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


**Jan Stupl**
SGT / NASA Ames Research Center

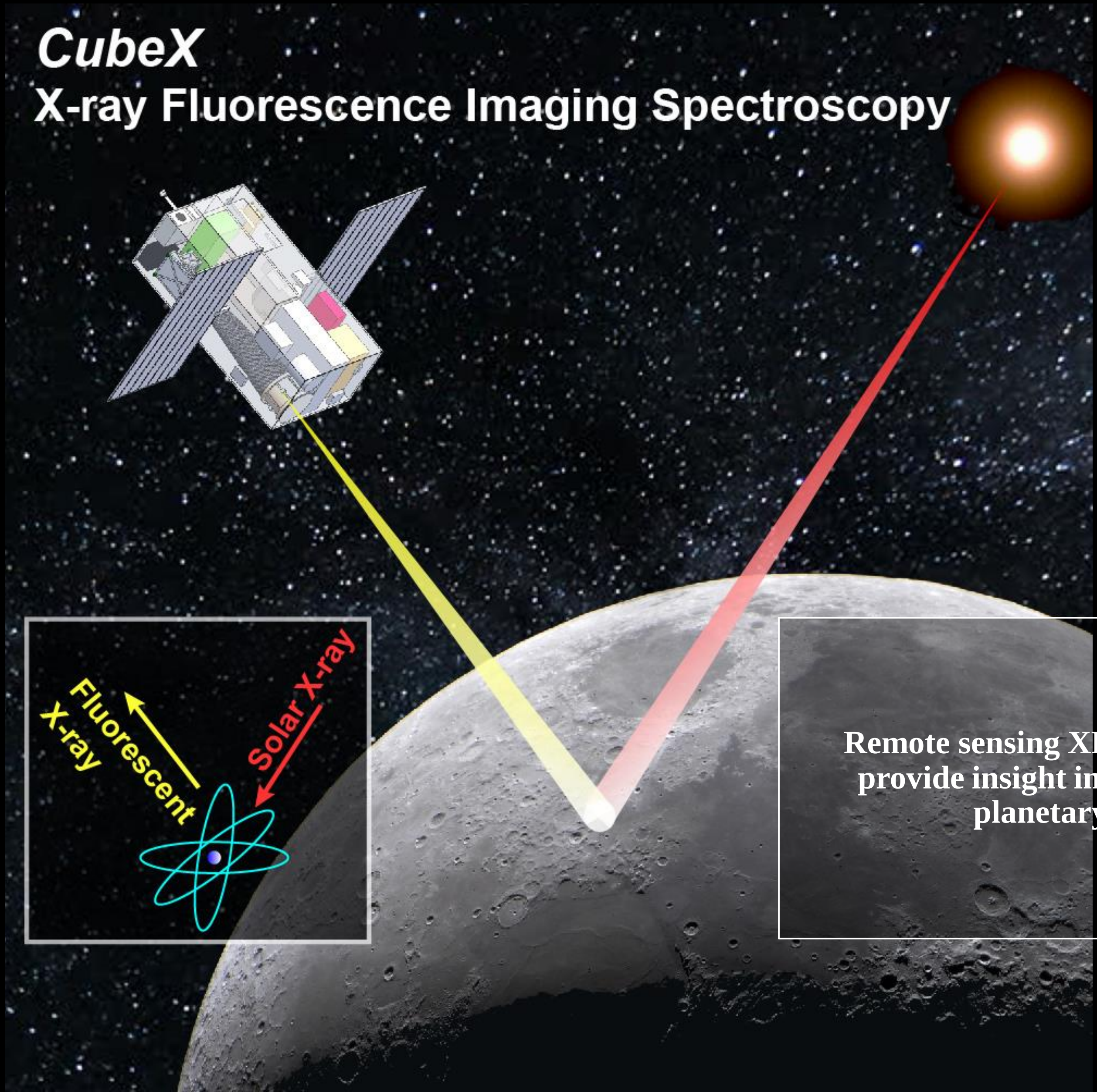
**Jaesub Hong**
Harvard

**& the CubeX team**


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

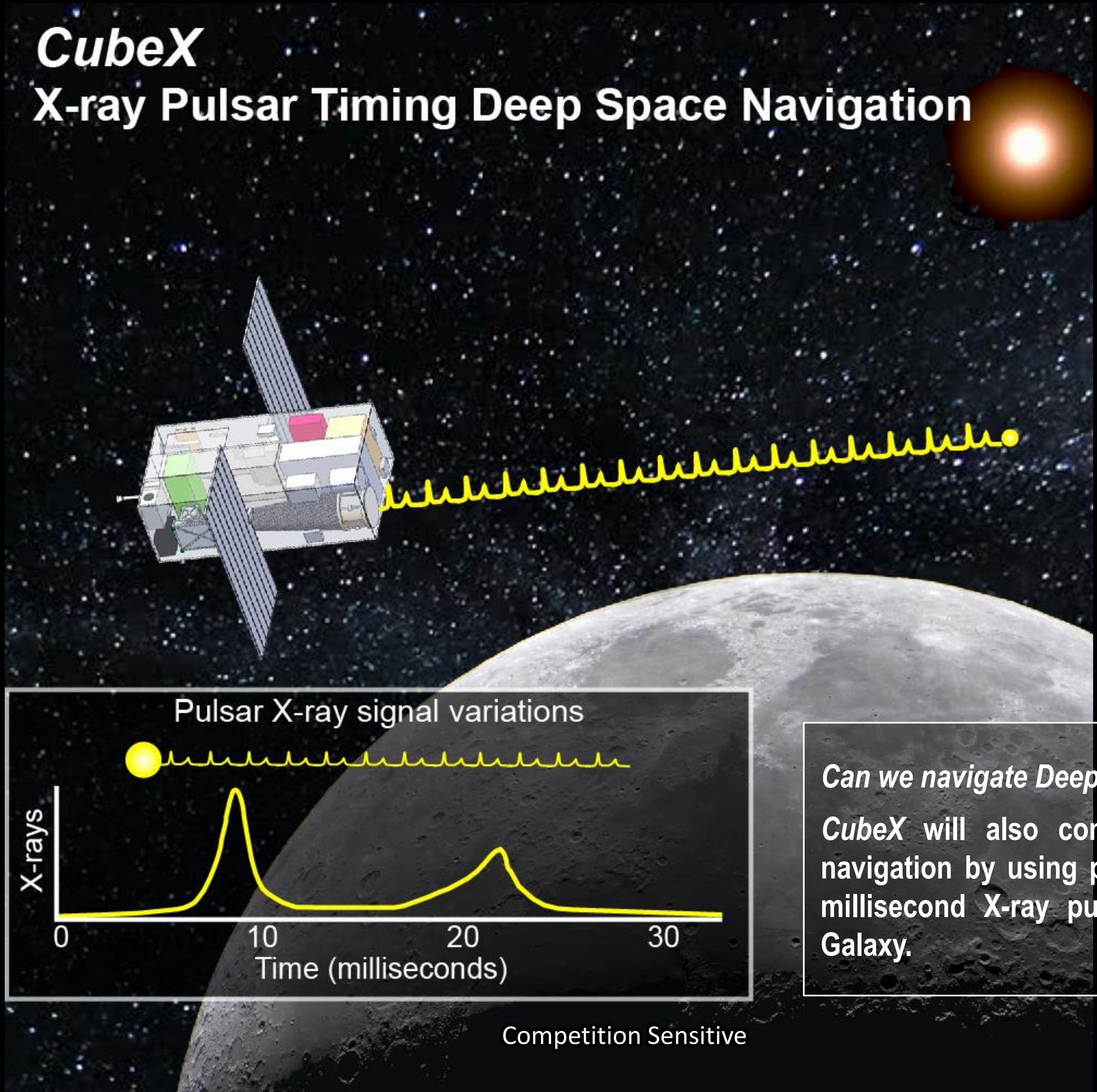
# 1) The CubeX Instrument

# CubeX combines XRF with XNAV capabilities:




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

# *CubeX* combines *XRF* with *XNAV* capabilities:

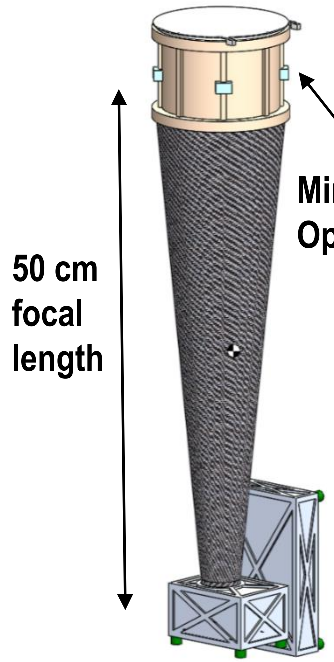



