# CubeSat X-ray Telescope (CubeX) for X-ray Fluorescence Imaging and X-ray Pulsar Timing based Navigation

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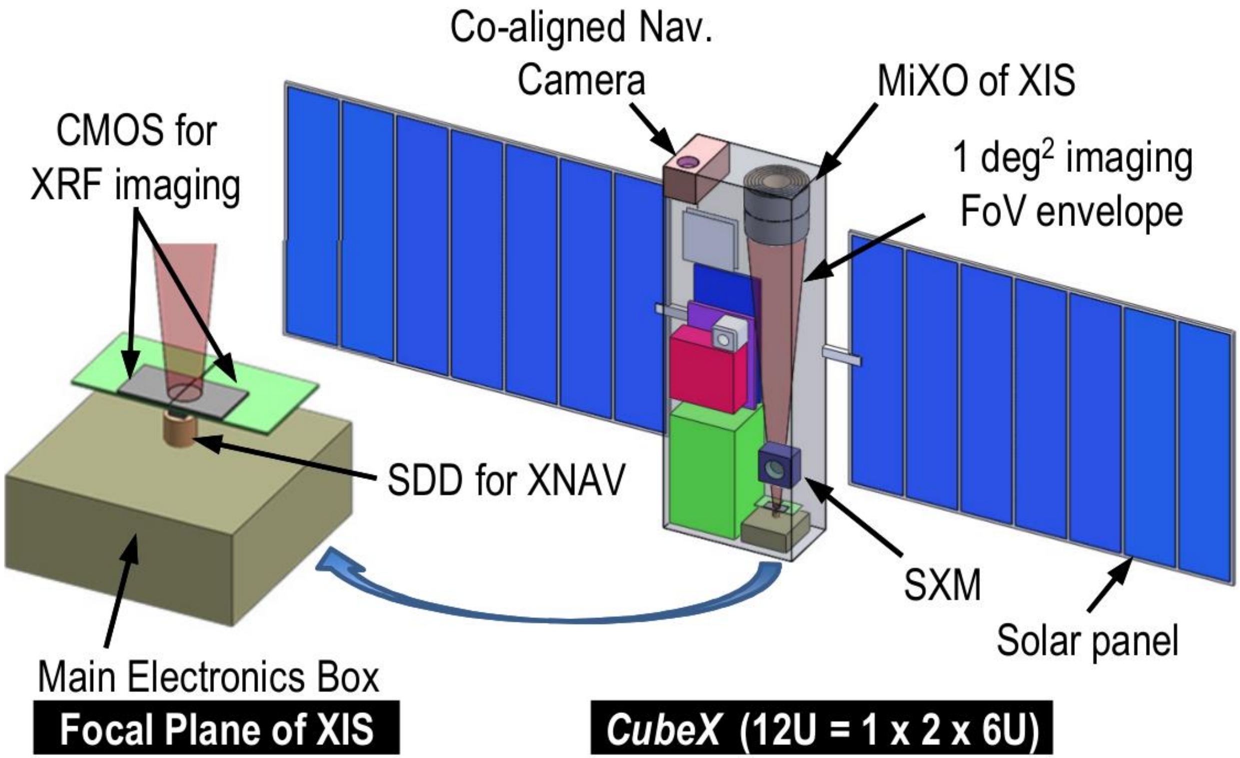
# CubeSat X-ray Telescope (CubeX)




- 12U CubeSat X-ray Telescope for X-ray Fluorescence (XRF) imaging and X-ray Pulsar Timing based Navigation (XNAV)
- *CubeX* for the Moon: Rideshare to the Moon as a 2ndary S/C on a primary mission
- Selected for NASA Planetary Science Deep Space SmallSat Studies

# *Science Goals for CubeX*

- **Map the surface elemental composition of diverse airless bodies using X-ray Fluorescence (XRF)**

  **Understand the formation and evolutionary history of the individual bodies and the workings of the Solar system as a whole.**

- **Conduct the feasibility and performance test of X-ray pulsar timing based deep space navigation (XNAV)**

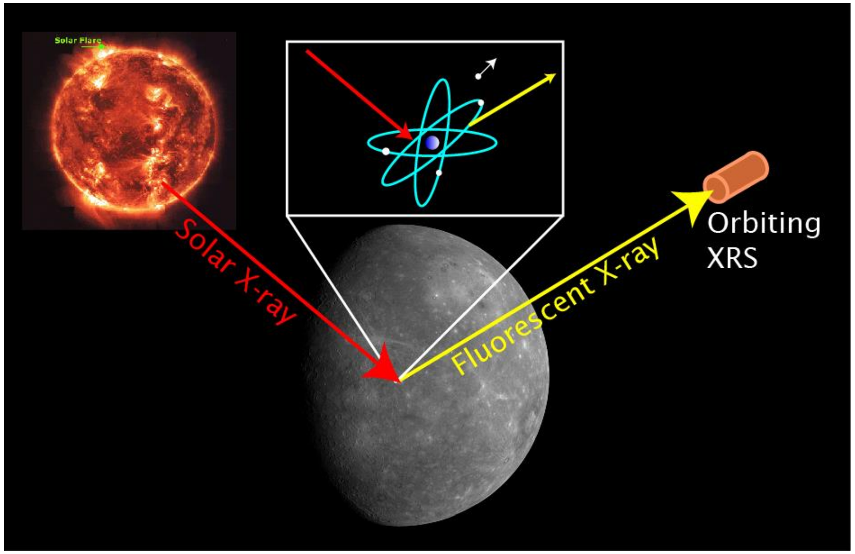
  **Lower operation costs of space navigation and enable autonomous deep space navigation.**

