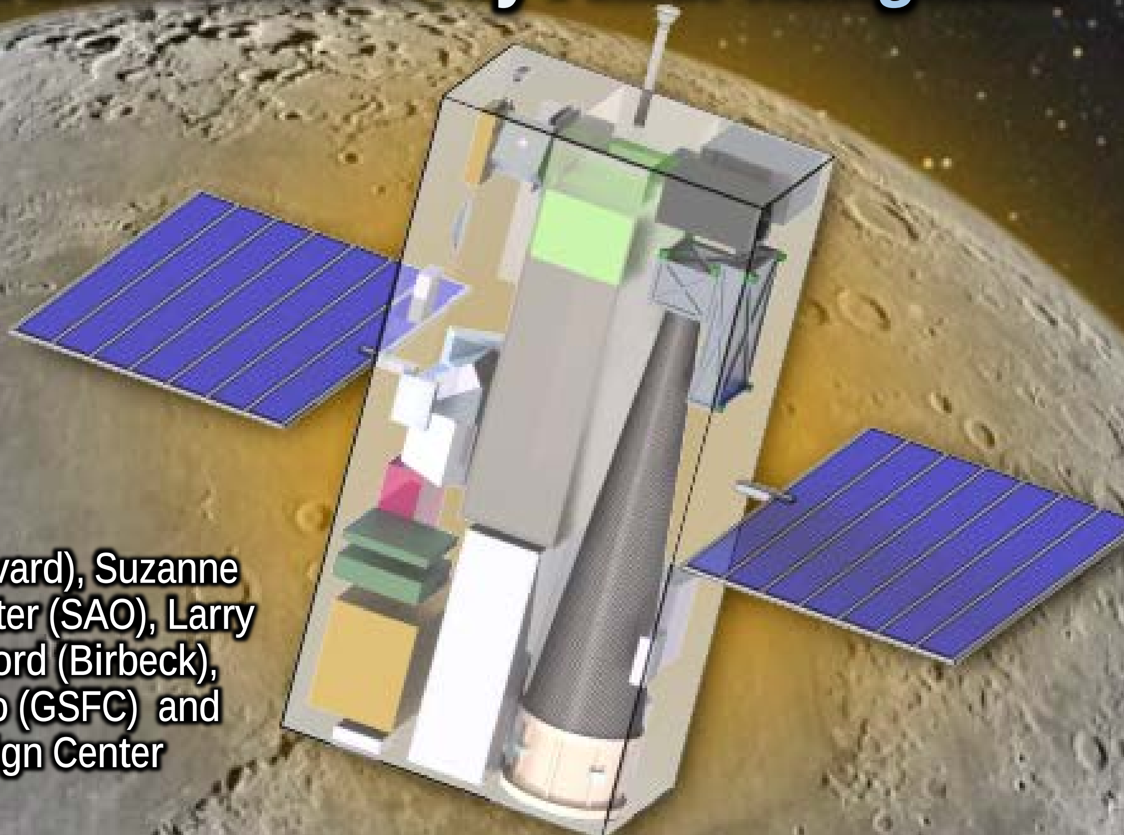
CubeSat X-ray Telescope for Lunar Elemental Abundance Mapping & Millisecond X-ray Pulsar Navigation



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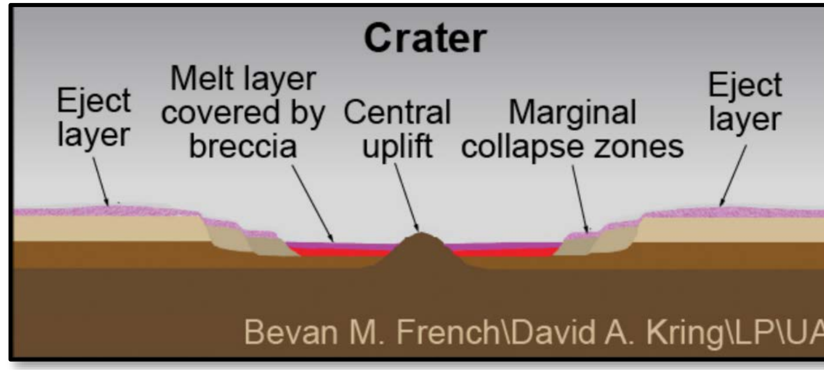
Jan 2018

