State of the Art: MinXSS CubeSat Performance … and CubIXSS future needs

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+ the MinXSS Team (including BCT!)

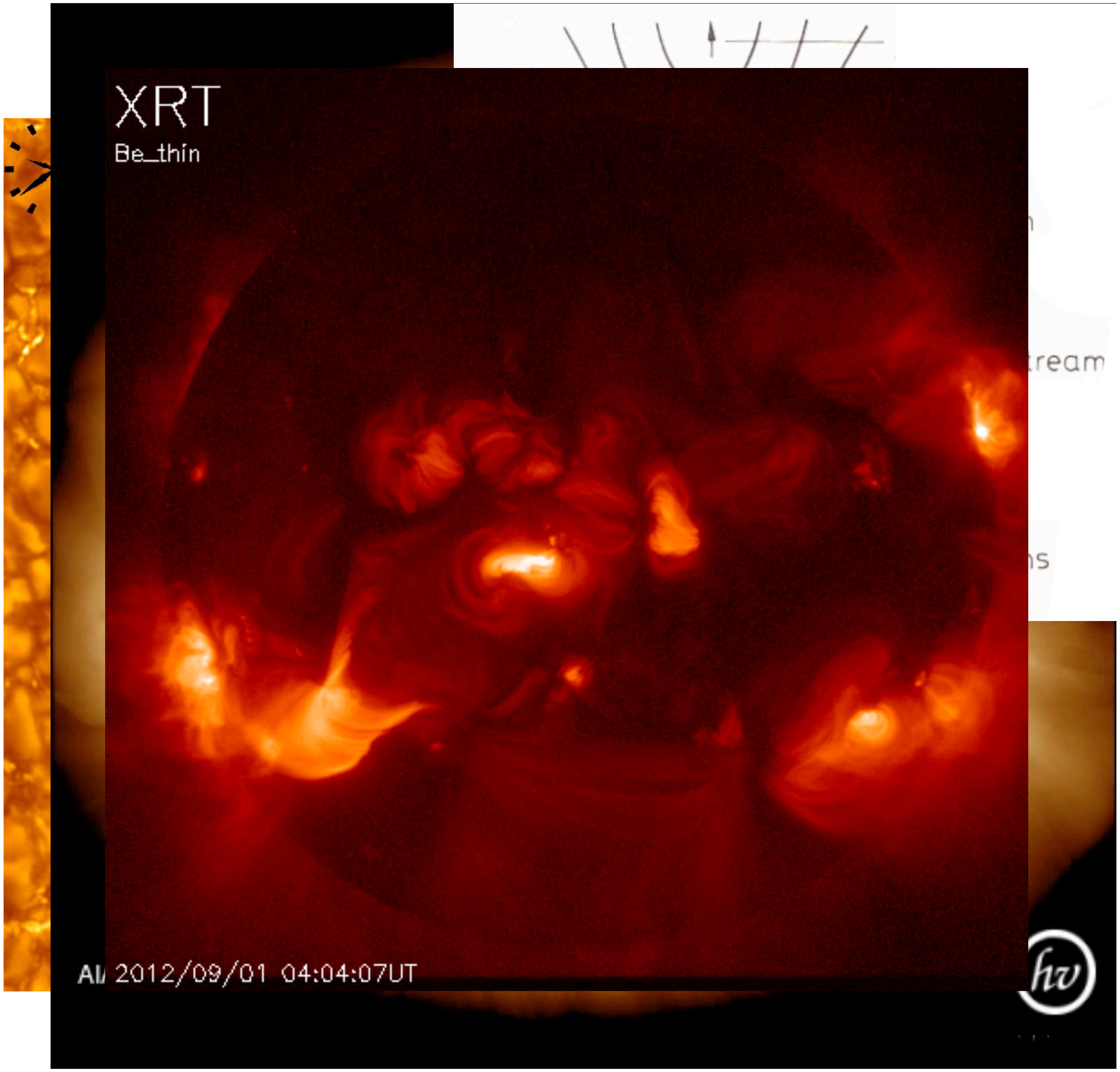
+ the CubIXSS Team

Overview

- Motivation (science)
- MinXSS overview
- MinXSS on-orbit performance
  - Including limitations and lessons learned
- CubIXSS – proposed new CubeSat mission
  - And needs/desires for improvements

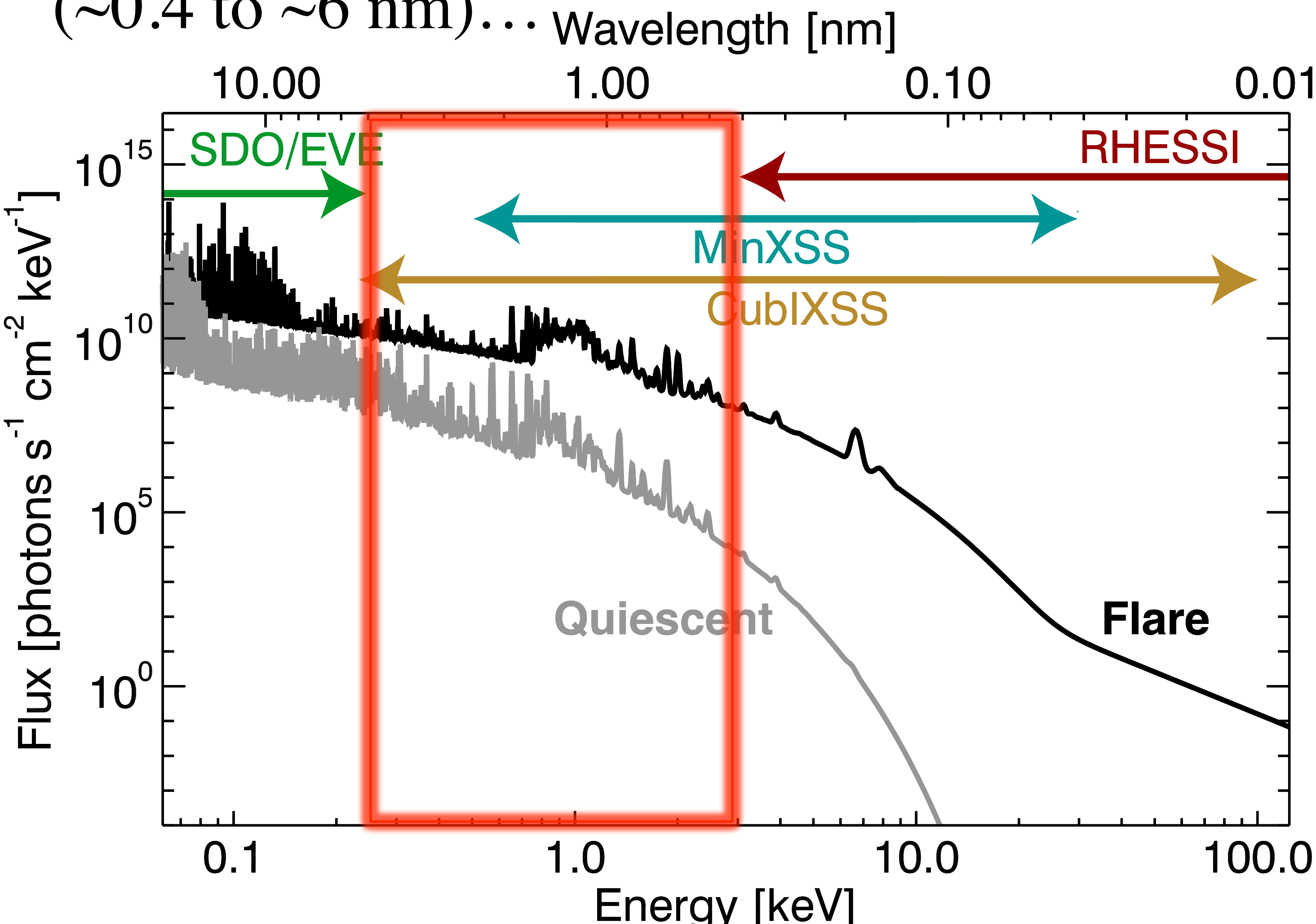
Our local star

dynamic



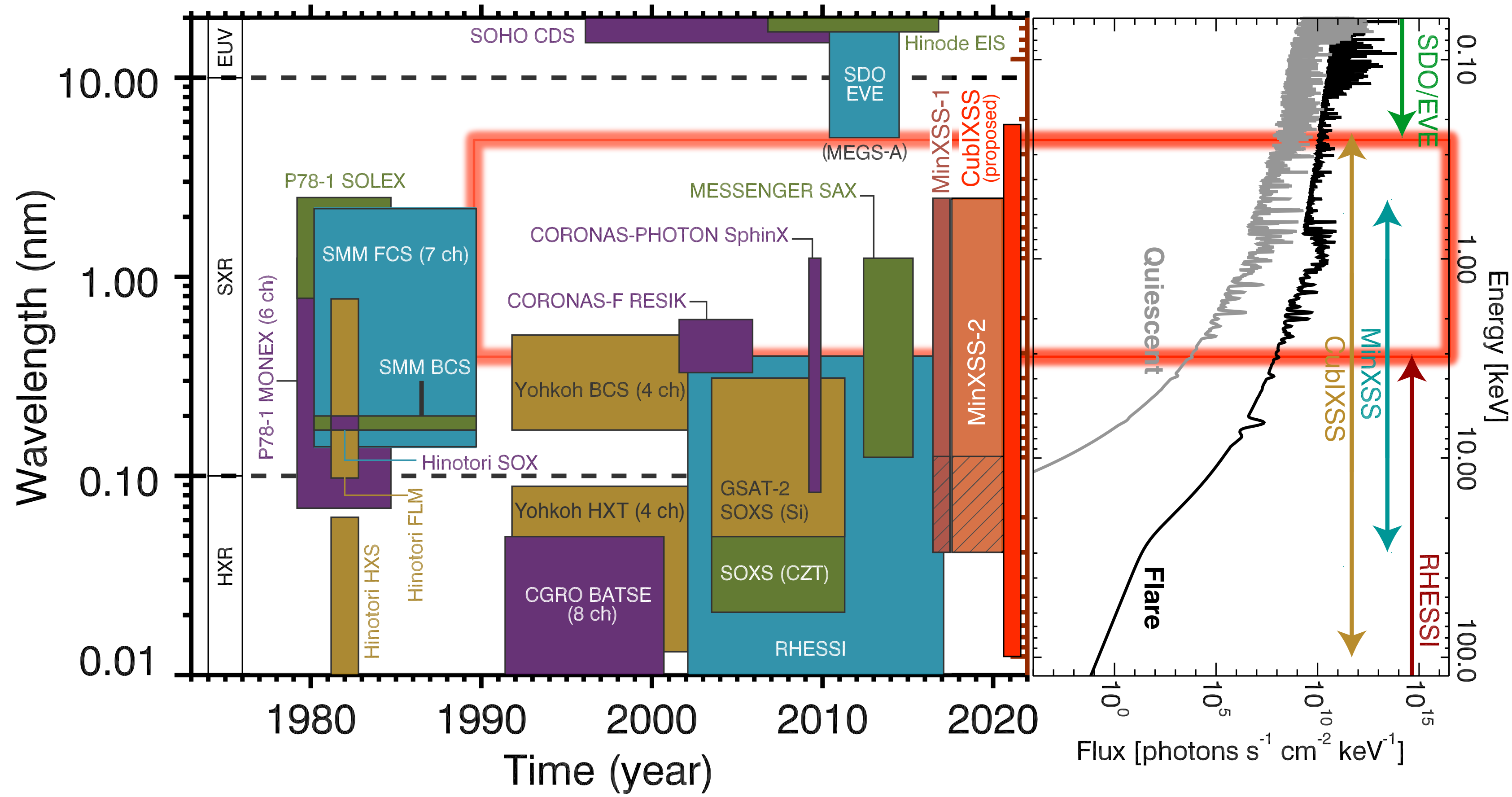
Spectrally-Resolved SXR Observations

- Crucial observational gap from ~0.2 to ~3 keV (~0.4 to ~6 nm)…



Spectrally-Resolved SXR Observations

- Crucial observational gap from ~0.2 to ~3 keV (~0.4 to ~6 nm) with very few spectrally-resolved observations in previous decades

