NICER

Neutron star Interior Composition ExploreR

Systems Engineering Seminar: Thoughts and Experiences on NICER

Charles Baker, Jim Kellogg

NASA

GSFC

Systems

MIT KAVLI INSTITUTE

DTU

BROAD REACH

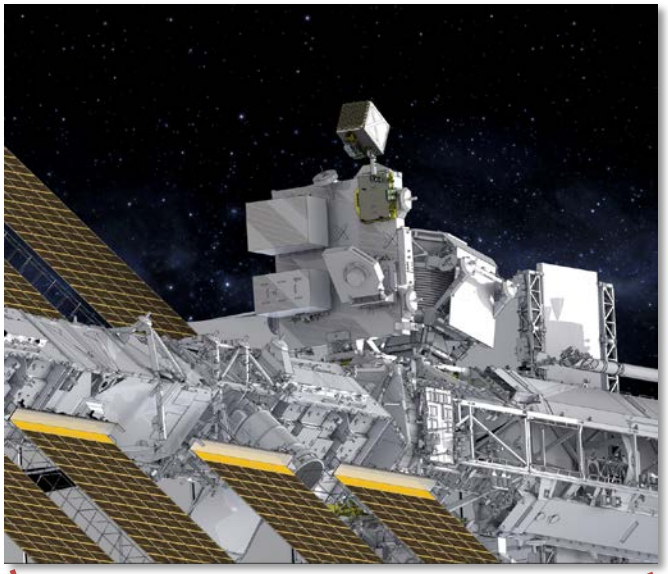
MOOG

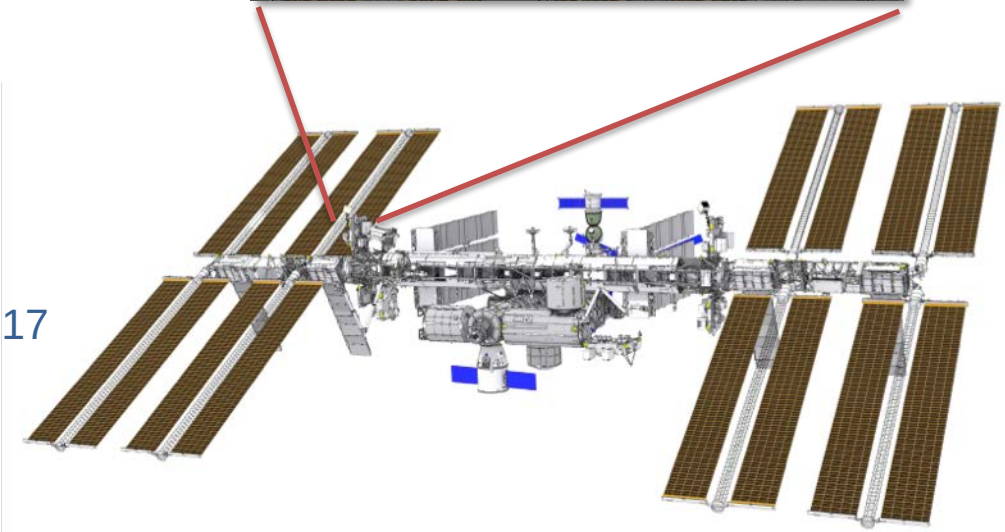
Agenda for the First Half

- NICER As Built
- SE Team Assignments
- Team Dynamics
- Document Tree
- ISS Lessons Learned

NICER: An Astrophysics Mission of Opportunity on the International Space Station

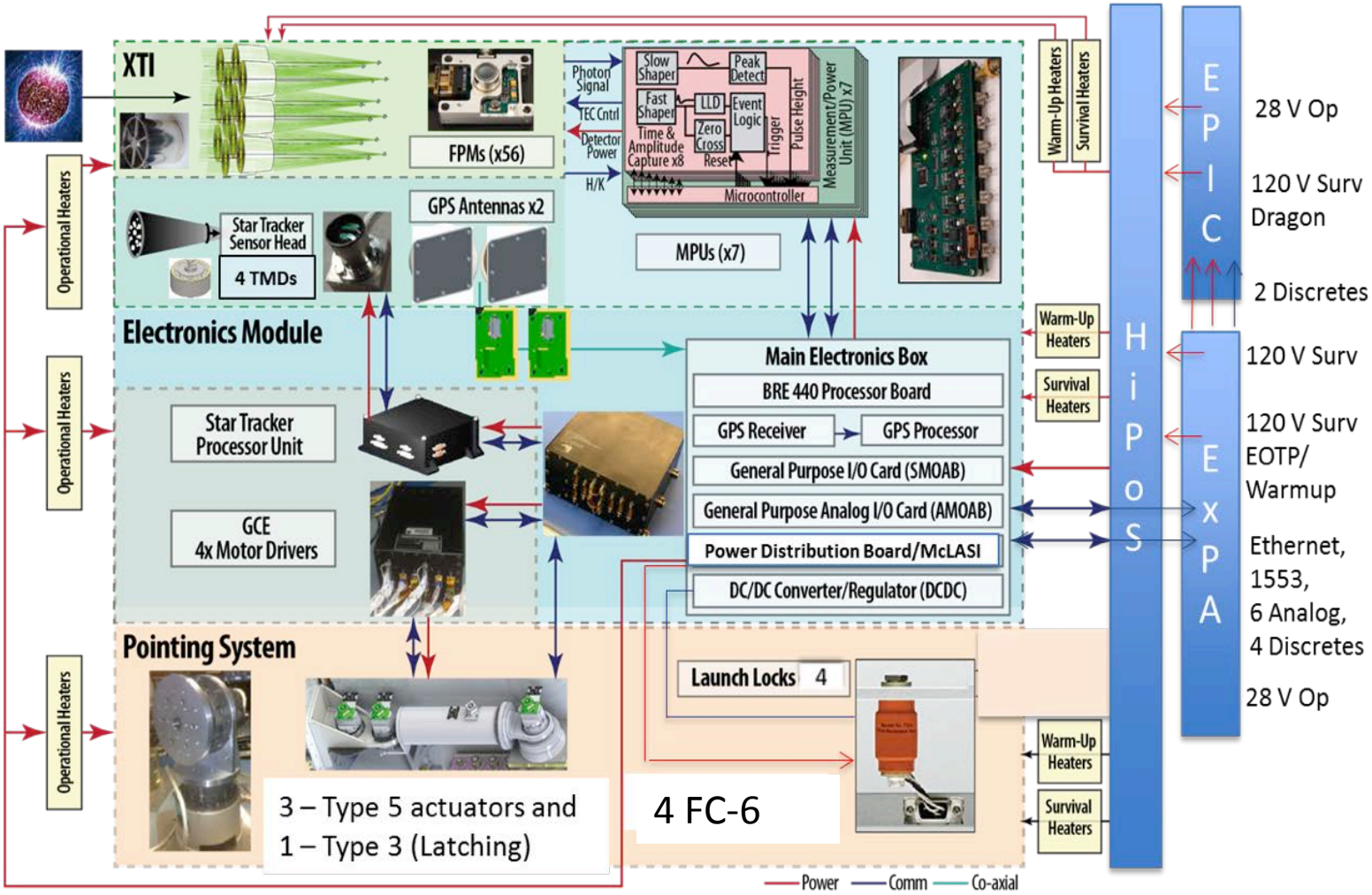
- ***Science:*** **Understanding ultra-dense matter through observations of neutron stars in the soft X-ray band**
- ***Launch:*** **Completed on June 3, 2017, SpaceX-11**
- ***Platform:*** **ISS ExPRESS Logistics Carrier (ELC), with active pointing over nearly a full hemisphere**
- ***Duration:*** **18 months + Guest Observer program**
- ***Instrument:*** **X-ray (0.2–12 keV) "concentrator" optics and silicon-drift detectors. GPS position & absolute time reference**
- ***Enhancements:***
  - **Guest Observer program**
  - **Demonstration of pulsar-based spacecraft navigation**



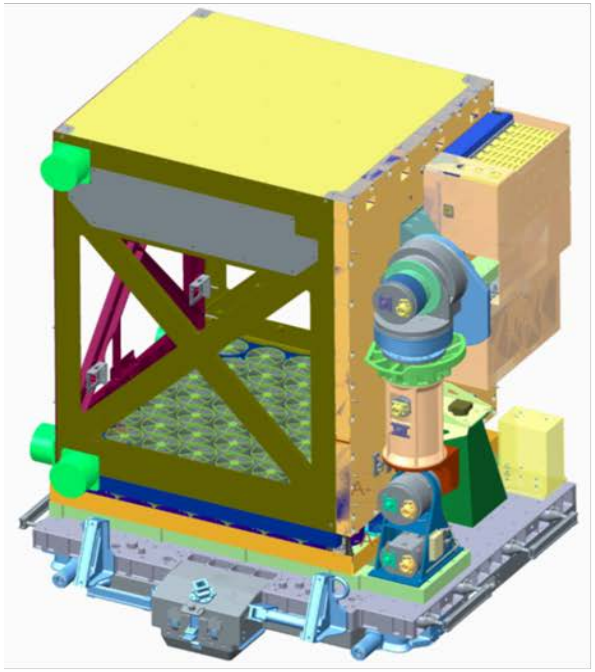


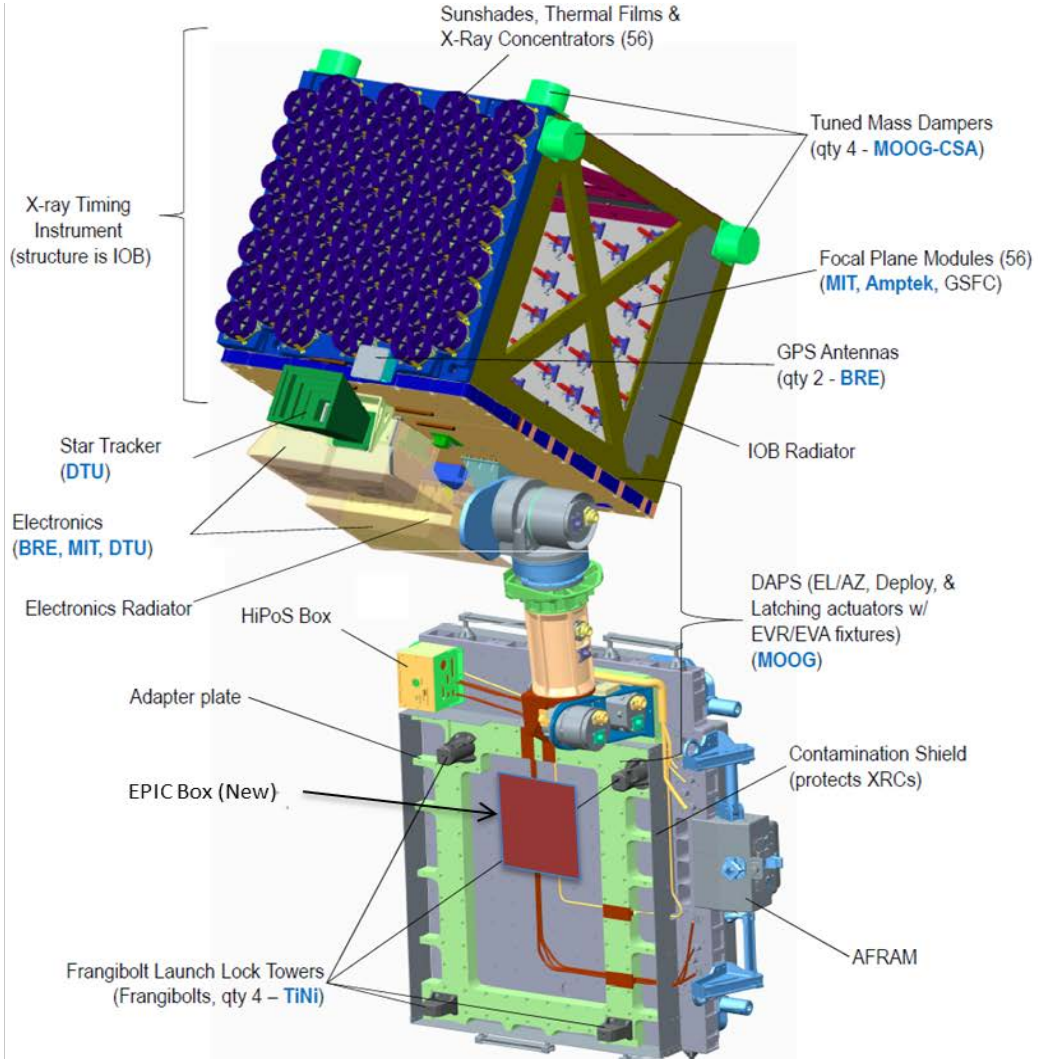
- ***Status:***
  - NICER installed on ISS on June 13, 2017
  - Commissioning completed
  - Payload performing very well

NICER Block Diagram



NICER Mechanical Layout





NICER SE Team was right sized for the NICER Payload

NICER PSE – Charles Baker
NICER ISE – Jim Kellogg
NICER SE – Ron Zellar
NICER SE – Todd Colangelo
NICER V&V – Kristina Pevear

Integration and Test – Karen Pham

Ground Systems – Bob Kozon

Mech Sys – Chuck Monroe/Son Ngo
Elec Sys – Andy Aylward
Thermal Sys – Dan Powers
Point Sys – Alice Liu
FSW Sys – Bruce Savadkin
Measurement Sys – Zaven Arzoumanian
Contamination Control – Tina Montt-Garcia

Deployment & Pointing Subsystem
GN&C Subsystem (ST, GPS, GCE, PFSW)
Detector System
Optics Subsystem
Structures Subsystem
Flight Software
MEB
Thermal Hardware Subsystem

Common Misconceptions of Class D

- Blind schedule and cost driven without Risk assessment
  - Every issue raised was addressed and most are mitigated within the NICER reserves
- No documentation
  - NICER eased the format of documentation, but not the substance
  - NICER used the PIP, I&T Plan, System Qualification Plan to document processes in one document rather than writing individual plans when feasible
- Unrealistic schedule that forces substandard work
  - NICER worked with the subsystem leads to ensure adequate time was allowed for high, medium, and low risk reduction within NICER's reserves
  - Schedule is often more subjected to the 5 minute rule (Eliminating even 5 minutes of critical path time per day often yields days per week. Transitions and end of the day can make or break schedule.
- Substandard quality avionics build
  - Single string elements of NICER were built to high standards
  - Redundant elements had long burn in and on the ground operations times
- Poorly managed and documented Interfaces
  - NICER came together and interfaced with Class A infrastructure in the ISS
  - NICER had outside partners (MIT, BRE, Moog, DTU) supplying hardware therefore we have detailed NICER Mechanical Interface Drawings and Interface Control Documents
- Test Program is schedule oriented
  - The test program for NICER was comprehensive to ensure infant mortality and design features were screened before launch
  - Operations risk was reduced through targeted mission simulations
  - Test As You Fly mentality was actively pursued to identify unknown-unknown risks

NICER Team Dynamics

- PI led and PI managed
- PI, PM, PSE, CSO involved in all key system level decisions
- Decisions were made quickly (generally <1 week, and possibly immediately), but only after considering all choices and hearing all the sides
- Decisions were sometimes adjusted based on outcomes from 1st decision direction
  - All on the project could present good evidence and or compelling advice to change a decision
- Blame is left for the historians, corrective action is what is sought after issues arise
- Large re-direction was done in person
- Team focused on mitigations to risks and healthy risk processes (all are involved, risks were actively tracked and updated monthly generally lowering the risk with the completion of mitigations)

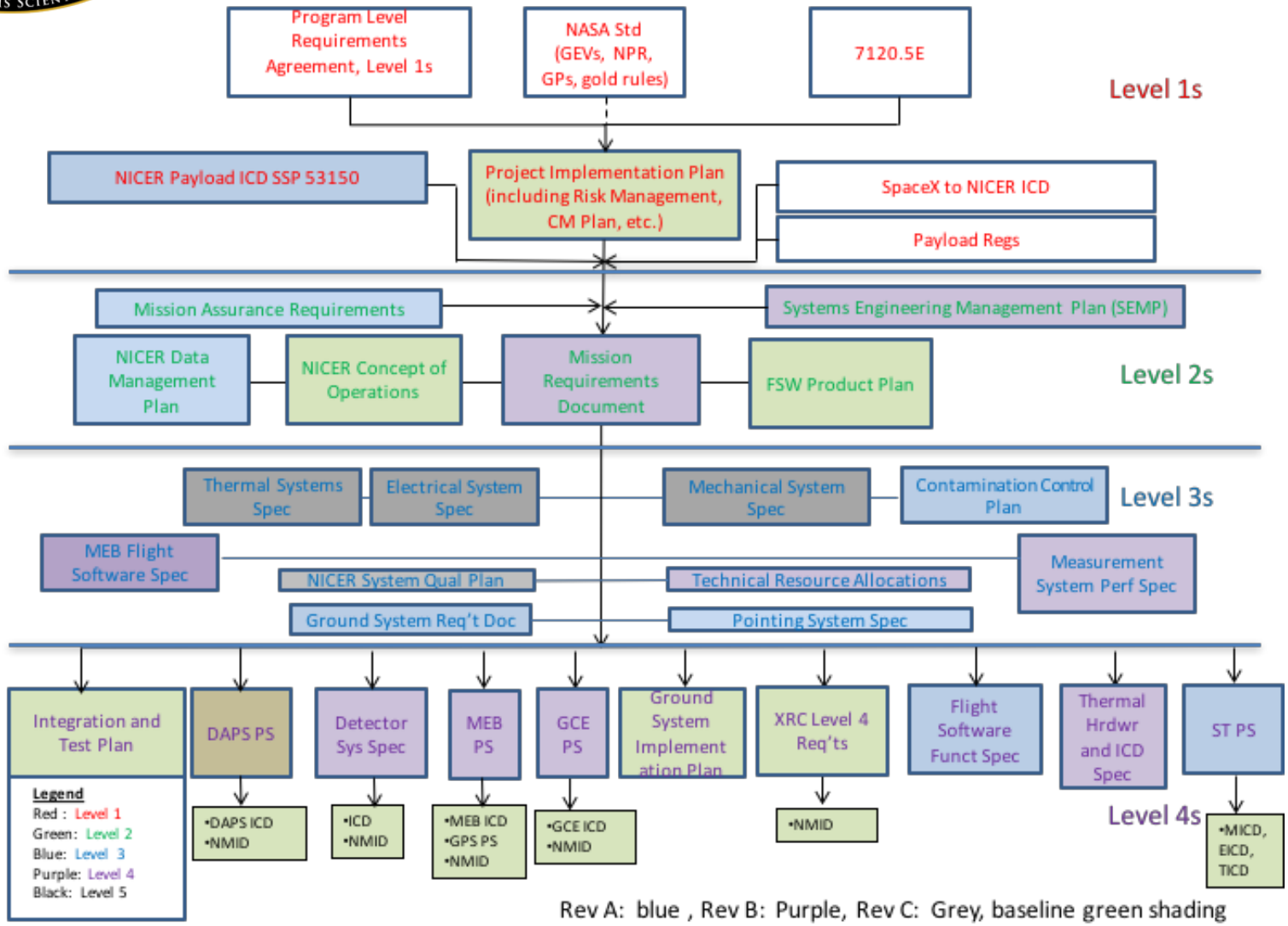
NICER Culture

- Co-location of in-house elements was critical
  - Subsystems not co-located were at a definite disadvantage
- SE and Management sought to be inclusive and appreciative
  - Takeout Fridays
  - Friday afternoon reflections
  - Parties to celebrate major milestones
  - Value team members and their contributions
  - Treat team members with gratitude to jobs well done and address problems as a team, don't focus on who to blame
  - Grow the A-team and slowly supplement (with added personnel) the experience that the current team may lack
- NICER didn't blame branches, partners or the institution, but rather alerts organizations to team needs
- Develop Partners who will go the extra mile for your project, be reasonable with them, assist them when needed.