***Can we navigate Deep Space autonomously?***

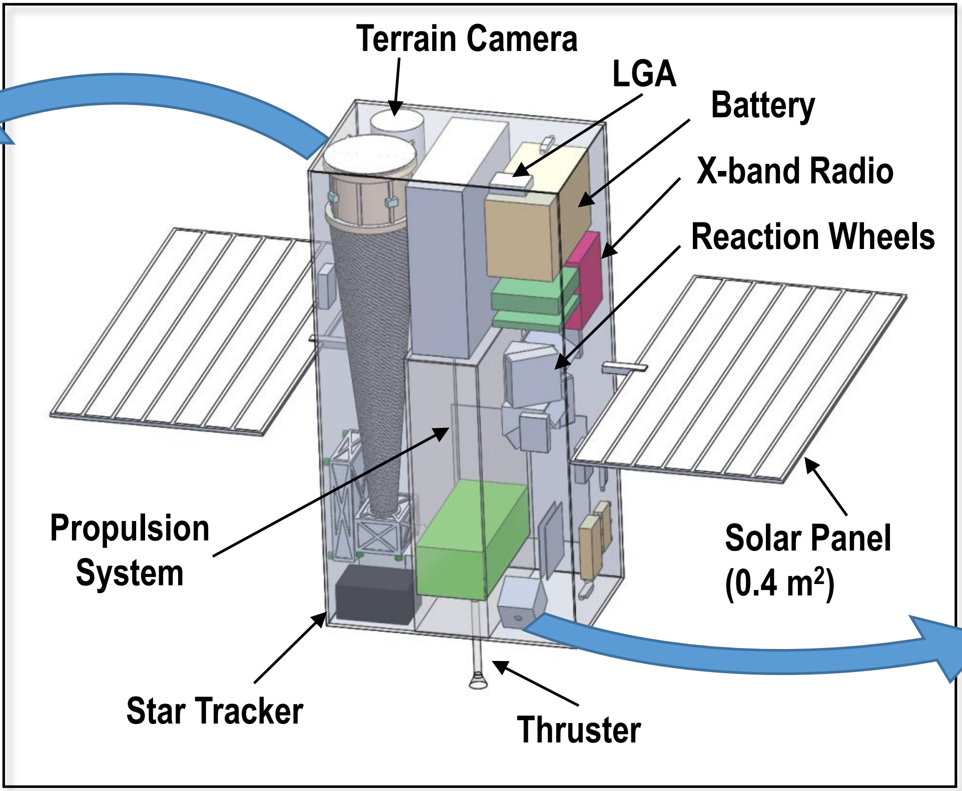
***CubeX*** **will also conduct semi-autonomous navigation by using precise time series from millisecond X-ray pulsars as "GPS" in our Galaxy.**

# CubeX: CubeSat X-ray Telescope

X-ray Imaging Spectrometer (XIS)



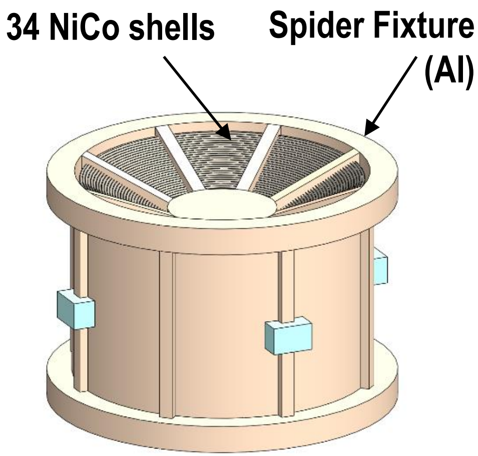

Focal plane of CMOS & SDD

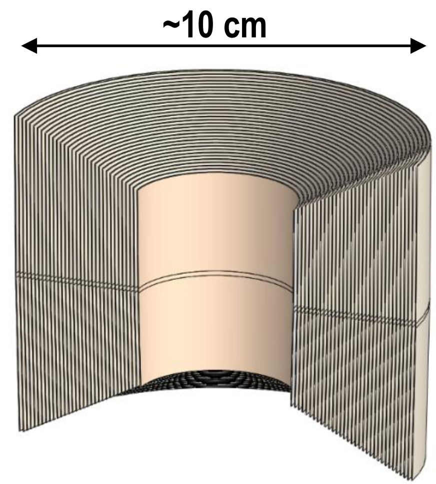



Solar X-ray Monitor (SXM)