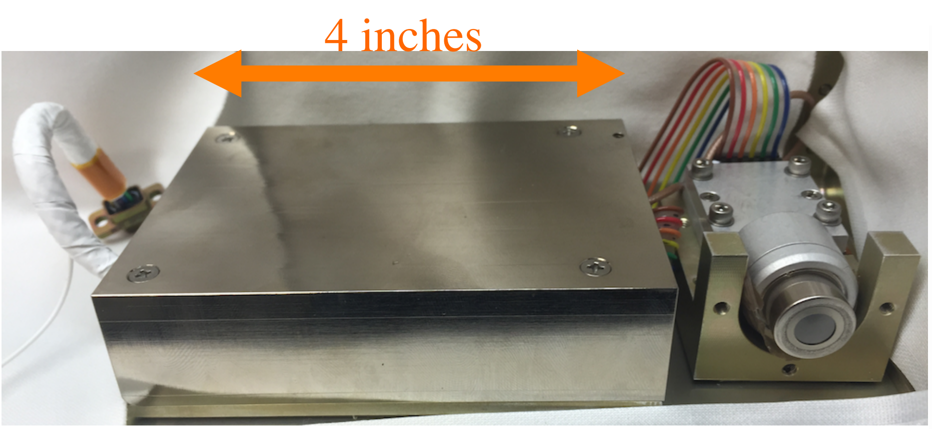


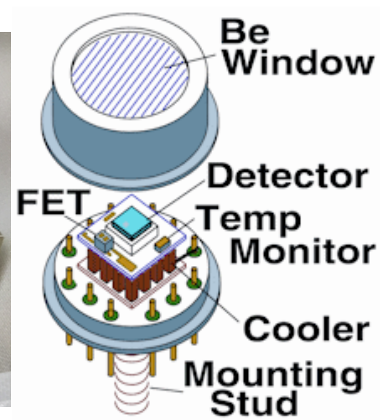
Spectrally-Resolved SXR Observations

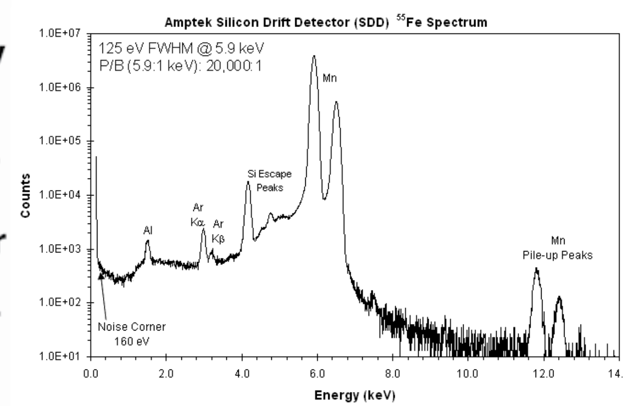
- Crucial observational gap from ~0.2 to ~3 keV (~0.4 to ~6 nm) with very few spectrally-resolved observations in previous decades
- Rich with med- and high-T lines and continuum for diagnostics of coronal plasma temperatures
- Extremely sensitive to temperature, esp. high T
- Especially important for non-flaring corona, where there is little >3 keV (<0.4 nm) emission
  - *Critical* for understanding heating and for interpreting nonthermal observations
- Large photon fluxes

X123 Soft X-ray Spectrometer

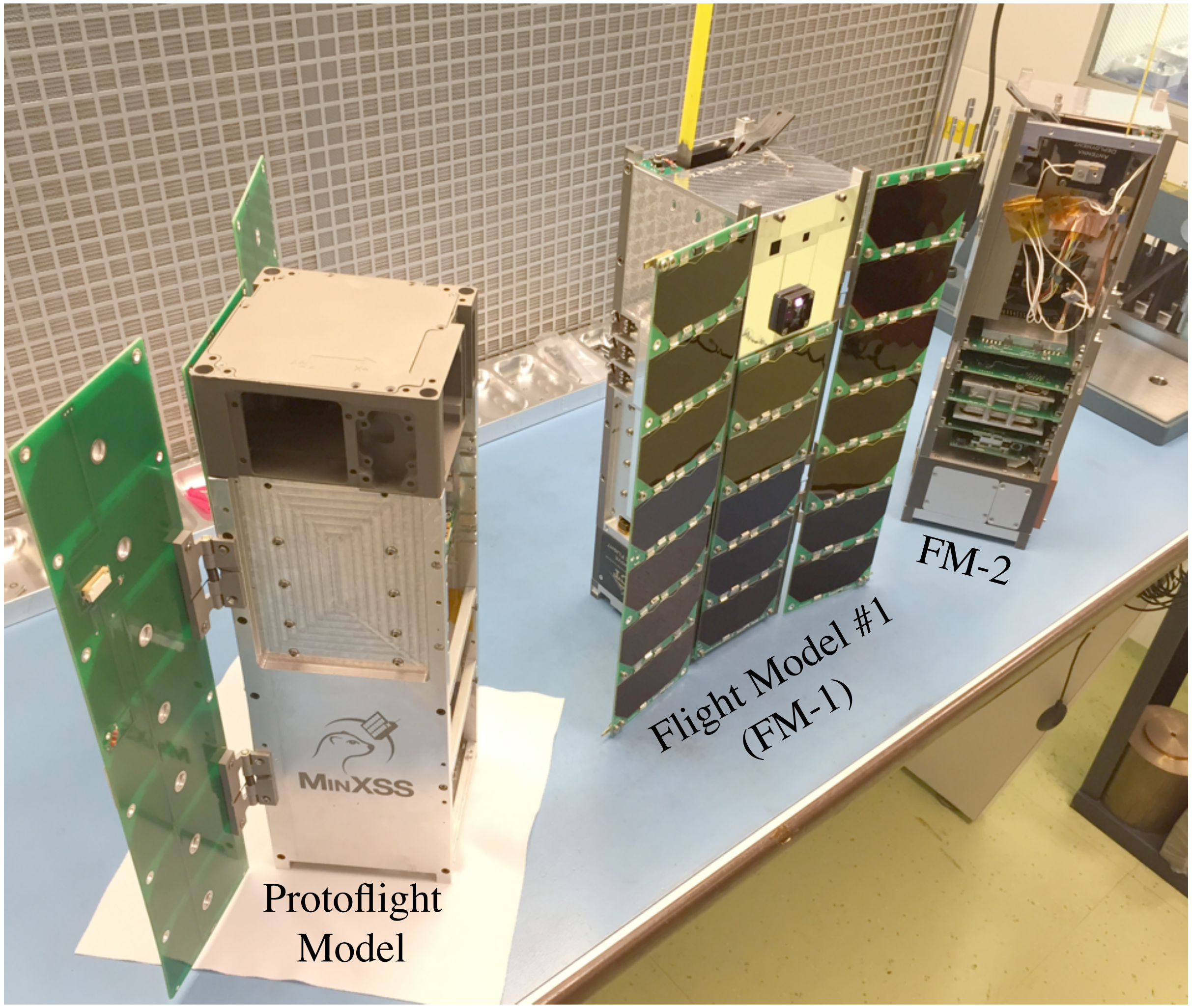
- Amptek X123-SDD X-ray spectrometer package:
  - 500 μm Silicon Drift Detector (SDD), 8 μm Be window
  - ~0.5–30 keV (~0.04–2.4 nm) @ ~0.15 keV FWHM
    - Up to ~200 kpcs, on-board pulse pileup rejection
  - All in one: TEC, HVPS, CPU included
  - 7 × 10 × 2.5 cm, ~300 g (with mods), ~2.5 W, $11K + mods







Miniature X-ray Solar Spectrometer

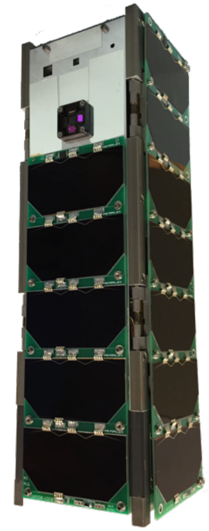


MinXSS-1 CubeSat

Deployed from ISS on May 16, 2016

MinXSS Science Team: Tom Woods (PI, LASP), Amir Caspi (SwRI), Phil Chamberlin (GSFC), Andrew Jones (LASP), Rick Kohnert (LASP), James Mason (LASP), Chris Moore (CU-APS), Scott Palo (CU-AES), Stan Solomon (NCAR-HAO)

MinXSS is NASA Science Mission Directorate's *first* CubeSat in space!



Led by CU Boulder's LASP, in collaboration with SwRI, NASA/GSFC, NCAR/HAO, and industry partners