- ***CubeX* for the Moon:**

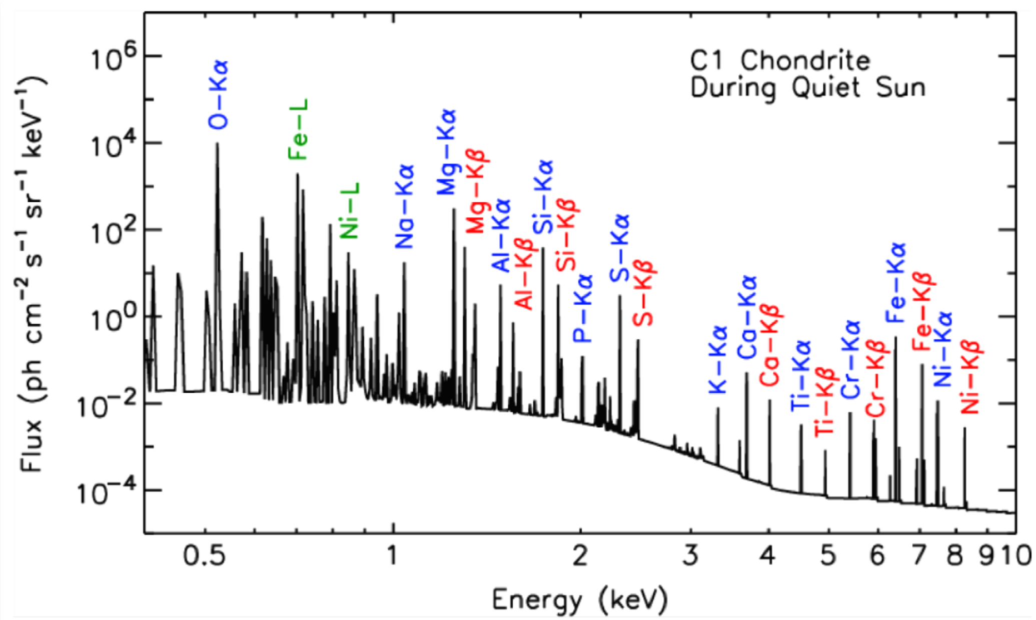
  **While CubeX can be used to study diverse airless bodies such as NEOs and Martian Moons, the Moon is a natural first step for the CubeSat/SmallSat concept development for both XRF imaging and XNAV test. Unprecented high resolution measurements of major rock-forming elements will greatly advance our knowledge of lunar geology. The Moon's proximity enables straightforward evaluation of the XNAV performance.**

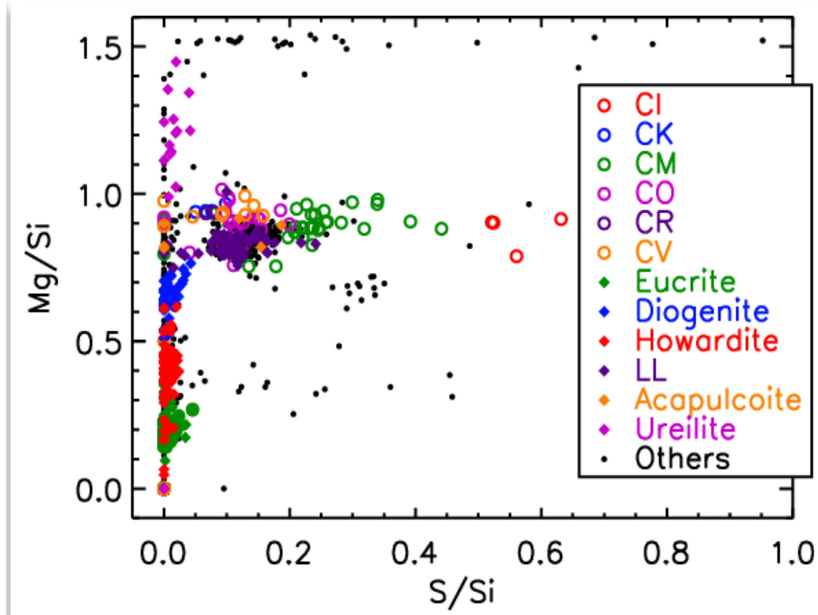
# X-ray Fluorescence (XRF)

- X-ray fluorescence (XRF) is unique to atomic elements.
- Detects XRF emitted by planetary surface due to excitation by solar coronal X-rays.
- Sensitive to most major rock-forming elements (e.g., Na, Mg, Al, Si, S, Ca, Ti, Fe)
- Probe <20 μm below surface
- XRF Spectroscopy is a demonstrated remote-sensing geochemical technique in planetary science



# *Elemental Abundance from X-ray Fluorescence*



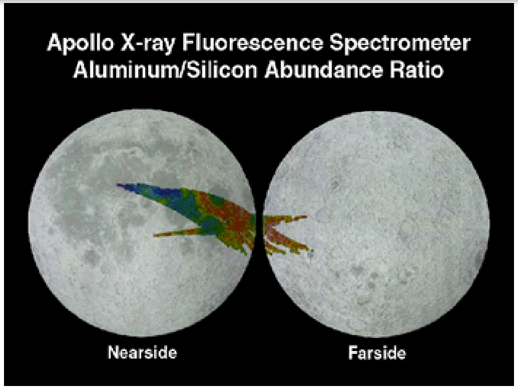




**Simulated XRF spectrum of an asteroid of CI chondrite composition at 1 AU during a quiet sun state illustrating diverse elemental composition (Nittler+2004)**

**Abundance ratios (Mg/Si vs. S/Si) as an identifier of a wide range of meteorite specimen types and geological processes**

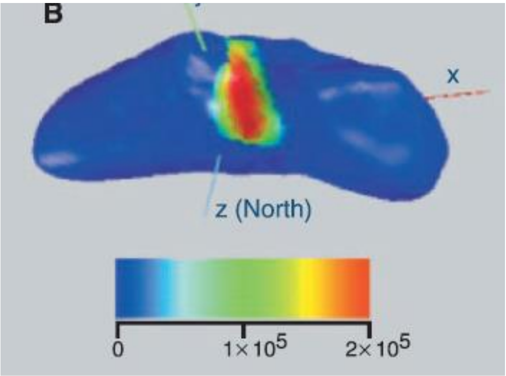
# Planetary XRF Heritage

- Moon:
  - Apollo 15, 16
  - Smart-1
  - Chandrayyan-1



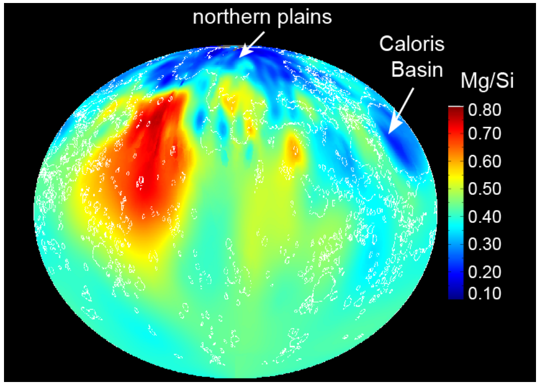

Adler+1972

- Asteroids:
  - NEAR-shoemaker (Eros)
  - Hayabusa (Itokawa)
  - OSIRIS-REx (Bennu)




