NEROC Panel on Radio Science in Space

MIT Haystack Observatory

Mike Hecht
MIT Haystack Observatory

NEROC in Space

Why is space important for NEROC?

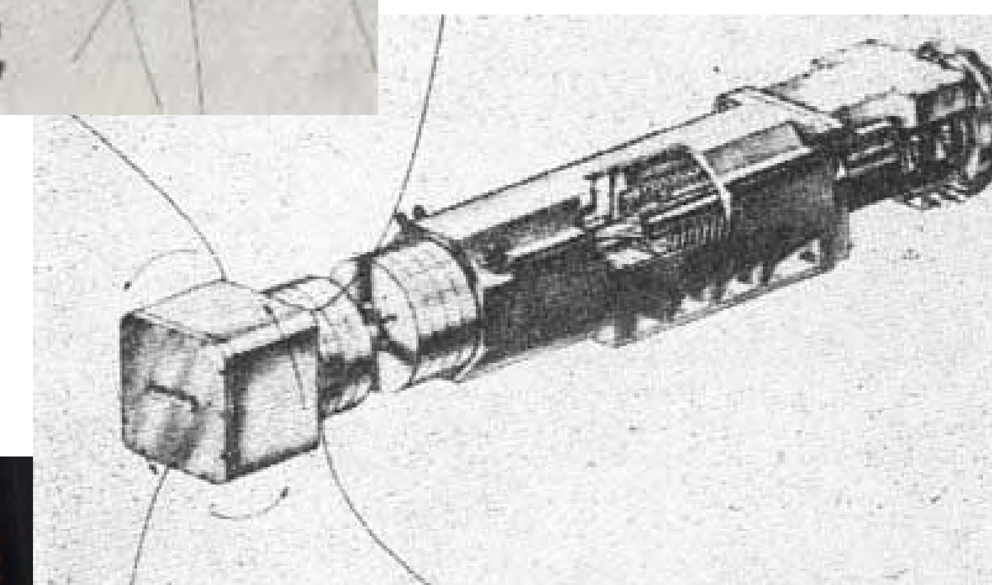
- Compelling science, relevant to our expertise, e.g.
  - Low frequency science not possible below the ionosphere
  - Longer VLBI baselines than possible on Earth
  - Planetary mission applications
- Growing opportunities within NASA for university-scale missions
- Radio bands on Earth are increasingly polluted

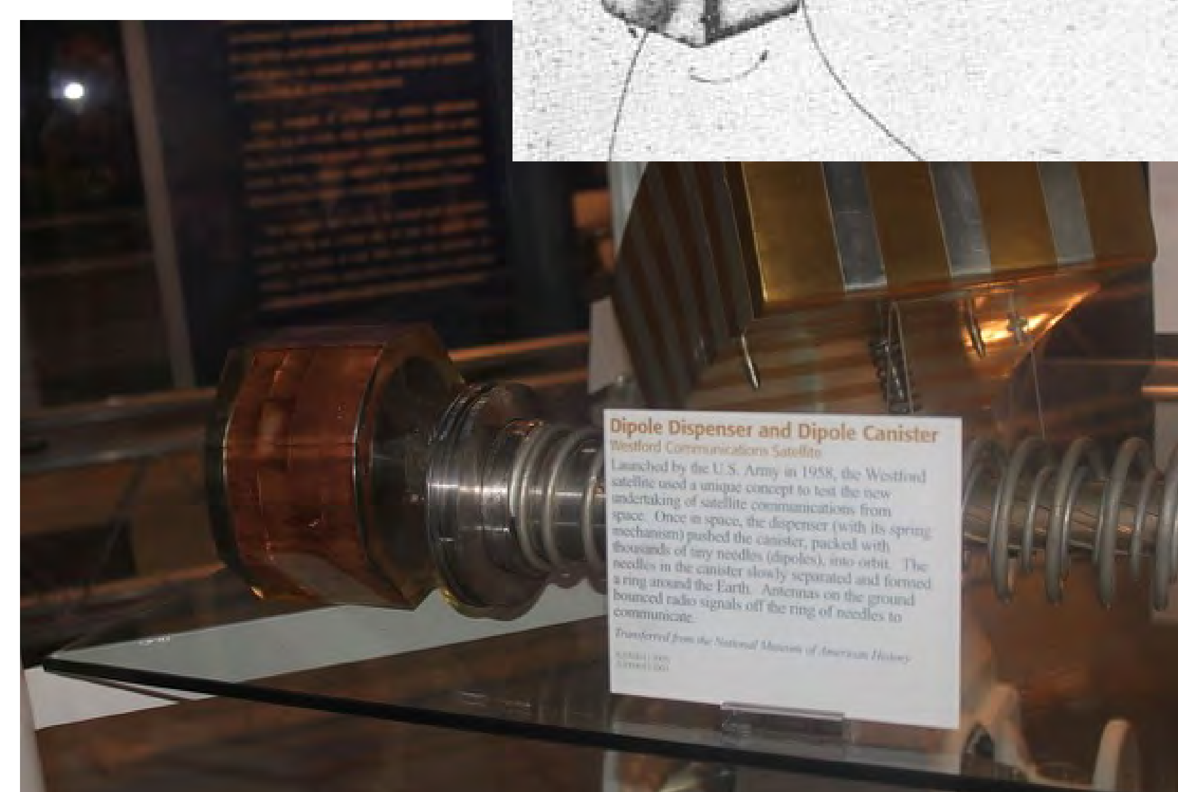
1. Things we've done and are doing at Haystack

NEROC in Space

Project West Ford (aka Project Needles)

- In 1961 and 1963, our Lincoln Lab predecessors launched 480 *million* small copper dipoles into a medium Earth orbit (3600 km).
- Using 18.5 m antennas, they successfully demonstrated communication at ~20 kbits/sec from Millstone (the present-day Haystack site) to Camp Parks, CA.
- Half-wave dipoles were designed to carry 7.75 and 8.35 GHz and to be separated by an average of 0.3 km
- Goal was jam-proof communications



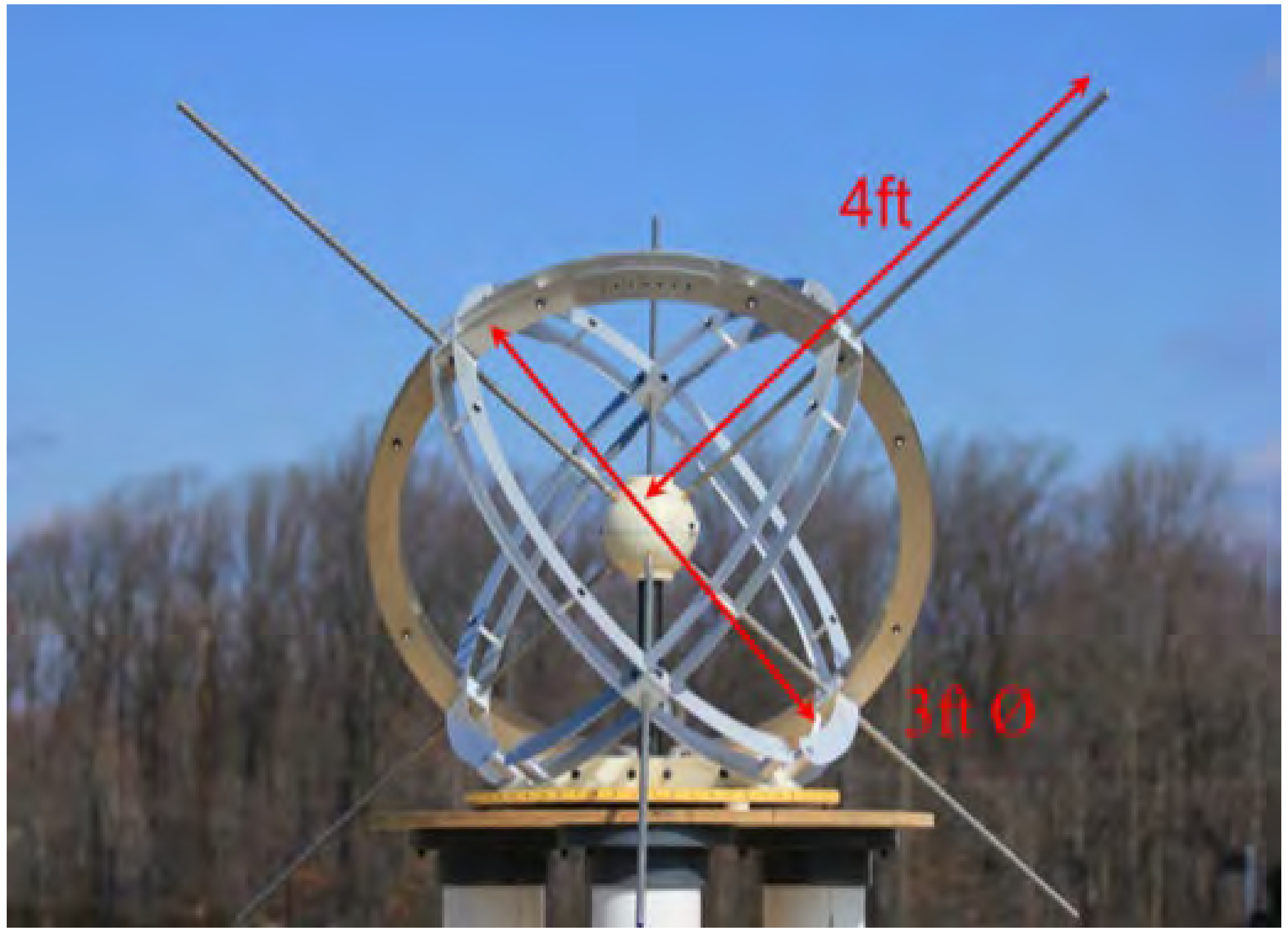


AERO & VISTA

AERO: Exploring the Aurora (PI Phil Erickson)

VISTA: Demonstrating HF Radio Interferometry with Vector Sensors (PI Frank Lind)

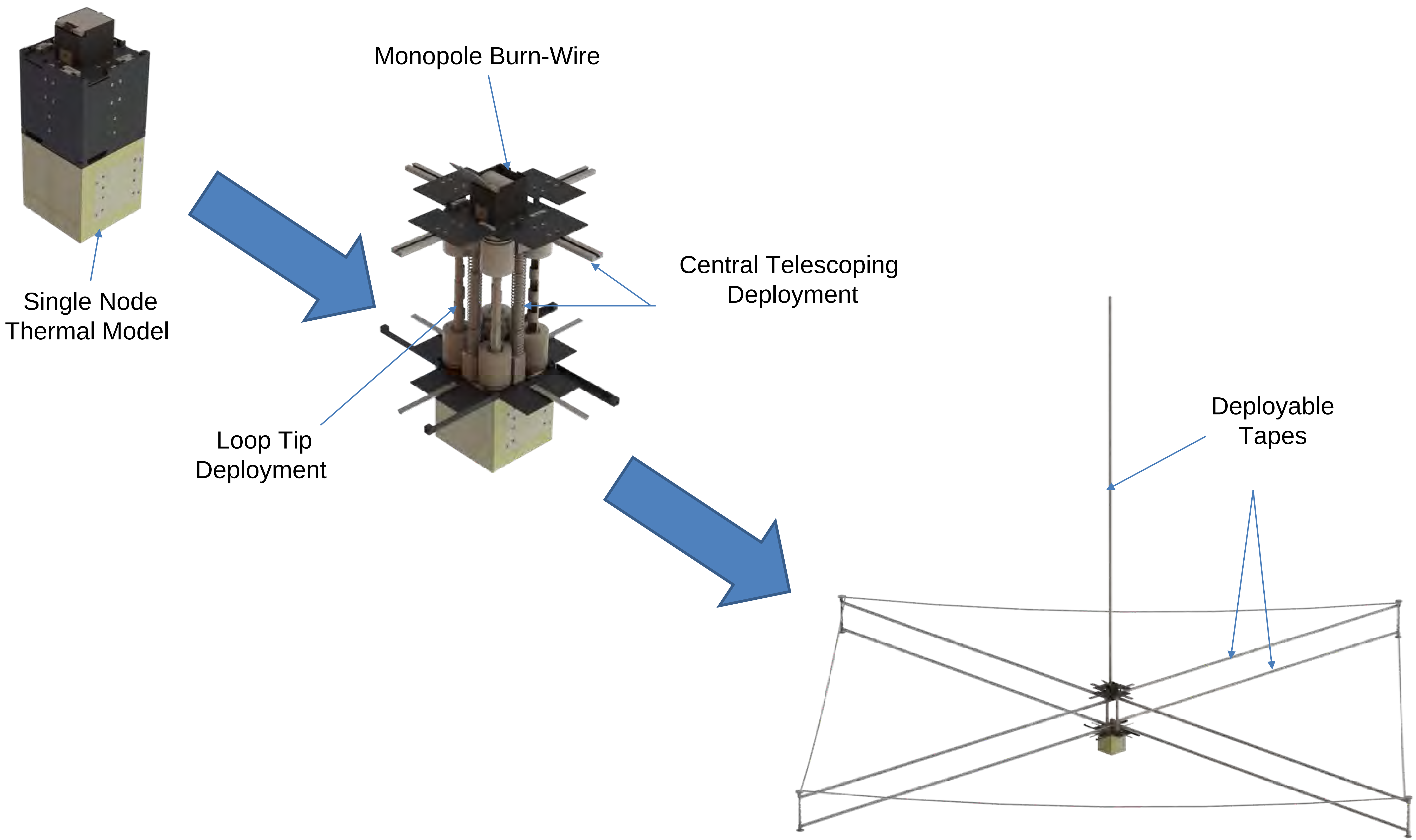
Electromagnetic Vector Sensing (with Lincoln Lab)



- 3 dipoles + 3 loops (electrically small)
- Measures full E and B field vectors
  - ExB = S (Poynting vector)
- Determines source intensity, polarization, and direction (to a few degrees)
- Some imaging capability

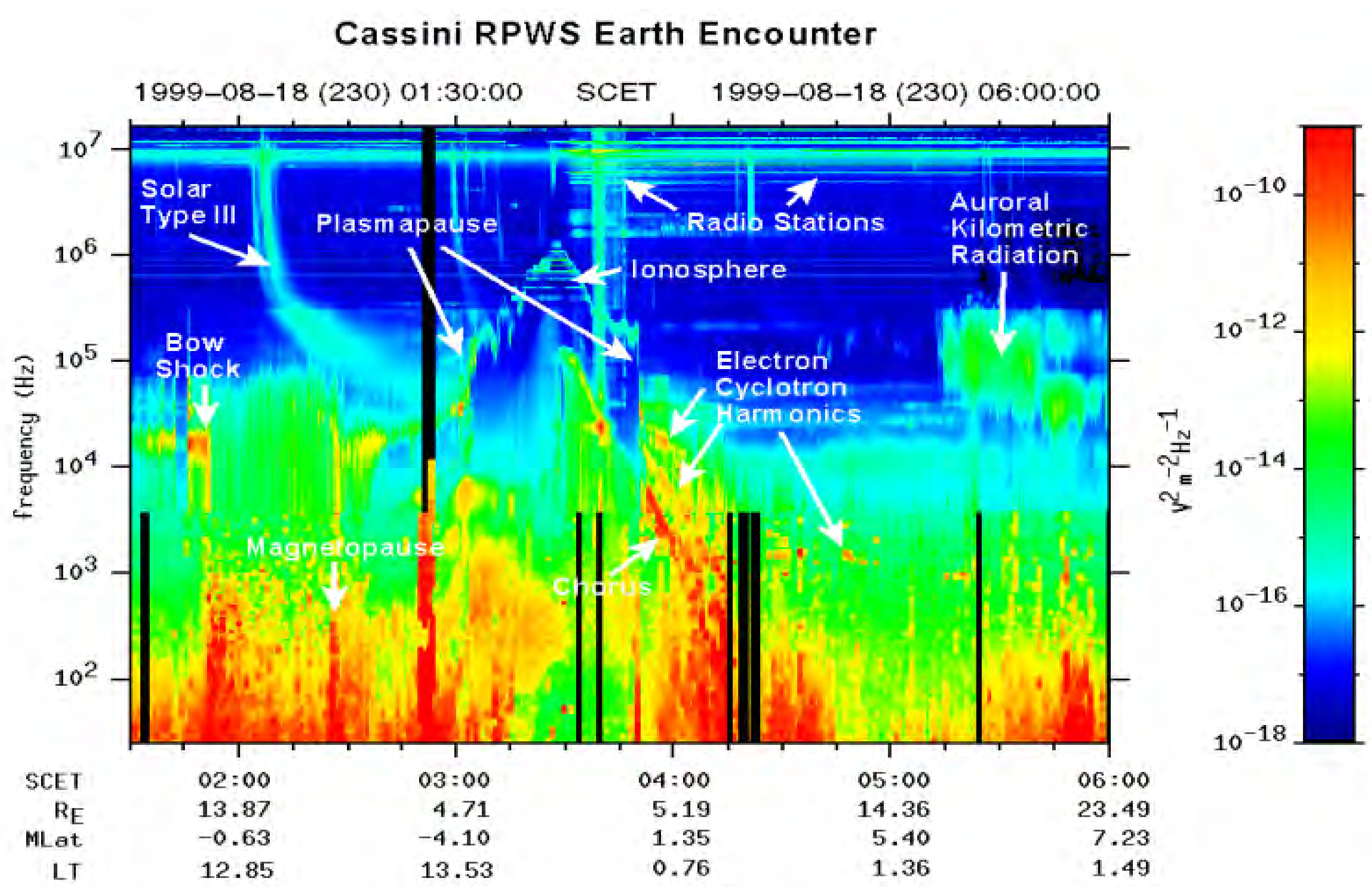
Spatially resolved detection with a single electrically small sensor!

