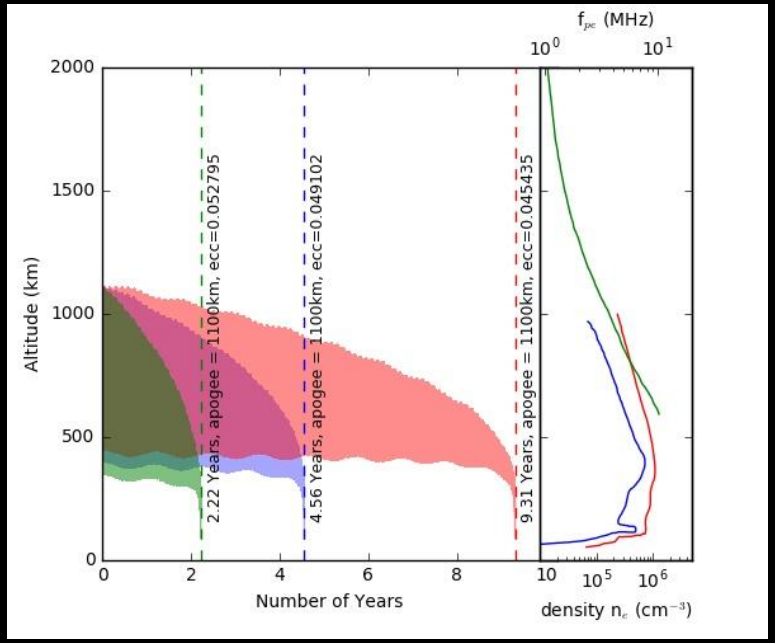
Radio Sources

- Lowest frequencies cut-off by the ionosphere.
  -> Need space based measurements.
- CURIE's primary frequency range: 0.1-40 MHz.

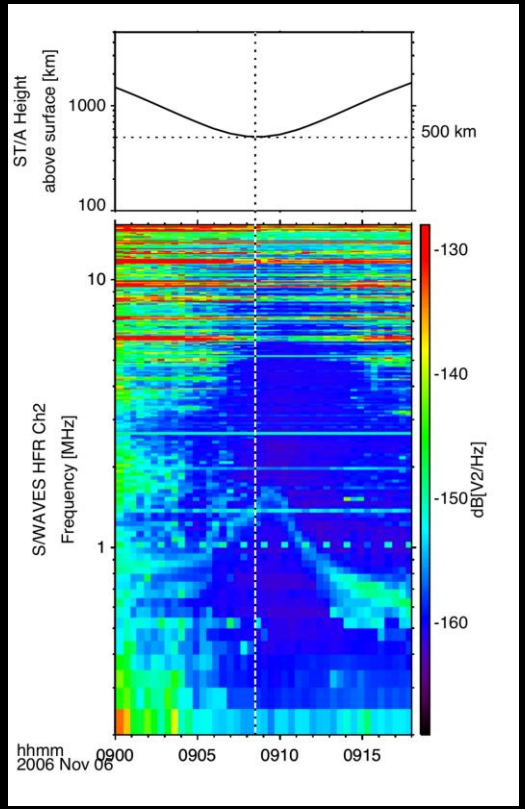


Ionospheric cut-off frequency $f_{pe}\,[kHz] \approx 9\sqrt{n_e\,[cm^{-3}]}$

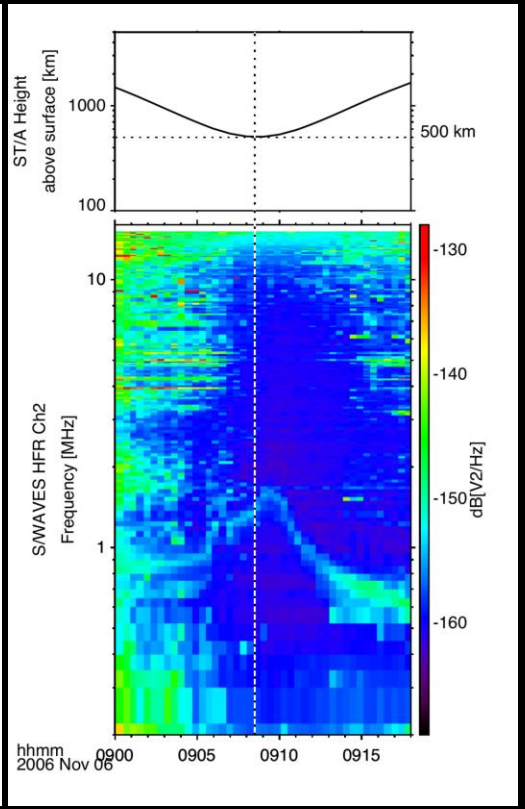
- Low Earth Elliptical Orbit, compromise between
  - Science (high apogee)
  - Operations