Analysis versus Test

- Requirements at the edge of achievable are much more expensive and time consuming
- Ideally requirements are checkable with a hand calc or simple model
  - Resist requirements that aren't verifable
- Often the cheapest way to meet/verify a requirement is to build an Engineering model or demonstration unit using inexpensive parts and try and demonstrate meeting the requirement
- Performing extensive analysis on things that could be built and tested is often the most expensive
- Iterating on the engineering model and testing should arrive at the optimum solution and highest confidence of flight build success for the least money
- Build engineering models for all difficult analytical problems

NICER Document Tree



ISS Interactions

- The ISS program is filled with fantastic, talented engineers
- The ISS platform works as a scientific platform for missions of opportunity.
- Discipline Experts support a multitude of payloads.
  - ISS organization is heavily stove piped to prevent overcommitting discipline experts.
  - Information transfer and working knowledge of your payload's specifics is isolated to a few individuals and even that is at a pretty high level.
- Requirement Closure Process:
  - Verifications are not reviewed in a timely manner (we had some open for >6 months)
  - Payload Developers should start this early, and be prepared for delay (Need to use your Research Integration Manager (RIM) and Payload Integration Manager (PIM) to keep this process moving)
  - Pushing Exceptions to requirements is a very slow process. More difficult ones took over a year. Need RIM and PIM to keep process going.
- SpaceX Interactions:
  - SpaceX is weak in the contamination control area.
  - If it isn't in the ICD, it probably won't happen.
  - SpaceX ICD came very late.
  - ICD is at a very high level.
  - SpaceX folks tend to be high competency.
  - Integration into trunk process seems to be changing constantly.
    - Ensure you are looking out for the safety of your own payload.
  - PIM and RIM should be directly helping this process.
- POIC Interactions
  - POIC has some very skilled set of folk and some folk who can get in the way of progress.
  - POIC doesn't have an ICD with Payloads but should.
  - POIC interactions occur really late.
  - Ensure you have a good POIC team by working with your PIM and RIM.

The important bits: The end game, NICER at the Cape

CRS-11 Launch with reused Dragon

June 3, 2017

SpaceX-11 Launch

Ascent

June 3, 2017

Ascent

Stage-1 Re-entry Burn

Launch and In-Orbit

Time Lapse

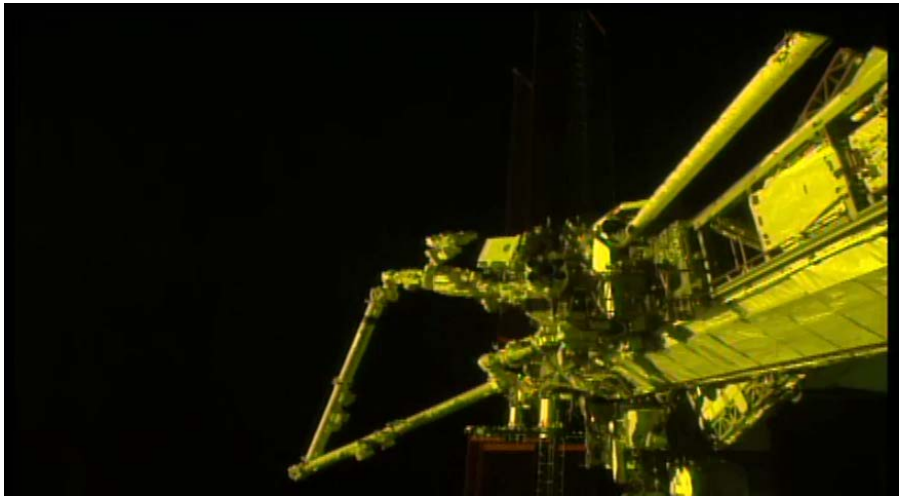
June 3, 2017

NICER in Space

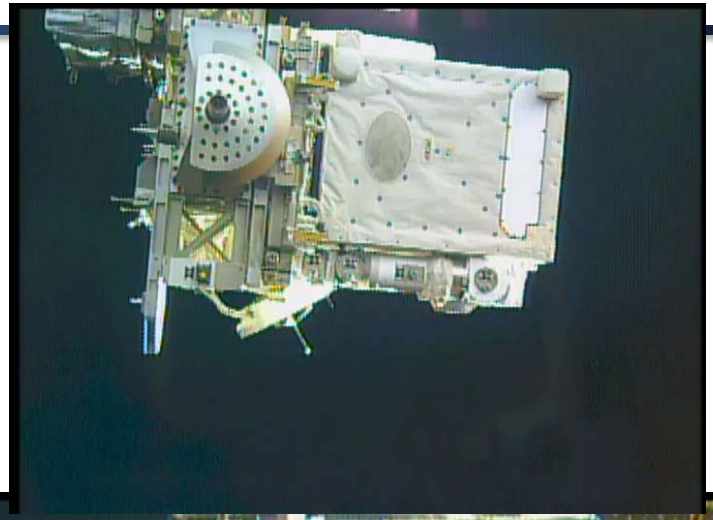
NICER in Trunk, View is incredible

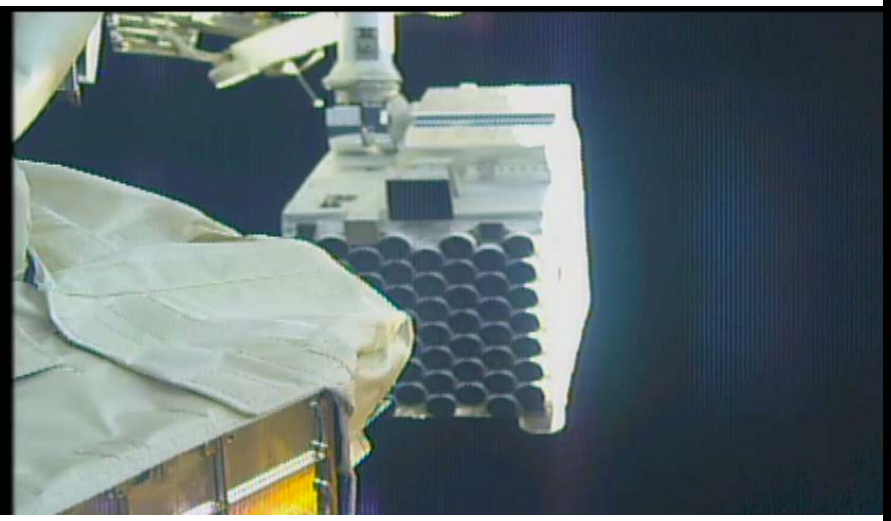
Extraction

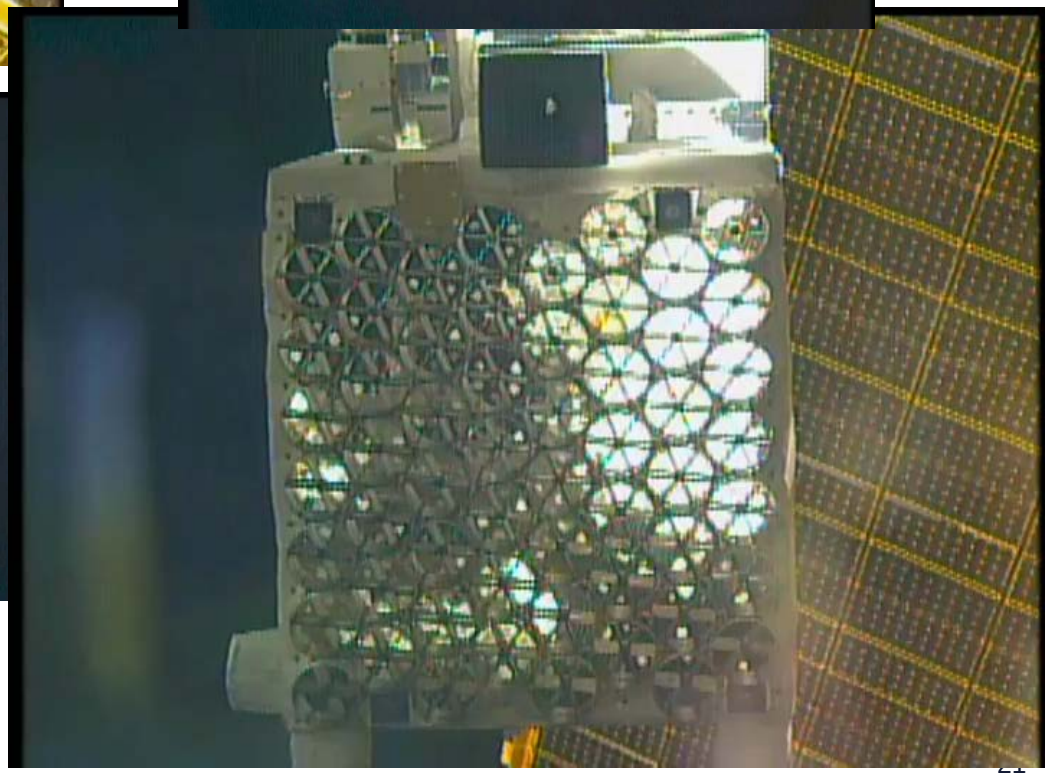
NICER EVR Removal, Trunk to EOTP to MT



NICER On-Orbit ROM (what other platform offers this!)







Summary

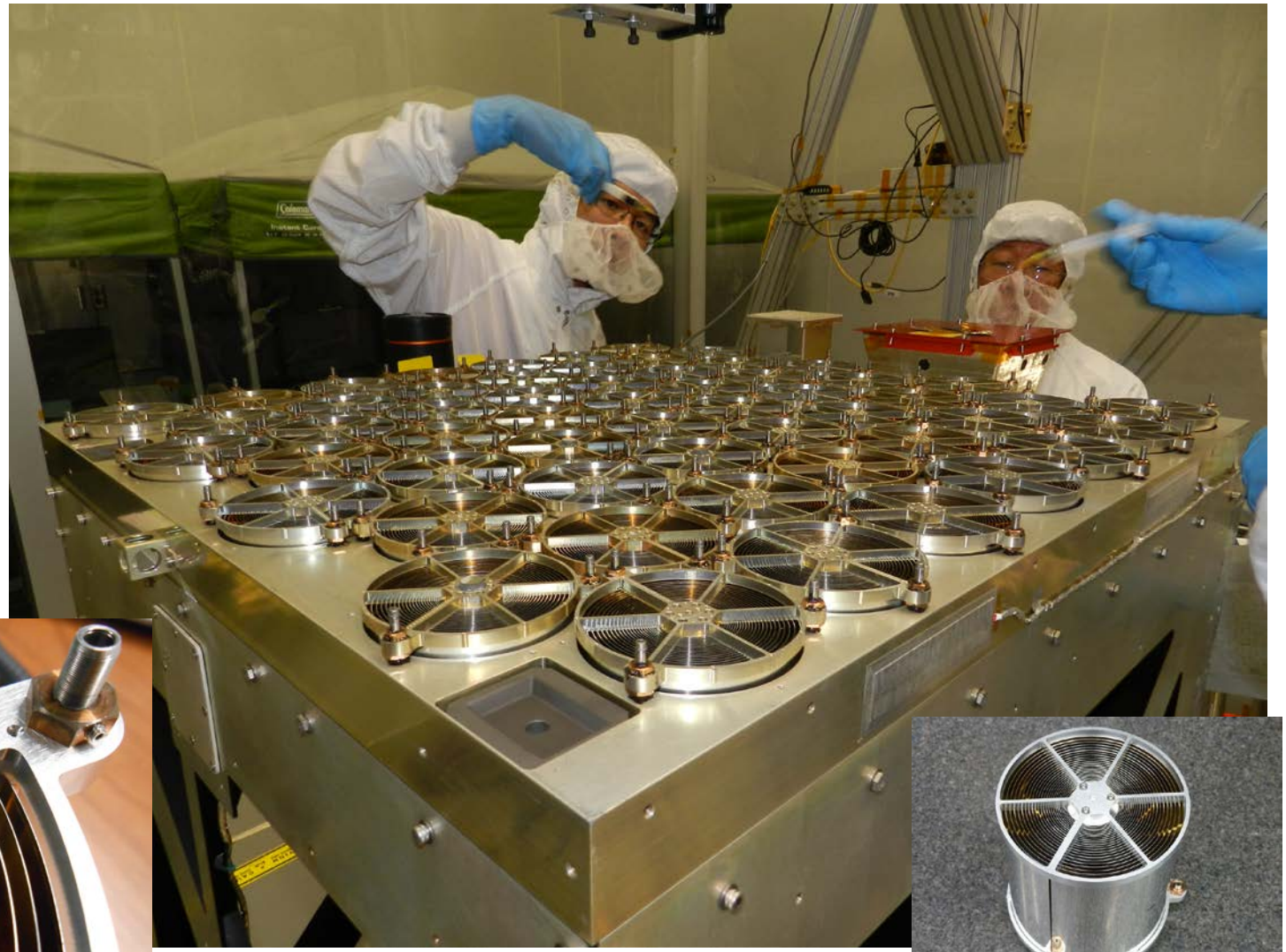
- ISS missions have their own challenges and rewards.
  - Like everything else, persevering and driving the process is always best.
- Class D missions can be developed and flown with high reliability using knowledge based risk management and good engineering practices.
- Develop driving requirements early, there is a window of opportunity for everything.
- It is often easier to test EM hardware to evaluate performance than performing an analysis.
- Making decisions quickly and bringing the team along with you is critical.
- Team dynamics matter to the success of any team.
- NICER Delivered 2 weeks ahead of schedule versus CSR and under budget with a payload that significantly exceeds performance requirements.

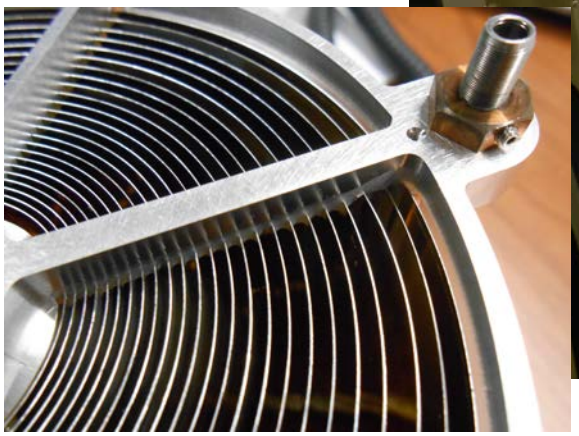
Agenda For the Second Half

- XRCs, FPMs and Alignment
  - XRCs and FPM designs
  - Collimator and alignment process
- Harnessing
- System Qualification Matrix and how it evolved
  - DAPS testing
  - XTI Tests prior to Payload
  - Class D testing
- Gold Rules Approach
- Launch Locks Close Call
- On Orbit Performance
- Lessons and Thoughts

Optical Bench Fully Populated with XRCs

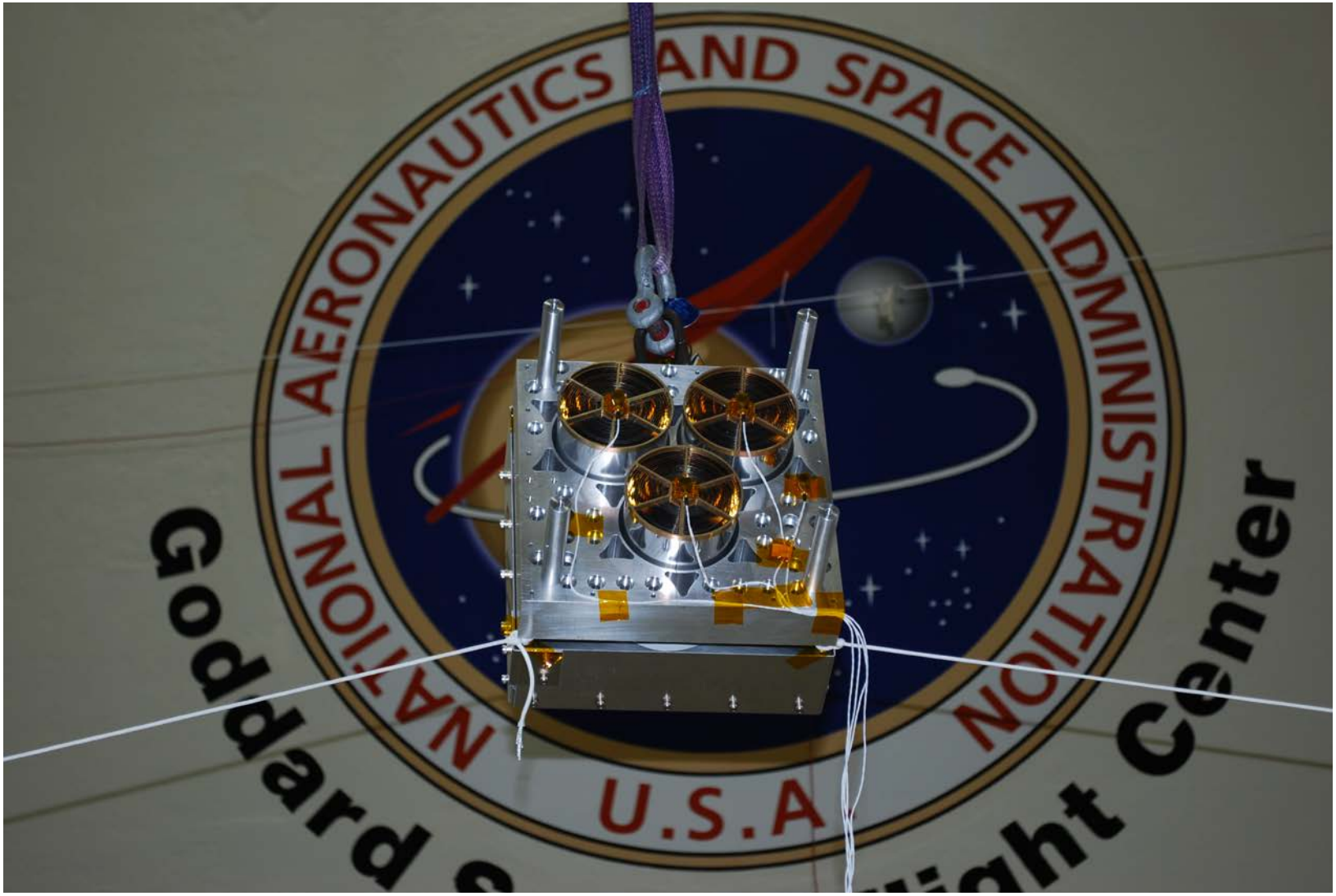
Lot's of testing at component level on prototypes and ETUs to prove out the XRC design



