XSOLARA
ExtraSolar Observing Low-Frequency Array for Radio Astronomy

Workshop for CubeSat-Based Low Frequency Radio Astronomy
Keck Institute For Space Studies
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Team

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Study Lead

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Team Members

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Sarah Hand
Kyle Olson
Rebekah Sosland
The University of Texas at Austin

Timeline

- XSOLARA team primary objective:
  - Feasible mission
  - High science return
  - Low cost
  - Student designed/built mission

- XSOLARA team constraints:
  - Only 3 months to work on
  - Team of 7 “full time” students
  - Limited resources

February
- Feb 1–20: Concept Generation

March
- March 1: Down-Select from different concepts
- March 26: Midterm Presentation
- May 1: Final Presentation
- May 4: Final Report Due

April
Science
“A time will come when men will stretch out their eyes. They should see planets like our Earth.”

-Christopher Wren, 1702
XSOLARA Goals

• **Science Goal:**
  – Detect extrasolar planets
  – Prove the concept that exoplanets can be detected with this method
  – Path finder mission

• **Education Public Outreach (EPO) Goal:**
  – Inspire and motivate students to do STEM
  – Provide hands on experience for college students
• Earth and gas giants of our solar system are “magnetic planets”
  – The interaction between solar wind and their “magnetospheres” generate radio-wavelength masers
  – In the case of Earth, its magnetic field contributes to its habitability
In 2004, an exoplanet orbiting HD 179949 located 90 light-years in Sagittarius was identified to have magnetic properties

- Hot spot that rotates around the star every 3 days (period of the planet)
  - Cause: Interaction between planet’s magnetic field and the star’s lower atmosphere
- Analogous to magnetic connections between Jupiter and its moons
Science background

• It’s likely that most or all giant exoplanets possess magnetic fields

• One could use this discovery to “detect” exoplanets
  – Extrasolar giant planets should emit at radio wavelength allowing for their direct detection

• Current searches:
  – Very Large Array (VLA)
    • 74 MHz/ 135-200 mJy
  – Metrewave Radio Telescope (GMRT)
    • 150 MHz/0.3-2mJy
Science Priority

• Huge limitation for all the ground-based telescopes:
  – Earth’s ionosphere
    • Cut off frequency of 10 MHz

• Need for a space-based radio telescope

XSOLARA
Science Objectives

Primary

- Detect known exoplanets in order to prove the concept that exoplanets can be detected by looking for magnetospheric emissions in low-frequency range.

Secondary

- Image and track transient solar disturbances. Observe Earth’s magnetospheric response to these coronal mass ejections (CMEs) and accurately predict geomagnetic storms days in advance.
Primary Objective

Primary

- Detect known exoplanets in order to prove the concept that exoplanets can be detected by looking for magnetospheric emissions in low-frequency range.

Scientific Investigations

- Observe pre-determined stars in 0.1-10 MHz frequency range
- Achieve sensitivities in order of mJy

Science Return Areas

- Enhancement of radio emission at the location of the target star
- Demonstrating that there is radio emission coming from the direction of the pre-determined star
- Prove the concept
Secondary Objective

Secondary
- Image and track transient solar disturbances. Observe Earth’s magnetospheric response to these coronal mass ejections (CMEs) and accurately predict geomagnetic storms days in advance.

Scientific Investigations
- Little to no modification to the system
- Observe solar disturbances in the low frequency range

Science Return Areas
- Image and track solar disturbances with spatial resolution
## Science Traceability

### XSOLARA

<table>
<thead>
<tr>
<th>Exploration Priorities</th>
<th>Science Objectives</th>
<th>Science Investigations</th>
<th>Specification</th>
<th>Parameter Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Goal I:</strong></td>
<td><strong>Science Goal 1c:</strong> Search for and exploit extrasolar planet</td>
<td><strong>Search for an extrasolar planetary magnetospheric emissions as a means of directly detecting and characterizing those planets.</strong></td>
<td><strong>Frequency</strong></td>
<td>0.1-10 MHz</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Observe the sky below Earth’s ionosphere cutoff freq.</strong></td>
<td><strong>Instantaneous aperture plane</strong></td>
<td>91</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Use Aperture Synthesis techniques</strong></td>
<td><strong>Bandwidth</strong></td>
<td>1 MHz</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><strong>Sensitivity</strong></td>
<td>120 mJy</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><strong>Number of Antennas</strong></td>
<td>14</td>
</tr>
<tr>
<td><strong>Goal II:</strong></td>
<td><strong>Science Goal 2c:</strong> Characterize the structure of extrasolar planets</td>
<td></td>
<td><strong>Relative time Knowledge</strong></td>
<td>500 nanosecond</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><strong>Relative Position Knowledge</strong></td>
<td>30 m</td>
</tr>
</tbody>
</table>
Sensitivity vs. # Antennas