Vector antenna deployment



Mission summary

- AERO and VISTA are twin 3U CubeSats that will launch & deploy together into a polar orbit, using drag to control separation.
- Individually, they will answer key scientific questions about the nature and sources of auroral radio emissions at wavelengths largely inaccessible from the surface.
- Together, they will demonstrate interferometric imaging, beamforming, and nulling using electromagnetic vector sensors at low frequencies (50 kHz – 5 MHz).



Perseverance – Coming soon to a planet near you!

- M2020 has traveled over 170 million miles on its 292.5 million mile journey to Mars.
- We are <37 million miles from Earth and <14 million from Mars
- One-way light time >200 sec.
- ***Entry minus 94 days.***

M. Hecht, *MIT/HO (PI)*

J. Hoffman, *MIT (DPI)*

G. Sanders, *JSC*

D. Rapp, *Consultant*

G. Voecks, *JPL*

K. Lackner, *ASU*

J. Hartvigsen, *Ceramatec*

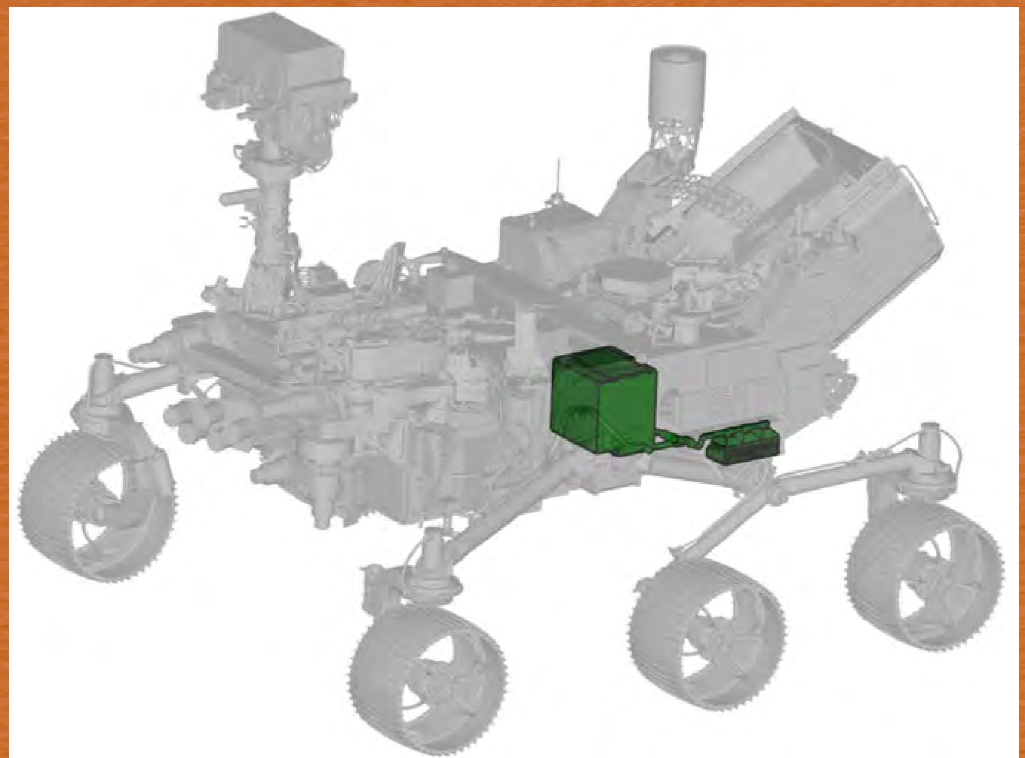
P. Smith, *Space Expl. Instr.*

W. T. Pike, *Imperial Coll.*

M. Madsen, *U. Copen.*

C. Graves, *DTU (Coll.)*

M. de la Torre Juarez, *JPL (Coll.)*



Jet Propulsion Laboratory
California Institute of Technology
J. Mellstrom , Project Manager

What will MOXIE do?

MOXIE
Mars Oxygen
ISRU Experiment

* **MOXIE is a 1:200 scale model of an ISRU plant for a human mission, ingesting CO_2 from the atmosphere and producing propellant-grade O_2**
* MOXIE will make 6-10 g of oxygen per hour
  * Like a smallish tree, or about 50% of what you breathe
* O_2 purity will be >99.6%.

Installation in Perseverance rover

Mars Oxygen ISRU Experiment

2. Things we'd like to do at Haystack

- Haystack in Space

NEROC in Space

MIT HAYSTACK OBSERVATORY

Vector Sensor Planetary Radar?

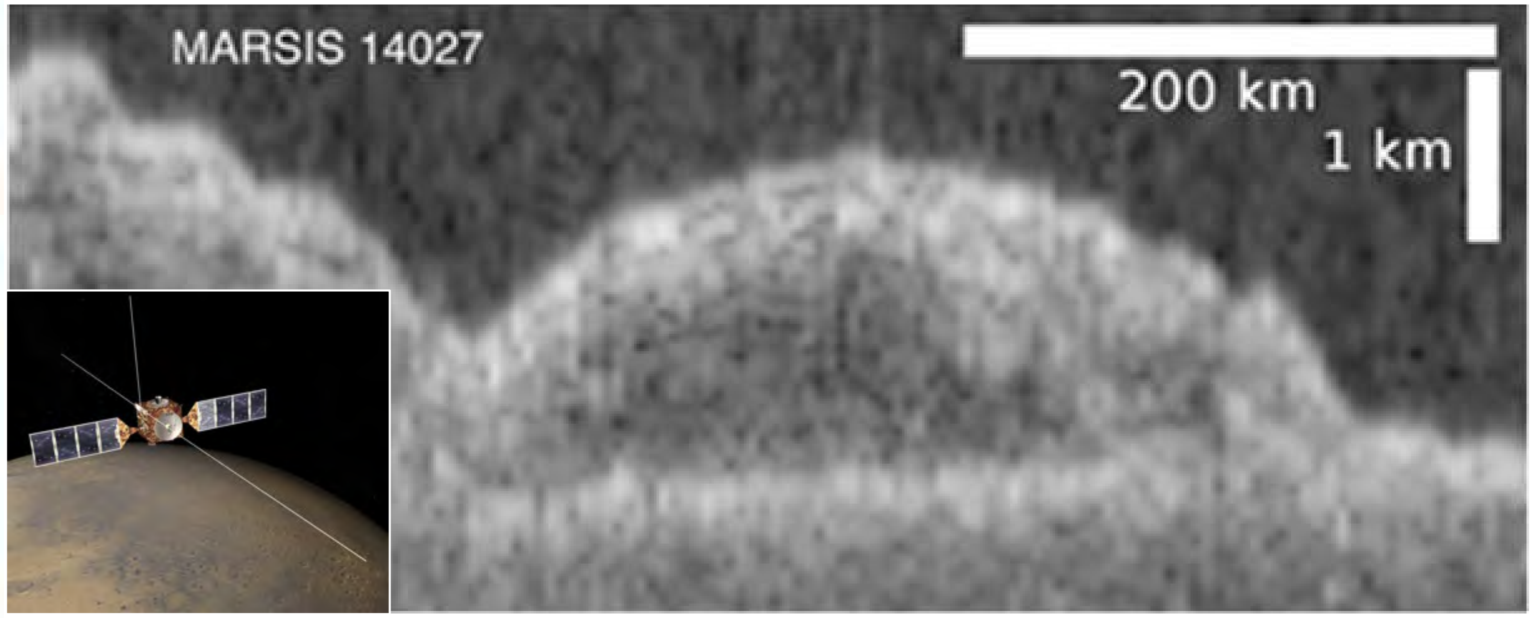
	ACORN Low	ACORN-High	MARSIS	SHARAD
Frequency band (MHz)*	10-37.5, 42.5-75	85-1000	1.3-5	15-25
Bandwidth (MHz)	5,15,25	75,150,300	1	10
Resolution (m)**	20, 6.6, 4	1.3,0.65,0.35	75	10
Transmit P_{pk}(W)	10	10	10	10
Transmit P_{ave}(W)	1.6	1.6	0.3	0.6
T_{pulse} (μsec)	32-128		30/250	85
PRF (Hz)	320/640/1280		127	350/700
Duty factor (%)	1-40		3.1	3/6
Ramb (km) ****	469/234/117		1180	429/214***
Prime Power (W)	50		60	Unk.
Polarization	Full		Single	Single
Clutter null	Angle/pol		Nadir ** element	No
Total Mass (kg)	9		20	15

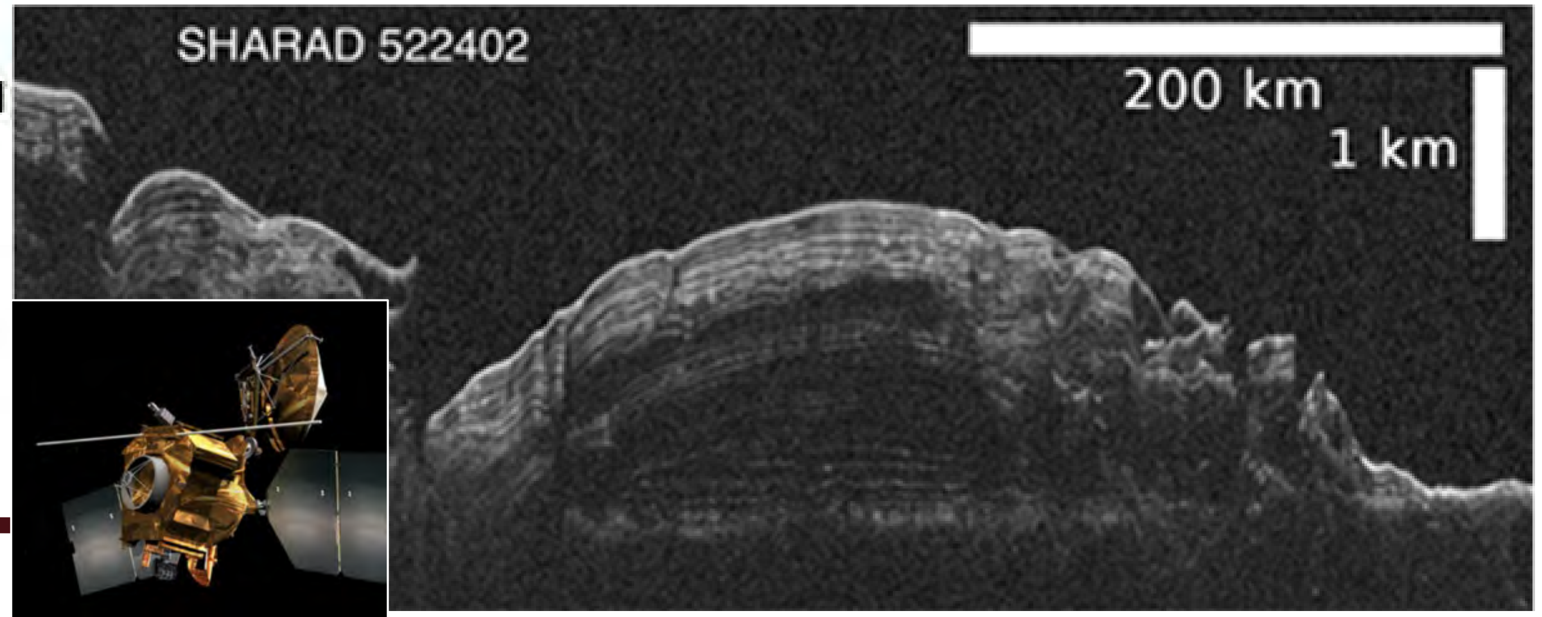
* The frequency and bandwidth listed here are the RF electronics. See later discussion for antenna bandwidth and efficiency consideration.

** Resolution is in ice, with $\varepsilon_r = 3$.

*** There was high noise in the nadir-pointing element that eliminated its utility.

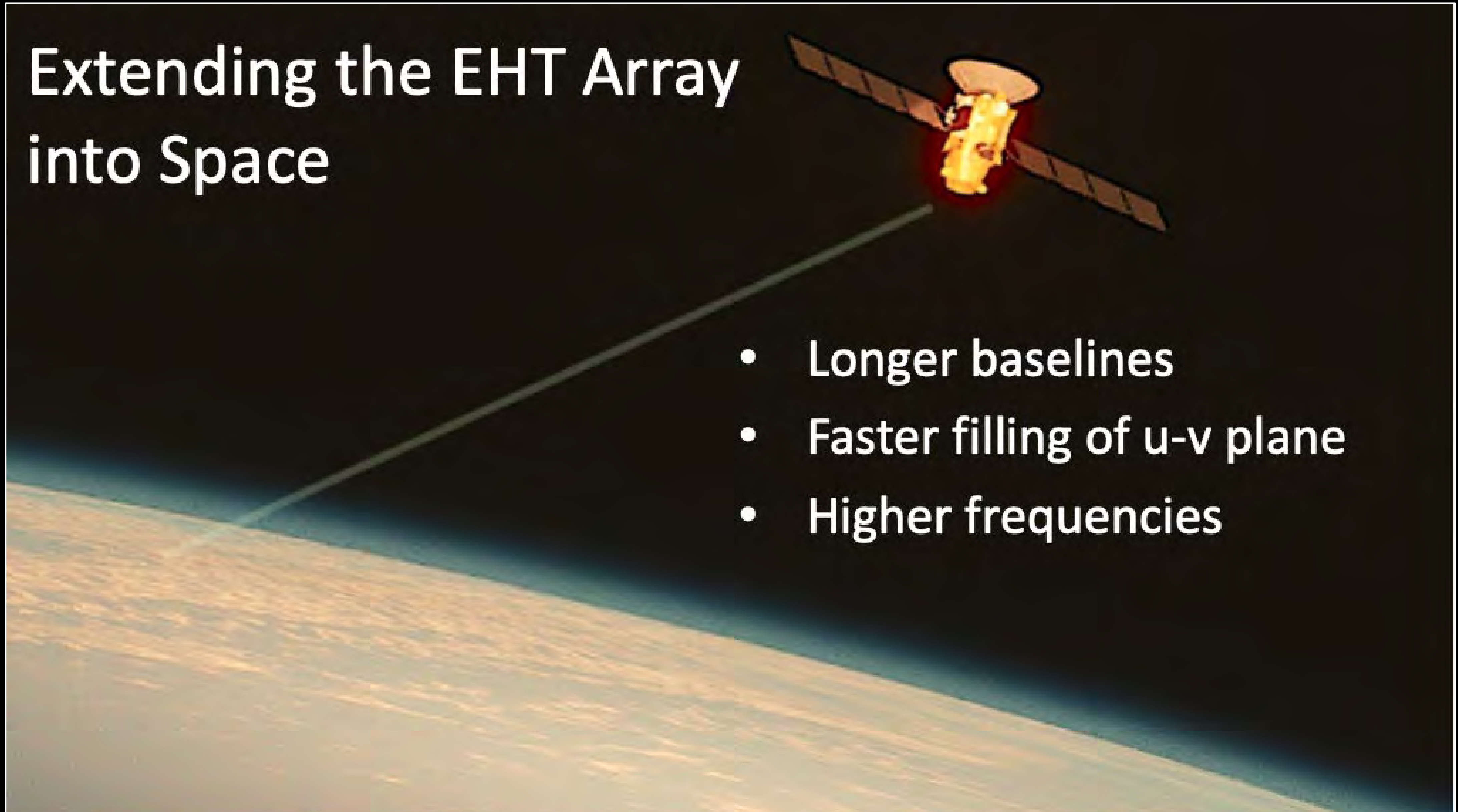
**** Ramb is the range ambiguity interval. Note that SHARAD typically operates with returns in the first range ambiguity interval.