- ~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

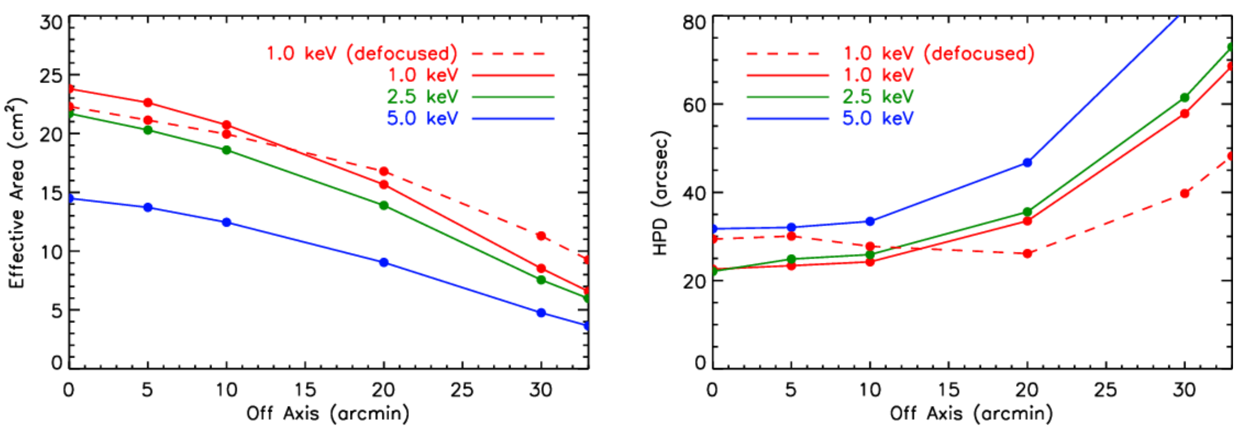
# Miniature Lightweight X-ray Optics (MiXO)



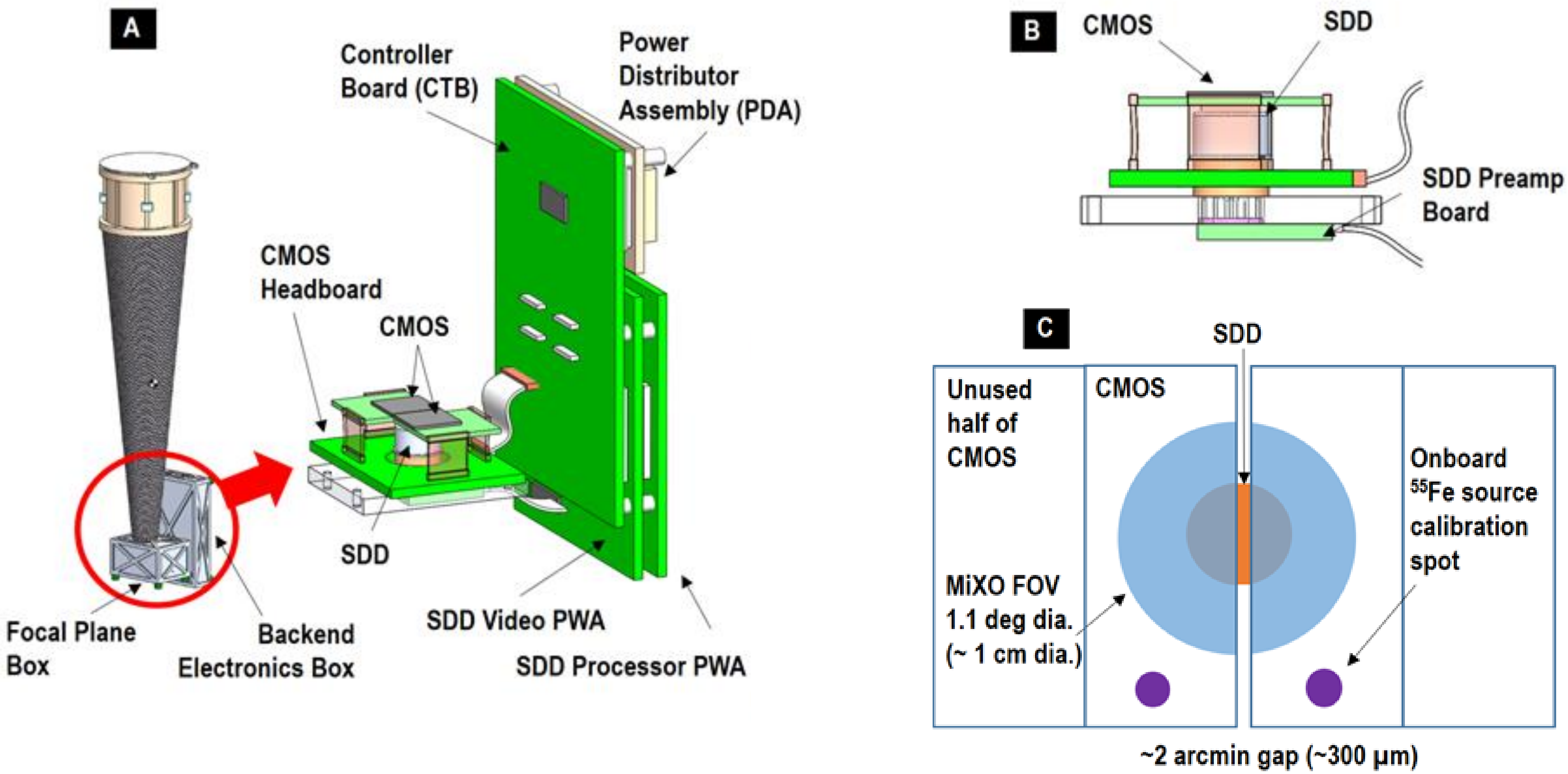

Cross-sectional view of 34 shells

- 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

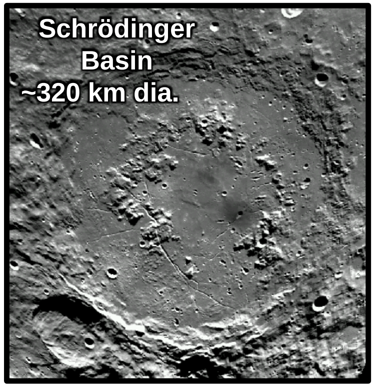



- 2 monolithic CMOS X-ray sensors: 16 µm pixel, <150 eV FWHM at 1 keV for XRF imaging spectroscopy
- Amptek SDD: < 1 µsec timing for XNAV
- Enable both XRF measurements and XNAV observations without moving parts