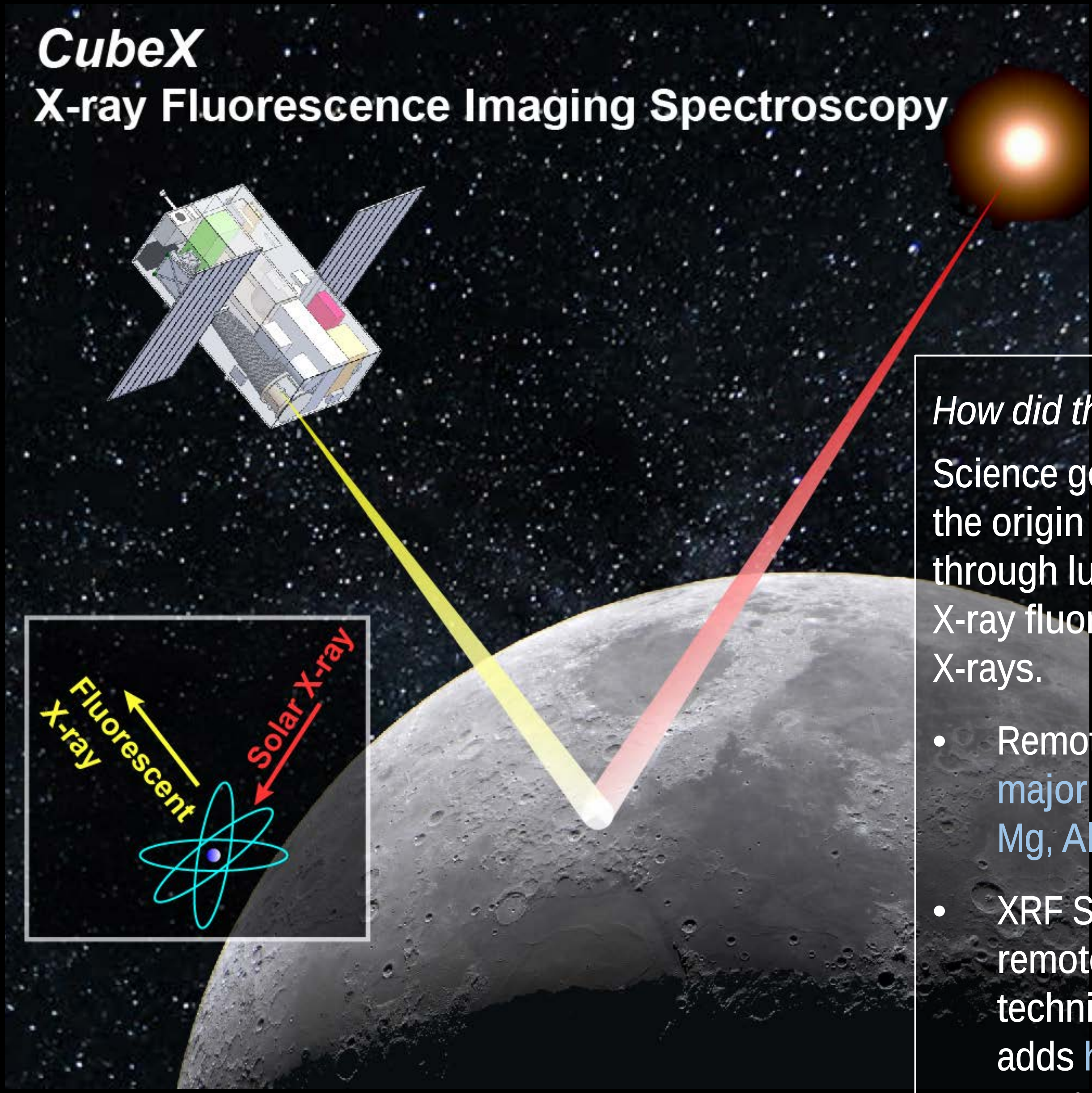
Primary Science Objectives of CubeX

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 ~1/10th – 1/20th of crater diameters.



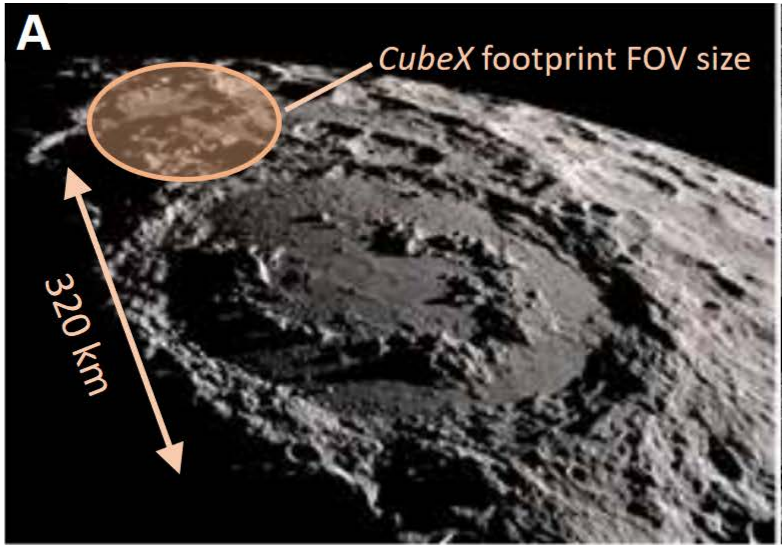
How did the Moon form and evolve?

Science goal of *CubeX* is to understand the origin and evolution of the Moon through lunar elemental composition from X-ray fluorescence (XRF) excited by Solar X-rays.

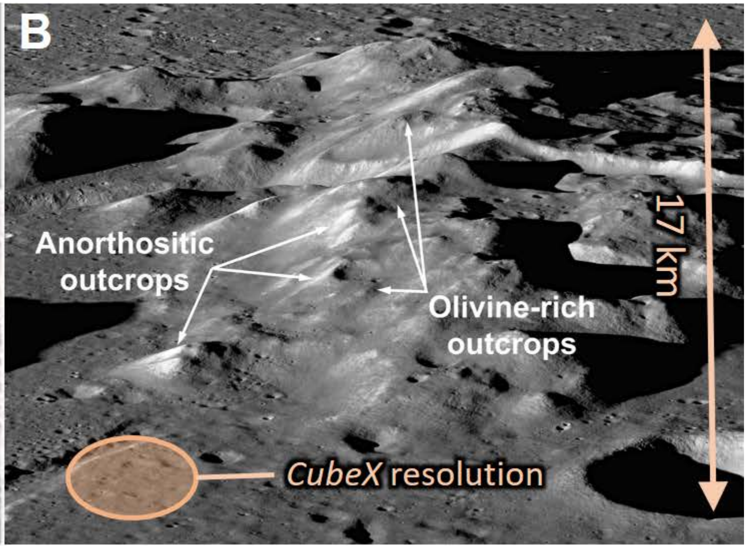
- Remote-sensing XRF sensitive to most major rock-forming elements (e.g., Na, Mg, Al, Si, S, Ca, Ti, Fe)
- XRF Spectroscopy is a demonstrated remote-sensing geochemical technique in planetary science: *CubeX* adds high resolution imaging to XRF spectroscopy

Elemental Abundance Mapping with CubeX

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).