44 students and over 40 professional scientists and engineers involved

Deployed: 16 May 2016
Days / Orbits: 267 / ~4200

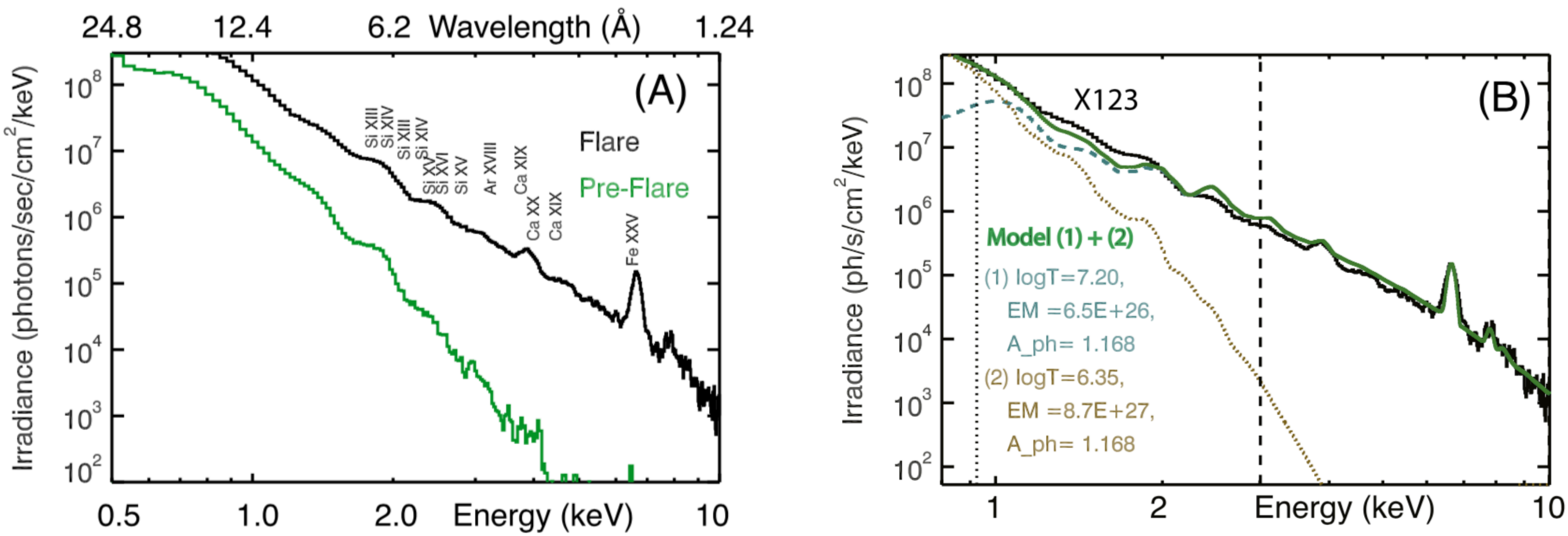
LEO, ~400 km, ~1 yr lifetime

~10 W power consumption
Power-positive w/ 35% margin

First light: 30 May 2016

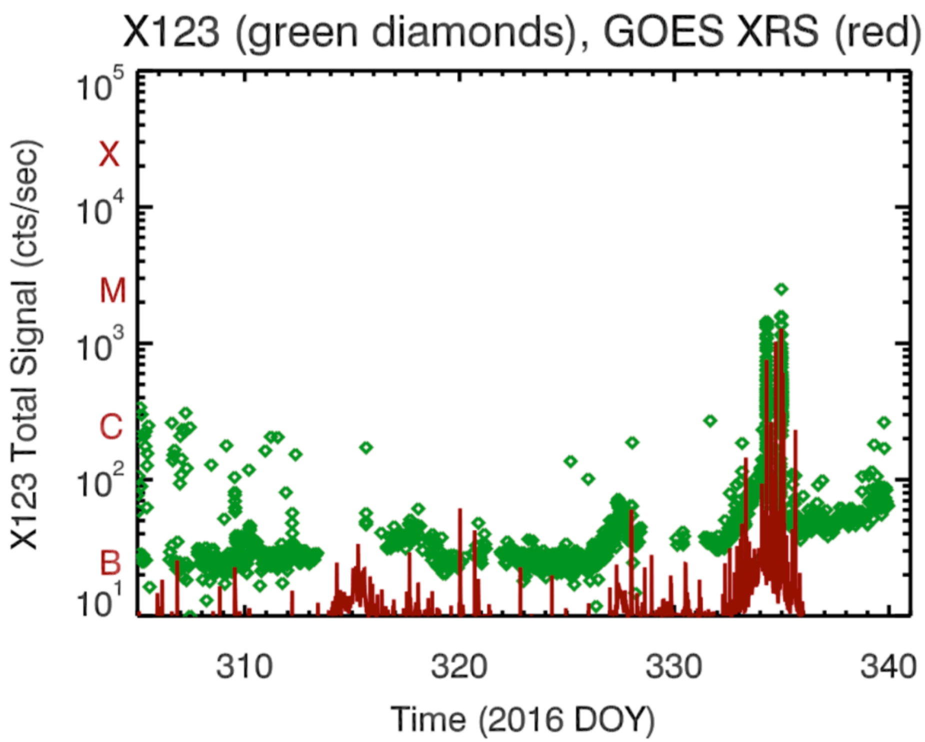
>36,000 10 s spectra downlinked
(>950,000 generated)

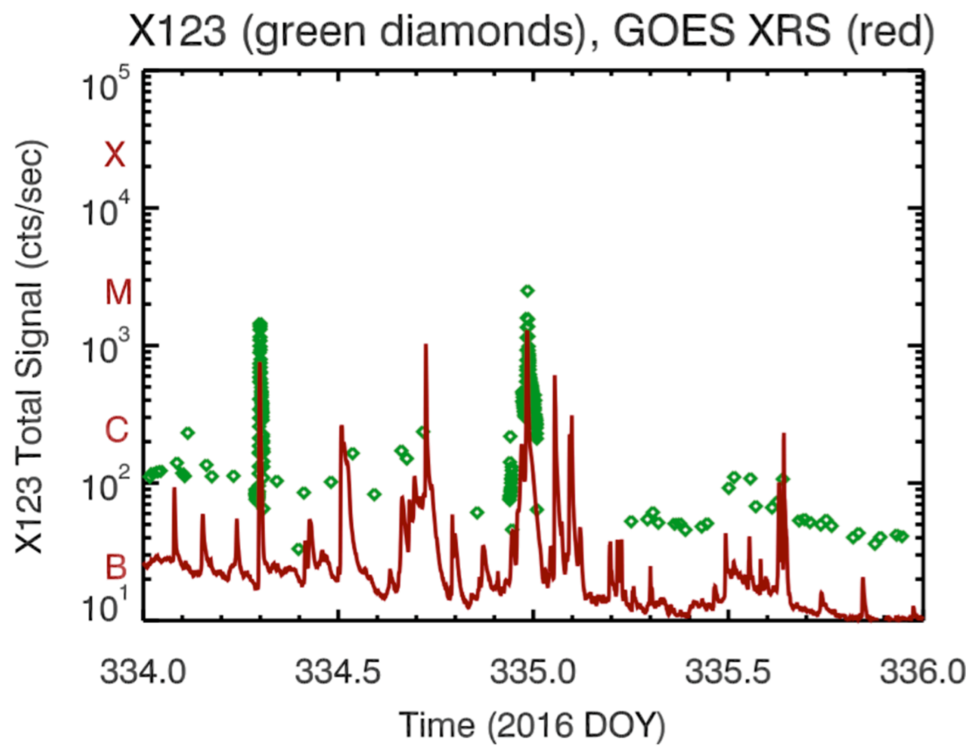
MinXSS SXR Observations



- Spectra cover 0.5–30 keV (~0.04–2.5 nm), although effective short limit is ~10 keV (~1.2 nm)
- Binned at ~0.03 keV (fixed in energy), ~0.15 keV FWHM
- Lines and continuum easily identifiable, fittable

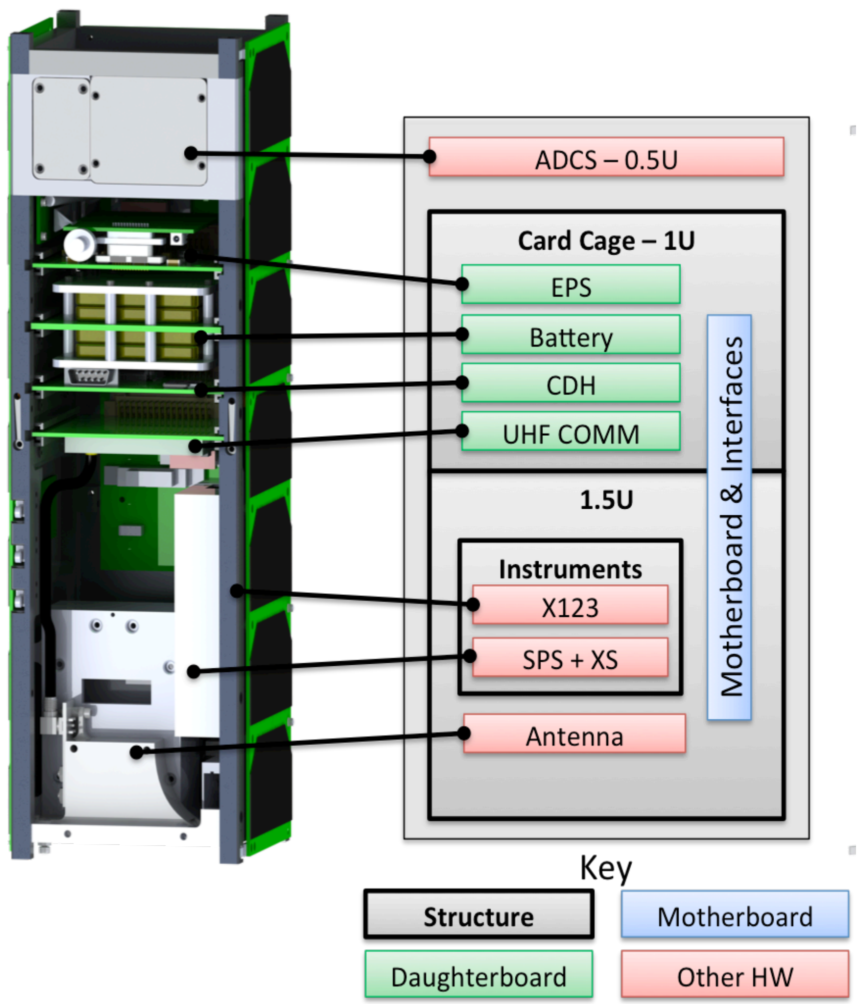
MinXSS SXR Observations

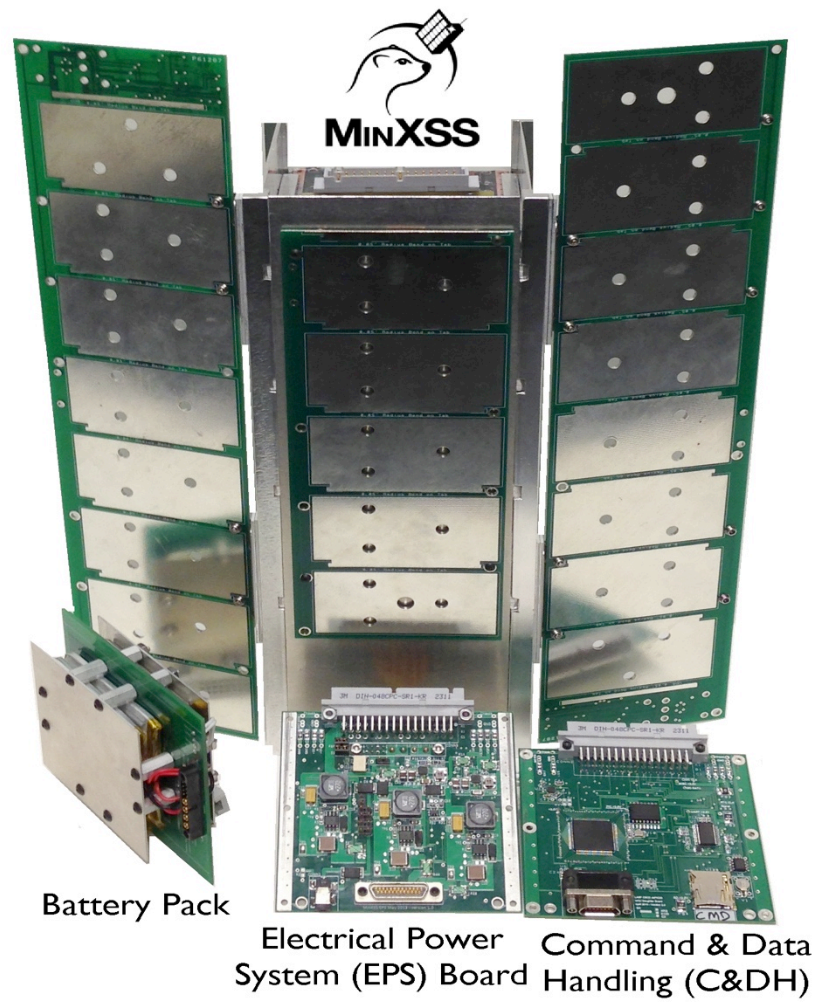




- X123 spectra are downlinked sparsely normally
- Selected times (esp. flares) are downlinked at full cadence (as available)
  - Only ~3–5% capture with single-station UHF radio comms!

MinXSS CubeSat Design Overview



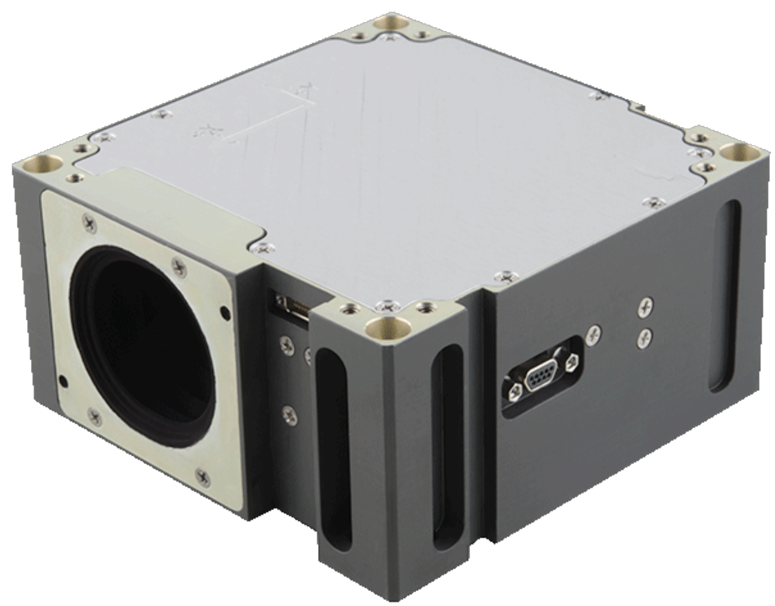


Acronyms: Command and Data Handling (CDH), Electrical Power System (EPS), Communications (COMM, Li-1 UHF Radio), Attitude Determination and Control System (ADCS, BCT), Solar Position Sensor (SPS), X-ray Sensor (XS), X123 is Amptek X-ray spectrometer.