# 2) The CubeX Lunar Mission

# Primary Science Objectives of CubeX

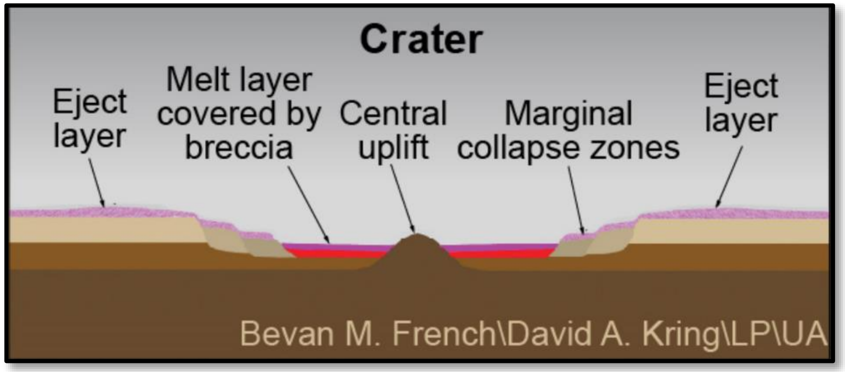
Identify and measure compositions of lunar lower crust and upper mantle outcrops excavated within and around impact craters.







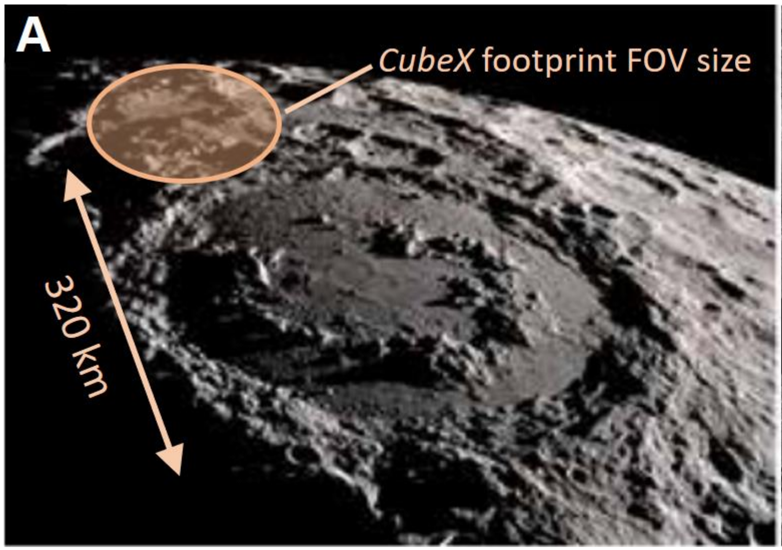
Example target sites guided by data from missions like *GRAIL*, *LRO*, *Kaguya*, covering diverse crater sizes in both the nearside and farside of the Moon



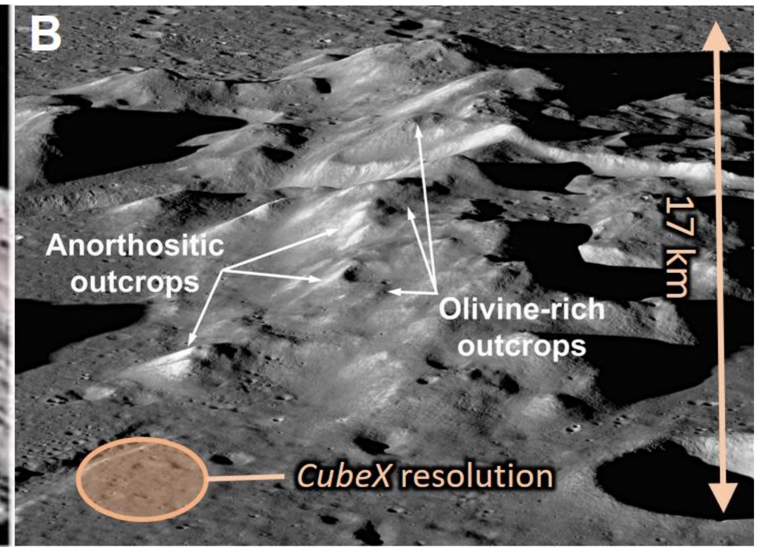

Depth of excavated material is ~1/10th – 1/20th of crater diameters.