Trombka+2000

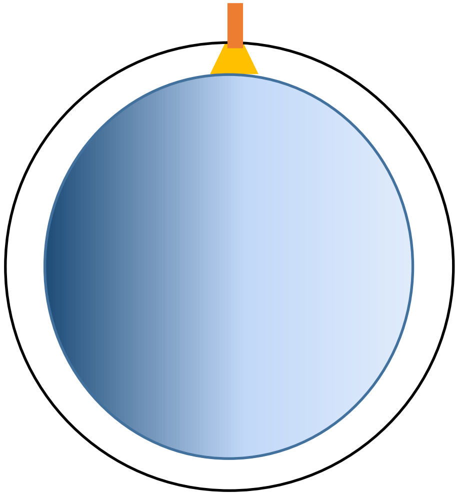
- Mercury:
  - MESSENGER
  - BepiColumbo




Weider+2015

# Imaging with Non-Focusing Instrument

- Large bodies such as the Moon allow a long term stable orbit for S/C near the target (i.e. $R_{orbit} \sim R_{radius}$)
- Here collimator instruments can measure regional variation with localized coverage, while the large FoV provides high throughput.
- At LLO (100 km, $P_{orbit} \sim 2$ hr) with 10 – 20 deg FoV, the footprint (i.e., resolution) is about 20 – 40 km.
- Solar Flares last a few min to a few hrs while the FoV of the instrument stays only about 13 – 26 sec on a given region of the footprint.



$R_{radius}$ = 1740 km

$Al_{orbit}$ = 100 km

# *Imaging with Focusing Optics*

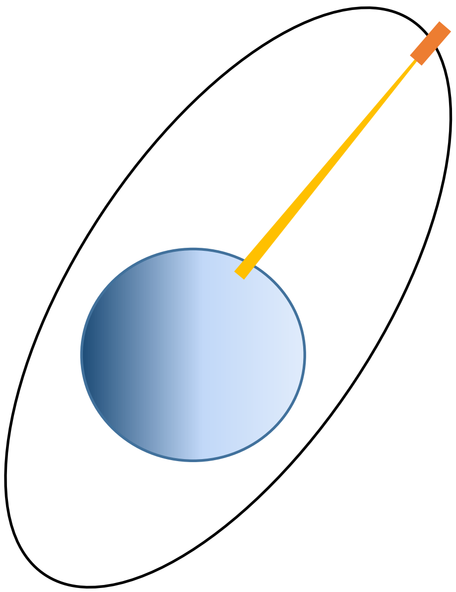
- ELO at 3000 x 8000 km with $P_{orbit}$ ~14 hr

- Focusing X-ray optics with < 1 arcmin angular resolution and ~ 1 sq. deg FoV at ELO can resolve ~1 – 2 km features with 50 – 150 km foot print.

- Can stare a spot for several hours: collect all XRFs from the region for a bright Solar flare.

  Bonus: Night time orbit also allows a continuous observation of X-ray pulsars for several hours: more realistic than NICER on ISS

- Still photon limited: expect a few cps from XRF at C solar states, requires a long integration and put a constraint on the launch date.



$R_{radius}$ = 1740 km

$Al_{orbit}$ = 3000 x 8000 km

# *Science Objectives of XRF imaging on the Moon*

1. Identify outcrops of lunar mantle on the surface to improve our understanding of Moon's formation

   Craters Peirce and Picard; Olivine-rich outcrops such as craters Aristarchus and Copernicus

2. Study the vertical composition of the lunar crust

   4 to 6 craters of sizes ranging from 10 to 200 km

3. Explore the composition and thermal evolution of the mantle

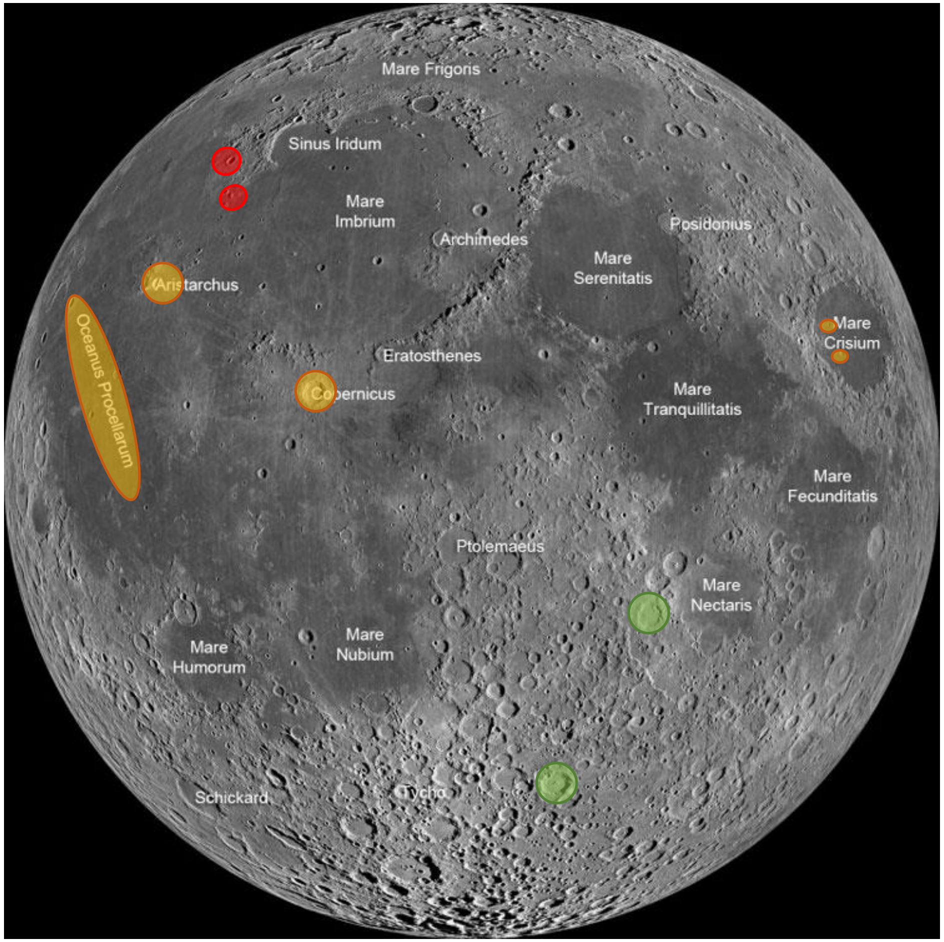
   Young lava flows of Oceanus Procellarum