Enabling Technology – precision ADCS

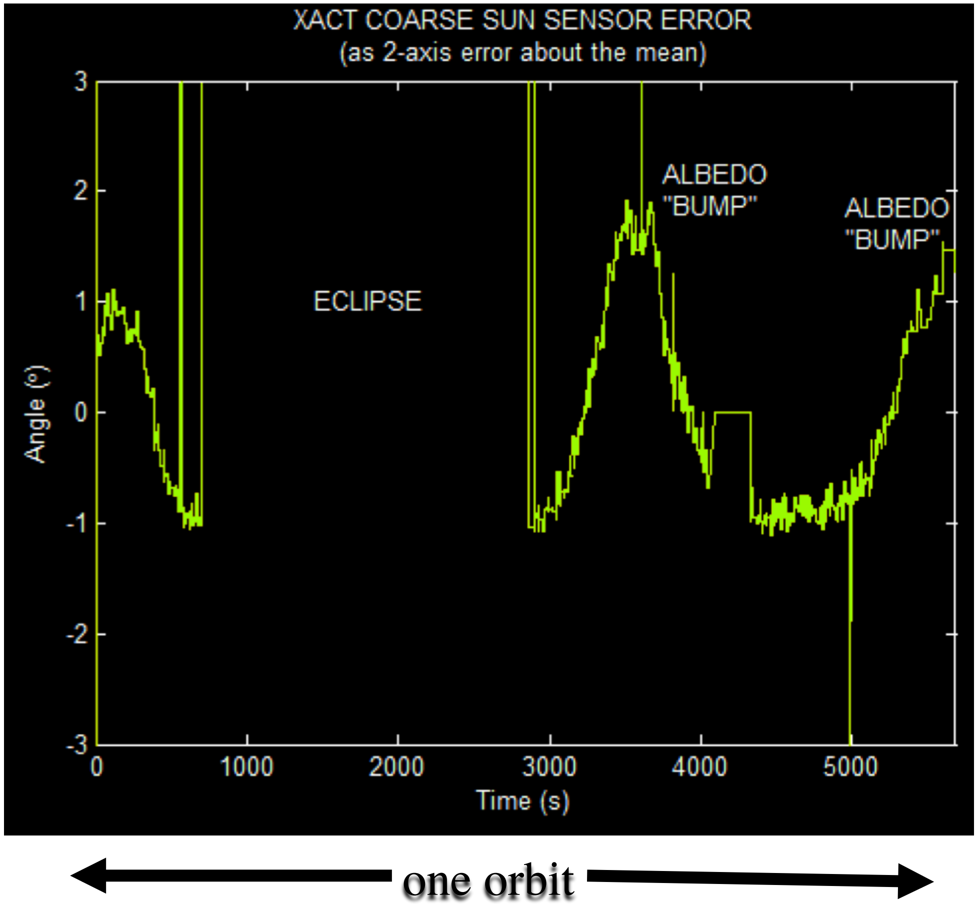
- Blue Canyon Technology (BCT) XACT ADCS specification
  - Mass: 850 g   Size: 0.5 U
  - Power: < 2 W using 5 V and 12 V DC
  - Pointing Accuracy: < 25 arc-sec
  - Pointing Stability: < 10 arc-sec
  - Slew Rate: > 10 deg/sec
  - ADCS components: star tracker, coarse sun sensor, 3 reaction wheels, 3 torque rods, magnetometer, IMU, ADCS processor

- Caveat: MinXSS science doesn't actually need this high a level of performance…



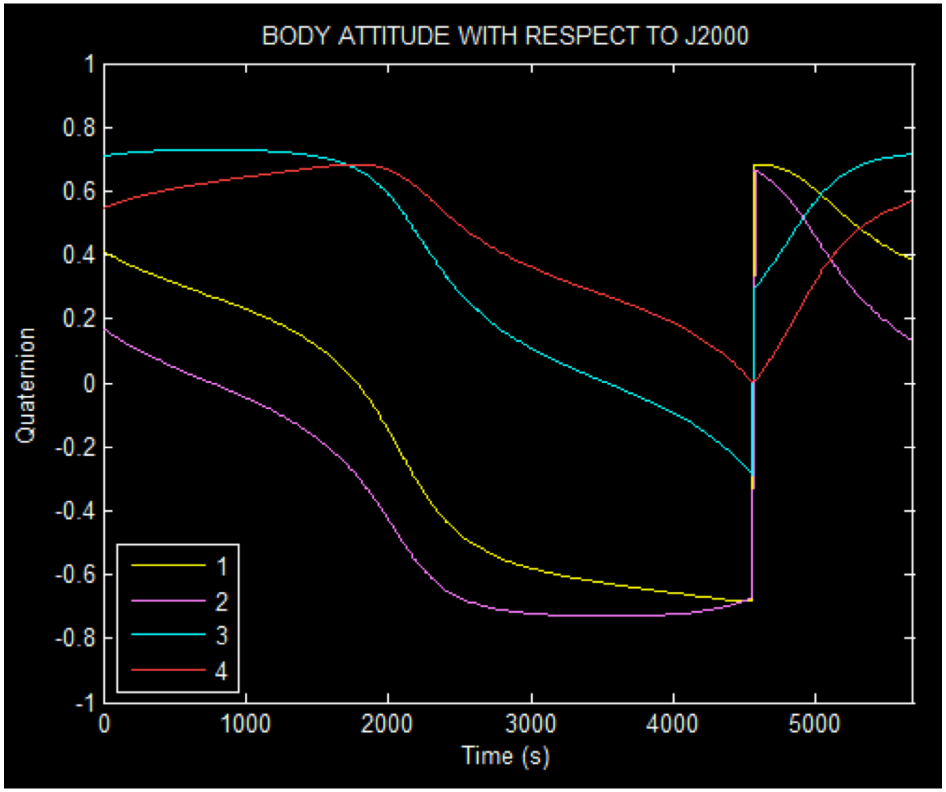
Pointing Performance – Safe Mode

- MinXSS deployment → XACT booted to safe
- XACT autonomously placed spacecraft in safe attitude with arrays on sun and low total momentum
  - Per first pass telemetry
- Safe mode algorithms reliably find and track the sun
  - Uses XACT coarse sun sensors (CSS)
  - In Fine Pointing data (right), albedo induces 2–3° error on CSS sun measurements

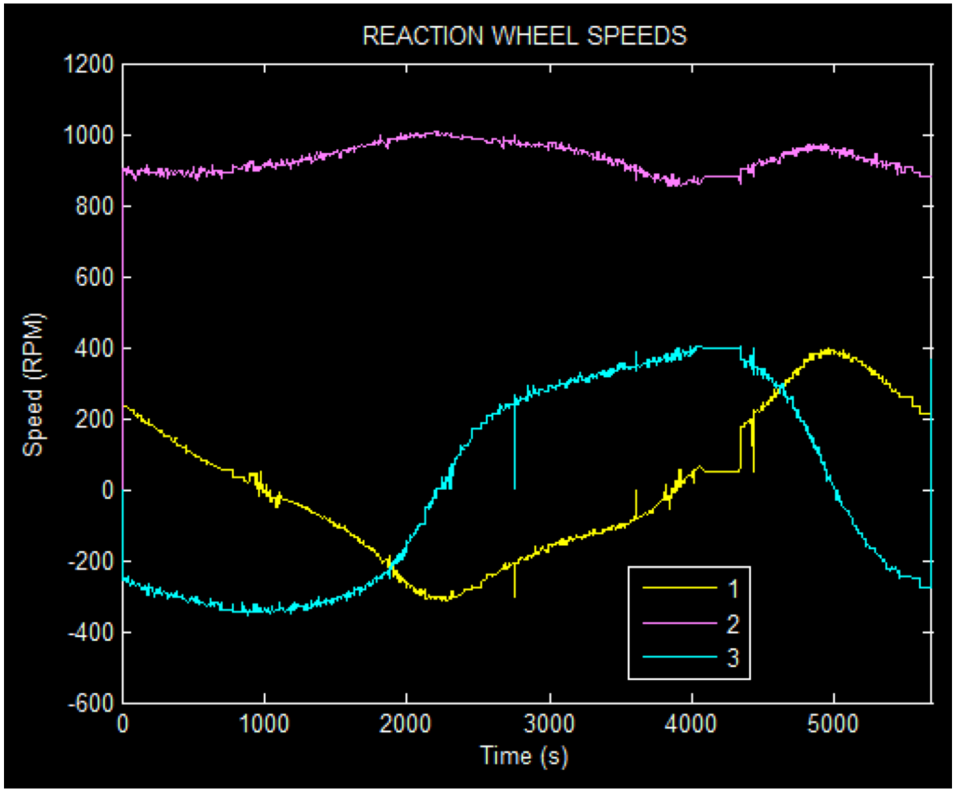


Typical MinXSS Attitude Control Scenario

- Spacecraft +X axis is sun-pointed (nearly constant in inertial space)
- One rotation about +X axis per orbit (star tracker to zenith)
- Telemetry plots here are subject to dropouts, include occasional parsing errors due to imperfect radio communications and C&DH system limitations (not XACT)



