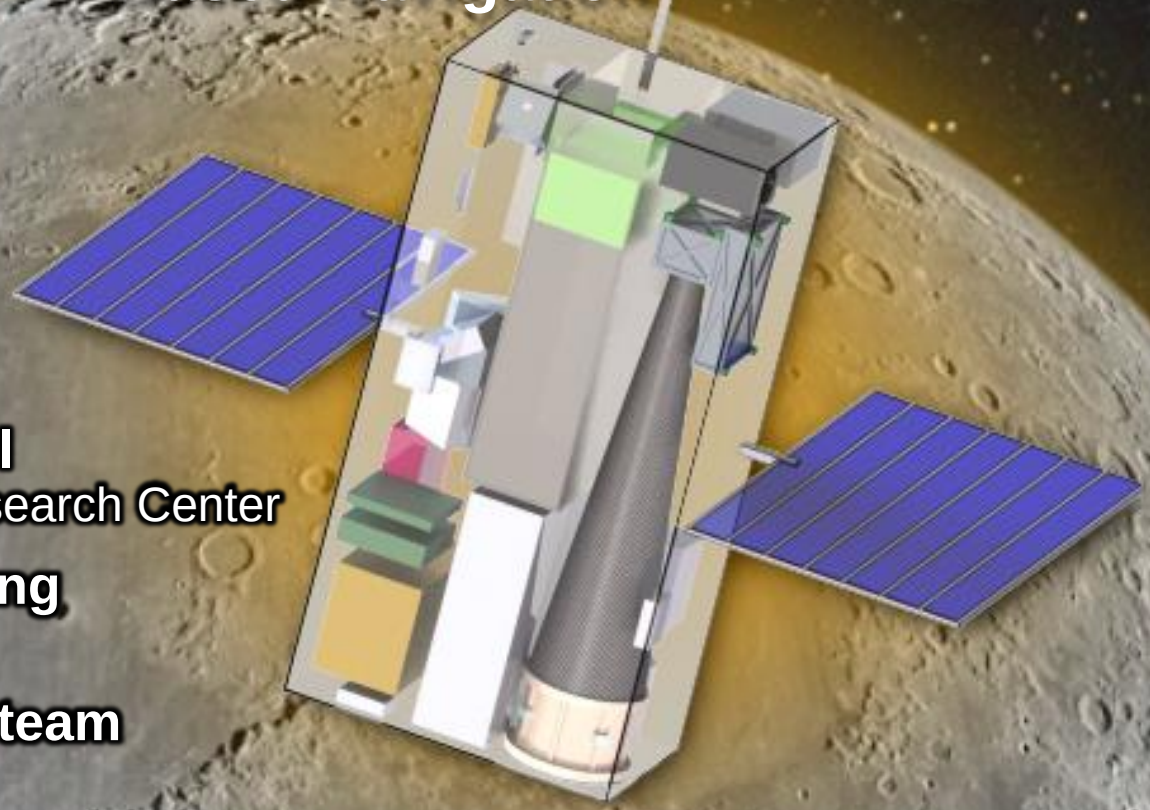
CubeX: A compact X-Ray Telescope Enables both X-Ray Fluorescence Imaging Spectroscopy and Pulsar Timing Based Navigation



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SGT / NASA Ames Research Center

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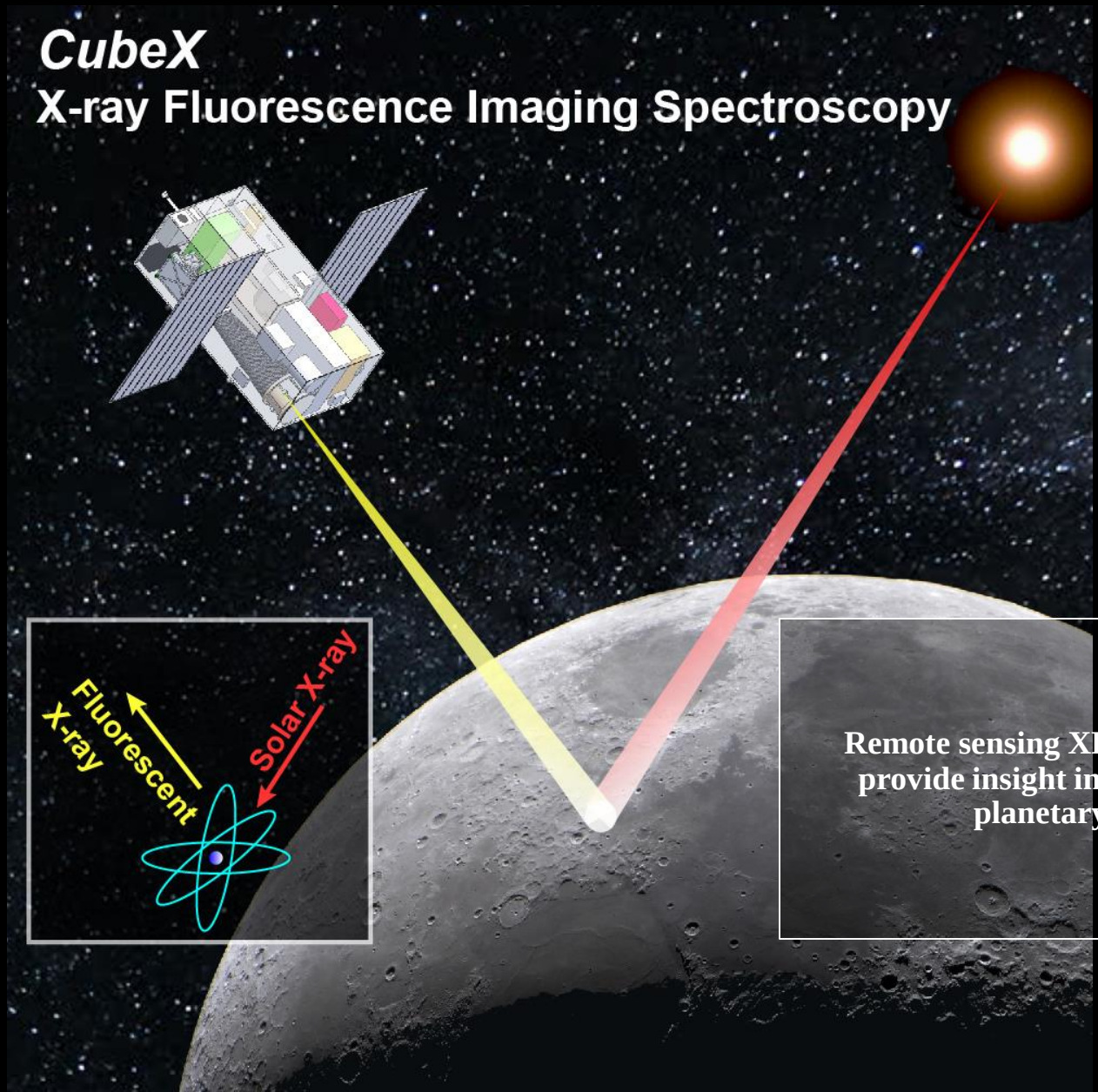
Harvard