# 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.

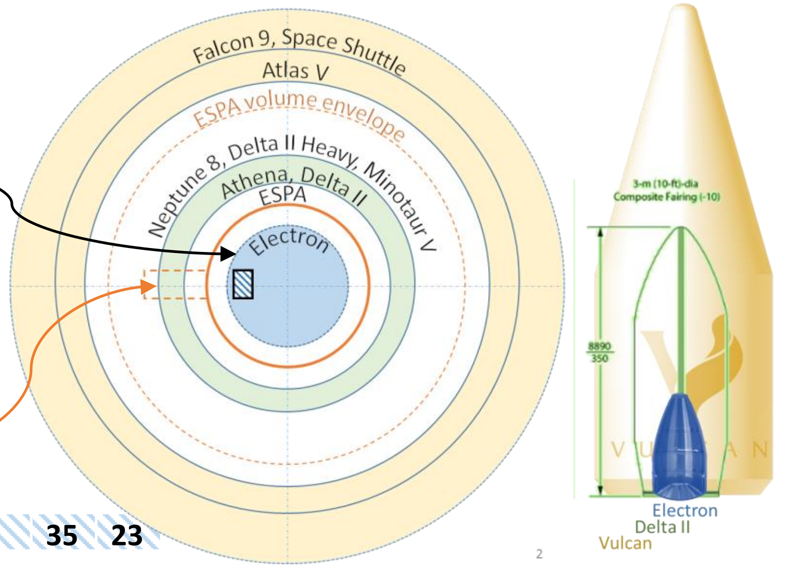
# Mission Concept

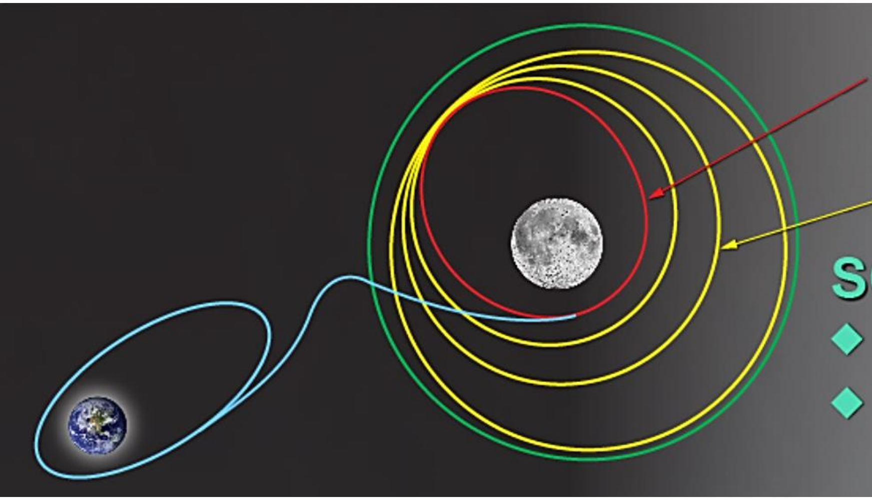
- ***CubeX*** **is currently designed as a secondary spacecraft, deployed into a common lunar orbit**
- **Launch during solar maximum (2023 – 2027)**

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**

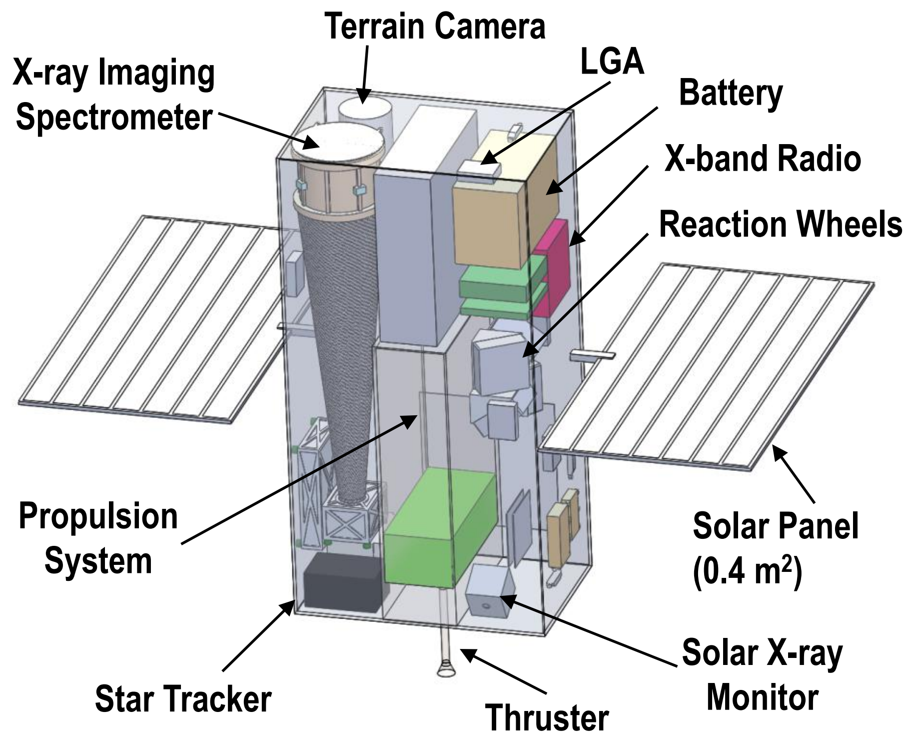
**4 orbit transfer maneuvers to science orbit ($\Delta V$ ~300 m/s raise)**