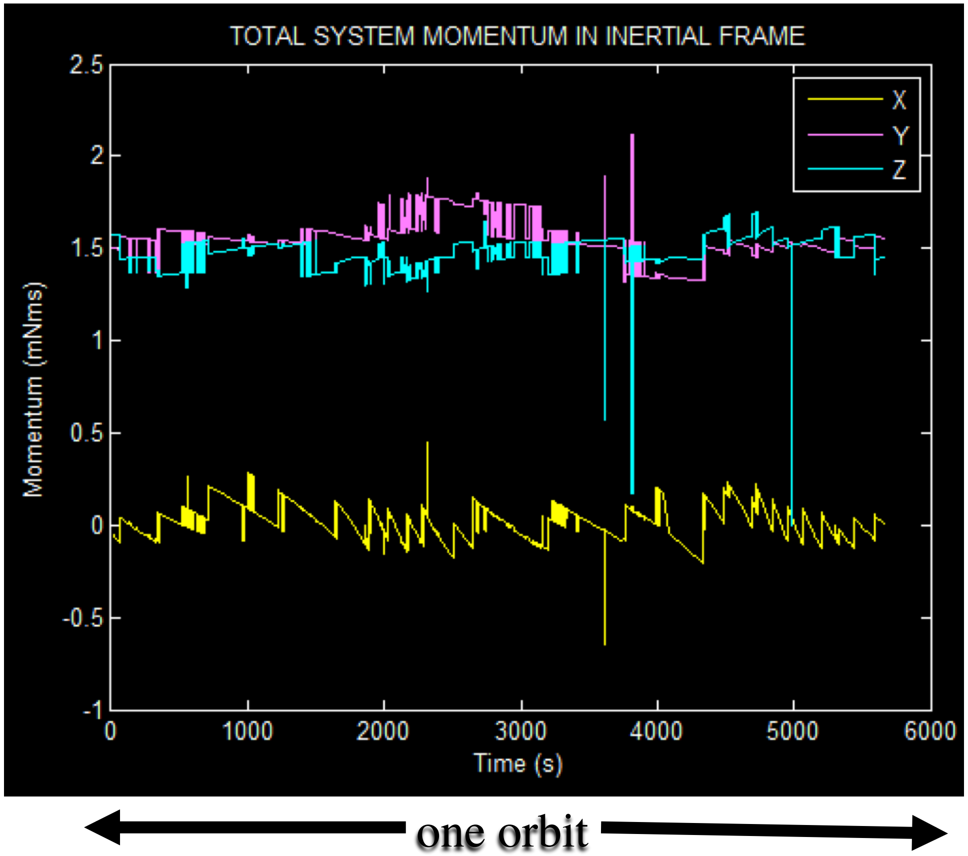
one orbit



one orbit

Pointing Performance – Momentum Accuracy

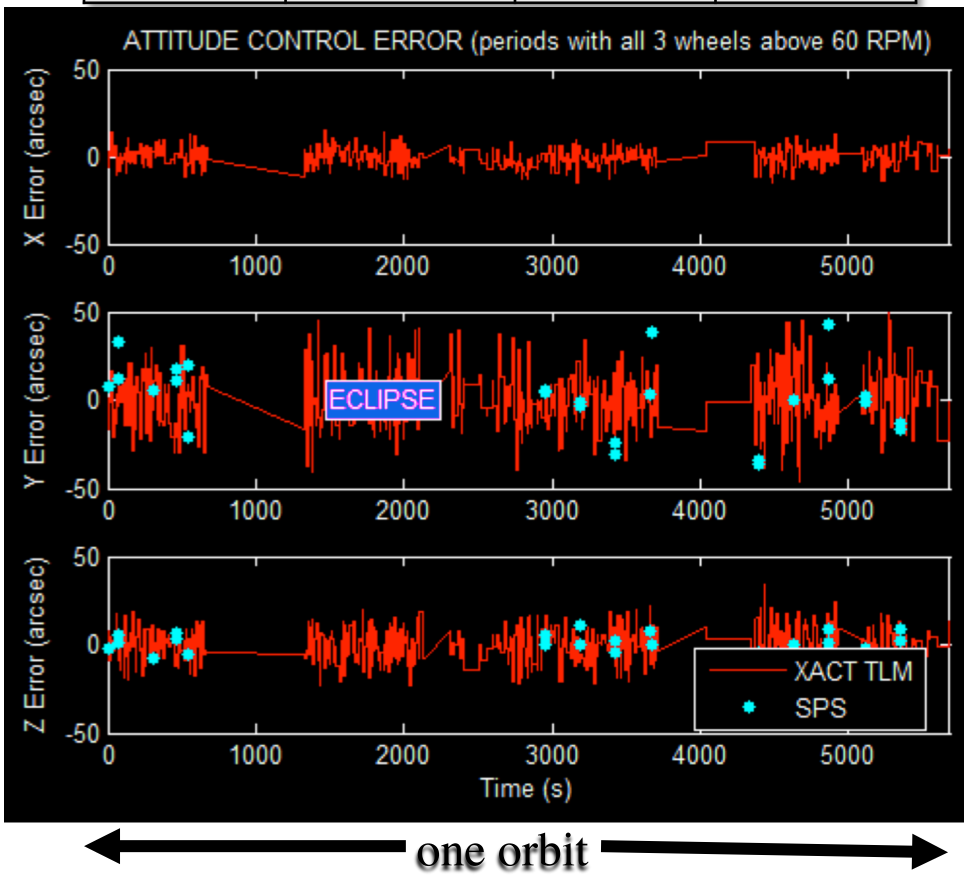
- Nonzero commanded momentum bias
  - [0, 1.5, 1.5] Nms — don't want wheel to stick at 0
  - Still have 0-crossings 4x / orbit — unavoidable with 3 wheels
    - XACT can support 4 wheels
- Momentum is accurately provided
  - Sawtooth in plot is artifact of reconstructing inertial frame momentum from telemetry points with different quantizations
  - Some telemetry frame errors
  - Actual control error: ~0.2 mNms



Pointing Performance – Highly Accurate

- Two independent measures of attitude control error
  - XACT telemetry based on star tracker, high-fidelity sun model
  - MinXSS fine Sun Point Sensor (SPS) with 2 asec dark noise
- Total error is calculated here for an entire orbit
  - Wheel zero speed-crossings excluded
  - Torque rods firing at all times (could manage this disturbance if desired)
  - No effort made to optimize wheel or torque rod operation

Body Axis	RMS Error (asec)		
	Per XACT	*Per SPS*	*Spec*
X	5.3	—	11
Y	15.8	20.1	25
Z	9.4	6.8	11*



Pointing Performance – Highly Accurate

- X axis shows 5 asec performance across tracker boresight (spec: 11)
- Y axis shows 16–20 asec performance, mostly about tracker boresight (spec: 25)
- Z axis shows 7–9 asec performance
  - Very low inertia makes this axis more sensitive to torque disturbances
  - Axis also has an about-tracker-boresight component
  - Long-term SPS data shows 7 asec performance over many days
- Significant unmeasured high-frequency motion is unlikely in general
  - In this data, two of three wheel speeds are often within tracker bandwidth
  - Same accuracy seen in data where 3rd wheel is also within tracker bandwidth

Body Axis	**RMS Error (asec)**		
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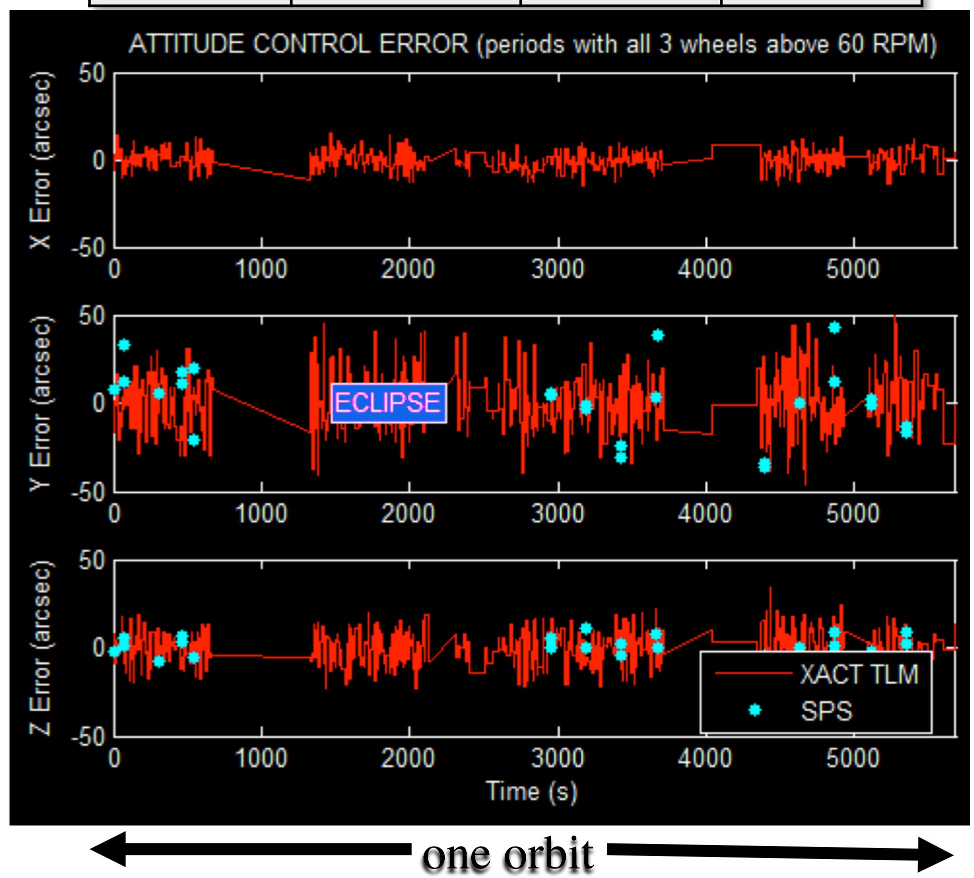

Pointing Performance – Highly Accurate

- Torque rods on
  - Off improves accuracy
- No effort to optimize wheel speeds

- Two star trackers even better
  - ~5 asec in axes // to one boresight
  - ~3.5 asec in third (perp.) axis

- BCT currently executing NASA Tipping Point contract for next-gen XACT for accuracy of ~2 asec, or better, in all axes
  - Some trackers already show this accuracy in ground testing
  - Flight in early 2018

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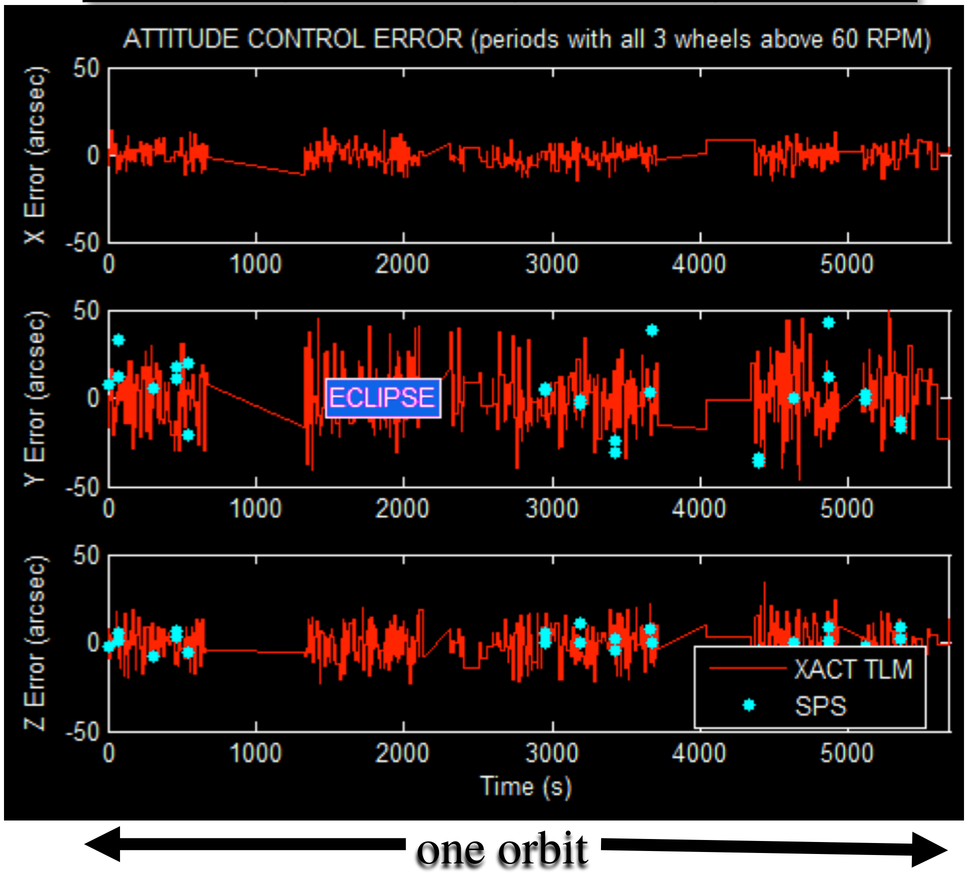
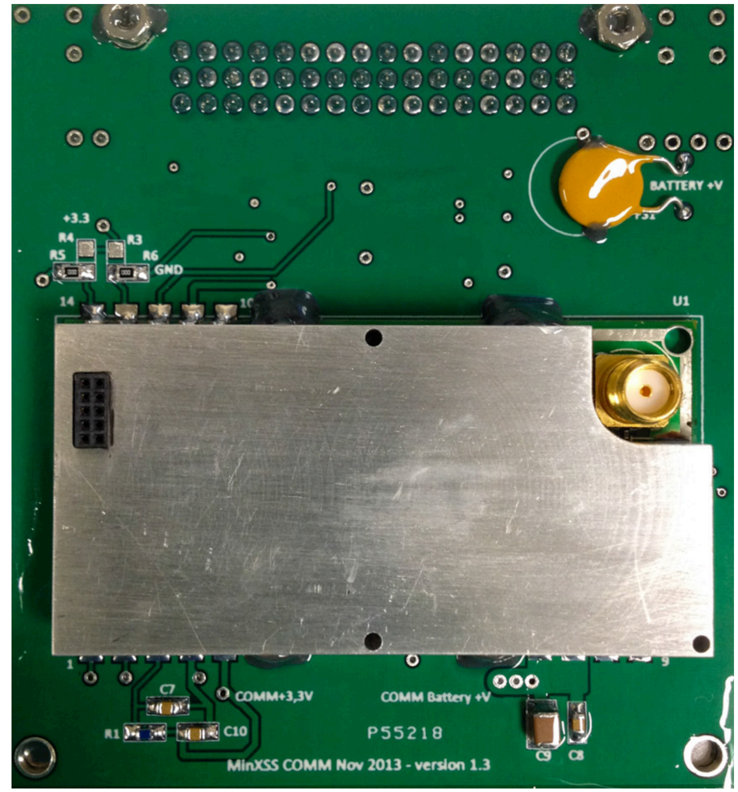