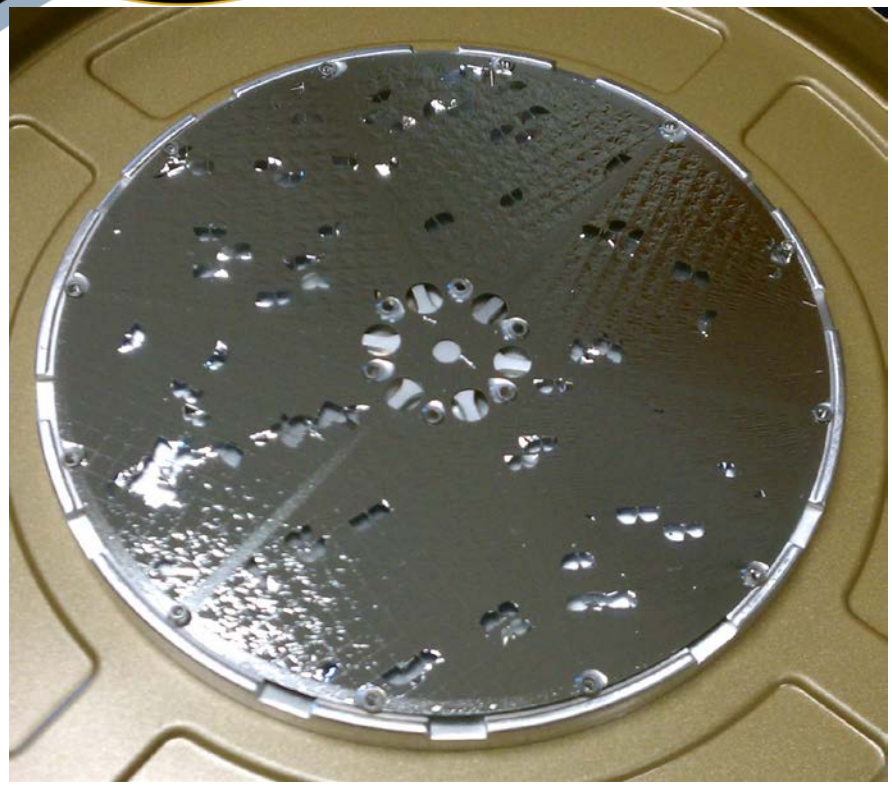


Thermal Shield installation

XRC ETU Acoustic Test



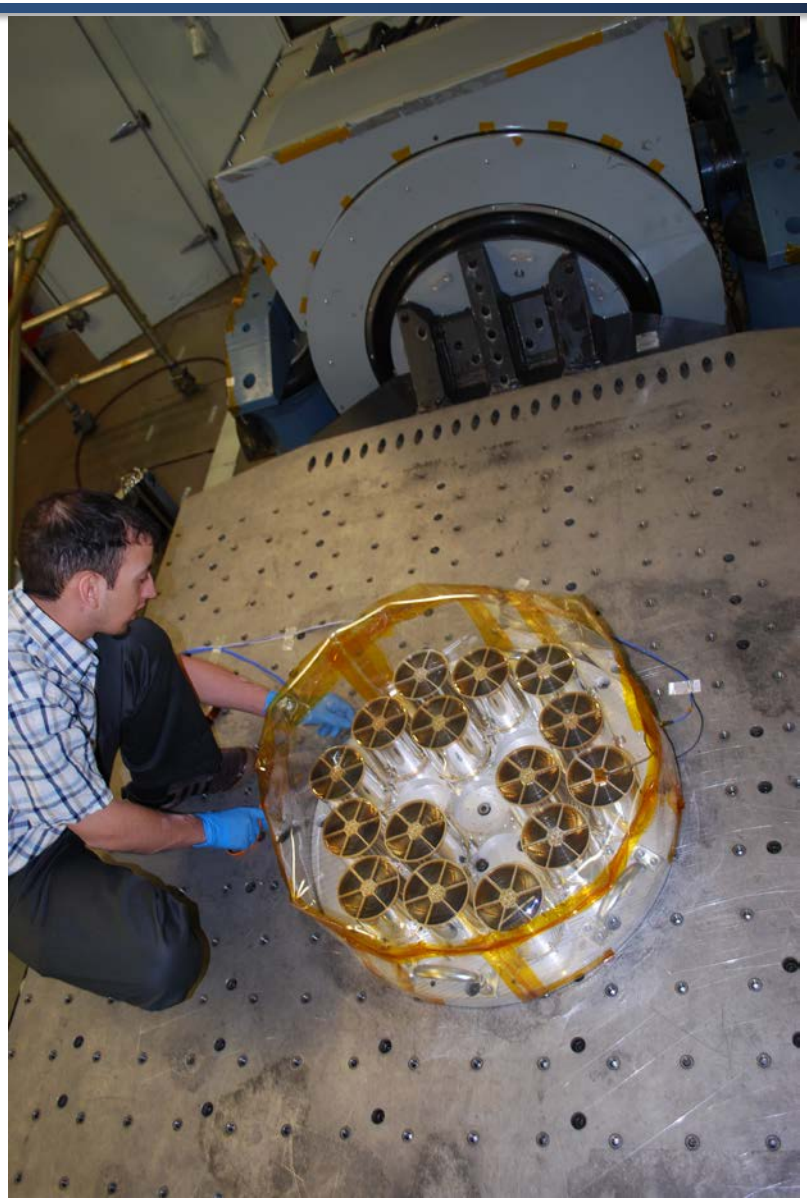
XRC Thermal Films after Acoustic



Early 120 nm film failures after acoustic testing due to poor grid quality. Worked with Materials Branch to determine root cause of failures.

Flight films with improved grids after acoustic testing.

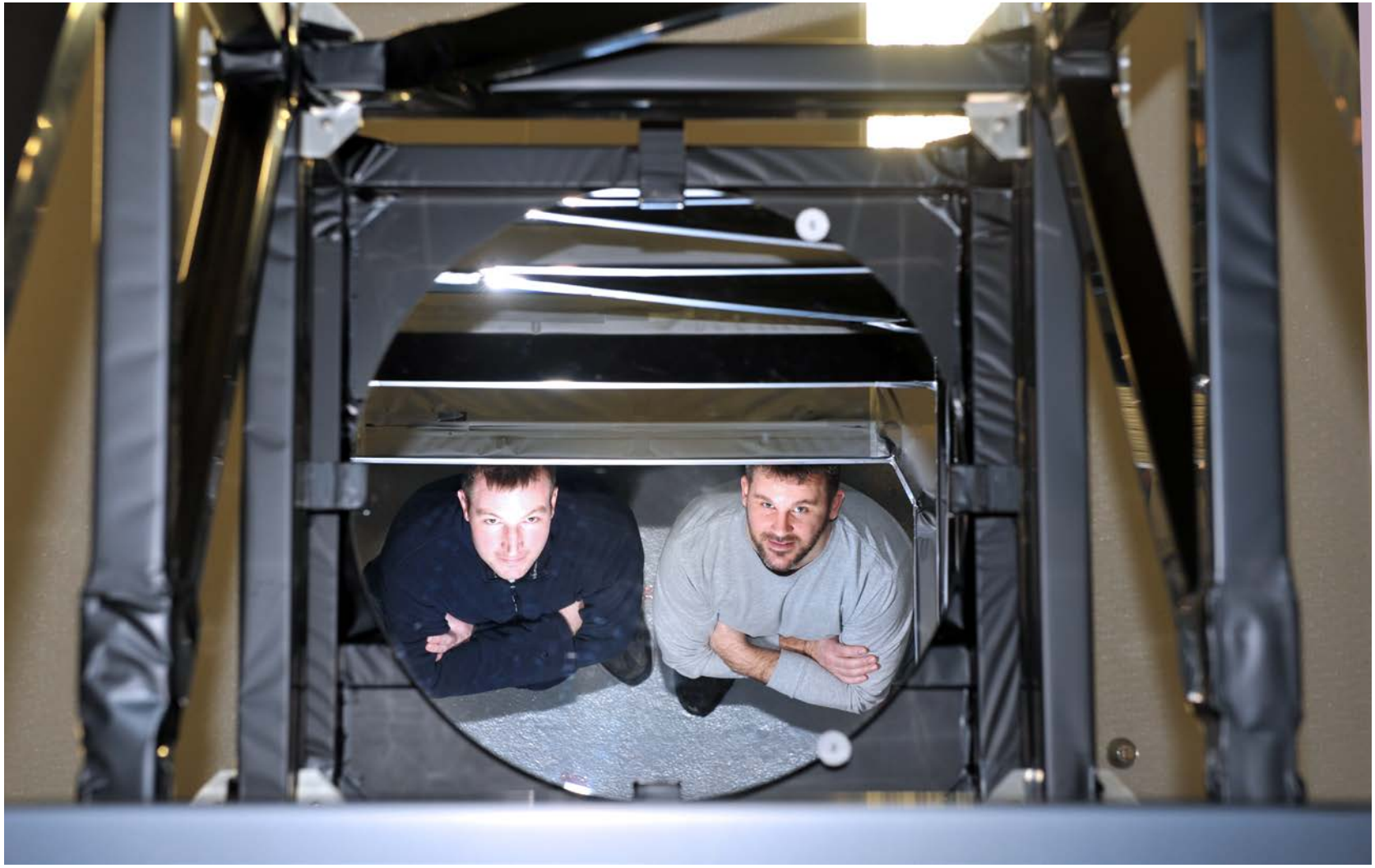
Lot Vibration Testing of Flight XRCs



Only a subset of XRCs were tested at the component level

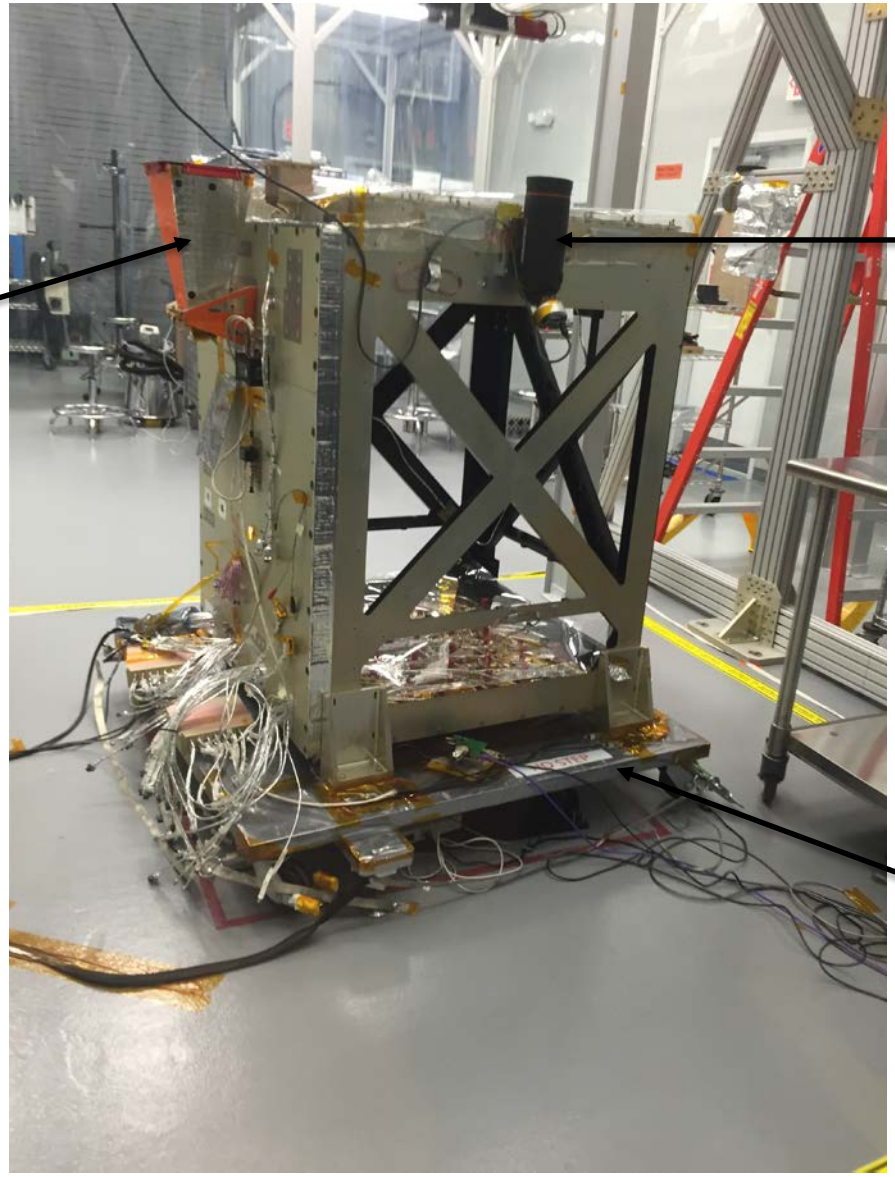
Alignment Collimator Under Construction in Building 5A