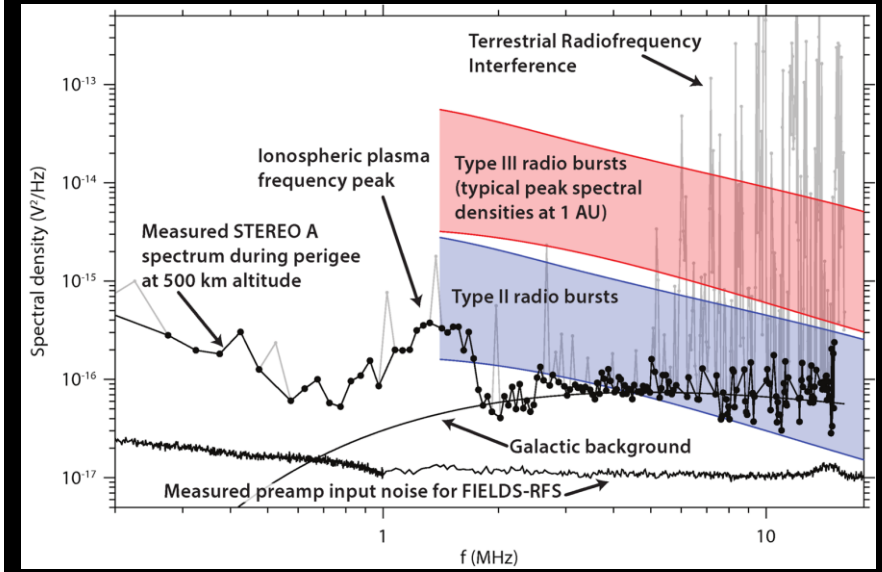
Radio Interference in LEO (STEREO Measurements)



STEREO-A



STEREO-A (RFI masked)

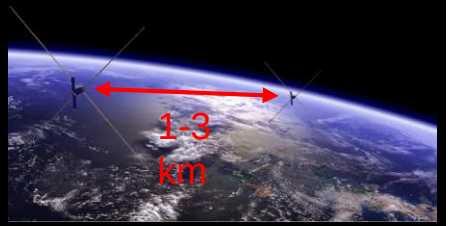


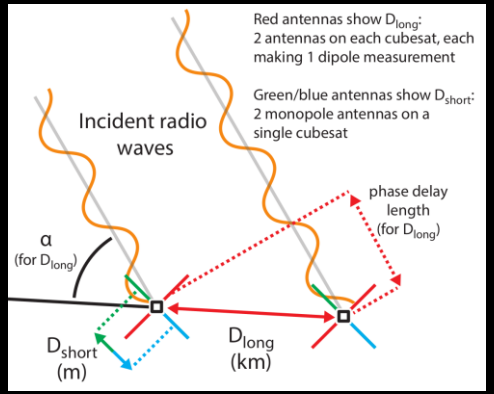
Spectral resolution

STEREO:	25 kHz
PSP/FIELDS:	9 kHz
CURIE:	1 kHz

Interferometry

- Two-element interferometer makes possible:
  - Interferometric direction finding
    - 2–3 arcmin or better, depending on projected baseline (spacecraft separation vector) and SNR.
  - Source size determination (Gaussian)
    - CURIE can sample the ~ 30 arcmin (at 10 MHz) angular source size typical of solar Type II and Type III bursts at 1 AU.
  - Imaging of static radio sources

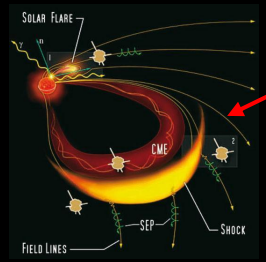


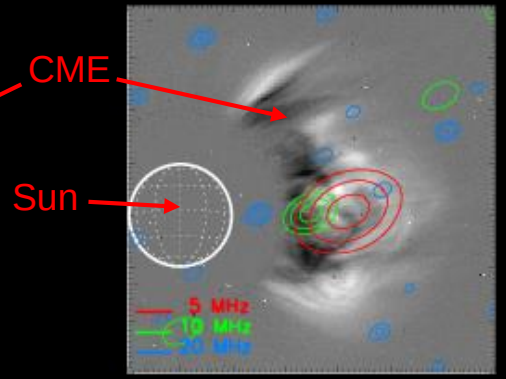


- Basic observables: correlated amplitude and relative phase (spatial coherence function)