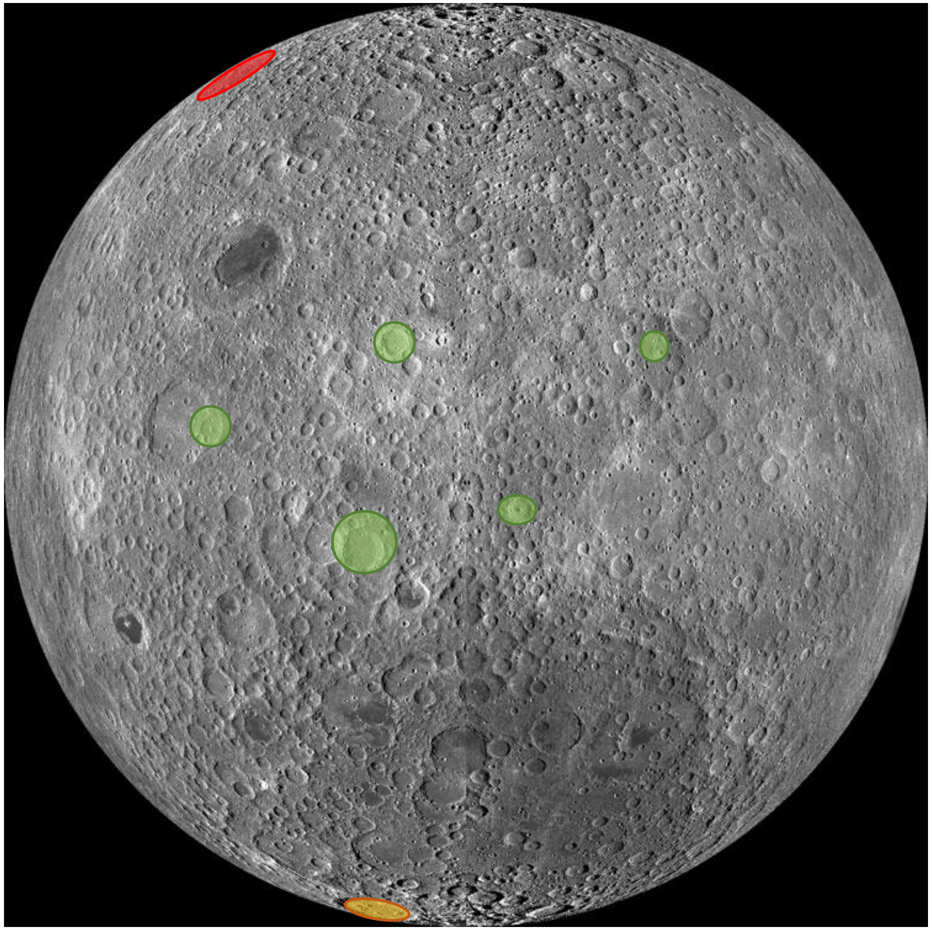
4. Study compositions of permanently shadow regions near South Pole*

   Schrondinger Basin near South pole: Provide a context of future sample return mission on South Pole-Aitken basin

   * X-rays detected by Chandra on the dark side of the Moon was interpreted as the results of CX between solar wind and neutral hydrogen in the Earth's geocorona (Wargelin+04). *CubeX* can determine this conclusively. If so, the observation can provide the baseline for instrumental background.

# Targets suggested in the proposal and the panel

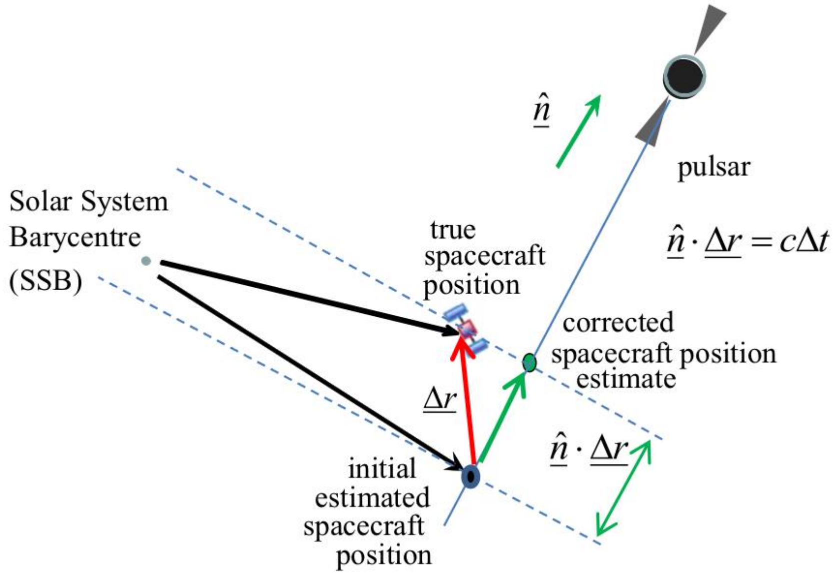


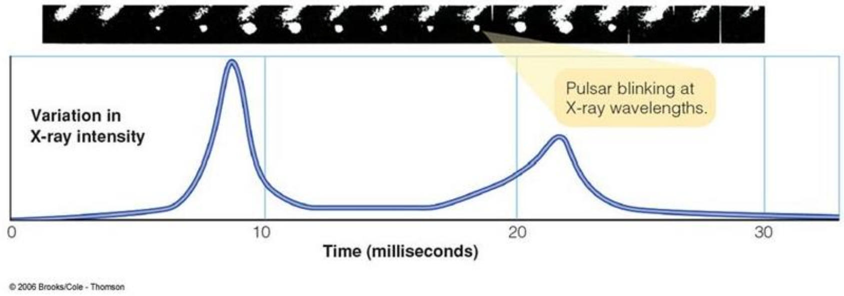



**Plan to select and prioritize ~20 targets (that cover the surface more or less evenly); at a given time, observe the target that is most suitable in terms of viewing and sun-lit angles, etc.**

