CubeX: A compact X-Ray Telescope Enables both X-Ray Fluorescence Imaging Spectroscopy and Pulsar Timing Based Navigation

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1) The CubeX Instrument
Remote sensing XRF measurements provide insight into the geology of planetary bodies.
Can we navigate Deep Space autonomously?

CubeX will also conduct semi-autonomous navigation by using precise time series from millisecond X-ray pulsars as “GPS” in our Galaxy.
• ~6U CubeSat X-ray Telescope: 5.8 kg with 8.6W (S/C: ~40U)
  **X-ray Imaging Spectrometer (XIS)** and **Solar X-ray Monitor (SXM)**
  **XIS** covers 0.4 – 7 keV with <150 eV FWHM @ 1 keV, 1 sq. deg FoV with < 1 arcmin Ang. Res.: 2 – 3 km resolution with 110 km foot print at 6000 km; < 1 µsec timing resolution for XNAV
  **SXM** covers >130 deg FWZI with energy range of 1 – 8 keV
Achieve <1 arcmin resolution over 1 sq. deg and 24 cm$^2$ on-axis & 12 cm$^2$ off-axis (@ 33 arcmin) effective area at 1 keV

- 34 lightweight NiCo ENR shells (200 µm thick) in a butterfly design with 10 cm dia. x 8 cm length envelope (~1.5 kg) for 50 cm focal length

Effective area (left) and angular resolution in HPD (right) as a function of off-axis for several discrete energies (color-coded) estimated by ray-tracing simulations.
• 2 monolithic CMOS X-ray sensors: 16 $\mu$m pixel, <150 eV FWHM at 1 keV for XRF imaging spectroscopy
• Amptek SDD: < 1 $\mu$sec timing for XNAV
• Enable both XRF measurements and XNAV observations without moving parts
2) The CubeX Lunar Mission
Identify and measure compositions of lunar lower crust and upper mantle outcrops excavated within and around impact craters.

Example target sites guided by data from missions like GRAIL, LRO, Kaguya, covering diverse crater sizes in both the nearside and farside of the Moon.

Depth of excavated material is \( \sim 1/10^{th} - 1/20^{th} \) of crater diameters.

Assist site selection for future sample collection and provide the larger context of the sample.
CubeX resolves outcrop features with high angular resolution (~2 – 3 km, 10x higher) while providing a large context with wide footprint (~110km).

(A) The morphology of a peak ring is evident in this view of the ~320-km-diameter Schrödinger basin on the Moon (NASA's Scientific Visualization Studio).

(B) A close-up view of a segment of the peak ring with rocks uplifted from mid- to lower-crustal levels by the impact event. LRO Camera image M1192453566 [Kring+16 & 17].

Anorthositic outcrops are generally considered to be from highlands, whereas olivine-rich outcrops are associated with the mantle or lower crust origin.
- **CubeX** is currently designed as a secondary spacecraft, deployed into a common lunar orbit.
- Launch during solar maximum (2023 – 2027)

**CubeX** canister mount orientation fits all fairings

**CubeX** ESPA-mount orientation option

**CubeX** size: L x W x H (cm) 68 35 23

**Lunar Orbit Insertion based on past missions:**

- 500 x 5000 km
- 4 orbit transfer maneuvers to science orbit ($\Delta V \sim 300$ m/s raise)

**SCIENCE ORBIT:**
- 1 yr science operation (1.5 yr mission lifetime)
- Quasi frozen circular polar orbit at 6000 km, 17 hour period, ideal for both lunar XRF and XNAV operations
## CubeX Spacecraft