MinXSS Communications

- AstroDev Lithium-1 radio (UHF)
  - Mass: 164 g   Size: 0.15 U (radio only)
  - Power: < 4 W output (agile)
    - Input < 11 W
  - UHF (400–430, 430–450 MHz), VHF
  - AX.25 framing
  - $5,000



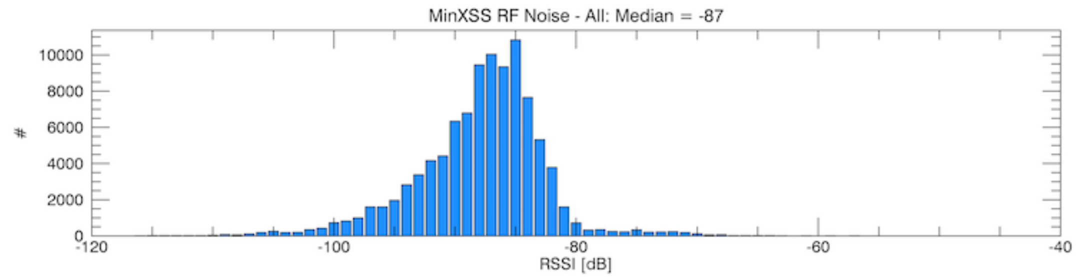
- Low data rates (9600 bps)
- Not easily customizable
- Some hang-ups, requires power-cycle
- Single person, limited support available

MinXSS Communications

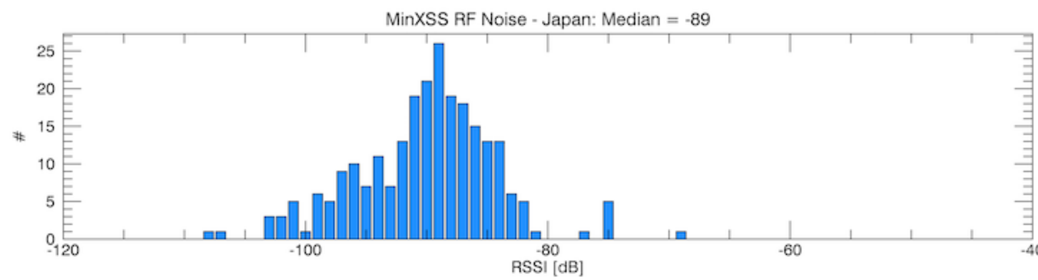
- Single station, custom built, double-yagi
- Poor data capture (high noise, poor on-board radio performance)
  - Second station in Parker, CO much better

MinXSS Communications

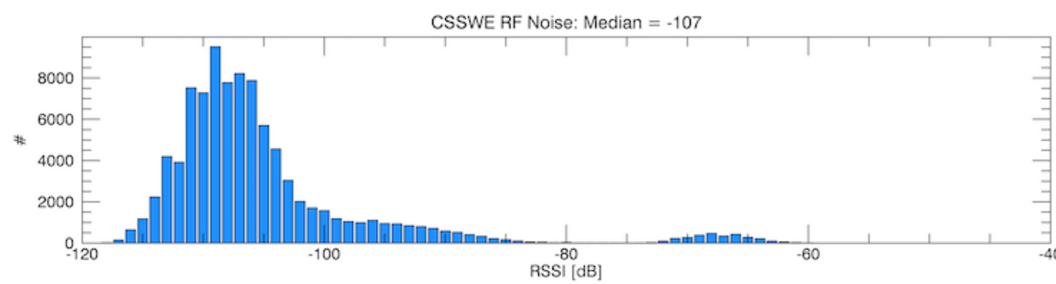
- Data capture is low; limited by:
  - Data rate (9600 bps)
  - Single ground station
  - Poor signal and acquisition



- HK: ~1.5% capture
  - 3 sec cadence; 255 bytes
  - ~7.5M generated, ~100k rec.



- Science: ~3.6% capture
  - 10 sec cadence; 255 – 3584 by
  - ~1M generated, ~36k received



- ADCS: Not prioritized

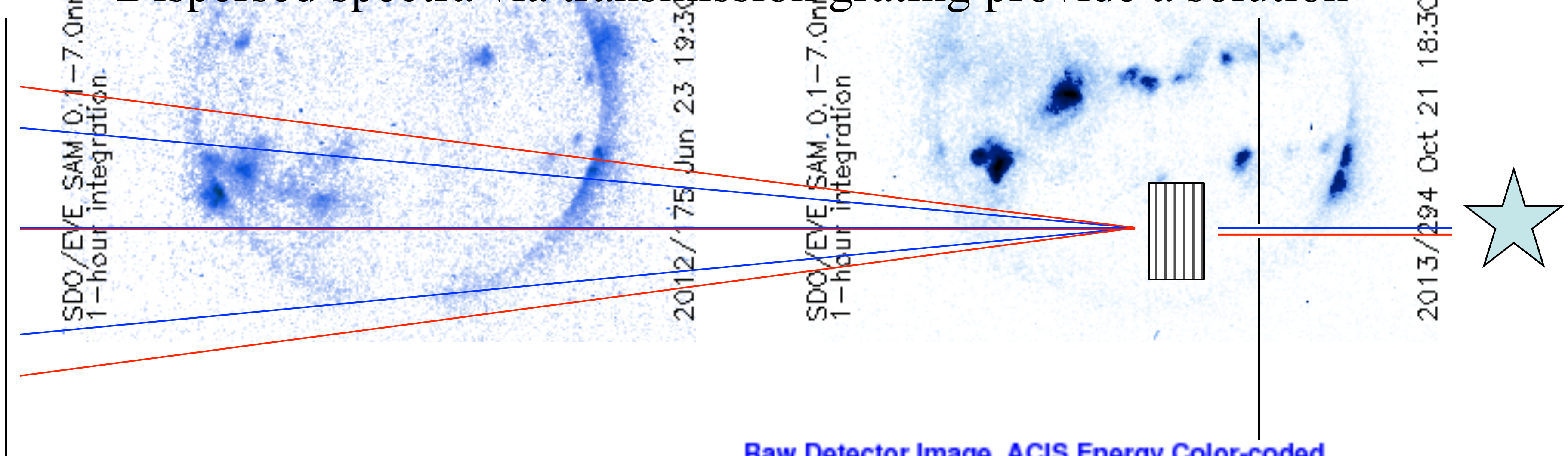
Limitations / Solutions

- No spatial resolution!

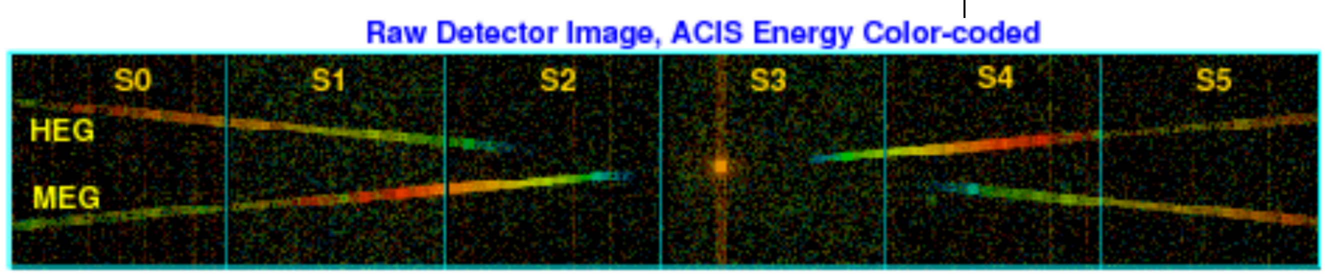
⇒ Pinhole provides spatial resolution at low cost/mass/complexity (limited photon throughput NOT a problem)

- For < 0.5 keV, electronic noise dominates
  - Single-photon measurements are impractical / not possible

⇒ Dispersed spectra via transmission grating provide a solution

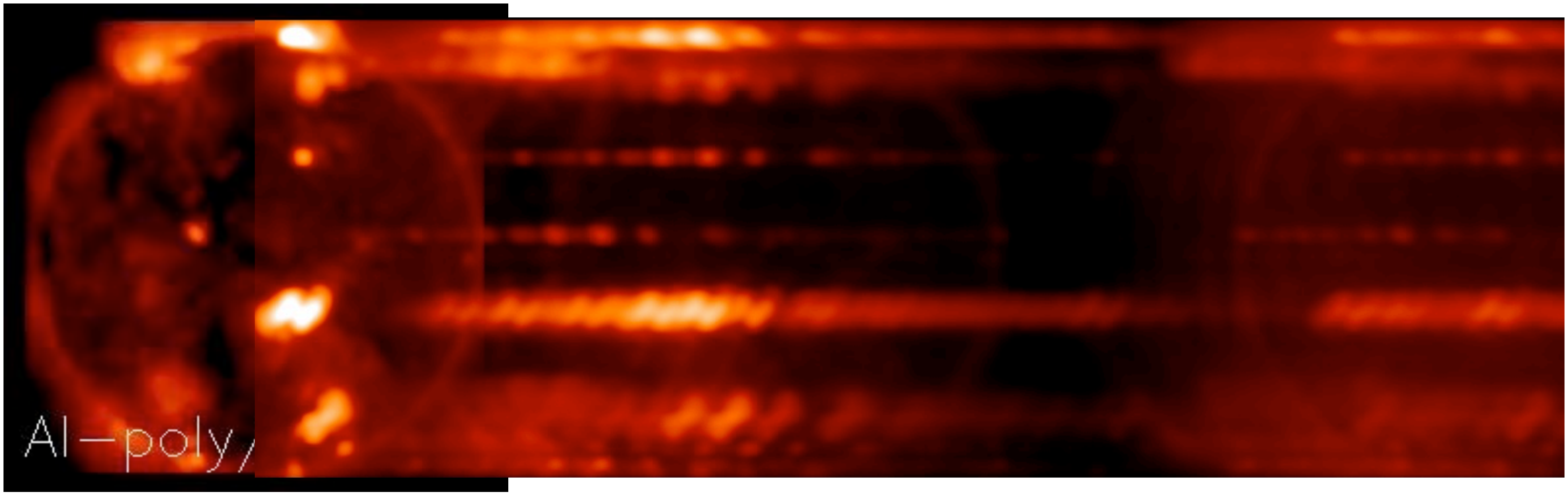


Chandra HETG image for point sources (stars)