# Science Objectives of XNAV

5. **Demonstrate the precision of delta-correction from a given pulsar**



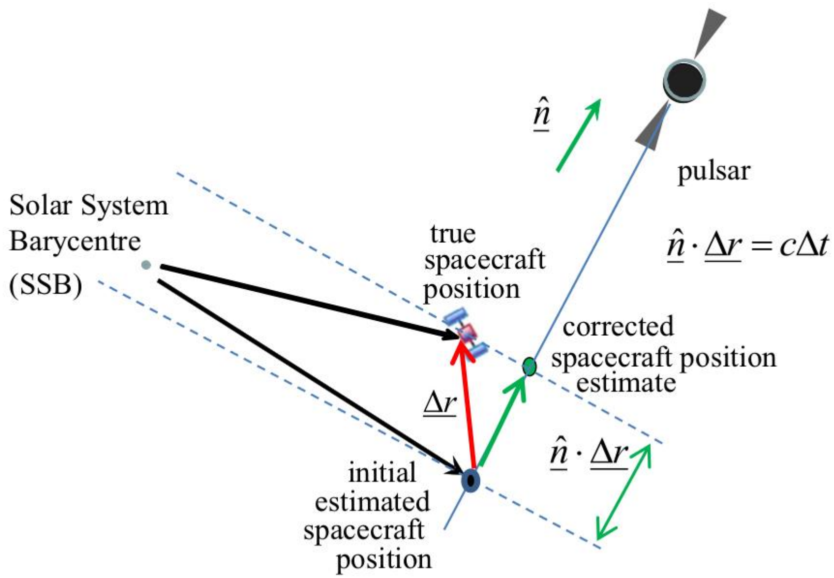

**Pulsations from Crab: 33 ms period**

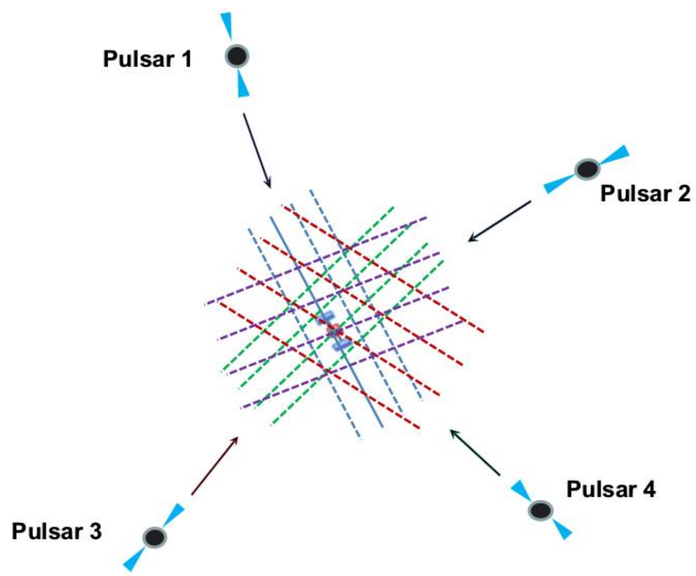
**Shemar+16, Winternitz+16 (NICER):**

**Crab, B1937+21, B1821-24, J0437-4715, J1012+5308**

# Science Objectives of XNAV

5. **Demonstrate the precision of delta-correction from a given pulsar**
6. **Attempt to measure the absolute position using sequential observations of 3 or more pulsars***



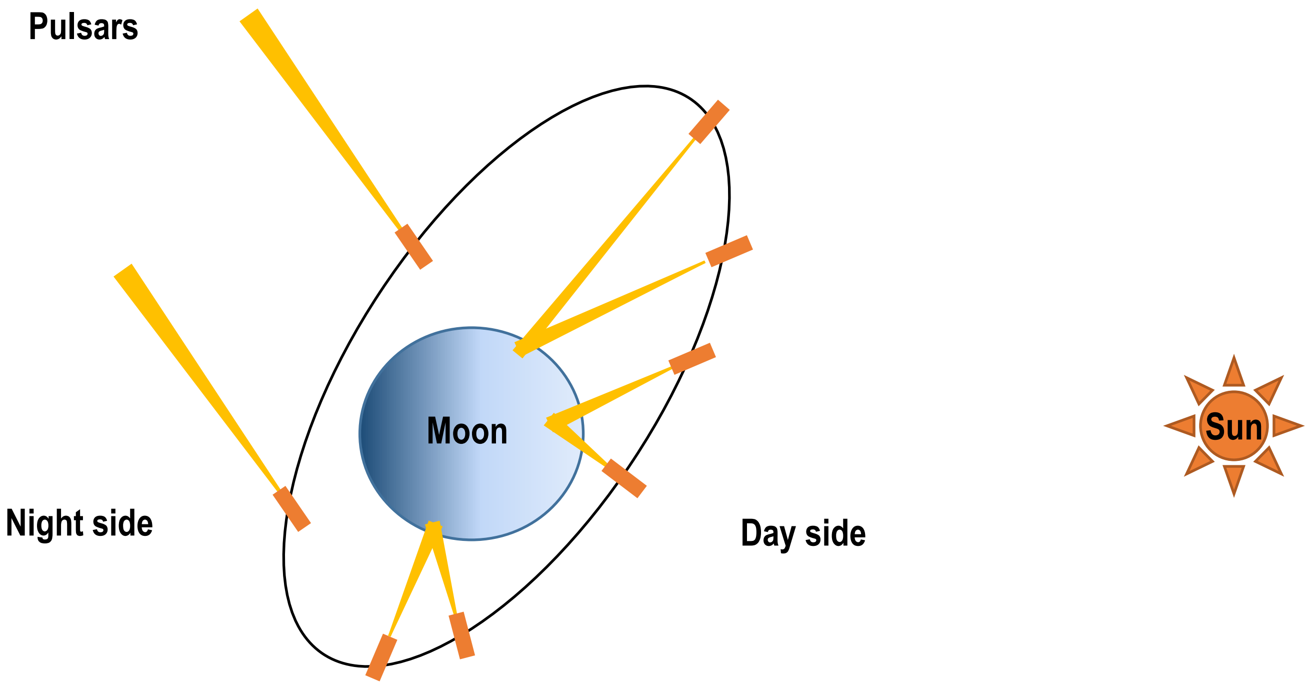




**Shemar+16, Winternitz+16 (NICER):**

**Crab, B1937+21, B1821-24, J0437-4715, J1012+5308**

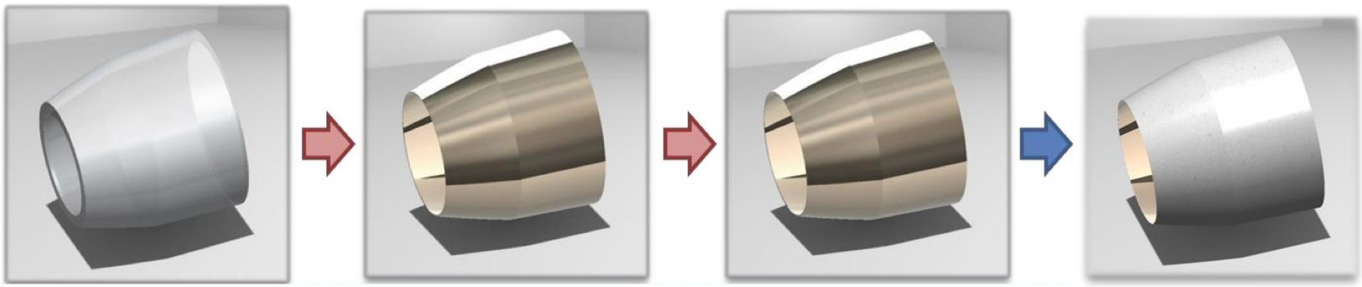
# Observation Sequence Example

- On the lunar day side, point a few target regions on the Moon, depending on their accessibility  (55% of the duty cycle)
- On the lunar night side, point at one or two target pulsars only if they are visible (16% of duty cycle)