<table>
<thead>
<tr>
<th>Resource</th>
<th>Current best estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total launch mass</td>
<td>43 kg</td>
</tr>
<tr>
<td>Total power draw</td>
<td>72 W</td>
</tr>
<tr>
<td>S/C delta-V</td>
<td>300 m/s</td>
</tr>
<tr>
<td>S/C data storage volume</td>
<td>8 GB</td>
</tr>
<tr>
<td>Data rate</td>
<td>256 kbps</td>
</tr>
<tr>
<td>Pointing control &amp; knowledge</td>
<td>30 arcseconds &amp; 6 arcseconds</td>
</tr>
<tr>
<td>Mission lifetime (science operation)</td>
<td>1.5 yr (1 yr)</td>
</tr>
</tbody>
</table>

**Diagram:**
- Solar Panel (0.4 m²)
- Battery
- X-band Radio
- Reaction Wheels
- Terrain Camera
- LGA
- X-ray Imaging Spectrometer
- Propulsion System
- Star Tracker
- Thruster
- Solar X-ray Monitor

**Total Vol:** 35 x 23 x 68 cm
**Total Mass:** 43 kg
• ~90% of 1 year science operation

• Targeted observations during day time
  • except for calibration sites at North and South poles during night time
  • > 2 hr per orbit for each target site
  • ~2 – 3 km resolution with ~110 km FOV to cover and resolve key features

• 6 prime science targets and 3 calibration sites

• Accumulate > 0.5 Msec exposure/site at C1 solar state to meet science requirements
  e.g., < 30% error of abundance ratio at ~3 km scale

Polar circular orbit at 6000 km
CubeX can perform XNAV in more realistic environments for deep space navigation than NICER on ISS (only 20 min per orbit for each pulsar)

CubeX science requirements & mission ops are compatible with XNAV tech demo.

- ~10% of 1 year science operation:
  - ~6 XNAV ops total with
  - ~6 days per ops

- Goal: achieve < 20 km precision

- > 2hr per orbit for each pulsar
• *CubeX* is a compact X-ray focusing telescope that can provide both X-ray Fluorescence measurements and X-ray timing measurements:
  - The spectrometer can identify and measure elemental abundance in bodies throughout the solar system.
  - Timing measurements enable semi-autonomous deep space navigation using X-ray millisecond pulsars (XNAV).

• A lunar *CubeX* mission could explore lunar mantle and lower crust material, which will deepen our understanding of the formation and evolution of the Moon, in time for next lunar sample return missions and demonstrate XNAV capabilities.

• **Autonomous navigation** becomes essential in a new era of interplanetary exploration with a large number of SmallSats/CubeSats.

• A large number of low-cost *CubeX* S/C could revolutionize our understanding of NEOs and other airless bodies through rapid deployment to multiple targets.
## CubeX Team

### Management, SOC, MOC
- **Suzanne Romaine** (SAO) - PI; MiXO Lead
- **Jaesub Hong** (Harvard) - D-PI; Instrument Design
- **Janet Evans** (SAO) - SOC

### Instruments
- **Ralph Kraft** (SAO) - XIS Lead
- **Almus Kenter** (SAO) - CMOS Lead
- **Gregory Prigozhin** (MIT) - SDD Sensor Lead
- **Rebecca Masterson** (MIT) - Instrument Mgmt, SXM Lead

### Lunar and XRF Science
- **Ian Crawford** (Birkbeck) - Lunar Science Lead
- **David Kring** (LPI) - Lunar Scientist
- **Noah Petro** (GSFC) - Lunar Scientist
- **Larry Nittler** (Carnegie) - Planetary XRF Scientist

### XNAV
- **Keith Gendreau** (GSFC) - XNAV Lead
- **Jason Mitchell** (GSFC) - GEONS Lead
- **Luke Winternitz** (GSFC) - XNAV Plan and GEONS Sim

### Co-Is and Collaborators
- **Brian Ramsey** (MSFC) - MiXO
- **Kirian Kilaru** (MSFC) - MiXO
- **Daniele Spiga** (INAF) - MiXO
- **Vinay Kashyap** (SAO) - MiXO
- **Thomas Gauron** (SAO) - CMOS & Backend Elec.
- **Joel Villasenor** (MIT) - SDD
- **Mark Chados** (MIT) - SXM
- **Branden Allen** (Harvard) - SXM
- **Ian Evans** (SAO) - SOC
- **Jonathan Schonfeld** (SAO) - Science Program Manager