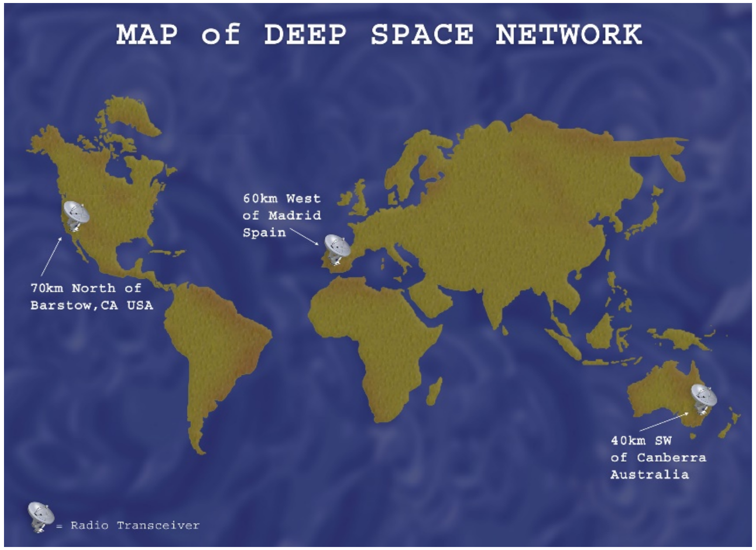


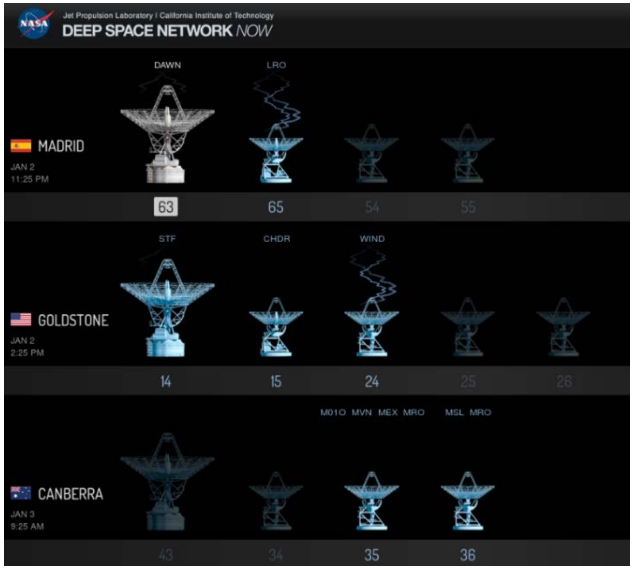
(B) A close-up view of a segment of the peak ring with rocks uplifted from mid- to lower-crustal levels by the impact event. *LRO* Camera image M1192453566 [Kring+16 & 17].

Anorthositic outcrops are generally considered to be from highlands, whereas olivine-rich outcrops are associated with the mantle or lower crust origin.

II. Can We Navigate Deep Space Autonomously?

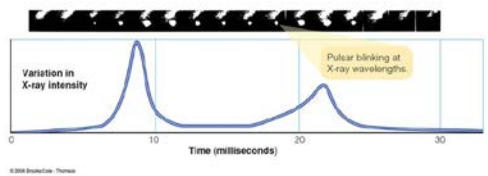
- Deep space navigation is a critical issue for interplanetary missions.
- Current deep space navigation relies on a global network of large ground-based radio antennas such as NASA DSN and ESA ESTRACK.
    - Performance degrades while the operational cost increases as the S/C travels farther away from Earth.
- A new era of low-cost SmallSats/CubeSats based space exploration will require more autonomous deep space navigation.