# *Miniature Lightweight Focusing X-ray Optics (MiXO)*

- **NiCo+Ceramic hybrid coating technology using plasma thermal spray (PTS) enables lightweight Wolter-I optics in small form factor suitable for diverse planetary missions.**
- **Thin NiCo layer provides mandrel surface quality (~15") and lightweight ceramic layer provides high stiffness.**

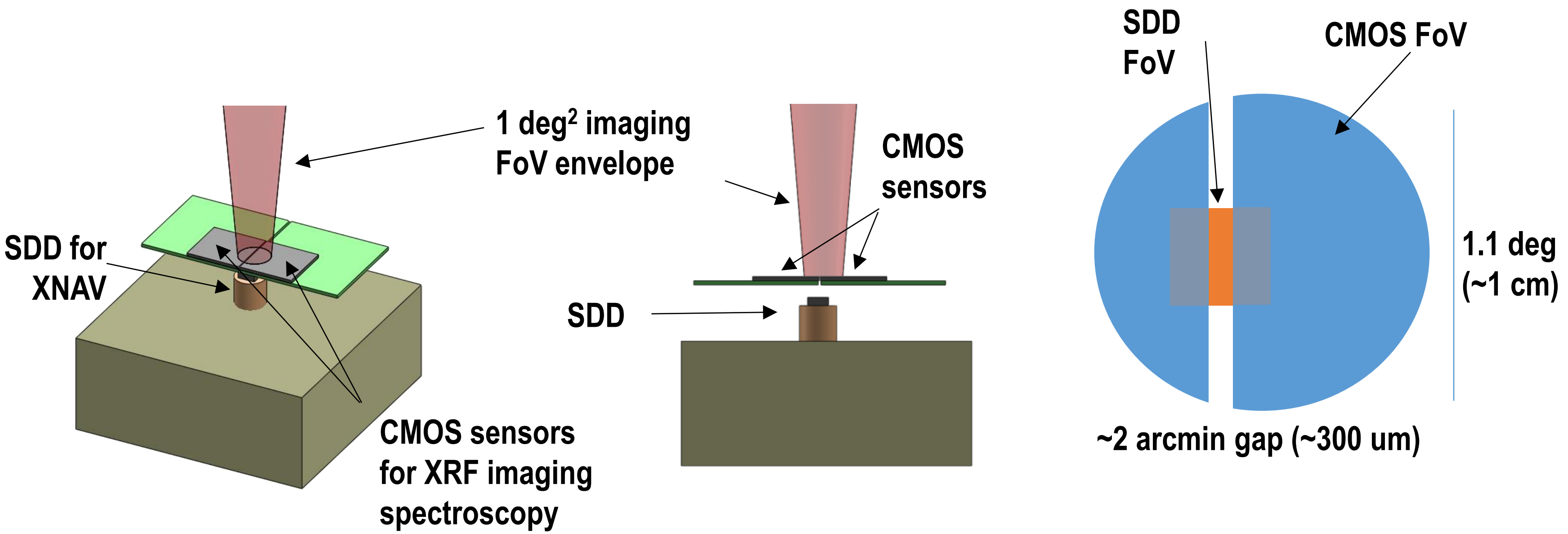


| Chandra | XMM-Newton | Spektr-RG | MiXO |
|---|---|---|---|
| 20 mm Zerodur | 1 mm Ni | 250 µm NiCo | <20 µm NiCo + <200 µm $Al_2O_3$ |
| 70 kg* | 12 kg* | 2.9 kg* | <0.9 kg* |

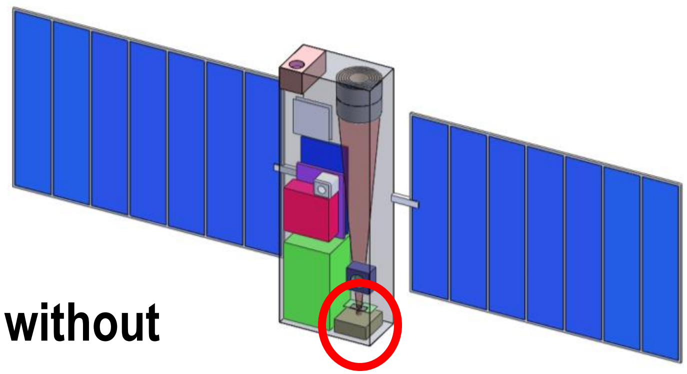
***Mass for a single shell of Wolter-I optics with a 70 cm diameter and 60 cm long.**

- **For planetary mission, optics will be typically ~2 – 15 cm dia x ~10 cm long, and the complete optics package of multiple shells with support structure will weigh less than ~1–2 kg, while providing >~50 $cm^2$ effective area at 1 keV.**
- **MiXO is being developed under NASA Planetary Instrument Concepts for the Advancement of Solar System Observations (PICASSO)**

# Focal Plane Design for both XRF imaging an XNAV




- 2 Monolithic CMOS X-ray sensors (16 $\mu$m pixel, 1024x1024) for XRF imaging
- Amptek SDD (< 1 $\mu$sec timing) for XNAV
- Energy range: 0.5 – 8 keV, FWHM <200 eV at 6 keV
- Enable both XRF imaging and XNAV observations without moving parts



# Mission Overview of CubeX

- Rideshare to the Moon as a 2ndary S/C on a primary mission
- Inserted to a high latitude elliptical lunar orbit (~14 hr period): 4000 x 6000 km, which will decay to 2000 x 8000 km in a year
- High resolution imaging enabled by Miniature lightweight X-ray Optics (MiXO) in CubeX allows flexible observing conditions from relatively stable elliptical polar lunar orbits.
- A combination of monolithic CMOS X-ray imaging sensors and high timing resolution SDD will enable both XRF imaging spectroscopy and XNAV observations without moving parts.
- CubeX will study ~8–10 key regions (~35–140 km) of geological interest on the Moon for 1 year to produce high resolution (~0.6–2.3 km) elemental abundance map of each region.
- CubeX will also conduct delta-correction using the Crab pulsar and PSR B1937+21, and evaluate the performance of absolute navigation by sequential observations of several millisecond pulsars during the dark side of the orbits.