**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) |



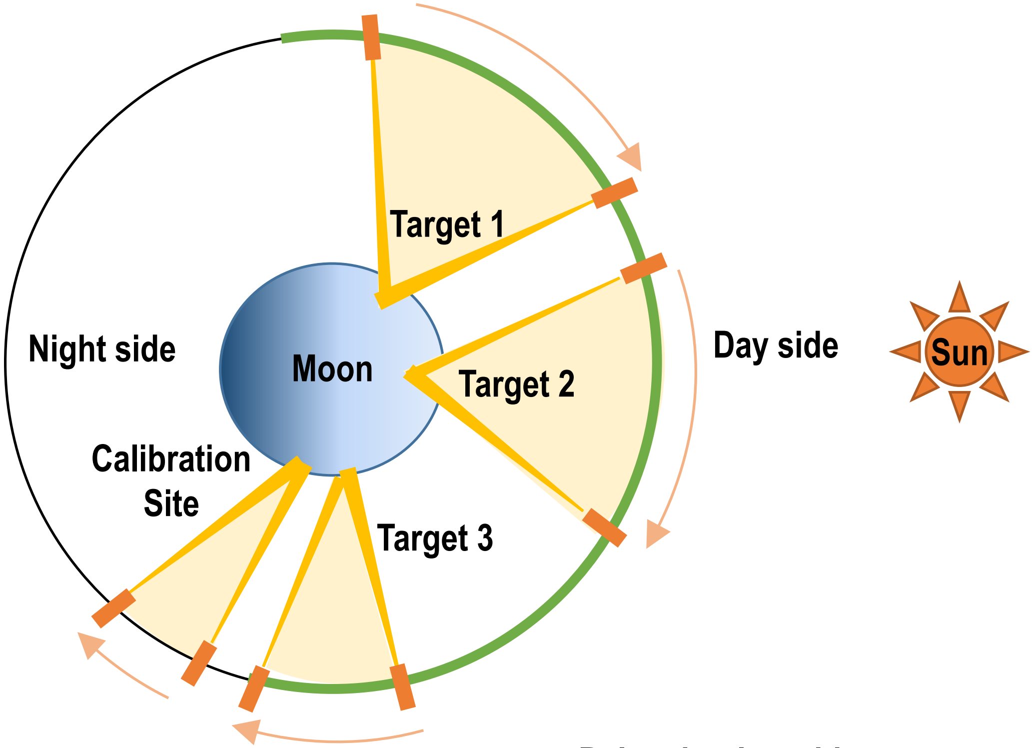

**Total Vol: 35 x 23 x 68 cm**

**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

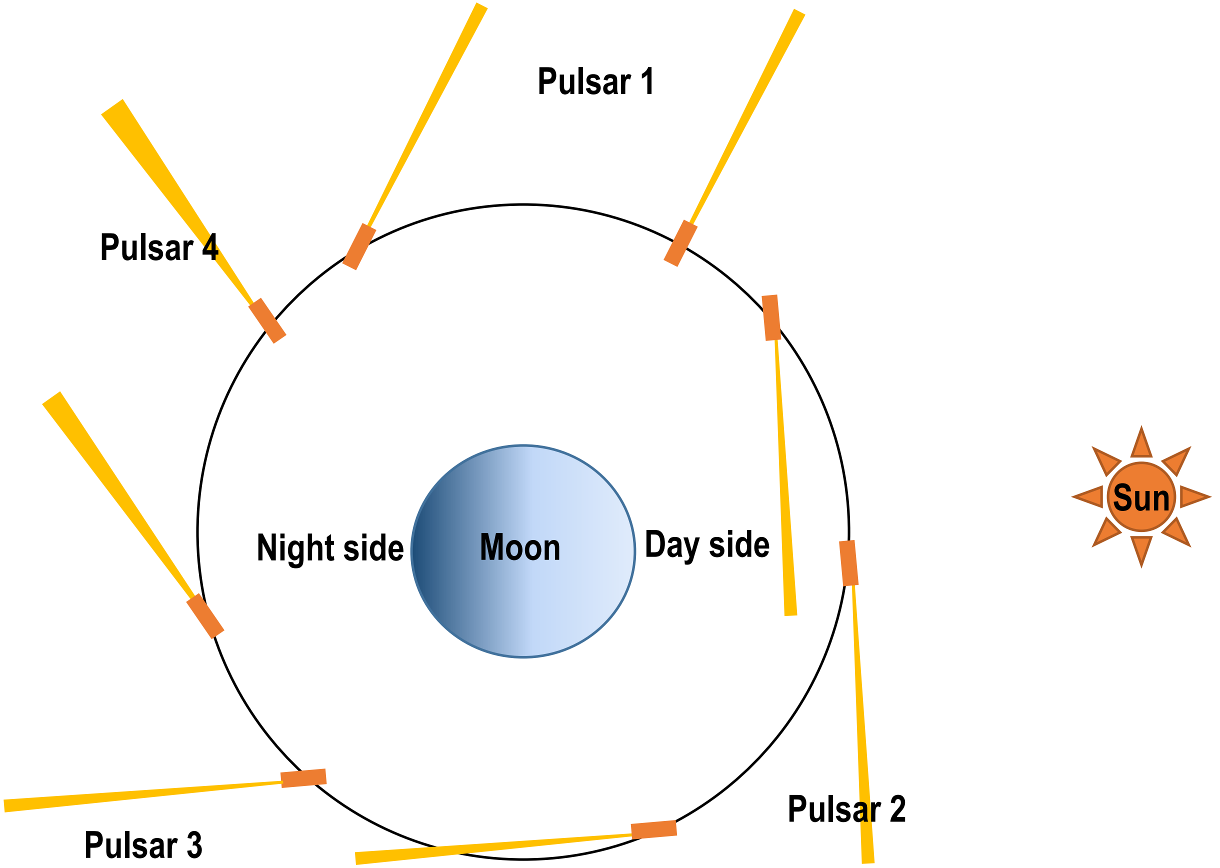
  e.g., < 30% error of abundance ratio at ~3 km scale




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 & 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

| | |
|---|---|
| Brian Ramsey (MSFC) | MiXO |
| 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 |