Bare minimum number of antennas needed for a synthesis array. Can get 80% of the possible phase data and 78% of the amplitude data.

- **180 days of mission, 10 antennas**
  - 125 mJy
- **180 days of mission, 14 antennas**
  - 120 mJy
- **365 days of mission, 10 antennas**
  - 90 mJy
- **365 days of mission, 40 antennas**
  - 24 mJy

6 Month Mission
Science Instrument

- Simple dipole antenna
- “STEM” technology
  - Storable Tubular Extendable Member
  - Manufactured in beryllium copper
  - 11 meter in length
  - Flight heritage:
    - Voyager
    - Hubble
    - Many more
- Modified MF/HF receiver
  - Capable of frequency range 0.1-10 MHz
  - Proven technology
Mission Design
Mothership/CubeSat Platform

Mothership

- Modified ESPA ring

3U CubeSat

- CubeSats
  - 34x10x10 cm
  - 4 kg
  - Low-cost
  - Student built

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CubeSat Components

- Science Receiver
- Star Camera
- Thruster
- Gyroscopes
- Flight Computer
- Patch Antenna
- Science Antenna
- Reaction Wheels
- Sun Sensors
- Power Board
- Battery Board

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Criteria

• Minimize terrestrial radio interference
  – Heavy use of the radio spectrum in the relevant frequency (AM radio band)
• Avoid “break-out” of terrestrial signals
• Largest accessible fraction of sky at any given time
• Stable orbit to minimize station keeping

Distant Retrograde Orbit (DRO) at 1.2 million km from Earth
Trajectory

Final Orbit:
- 1.2 x 1.0 million km
- Ecliptic Inclination: 3.0 deg
- Ecliptic Node (initial): 90 deg to sun
- Period: 94 days

Earth – GEO
- Secondary payload

GEO – DRO
- 1200 m/s ΔV from Mothership

DRO insertion
- 137 m/s ΔV from Mothership

CubeSats Deployed
- Only 7 m/s ΔV for station keeping
• No particular configuration will be followed
• CubeSat deployment timing
  – $t = t_0 + 10$ minutes
• CubeSat deployment $\Delta V$
  – 0.1 m/s

- Need to have position knowledge of each CubeSat
- No need to control the position of each CubeSat
- No need to point the science antenna
- Can use the drift rate in our advantage to change angular resolution over time
Current Design Status

• Design Maturity
  – Currently XSOLARA is a feasibility study
  – Components and data shown are to demonstrate the design is reasonable and achievable

• Technical Margins
  – Resource margins meet JPL design principles for Concept Review
  – Resource margins will be continuously monitored

• Cost
  – University and hardware costs will be shown
<table>
<thead>
<tr>
<th>Subsystem</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mothership</td>
</tr>
<tr>
<td>Propulsion</td>
</tr>
<tr>
<td>Communication</td>
</tr>
<tr>
<td>ADCS</td>
</tr>
<tr>
<td>Power</td>
</tr>
<tr>
<td>C&amp;DH</td>
</tr>
<tr>
<td>Structure</td>
</tr>
</tbody>
</table>

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Mothership
Mothership: SHERPA 2200

• Gross Mass: 2000 kg
• Capable of 2200 m/s of $\Delta V$
• Size/Volume: Standard ESPA ring (1575 mm) interface
• Currently rated for Cis-Lunar environments, can be modified for DRO
• All subsystems are compatible with XSOLARA’s mission with slight modifications in the communication and attitude control subsystems
Andrews CubeSat Launcher
- 2 launchers attach directly to SHERPA
- Each launcher holds 10 3U CubeSats
- Uses the ISIS-POD launcher
- Contains a sequencer that automatically dispenses the CubeSats in a collision-free environment
- Capable of recording data from and photographing separation
Launch Services