# END

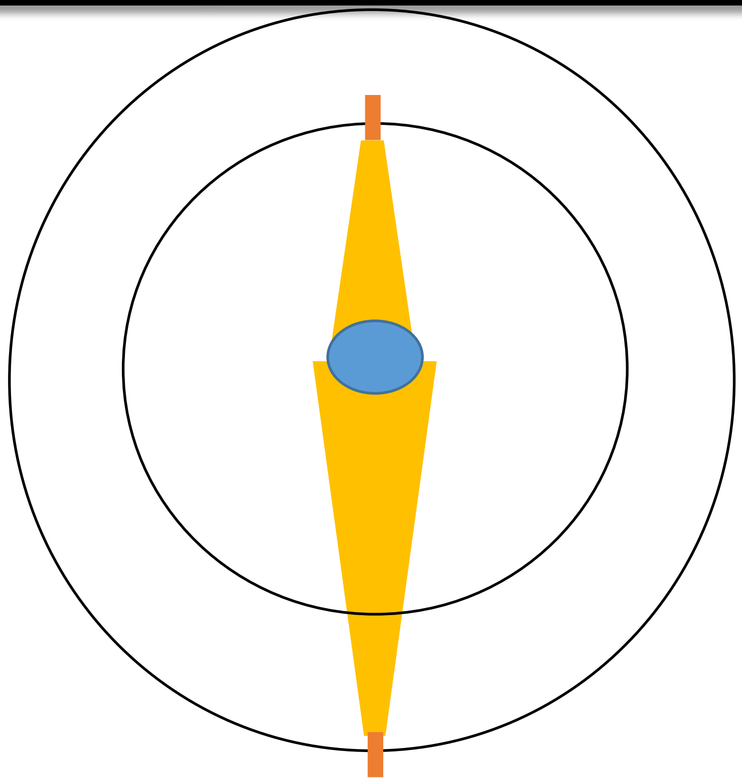
# Expected Performance of XRF Imaging

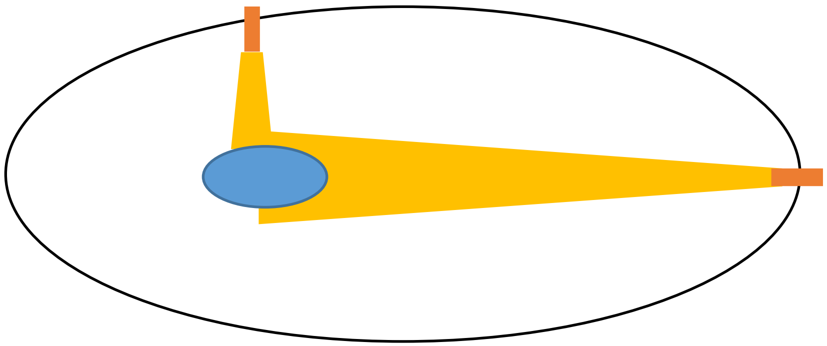
| Line | Energy (keV) | Count Rate (cps) | Total Counts (1 Ms) | Counts over ~3.6 km | S/N over ~3.6 km | Counts over ~1.8 km | S/N over ~1.8 km |
|---|---|---|---|---|---|---|---|
| O-K | 0.52 | 1.6 | **$1.6 \times 10^6$** | 1600 | **530** | 390 | **130** |
| Mg-K | 1.25 | 0.073 | **73,000** | 73 | **25** | 18 | **6** |
| Al-K | 1.49 | 0.11 | **110,000** | 110 | **37** | 27 | **9** |
| Si-K | 1.74 | 0.25 | **250,000** | 250 | **84** | 62 | **21** |
| Ca-K | 3.69 | 0.0095 | **9,500** | 9.5 | **3.2** | 2.4 | **0.8** |
| Fe-L | 0.71 | 0.47 | **473,000** | 470 | **160** | 120 | **40** |
| Bkg | | ~0.0044 | ~4400 | 4.4 | | 1.1 | |

- **FoV: ~110 km, Angular resolution: ~1.8 km at 6000 km Lunar circular frozen orbit**
- **~ 1 cps in 0.6 to 10 keV from the Solar C1 state on average near solar maximum**
- **Lunar basalt: O: 43%, Mg: 3.9%, Al: 9.4%, Si: 21%, Ca: 9.3%, Fe: 12%**

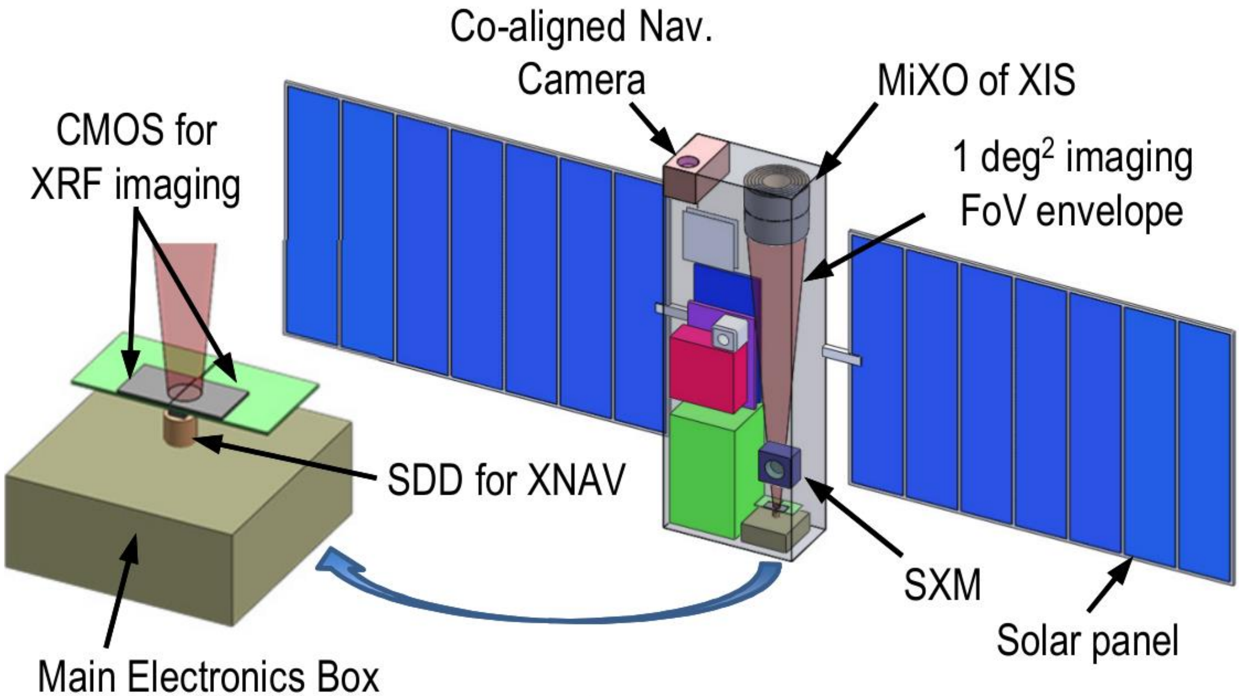
# Limitation in Imaging by Non-Focusing Instruments