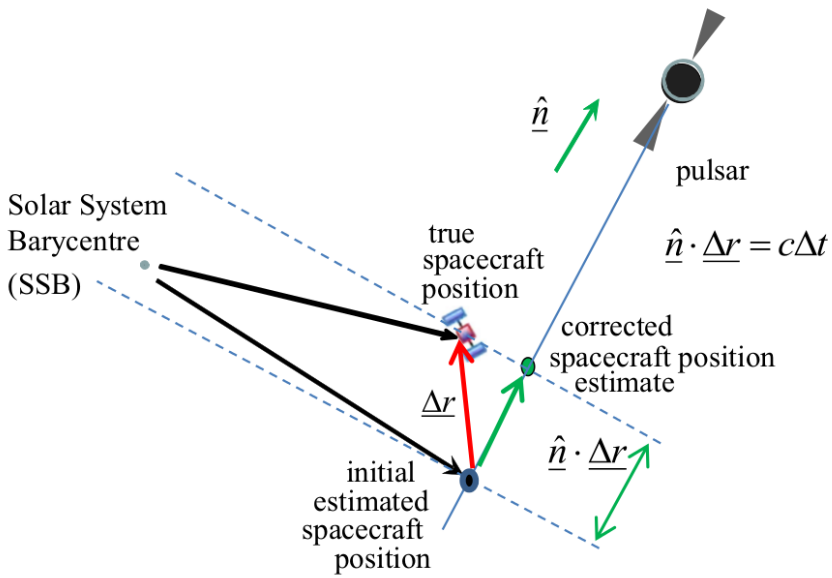




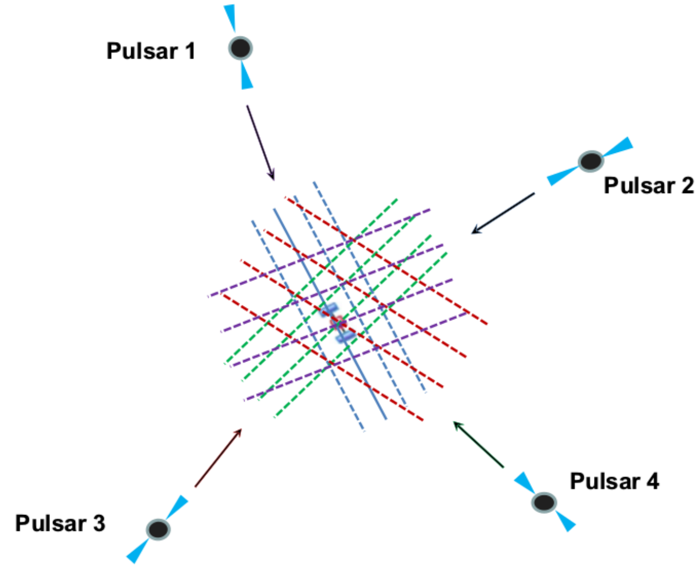
X-ray Pulsar Timing Based Navigation

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





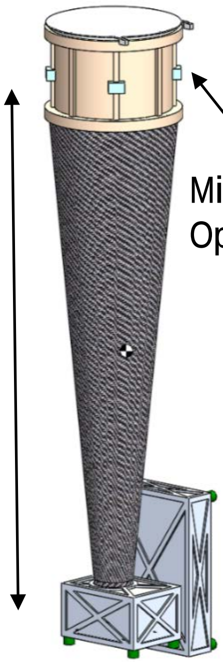
Shemar+16

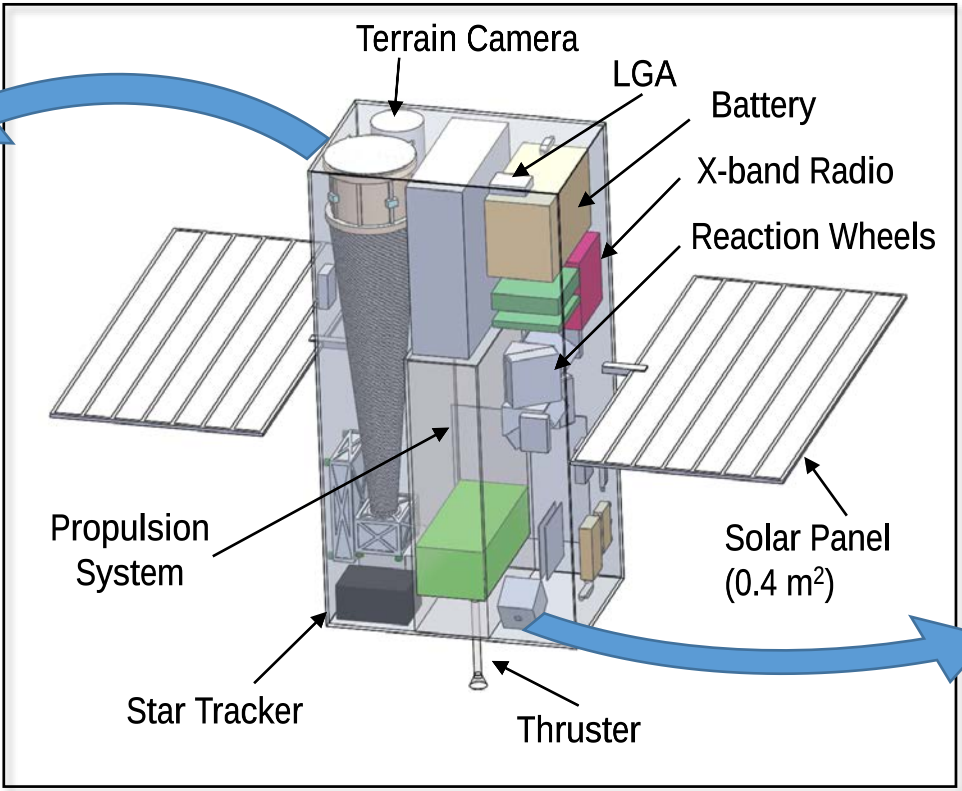


- Repeat the measurements for 3 or 4 pulsars to locate the S/C position or determine the S/C trajectory
- MSPs are “GPS” of the Galaxy

CubeX: CubeSat X-ray Telescope

X-ray Imaging Spectrometer (XIS)

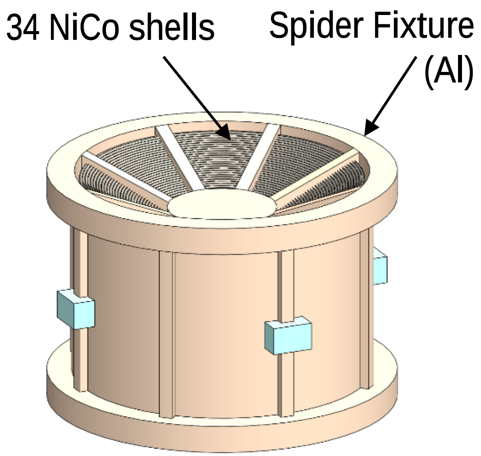


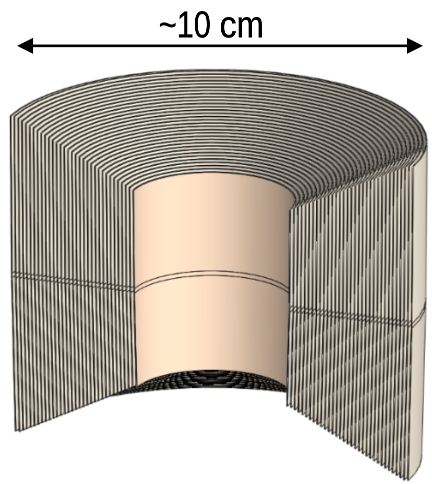


Solar X-ray Monitor (SXM)