$$\mathcal{V}_{ij}(\omega) = \frac{< V_i V_j^* >}{\sqrt{< V_i V_i^* >}\sqrt{< V_j V_j^* >}} = \frac{e^{i\mathbf{k}\cdot(\mathbf{x}_i - \mathbf{x}_j)}}{\sqrt{1+(n_i/V_0)^2}\sqrt{1+(n_j/V_0)^2}} = \gamma(\omega)^2 e^{i\Delta\theta(\omega)}$$

$$\Delta\theta(\omega) = \mathbf{k}\cdot(\mathbf{x}_j - \mathbf{x}_i) = \frac{2\pi}{\lambda}|\mathbf{x}_j - \mathbf{x}_i|\cos\alpha_{ij}$$



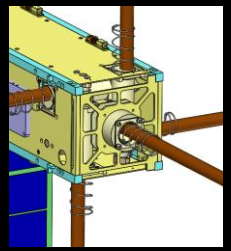


- Four or more CURIE Cubesats would allow snapshot imaging of transient events.

CURIE Instrument Heritage

Parker Solar Probe

- Launch in July 2018 (recommended by NASA/NRC for 30 years)
- NASA Heliophysics ‘Living with a Star’ Mission
- Perihelion at 9.8 solar radii
- Primarily *in situ* instruments



- The CURIE instrument is derivative of the PSP/FIELDS radio frequency spectrometer (currently TRL 7, soon TRL 8).
- CURIE is using deployable stacer antennas previously built by SSL and used on STEREO, THEMIS, POLAR and FAST.

536 S.D. Bale et al.

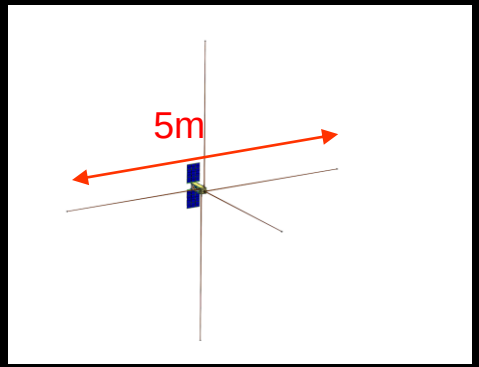
Fig. 6 Beryllium copper stacer antenna element. The aspect ratio is exaggerated here for display purposes

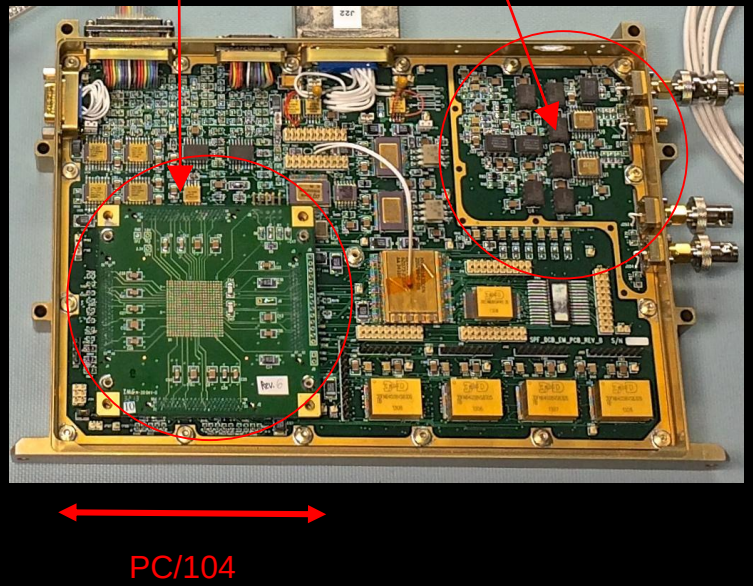
Instrument Heritage and Development

CURIE-RFS is a digital radio spectrometer based on PSP/FIELDS:

Leverages heritage / development.

- Improved absolute **time** to few ns
  - chip-scale atomic clock.
- Improved **frequency** resolution (1 kHz)
  - Redesign of the PSP/FIELDS instrument
- Added frequency channel
  - Antennas in three dimensions allows polarization measurements.