• Launch opportunities:
  – Falcon 9
  – Falcon Heavy
  – Delta IV
  – Atlas V
  – Minotaur IV SLV

• Andrews Space will be providing the launch vehicle, SHERPA, and CubeSat launcher for XSOLARA

• First flight scheduled for 2014
Propulsion
- CubeSat propulsion system:
  - Cold Gas system
  - Must provide at least 7 m/s ΔV

- CubeSat propulsion system can hold up to 0.09 kg of propellant providing up to 15 m/s ΔV

<table>
<thead>
<tr>
<th>CubeSat Cold Gas Mass</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass of 1 CubeSat (kg)</td>
<td>4.00</td>
<td>4.00</td>
</tr>
<tr>
<td>ΔV (m/s)</td>
<td>15.20</td>
<td>7.00</td>
</tr>
<tr>
<td>ISP (s)</td>
<td>70</td>
<td>70</td>
</tr>
<tr>
<td>Propellant mass (kg)</td>
<td>0.09</td>
<td>0.04</td>
</tr>
</tbody>
</table>

- CubeSat can provide more than double XSOLARA’s station keeping needs
Hardware

• CubeSat propulsion system:
  – Austin Satellite Design
  – R-236fa cold gas refrigerant
  – 1 thruster per CubeSat for station keeping

• Complete module
  – Tanks and plumbing built into one piece made from solid stereolithography plastic
Communication
Constraints

**Mothership**
- Power is limited by SHERPA’s capabilities
  - 150 W allotted to the Communication Subsystem
  - 140 W only includes transmit power
  - Maximize bit rate within this limitation
- Minimum downlink data rate is determined by Nyquist Sampling Rate

**CubeSats**
- Data rate is limited by the Mothership’s data rate
- Determined by modulation and Eb/No requirements
- 0.1 to 10 MHz frequency range
  - Determines minimum bit rate via Nyquist Sampling
  - Limits hardware possibilities and selection
- Transmit power will be rounded up to 0.5 W to account for any errors that may be experienced throughout the mission
Mothership

- The Mothership will have nearly constant uplink and downlink communication with the Deep Space Network’s 34m antennas via X Band frequency
- Equipped with a 0.5m High Gain Antenna (~30dB), multiple receivers and patch antennas
- Receivers will be unique to XSOLARA’s requirements
- SHERPA shall allocate ~150 W to the communication subsystem
  - Approximately 140 Watts will be used in transmit/receiving power
• 37.7 Mbps (Maximum performance)
  – Minimum set by Nyquist Sampling
    • Bit Rate=N*2*df*b
  – Constrained by available power
• PM-BPSK Modulation
  – Binary Phase Shift Keying
  – Converts to binary: robust and compact
• Transmit Power: 140.33 W
  – Worst Case Scenario
  – Highest Performance

<table>
<thead>
<tr>
<th>Mothership to Earth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Downlink</td>
</tr>
<tr>
<td>Linear</td>
</tr>
<tr>
<td>dB</td>
</tr>
<tr>
<td>η-comm</td>
</tr>
<tr>
<td>η-mother</td>
</tr>
<tr>
<td>η-DSN</td>
</tr>
<tr>
<td>D-DSN</td>
</tr>
<tr>
<td>D-mother</td>
</tr>
<tr>
<td>Frequency</td>
</tr>
<tr>
<td>Speed of Light</td>
</tr>
<tr>
<td>λ</td>
</tr>
<tr>
<td>Distance</td>
</tr>
<tr>
<td>Gtrans</td>
</tr>
<tr>
<td>Grec</td>
</tr>
<tr>
<td>λs</td>
</tr>
<tr>
<td>λa</td>
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<td>λθ</td>
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<td>k</td>
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<td>k</td>
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<td>Ts</td>
</tr>
<tr>
<td>B</td>
</tr>
<tr>
<td>I</td>
</tr>
<tr>
<td>Eb/No req</td>
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<tr>
<td>Link Margin</td>
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<td>Eb/No des</td>
</tr>
<tr>
<td>Pin</td>
</tr>
<tr>
<td>Margin</td>
</tr>
<tr>
<td>Pin Total</td>
</tr>
<tr>
<td>Prec</td>
</tr>
</tbody>
</table>
CubeSats