- ~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

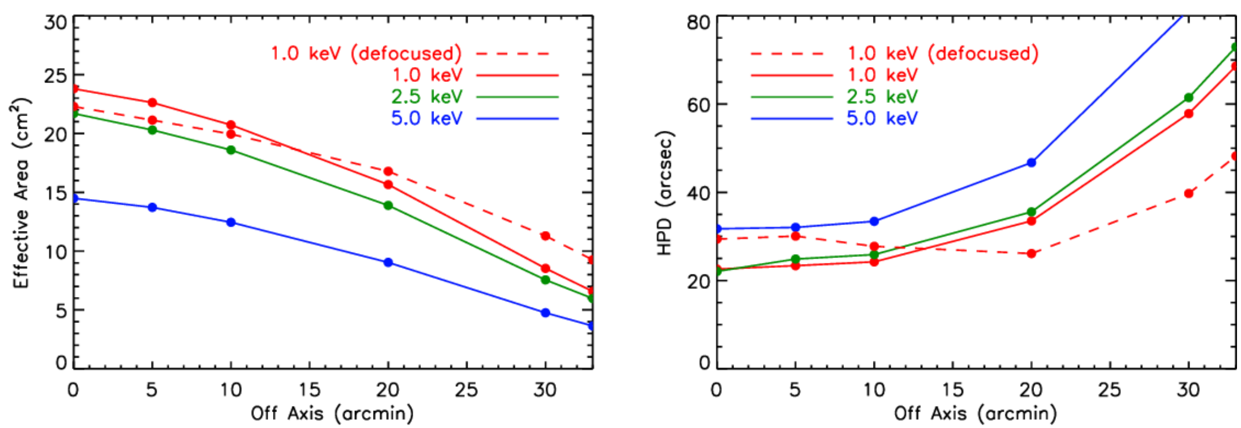
Miniature Lightweight X-ray Optics (MiXO)





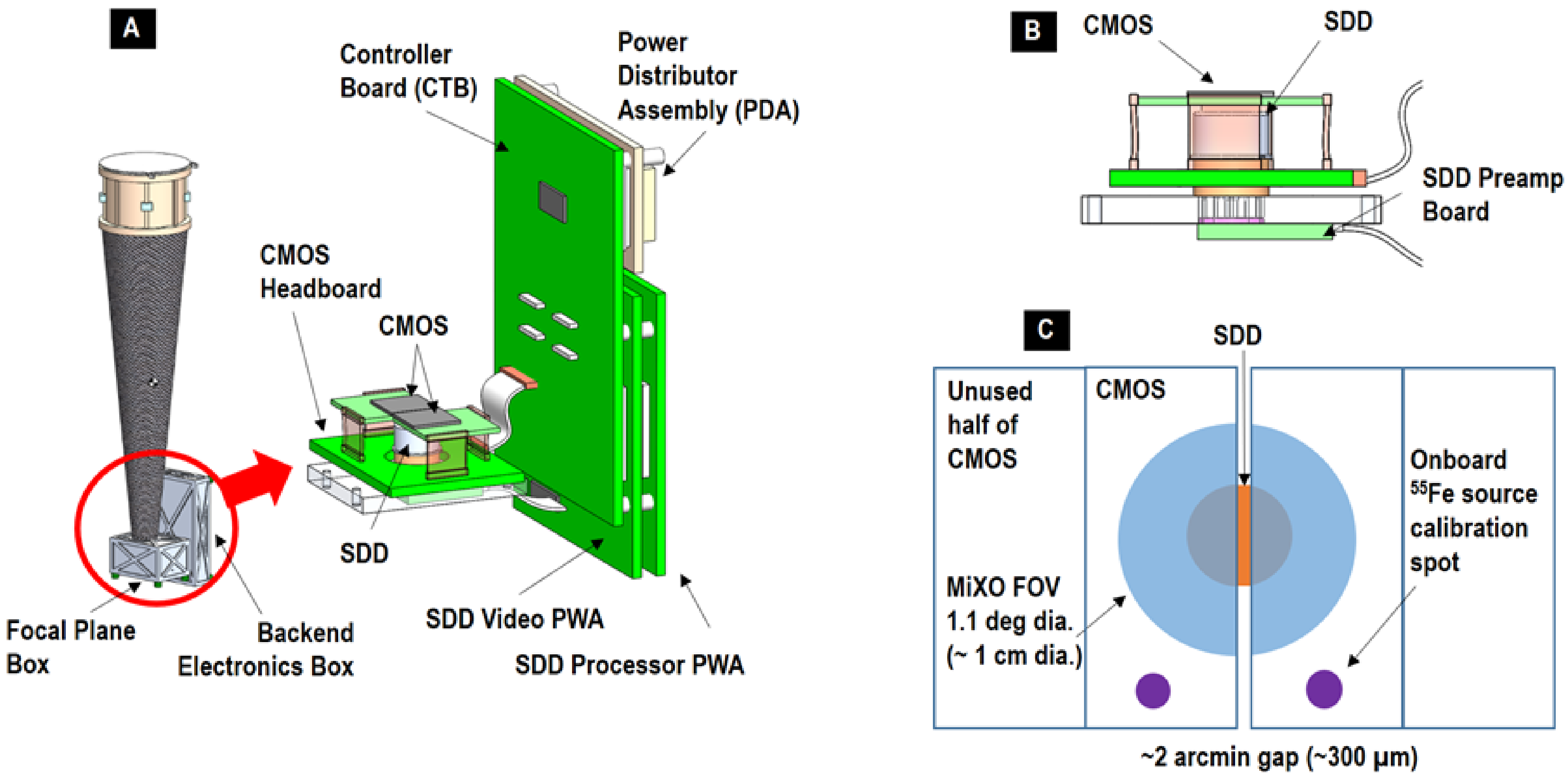
Cross-sectional view of 34 shells

- 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.