& the CubeX team

32nd Annual AIAA/USU Conference on Small Satellites – August 2018

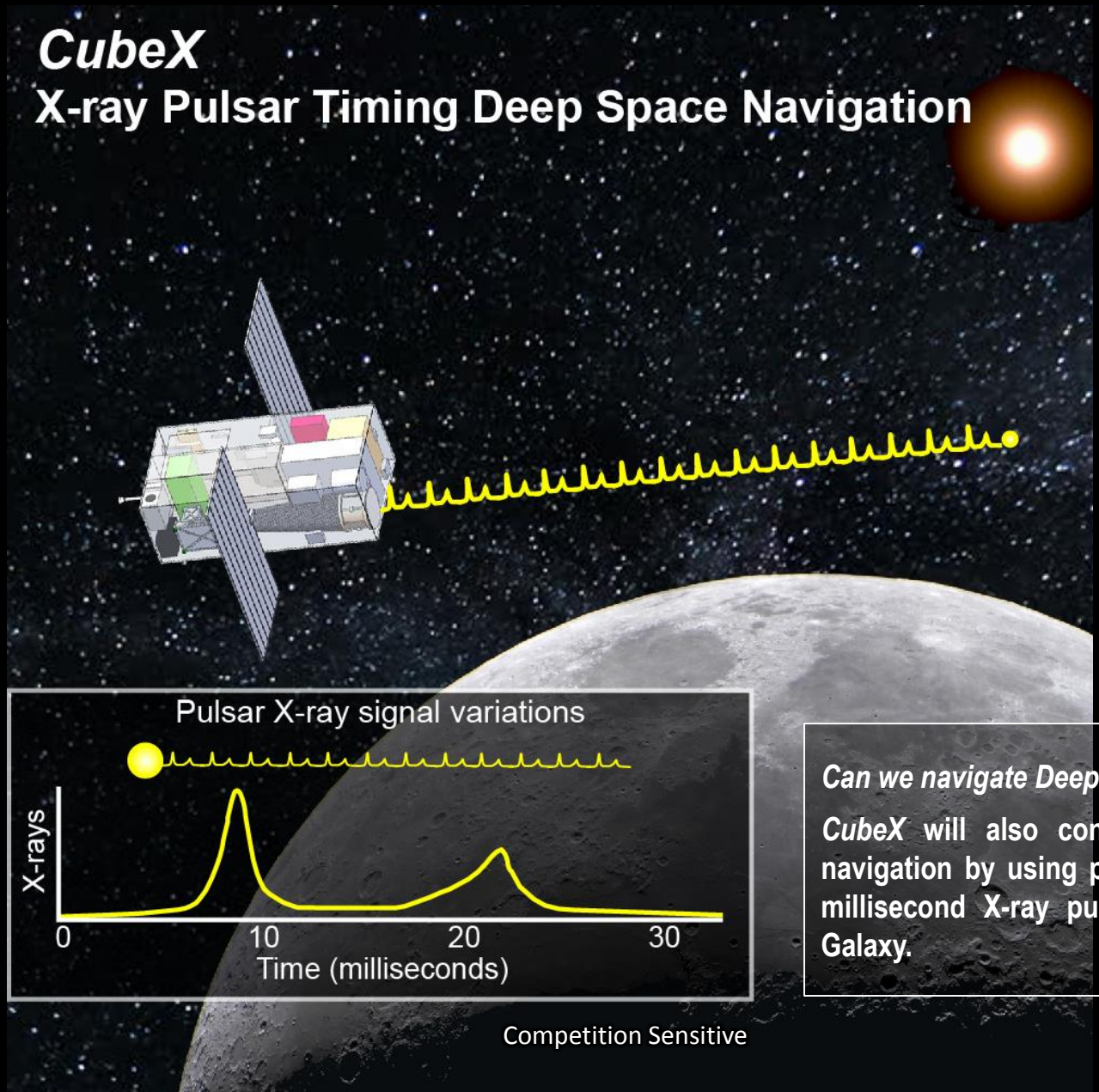
1) The CubeX Instrument

CubeX combines XRF with XNAV capabilities:



Remote sensing XRF measurements provide insight into the geology of planetary bodies.

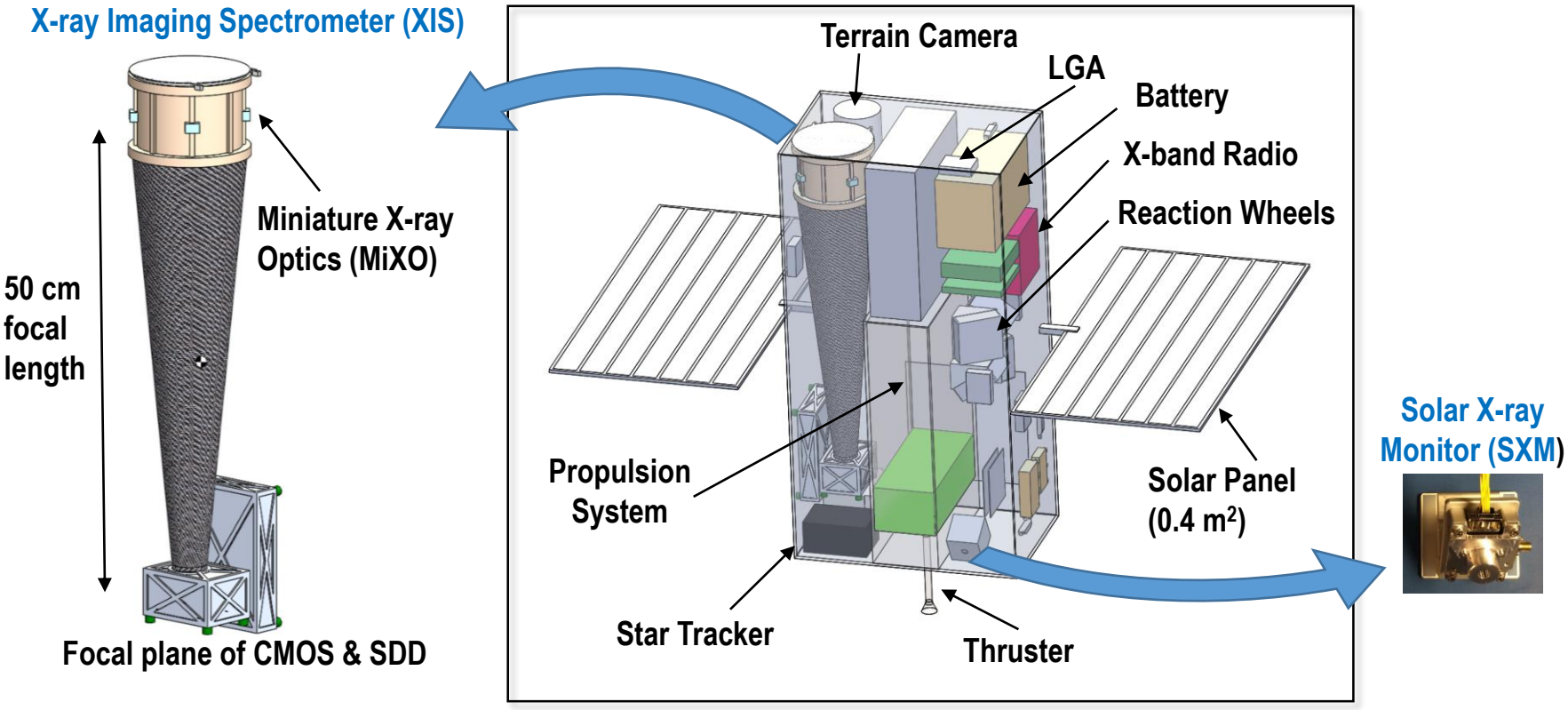
CubeX combines XRF with XNAV capabilities:



Can we navigate Deep Space autonomously?

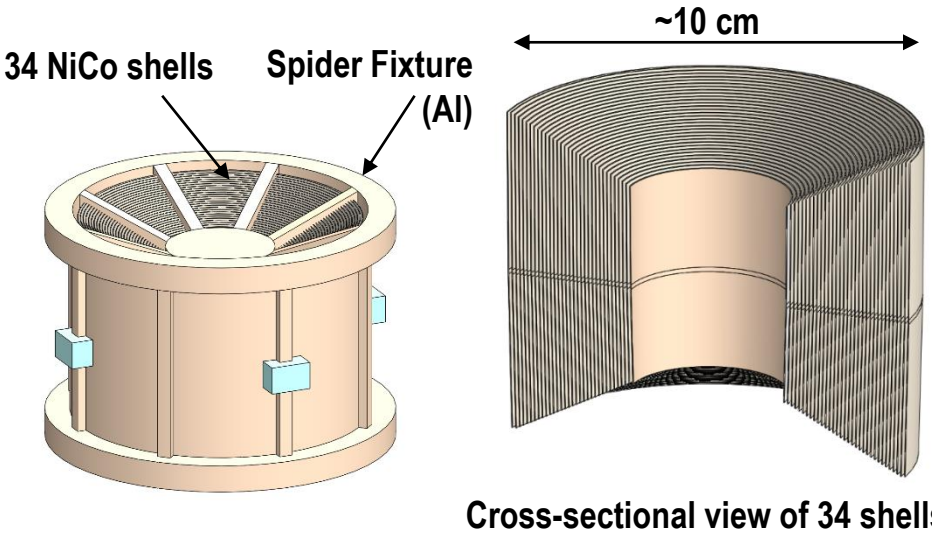
CubeX **will also conduct semi-autonomous navigation by using precise time series from millisecond X-ray pulsars as "GPS" in our Galaxy.**

CubeX: CubeSat X-ray Telescope



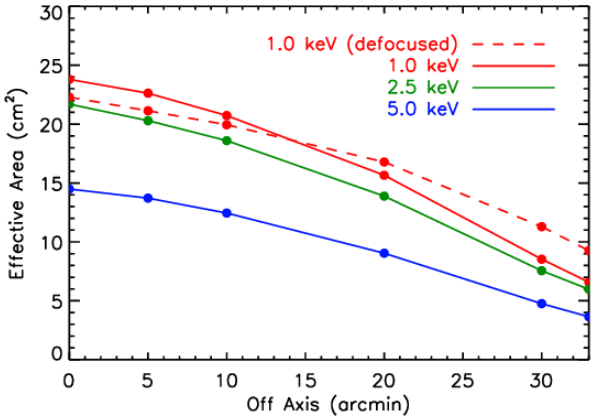
- ~6U CubeSat X-ray Telescope: 5.8 kg with 8.6W (S/C: ~40U)
  X-ray Imaging Spectrometer (XIS) and Solar X-ray Monitor (SXM)
- XIS covers 0.4 – 7 keV with <150 eV FWHM @ 1 keV, 1 sq. deg FoV with < 1 arcmin Ang. Res.: 2 – 3 km resolution with 110 km foot print at 6000 km; < 1 μsec timing resolution for XNAV
- SXM covers >130 deg FWZI with energy range of 1 – 8 keV

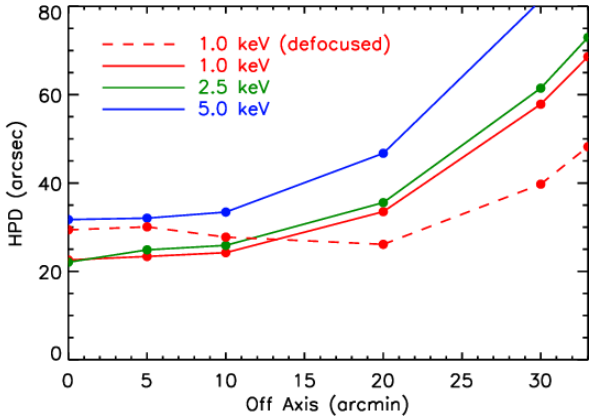
Miniature Lightweight X-ray Optics (MiXO)