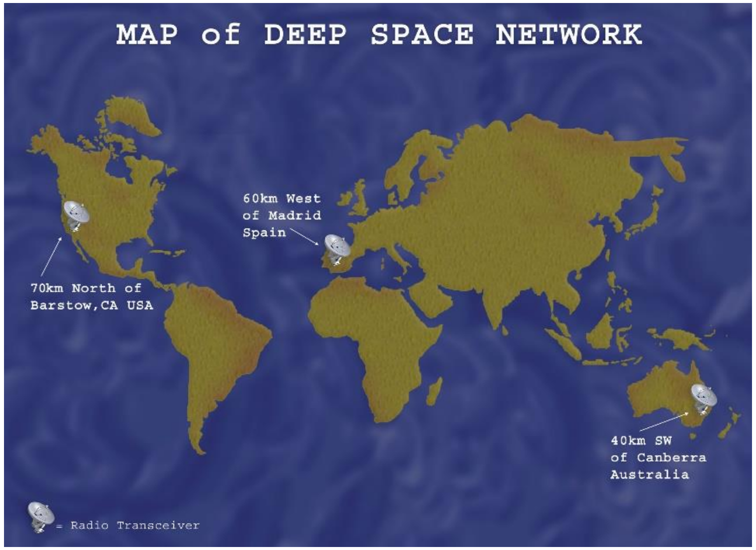
## Mission & S/C Design

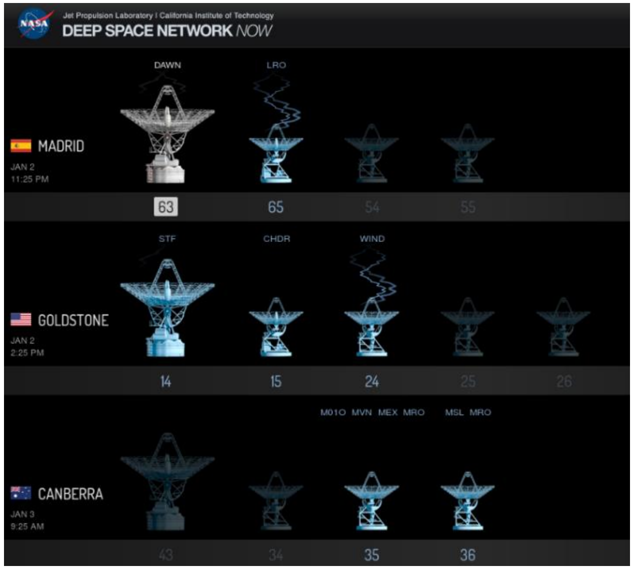
| | |
|---|---|
| Jan Stupl (SGT/ARC) | Project Manager |
| Sam Montez (MEI/ARC) | Capture Lead |
| Brittany Wickizer (ARC) | Systems Engineer |
| Arwen Dave (MEI/ARC) | Deputy Systems Engineer |
| Ashley Clark (ARC) | ADCS |
| Andres Dono-Perez (MEI/ARC) | Propulsion |
| Monica Ebert (SGT/ARC) | Radiation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

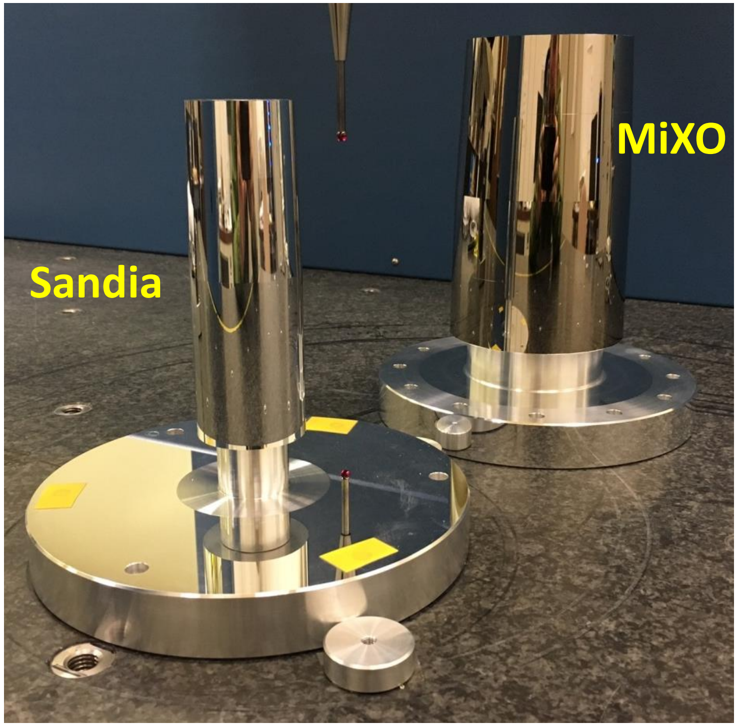
- **Deep space navigation is a critical issue for interplanetary missions.**
- **Current deep space navigation relies on a global network of large ground-based radio antennas such as NASA DSN and ESA ESTRACK.**
  - **Performance degrades while the operational cost increases as the S/C travels farther 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

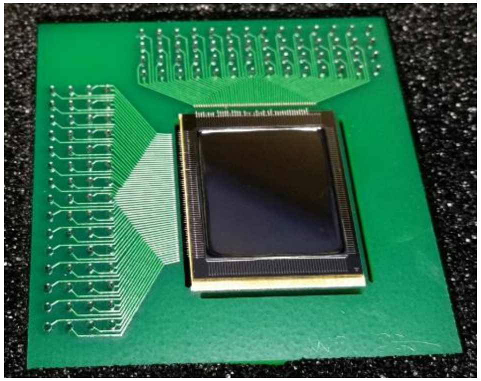
- TRL 5: currently being developed under NASA APRA and PICASSO programs.




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

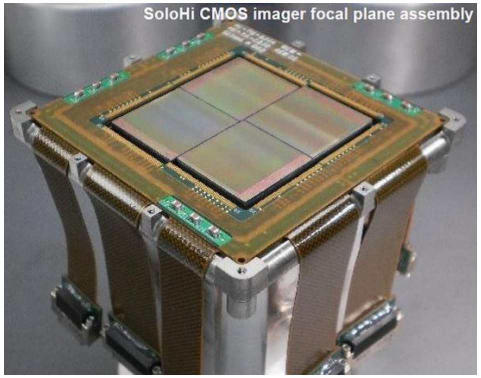
- Typical mandrels used for small optics effort:
  Left: 4.5cm diameter x 6cm length
  Right: 9cm diameter x 10 cm length (MIXO mandrel)
- Both mandrels fabricated at MSFC have ~ 15 arcsec figure, 3Å μr

# Monolithic CMOS X-ray Sensors for XRF Detection

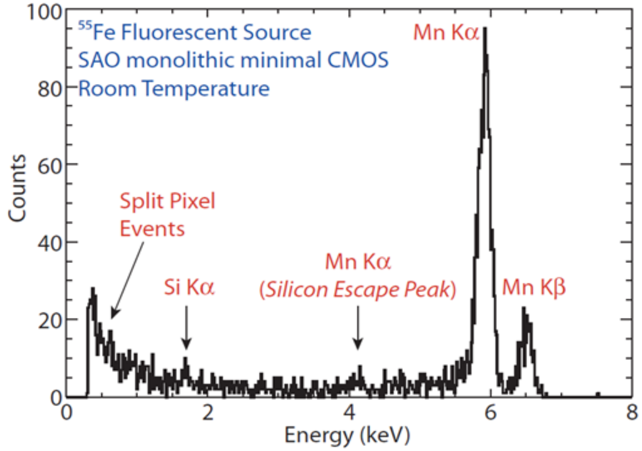


▲ SAO/SRI BM III:
1k x 1k pixels, 16 μm pitch,
Back Illuminated (BI)

