DESIGN DEVELOPMENT OF A COMBINED DEPLOYMENT AND POINTING SYSTEM FOR THE INTERNATIONAL SPACE STATION NEUTRON STAR INTERIOR COMPOSITION EXPLORER TELESCOPE

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ABSTRACT

This paper describes the design of a unique suite of mechanisms which make up the Deployment and Pointing System (DAPS) for the Neutron Star Interior Composition Explorer (NICER/SEXTANT) instrument, an X-Ray telescope, which will be mounted on the International Space Station (ISS). The DAPS system uses 4 stepper motor actuators to deploy the telescope box, latch it in the deployed position, and allow it to track sky targets. The DAPS gimbal architecture provides full-hemisphere coverage, and is fully re-stowable. The compact design of the mechanism allowed the majority of total instrument volume to be used for science. Override features allow DAPS to be stowed by ISS robotics.

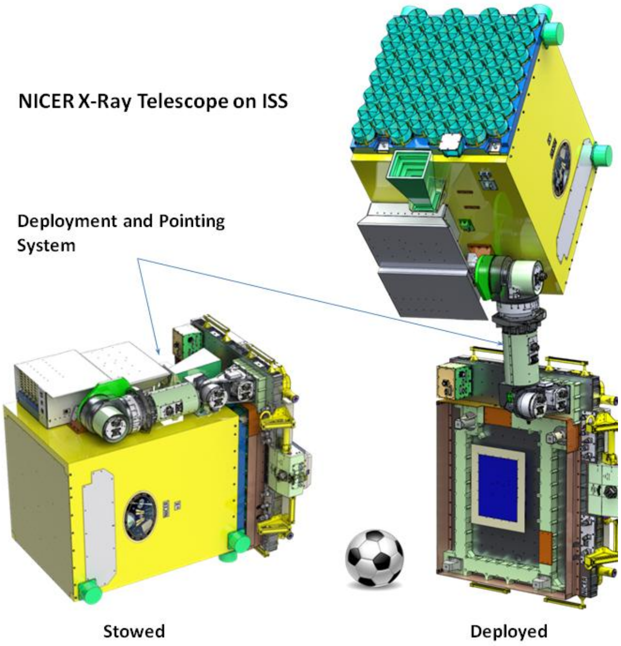

Figure 1. NICER/SEXTANT in the stowed and deployed configurations

1. NICER/SEXTANT INSTRUMENT

The Neutron Star Interior Composition Explorer (NICER) / Station Explorer for X-Ray Timing and Navigation (SEXTANT) is a deployable, clustered array of 56 soft X-ray telescopes that will be installed on the International Space Station (ISS). The telescope cluster will track astronomical targets with a 3σ error of < 0.6 milliradians (2 arcminute) of pointing error. NICER/SEXTANT will also demonstrate pulsar-based celestial navigation, and will be used as a receiver for experimental X-ray communications.

1.1. ISS Mission Implementation

NICER/SEXTANT will be delivered to ISS via the SpaceX Dragon vehicle in 2016, and has a mission lifetime of at least 2 years. During that time, the instrument will require 2-axis, full hemisphere pointing at >95% duty cycle, and many stow/deploy cycles. The instrument utilizes the Active Flight Releasable Attachment Mechanism (AFRAM) interface and will be robotically installed at Express Logistics Carrier #2 (ELC2), Site 7, shown below in Fig. 2.

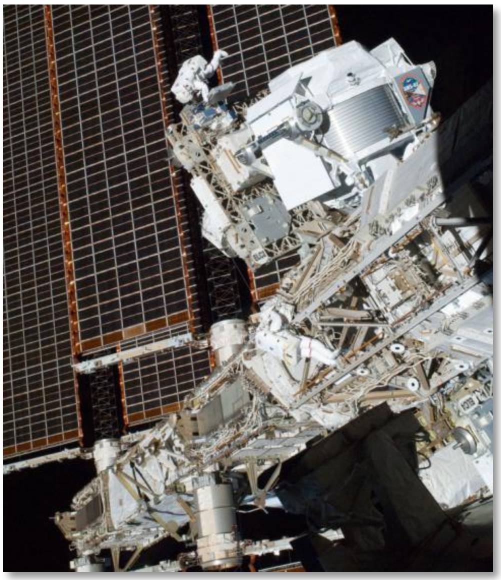

Figure 2. NICER/SEXTANT will be mounted to ELC2, approximately where the EVA crew member is shown.