- Power was calculated at maximum distance from Mothership
- Equipped with a Low Gain antenna (~6dB), patch antennas, receivers, and a science antenna
• 2.67 Mbps (Maximum Performance)
  – Minimum set by Nyquist Sampling
    • Bit Rate=N*2*df*b
  – Constrained by Mothership’s data rate

• Transmit Power: 0.125 W
  – Round to 0.5 W
  – Worst Case Scenario
  – Highest Performance

<table>
<thead>
<tr>
<th>CubeSat to Mothership</th>
<th>Downlink</th>
<th>Linear</th>
<th>dB</th>
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</thead>
<tbody>
<tr>
<td>η-comm</td>
<td>0.3</td>
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<td></td>
</tr>
<tr>
<td>η-cube</td>
<td>0.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>η-mother</td>
<td>0.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D-mother</td>
<td>0.5</td>
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<td></td>
</tr>
<tr>
<td>D-cube</td>
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<tr>
<td>Frequency</td>
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</tr>
<tr>
<td>Speed of Light</td>
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<tr>
<td>λ</td>
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<tr>
<td>Distance</td>
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<tr>
<td>Gtrans</td>
<td>3.98</td>
<td>6</td>
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<tr>
<td>Grec</td>
<td>1.64</td>
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<tr>
<td>Ls</td>
<td>2.25E-13</td>
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<tr>
<td>La</td>
<td>1</td>
<td>0</td>
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</tr>
<tr>
<td>Lφ</td>
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<td>k</td>
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<td>B</td>
<td>2.67E+06</td>
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<tr>
<td>l</td>
<td>2.00</td>
<td>3</td>
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</tr>
<tr>
<td>Eb/No req</td>
<td>1.82</td>
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<tr>
<td>Link Margin</td>
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<tr>
<td>Eb/No des</td>
<td>11.48</td>
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<tr>
<td>Pin</td>
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<tr>
<td>Margin</td>
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<tr>
<td>Pin Total</td>
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</tr>
<tr>
<td>Prec</td>
<td>4.2372E-14</td>
<td></td>
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</tr>
</tbody>
</table>
Mothership
• High Gain Antenna
  – 0.5 m
  – Gain on ~30 dB
  – Efficiency of 60%
• UHF Receiver
• Patch Antennas
• X-Band Receiver

CubeSat
• 3 Patch Antennas
• 1 Science Dipole Antenna
  – STEM JIB Antenna (11m)
• 1 MF/HF Receiver
• UHF Receiver
**Constraints**

**CubeSat**
- **Power Constraint:**
  - Keep solar panels facing toward the Sun at ±5.5°

- **Volume/ Mass Constraint:**
  - 1U dedicated to ADC

- **Propulsion Constraint:**
  - The CubeSats have a limited amount of propellant onboard

**Mothership**
- **Pointing Constraint:**
  - The Mothership's HGA must be pointed at Earth at ±1.75° at all times

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Instrument</th>
<th>Control Requirement</th>
<th>Determination Capability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mothership COM</td>
<td>HGA</td>
<td>±1.75°</td>
<td>Not Given</td>
</tr>
<tr>
<td>CubeSat EPS</td>
<td>Solar Array</td>
<td>±5.5°</td>
<td>±0.1°</td>
</tr>
</tbody>
</table>
Baseline

Disturbance Torques

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### Analysis of Reaction Wheels for a 3U CubeSat

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Period of DRO (Days)</td>
<td>94</td>
</tr>
<tr>
<td>Distance Between Cg and Cp (m)</td>
<td>0.029</td>
</tr>
<tr>
<td>Solar Radiation Pressure at DRO – Tps (N*m)</td>
<td>7.12E-9</td>
</tr>
<tr>
<td>Sinclair Reaction Wheel Capability (Nms)</td>
<td>7.00E-3</td>
</tr>
<tr>
<td>Momentum Storage in Momentum Wheels (Nms)</td>
<td>5.79E-2</td>
</tr>
<tr>
<td>Days Between Unloading (days)</td>
<td>8.27</td>
</tr>
</tbody>
</table>
Baseline