Cross-sectional view of 34 shells

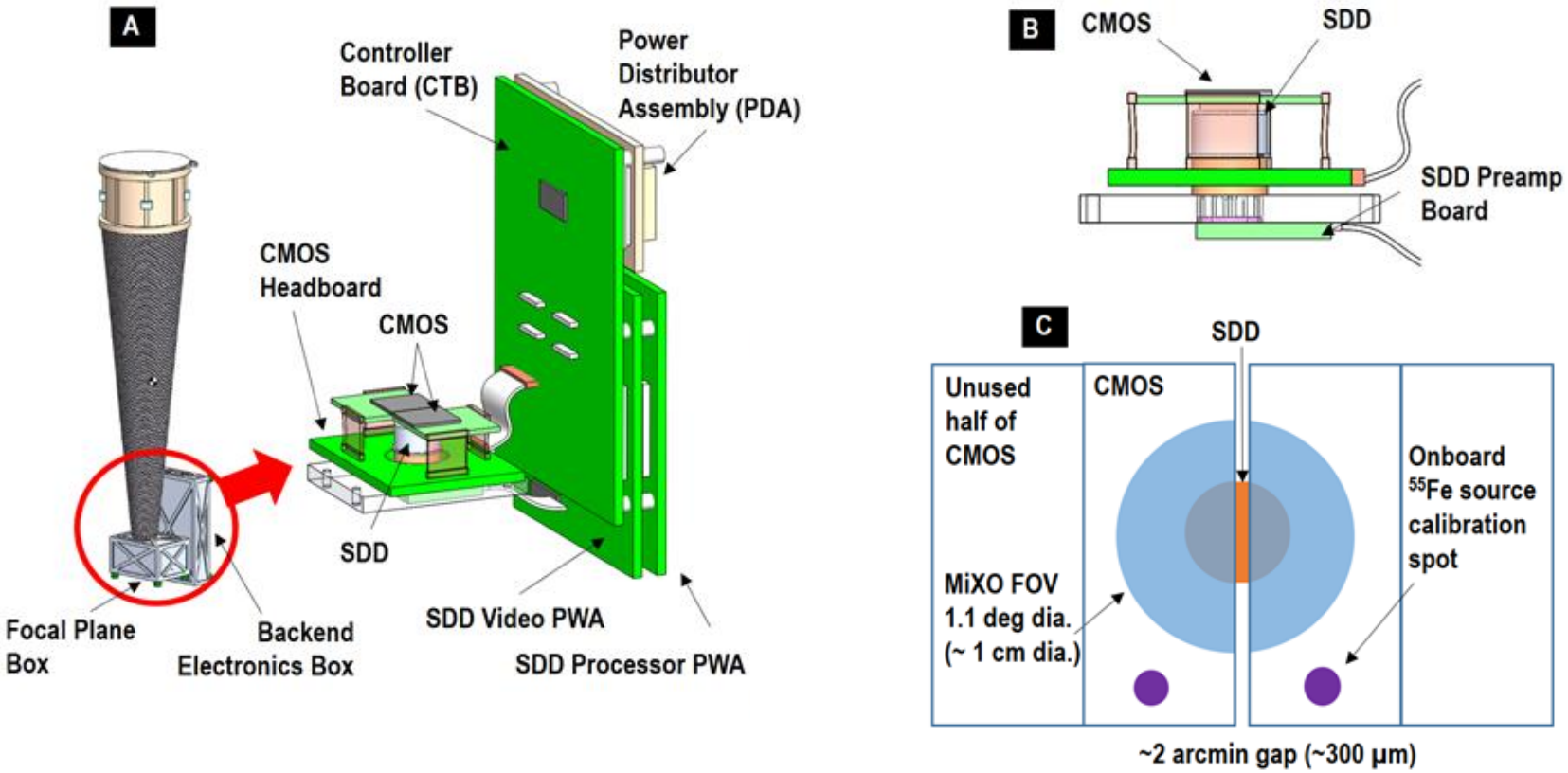
- Achieve <1 arcmin resolution over 1 sq. deg and 24 cm^2 on-axis & 12 cm^2 off-axis (@ 33 arcmin) effective area at 1 keV
- 34 lightweight NiCo ENR shells (200 μm thick) in a butterfly design with 10 cm dia. x 8 cm length envelope (~1.5 kg) for 50 cm focal length





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

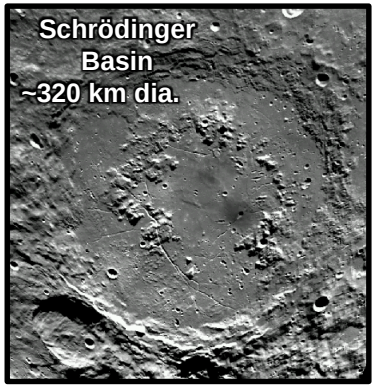


- 2 monolithic CMOS X-ray sensors: 16 μm pixel, <150 eV FWHM at 1 keV for XRF imaging spectroscopy
- Amptek SDD: < 1 μsec timing for XNAV
- Enable both XRF measurements and XNAV observations without moving parts

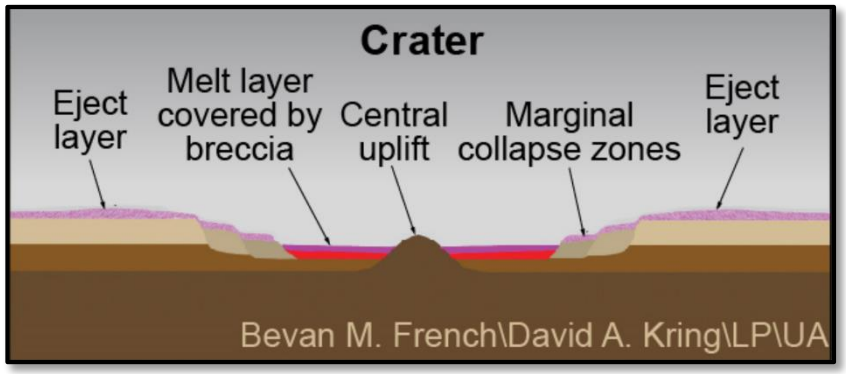
2) The CubeX Lunar Mission

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

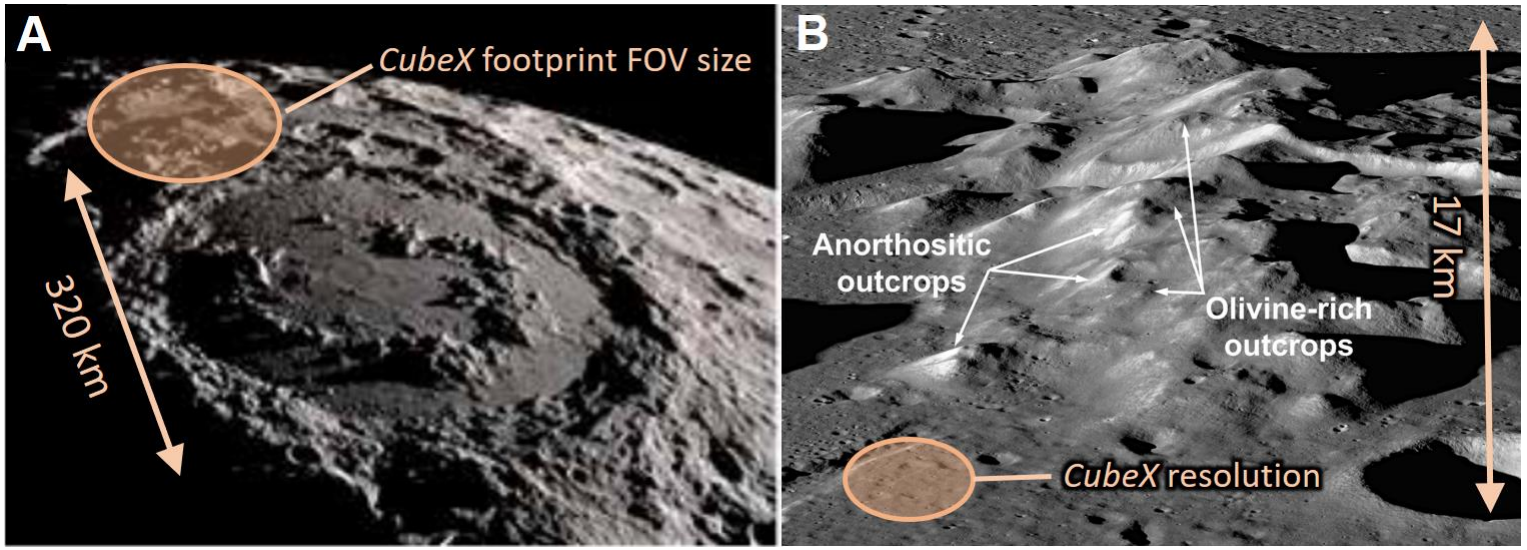


Depth of excexcavated material is ~1/10th – 1/20th of crater diameters.