### Mission & S/C Design
- **Jan Stupl** (SGT/ARC) - Project Manager
- **Sam Montez** (MEI/ARC) - Capture Lead
- **Brittany Wickizer** (ARC) - Systems Engineer
- **Arwen Dave** (MEI/ARC) - Deputy Systems Engineer
- **Ashley Clark** (ARC) - ADCS
- **Andres Dono-Perez** (MEI/ARC) - Propulsion
- **Monica Ebert** (SGT/ARC) - Radiation
- **Ali Kashani** (MEI/ARC) - Thermal
- **Daniel Larrabee** (MEI/ARC) - C&DH and Power/EE
- **David Mauro** (SGT/ARC) - Telecom
- **Laura Plice** (Metis/ARC) - Orbit Analysis
- **Joel Mueting** (Metis/ARC) - Orbit Analysis
- **Karolyn Ronzano** (MEI/ARC) - Mission Schedule
- **Duy Nguyen** (BAH/ARC) - Cost Analysis
- **Yueh-Liang Shen** (BAH/ARC) - Cost Analysis
- **Kellen Bonner** (MEI/ARC) - Structures
- **Tim Snyder** (MEI/ARC) - Structures
BACKUP
Deep space navigation is a critical issue for interplanetary missions.

Current deep space navigation relies on a global network of large ground-based radio antennas such as NASA DSN and ESA ESTRACK.

- Performance degrades while the operational cost increases as the S/C travels farther away from Earth.

A new era of low-cost SmallSats/CubeSats based space exploration will require more autonomous deep space navigation.
Technology Development of MiXO

- TRL 5: currently being developed under NASA APRA and PICASSO programs.

- Typical mandrels used for small optics effort:
  - Left: 4.5cm diameter x 6cm length
  - Right: 9cm diameter x 10 cm length (MIXO mandrel)

- Both mandrels fabricated at MSFC have ~ 15 arcsec figure, 3Å μr
Monolithic CMOS X-ray Sensors for XRF Detection

• CMOS X-ray sensors are becoming the state of art X-ray detector

• SAO/SRI(Sarnoff) Big Minimal (BM) III: CubeX focal plane devices
  • The same family of the chip and same signal-chain are flight ready: Solar Orbiter - SoloHi, Solar Probe Plus - WISPR

• Advantages of CMOS sensors:
  • Inherently high radiational tolerance: >1000x better than CCDs
  • High temperature operation (<150 eV FWHM at 1 keV at 0C)
  • Wide dynamic range: ideal for high XRF flux during solar flares

▲ SAO/SRI BM III:
  1k x 1k pixels, 16 µm pitch, Back Illuminated (BI)

▲ SoloHi 2x2 abutable flight Mo package

55Fe spectrum taken with monolithic CMOS BM-II minimal at room temperature
Solar X-ray Monitor (SXM)

- A simplified version of SXM in OSIRIS-REx / REXIS
- SDD: off-the-shelf item from Amptek
- REXIS SXM functions normally since launch in Sep. 2016

SDD TO-8 Module
- COTS item from Amptek
- Be Optical Blocking Filter
- SDD Cooling with 2-Stage TEC
- SDD substrate and detector

Pre-amp Board
- Initial signal conditioning for the output signals from the SDD
- Routing for TEC power and BIAS
- ~3.5 cm x 3.5 cm

Collimator and Bracket
- Correct Angle to the Sun
- Correct FoV
- Throughput Regulation
CubeX combines XRF with XNAV capabilities: X-ray Pulsar Timing Based Navigation

- Measure the peak of the pulsation profile from stable millisecond pulsars (MSPs)

- Repeat the measurements for 3 or 4 pulsars to locate the S/C position or determine the S/C trajectory

- MSPs are “GPS” of the Galaxy