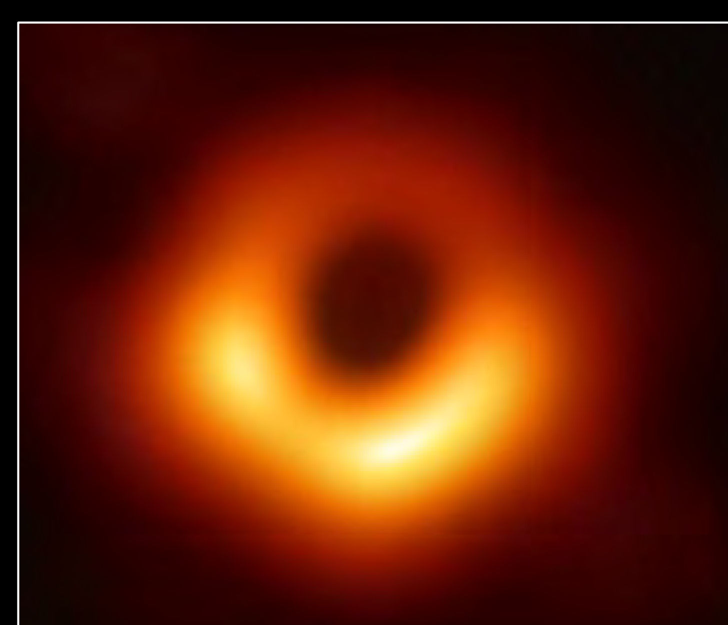


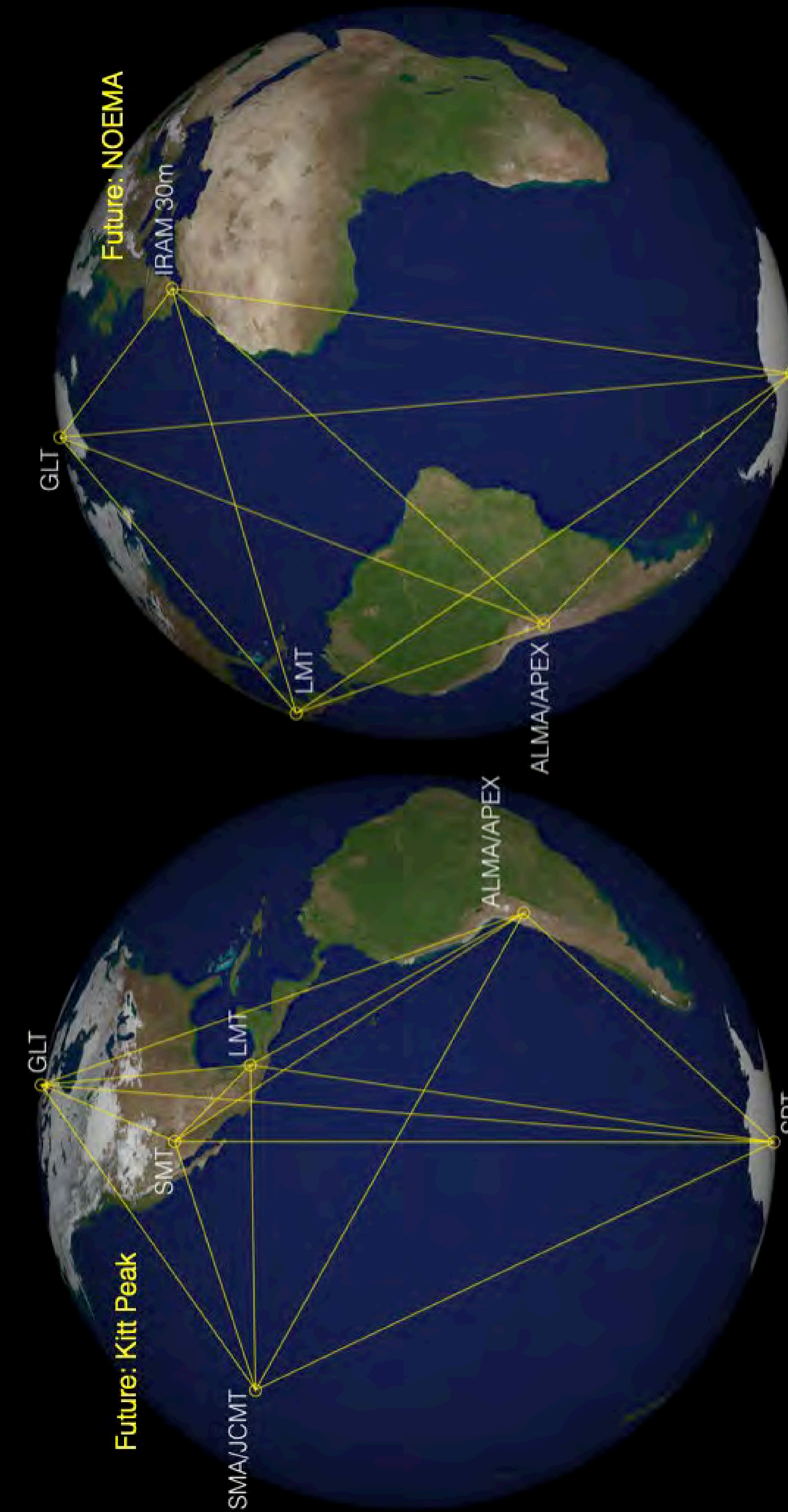


Extending the EHT Array into Space

- Longer baselines
- Faster filling of u-v plane
- Higher frequencies

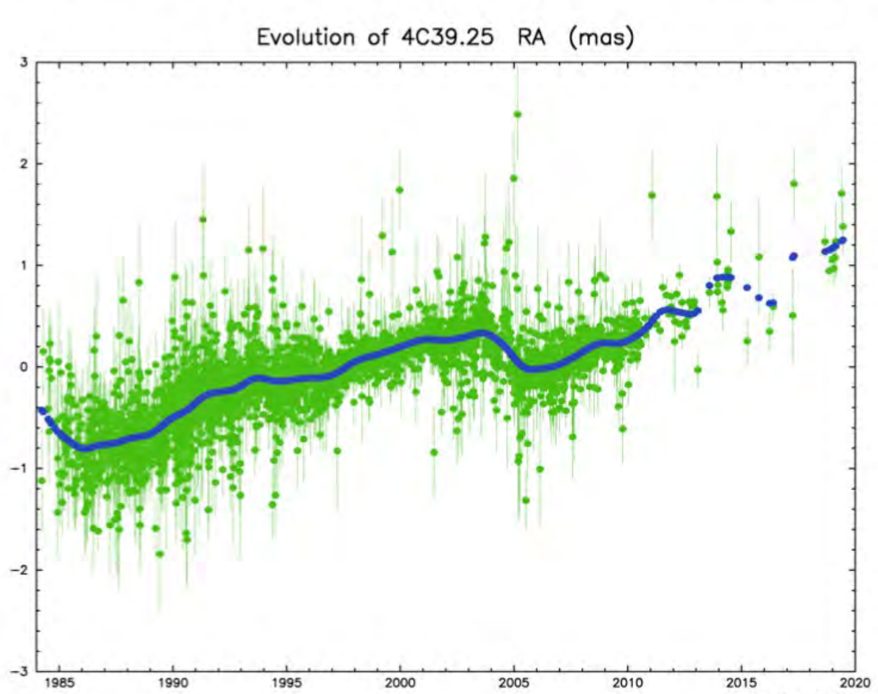




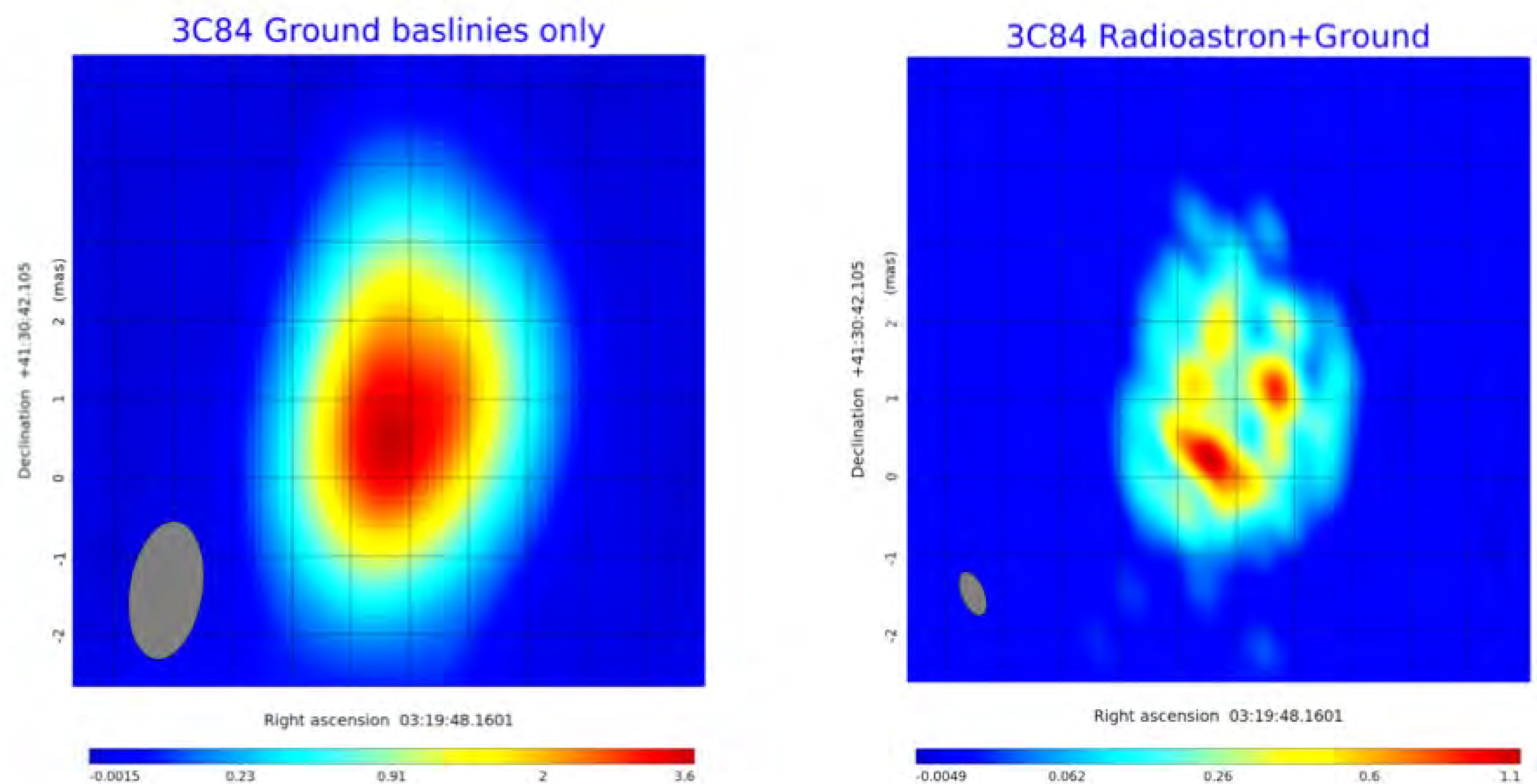


Geodesy: VGOS in Space

Time series of source positions from the space geodesy program



3C84 C-band image



FWHM 1.8×0.9 mas

FWHM 0.60×0.3 mas

The "core" reveals rich structure!

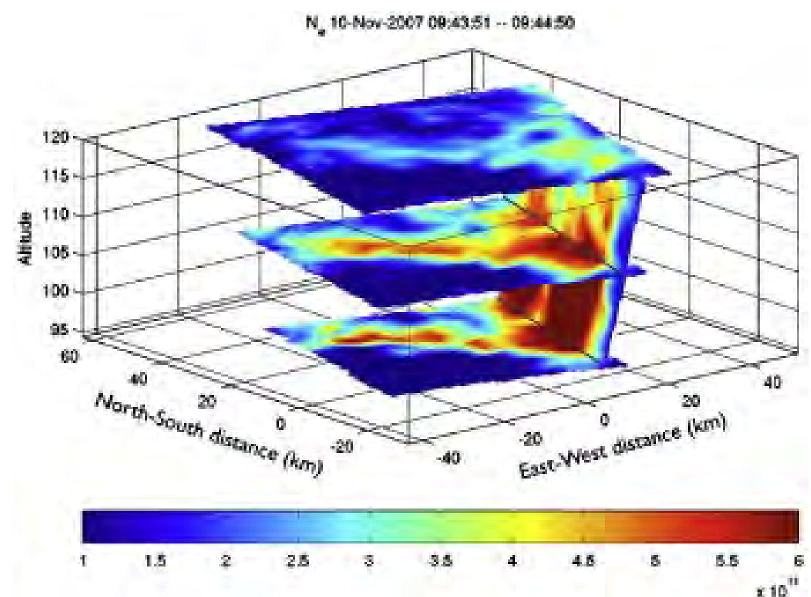
3. Four things we can do together

NEROC in Space

1. Projects too big for just one of us

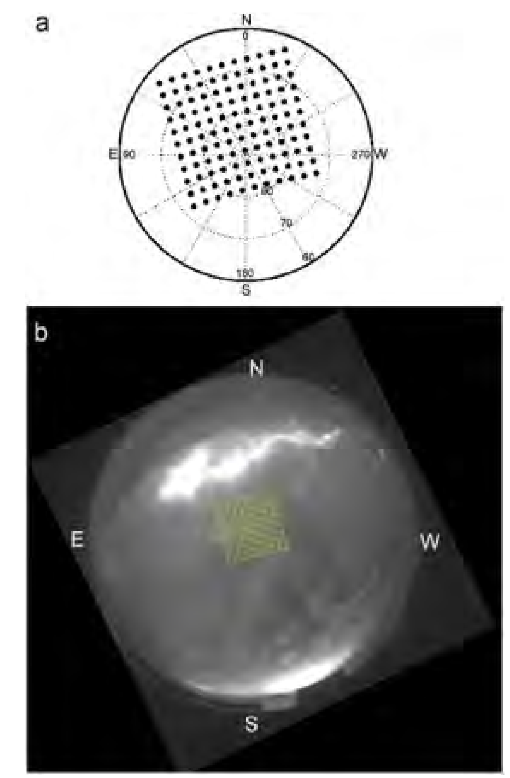
- Heliophysics missions
  - H-TIDES & HFORT Science/Technology
    - Increasing cap to ~$10M for HFORT
    - Source of AERO and VISTA funding
  - Regular SALMON calls ($50M-$75M) for rideshare
  - MIDEX call (~$150M)
- Astrophysics missions & mission studies
  - Occasional SALMON calls ($35M-$75M)
  - Typically preceded by mission study calls (~$150K)
- Planetary science missions (focus on instruments)
  - SALMON
  - SIMPLEx 2018 (rideshares)
  - Discovery PI-led missions (~$450M)
  - Flagship missions

2. Coordinated Science Observations



Semeter et al. 2009

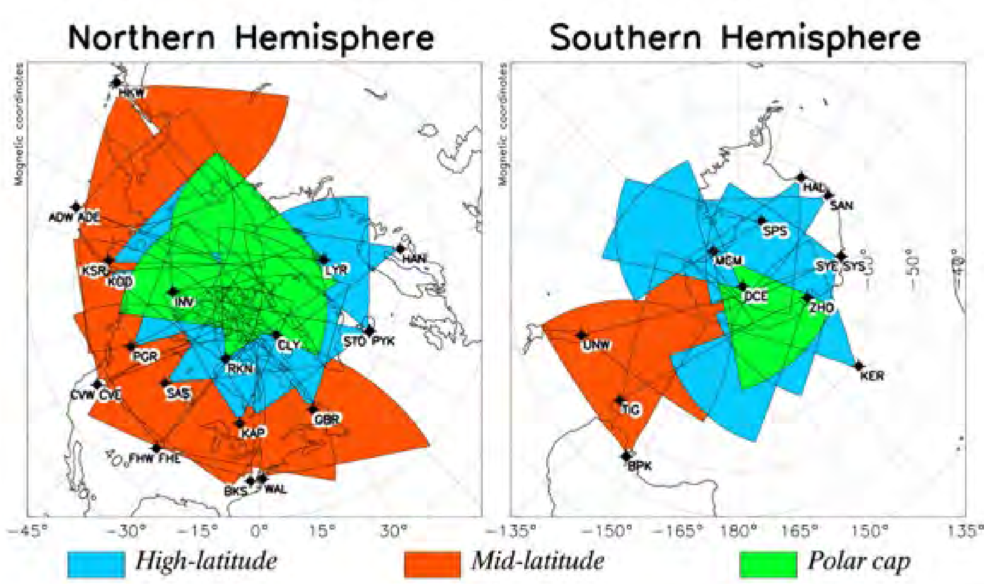
AMSIR / EISCAT 3D Incoherent Scatter Radar Auroral Diagnostics

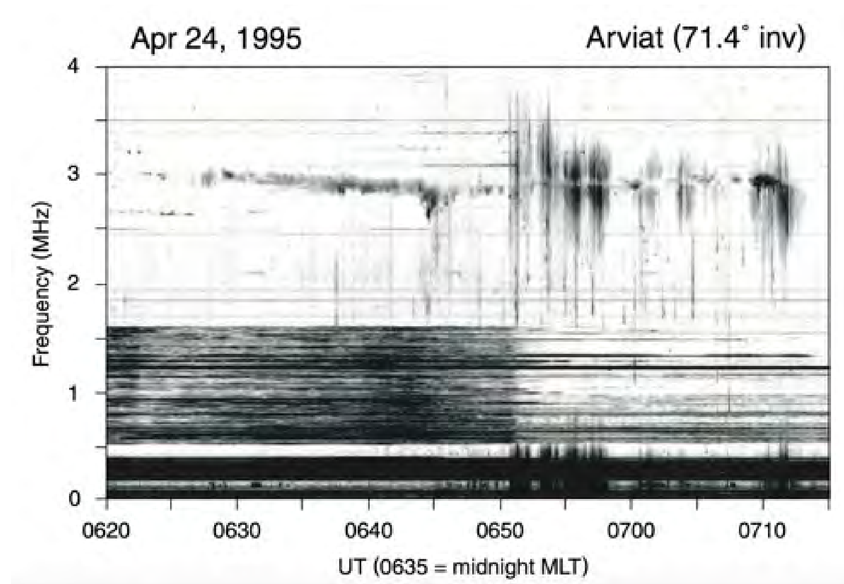


Optical Auroral Diagnostics

Semeter et al. 2009

HF Radar Auroral Diagnostics (SuperDARN)





Labelle 2006

Ground Based Radio Receivers

3. Sharing resources:

Westford's 18-m "ground station"

- Primary Use for NASA Geodesy Program Development
- Several days per week for Geodesy ops
- Prime focus QHFR feed (2 to 14 GHz)
- Cryogenic LNAs (Tsys ~ 80 to 120K)
- Prime and Cassegrain feed points
- Single operator for monitoring
- Less accurate in 'fast slew' modes

The 18 m Westford Radio telescope at MIT Haystack Observatory.