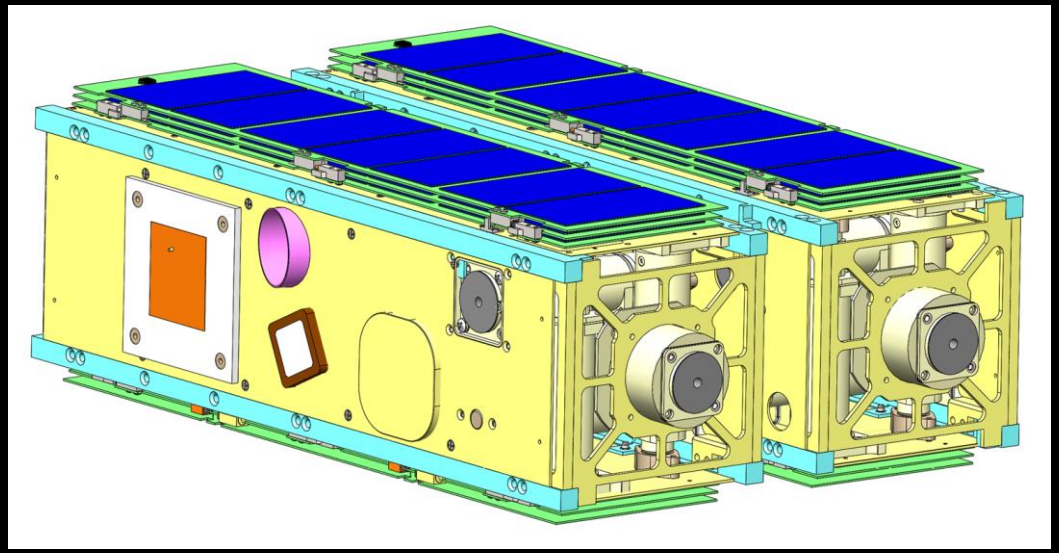
Spacecraft design

Main stack

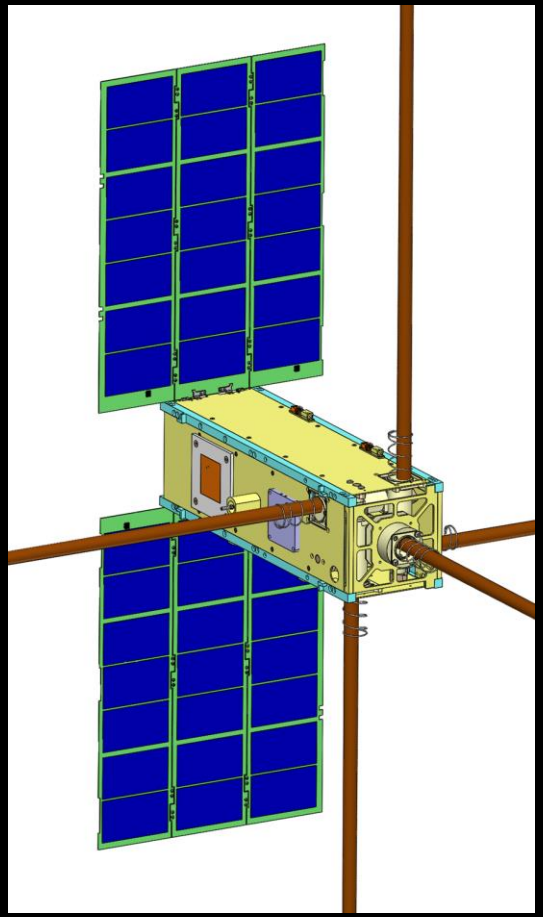
- OBC
- S-band transmitter
- Globalstar modem
- UHF transceiver
- GPS
- Star Tracker
- Thruster
- EPS

Instrument

- Stacer antennas
- Preamplifiers
- Analog Interface Board
- Digital Interface Board
- Atomic Clock Board
- GPS