View into Collimator Mirror

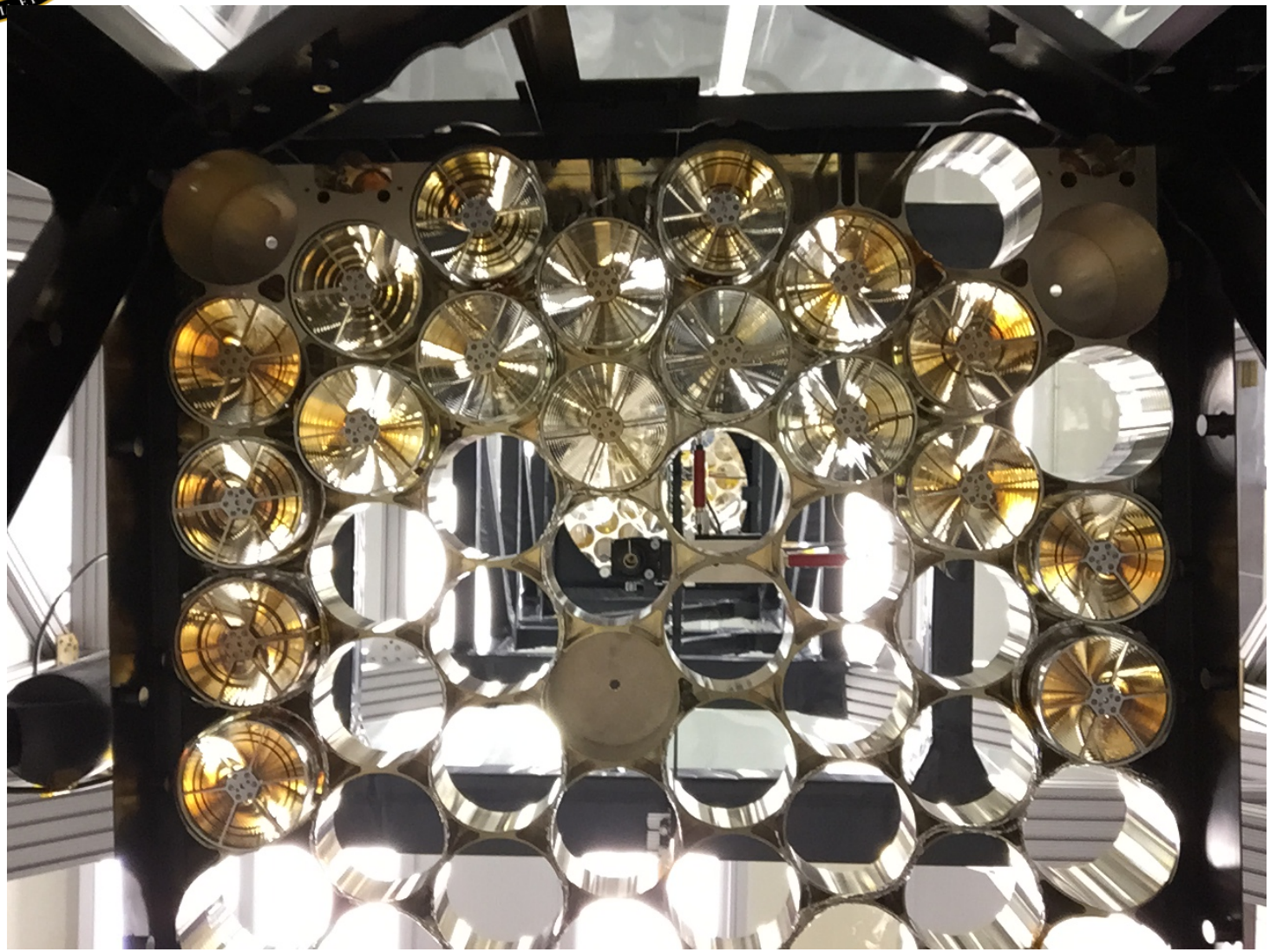


Collimator in Custom Clean Tent

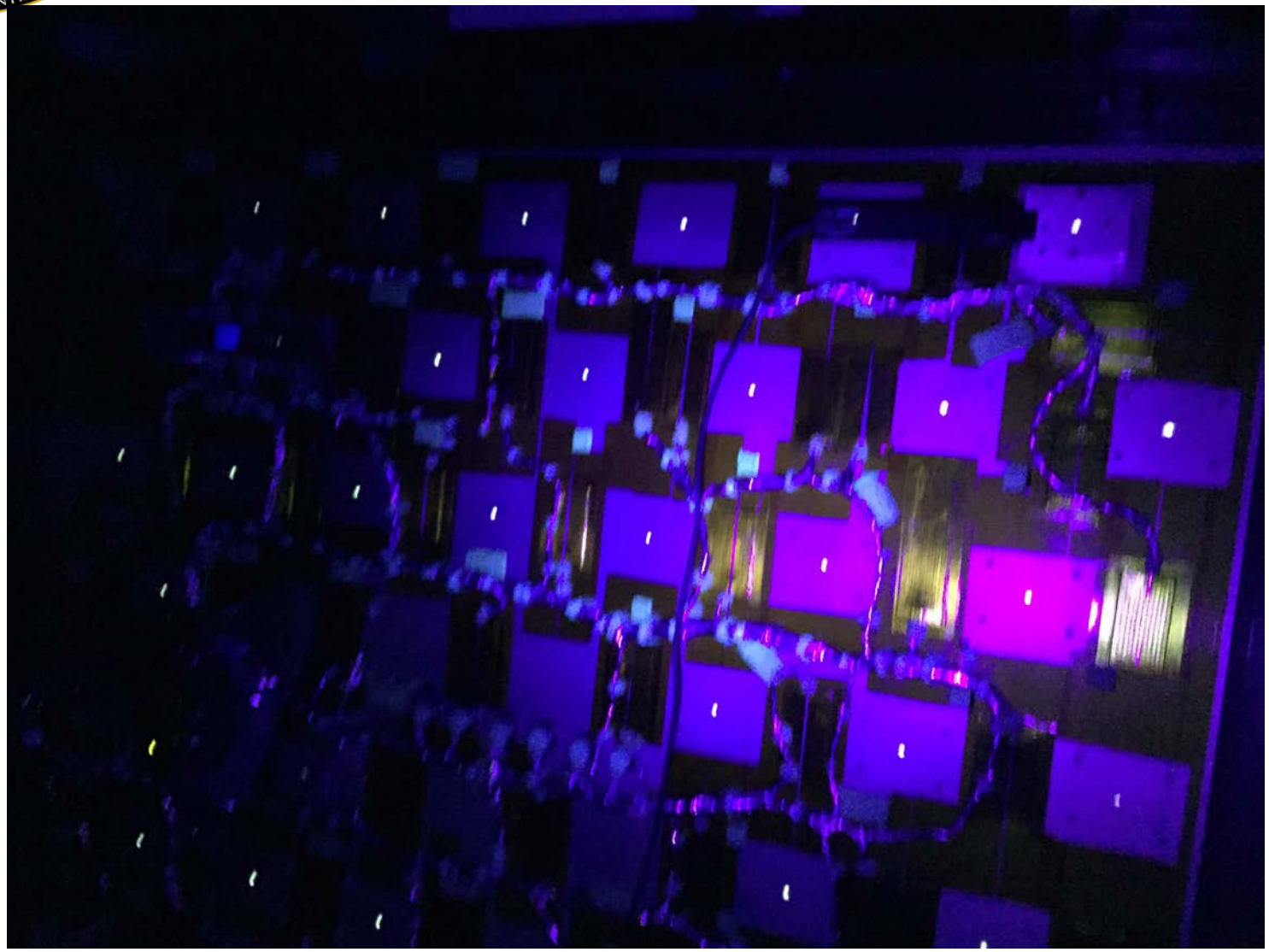
NICER XTI in the Collimator



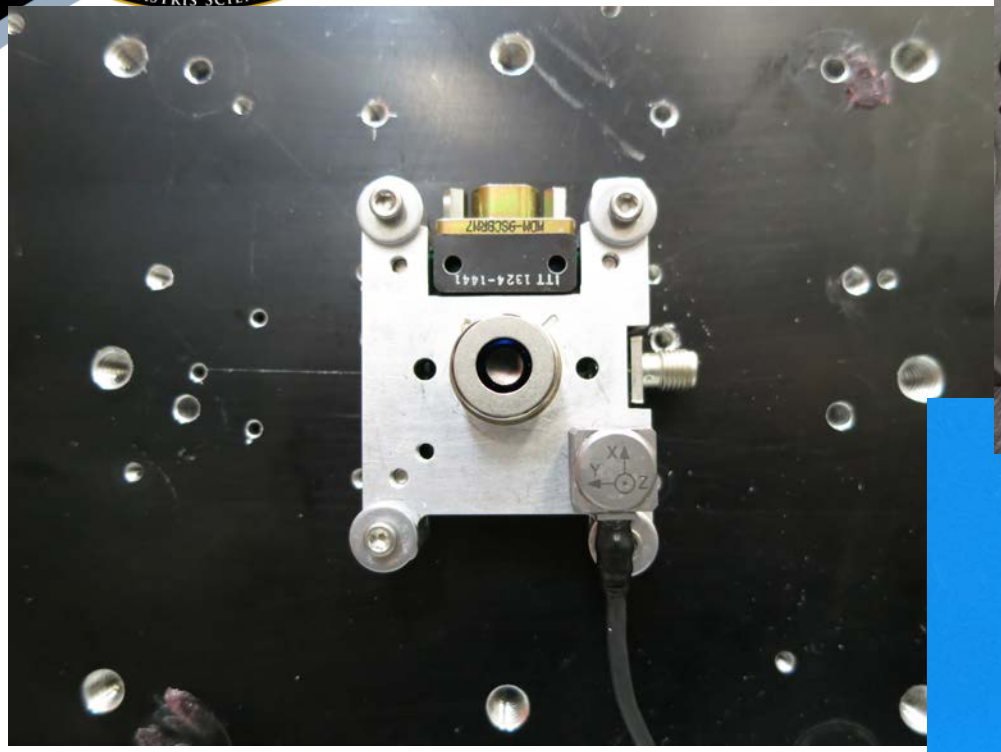
NICER View into Collimator



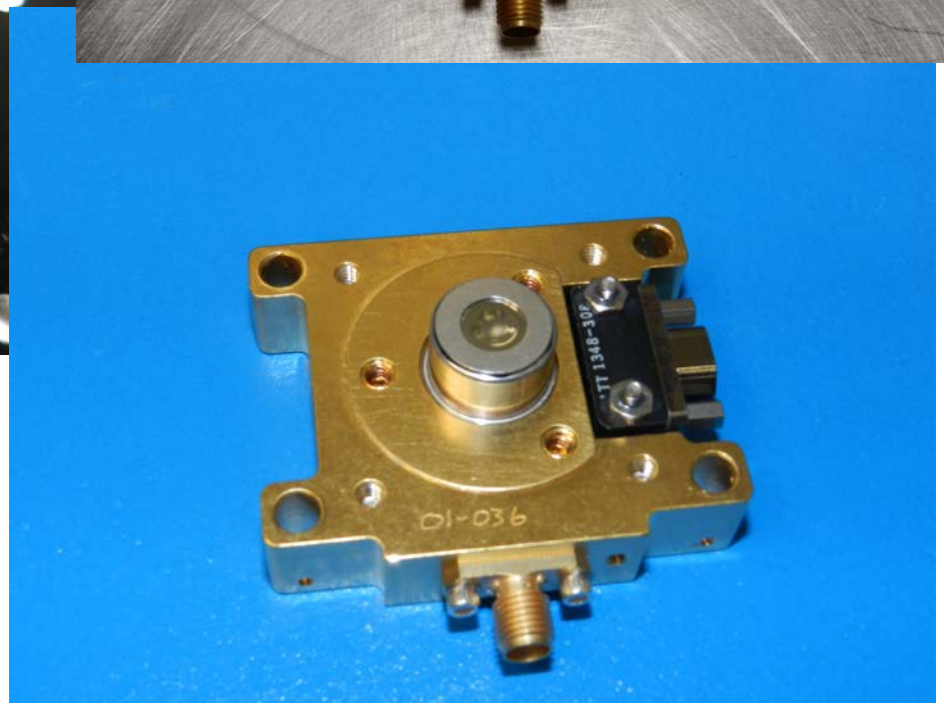
XRC Focal Points on Detector Plate



Focal Plane Modules with SDD



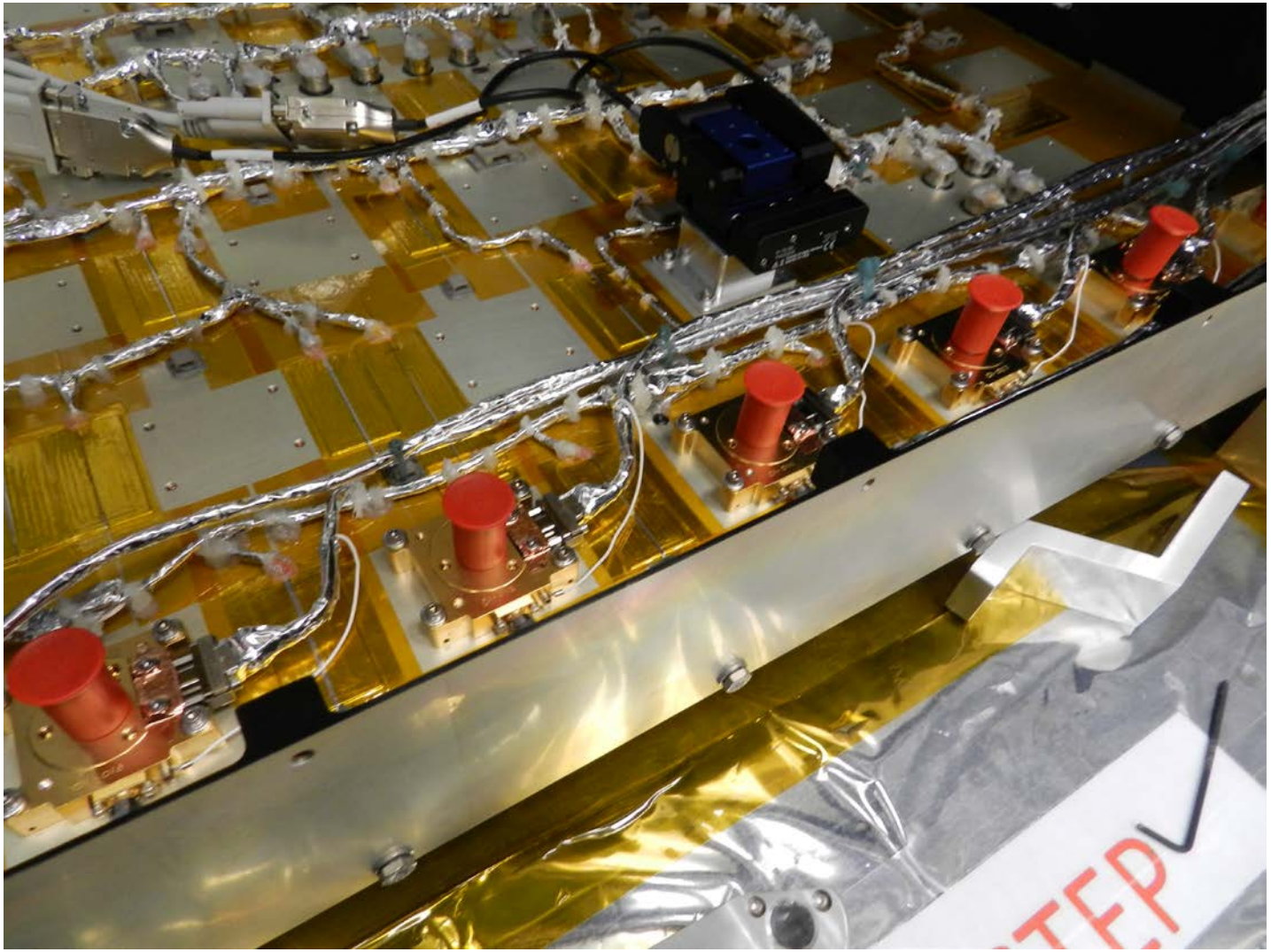
Prototype During Vibration



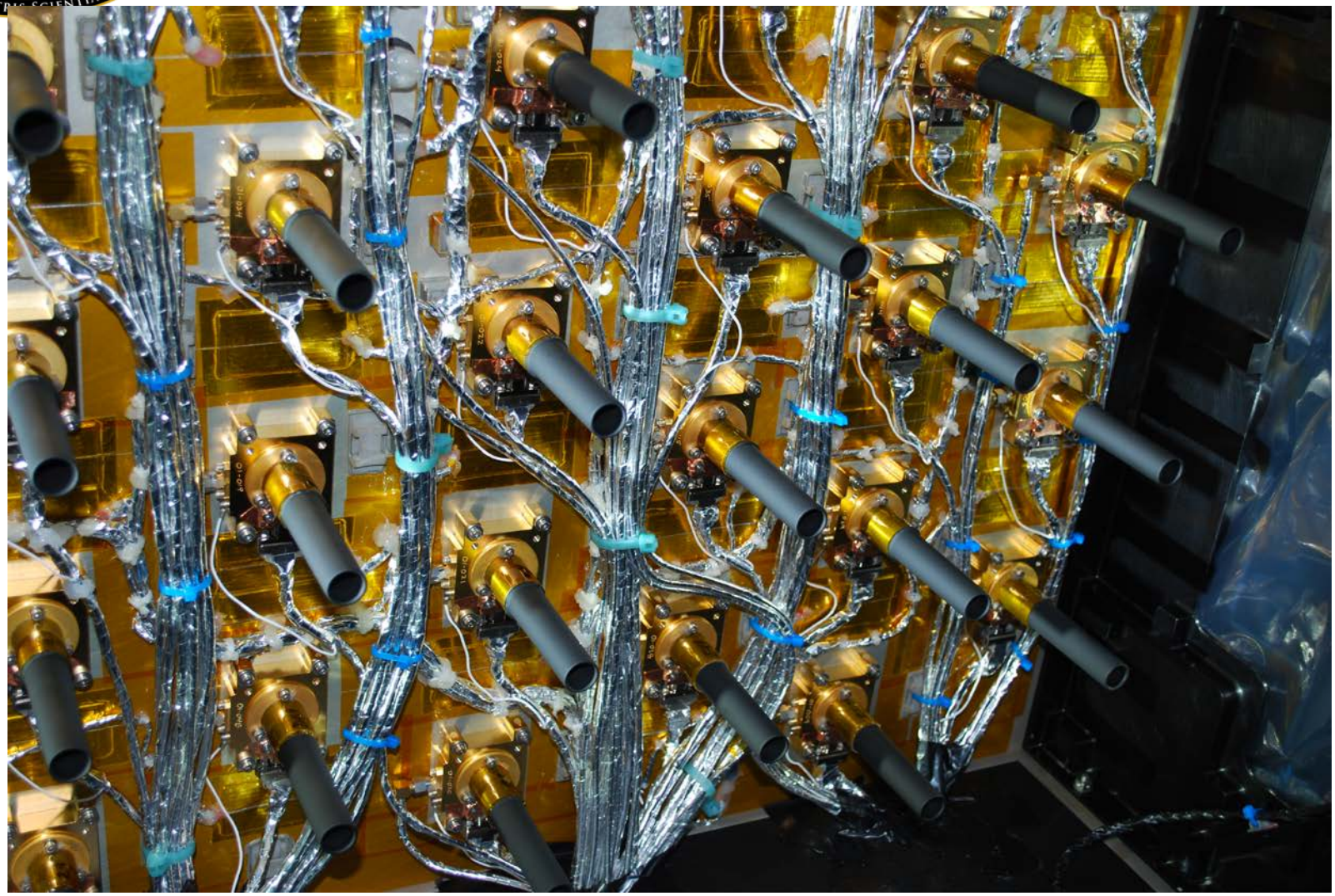
Flight FPM

FPMs used commercial Silicon Drift Detectors (SDDs) from Amptek

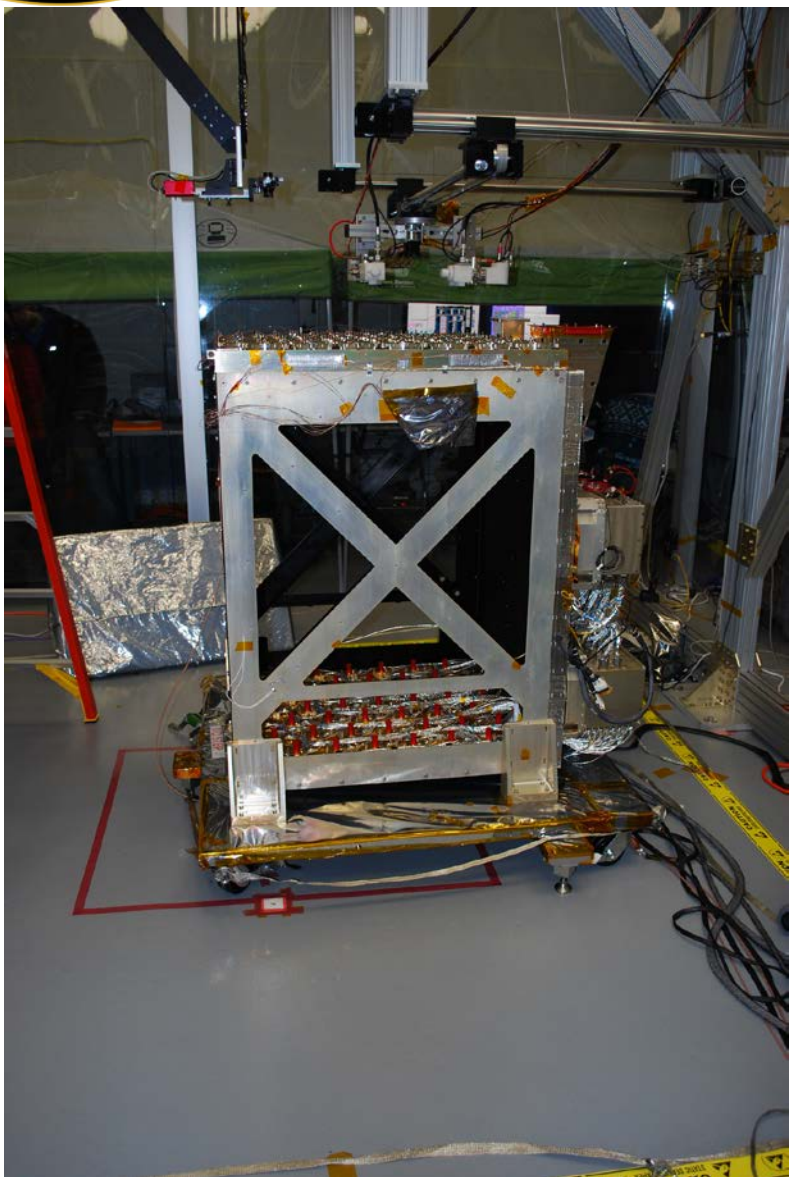
Integrating/Aligning FPMs

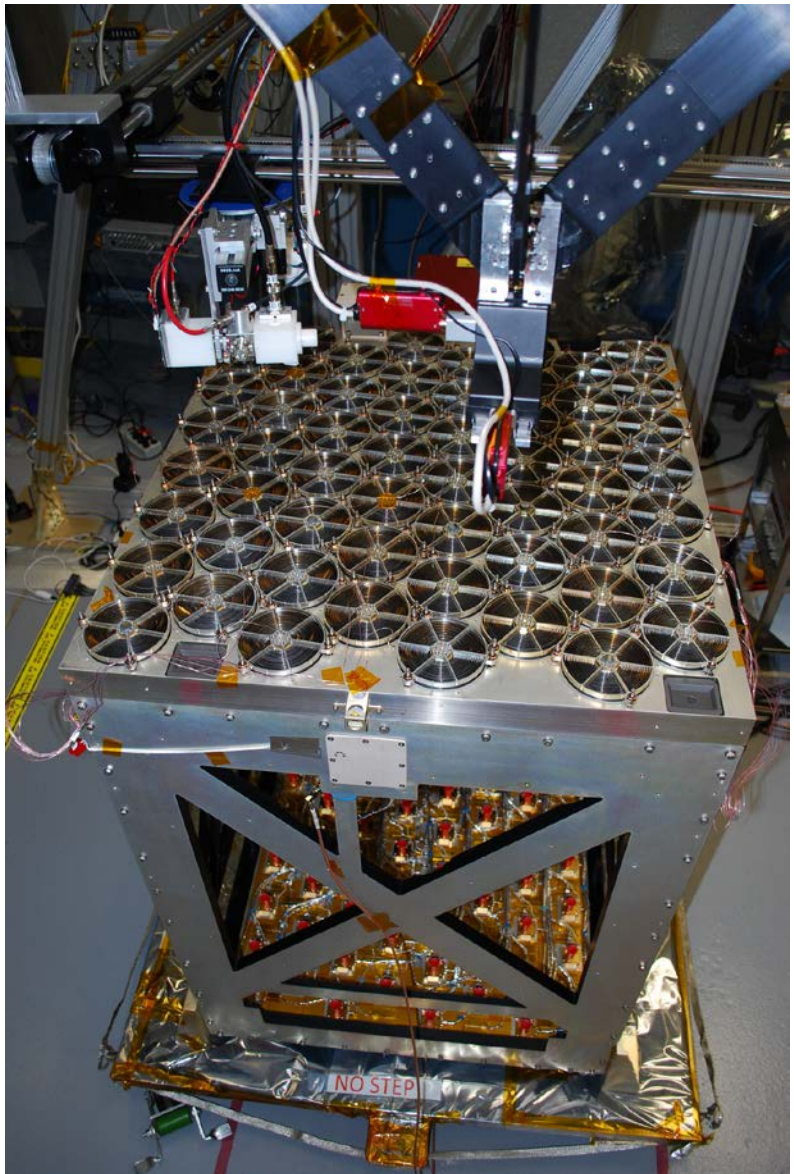


Fully Integrated FPMs

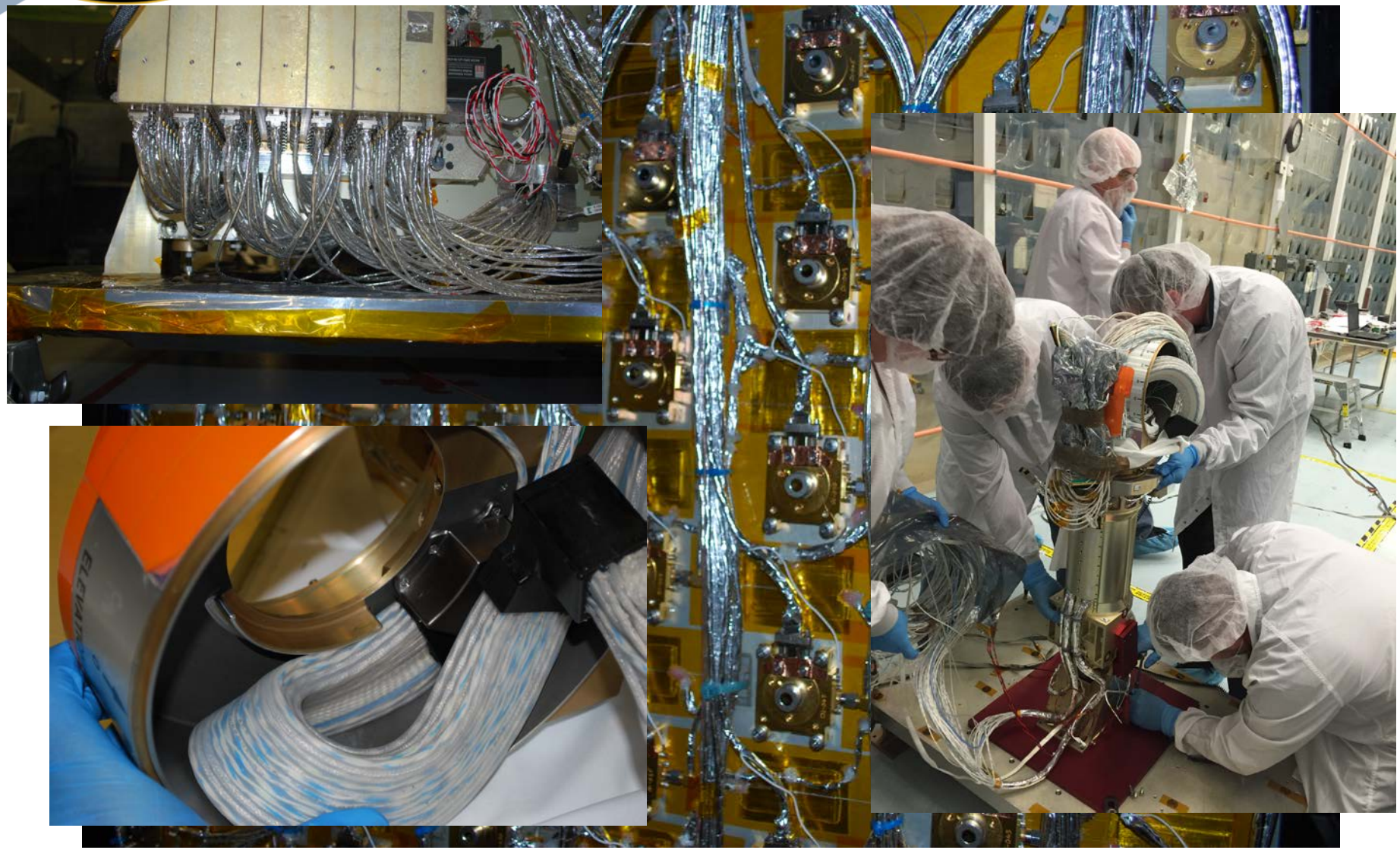


XTI with timing calibration GSE

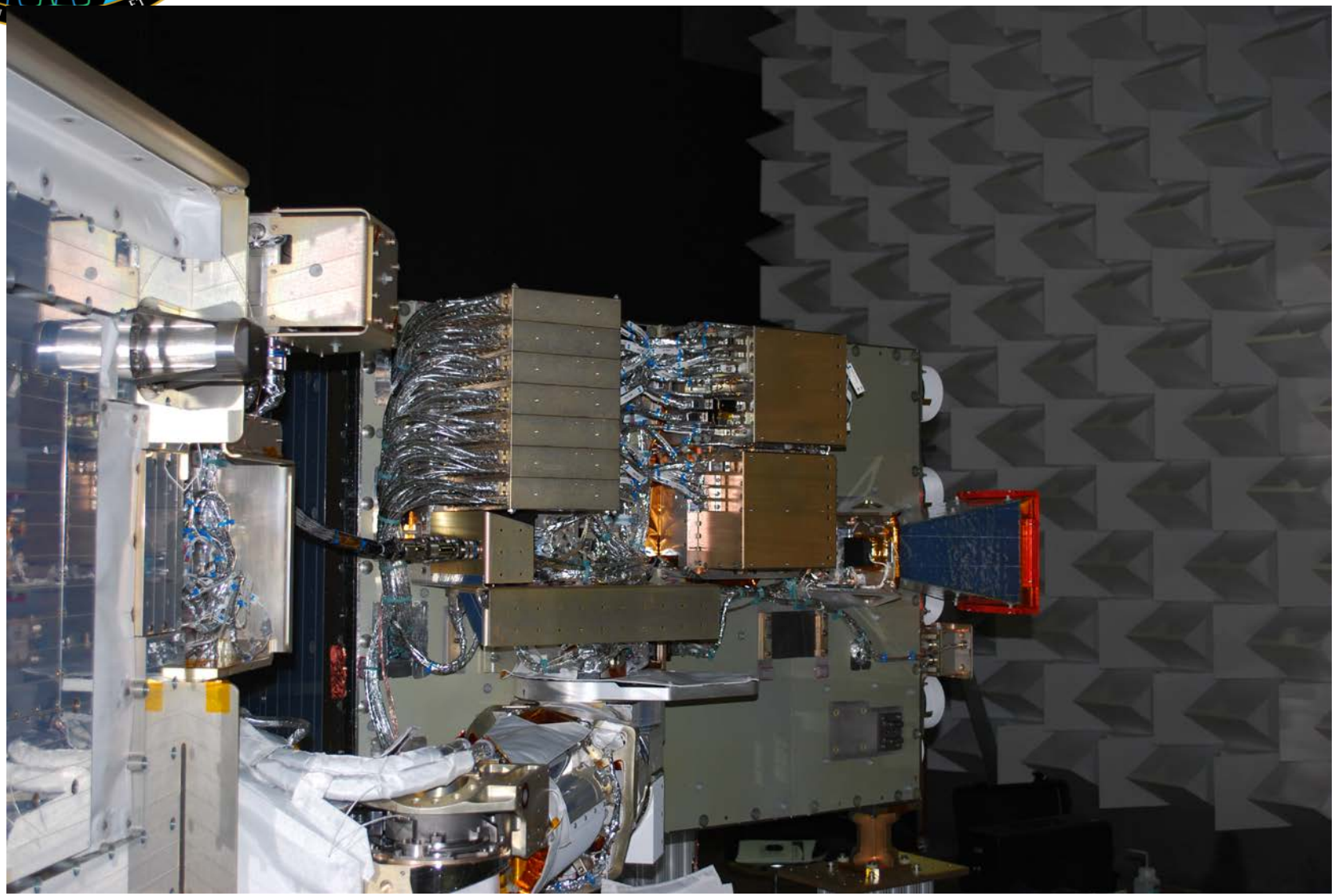




Harness Routing Takes Work and Planning



Final Harness Routing

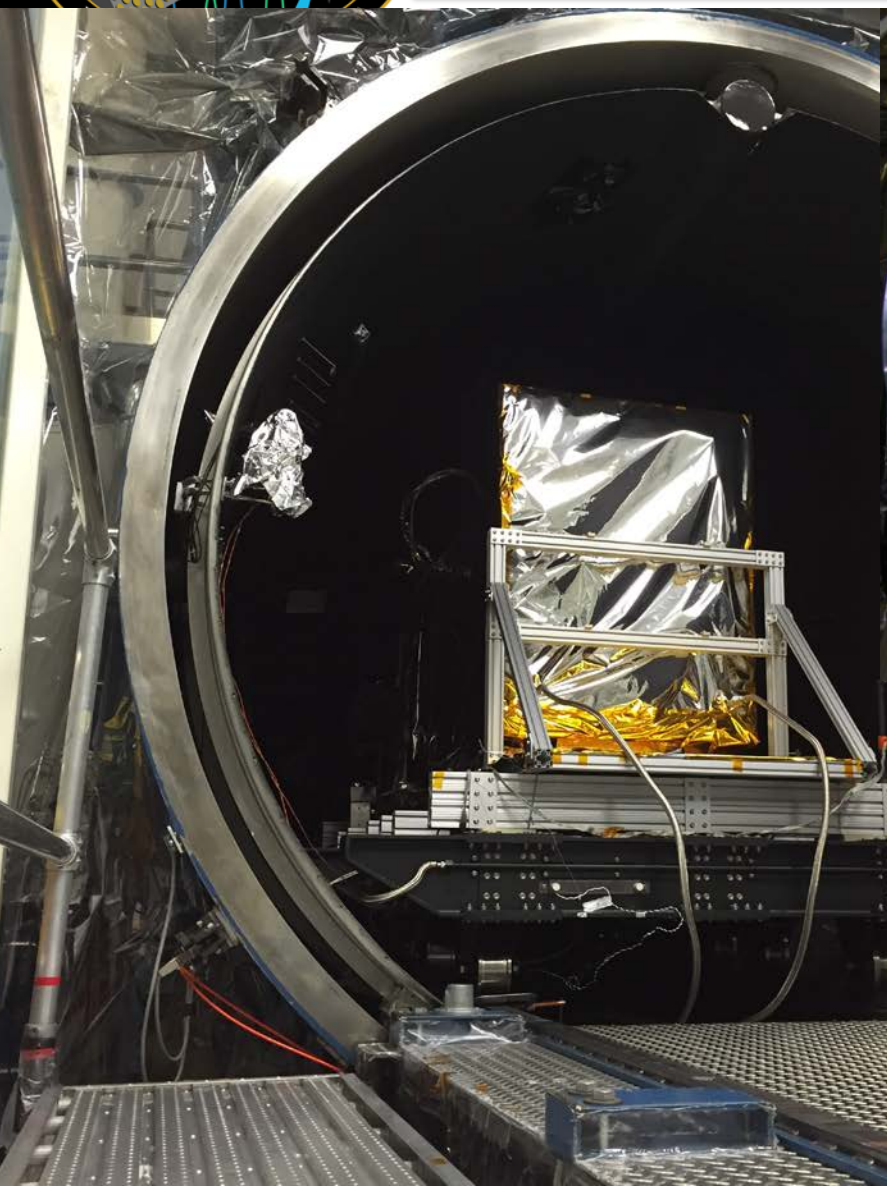


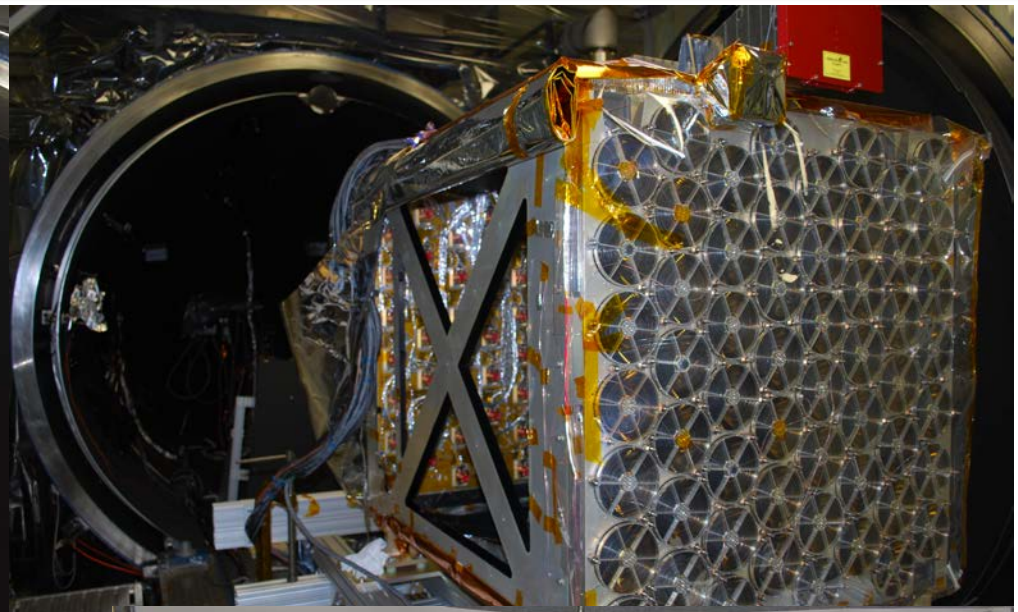
Environmental Verification Matrix Evolved Throughout the Mission

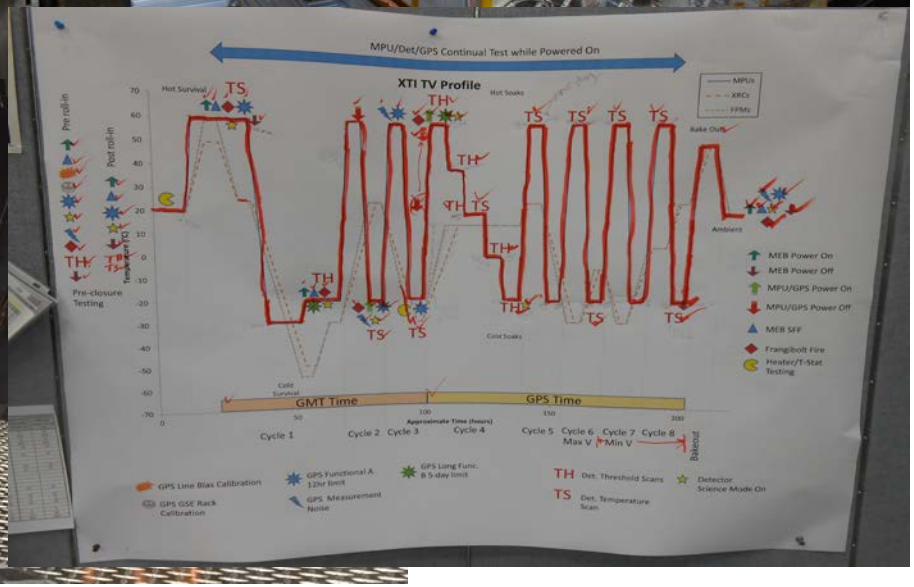
END ITEM DESCRIPTION	LEVEL OF ASSY	Unit Type	QUANTITY	FUNCTL / PERFORMANCE	STRUCTURAL ANALYSIS	THERMAL ANALYSIS	SINE BURST/ STRENGTH	SHOCK TEST	RANDOM VIBRATION	ACOUSTICS	MODAL SURVEY (1)	MASS PROPERTIES (1) (2)	EMI / EMC	MAGNETICS	THERMAL VACUUM	THERMAL BALANCE	BAKEOUT	SHARP EDGE INSP	HI-POT TEST
NICER Payload	P/L	FLT	1	X	X	X		P	P	P		X	X	X	P(16)	X	X	X	
XTI (Instrument)	I	FLT	1	X	X	X						X			X(17)		X		
Instrument Optical Bench (IOB)	A	FLT	1		X	X						X							
XRCs	A	FLT	56	X	X	X	An		P/A(13)			X							
FPM/SDD	A	FLT	56	X	X	X	An		P/A			X			P(6)				
