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.
Why is space important for us?

• Compelling science, relevant to our expertise, e.g.
  – Low frequency science not possible below the ionosphere
  – Longer VLBI baselines than possible on Earth

• Growing opportunities within NASA
  – NASA is embracing small tag-along missions ($5-$50M) with relatively aggressive risk posture (SIMPLEX, SALMON, etc.)
  – In comparison, NSF radio opportunities are static or shrinking

• Radio bands on Earth are increasingly polluted
  – Equivalent to the Dark Sky problem for optical astronomy

• Doesn’t take a NASA Lab! (Though they can help). Several NEROC Institutions already hosting missions.
How can we play? What’s our edge?

◆ Local technologies
  – Haystack
    • RAPID-related technologies
  – Lincoln Lab
    ✓ Vector sensors & radios
    • Laser comm
    • Directed laser energy

◆ Local facilities
  – Mission science enhancement
    ✓ Ionosphere with MHGF (Van Allen Probes)
    ✓ Jupiter emissions with RAPID (JUNO)
    • Radio bursts with RAPID (SunRISE)
  – Ground support
    • Ground stations (Westford)
    ✓ Scientific databases such as Madrigal

◆ Limited only by your imagination
Still, it’s not so easy...

◆ Proposals are high payoff, but long odds
  – Can take several tries before winning with a particular concept

◆ NASA is struggling with SmallSat risk posture
  – As SmallSats evolve from educational vehicles to mainstream scientific platforms, NASA is under pressure to accept less formal risk management and mission assurance.
  – But NASA labs and aerospace organizations are getting into the high-end SmallSat science business.
Focus on HF:
For <10 MHz, you need to go to space

- Radio Astronomy Explorers (RAE) I & II
- Electric field probes (Ulysses, WIND, Cassini, STEREO)
- Interferometry on CLUSTER measured AKR angle of arrival
The Auroral Emission Radio Observer (AERO) is a 90-day CubeSat mission in polar orbit that will qualify and validate a novel electromagnetic vector sensor (VS) while answering key scientific questions about the nature and sources of auroral radio emissions. These questions cannot be addressed from the ground due to shielding by the ionosphere.

Radio spectrograms, typical of what AERO may encounter, measured with a sounding rocket.
HeRO

- Science target was radio bursts at low frequency (farther from sun) as indicators of acceleration phenomena at shock front
- Significant ground element based on RAPID
- Proposed to SMEx/SALMON
- Similar mission (SunRISE) was selected
How to build an HF Interferometer in space

- 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 (& desaturate reaction wheels)
- Either GPS or an internal beacon system to accurately determine positions
- Antennas (electrically short 3-axis monopole or vector sensor)
- Correlation: On the ground or in space?
- Timing: Chip-scale atomic clock?
How about an HF tomograph?

- BeaconSats and SensorSats (or Simultaneous Transmit & Receive)
- Determine 4D structure of solar wind
- Measure electron current density and Faraday rotation along Tx/Rx path
- Monitor ICMEs incoming to Earth
Or astrophysics?

- EDGES observed 21-cm absorption from first stars!
- Confirmation behind moon (away from Earth foreground noise) is very attractive
- Can be achieved with CubeSat 1000 km above lunar surface (to put moon in null of dipole).

CoDEx CubeSat approach
Space Logistics (deWeck group)

Exploration Infrastructure
Radio-based navigation
Space Solar Power for the Moon?

- 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 m² solar panel

<table>
<thead>
<tr>
<th>Spot size</th>
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<tbody>
<tr>
<td>Pointing accuracy (arcsec)</td>
<td>1</td>
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<tr>
<td>Wavelength (μm)</td>
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<tr>
<td>Orbit height (km)</td>
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<tr>
<td>Mirror diameter (cm)</td>
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<tr>
<td>Dispersion (arcsec)</td>
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<tr>
<td>Minimum spot size (m)</td>
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<tr>
<td>Pointing accuracy (m)</td>
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<table>
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<tr>
<th>Broadcast power</th>
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<tr>
<td>Link time per orbit (min)</td>
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<tr>
<td>Orbit period (min)</td>
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<tr>
<td>Orbiter panel area (m²)</td>
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<tr>
<td>Solar constant (W/m²)</td>
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<tr>
<td>Orbiter panel efficiency (%)</td>
<td>25%</td>
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<td>Illumination duty cycle</td>
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<td>Energy collected (kW-hr/orbit)</td>
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<tr>
<td>Laser wall plug efficiency (%)</td>
<td>50%</td>
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<td>Radiated power (kW)</td>
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<tr>
<td>Lander panel efficiency (%)</td>
<td>50%</td>
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<tr>
<td>Geometric collection efficiency</td>
<td>80%</td>
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<tr>
<td>Surface illumination (kW/m²)</td>
<td>8.9</td>
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<tr>
<td>Average surface power (W)</td>
<td>108.3</td>
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Getting Mark Watney home
Mars Oxygen ISRU Experiment

GOT OXYGEN?
What’s in MOXIE?

Meyen (2015)
Making $\text{O}_2$ with SOXE

- **Cathode**: $\text{CO}_2 \rightarrow 2\text{e}^- \rightarrow \text{Ni}/\text{CeO}_2 \rightarrow 2\text{CO}$
- **Electrolyte**: YSZ
- **Anode**: $\text{O}_2 \rightarrow 4\text{e}^- \rightarrow \text{LSM}$

**Diagram**

- **CO$_2$ Inlet Plenum**
- **Anode Interconnect**
- **Electrolyte**
- **Cathode Interconnect**
- **CO$_2$ Outlet Plenum**

- **CO$_2$ Feed**
- **O$_2$ Exhaust**
- **Endplate (-)**
- **Midplate (±)**
- **Endplate (+)**
What will MOXIE do?

- MOXIE is a 1:200 scale model of an ISRU plant for a human mission.

- When running, MOXIE will make 6-10 g of oxygen per hour (about half as much as you need to breathe).

- MOXIE will run for about an hour, approximately one day out of every 2 months.
Backup: More MOXIE
Packing for Mars…

* Cargo mission
  * HABitat
  * Descent/Ascent Vehicle (DAV)
  * Mobility systems (pressurized & unpressurized rovers)
  * Power systems (Kilopower reactor? Photovoltaic?)
  * Propellant (Fuel & oxidizer) or ISRU plant

* Human mission
  * Mars Transfer Vehicle
  * The Crew
  * Toothbrush, etc.
The Itinerary...

2037 Crew Mission

- Earth Arrival: 02/27/2040
- Mars Arrival: 02/17/2038
- Mars Departure: 08/10/2039
- Earth Departure: 08/27/2037
- Mars Stay Time: 539 days

174 days
201 days
The luggage...

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<tr>
<th>Surface Systems</th>
<th>Quantity</th>
<th>Habitat Lander System Mass (kg)</th>
<th>DAV Lander System Mass (kg)</th>
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<td>Crew Consumables</td>
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<td>Science</td>
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<td>Robotic Rovers</td>
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<td>Drill</td>
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<td>Unpressurized Rover</td>
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<td>Pressurized Rover Growth</td>
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<tr>
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<td>Traverse Cache</td>
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<td>Habitat Growth</td>
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<td>Stationary Power System</td>
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<td>1,130</td>
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<tr>
<td><strong>Total Surface Systems</strong></td>
<td>-</td>
<td><strong>40,400</strong></td>
<td><strong>18,430</strong></td>
</tr>
</tbody>
</table>

Plus: Propellant to leave Mars!
- 27 tons of $O_2$
- 7 tons $CH_4$