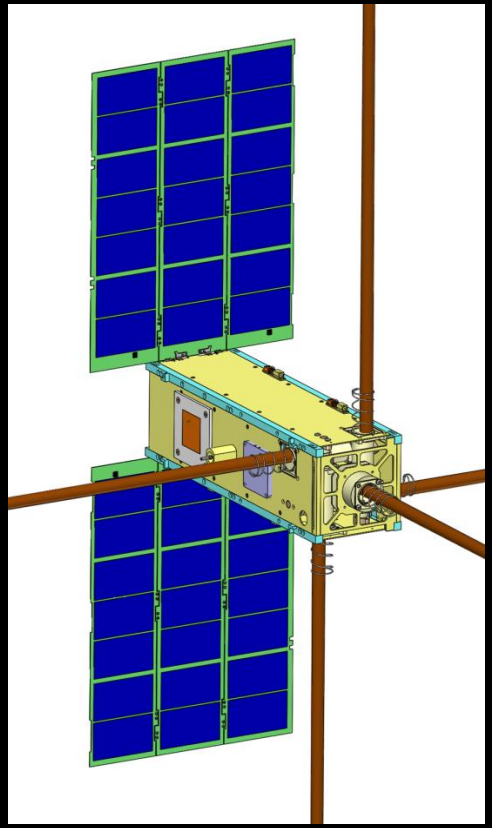


CURIE will launch as a 6U and separate into two 3U Cubesats once in orbit.

