Solar Observing Low-frequency Array for Radio Astronomy (SOLARA)

Exploring the last frontier of the EM spectrum

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From the beginning of astronomy to recent times, only light visible to the human eye could be observed.
Ultra Low Frequency Observations

- Ionosphere blocks/reflects wavelengths below ~10 MHz
  - Space-based observatory
- Long wavelengths require large apertures for angular resolution ($\vartheta = \lambda/D$)
- Monolithic apertures are impractical
  - INTERFEROMETRY (sparse aperture)
- Interferometer baseline measurement requirements easier at long wavelengths ($\mu \approx \lambda/10$)
- Solution: *CubeSat interferometer in space*
Astronomy at long wavelengths: Coronal Mass Ejections (CMEs)

- Danger to spacecraft, astronauts, and terrestrial power grids
- SOLARA can track CMEs in 3D by monitoring radio bursts generated by shock waves
- Type of radio burst indicates how dangerous a solar storm will be to Earth

Image Credit: NASA/ESA
Astronomy at long wavelengths: Giant Planet Magnetospheres

- **5 planets with strong magnetic fields** in the solar system: Earth, Jupiter, Saturn, Uranus, Neptune
- **No** spatially resolved imaging of radio sources below ionospheric cut-off
- Voyager s (launched 1973) were first and last to study long wavelength radio emissions from all giant planets
CubeSat Implementation
Radio Science Instrument

- 2 deployable “active” BeCu dipole antennas (6 m) orthogonal to each other
- Low-noise amplifier
- Payload and Telemetry System (PTS): customized radio receiver
  - FPGA-based
  - 1 Hz frequency tuning
  - Bandwidths from 1 kHz to 10 MHz
  - Optimized for 100 kHz to 10 MHz

Stored Tubular Extendible Member (STEM) deployable antenna (Northrop-Grumman)
Interferometry

- Aperture synthesis interferometry
- **Distributed correlator** – no central hub
- 190 unique baselines (20 spacecraft)
- Array will grow over time, increasing angular resolution
  - 1 – 60 arcminutes @ 1 MHz

Present: Ground-based, central correlator

SOLARA: space-based, distributed correlation

Very Large Array (VLA), New Mexico, USA

UHF Radio Telescope at Fuji Station
Formation Flight (Lite)

• Relaxed metrology requirements – accurate baseline measurement necessary, but NOT control
• “Beginner” formation flight – only occasional corrections/adjustments required, not constant formation maintenance (open loop)
• Intersatellite ranging: SARA (S-band)
• Constellation orientation - aggregated star tracker measurements
Communication: SARA

- **Separated Antennas Reconfigurable Array (SARA)** will use the SOLARA constellation as a platform to test the technology of MIMO systems in space.
- **Key idea**: multiple antennas opportuneely aggregated to form a highly directional array by combining signals in phase.
- 2 S-Band channels for each spacecraft:
  - One for Earth communication
  - One for inter-satellite links
- **Master-slave configuration**
  - Comm to Earth (time, data) coordinated by master
  - Intersatellite clocks and ranges exchanged frequently
- **SARA gain**: 23 dB, 57 kbps from LL1 vs. CubeSat gain: 6dB, 2.4 kbps from LL1
Propulsion: Electrospray Patch Thrusters

Electrospray thrusters developed by **Prof. Paulo Lozano** of MIT’s Space Propulsion Lab

- High voltage grids (1-2 kV) accelerate ions to provide thrust
- Small footprint (1 cm²)
- Ionic liquid propellant:
  - No vapor pressure
  - No pressure vessels or plumbing
  - No combustion
- High Isp (~3500), low propellant mass
- ~1 μN per thruster
- Thrusters will be tested in precursor missions

Images adapted from Lozano & Courtney, 2010
Carrier Vehicle – GTO to LL1 transfer

- Transports SOLARA/SARA CubeSats to LL1 destination
- Radiation protection while in transit
- High gain communications
- Back-up central hub for array
Journey to LL₁

Initial Geostationary Transfer Orbit (GTO)

Expanding Elliptical Orbits (~3 months)

Injection into Lissajous orbit about LL₁

Earth-Moon Lagrange Points
Subsystems

- **ADCS** – thrusters are actuators, star tracker, sun sensors, gyros provide attitude estimate
- **Power** – deployable solar wings provide 30 W power. Orbit allows near-continuous sunlight
- **Avionics** – ARM7-based flight computer will provide ADCS calculations and housekeeping
- **Structure** – custom 6U structure manufactured from aluminum
- **Thermal** – LL1 orbit and sun-pointing solar panels provides a stable thermal environment. Antisun-facing spacecraft sides used as radiators
Strategy and Schedule

• Three-phase implementation:
  – Phase 1: Thruster demonstration precursor mission - 2014
  – Phase 2: Science payload demonstration in LEO (2-3 CubeSats) – 2015-2017
  – Phase 3: Full array launch and deployment in LL1 – 2018-2020
Conclusions

- Ambitious but feasible – **high risk, high reward**
- Precursor missions reduce risk and raise TRL of novel technologies
- Full redundancy – no single point of failure, tolerant to CubeSat losses
- Convergence of technologies to make SOLARA/SARA possible – **paradigm shift**

**Existing Technologies:**
- Deployable STEM antennas
- S-band inter-satellite ranging (PRISMA)
- CubeSat star tracker
- ADS sensor-enabled solar panels
- FPGA-based correlation
- Multi-CubeSat delivery

**Novel/developing Technologies:**
- SARA
- Electrospray thrusters
- PTS (radio science receiver)
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This work references NASA proposals for the ALFA and SIRA missions
Back-Up Slides
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<th>Frequency</th>
<th>Wavelength</th>
<th>θ @ 10 km</th>
<th>θ @ 100 km</th>
<th>θ @ 1000 km</th>
<th>θ @ 10,000 km</th>
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<td>30 MHz</td>
<td>10 m</td>
<td>3.4’</td>
<td>20.63”</td>
<td>2.06”</td>
<td>0.2”</td>
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<tr>
<td>10 MHz</td>
<td>30 m</td>
<td>10.31’</td>
<td>1’</td>
<td>6.19”</td>
<td>0.62”</td>
</tr>
<tr>
<td>1 MHz</td>
<td>300 m</td>
<td>1.719°</td>
<td>10.31’</td>
<td>1’</td>
<td>6.19”</td>
</tr>
<tr>
<td>100 kHz</td>
<td>3000 m</td>
<td>17.19°</td>
<td>1.719°</td>
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<tr>
<td>30 kHz</td>
<td>10,000 m</td>
<td>57.29°</td>
<td>5.73°</td>
<td>34.38’</td>
<td>3.43’</td>
</tr>
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CubeSat Implementation

- Solar panel "wings"
- Electrospray patch thrusters
- 3 m BeCu deployable antenna
- Star tracker lens
- S-band patch antennas