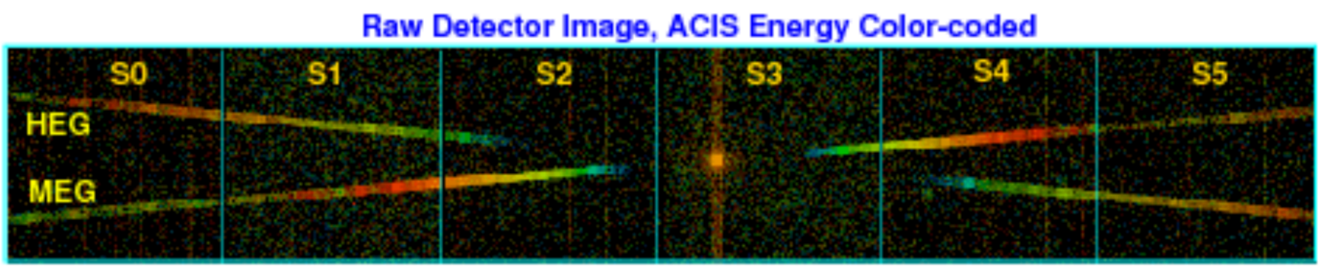


Multi-Order X-ray Spectral Imager

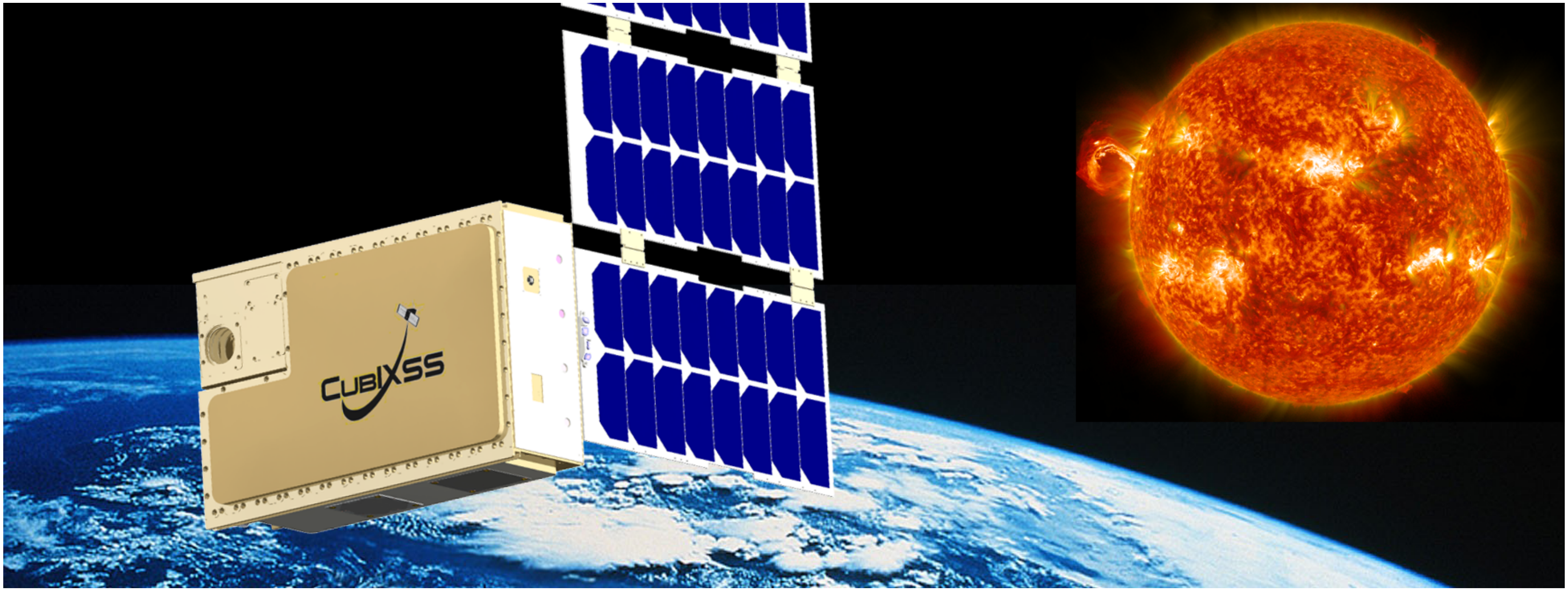
- Combination of pinhole imaging and transmission grating dispersion yields full-Sun "overlappograph" with 0^{th} order and dispersed orders on same detector



Chandra HTG image for point sources (stars)



New Proposed Mission



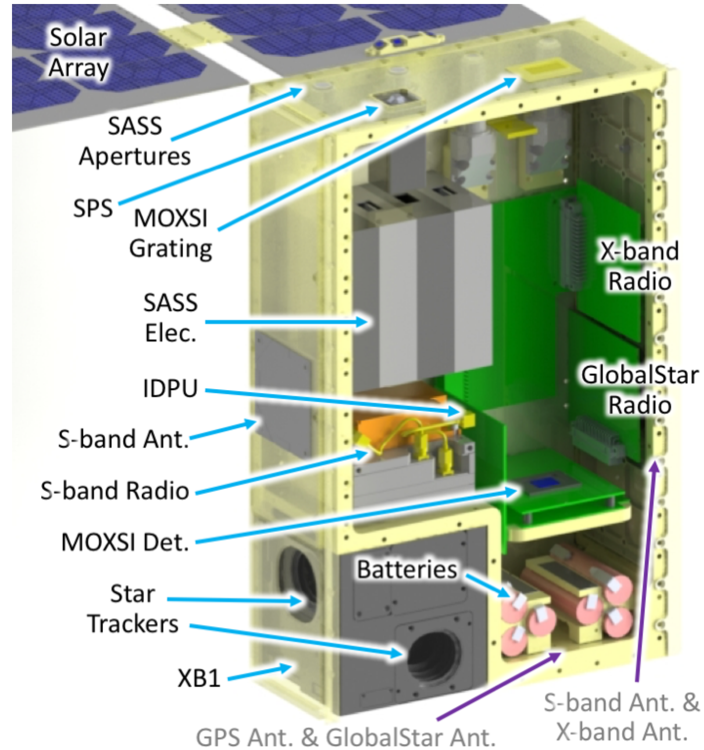
CubIXSS:

CubeSat Imaging X-ray Solar Spectrometer

- Goal: Improve physical understanding of thermal plasma processes and impulsive energy release in the solar corona, from quiescence to flares

CubIXSS: Spectroscopy & Imaging

- 6U CubeSat, proposed to H-TIDeS
- 2019 launch, LEO
  - *Optimized for solar minimum*
- Novel instrument suite includes:
  - Soft and hard X-ray spectrometers (spatially-integrated)
  - Soft X-ray imaging spectrograph (first solar imager on a CubeSat)

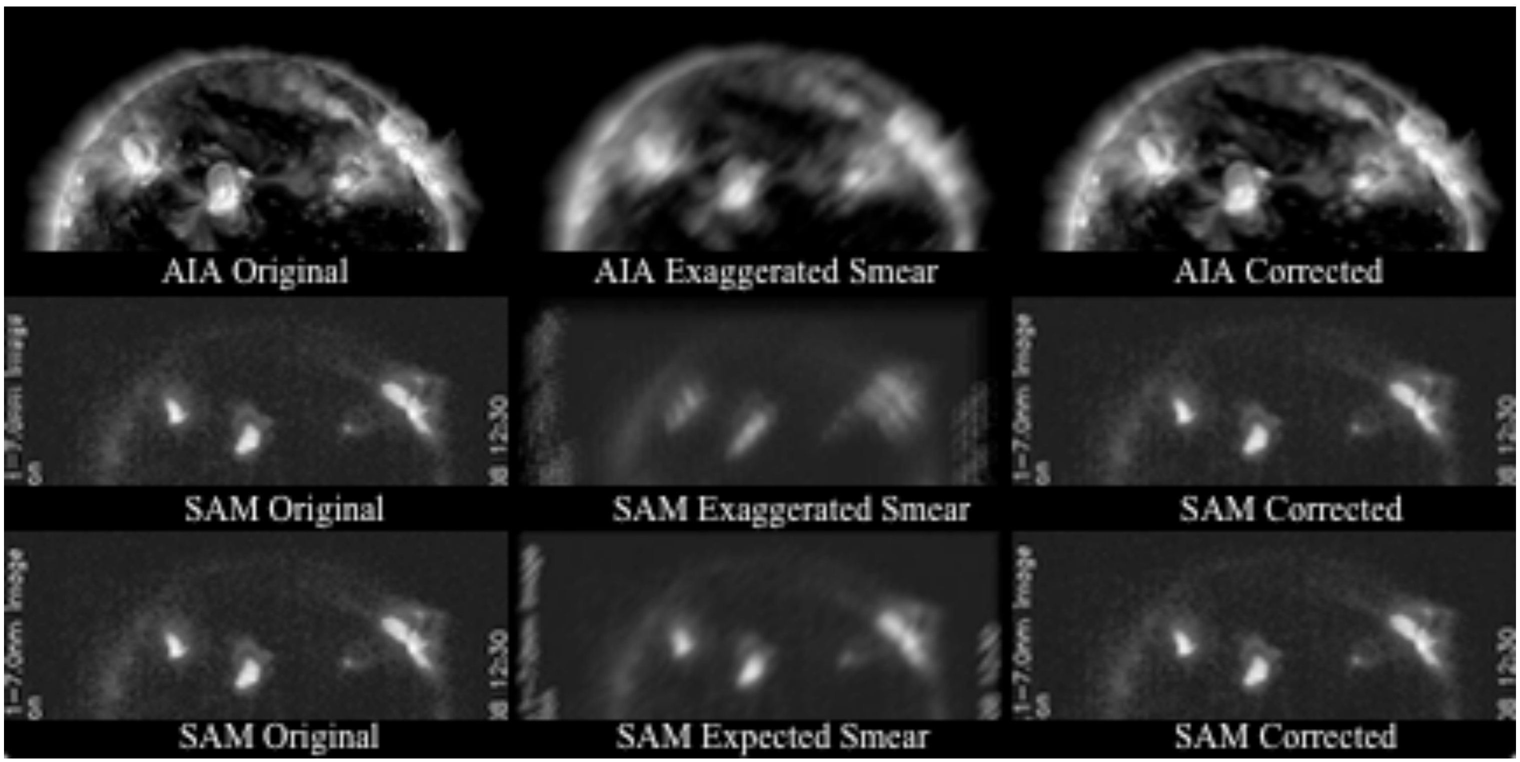


CubIXSS Instrument Summary

	Small Assembly for Solar Spectroscopy (SASS)	Multi-Order X-ray Spectral Imager (MOXSI)
Spectral range	SASS-S: ~0.5–30 keV SASS-H: ~5–100 keV	~1–55 Å (~0.22–12 keV)
Spectral res.	SASS-S: ~0.15 keV FWHM SASS-H: ~1 keV FWHM	~0.25 Å FWHM (~0.06 Å/pixel detector scale)
Spatial res.	N/A (spatially-integrated)	~25 arcsec FWHM (~6 arcsec/pixel detector scale)
Cadence	~1 s	~20 s

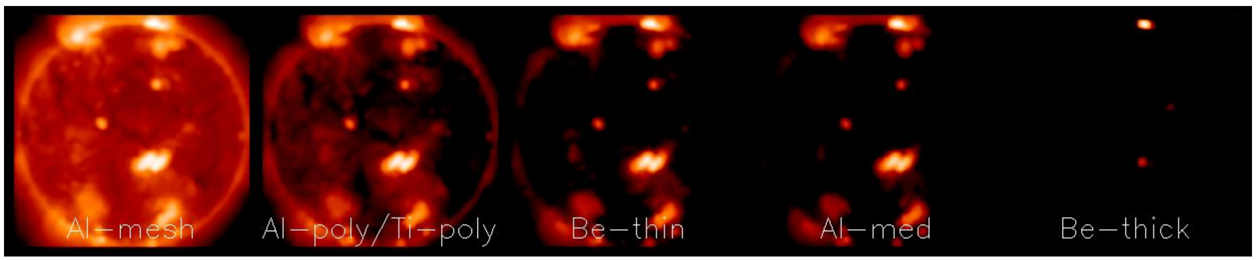
MOXSI for CubIXSS

- On-board image motion compensation by summing co-registered high-cadence images to relax pointing control and stability requirements
- Can exploit jitter for higher effective resolution