Dynamical/Mechanical Properties	Measured Values
Aperture Size	18.3 meters
Surface Accuracy	0. " RMS
Azimuth	< 4.0 °/sec
Elevation	< 3.0 °/sec
Polarization	Feed Selected
Azimuth Travel	Full with cable wrap.
Elevation Range	4 ° to 87 °
Pointing Accuracy	~ 0.005° RMS
Tracking Accuracy	~ 0.02° RMS

4. Designing missions together??

- Many space agencies and aerospace companies have *mission design centers*, such as JPL's Team X.

- These centers use concurrent engineering to support proposals by quickly designing all aspects of a mission, from thermal design to navigation and from budget and schedule to mission assurance.
- We are exploring equipping groups of students with models and training to engage in similar exercises in support of SmallSat and CubeSat missions
- **Team NEROC??**

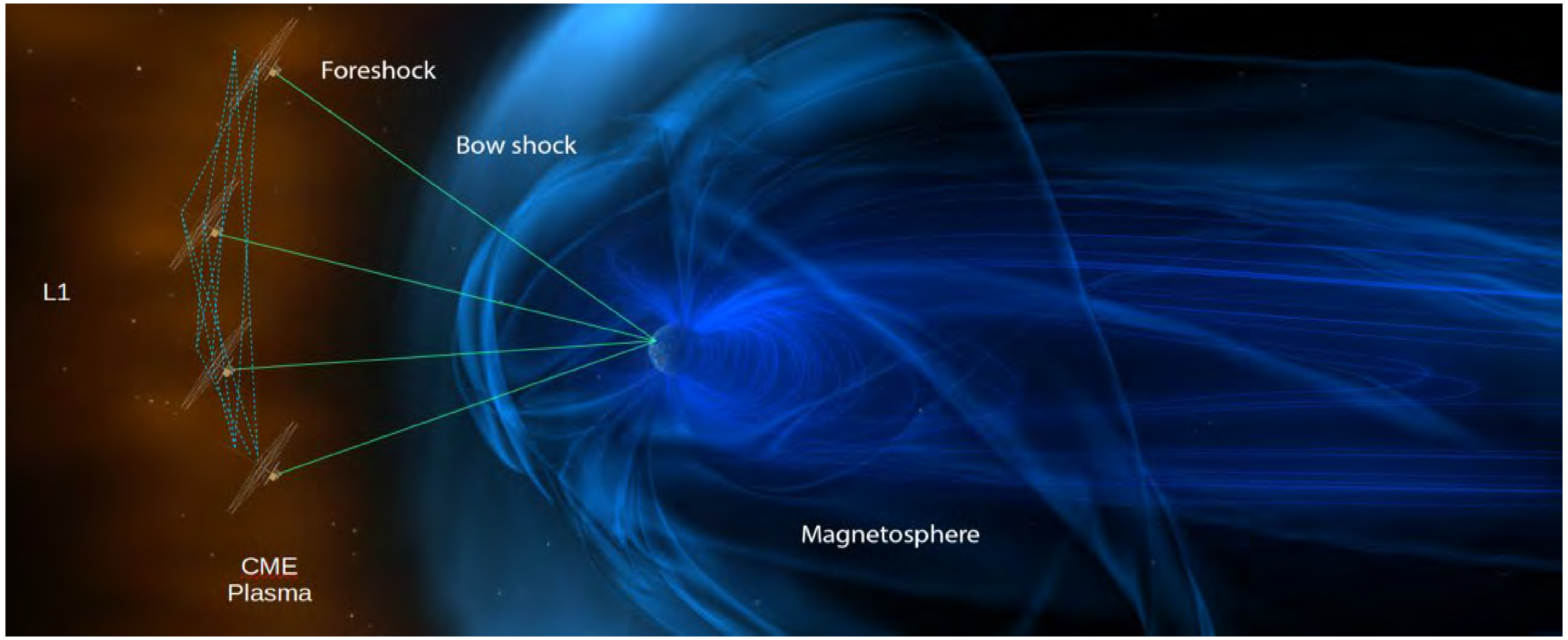
Backup

GENERAL

MIT HAYSTACK OBSERVATORY

SmallSat Topics of interest

- Heliophysics
  - Interferometry of solar radio bursts
  - Auroral studies
  - Beacon tomography networks
- Astrophysics
  - EHT in space?
  - Bent-pipe Earth-based interferometry
  - Validation of cosmic dawn detection: EDGES in space
- Earth science
  - Long baseline geodetic VLBI
- Planetary Science
  - Compact shallow ground-penetrating radar for orbital missions
- Space Infrastructure
  - Autonomous navigation using time variable and spectral line radio sources
  - Beamed power satellites for lunar and planetary surface exploration

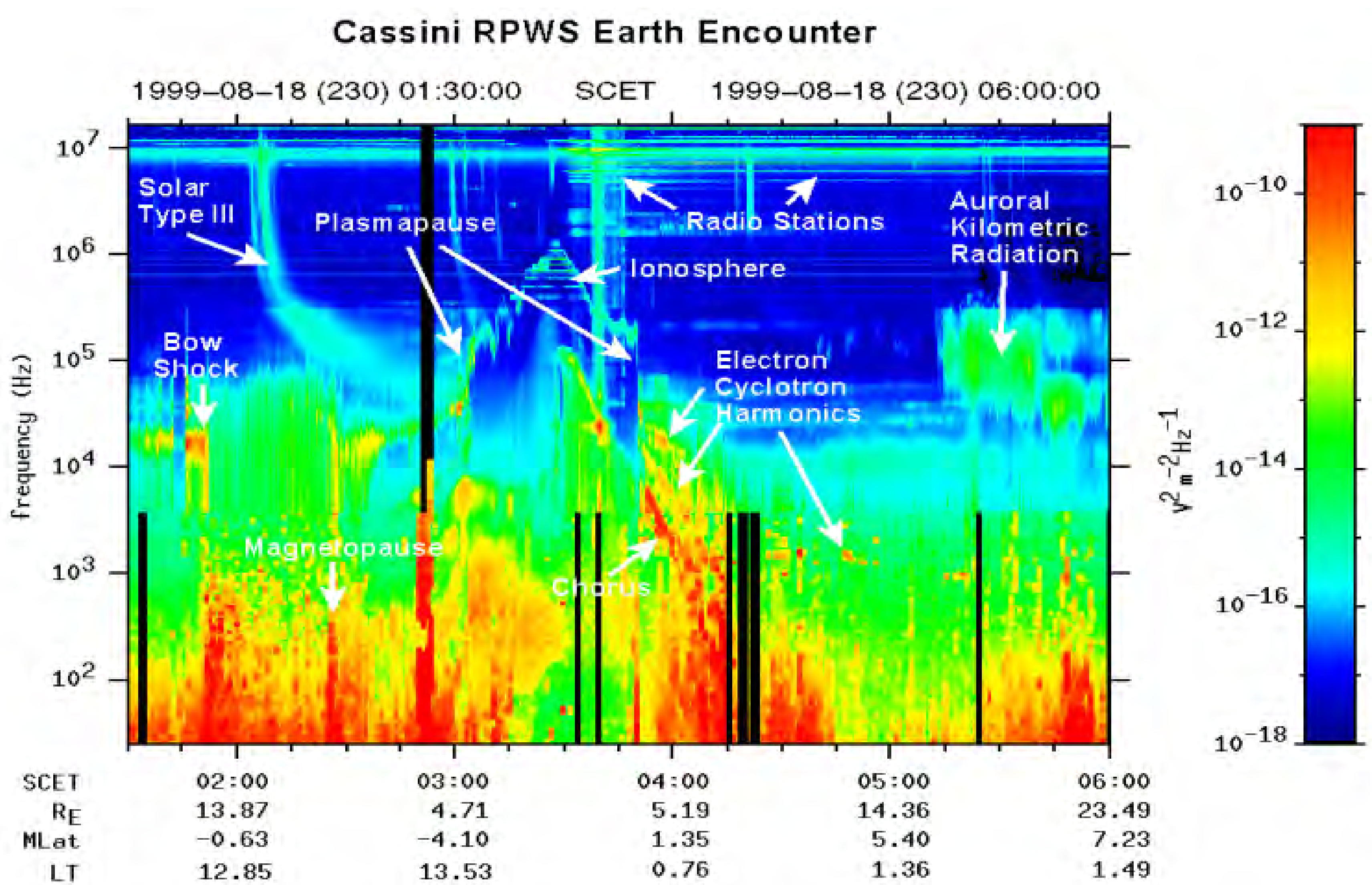


SmallSats for

HELIOPHYSICS

For HF (<10 MHz), need to go to space

- Radio Astronomy Explorers (RAE) I & II
- Electric field probes (Ulysses, WIND, Cassini, STEREO)
- Limited interferometry (traditionally big & complex).
  - CLUSTER measured AKR angle of arrival

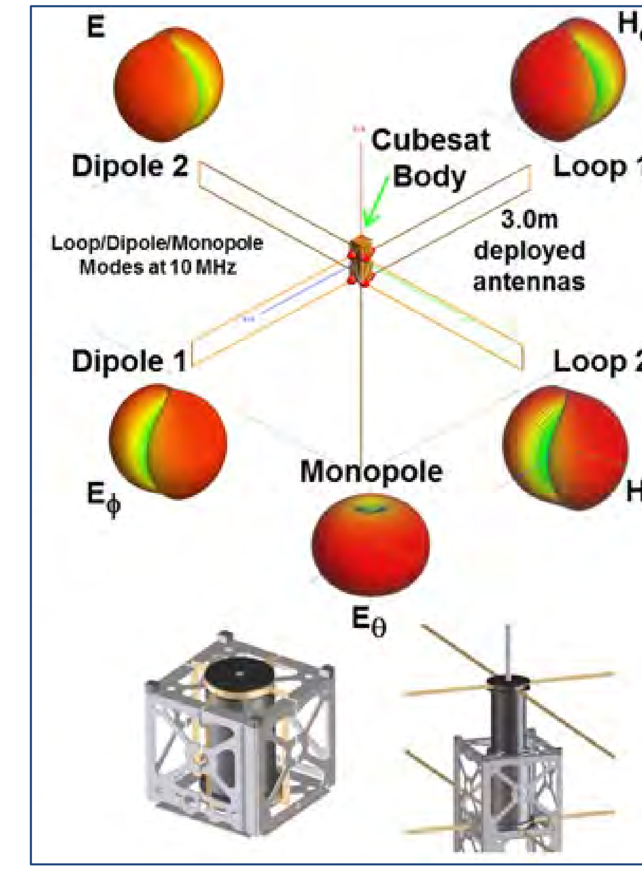


AERO Science questions

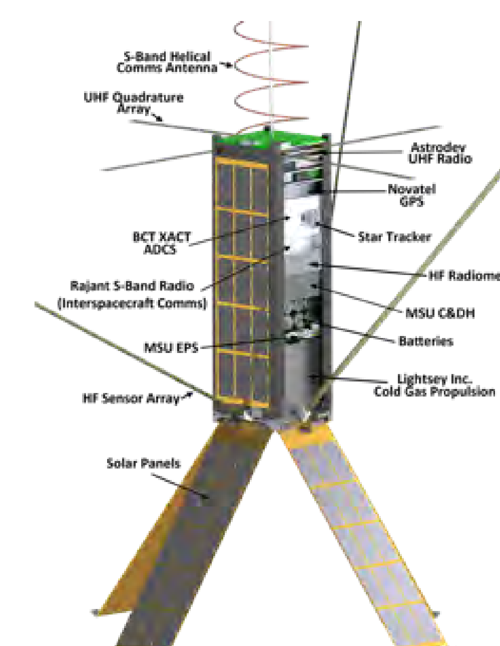
Science Question	Measurement
Primary: **Does AKR couple to modes that propagate to low altitudes?** If so, is the propagation ducted or non-ducted? **How are MF burst emissions generated?** Is the source in the topside or bottomside? Extended or concentrated?	Determine apparent direction, time, amplitude, frequency and mode dependence of emissions
Secondary: How do the locations of roar, burst, AKR, and LF hiss relate to the auroral current system and to auroral arcs?	Relate strong auroral radio emissions to magnetic & optical signatures in Birkeland Region 1.
Technology: Can polarized auroral emission from concentrated sources be localized with a vector sensor? How do vector sensors perform as interferometer elements?	Validate angle of arrival determination for strong sources. Compare

How to build an HF space Interferometer

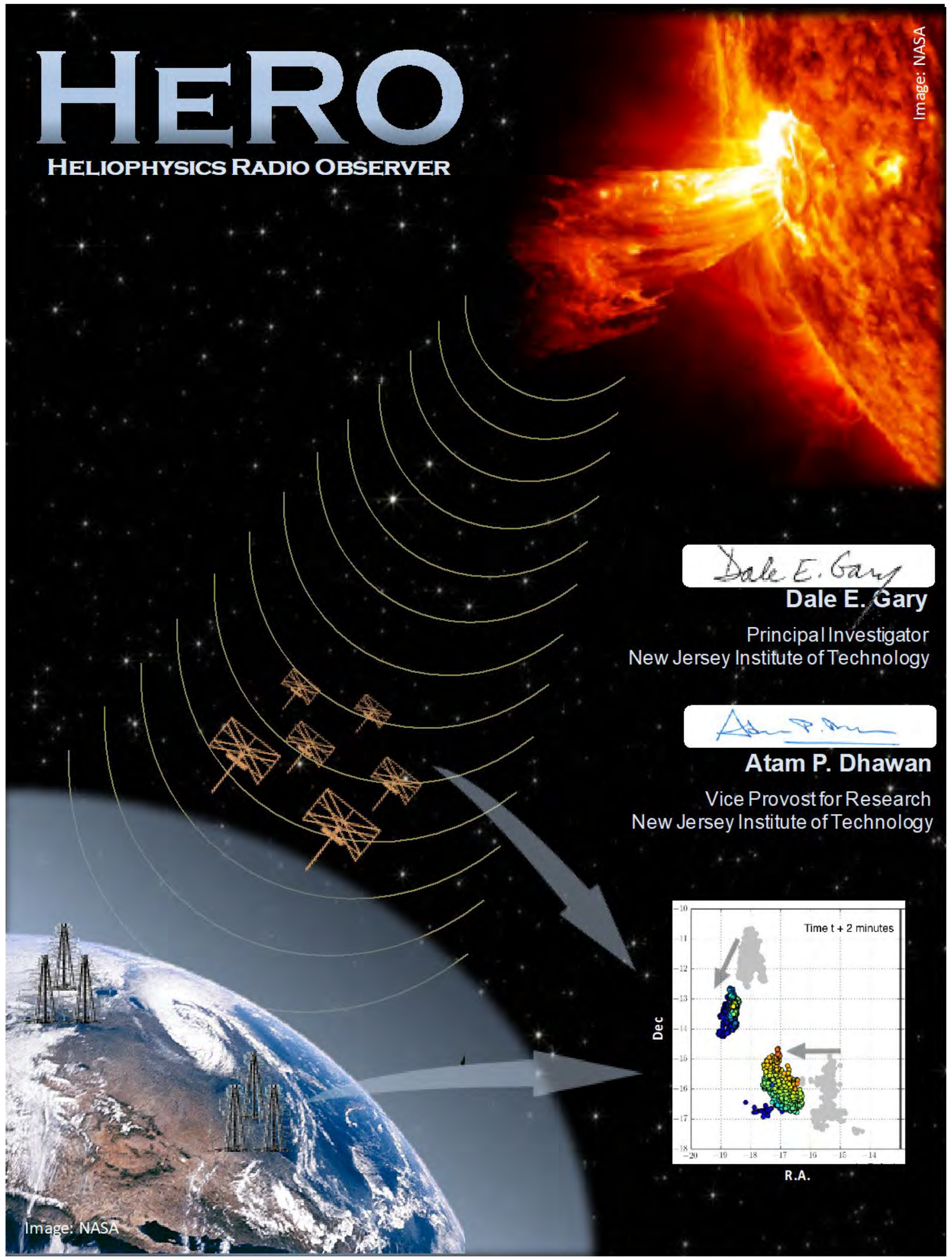
- At least 4 CubeSats separated by 1 -10 km
- Frequency band: 50 kHz-20 MHz
- Geosynchronous orbit to get above ionosphere
- Propulsion to hold approximate positions
- GPS or an internal beacon system to precisely determine relative positions
- Compact antennas (electrically short 3-axis monopole or vector sensor)
- Timing: Chip-scale atomic clock
- High bandwidth laser downlink (many Gb/s)
- Correlation on the ground