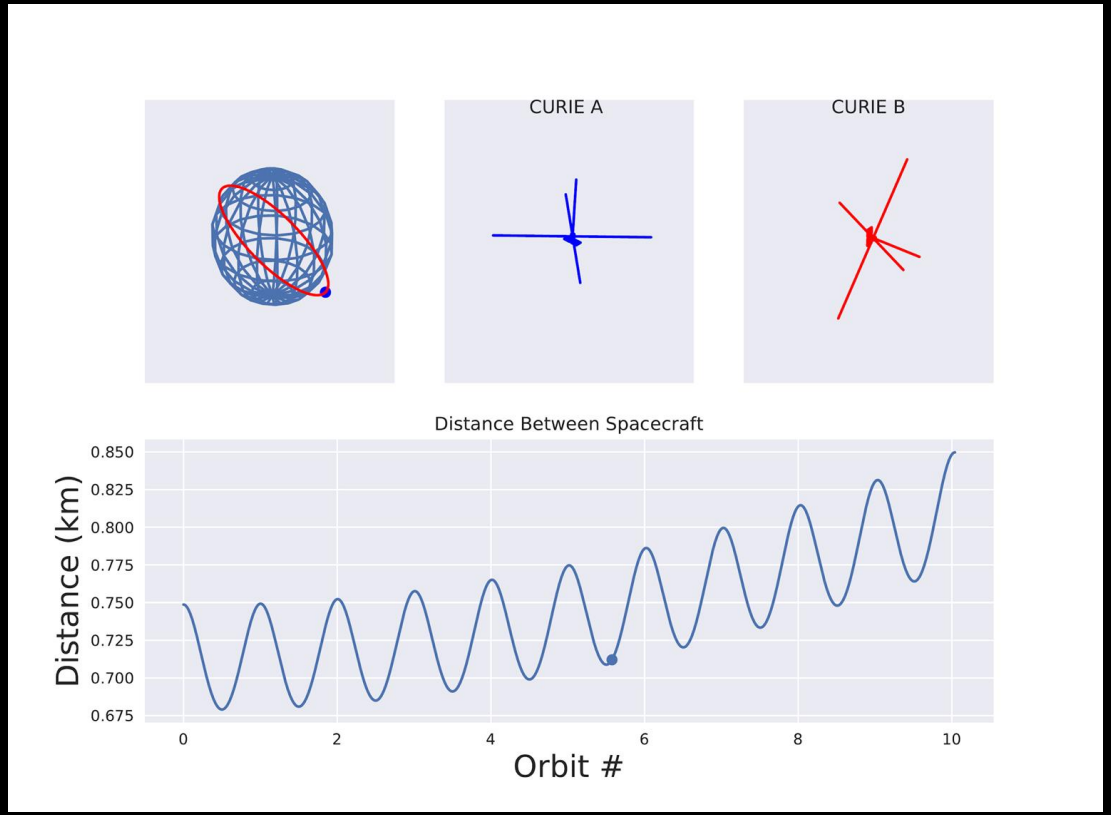


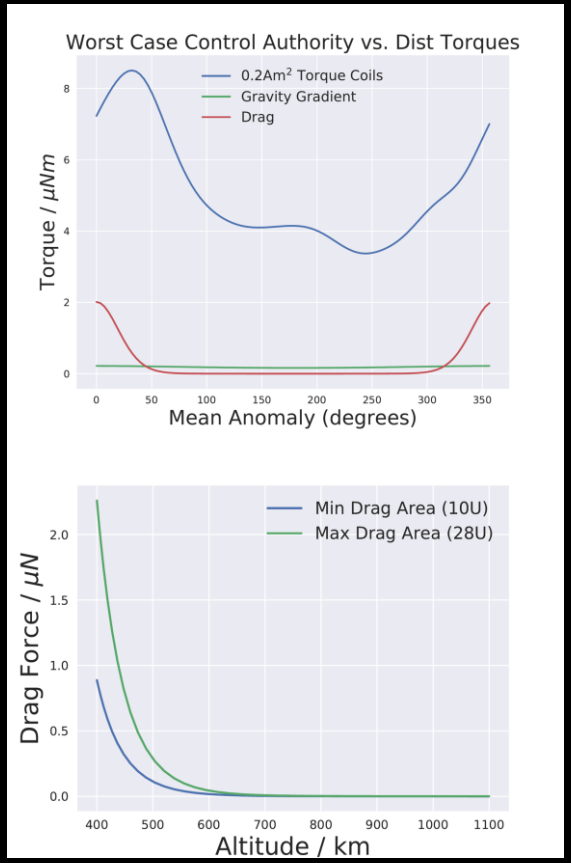
ADCS / Orbit

- Three axis stabilized
- Attitude and position knowledge:
  - Star tracker
  - Magnetometer
  - GPS
  - Photo diodes
- Attitude control:
  - Torque coils
  - Reaction wheel (z-axis)
  - Cold gas thruster (z-axis)
- Orbit control:
  - 400 - 1100 km, inclination 27° - 45° (ideal)
  - Spacecraft separation: 1 - 3 km (science dictates knowledge more important than exact control)
  - In-house developed combined attitude controller / orbit propagator
  - Separation control using both thruster and differential drag.
  - Drag important around perigee.



Drag Simulation



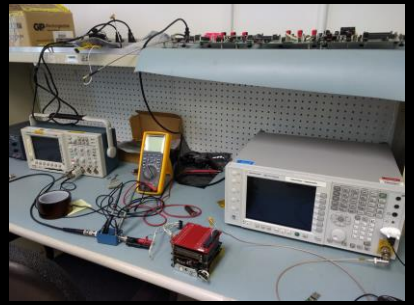


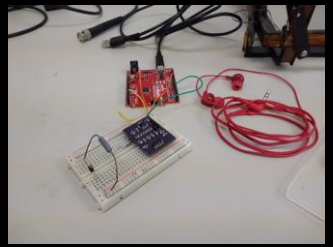
Simulation: attitude stabilized with a pointing controller using a z-axis reaction wheel and torque coils. Different orientation leads to differential drag, increasing separation.

Hardware Development Status

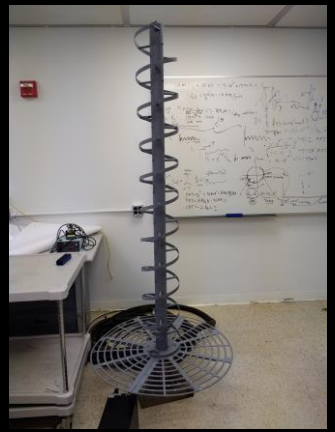
In-house development status

- Instrument
  - Preamplifiers (built)
  - Analog Interface Board (layout)
  - Digital Interface Board (layout)
  - Stacer Antennas (preparing order)
  - EMC/EMI noise environment testing (bench testing)
- Solar Panels
  - Mechanical/Electrical Design (rev A done).
  - Hinges / PCB (fabrication).
- Bus
  - Mechanical design (done, not fabricated)
  - 6U attachment and separation mechanism design (done, not fabricated)
- Torque rods
  - Testing core materials
- Magnetometer (magnetoresistive)
  - Bench testing





- Comms Antennas
  - S-band patch (simulated,built, testing)
- Dedicated Cubesat Groundstation (separate from SSL/BSG/MOC
  - Antennas (field testing)



Cubesat Radio Interferometry Experiment - CURIE

- First path-finder mission for future low frequency interferometer observatory in space.
  - Low frequency observations (0.1 - 40 MHz).
  - Two Cubesats flying in formation in Low Earth Orbit, with a few km separation.
- Built and operated from Space Sciences Laboratory (SSL) / UC Berkeley.
- Funded by NASA (4 year program).
  - Heliophysics Technology and Instrument Development for Science (HTIDS/LCAS).
- The future
  - Larger array (more Cubesats): Imaging of transient events
  - Dark side of the moon to observe early Universe (redshifted H, He), epoch of re-ionization.