- 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



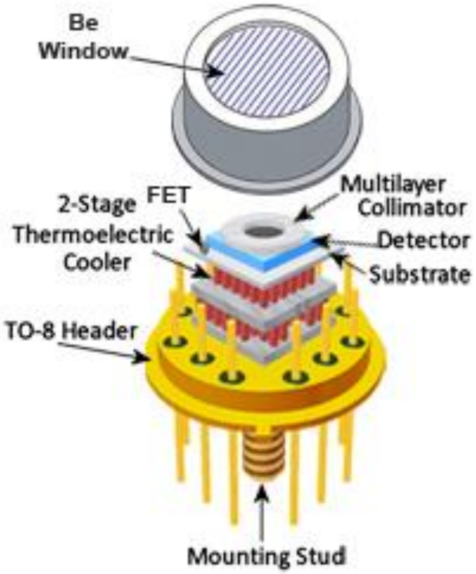

▲ SoloHi 2x2 abuttable flight Mo package

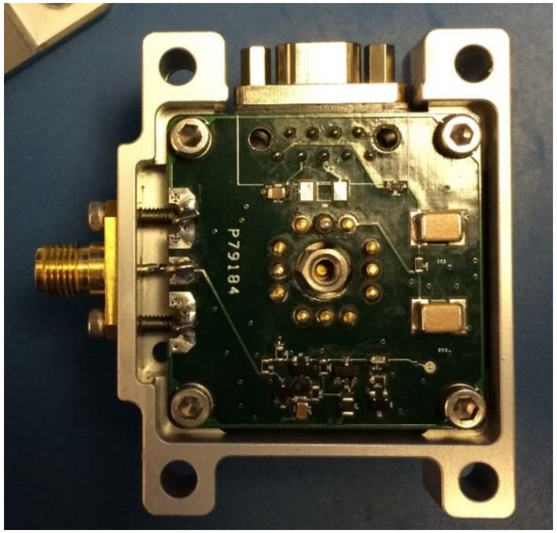


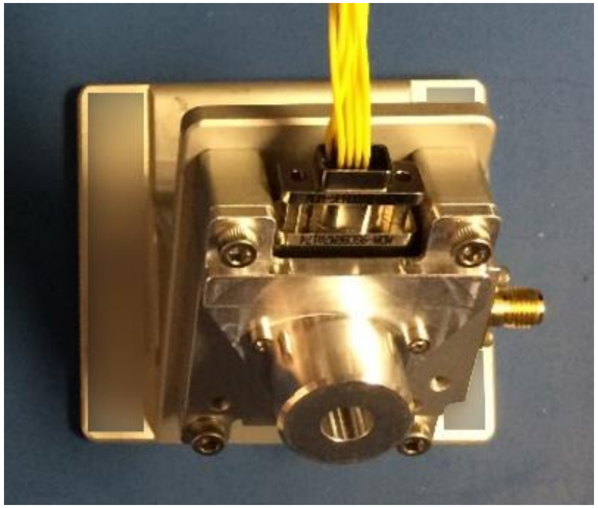

$^{55}Fe$ spectrum taken with monolithic CMOS BM-II minimal **at room temperature**

# 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



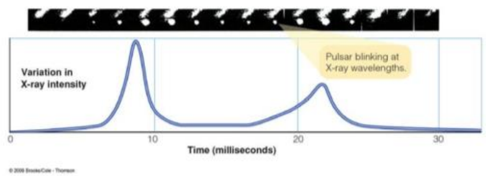
**SDD TO-8 Module**
- COTS item from Amptek
- Be Optical Blocking Filter
- SDD Cooling with 2-Stage TEC
- SDD substrate and detector

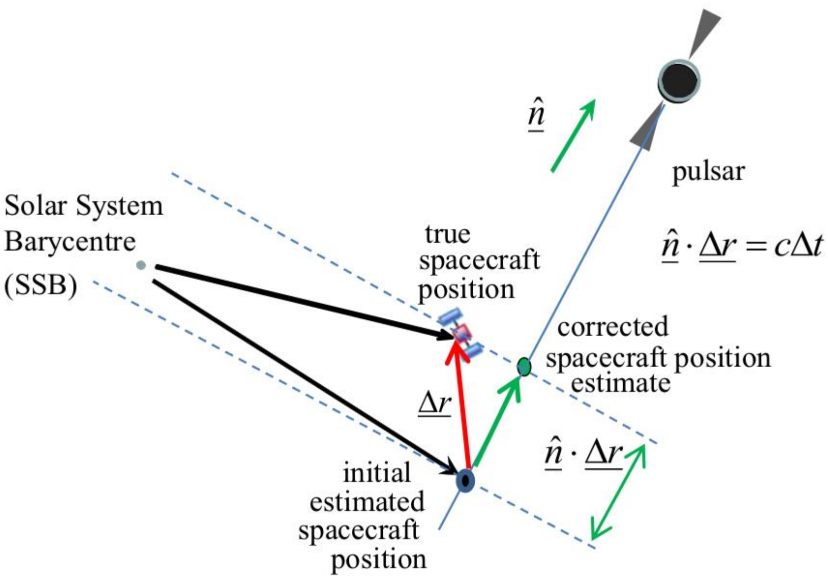
**Pre-amp Board**
- Initial signal conditioning for the output signals from the SDD
- Routing for TEC power and BIAS
- ~3.5 cm x 3.5 cm

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

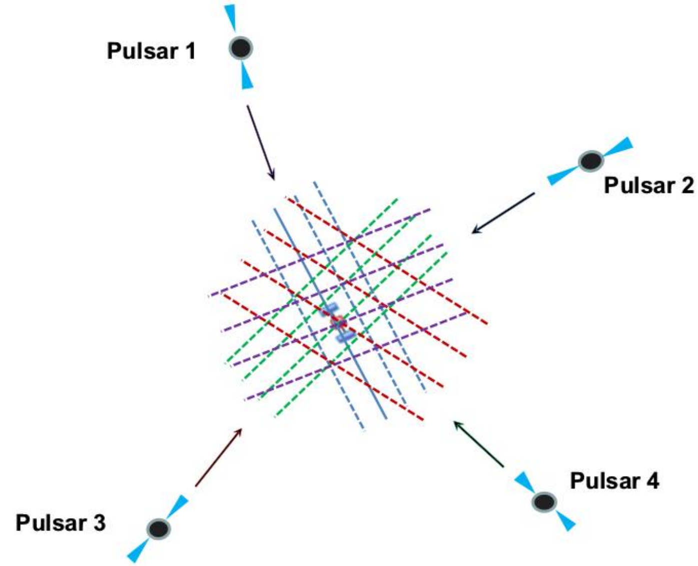
# CubeX combines XRF with XNAV capabilities: X-ray Pulsar Timing Based Navigation

- **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**