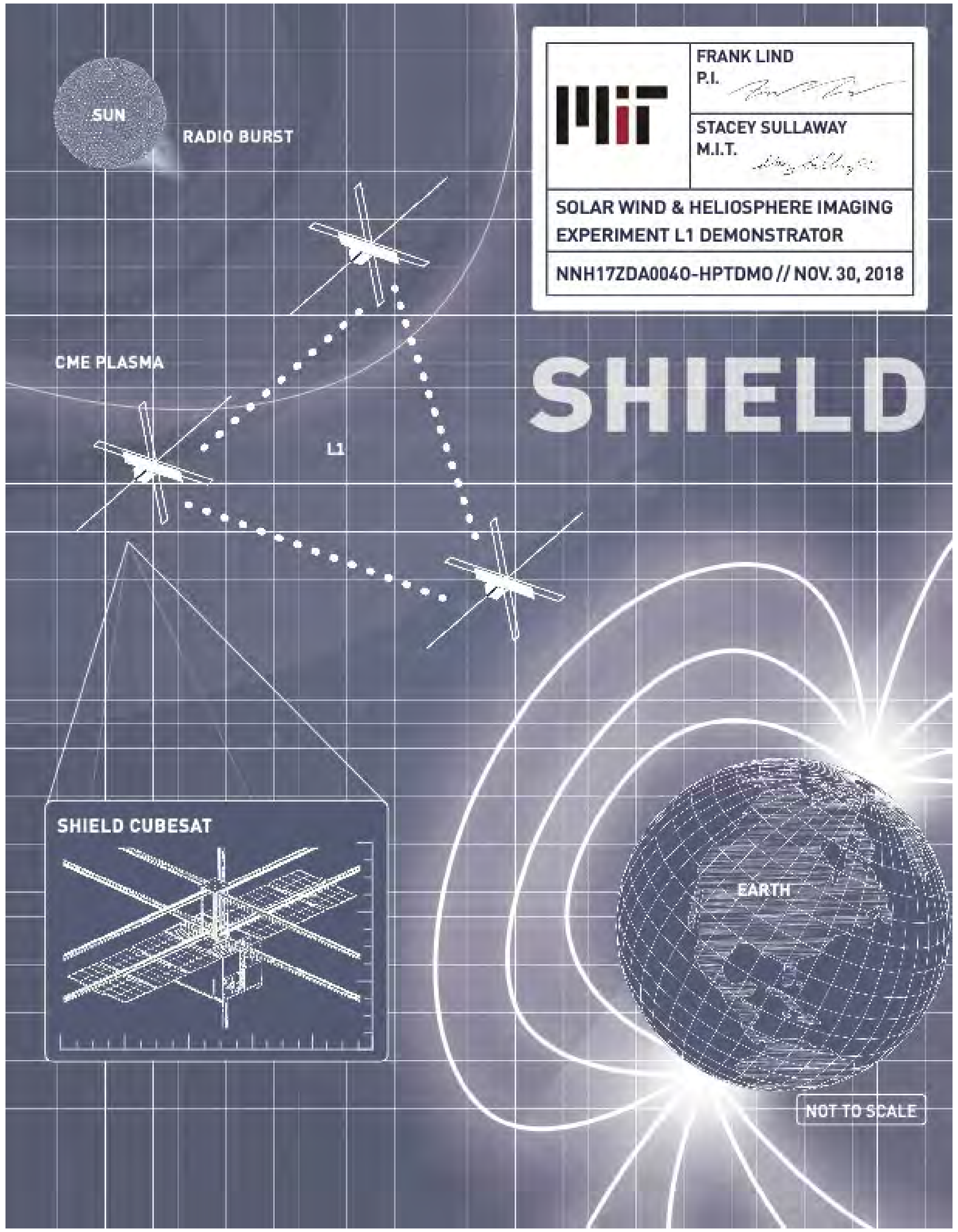


Vector antennas



Next target – solar radio bursts





Backup

ASTROPHYSICS

EHT Science: Space VLBI at <1 mm

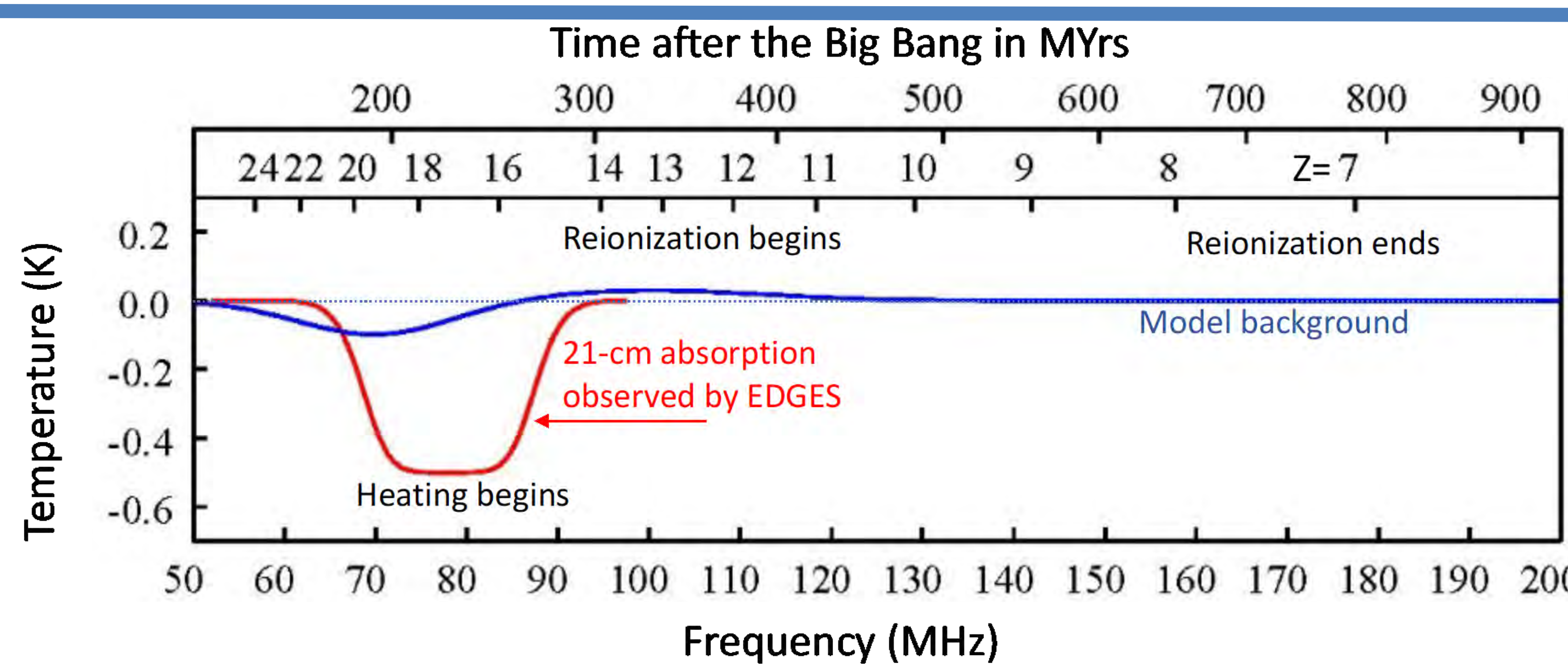
Challenges:

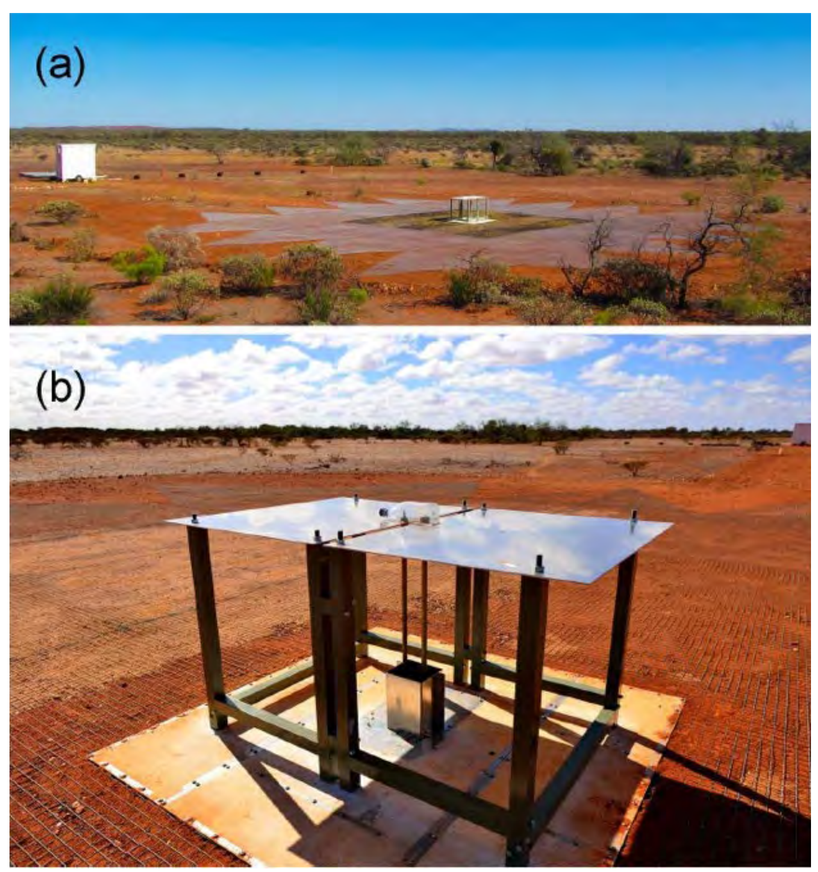
- High precision antenna >3 m
  - Deployable from ESPA may be possible
- Many Gb/s download needed
  - TBird lasercom ok
- Low temperature receiver
  - Not necessarily 4K, HEMT may be ok
- High precision clock
  - Could condition crystal oscillator

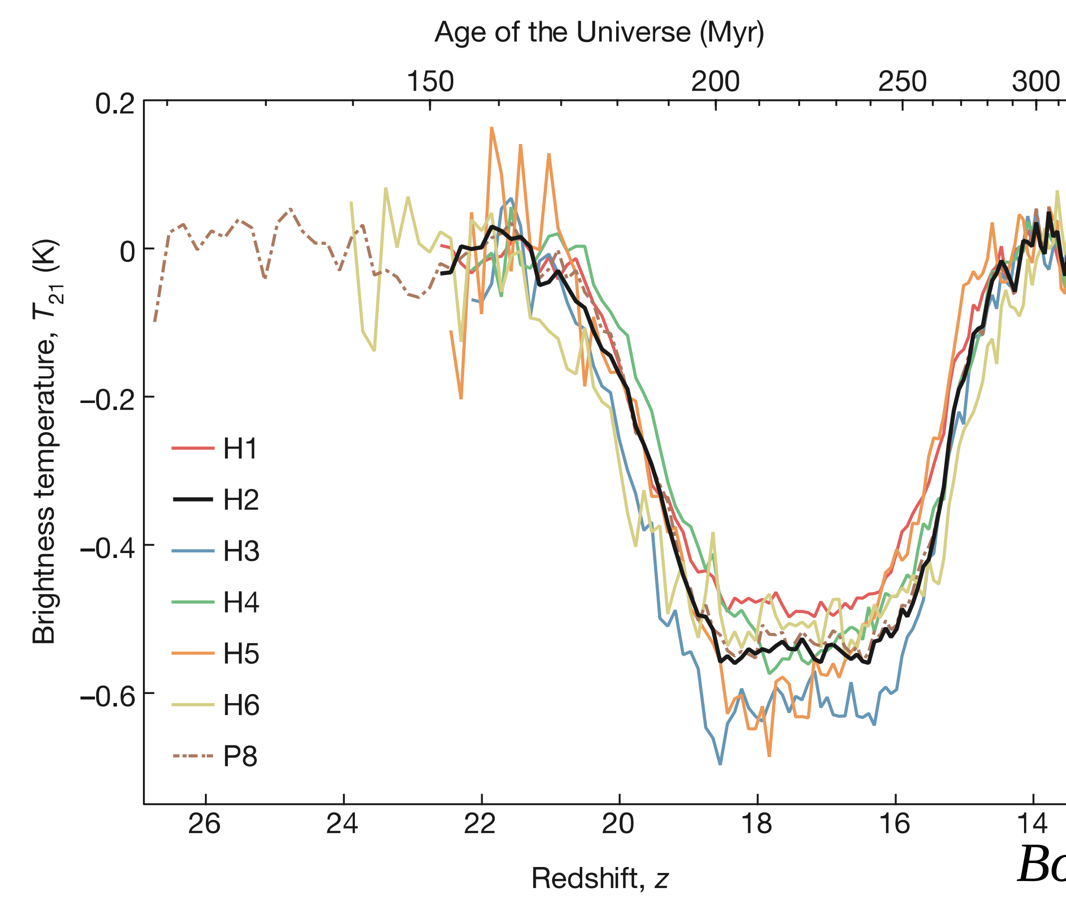
Low hanging fruit?

- Bent-pipe lasercom from remote locations, especially South Pole telescope

EoR Science: EDGES (Bowman & Rogers)





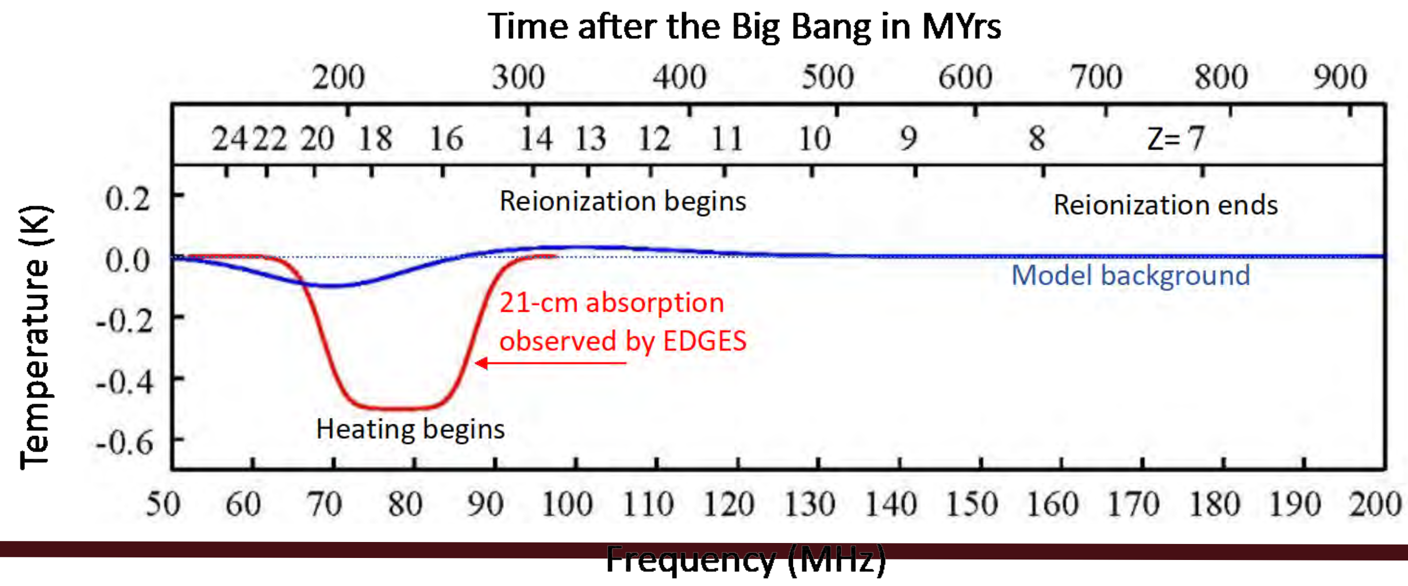


Bowman et al 2018

EDGES History

CoDEx
The Cosmic Dawn Explorer

- EDGES observation of 78 MHz absorption feature was a major breakthrough in EoR research
- Depth of absorption may imply a fundamentally new physical understanding of the early universe (Dark matter interactions? Underestimated black hole contribution?)
- EDGES is an extremely sensitive, low-SNR measurement that has proven challenging for other groups to replicate
  - Community has been appropriately reserved about accepting the result without confirmation
- Foreground removal requires 5 term fit to reveal feature
  - Physically based and validated by experiment variation
  - Nonetheless, could achieve similar result with simple forms (e.g gaussian plus sinusoid) that are conceivably artifact-based