Heaters/T-stats/T-misters	C	FLT		X		X													
MPU	C	FLT	7	X	X	X	P		P			X							
Electronics																			
MEB	C	FLT	1	X	X	X	An		P			X	X		P		X		
GPS Antenna	C	FLT	2	X			P		P			X	X		P(8)		X		
GPS Front End Electronics	C	FLT	2	X	X		An		P			X	X		P		X		
GPS Low Pass Filters	C	FLT	2	X					P			X			P				
HiPoS	C	FLT	1	X	X	X	P		P			X			P(8)		X		
EPIC	C	FLT	1	X	X	X	An		P			X	X		P		X		
Pointing System																			
GCE	C	FLT	1	X	X	X	An		P			X	X		P		X		
Tracker CHU/Bracket	C	FLT	1	X	X	X	S		P			X	X		P		X		
Tracker DPU	C	FLT	1	X	X	X	S		P			X	X		P		X		
Tracker Baffle	C	FLT	1	X	X	X	P		P			X			P(8)		X		
DAPS	C	FLT	1	X	X	X	P	X	P			X			P(9)	X	X		
Tuned Mass Dampers	C	FLT	4	X	X		An	P	P			X			P(8)				
Other Flight Hardware																			
Machined Structural Plates & Brackets	C	FLT			X	X						X							
XTI Baseplate (Al Honeycomb)	A	FLT	1		X	X	P(10)					X							
Electrical Harness	C	FLT		X		X						X					X		X
XRC Thermal Film/Mesh	C	FLT	56		X	X						X							
Sunshades	C	FLT	56		X	X	P					X					X(5)		
Electronics Decks/PCM Panels/Flexures	C	FLT	2	X	X	X	An/P					X			P		X		
SDD Shields (Traffic Cones)	C	FLT	56		X	X						X					X(5)		
Frangibolt Actuator & Bolt	C	FLT	4	X	X	X	X	X				X							
Thermal Blankets	C	FLT				X						X					X		
Structural Verification Unit (SVU)	P/L	Mixed	1		X	X	Q	Q	P	P	X				X(15)				
IOB	A	ETU	1		X	X					X								
XRCs	A	ETU	7		X	X			X										
FPM/SDD	A	ETU	1		X	X													
Sunshades	C	ETU	3		X	X													
XRC Thermal Film/Mesh	C	C	3		X	X													
Adapter Plate	C	FLT	1		X	X													
EPIC Chasis w PCB/relay	C	ETU	1																
Launch Lock Tower & V-guide	A	FLT	4	X	X	X		X				X							