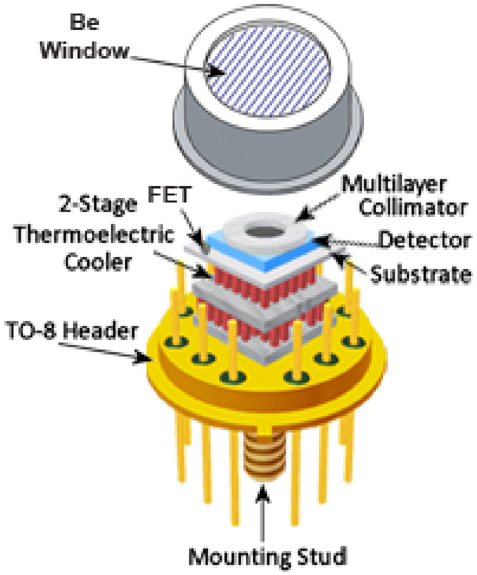
Focal Plane Design Overview



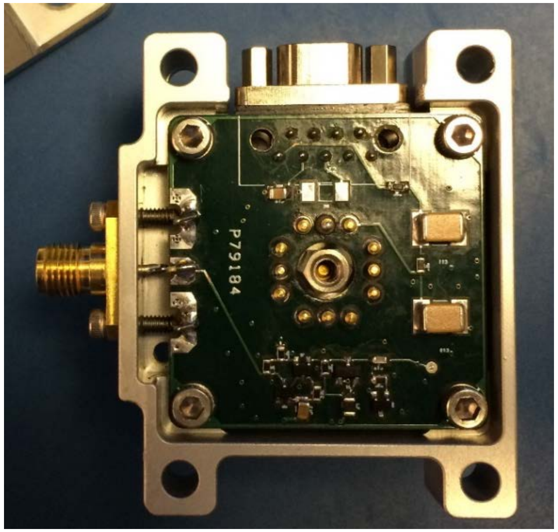
- 2 monolithic CMOS X-ray sensors: 16 µm pixel, <150 eV FWHM at 1 keV for XRF imaging spectroscopy
- Amptek SDD: < 1 µsec timing for XNAV
- Enable both XRF measurements and XNAV observations without moving parts

Solar X-ray Monitor (SXM)

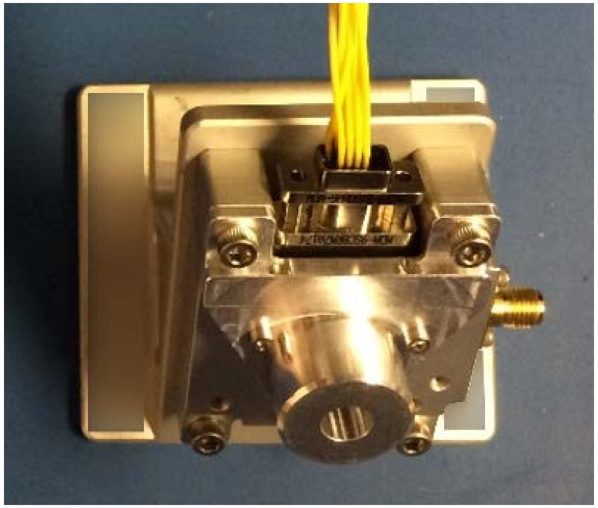
- A simplified version of SXM in *OSIRIS-REx* / REXIS
- SDD: off-the-shelf item from Amptek
- REXIS SXM functions normally since launch in Sep. 2016



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



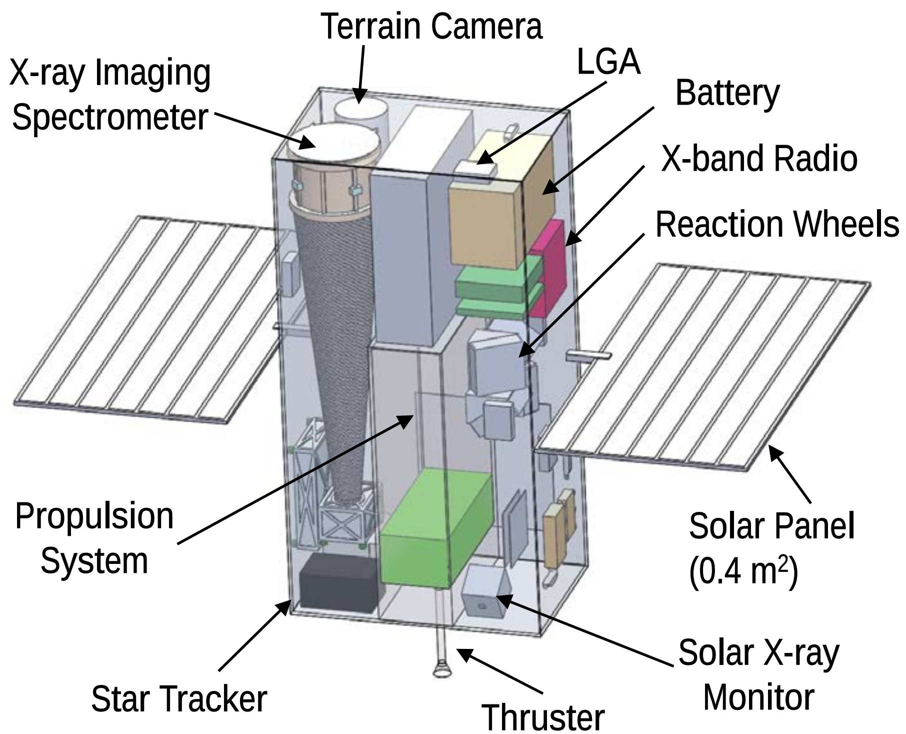
<u>Pre-amp Board</u>
- Initial signal conditioning for the output signals from the SDD
- Routing for TEC power and BIAS
- ~3.5 cm x 3.5 cm