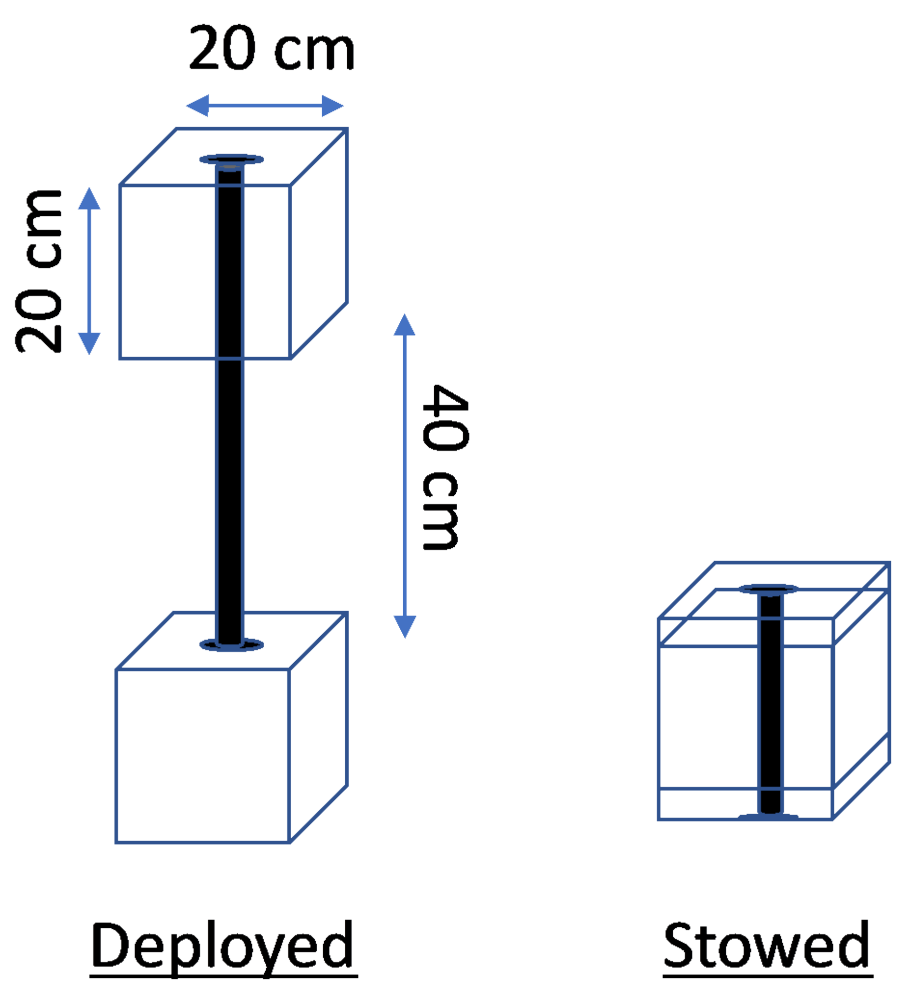


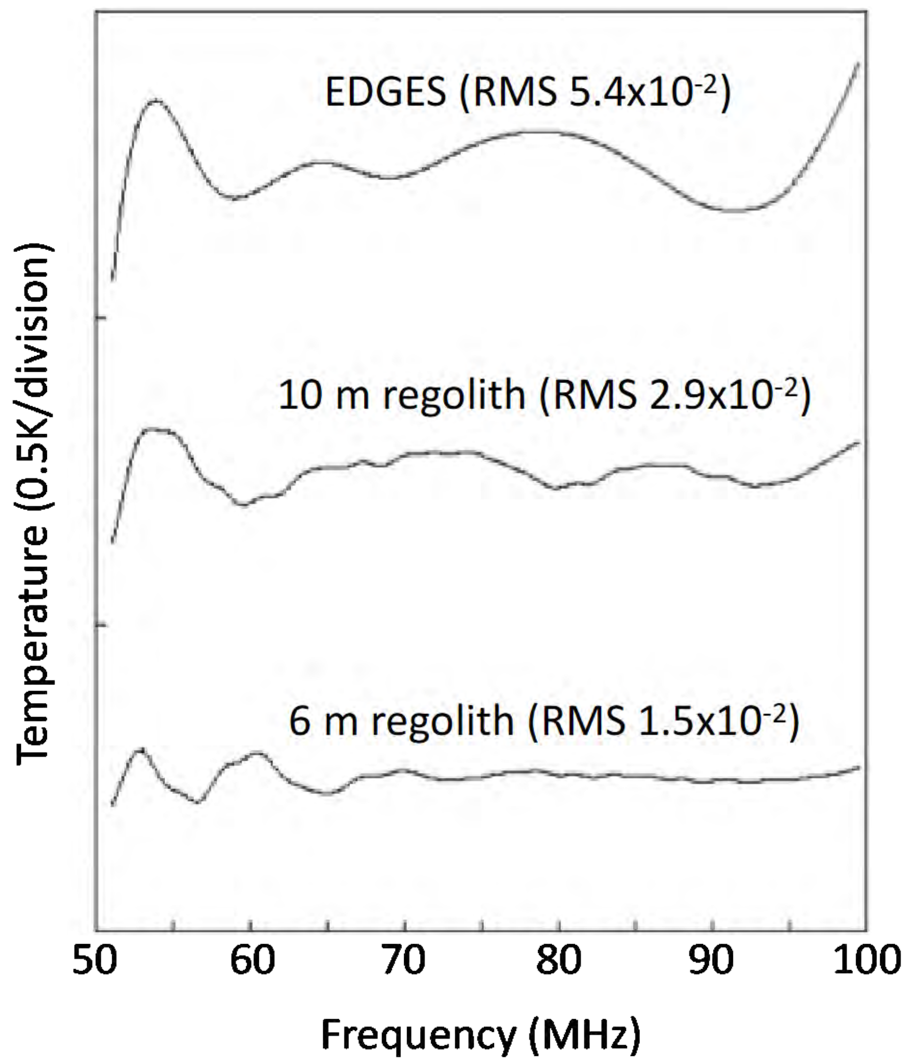
CubeSat validation concept

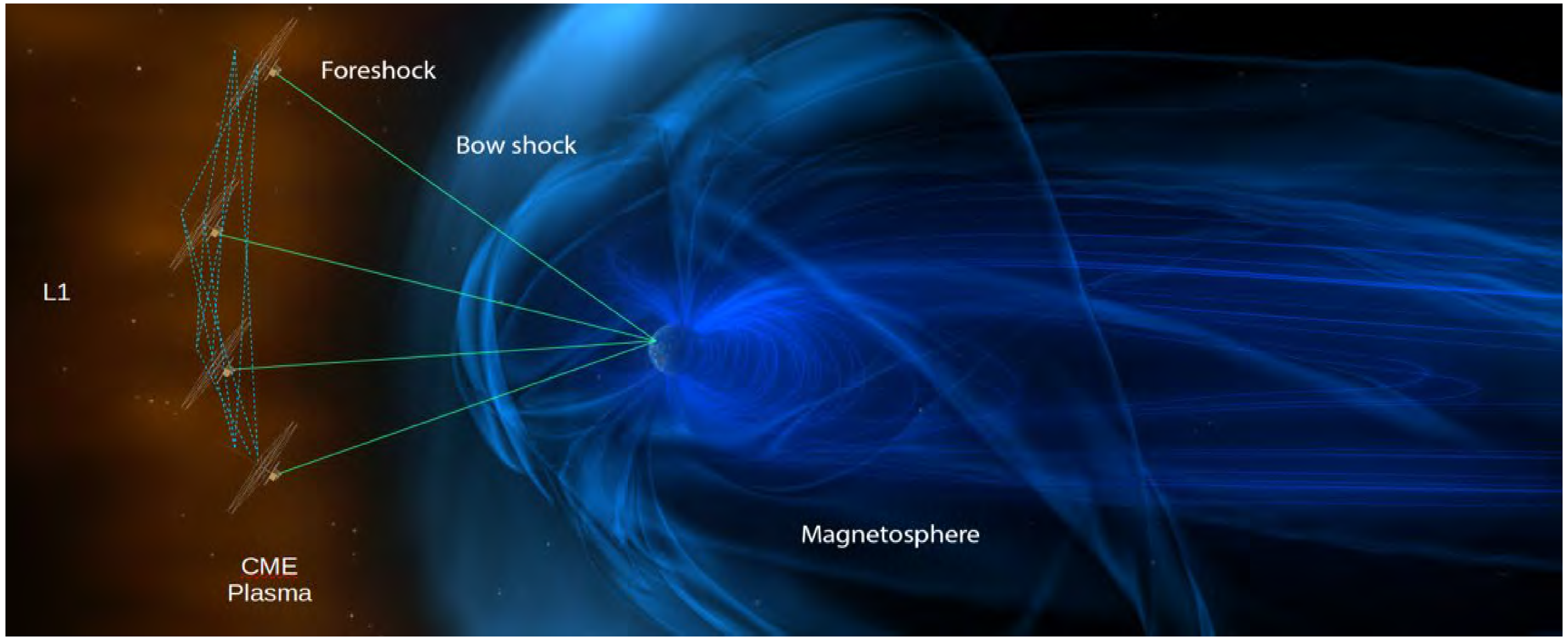
- Primary objective: Validate EDGES measurement in an FM-free and atmosphere-free environment
  - Sky sources remain challenging, including reflection of relatively unknown lunar near-surface
  - But the foreground is sufficiently simpler and different that a confirming observation would be definitive
- 12U CubeSat in lunar orbit with height between 1000-1500 km
  - Orient antenna to put lunar surface in null → >1000 km
  - Too high → insufficient time in lunar shadow
- Low TRL but low degree of difficulty
  - EDGES hardware is essentially in CubeSat-scale format
  - High SNR, need only a few days duration (several hours in shadow)
  - Low data rates, low power
  - One simple linear deployment
- Challenge is in precision calibration (and subsequent data analysis)

Antenna design approach

- Electrically small with very low chromaticity
- Monopole puts null in nadir direction, but otherwise samples moon uniformly (moon is at ~300K compared to ~20,000K sky)
- There is plenty of SNR; chromaticity is the challenge!







Backup

HELIOPHYSICS

Mission Objectives

Table 1: Top level objectives for AERO and VISTA missions.

AERO	VISTA
AO1: Characterize auroral radio emissions in the ionosphere	VO1: Demonstrate vector sensor interferometry (VSI) in space
AO2: Connect radio emissions to overall auroral geospace system	VO2: Apply VSI to auroral radio emissions
AO3: Demonstrate polarimetric HF radio signal detection [Tech validation]	VO3: Characterize low Earth orbit (LEO) radio frequency interference (RFI) environment [at HF frequencies]

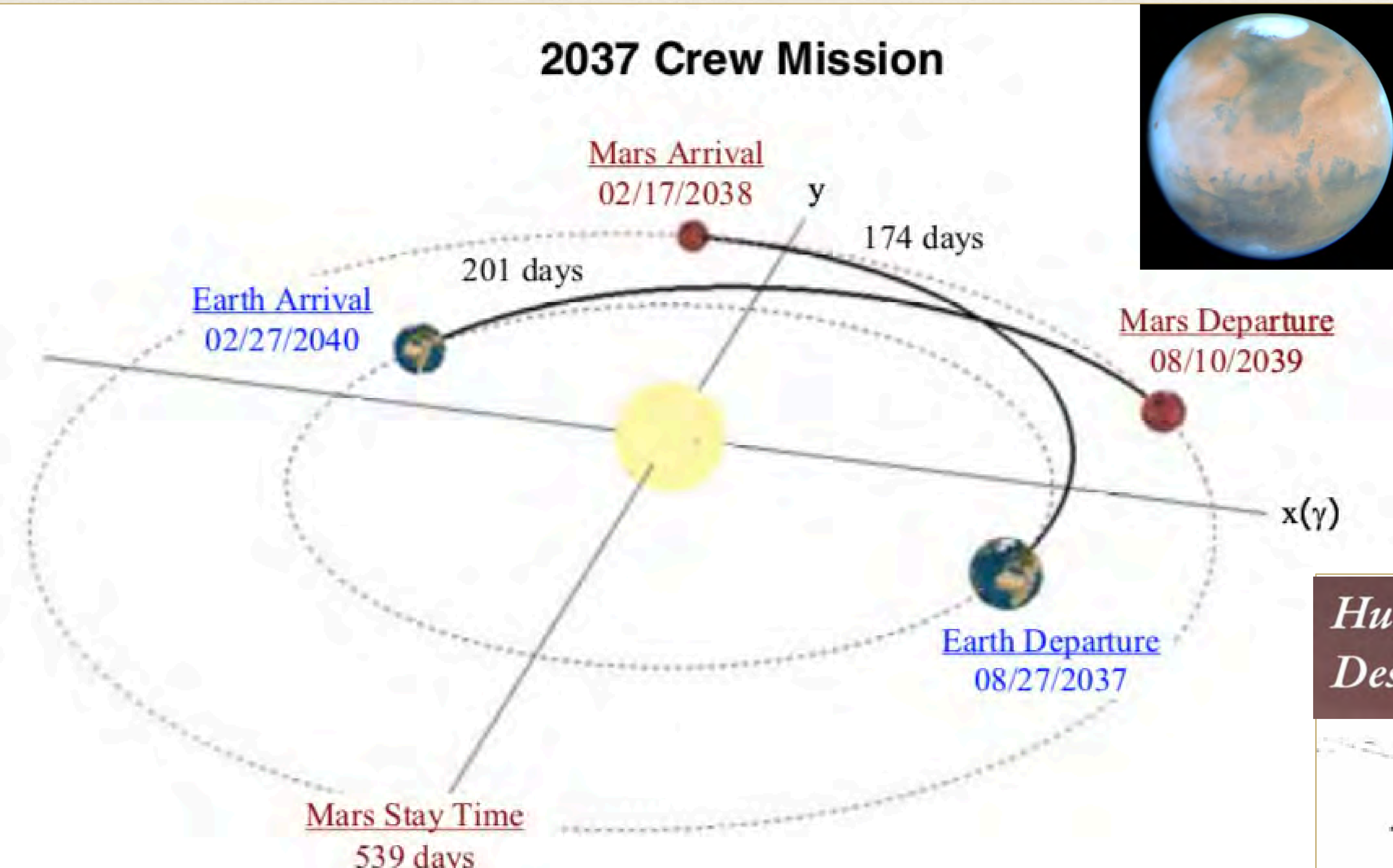
Nominal launch date in 1st Quarter of 2022

Backup

More MOXIE

On the road to… Mars!

MOXIE
Mars Oxygen
ISRU Experiment

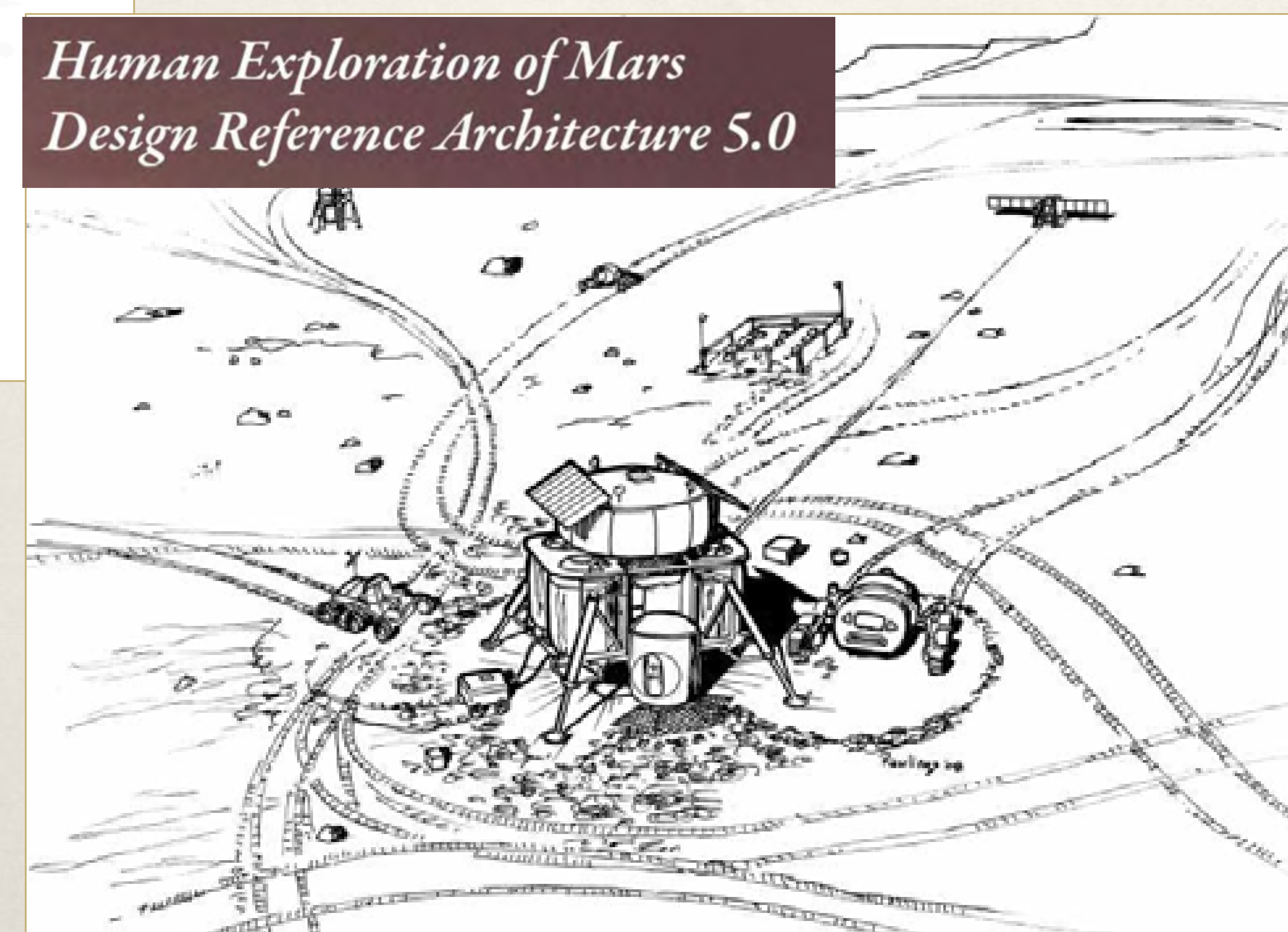


Cargo mission

- HABitat
- Descent/Ascent Vehicle (DAV)
- Rovers (pressurized & unpressurized?)
- 25-30 kW power plant (Kilopower? Photovoltaic?)
- 32 tons propellant (Fuel & oxidizer) or ISRU plant
- …

Human mission

- Mars Transfer Vehicle
- The Crew
- Toothbrush, etc.