Qualified at Component Level Only

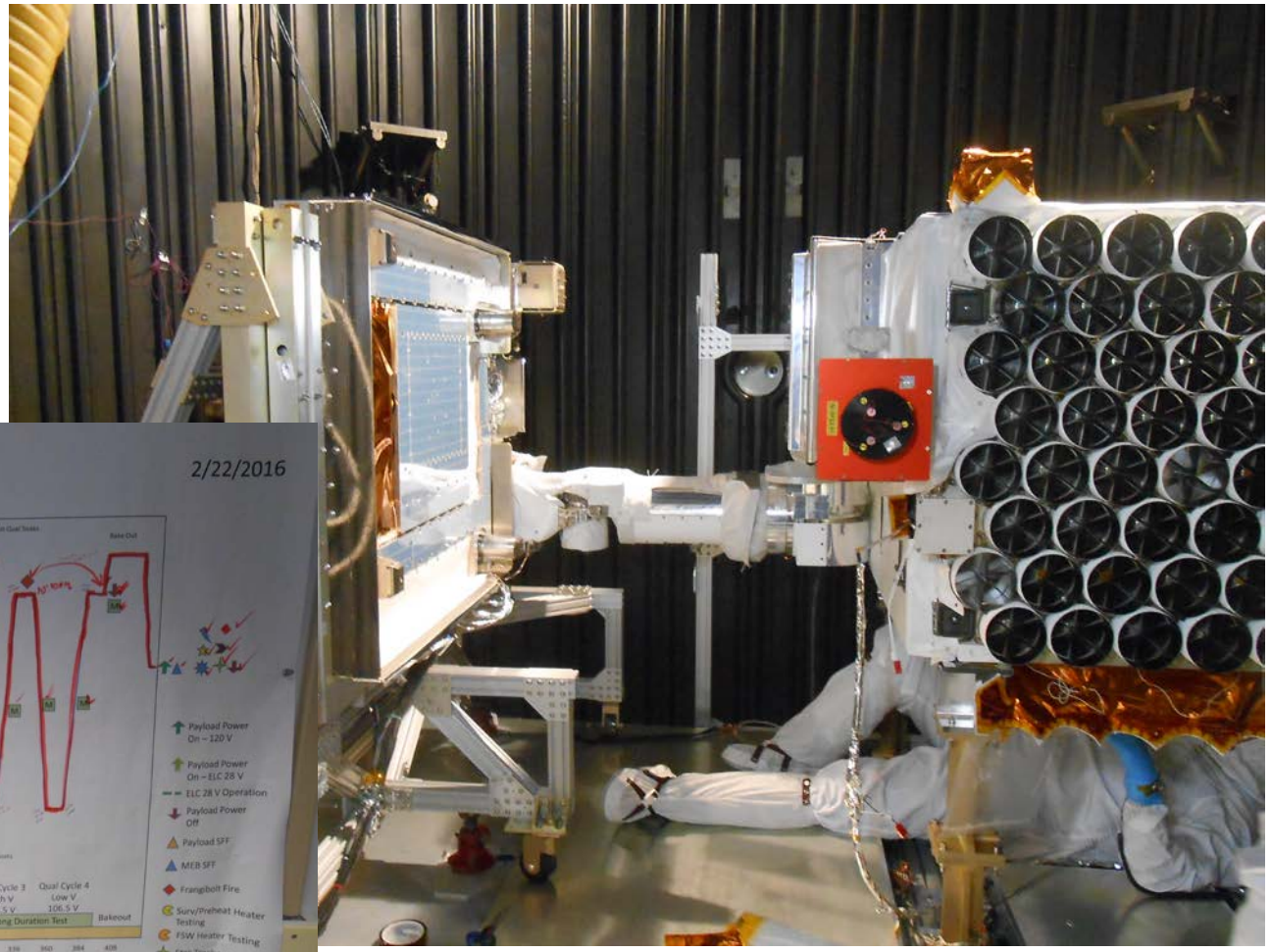
XTI Tvac Testing

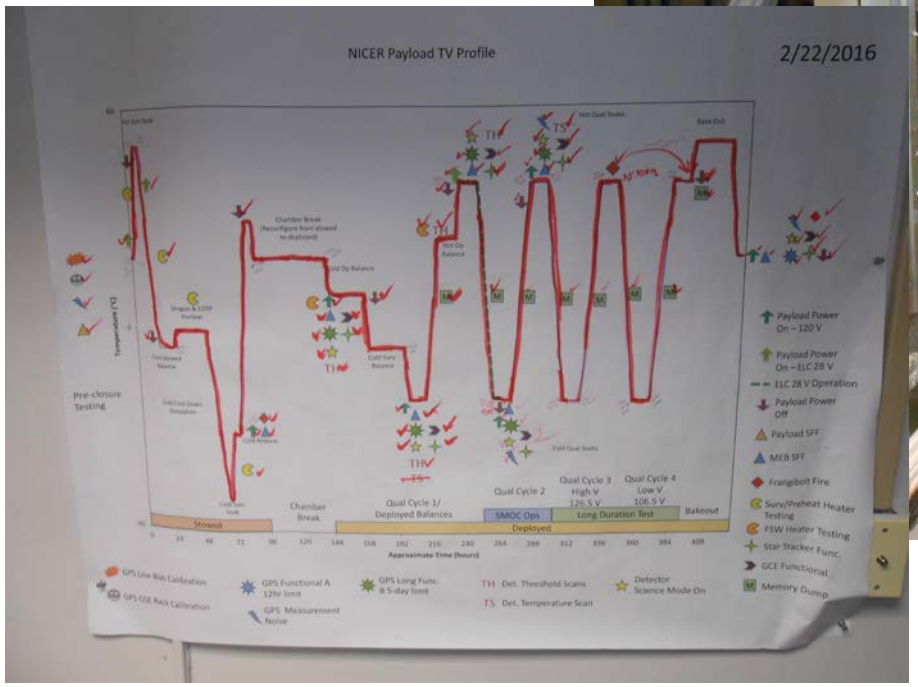




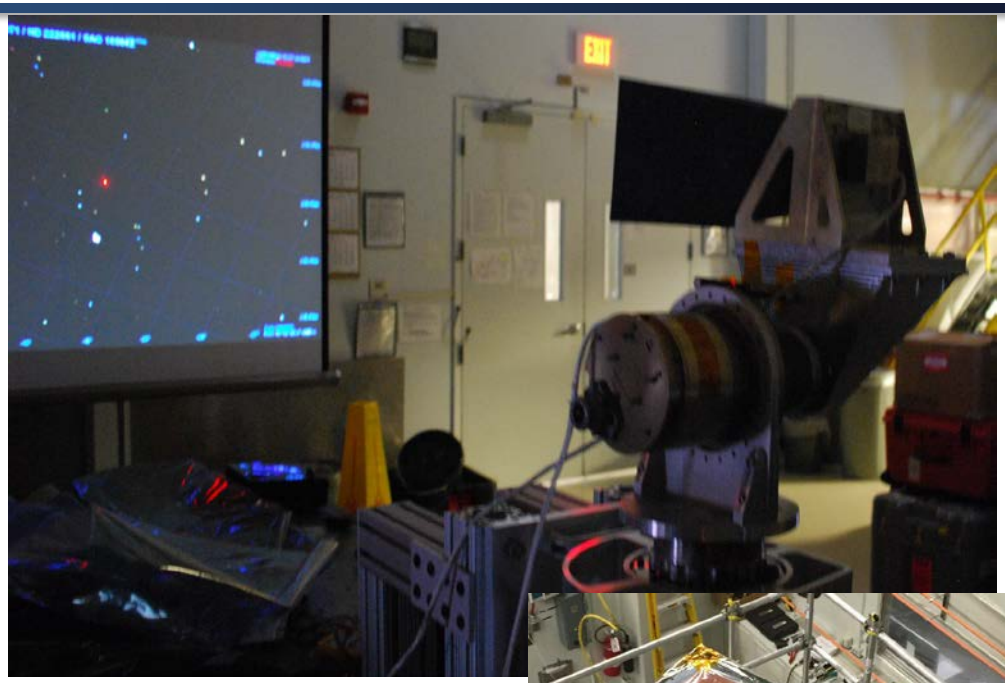


Payload Tvac Testing

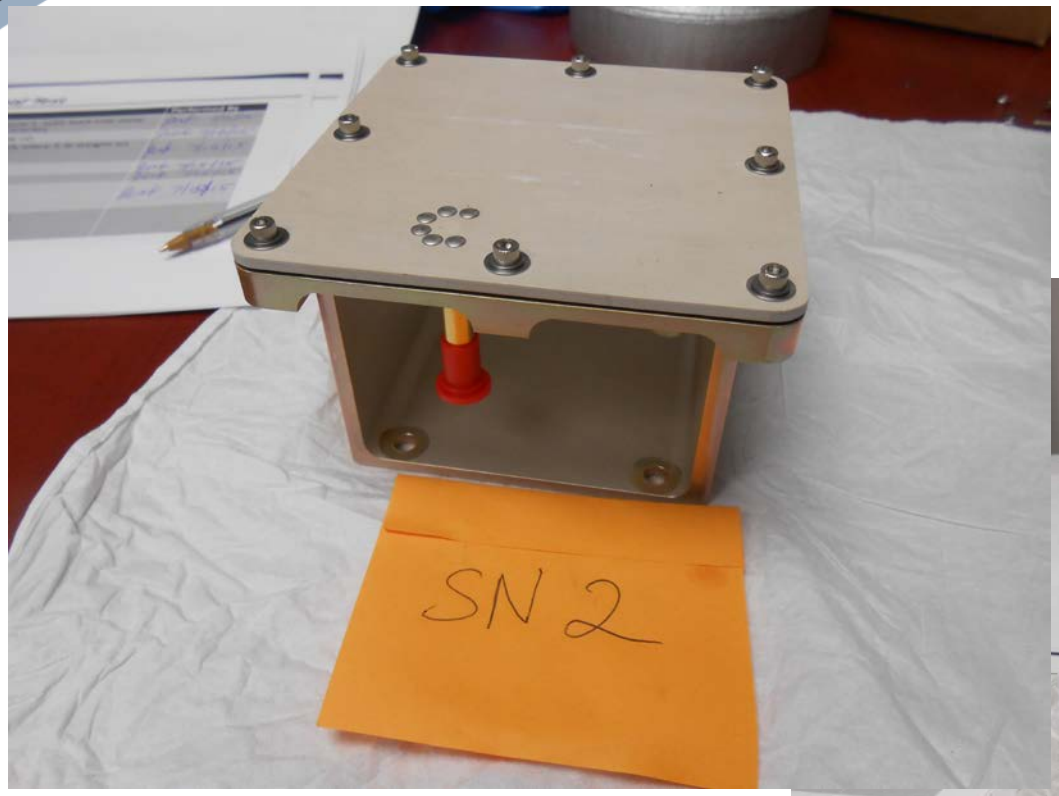




DAPS/Pointing System Testing



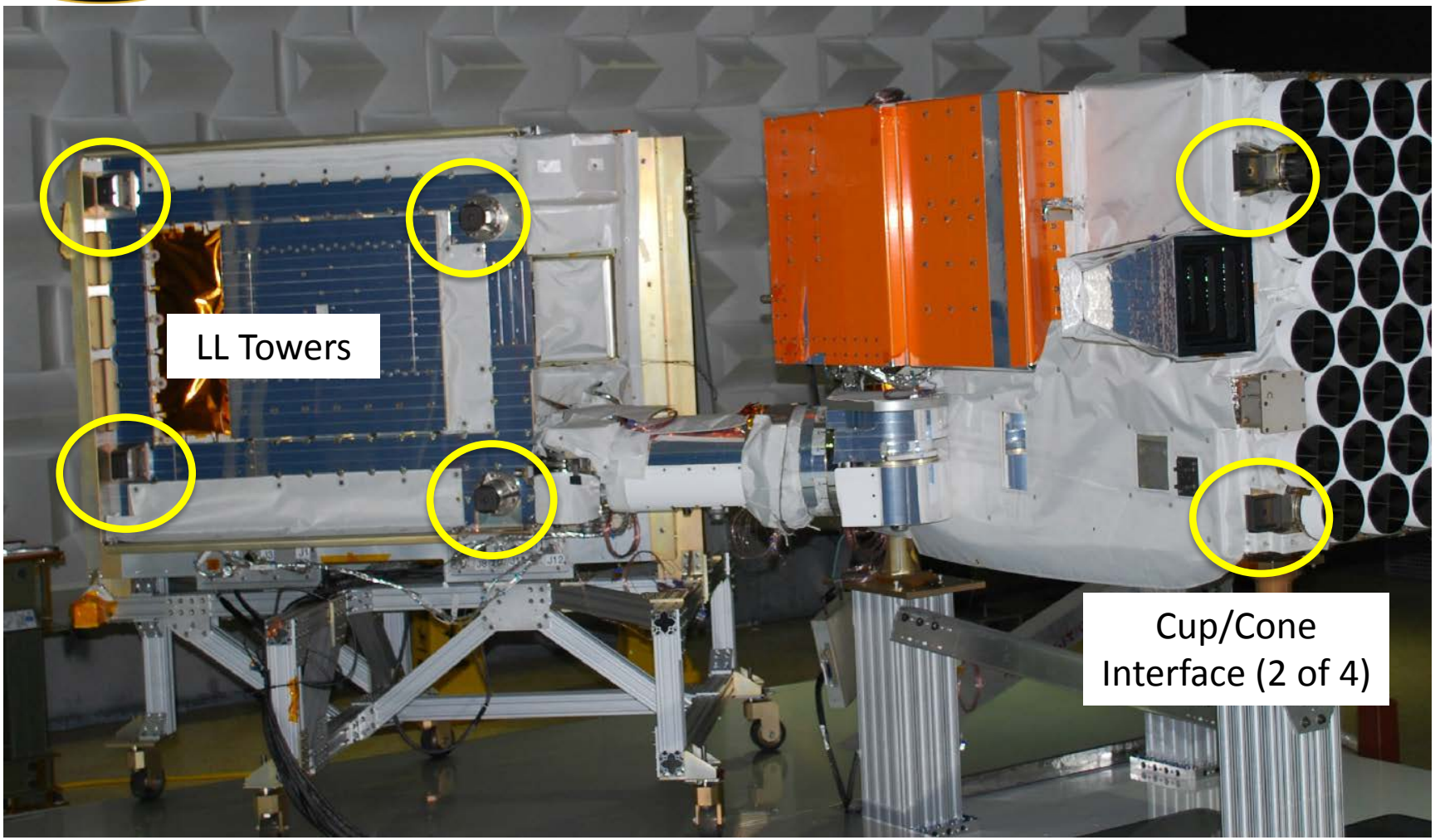
Class D Proof Test, GPS Antenna



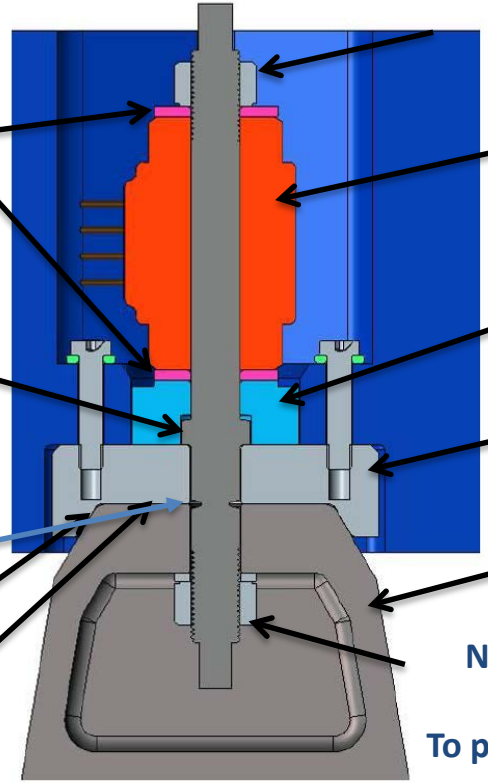
NICER Class D GOLD Rule Process

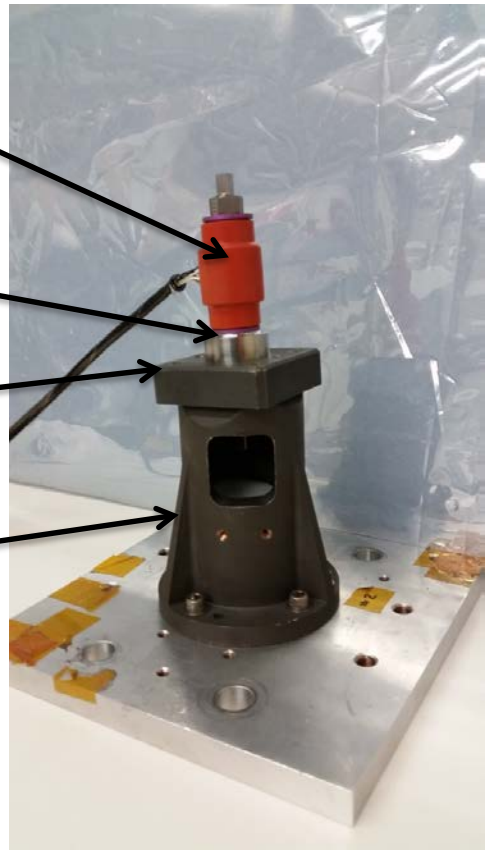
- GOLD Rules evaluated per GSFC-STD-1000, Rev-F
- A compliance matrix was generated and maintained
  - Identified applicable rules and their compliance
  - Identified required waivers
- All waivers were written up as Powerpoint presentations, official waiver forms not used
- Obtained Rule Owner concurrence for all waivers and had all waivers reviewed by the AETD Chief Engineer
- GOLD Rule waivers approved at the NICER project level, no waiver submission through codes 300, 400 or 500

Frangibolt Launch Locks Close Call



Launch Lock Design (4 places)



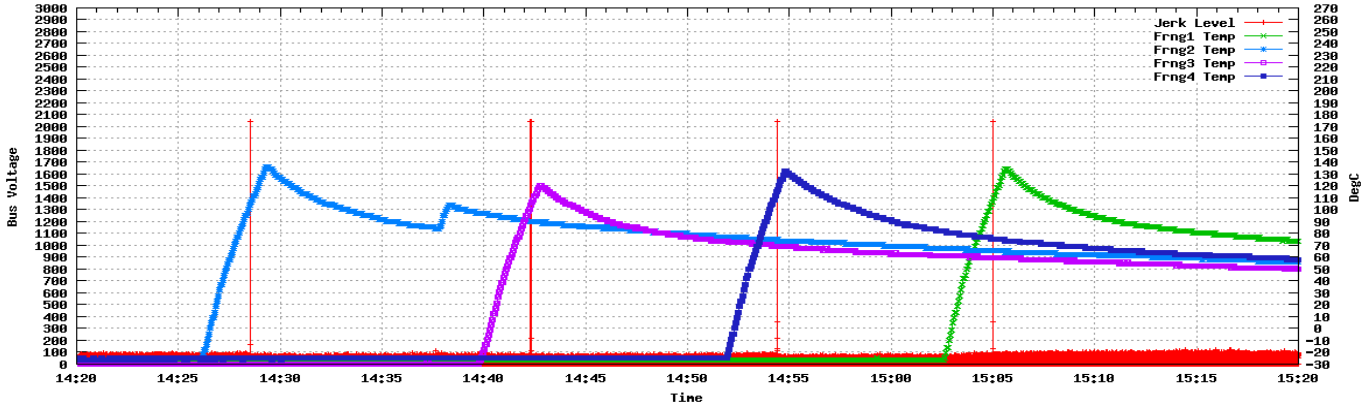


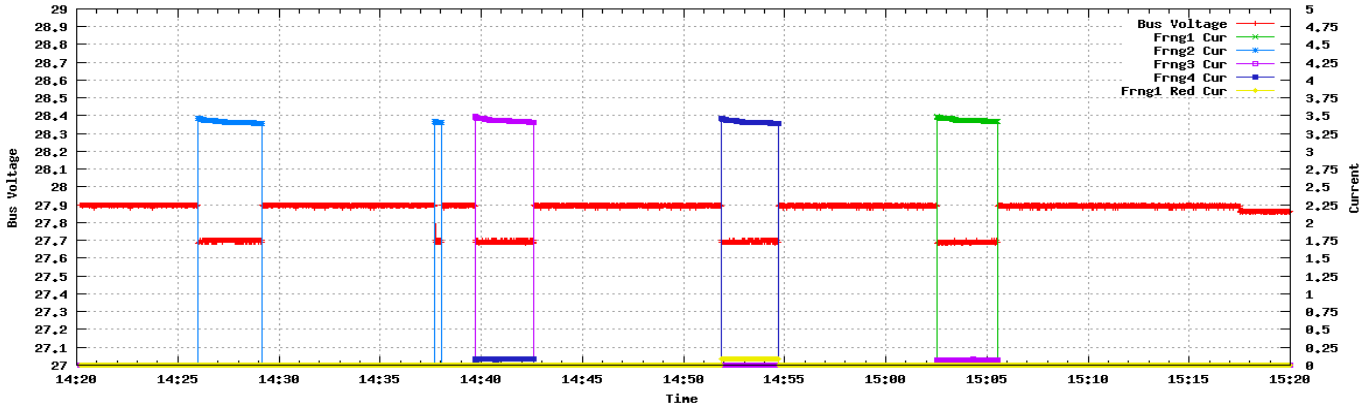
Unique feature of this design: The NICER design removes the Frangibolt actuator from the primary load path by use of the bolt shoulder and collar. This was done to prevent joint gapping as the actuator rated limit was well below the external loads from launch vehicle and the actuator tests showed permanent compression of actuator after gapping in standard implementation.