<u>Collimator and Bracket</u>
- Correct Angle to the Sun
- Correct FoV
- Throughput Regulation

CubeX Spacecraft

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



Total Vol: 35 x 23 x 68 cm

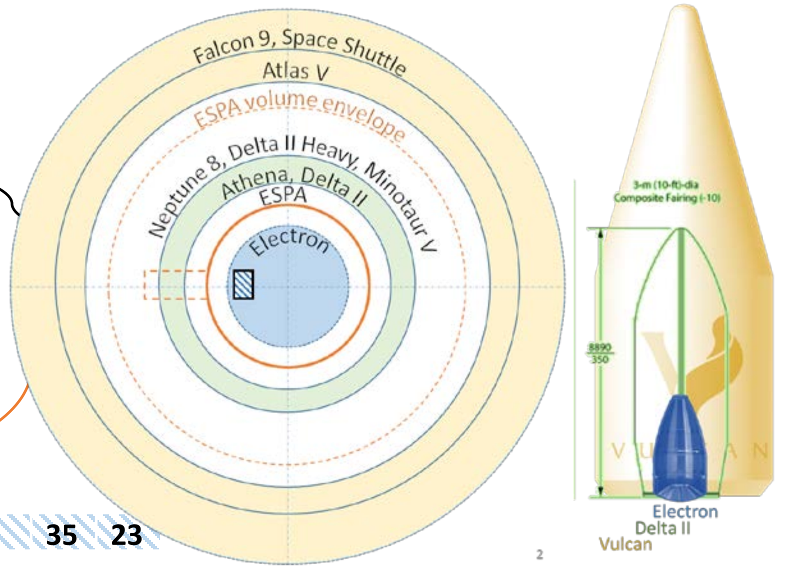
Total Mass: 43 kg

CubeX Mission Concept

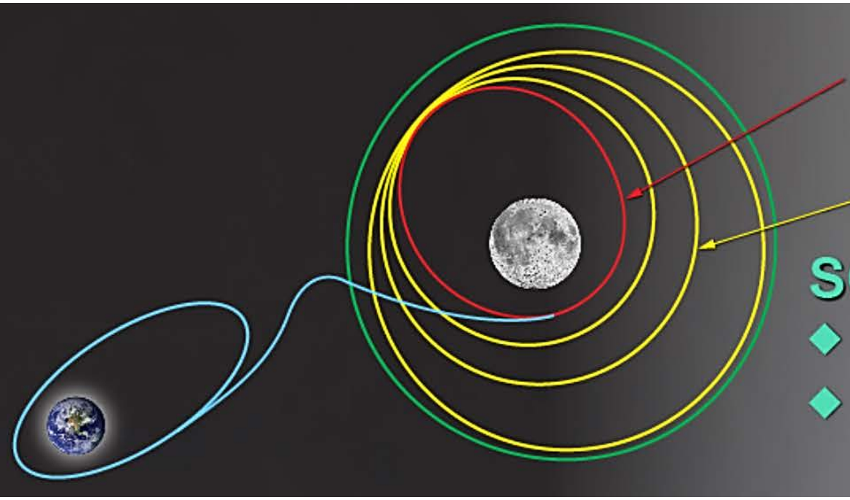
- *CubeX* is currently designed as a secondary spacecraft, deployed into a common lunar orbit
- Launch during solar maximum (2023 – 2027)

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 (ΔV ~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**