Assist site selection for future sample collection and provide the larger context of the sample

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].

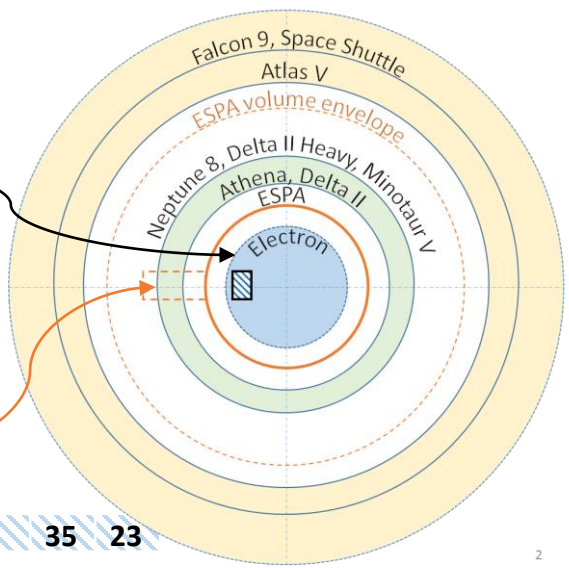
Anorthositic outcrops are generally considered to be from highlands, whereas olivine-rich outcrops are associated with the mantle or lower crust origin.

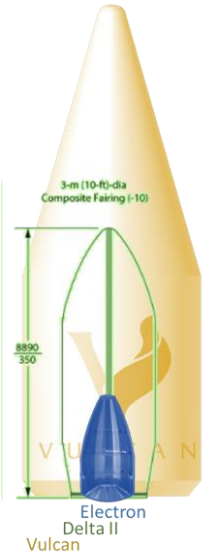
Mission Concept

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

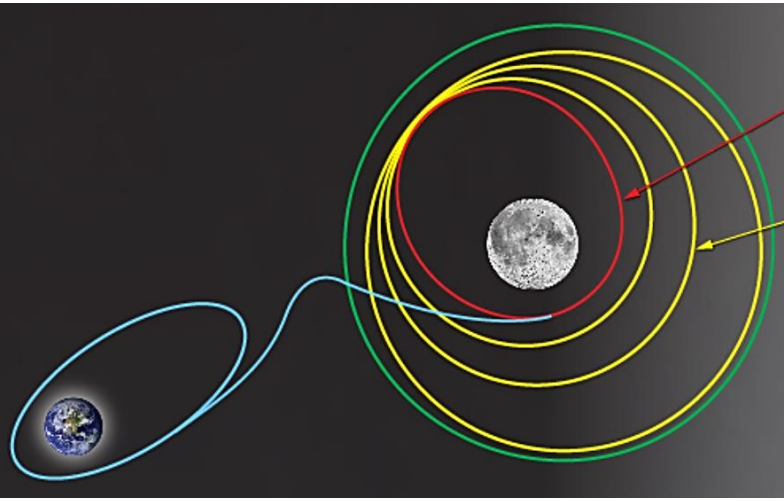
CubeX canister mount orientation fits all fairings

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

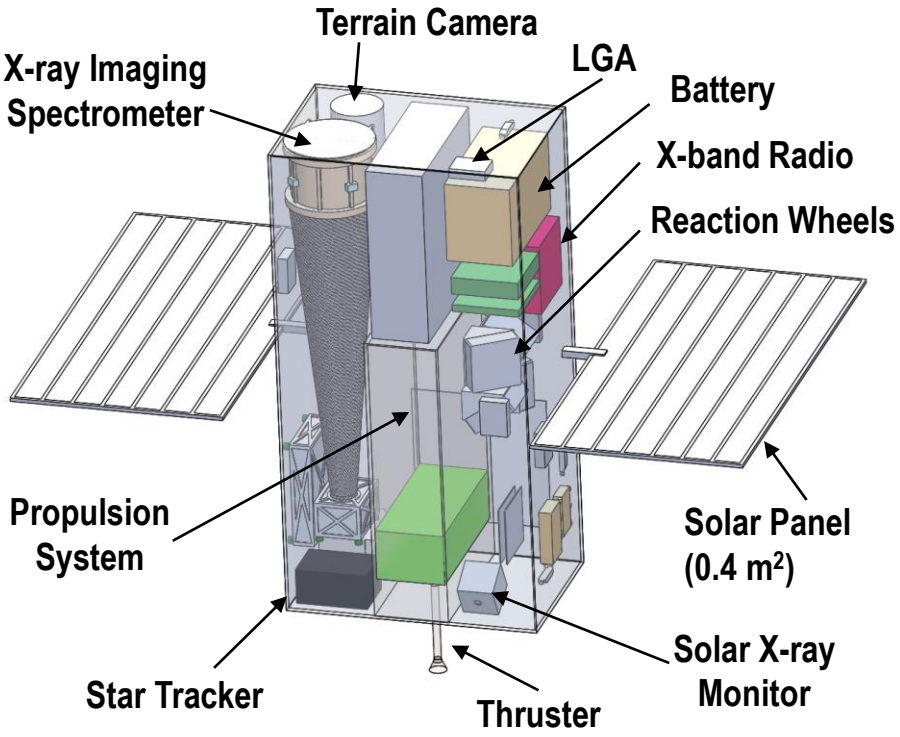
4 orbit transfer maneuvers to science orbit (ΔV ~300 m/s raise)

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**

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)