Successful Frangibolt actuation from Flight Payload Thermal Balance

- Note the they all have the characteristic long cool down

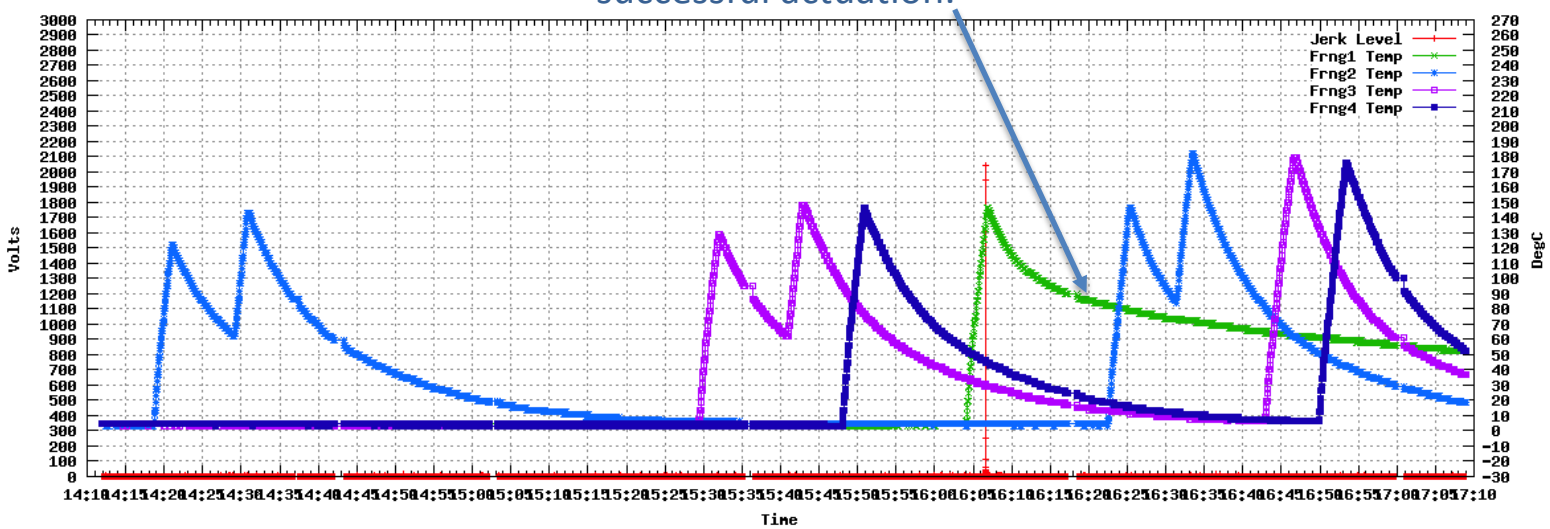
nch Locks

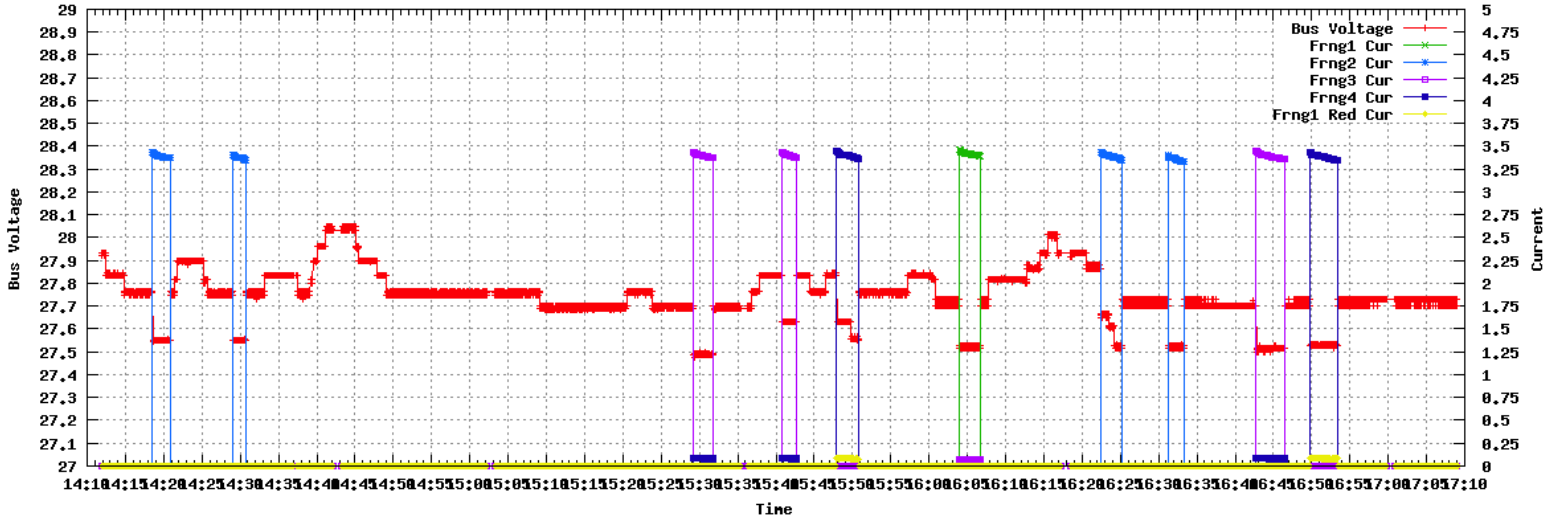




Flight Frangibolt Telemetry showing only FB1 with successful Actuation

Note: Only Frangibolt 1 shows characteristic long cool down time representative of successful actuation.

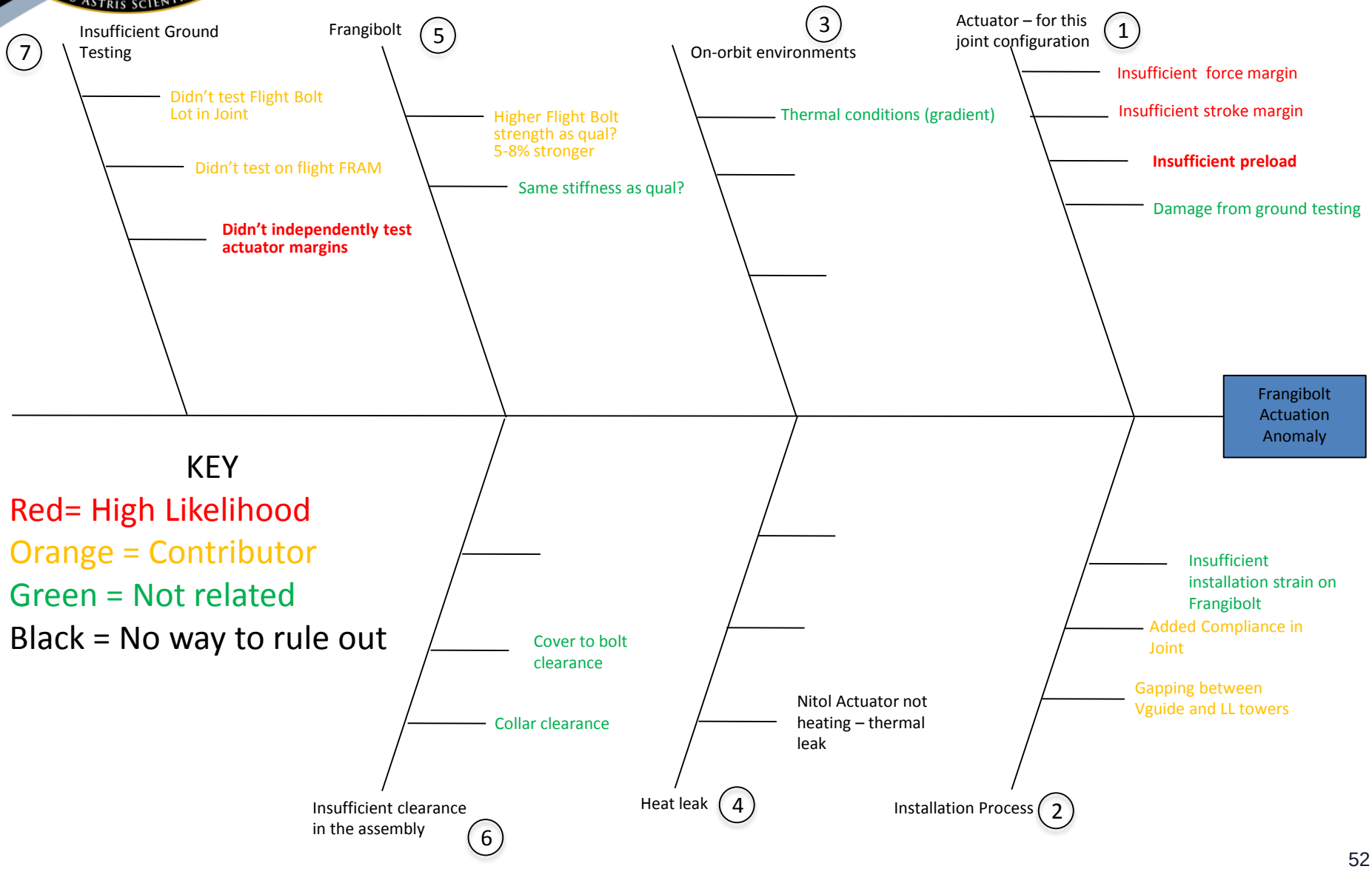




What We Did to Address Problem?

- Held telecon with TiNi and GSFC team later that day, developed the following recommendations:
  1. Heat baseplate as high as possible to minimize heat leaks
  2. Start with bolt as cold as possible (mutually exclusive with #1)
  3. Go to higher temperature in case there is a heat leak
  4. Keep cycling, fatigue may cause the bolt to fail (Len Wang recommendation)
- Overnight the ops team continued to cycle the frangibolt actuators.
  - Warmed baseplate to 30 C to minimize any thermal leaks.
- Frangibolts 2 and 3 successfully fired when cycled up to ~180 C
  - Both after 6 total cycles (3 cycles after temp changes made)
  - Determination made based on thermal cooldown profile
  - MIRU accel turned off due to temperature concerns with base plate at 30C
- Frangibolt 4 fired after 23 thermal cycles

Frangibolt Anomaly Fish Bone



KEY

Red= High Likelihood

Orange = Contributor

Green = Not related

Black = No way to rule out

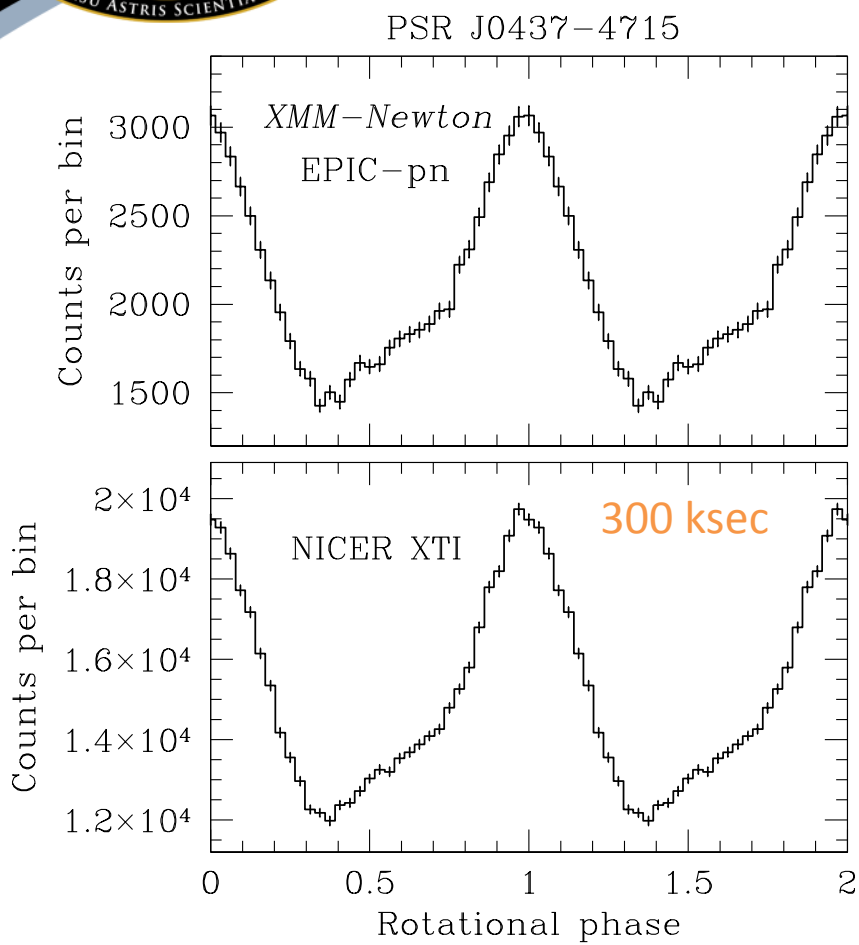
Frangibolt Anomaly Fish Bone Summary

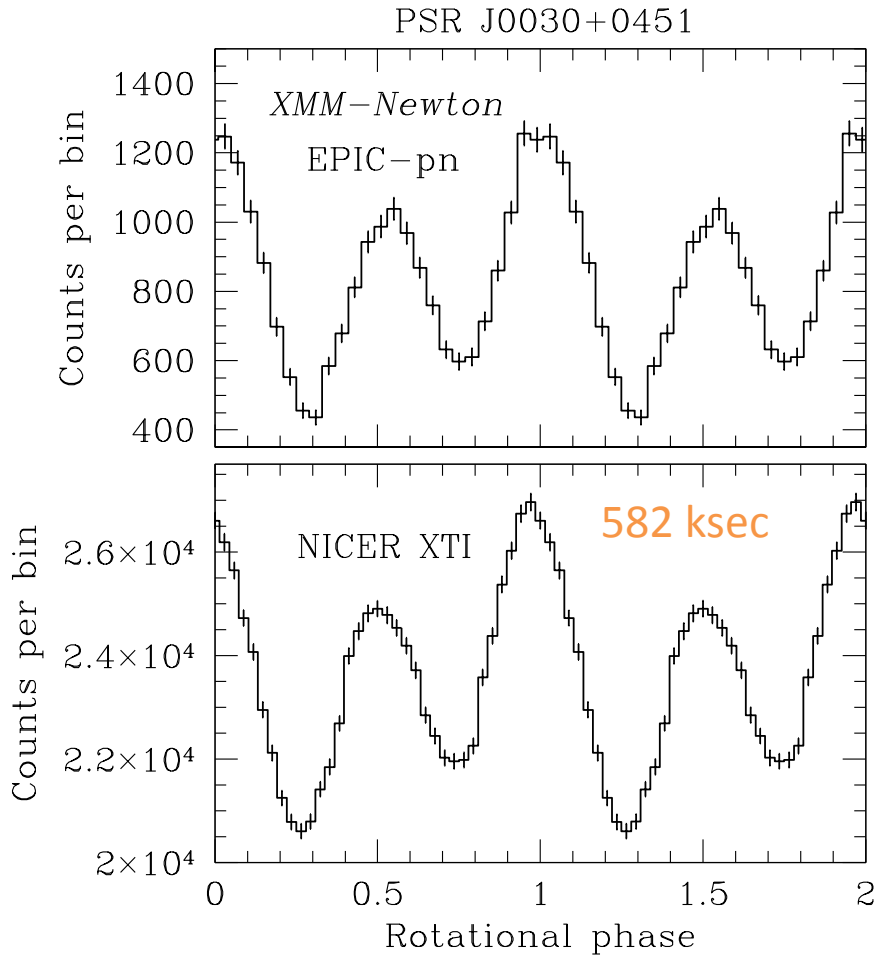
1. Actuator for this joint configuration	
Insufficient force margin	Actuation Margins Highly Dependent on Actuator Preload
Insufficient stroke margin	Actuation Margins Highly Dependent on Actuator Preload
Insufficient Actuator Preload (not bolt)	Actuation Margins Highly Dependent on Actuator Preload
Damage from ground testing	Dimensions from delivery to flight all within specifications - TINI verified not a concern
2. Installation Process	
Insufficient Installation Strain on Frangibolt	GSFC Bolt Strain same as TINI standard design across grip length, different distribution however
Added Compliance in Joint	Imperfect mating between v-guide and tower likely due to redundant boundary and imperfect FRAM
Gapping Between Vguide and tower	Imperfect mating between v-guide and tower likely due to redundant boundary and imperfect FRAM
3. On-Orbit Environments	
Thermal conditions (gradient)	Thermal Conditions were in family with ground tests
4. Heat Leak	
Nitol Actuator not being heated due to heat leak	Possible, but seems unlikely due to happening to all 4. Never a problem noted on ground tests.
5. Frangibolt	
Higher Flight bolt strength	Flight Lot was 5-8% stronger than qual lot, this contributed to reduced margins
Same stiffness as qual	Flight Low stiffness nearly the same as qual.
6. Insufficient Clearance in the Assembly	
Cover to bolt Clearance	Clearance verified to be 0.20" from assembly stackup
Collar Clearance to Bolt Shoulder	Measured clearance is 4.4X required clearance to fracture bolt. 0.042" vs 0.0095"
7. Insufficient Ground Testing	
Didn't Test Flight Bolt Lot In Joint	Not a cause, but would likely have shown the issue on the ground
Didn't Test on Flight FRAM	Not a cause, but would likely have shown the issue on the ground
Didn't Independently Test Actuator Margins	A properly designed test would have likely identified inadquate actuator margins for this joint.

Modeling surface emission to infer M-R

Gravitational light-bending saves the day!

Early NICER lightcurve results

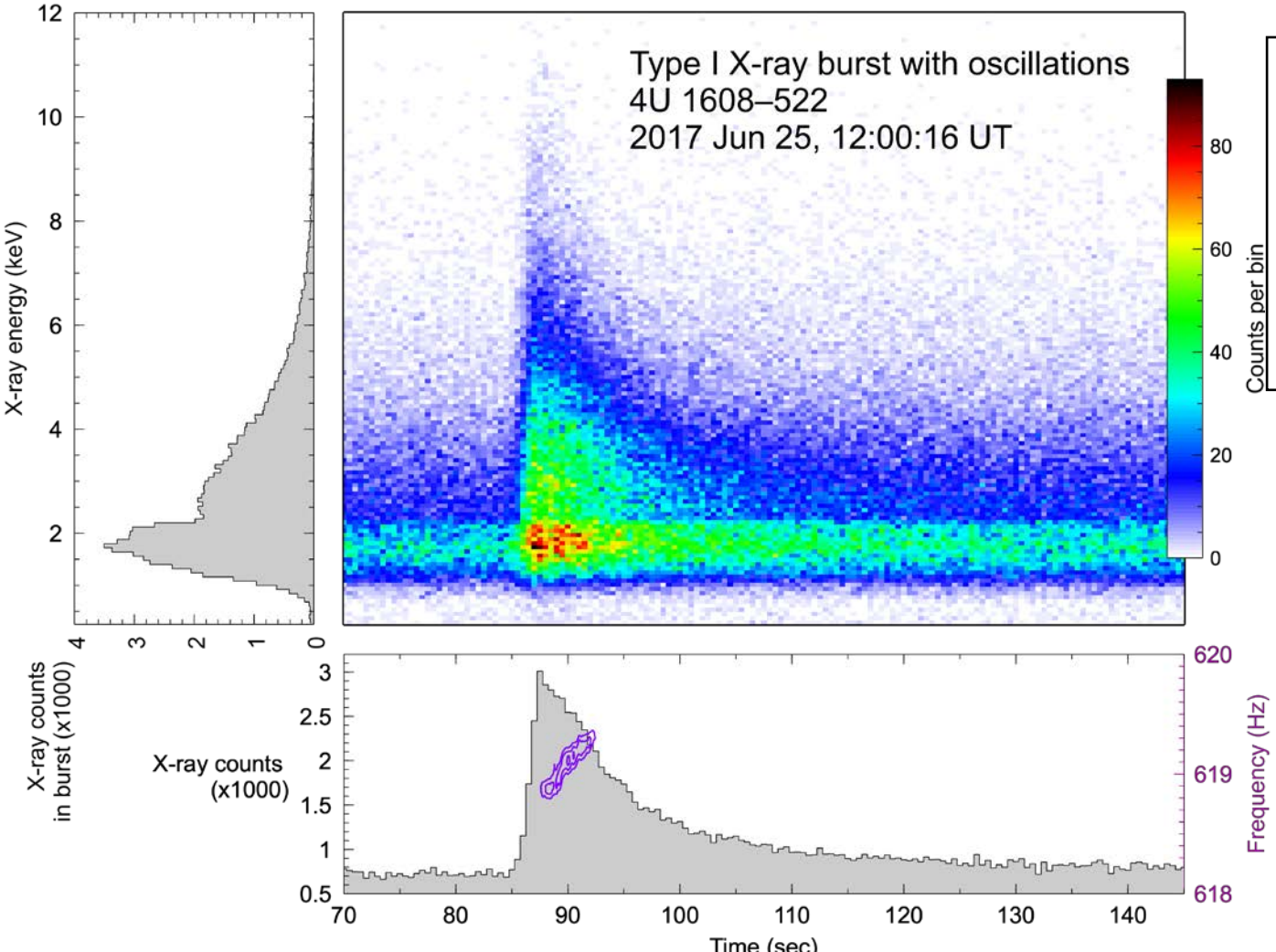




NICER exposures to date — one-third of eventual totals — surpass best that could be done with prior instrumentation