Observation Sequence Example for Lunar XRF

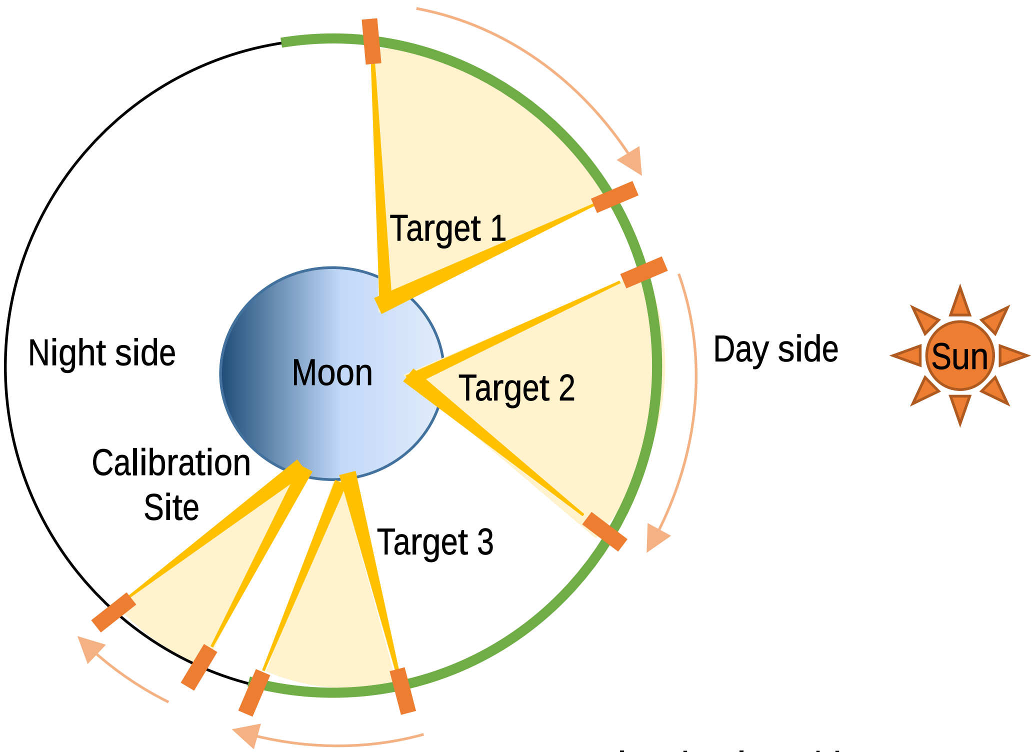
- ~90% of 1 year science operation

- 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

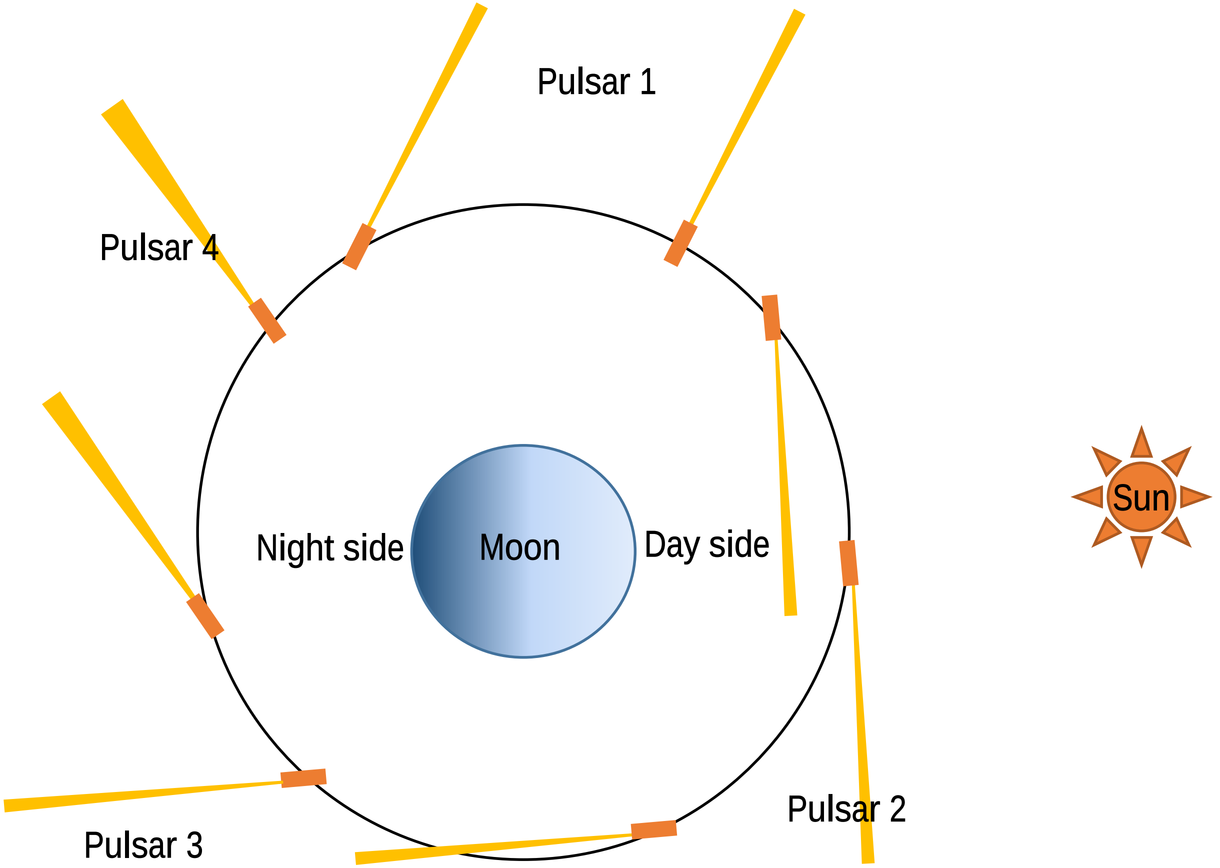
  e.g., < 30% error of abundance ratio at ~3 km scale



Polar circular orbit at 6000 km

Observation Sequence Example: XNAV

- ~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 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.

Summary

- *CubeX* will identify and measure elemental abundance of 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.

- *CubeX* will demonstrate semi-autonomous deep space navigation using X-ray millisecond pulsars. Autonomous navigation becomes essential in a new era of interplanetary exploration with a large number of SmallSats/CubeSats.

- Advances in X-ray telescopes and detectors such as Miniature lightweight X-ray Optics (MiXO), monolithic CMOS X-ray imaging sensors and high timing resolution SDDs enable these ambitious objectives with a small form factor, opening a new era of planetary XRF spectroscopy and deep space navigation.

- The *CubeX* mission design closes for science requirements, spacecraft and mission implementation. The design fits mass, volume and cost constraints of the PSDS3 call.

Backup Slides

CubeX Team

Management, SOC, MOC

Suzanne Romaine (SAO)	PI; MiXO Lead
Jaesub Hong (Harvard)	D-PI; Instrument Design
Janet Evans (SAO)	SOC
NASA ARC	Msn Design, S/C Design, MOC

Instruments

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Almus Kenter (SAO)	CMOS Lead
Gregory Prigozhin (MIT)	SDD Sensor Lead
Rebecca Masterson (MIT)	Instr Mgmt, SXM Lead

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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