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Baseline
Baseline
Baseline
Facing the Sun

- $\omega_{\text{max}}$
- $\omega_0$
- $-\omega_{\text{max}}$

4 days Facing the Sun
180° Turn
8 days Facing the Sun
180° Turn
8 days Facing the Sun

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Baseline

How to Maintain Max Moment of Inertia:

Top View

Side View

Front View

Max

Intermediate

Min
Hardware

Reaction Wheels: Sinclair Interplanetary  Sun Sensor: Space and Ground Systems UK
Hardware

3-axis Accelerometer: Analog Devices
3-axis Gyroscope: Honeywell

Star Camera: Computer-Matrix Vision, Lens-Schneider Optics
Designed By: Chris McBryde
Power
Constraints

CubeSat
- Provide power to all subsystems
- Volume/Mass:
  - Stay under a 1U in size
  - Minimize mass
- Cost:
  - Find components that are capable of the requirement but minimize cost

Mothership
- Use the SHERPA as designed
# CubeSat Power Budget

## Maximum Case

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Power (W)</th>
<th>30 % Contingency</th>
<th>Total Power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Attitude Determination &amp; Control</td>
<td>3.04 W</td>
<td>0.91</td>
<td>3.95 W</td>
</tr>
<tr>
<td>Command &amp; Data Handling</td>
<td>0.97 W</td>
<td>0.29</td>
<td>1.26 W</td>
</tr>
<tr>
<td>Communication</td>
<td>3.50 W</td>
<td>1.05</td>
<td>4.55 W</td>
</tr>
<tr>
<td>Power</td>
<td>0.01 W</td>
<td>0.00</td>
<td>0.01 W</td>
</tr>
<tr>
<td>Propulsion</td>
<td>0.80 W</td>
<td>0.24</td>
<td>1.04 W</td>
</tr>
<tr>
<td><strong>Total Power</strong></td>
<td></td>
<td></td>
<td><strong>10.81 W</strong></td>
</tr>
</tbody>
</table>

Other Power Modes: Slewing, Uplink, Downlink, and Safe
CubeSat Batteries

On Board Batteries
• Provide the spacecraft with power in the case of:
  – Eclipse
  – $\beta > 5.5^\circ$

Lithium-Polymer Batteries (30 W-hr)
• 3.3V and 5V regulated buses
• Built in inhibits to protect from shorts

Electrical Power System
• Built in inhibits

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Total Power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Attitude Determination &amp; Control</td>
<td>3.00 W</td>
</tr>
<tr>
<td>Command &amp; Data Handling</td>
<td>1.26 W</td>
</tr>
<tr>
<td>Communication</td>
<td>0.00 W</td>
</tr>
<tr>
<td>Power</td>
<td>0.01 W</td>
</tr>
<tr>
<td>Propulsion</td>
<td>0.00 W</td>
</tr>
<tr>
<td><strong>Total Power</strong></td>
<td><strong>4.27 W</strong></td>
</tr>
</tbody>
</table>
• **Deployable Solar Panels**
  – Need a maximum of 10.81 W for all subsystems
  – Non-deployable solar panels allow for up to 5.2 W
  – Allows for up to 11.27 W when deployed
  – 7 solar panels built with Ultra Triple Junction CICs solar cells on each deployable section
  – Thermal knife used for deployment after separation from ISIS-Pod
  – Based on Clyde Space and Pumpkin designs
C&DH
Constraints

Mothership
• Receive and handle commands from the ground station
• Transfer science data from the CubeSats to the ground station
• Interpret ranging data

CubeSat
• Receive and execute commands from Mothership
• Perform ranging functions
• Handle science data to be sent to the Mothership
Hardware

CubeSat system
- phyCore-LPC3250
  - 208 MHz CPU
  - 256 KB SRAM on-chip
  - 128 MB NAND Flash
  - Vector Floating Point (VFP)
  - Built on Linux OS framework
  - Coding will be in C++

- Oscillator:
  - Chip Scale Atomic Clock (CSAC) with 100 nanosecond accuracy
  - On board every CubeSat and Mothership
  - Synchronized upon release from the Mothership
CubeSat
• Each CubeSat will transmit a timestamp-encoded signal
• The other CubeSats will listen for the signal and timestamp this upon receipt
  – The CubeSat will determine the Δt between the timestamps
• After obtaining 13 ranges, ranging data will be transmitted to the Mothership