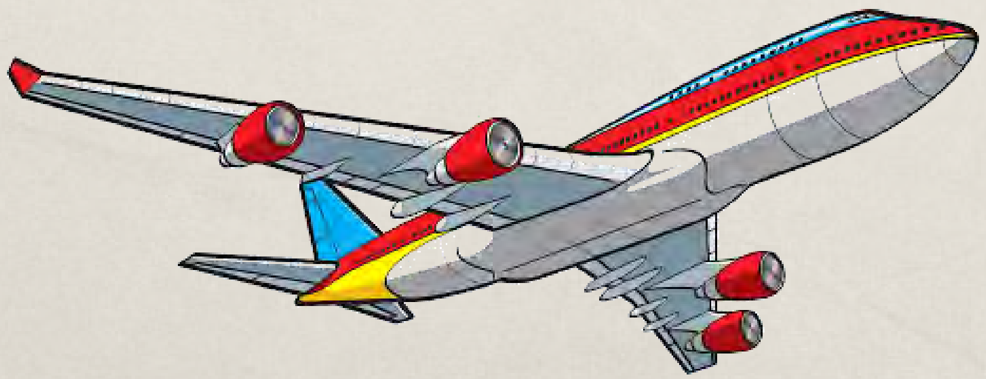


Why we need an “oxygenator:”

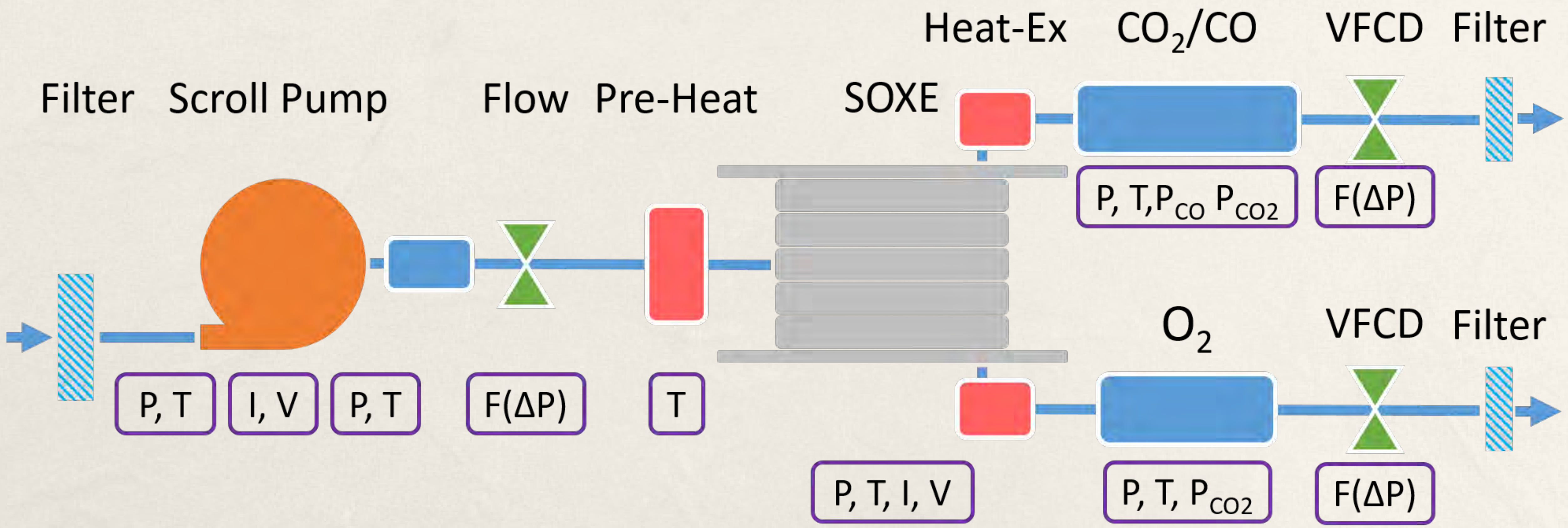
MOXIE Mars Oxygen ISRU Experiment

Everything that burns fuel needs to breathe!

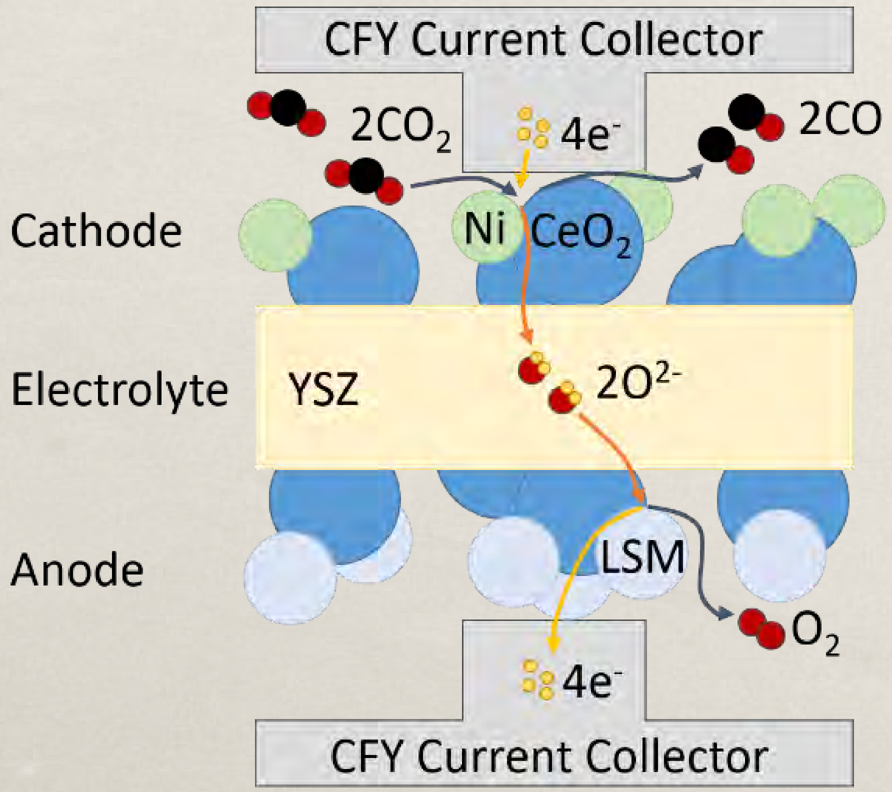
- ⋆ Oxygen weighs several times the weight of the fuel
- ⋆ The biggest fuel burner on Mars? The ***Ascent Vehicle!***
- ⋆ The single heaviest thing we need to bring with us to Mars? A full oxygen tank for the ascent vehicle.
- ⋆ To launch a crew of 4 takes **~25 tons** of O_2 & 7 tons of fuel
- ⋆ In a 150-day mission, the crew only breathes **~0.5 ton** O_2

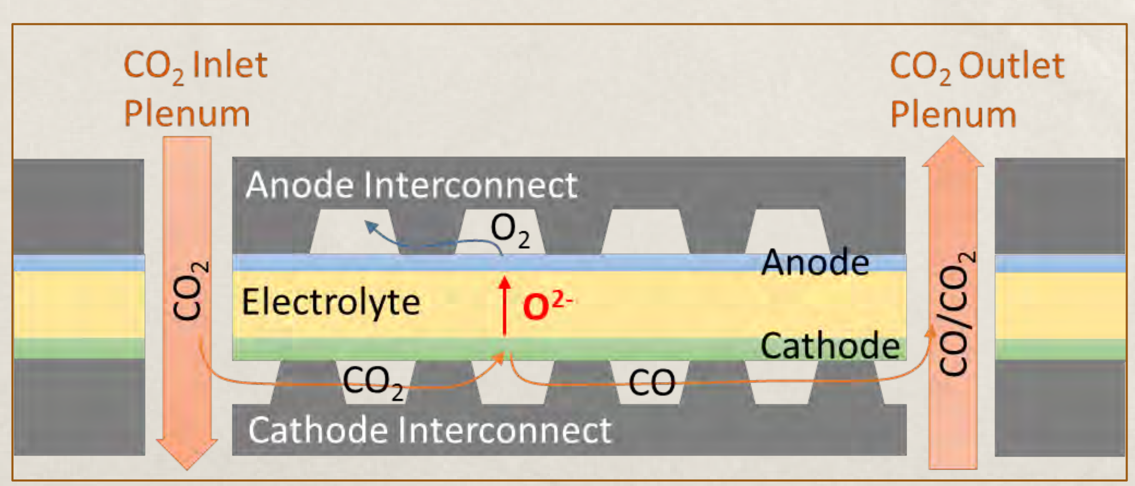


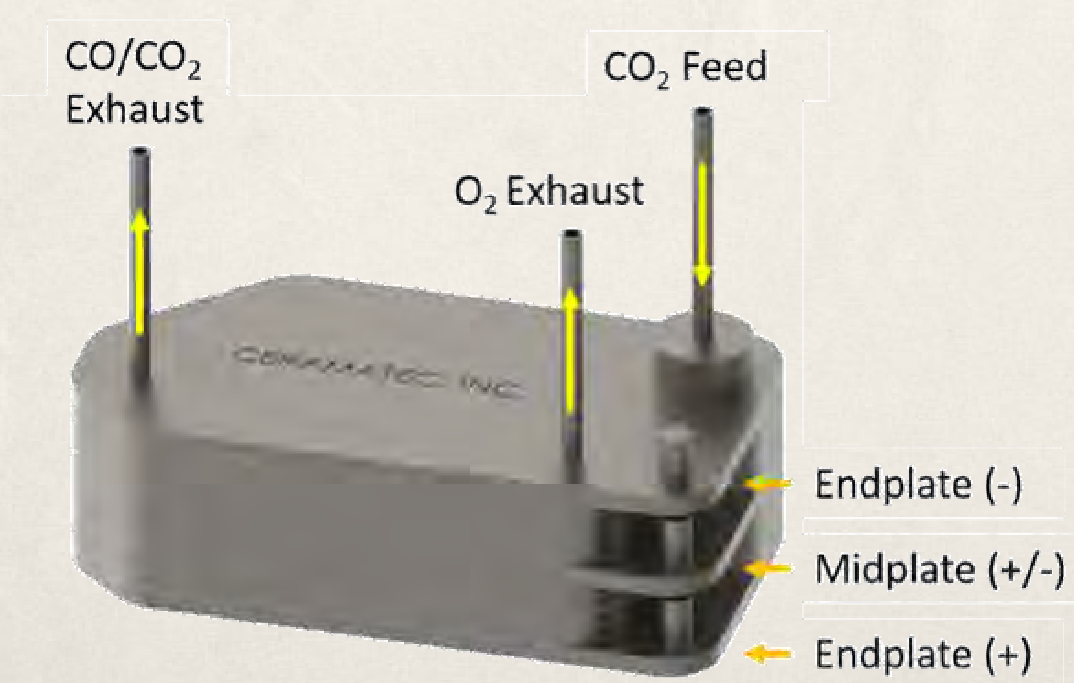
How does it work?



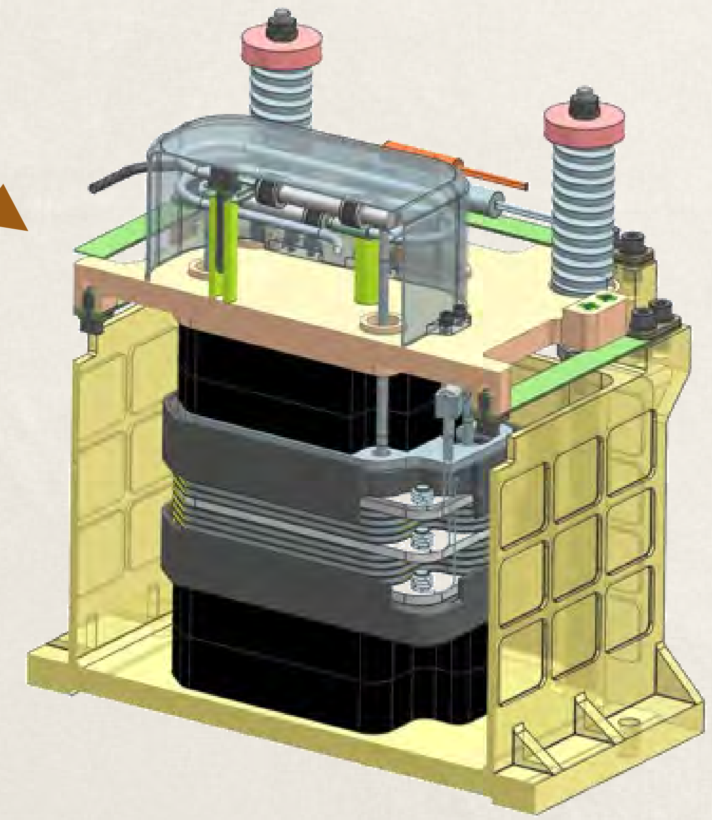
Meyen (2015)

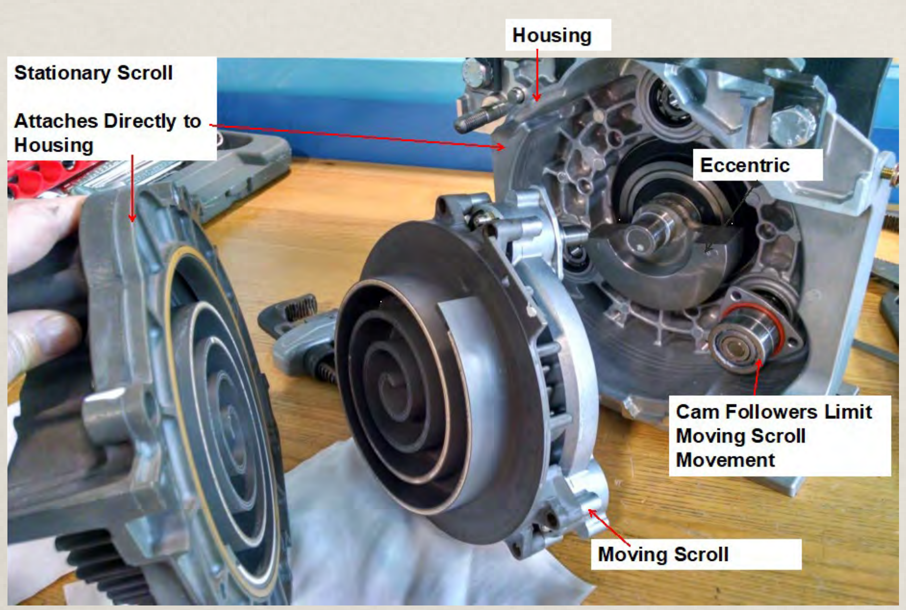


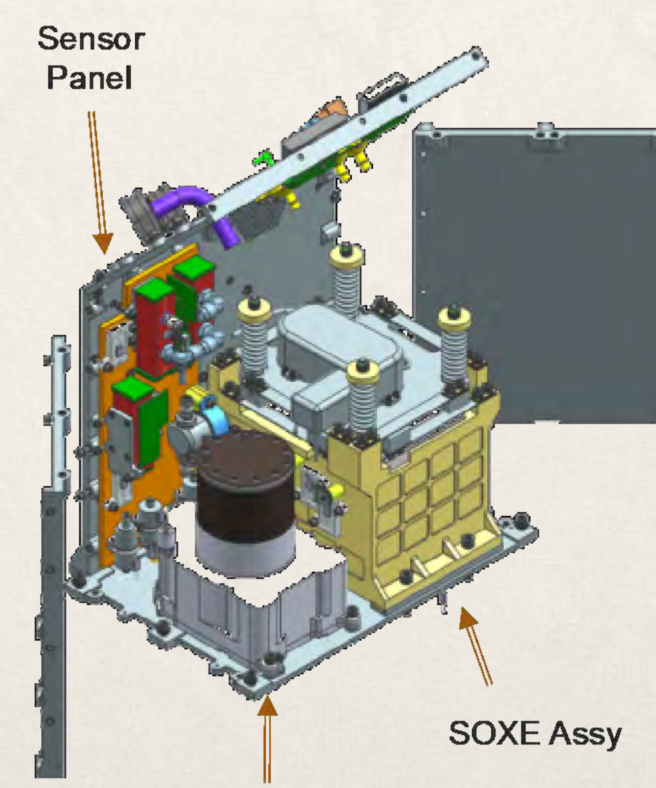




Putting MOXIE together



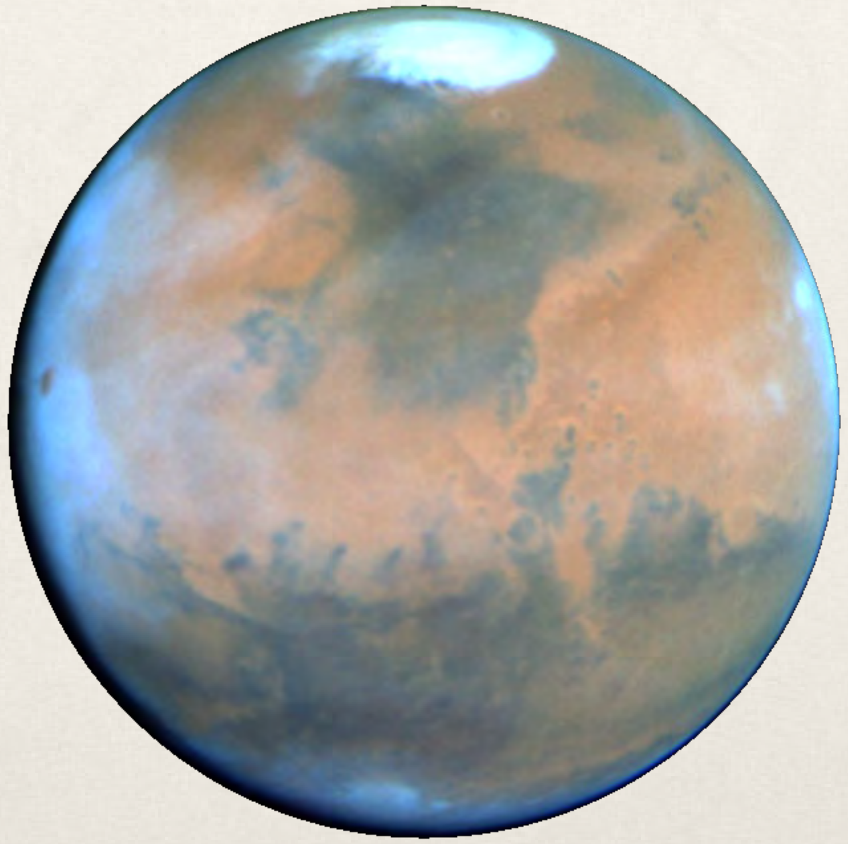




What will MOXIE do on Mars?