2. DEPLOYMENT AND POINTING SYSTEM (DAPS) MECHANISM

As an AFRAM-based payload, the NICER/SEXTANT instrument was subject to a limited launch envelope. It was important for the mechanism architecture to be compact, which allowed the majority of volume to be dedicated to science. An optimal architecture utilizing 4 actuators was devised which combined the deployment and pointing functions; this suite of mechanisms is called the Deployment and Pointing System (DAPS). It is similar to the architecture used to deploy and point the communications antenna on the Japanese Experiment Module [1].

2.1. Architecture

The DAPS system is comprised of a deployment actuator, a deployment latch actuator, with an azimuth actuator and elevation actuator arranged in a biaxial gimbal. The gimbal actuators are oriented in an elevation over azimuth configuration. The gimbal actuators and deployment actuators are separated by a 275 mm boom. The deployment actuators, at the base of the boom, are mounted to the AFRAM plate. The gimbal actuators are connected to the large X-Ray Timing Instrument (XTI) Box, which houses the X-Ray telescope array. The XTI has a mass of 172 kg, and DAPS must point it at rates of approximately 1 degree/sec during slew and less than 0.4 deg/sec during science target tracking. 4 frangible bolt launch locks constrain the XTI box directly to the AFRAM/Instrument Plate, which greatly reduces the launch loads that the DAPS will be subjected to.

2.2. Deployment

After the NICER/SEXTANT instrument is installed on the ELC, the launch locks are released and the DAPS deploys NICER/SEXTANT from the stowed configuration into the operational configuration. The deploy actuator rotates the DAPS boom, pointing actuators, and XTI 84 degrees, clearing the launch lock towers and placing the XTI box above the ELC2 structure. The deploy latch actuator then inserts a pawl into the rotor of the deploy actuator, mechanically latching it in place. The azimuth actuator then slightly rotates the XTI box to clear a hardstop feature, called the elevation hook. The hook is a simple linear bar connected to the boom. When the XTI is stowed, the hook is within a small ring on the XTI. This mechanically constrains the elevation from inadvertently shifting while the deploy actuator rotates, due to the large center of gravity offset of the XTI relative to the elevation axis. While the elevation actuator detent has positive margin to resist this inertial torque, the hook was implemented to provide positive mechanical constraint resulting in an additional layer of safety. It ensures that the XTI box cannot swing out during deployment and potentially contact the ISS solar arrays, less than 0.5 m away.

With the hardstop feature cleared, the elevation actuator rotates the XTI box up in elevation, resulting in NICER/SEXTANT fully deployed and ready to begin science operations. The azimuth and elevation actuators in the pointing gimbal then slew to and track various astronomical targets, typically observing 2 to 3 different targets per orbit. Continuous tracking of targets through zenith is interrupted through the 10 degree keyhole; relatively rapid azimuth slewing enables these targets to be immediately re-acquired as they cross out of the keyhole. The volume swept out by all degrees of freedom is shown in Fig. 3.

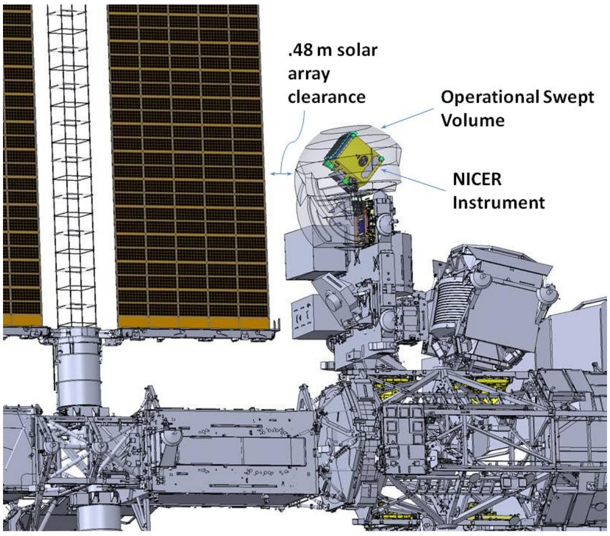

Figure 3. The operational swept volume NICER/SEXTANT is shown. The clearance between the swept volume the starboard solar array is also illustrated.