Mothership
• The data sets will then be interpolated to determine:
  – CubeSat geometry
  – Instantaneous position, velocity, and acceleration
• With this knowledge, the science objective can be met and station keeping may be performed
• Each satellite will transmit in sequence while the other 13 listen
• This technique requires minimal power to run and allows ranging on one frequency

Sequence
• CubeSat will transmit for 30 seconds
• Next 30 seconds “silent”

Total rotation
• Lasts 14 minutes
• Each CubeSat only broadcasting for 1/28th of total time
Structure
CubeSat Components

Science Receiver  Star Camera  Thruster  Gyroscopes  Flight Computer

Patch Antenna  Science Antenna  Reaction Wheels  Sun Sensors  Power Board  Battery Board
Structural Analysis

• Analyzed stresses and displacements of CubeSat shell components (FEA)
• FOS > 4 for all pressurized containers
• Estimated Launch Loads
  – Lateral load of 11 g’s
  – Axial load of 6 g’s
Structural Analysis

• Weakest Piece:
  – Payload Shell on ±X face

• FOS: 5

• Solutions:
  – Smaller cutouts
  – Thicker walls
  – Reinforce metal strip in middle
Management and Cost
# Timeline

<table>
<thead>
<tr>
<th>Phase</th>
<th>Duration (months)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>4</td>
</tr>
<tr>
<td>B</td>
<td>11</td>
</tr>
<tr>
<td>C</td>
<td>9</td>
</tr>
<tr>
<td>D</td>
<td>6</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>FY15</th>
<th>FY16</th>
<th>FY17</th>
<th>FY18</th>
<th>FY19</th>
<th>FY20</th>
<th>FY21</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
<td>B</td>
<td>C</td>
<td>D</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

30 months formulation and Implementation

The University of Texas at Austin
Costing Tool

- No cost model will accurately work for CubeSats
- Cost analysis is based on current CubeSat programs in different universities

**Small Satellite Cost Model (SSCM)**
- Used to compare the integration, testing, and program costs

**Quotes**
- “Quotes” for material components

**University Grassroots**
- Student labor cost
### Hardware Cost (CubeSat)

<table>
<thead>
<tr>
<th>Component</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propulsion</td>
<td>$19,500</td>
</tr>
<tr>
<td>ADC</td>
<td>$75,660</td>
</tr>
<tr>
<td>Communications</td>
<td>$13,000</td>
</tr>
<tr>
<td>Power</td>
<td>$35,600</td>
</tr>
<tr>
<td>Structure/Thermal</td>
<td>$12,000</td>
</tr>
<tr>
<td>Payload</td>
<td>$7,000</td>
</tr>
<tr>
<td><strong>Total (per CubeSat)</strong></td>
<td>$163,000</td>
</tr>
<tr>
<td><strong>Total (14 CubeSat)</strong></td>
<td><strong>$2.27 M</strong></td>
</tr>
</tbody>
</table>

- All costs include a 30% contingency
Assume two universities will be involved
- Each university will be in charge of 7 CubeSats

<table>
<thead>
<tr>
<th>Approximate Number</th>
<th>Annual Cost for Single Student</th>
<th>Total Cost Per Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>PhD 5</td>
<td>$55k</td>
<td>$275k</td>
</tr>
<tr>
<td>Masters 6</td>
<td>$38k</td>
<td>$228k</td>
</tr>
<tr>
<td>Undergraduate 60</td>
<td>$0</td>
<td>$0k</td>
</tr>
<tr>
<td>Total cost per year per University</td>
<td></td>
<td>$503k</td>
</tr>
<tr>
<td>Total cost per University</td>
<td>2.5 work years to Integrate, assemble and test</td>
<td>$1.25 M</td>
</tr>
<tr>
<td>Total cost</td>
<td>2 universities involved(30% Contin)</td>
<td>$3.25 M</td>
</tr>
</tbody>
</table>
### Launch Vehicle/Mothership