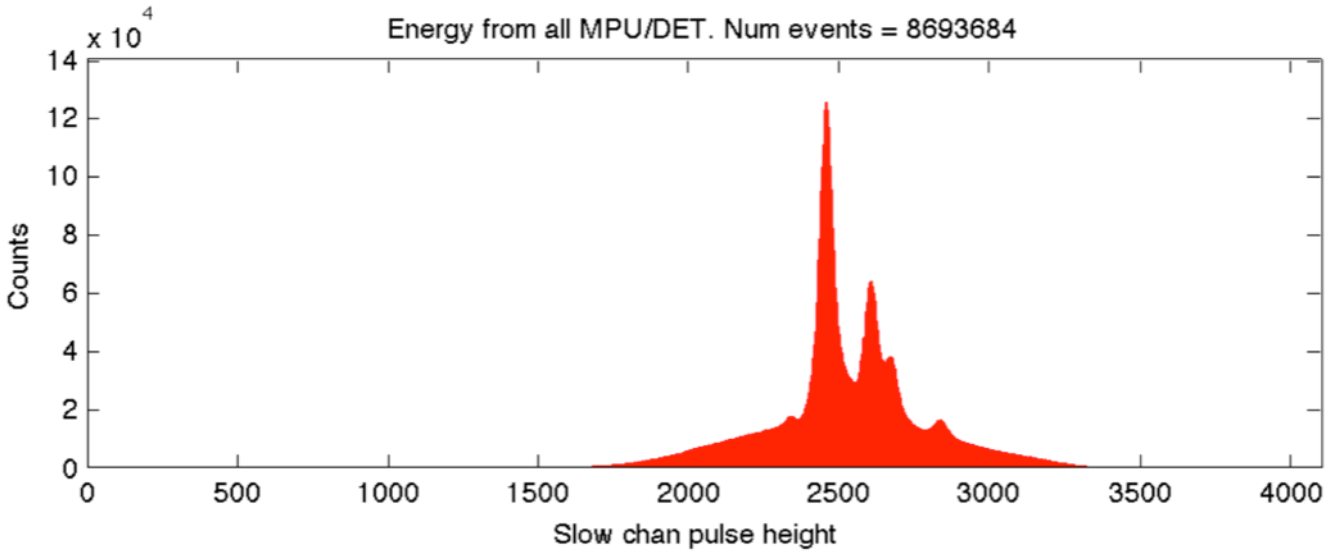
First-light Highlights

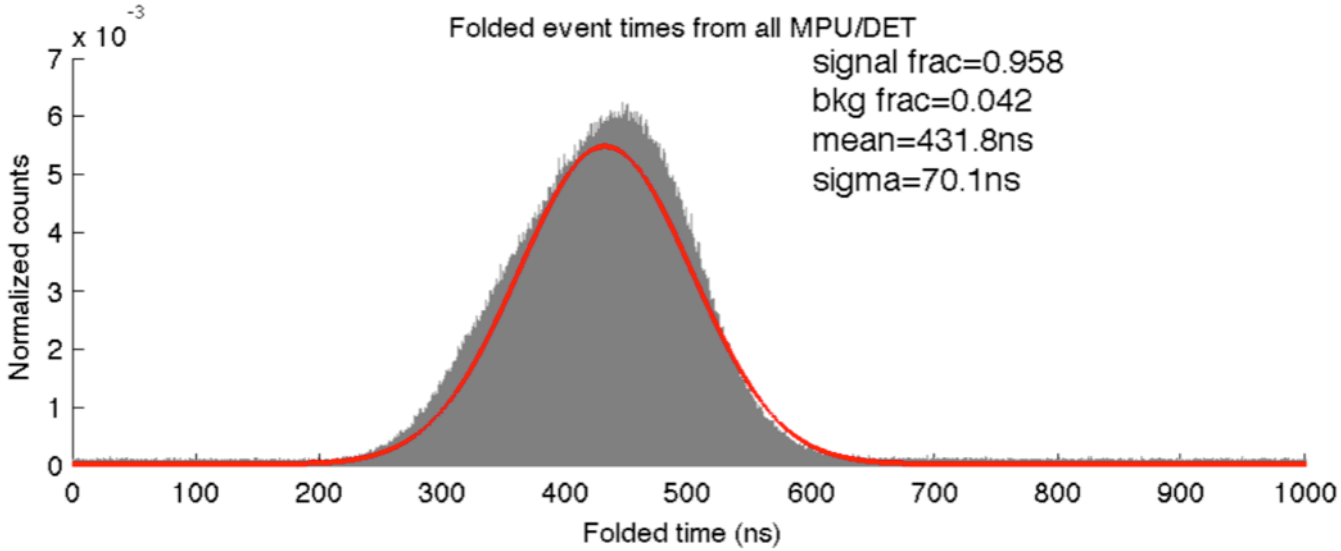
- **619 Hz burst oscillations from LMXB 4U 1608–522**



Capabilities — Time-stamping accuracy

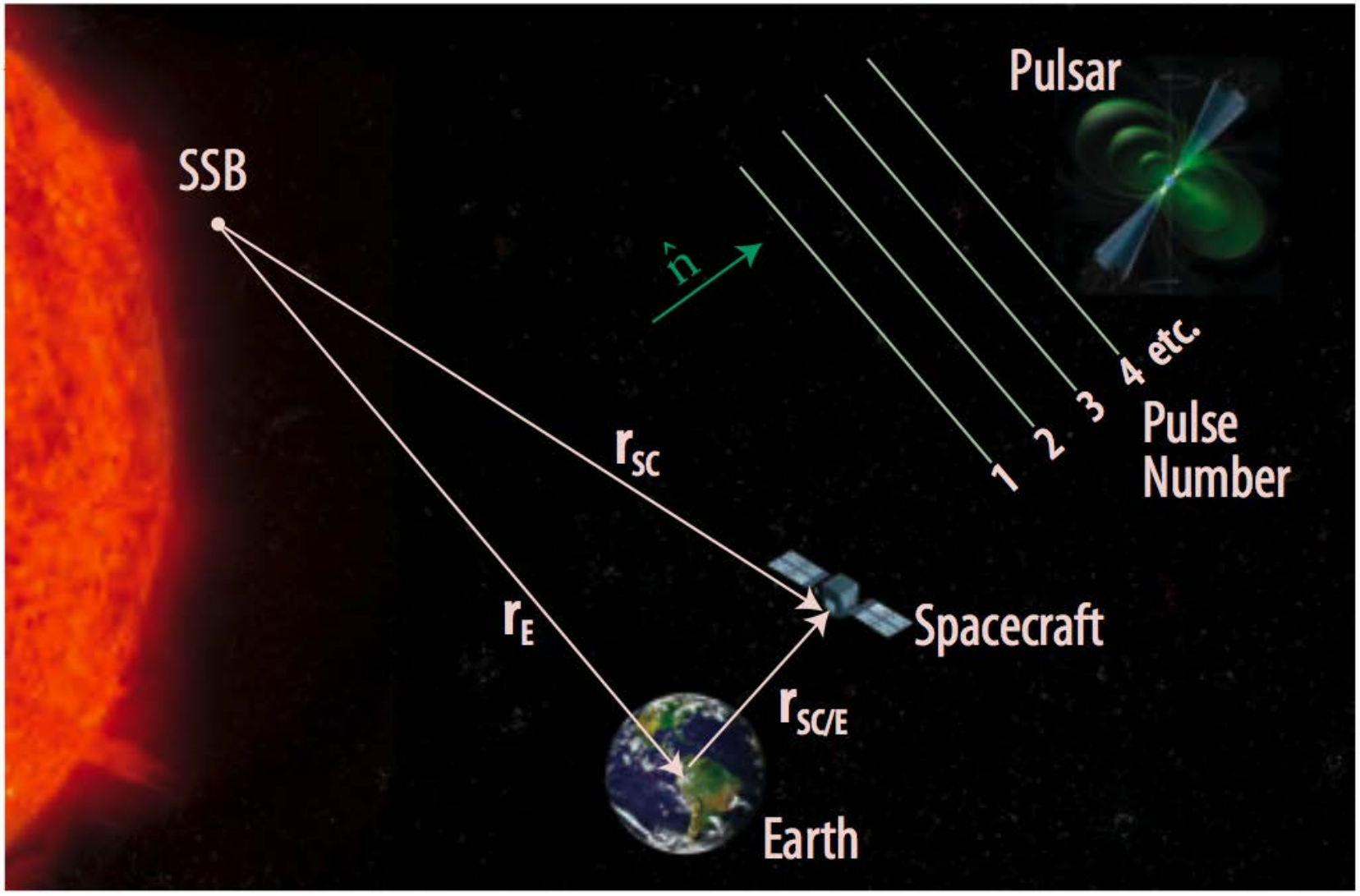
- **Instrument-level timing precision: 70 ns RMS**
- **With GPS reference time and position un-certainties: 85 ns RMS**



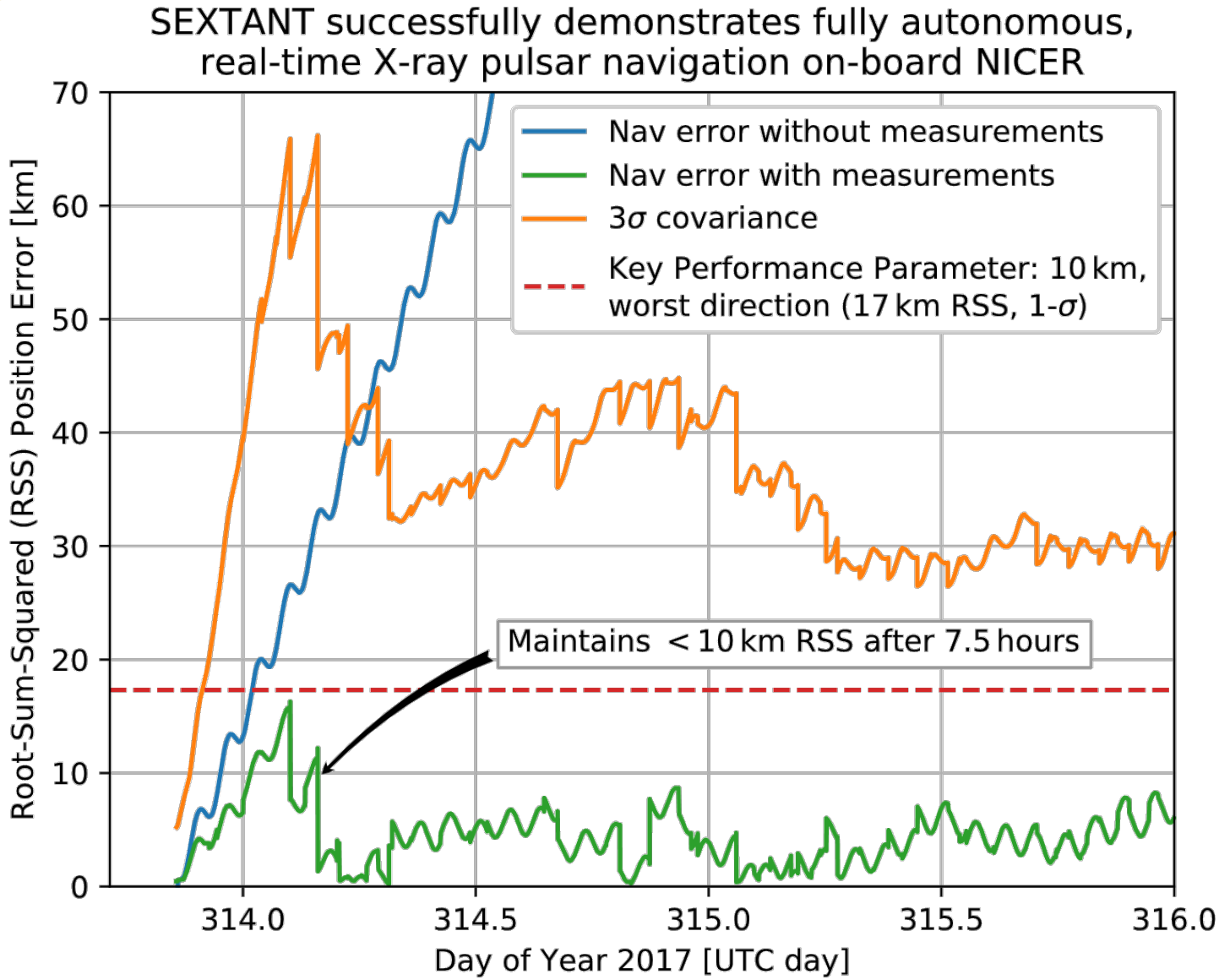


SEXTANT — Method

Inverting traditional pulsar-timing techniques



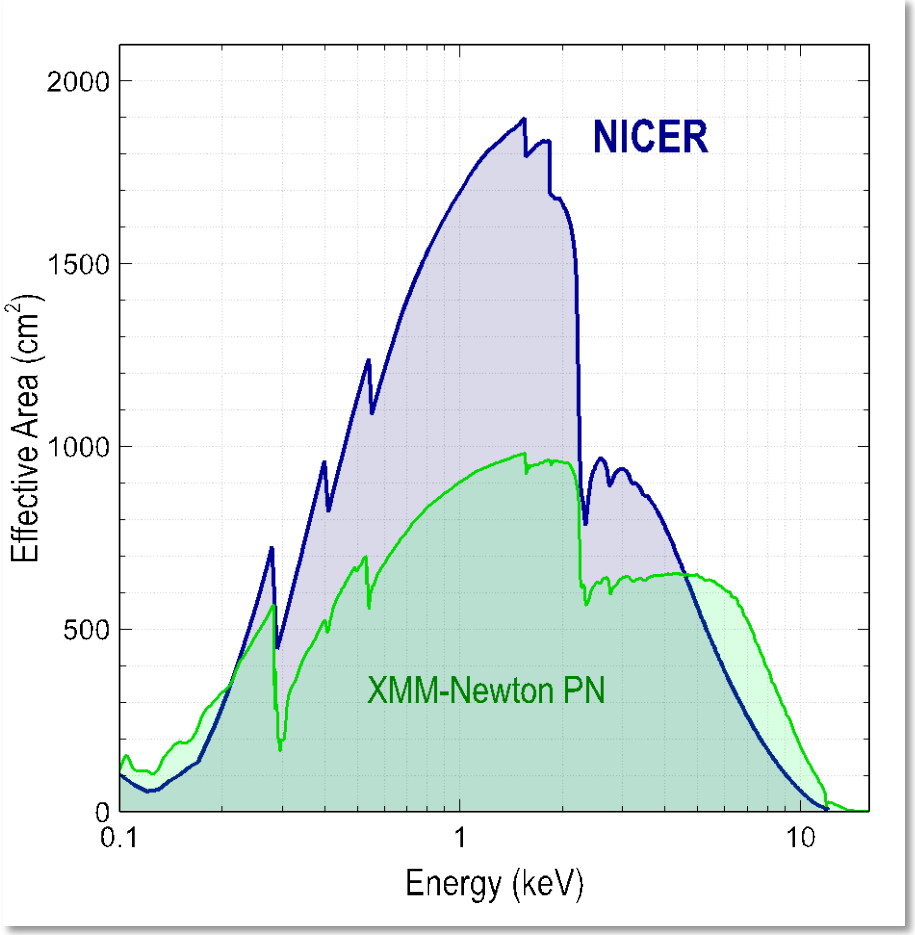
Success!


SEXTANT successfully demonstrates fully autonomous, real-time X-ray pulsar navigation on-board NICER
Nav error without measurements
Nav error with measurements
3σ covariance
Key Performance Parameter: 10 km, worst direction (17 km RSS, 1-σ)
Maintains < 10 km RSS after 7.5 hours
Root-Sum-Squared (RSS) Position Error [km]
Day of Year 2017 [UTC day]
0
10
20
30
40
50
60
70
314.0
314.5
315.0
315.5
316.0

NICER Science-Enabling Capabilities

An unprecedented combination of time resolution, energy resolution, and sensitivity

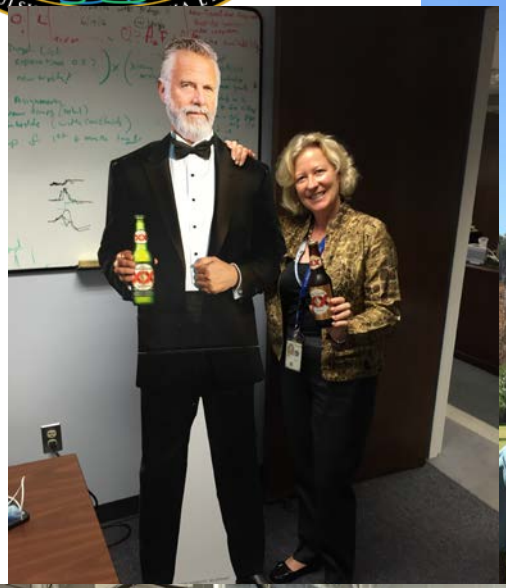
- **Spectral band: 0.2–12 keV**
  - **Well matched to neutron stars**
  - **Overlaps RXTE and XMM-*Newton***
- **Timing resolution: <100 nsec RMS absolute**
  - **50x better than RXTE**
  - **~1000x better than XMM-*Newton***
- **Energy resolution: 2.5% @ 6 keV**
  - **10x better than RXTE**
- **Angular resolution: 6 arcmin (non-imaging)**
  - **10x better than RXTE**
- **Sensitivity, 5σ: 5.3 x 10^{-14} erg/s/cm^2**
  - **0.5–10 keV in 10 ksec (Crab-like spectrum)**
  - **20x better than RXTE**
  - **3x better than XMM-*Newton*'s timing capability**

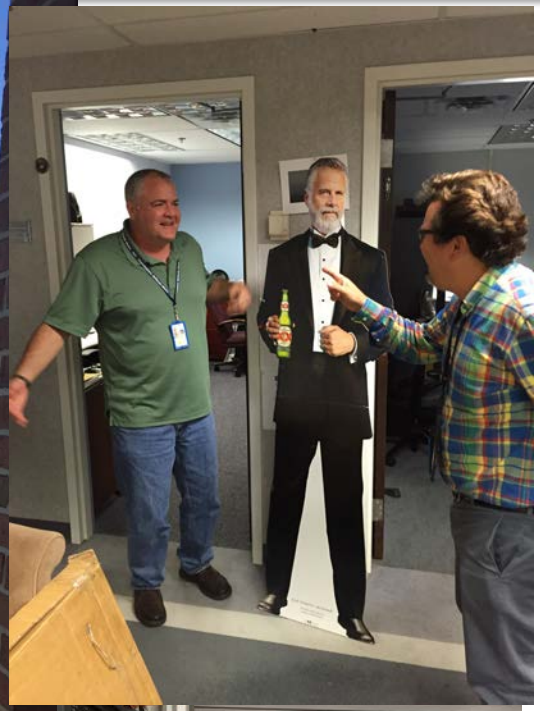


My Lessons Learned for Class D

- **Many at GSFC, reviewers and your own team members, may not comfortable with the level of risk acceptance of Class D missions**
- **Perform lots of low cost testing to refine component designs (XRCs, detectors)**
- **Develop a good relationship with QA, include them in decision process**
- **Ask for help when you need it, there is a lot of expertise on Center**

…and have a good mascot!





It takes a team!