2.3. Re-Stowage

The NICER/SEXTANT instrument must occasionally return to the stowed configuration for ISS maneuvers, crew Extra-Vehicular Activity (EVA), local Extra-Vehicular Robotic (EVR) operations, and visiting vehicle proximity operations. The instrument also must be stowed prior to robotic removal and disposal. The DAPS stow process is the exact reverse of the deployment process. To increase the stowed stiffness after the initial (and permanent) release of the XTI launch locks, shear-bearing indexing conical surfaces on the AFRAM plate must engage their corresponding cups on the XTI. The alignment of these mating surfaces is critical to NICER/SEXTANT meeting it’s stowed stiffness requirement. The DAPS ensures that these surfaces align correctly prior to mating by using a precision guide channel which forces the relatively coarse positioning ability of the actuators into a repeatable precision trajectory which guarantees proper alignment upon contact. A guide pin on the XTI engages a precision slot on the DAPS bracket near the deploy actuator as the DAPS deploy actuator rotates through TBD degrees, nearing the final stowed hardstop. Azimuth position errors are corrected by the stow alignment slot. The torque resulting from engagement of the guide slot will backdrive the azimuth actuator into the correct orientation for engagement. The elevation axis is limited by hardstops within the actuator at 0 (stowed, end of travel) and 172 (maximum elevation, end of travel) degrees.

2.4. External Hardstops

At some low intermediate elevations, and certain azimuth angles ranges, the XTI box could contact the ELC2. To prevent this from occurring, an external hardstop was incorporated into DAPS called the guardrail. The guardrail hardstop prevents any contact between the XTI and ELC2, while allowing elevations as low as 63 deg (~ 30 deg below the ISS local horizontal). The guardrail hardstop is a circular rail which collars the azimuth actuator and is fixed to the end of the boom. A limit bar protrudes from the elevation actuator output, and physically contacts the guardrail surface to constrain elevation motion. The guardrail has various flat profiles to allow the limit bar to clear it in the stow azimuth range. This hardstop architecture limits the minimum elevation of the XTI box to between 63 and 70 degrees in the ram azimuth quadrant, 80 degrees for most other azimuths, and allows elevations down to zero degrees only for engagement/disengagement of the elevation hook and stowing.

3. MECHANISM DESCRIPTION

The DAPS biaxial gimbal actuators must meet instrument pointing performance requirements, despite the small amount of torque noise, and resulting pointing error they inherently produce.

4. POINTING PERFORMANCE

The 3σ pointing performance allocation for the DAPS is 0.32 milliradian (66 arcsecond), and is summarized in Tab. 1.

Table 1. Pointing Budget

NICER/SEXTANT Pointing Budget	**Estimated arcsec**	**Requirement arcsec**
Overall Instrument Pointing	87.2	120
ISS Low Frequency	±40	±53
star tracker calibration & structural/optical analysis	±9	11.5
DAPS System	**46.3**	**66**

Early analysis showed that the actuators induced pointing error is much greater than the requirement. As expected, the largest error occurs when the actuator step rate coincides with structural resonant frequencies.

The NICER/SEXTANT payload has resonant structural frequencies <10 Hz which are excited by the pointing actuators. Since the operational actuator step rates will always pass through this frequency range, there are no feasible workarounds to avoid exciting these low frequency structural modes.

In order to reduce the excited pointing errors and meet the requirement, several mitigation methods have been implemented, including microstepping, actuator detent torque reduction, and the use of dampers.

4.1. Microstepping

Implementation of microstepping in the actuator drive electronics was the first measure taken to reduce the stepper motor induced pointing error. Microstepping breaks a single cardinal step into smaller ones and softens the impacts on the output load, instead of moving through a single motor step quickly and generating a larger impulsive torque on the system. While microstepping did reduce the stepper induced pointing error, it was not sufficient to meet the pointing requirements. The issue resides in the motor detent torque. The motor powered torque must overcome the detent torque before it can move the motor from one step to the next step, even when microstepping. Overcoming the detent torque essentially generates torque impulses that exceed the detent torque. While these torque impulses are smaller than the cardinal step torque levels, they generate disturbances on the instrument and limit the benefits gained by microstepping.

4.2. Detent Torque

The DAPS vendor recommended a reduction in the detent torque in order to further reduce the pointing errors. The detent torque was reduced by increasing the air gap between the rotor and stator. This also reduced the motor constant, and more power would be required to maintain torque output, but this was acceptable. This was tested on a development motor, which was used to determine the air gap size which balanced detent torque and motor constant. The same air gap modification procedures demonstrated on the test motor were used to manufacture the NICER/SEXTANT engineering test unit and flight actuators. The NICER/SEXTANT pointing actuator detent torque levels were lowered to less than 0.03 N-m at the output. The detent torque reduction had reduced the overall stepper-induced pointing error. Unfortunately, when the stepper actuator rates crossed the low frequency structural modes, the pointing error level was still exceeded the requirement.