<table>
<thead>
<tr>
<th>Component</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Launch Vehicle to GEO</td>
<td></td>
</tr>
<tr>
<td>SHERPA to DRO</td>
<td></td>
</tr>
<tr>
<td>SHERPA</td>
<td></td>
</tr>
<tr>
<td>IA&amp;T</td>
<td></td>
</tr>
<tr>
<td>Program Level</td>
<td></td>
</tr>
<tr>
<td>Ground Support</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$38 M</strong></td>
</tr>
</tbody>
</table>

### Program Level Cost

<table>
<thead>
<tr>
<th>Component</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Systems Engineering</td>
<td></td>
</tr>
<tr>
<td>Program Management</td>
<td></td>
</tr>
<tr>
<td>Reliability</td>
<td></td>
</tr>
<tr>
<td>Planning</td>
<td></td>
</tr>
<tr>
<td>Requirements flow down</td>
<td></td>
</tr>
<tr>
<td>Quality assurance</td>
<td></td>
</tr>
<tr>
<td>Project Control</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$0.5 M</strong></td>
</tr>
</tbody>
</table>
## Total Cost

<table>
<thead>
<tr>
<th>Component</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>CubeSat Hardware</td>
<td>$2.27 M</td>
</tr>
<tr>
<td>IA&amp;T</td>
<td>$3.25 M</td>
</tr>
<tr>
<td>Program Level</td>
<td>$0.5 M</td>
</tr>
<tr>
<td>Launch Vehicle &amp; SHERPA</td>
<td>$38.0 M</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$44.02 M</strong></td>
</tr>
</tbody>
</table>
XSOLARA Conclusion
Overview of XSOLARA subsystems

**Payload**
- The only payload for XSOLARA is its 11 meter dipole antenna. Simple, reliable and proven technology

**Communication**
- All the data can be sent back to Earth with ample link margin
- High bandwidth will ensure data quality

**Power**
- Even in the worst case scenario, the system does not exceed available power.

**ADCS**
- No pointing requirement for the science payload but XSOLARA’s ADCS can control the CubeSat to a very good accuracy

**Propulsion**
- Propulsion system can provide up to 15 m/s for each CubeSat.
- Only 7 m/s is needed for the entire mission duration

**Structures**
- CubeSat structure is well known and proven
- CubeSat can stand all the stresses and vibrations throughout its lifetime
### Mass Budget

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Payload</td>
<td>300 g</td>
</tr>
<tr>
<td>Propulsion</td>
<td>379.1 g</td>
</tr>
<tr>
<td>ADC</td>
<td>611.6 g</td>
</tr>
<tr>
<td>Communications</td>
<td>465.3 g</td>
</tr>
<tr>
<td>Power</td>
<td>83.4 g</td>
</tr>
<tr>
<td>Structure</td>
<td>676.5 g</td>
</tr>
<tr>
<td>Thermal</td>
<td>165 g</td>
</tr>
<tr>
<td>Spacecraft Dry Mass</td>
<td>3542.2 g</td>
</tr>
<tr>
<td>Propellant</td>
<td>147.7 g</td>
</tr>
<tr>
<td>Loaded Mass</td>
<td>3689.6 g</td>
</tr>
<tr>
<td>Margin</td>
<td>310.4 g</td>
</tr>
</tbody>
</table>

### XSOLARA capability

<table>
<thead>
<tr>
<th>Component</th>
<th>Required</th>
<th>Capability</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of Satellites</td>
<td>10</td>
<td>14</td>
</tr>
<tr>
<td>Pointing (deg)</td>
<td>5.5</td>
<td>0.1</td>
</tr>
<tr>
<td>Propellant (kg)</td>
<td>0.04</td>
<td>0.09</td>
</tr>
<tr>
<td>Data rate (Mbps)</td>
<td>28</td>
<td>37.37</td>
</tr>
<tr>
<td>Power (W)</td>
<td>10.81</td>
<td>11.27</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>3.698</td>
<td>4</td>
</tr>
</tbody>
</table>
What has been done...

- Ground-based arrays with tens of antennas have been built
- None of them can observe in 0.1-10MHz frequency
What we can contribute...