- Low gravity of small bodies does not allow a long term stable orbit for S/C near the target (i.e. $R_{orbit} >> R_{radius}$)
- Many small targets such as asteroids and comets are far from spherical shapes. Other complication such as smaller satellites and debris often hinder close approach or orbit.
- Here collimator instruments cannot make useful measurements unless the FoV is fully occupied by the target due to high internal/external background. (The soft X-ray sky is not dark!)
- Surface morphology and viewing angle require higher angular resolution than the resolution footprint at the nadir of the surface.



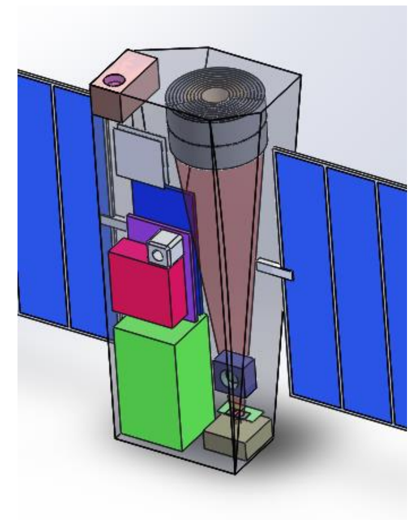


# *CubeSat X-ray Telescope (CubeX)* *1 x 2 x 6U vs. 1.5 x 2.5 x 6U*




Focal Plane of XIS

*CubeX* (12U = 1 x 2 x 6U)

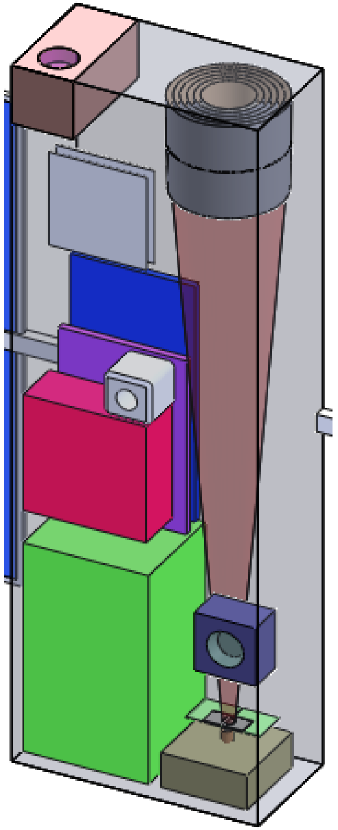


*CubeX* (1.5 x 2.5 x 6U)

- **Map the surface elemental abundance of airless bodies from X-ray fluorescence (XRF) induced by solar X-ray flux**
  - ***CubeX* for the Moon: map >8 target regions of special interest: e.g., craters that potentially exposed mantle material (high Mg oblivine rich)**
- **Conduct feasibility and performance tests of X-ray pulsar timing navigation (XNAV)**
  - ***CubeX* for the Moon: enables continuous pulsar observations for several hours during night time of high altitude ellpitical orbits (4000 x 6000 km, 14 hr period), Proximity to the Moon allows ~2 km positional information of spacecraft.**

# CubeSat X-ray Telescope (CubeX)
# Fixed 12U Configuration (1U x 2U x 6U)

| Key Payload & Mission Characteristics (12U) | |
|---|---|
| **Payload: X-ray Imaging Spectrometer (XIS: MiXO + 2 CMOS + SDD) & Solar X-ray Monitor (SXM: SDD + Collimator)** | |
| Mass & Form Factor<br>Power<br>Data Rate | 9.5 kg in 1 x 1 x 6U for XIS + SXM<br>14W average (17W peak)<br>8 MB/day (15 MB/day for Crab obs) |
| Effective Area<br>Ang. Res. & FoV | >25 cm$^2$ at 1 keV (MiXO)<br><1 arcmin over 1 sq. deg (MiXO+ 2 CMOS) |
| Spectral res. & range<br>Time resolution | <200 eV at 6 keV, 0.2–8 keV for XRF<br>1 μs (SDD) for XNAV |
| **Mission Characteristics** | |
| Type, Cost<br>Mass & Form Factor<br>Solar Panel<br>Comm. | Secondary mission, $36M<br>18 kg in 12U (=1 x 2 x 6U)<br>Max 89 W power supply<br>Iris V2 (max 300MB/day for 3 hr contact) |
| ADCS | ~2 km position knowledge for XNAV<br>~30" pointing knowledge for XRF and XNAV |
| Lifetime, Launch | 1 year from a 2023-2027 launch for solar max. |
| Orbit Design | Elliptical Polar Lunar Orbit, ~14 hr period,<br>Insertion to 4000 x 6000 km orbit via primary |
| Propulsion | Low thrust trajectory with Hall thruster to<br>2000 x 8000 km orbit after 1 year |
| Operation (75% duty) | 55% XRF +16% XNAV+ 2% Telemetry +2% EP |
| MOC, SOC | ARC MMOC, SAO |



# Instrumental Requirements for the XRF imaging

- < 200 eV at 6 keV spectral resolution
- Focusing optics with imaging X-ray sensors (CMOS)
  30" knowledge, 2' pointing (except for objective 4)
  Altitude: >1000 km, <10,000 km
- Launch near solar maximum (C Solar state or solar flares)
- Long mission lifetime (> 1 Msec for each target region)
- Continuous observations for a few hrs (to catch XRFs from full duration of flares)
- Targets except for objective 4 should be sun-lit: angle TBR
- SXM (40 deg FoV) to monitor solar activities

# Instrumental Requirements for XNAV (No Nav. Implementation)

- < 1 us timing resolution: NICER SDD (~ 100 ns)
- Atomic clock (good for several hrs for the Moon CubeX)
- Focusing optics to detect (faint) pulsars

  30” knowledge, 1’ pointing (at least for one direction)
- Continuous observations of X-ray pulsars for several hrs
  - Shemar+16, Winternitz+16 (NICER):
  - Crab, B1937+21, B1821-24, J0437-4715, J1012+5308
- Positional knowledge: ~ 2 km for expected accuracy of XNAV ~5 – 10 km