4.3. Tuned Mass Dampers

One of the techniques for reducing vibratory motion is the tuned mass damper (TMD). The TMD is a resonant device designed to dissipate vibrational energy from the structure. They are passive mechanical devices that do not require power or electronics. The TMDs are particularly effective for NICER/SEXTANT, as they suppress low-frequency vibration excited by both stepper and ISS-induced disturbances. The NICER/SEXTANT TMDs were designed to provide 1-3% damping ratio for the first three flexible-body modes. They are oriented to reduce vibrations along the axes where the vibrational displacement occurs. The mounting locations of TMDs are shown in Fig. 4.

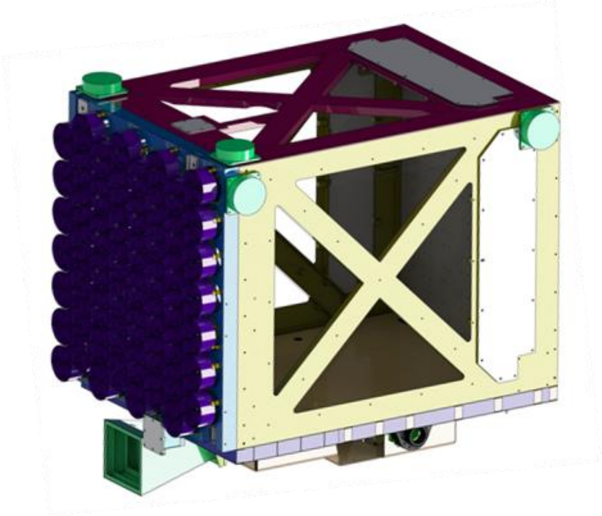

Figure 4. Tuned Mass Dampers, shown in green, were added to the corners of the XTI box

A sample of stepper-induced jitter results for the performance with and without TMDs are shown in Fig. 5.

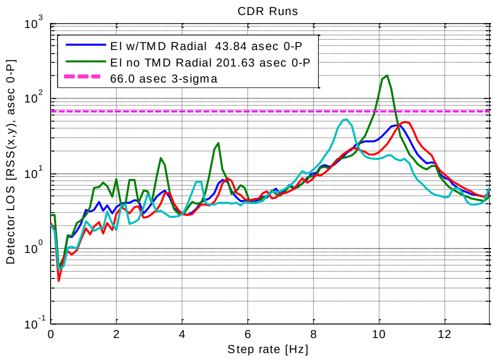

Figure 5. The elevation actuator exceeds the 66 arcsecond requirement when step rates are near 10 Hz

As shown in Fig 5., The TMDs were critical in meeting the pointing performance requirement. They greatly reduced the structural vibrations when the step rates pass through the structural mode frequencies. Similar results are shown in Fig. 6 for the ISS-induced jitter, where the TMDs not only reduced the peak jitter, but also stabilize the pointing performance due to ISS disturbance frequency variations.

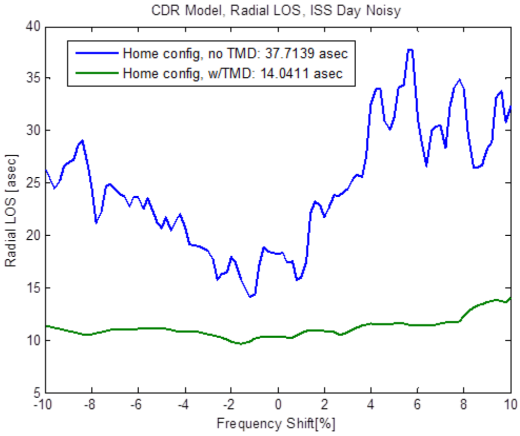

Figure 6. Addition of the TMDs reduced the overall predicted pointing error (Radial LOS in the graph) by a factor of 2.7

A combination of relatively low-cost techniques that included microstepping, low-detent torque, and TMDs were used to improve the NICER/SEXTANT pointing performance and meet the NICER/SEXTANT pointing requirement with adequate margin. Several tests (see Fig. 10) are currently underway to validate the pointing performance on the ground prior to launch.

5. ISS REQUIREMENTS EFFECTS

The DAPS had to meet additional requirements from the space station program. Contingency considerations required that the NICER/SEXTANT instrument have interfaces to the ISS Special Purpose Dexterous Manipulator (SPDM) teleoperated robot. These interfaces would allow the SPDM to return the instrument to the stowed configuration if DAPS failed. This is necessary as the payload must be in the stowed configuration to fit within the disposal vehicle.