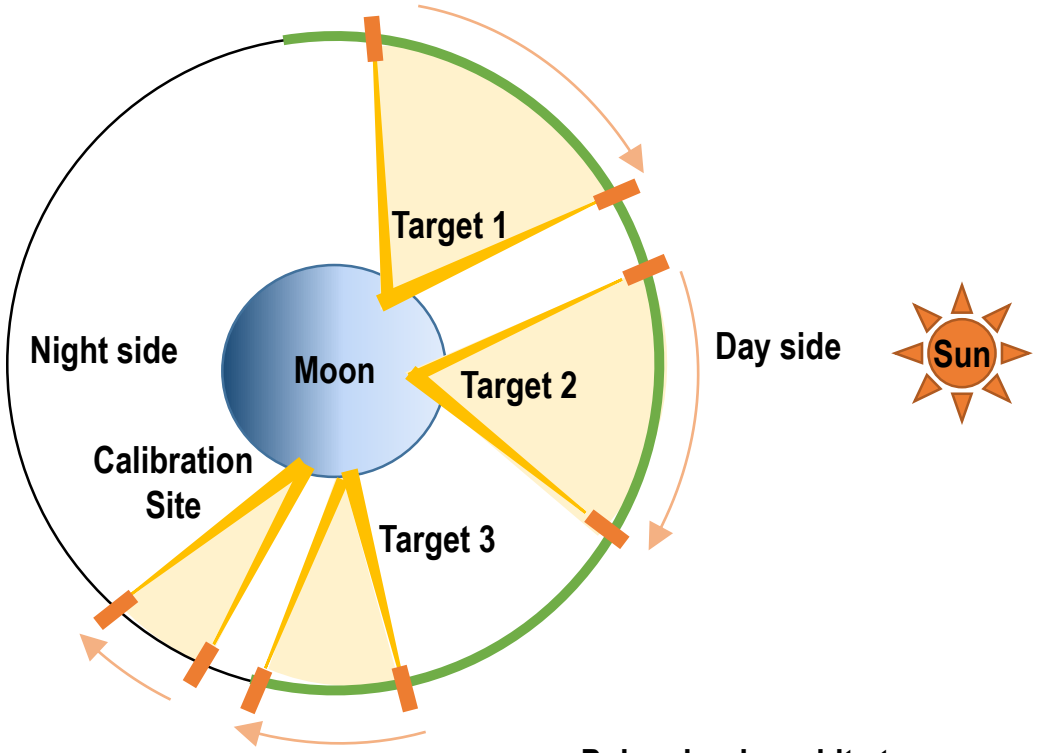


Total Vol: 35 x 23 x 68 cm

Total Mass: 43 kg

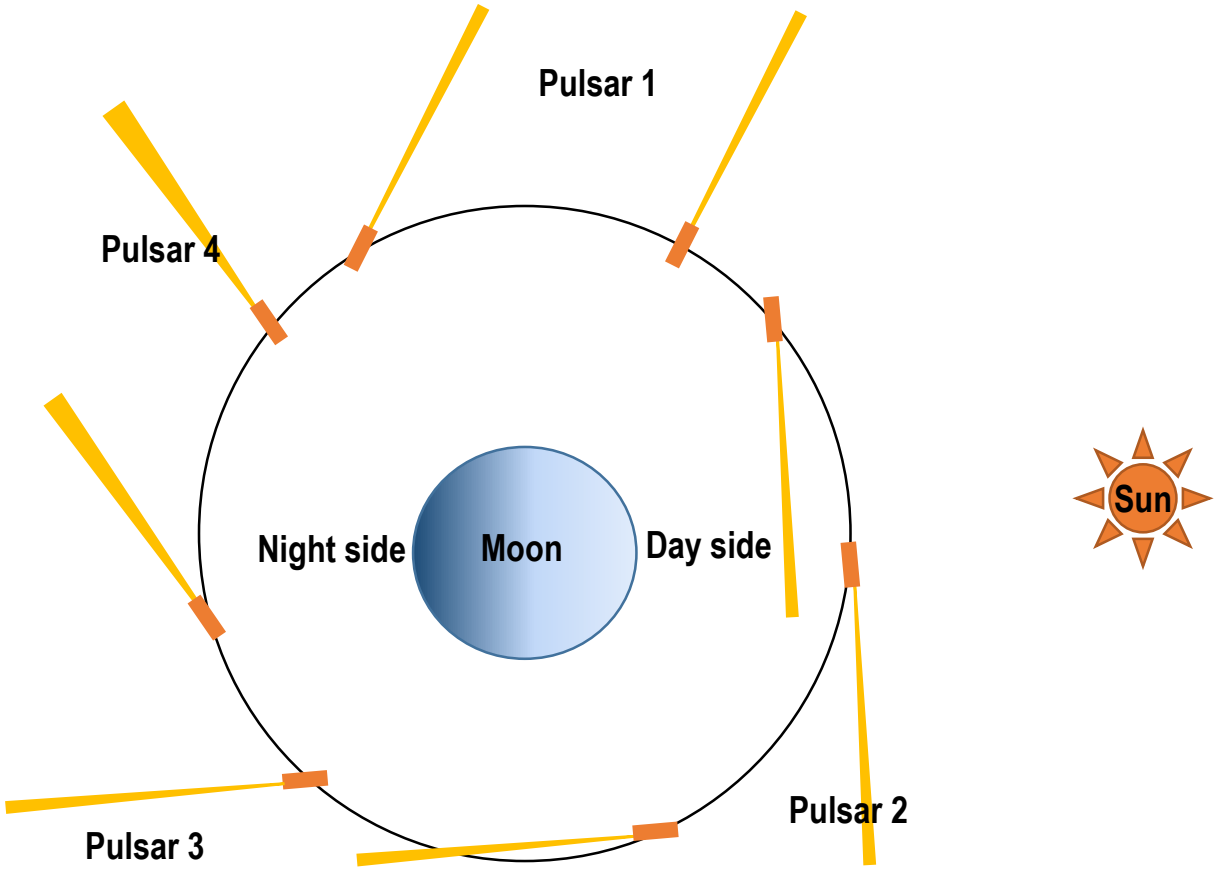
Observation Sequence Example for Lunar XRF

- ~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



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 & Outlook

- *CubeX* is a compact X-ray focusing telescope than 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
NASA ARC	Mission Design, S/C Design, MOC

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

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Kiran 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
Martin Elvis (SAO)	Lunar and XRF Science
Richard Binzel (MIT)	Planetary XRF Science
Jonathan Grindlay (Harvard)	X-ray Telescope Design
William Boynton (U. Arizona)	Planetary Instruments