MOXSI for CubIXSS

- Dispersed spectrum is rich, but complex to analyze alone
- Non-dispersed images w/ coarse spectral information provide spatial kernel *and* initial spectrum for forward modeling
- MOXSI has 5 additional pinholes to create *Hinode*/XRT-like filtergrams to provide this spatial kernel and spectral seed
  - Filters optimized for temperature coverage and dynamic range

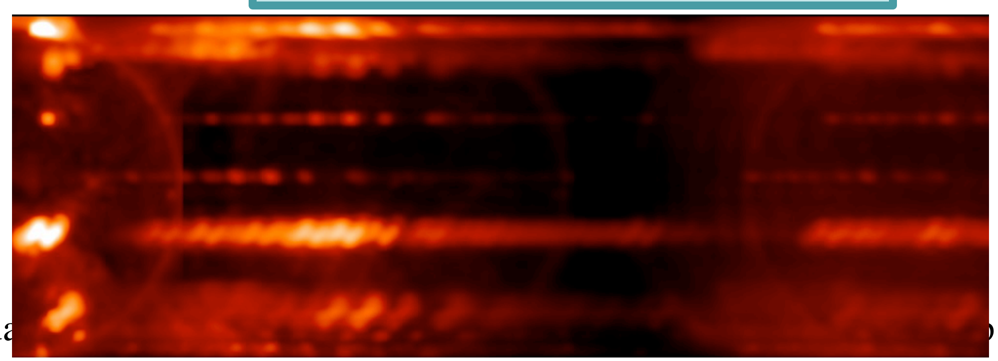


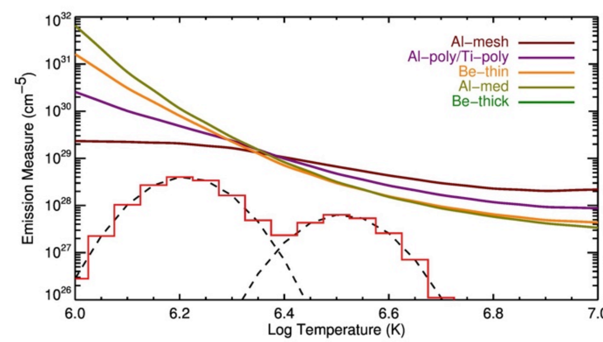
MOXSI data analysis: forward fit 2D map of DEM and FIP bias.

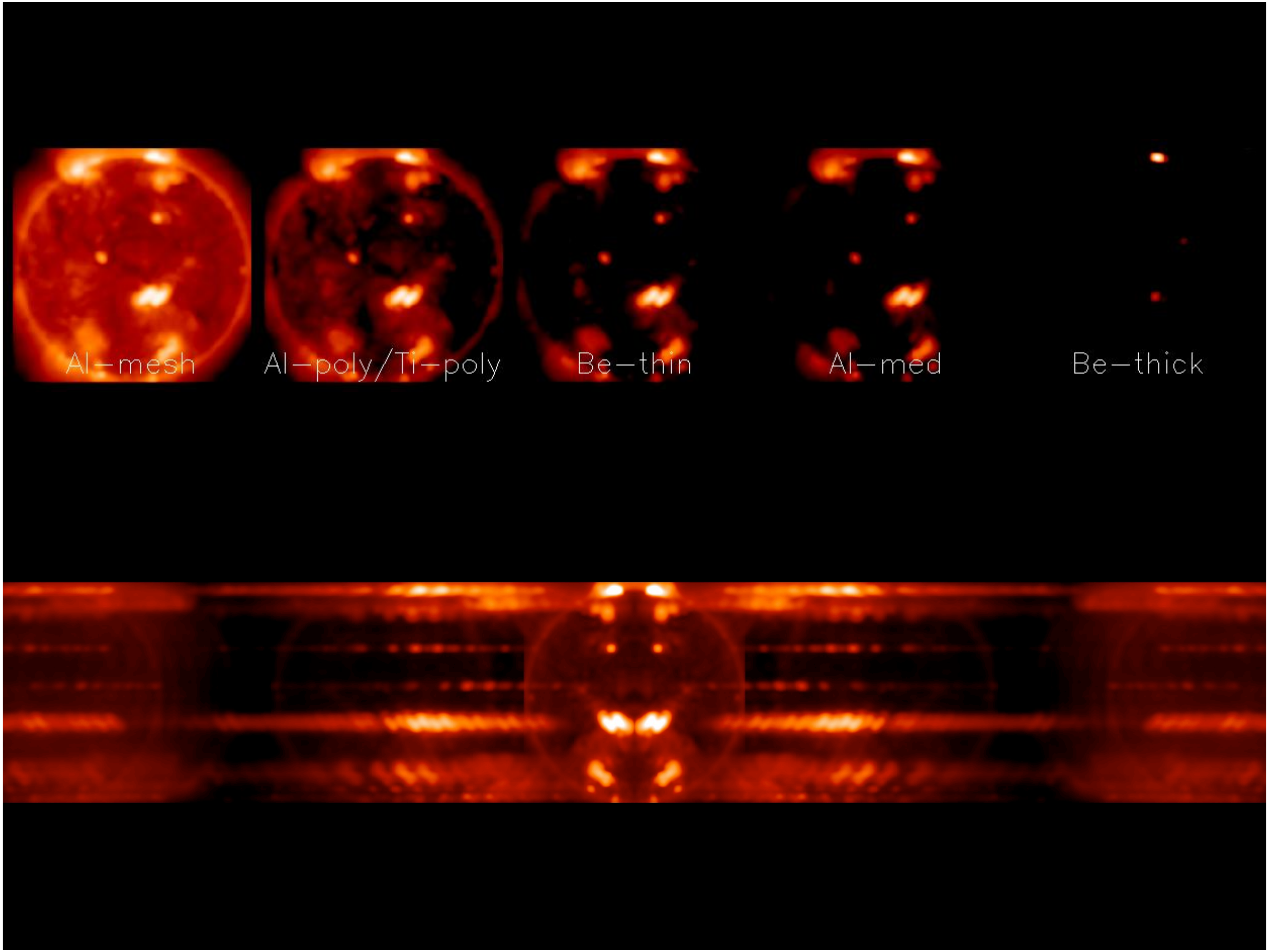
Seed DEM with filter images
Iterate with dispersed images

North

MOXSI records the 5 filtergram images and the "overlappogram" on the same detector *simultaneously*



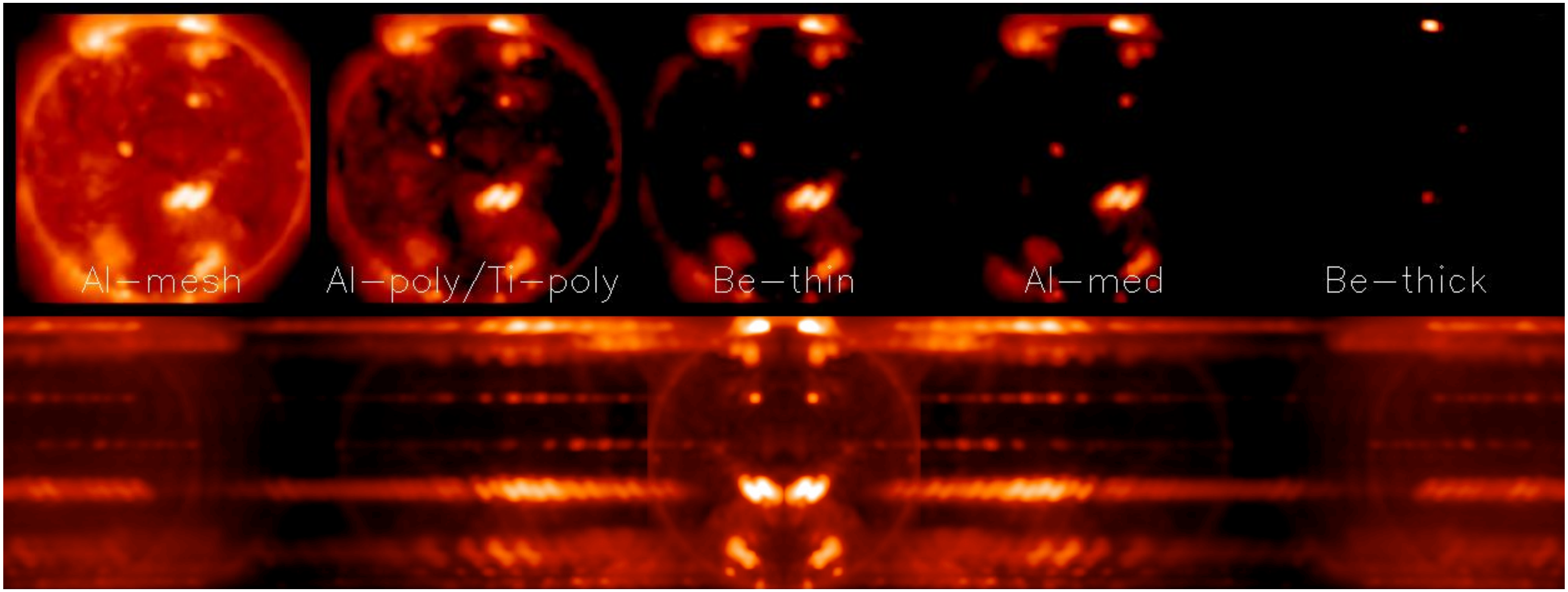




Al−mesh
Al−poly/Ti−poly
Be−thin
Al−med
Be−thick

CubIXSS Trade-Offs

- Detector is 1500x2000 pixels (e2v CIS115)
- Baseline science requires ~1000x2000 = 2 Mpix = 4 MB every 20 sec
  - Even w/ 5x compression, ~2.4 GB/day
  - Can easily increase 10x with higher cadence, more pixels/supersampling, etc.
- X-band comms limited to ~10 Mbps for non-Earth-observers
  - Ka is still vaporware (and AFAIK only from Tethers)



CubIXSS Resource Budget

Subsystem	Manuf.	Orbit-Average Power (W)				
		Draw	Duty	Avg.	Cont.	**Total**
[SNIP]	–	–	–	–	–	**–**
X-band Radio (Tx)	[redacted]	10.0	3%	0.3	20%	**0.4**
S-band Radio (Rx / Tx)	[redacted]	0.8	100%	0.8	10%	**0.9**
		15.0	3%	0.5	10%	**0.6**
GlobalStar Radio (Rx / Tx)	GlobalStar	0.5	100%	0.5	10%	**0.6**
		3.7	3%	0.1	10%	**0.1**
[SNIP]	–	–	–	–	–	**–**

- Baseline ConOps = 2.6 W orbit-average comm power
  - Assumes only 3% duty cycle for Tx (~5–6 ground passes per day)
  - Sufficient for 100% data capture with margin for baseline science, but…
  - More data = more science! (Higher cadence, higher resolution, etc.)
- More data = more Tx time = more power, more money
  - 10x more data = 10x time = 12.5 W OA comm power… + 10x ground-comm $$$
  - Cannot realistically accept either one, given resource limitations
  - 100x more data = fuhgeddaboudit!
- Laser comms enables more science w/o more power, more money

Scaling Up to Larger SmallSats

- Better spatial resolution enables spectroscopy *within* sources
- ~7" achievable in 1.5m distance (e.g., SMEX or MoO)

- Requires more pixels to accommodate higher resolution with same FoV and spectral passband
- Higher cadence for better science
  - More dynamics
  - Sub-pixel sampling for super-resolution

➔ Need higher data rates! 50 Mbps OK, 1 Gbps enables!