- XSOLARA can provide science not obtainable from Earth Observing platforms
- Observation in low frequency with a sensitivity enough to detect exoplanets
- Path way to larger scale missions to follow up
- Create a whole new category of missions with CubeSats
• Top universities will be designing and building XSOLARA

• **INSPIRE**: XSOLARA will inspire K-12 students to do STEM

• **ENGAGE**: Involved universities will commit to engage K-12 students by having tours, conference, etc.

• **EDUCATE**: College students will be directly involved

• **EMPLOY**: Involved students are best candidates for NASA employment
Exoplanets are among the top priorities for NASA

XSOLARA will have direct impact to many college students and indirect impact to thousands of K-12 students

CubeSats are simple, cheap and low risk

XSOLARA will cost only 43 million dollars
Backup slides
Thermal

- Operating Temp (0-45°C)
- Star tracker defines boundaries

<table>
<thead>
<tr>
<th>Components</th>
<th>Coldest Temperature (°C)</th>
<th>Hottest Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Star Camera</td>
<td>0</td>
<td>45</td>
</tr>
<tr>
<td>Reaction Wheels</td>
<td>-40</td>
<td>70</td>
</tr>
<tr>
<td>Gyros</td>
<td>-45</td>
<td>85</td>
</tr>
<tr>
<td>LPC 3250</td>
<td>-40</td>
<td>85</td>
</tr>
<tr>
<td>Sun Sensors</td>
<td>-25</td>
<td>50</td>
</tr>
<tr>
<td>Battery Board + EPS</td>
<td>-40</td>
<td>85</td>
</tr>
</tbody>
</table>
Single Node Analysis

• Spreadsheet Calculation
• Assumptions:
  – Spherical Satellite
  – No Conduction or Internal Radiation
  – Outer Planet Albedo/IR
  – Only Solar Cells
• Average Spacecraft Temperature:
  – 293 K

<table>
<thead>
<tr>
<th>External Constants (W/m²)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar Heat Flux</td>
<td>1345</td>
</tr>
<tr>
<td>Albedo</td>
<td>387</td>
</tr>
<tr>
<td>Planetary IR</td>
<td>235</td>
</tr>
</tbody>
</table>
• Temperature Gradient
  – Hot Case: 295 K
  – Cold Case: 197 K
• Typical Range for Satellite is 125 K (~30% Margin)
• Multi-Layer Insulation (MLI) – Kapton Tape to be used
• Assume 6 month mission life in deep space
• Including Solar Events lasting 3 days each
  – Total dosage results in 17-22 rads over 6 month period
• 2.5mm CubeSat wall thickness
• ~110,000 rads max dosage (for glass instruments)
• Well below dangerous levels
### MLI – Kapton Tape

<table>
<thead>
<tr>
<th>Description</th>
<th>Kapton Tape on Aluminum Shell</th>
<th>Polyethylene/RXF 1</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Description</strong></td>
<td>Aluminum shell of spacecraft coated with reflective Kapton Tape</td>
<td>Rigid plastic material derived from polyethylene</td>
</tr>
<tr>
<td><strong>Cost</strong></td>
<td>Tape: $1.61 per sq ft</td>
<td>Unknown since product still under development</td>
</tr>
<tr>
<td></td>
<td>Sheet: $9.00 per sq ft</td>
<td></td>
</tr>
<tr>
<td><strong>Pros</strong></td>
<td>Cheaper</td>
<td>Light, flexible, durable</td>
</tr>
<tr>
<td></td>
<td>Tested through heritage</td>
<td>Superior radiation shielding (could potentially protect humans)</td>
</tr>
<tr>
<td></td>
<td>Feasible/Sturdy</td>
<td></td>
</tr>
<tr>
<td><strong>Cons</strong></td>
<td>Heavy</td>
<td>Projected to be costly</td>
</tr>
<tr>
<td></td>
<td>Not good at dealing with micrometeorite impacts</td>
<td>Sensitive to thermal activity</td>
</tr>
<tr>
<td></td>
<td>Mediocre radiation shielding (needs to be coupled with Rad-Hard equipment)</td>
<td>No heritage</td>
</tr>
</tbody>
</table>
CubeSat-Mothership Relay
- 14 CubeSats will communicate to the Mothership via UHF relay
- CubeSat to Mothership frequency will be within the authorized space to space link
  - 0.4 GHz to 0.6 GHz
  - XSOLARA will utilize 0.5 GHz until authorized frequency is specified