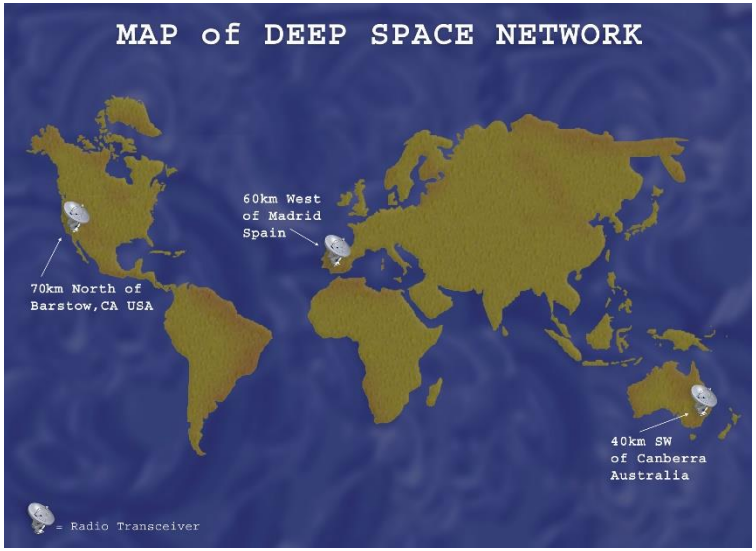
Mission & S/C Design

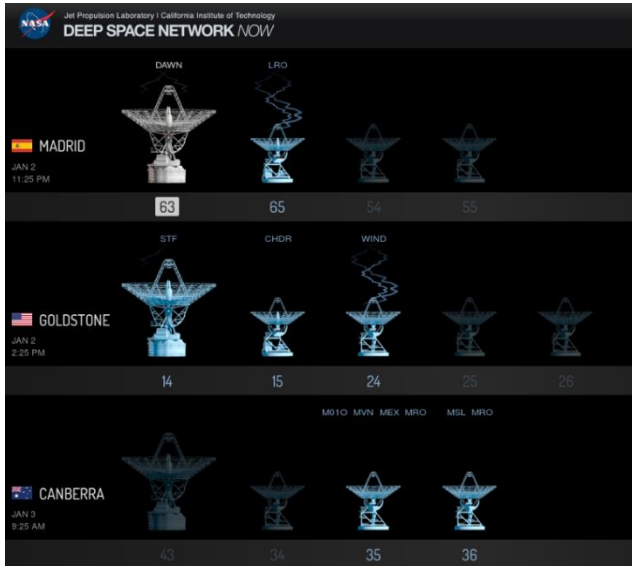
Jan Stupl (SGT/ARC)	Project Manager
Sam Montez (MEI/ARC)	Capture Lead
Brittany Wickizer (ARC)	Systems Engineer
Arwen Dave (MEI/ARC)	Deputy Systems Engineer
Ashley Clark (ARC)	ADCS
Andres Dono-Perez (MEI/ARC)	Propulsion
Monica Ebert (SGT/ARC)	Radiation
Ali Kashani (MEI/ARC)	Thermal
Daniel Larrabee (MEI/ARC)	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

II. Can We Navigate Deep Space Autonomously?

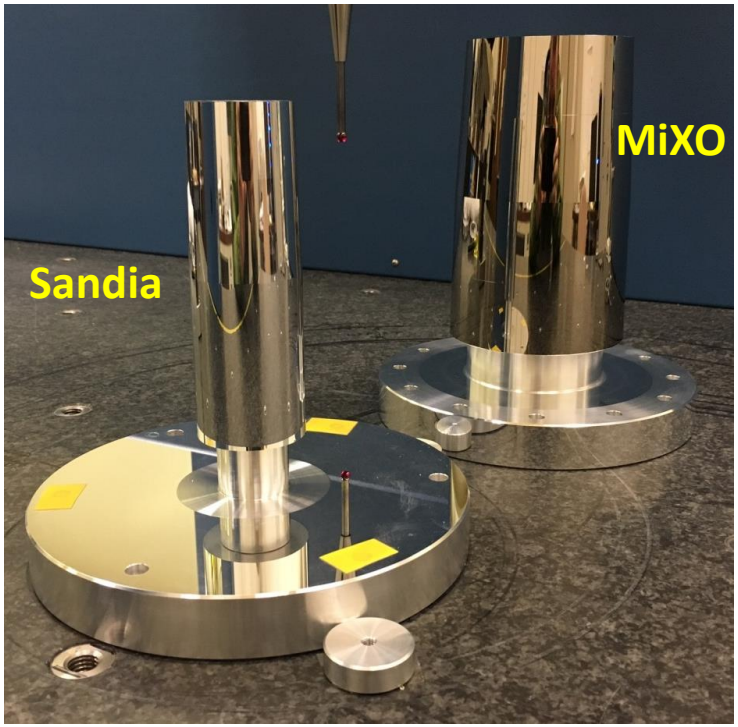
- Deep space navigation is a critical issue for interplanetary missions.
- Current deep space navigation relies on a global network of large ground-based radio antennas such as NASA DSN and ESA ESTRACK.
  - Performance degrades while the operational cost increases as the S/C travels farther away from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





Technology Development of MiXO

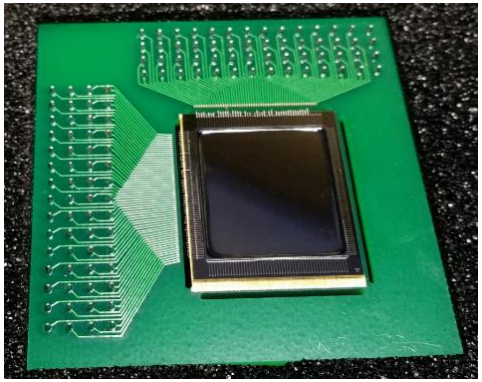
- TRL 5: currently being developed under NASA APRA and PICASSO programs.



Mandrel (*left*) and replicated NiCo optic (*right*)

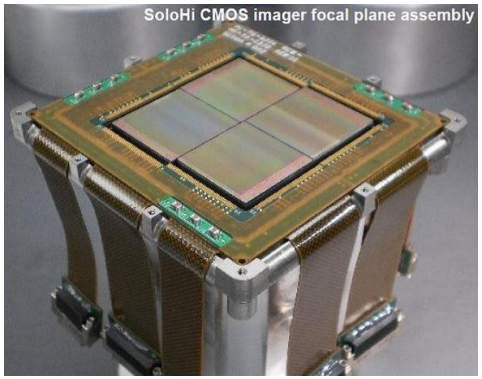
- Typical mandrels used for small optics effort:
  - Left: 4.5cm diameter x 6cm length
  - Right: 9cm diameter x 10 cm length (MIXO mandrel)
- Both mandrels fabricated at MSFC have ~ 15 arcsec figure, 3Å μr

Monolithic CMOS X-ray Sensors for XRF Detection

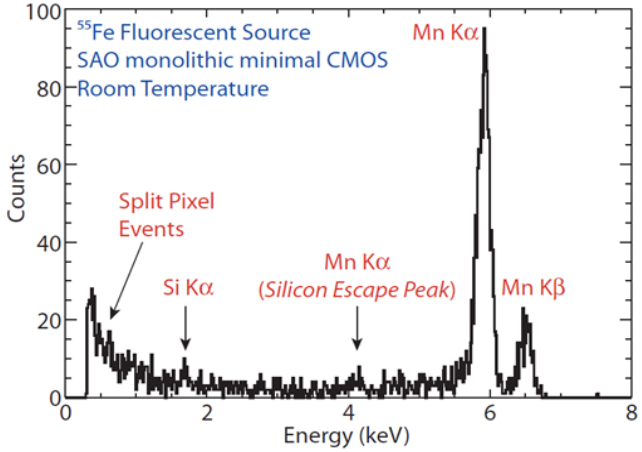


▲ SAO/SRI BM III:
1k x 1k pixels, 16 µm pitch,
Back Illuminated (BI)