MOXIE
Mars Oxygen
ISRU Experiment

- We expect a "MOXIE sol" every 2 months or so
  - MOXIE will run for a ~2 hour session. Much of that time is spent heating the SOXE to 800°C, the rest making oxygen.
  - One run will consume ~1000 W-hr of spacecraft energy – the full payload allocation for a typical sol!
- We're planning 3 mission phases:
  - *Characterization*
  - *Operation*
  - *Experimentation*



Sponsors and Partners

MOXIE
Mars Oxygen
ISRU Experiment

- Supported by HEO/AES, STMD/Tech Demos
- Mars 2020 Project managed by SMD

Thank you,

ISRU Technology,
NASA GRC
Aarhus wind tunnel

MOXIE is brought to you by…

Massachusetts Institute of Technology

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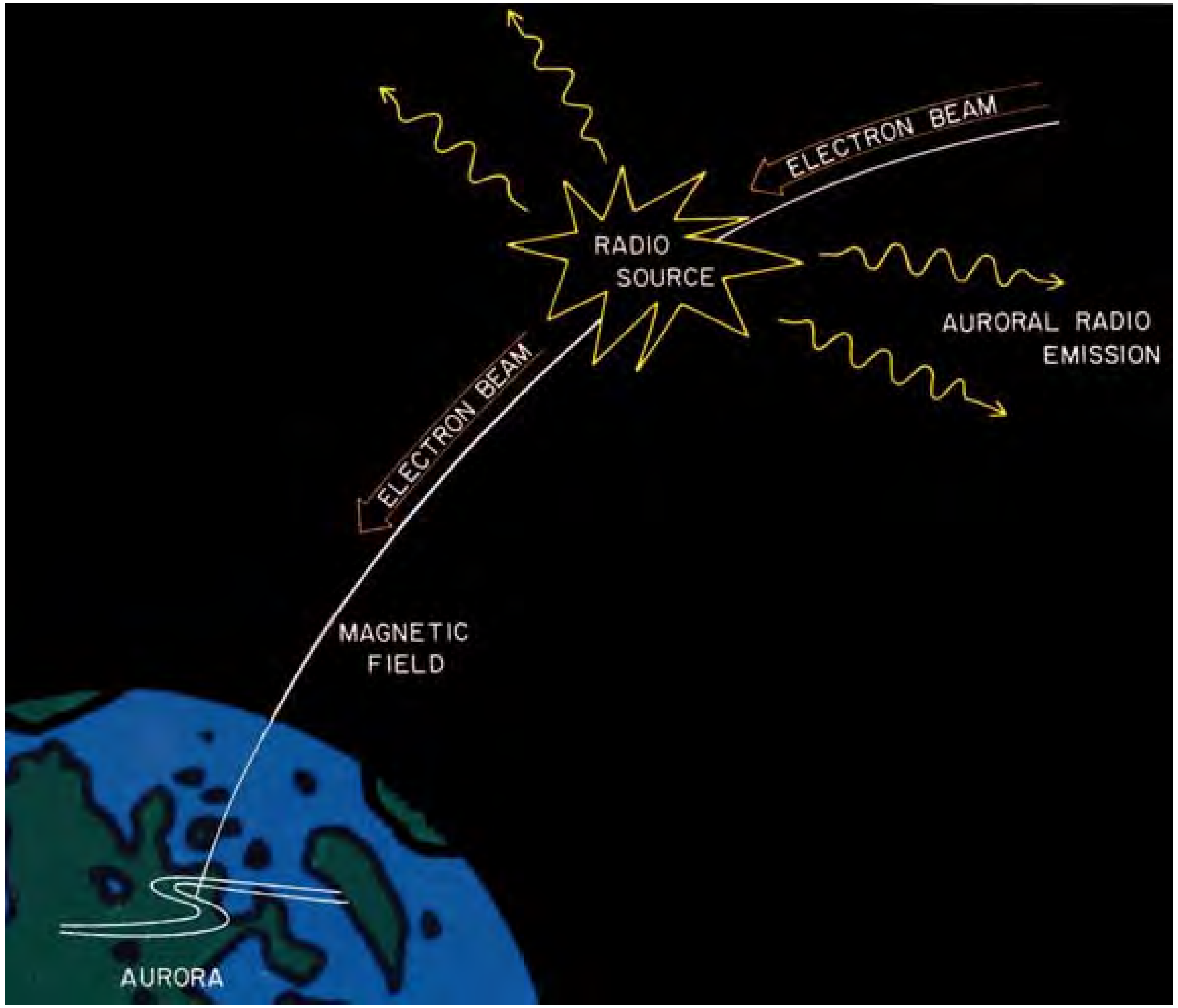
OxEon energy

Backup

More AeroVista

Auroral Kilometric Radio Emission



U. Iowa, "Prof. D. Gurnett's Favorite Space Sounds" (http://www-pw.physics.uiowa.edu/space-audio/sounds/)

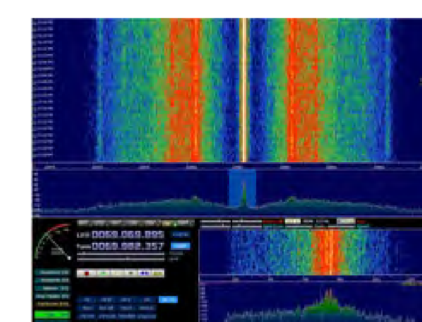
4
5

MSU 21 meter

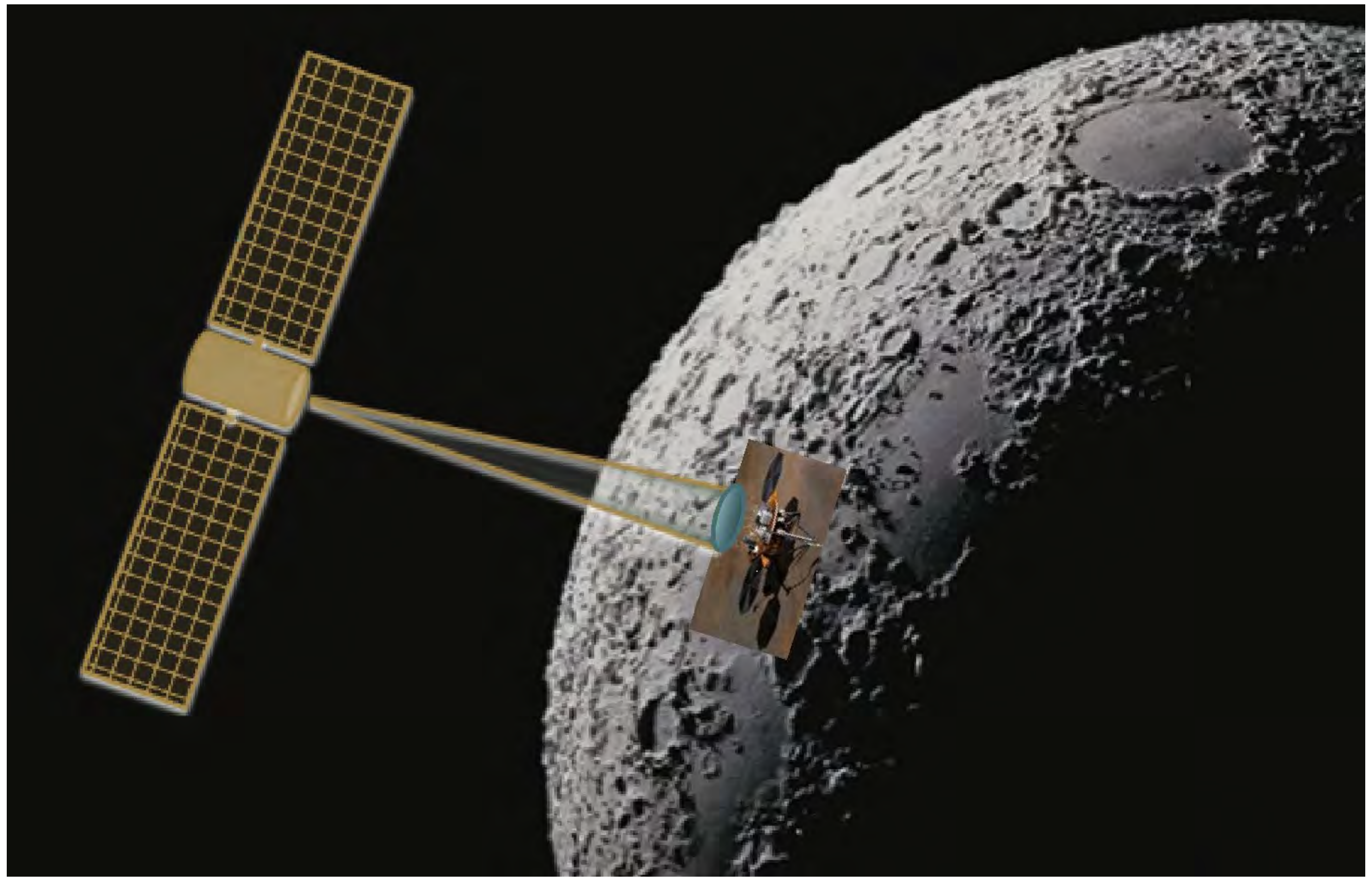
- MSU 21 Meter
  - Fully DSN Compatible ground station (DSS-17)

- Full Remote Control of All Systems
- X-Band Downlink Currently- Uplink planned
- NASA NEN Compatible
- Software-Defined TT&C Processor (SoftFEP) and High Data Rate Digitizer for Experimental Missions
- Extensive use of Student Operators (STEM Engagement)
- Heritage with LRO, Planetlabs Dove, ISEE-3, and many cubesats (e.g. ASTERIA, Firefly, etc...)

Radio Band	Frequency Range	Gain	Uses of Band
UHF	400-480 MHz	30 dBi	Satellite Telecom
S-Band	2.2-2.5 GHz	52.8 dBi	Both Satellite Telecom and Radio Astronomy
X-Band	7.0-8.4GHz	62.0 dBi	Primarily Satellite Telecom
Ku-Band	11.2-12.7 GHz	65.50 dBi	Primarily Satellite Telecom



ISEE-3 Carrier
During Lunar Fly-by
Sept 2014



Backup

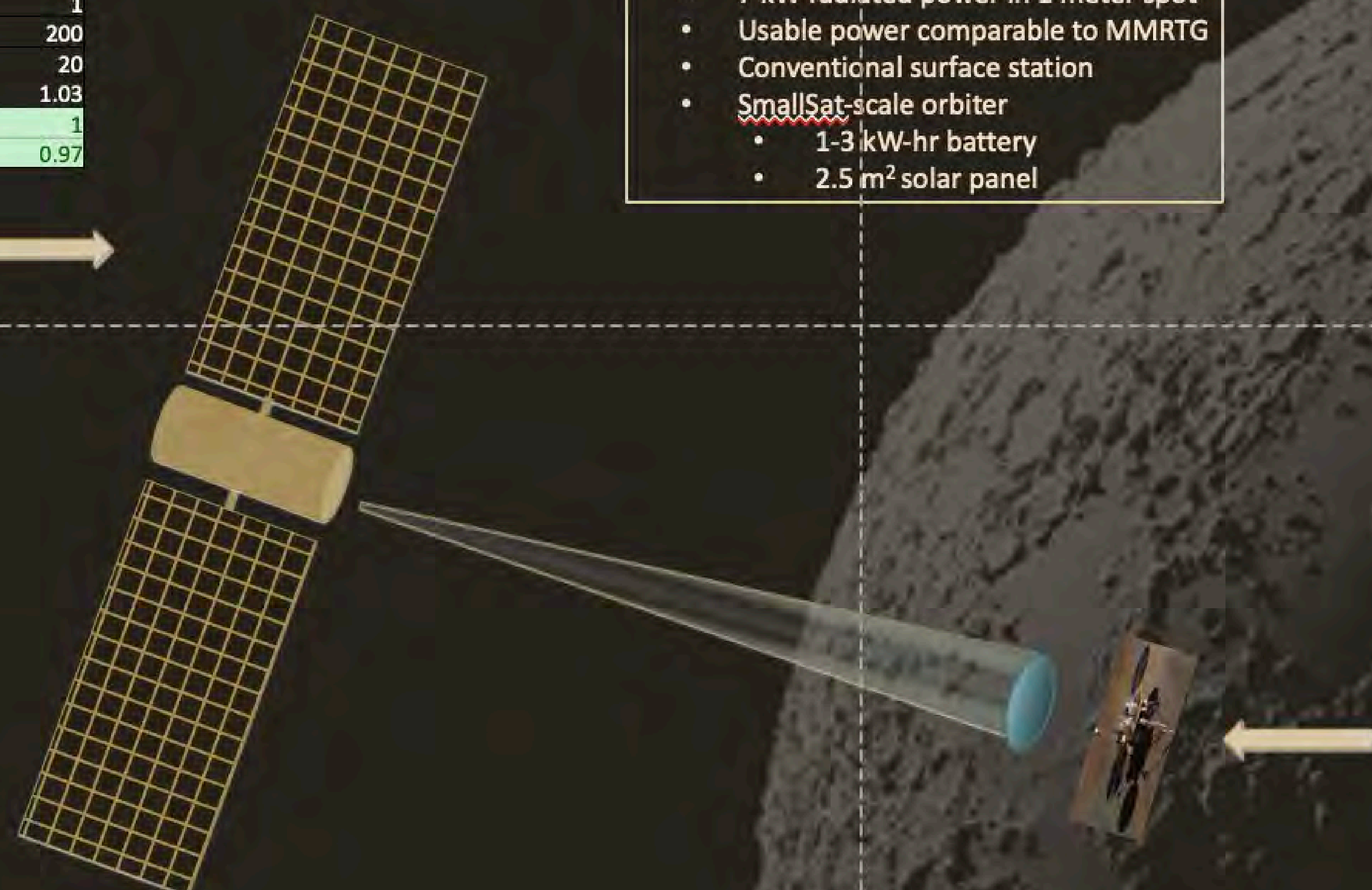
EXPLORATION

Space solar power for the Moon and Mars?

Spot size	
Pointing accuracy (arcsec)	1
Wavelength (μm)	1
Orbit height (km)	200
Mirror diameter (cm)	20
Dispersion (arcsec)	1.03
Minimum spot size (m)	1
Pointing accuracy (m)	0.97

Example: Power for a robotic lander

- 7 kW radiated power in 1 meter spot
- Usable power comparable to MMRTG
- Conventional surface station
- SmallSat-scale orbiter
  - 1-3 kW-hr battery
  - 2.5 m^2 solar panel



Broadcast power	
Link time per orbit (min)	4
Orbit period (min)	132
Orbiter panel area (m^2)	2.5
Solar constant (W/m^2)	1361
Orbiter panel efficiency (%)	25%
Illumination duty cycle	50%
Energy collected (kW-hr/orbit)	0.94
Laser wall plug efficiency (%)	50%
Radiated power (kW)	7.0
Lander panel efficiency (%)	50%
Geometric collection efficiency	80%
Surface illumination (kW/m^2)	8.9
Average surface power (W)	108.3

State of the Technology:

- Lasers:
  - Coherent bundles of fiber lasers deliver 5-50 kW in package appropriate for orbiters
  - Packaging for space, especially thermal management, is an engineering challenge
- Mirror Pointing
  - 1 arcsec gimbaling routinely achieved for SmallSats (e.g. ASTERIA)
  - For power beaming, can use feedback from ground

Scaling up for human missions (Moon & Mars)

- ISRU will need ~25 kW (230x the above example)
- Chain of ~30 satellites provides continuous illumination
- ~8x radiated laser power feasible for each satellite

Example: Power for a lunar lander

MOXIE Mars Oxygen ISRU Experiment

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- Usable power comparable to MMRTG
- Conventional surface station
- SmallSat-scale orbiter
  - 1 kW-hr battery
  - 2.5 m^2 solar panel

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Radio-based navigation