- 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



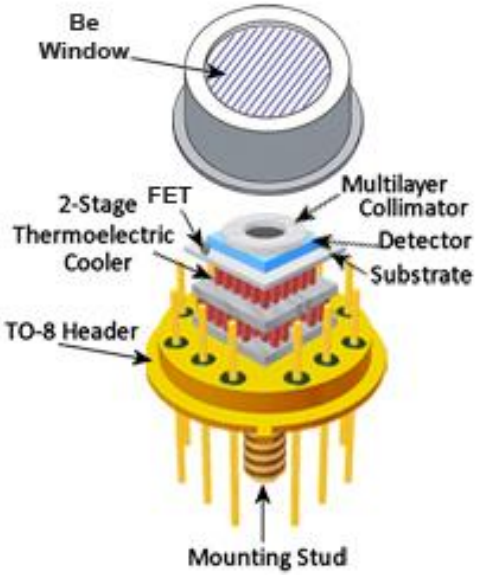
▲ SoloHi 2x2 abuttable flight Mo package

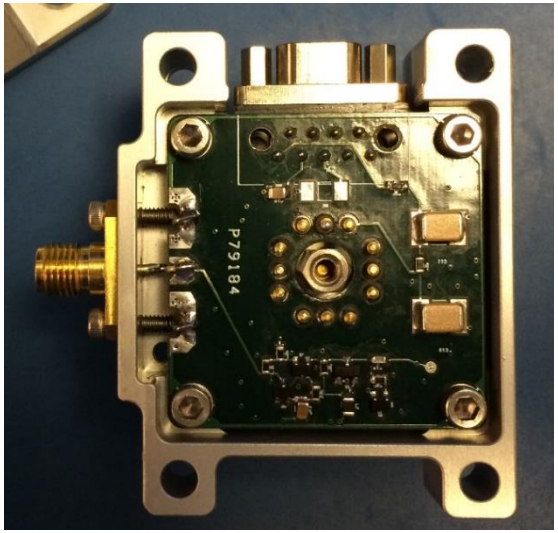


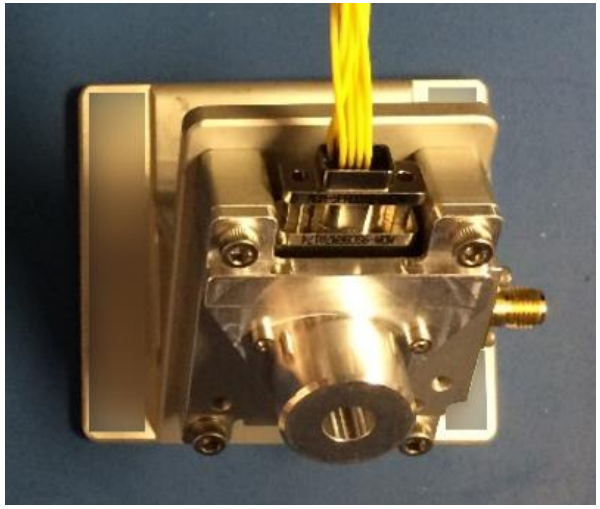
^{55}Fe spectrum taken with monolithic CMOS BM-II minimal **at room temperature**

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**







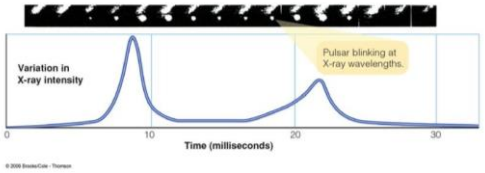
SDD TO-8 Module
- COTS item from Amptek
- Be Optical Blocking Filter
- SDD Cooling with 2-Stage TEC
- SDD substrate and detector

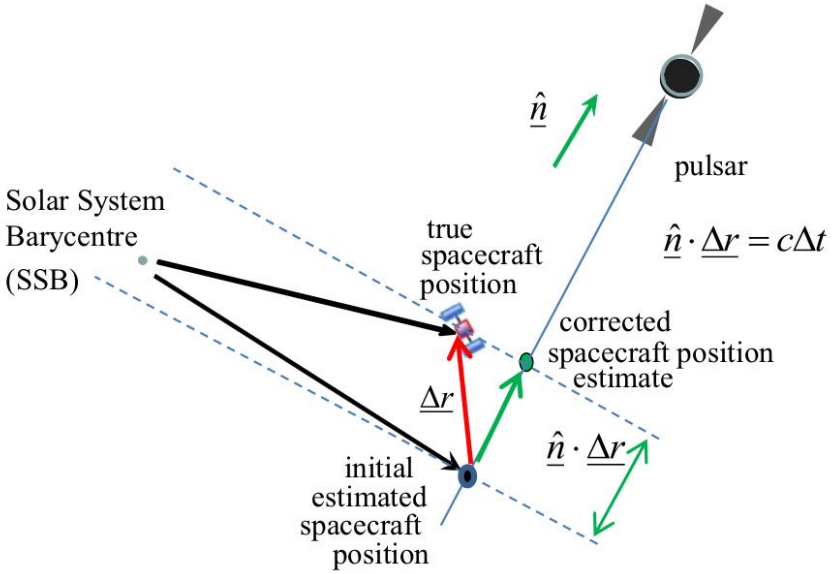
Pre-amp Board
- Initial signal conditioning for the output signals from the SDD
- Routing for TEC power and BIAS
- ~3.5 cm x 3.5 cm

Collimator and Bracket
- Correct Angle to the Sun
- Correct FoV
- Throughput Regulation

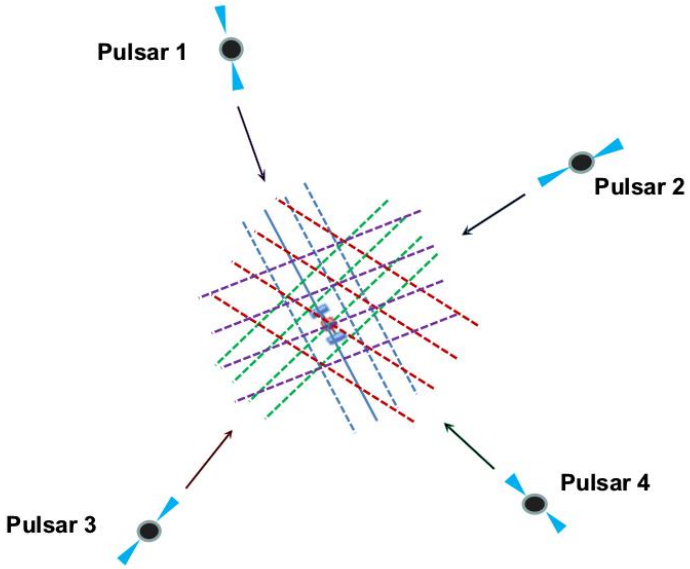
CubeX combines XRF with XNAV capabilities: X-ray Pulsar Timing Based Navigation

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





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**