5.1 Robotic Interfaces

Each of the four actuators has a standard 7/16 inch EVR torque bolt coupled to the motor shaft. These bolts serve as an interface through which torque can be applied to drive the motor shaft, which is amplified by the harmonic drive gearing and rotates the actuator output. The torque bolts reside within Micro-Conical Fixture (MCF) Standard Dexterous Grapple Fixtures (SDGF) with their associated Modified Truncated Cone (MTC) visual alignment targets. These EVR interfaces are shown on the engineering test unit (ETU) actuator in Fig. 7, below.

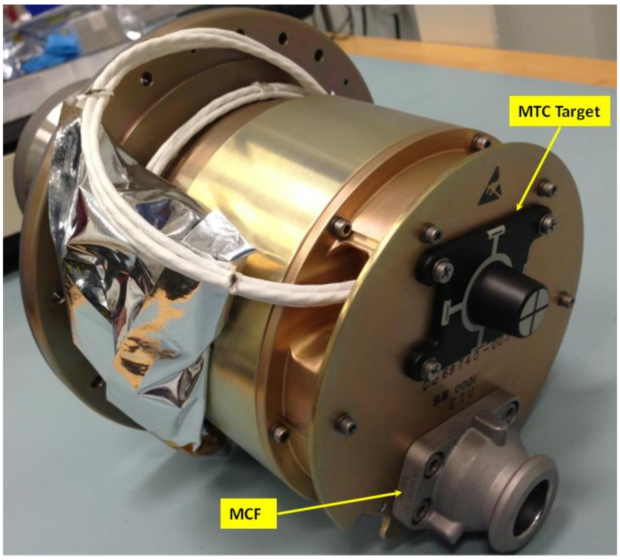

Figure 7. Robotic interfaces are shown on the DAPS ETU actuator. The black MTC target sits above the MCF grapple fixture on the actuator face. The EVR bolt is buried within the MCF.

These bolts and EVR interfaces are on the motor faces of all DAPS actuators except the Azimuth pointing actuator. This actuator has the motor face buried within the boom and required a 90 degree gear box extension to allow the EVR bolt, MCF, & MCT to be accessible by SPDM. These interfaces are shown in Fig. 8.

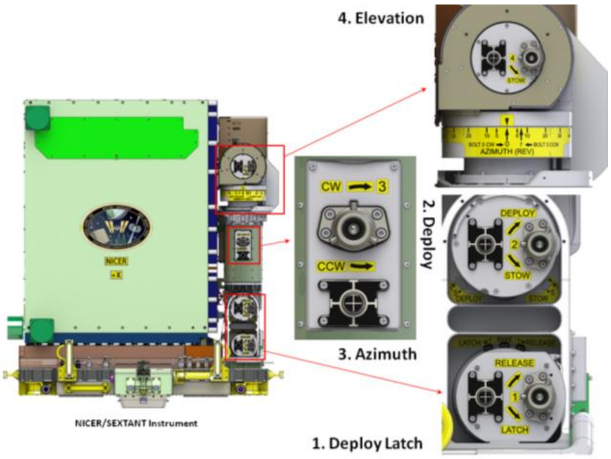

Figure 8. DAPS ISS Robotic Interfaces. Each actuator has a MCT grapple fixture, a MTC visual target, and external labels.

To accommodate an accidental runaway impact of the SPDM robot, DAPS had to demonstrate fracture margin against an impact of 556 N (125 lbf), and an EVA kick load of 556 N (125 lbf).

5.2 Torque Limiting

The minimum input from the SPDM torque driver is 6.7 N-m (5 ft-lbf). Should this amount of torque drive a DAPS actuator into a hardstop, internal damage may occur. A torque-limiter was built into the EVR interface to prevent accidental damage. Torque levels of 0.73 N-m (~6.5 in-lbf) are transmitted through the torque limiter.

5.3 External Markings

To facilitate the contingency robotic restow operation and meet Design for Minimum Risk (DFMR) requirements, external status markings and indicators (arrows on moving tabs) were implemented which indicated the displacement position of each axis. Each actuator had gradations labelled with return to stow position EVR turn counts, and arrows indicated the direction to rotate the EVR bolt to return each axis to the stowed position. The location of these gradations and markings were unique for each axis. To meet EVA legibility requirements, the text was ~6.7 mm (18 pt.) or larger.

6. VERIFICATION

The DAPS is being developed as a protoflight unit, with a single ETU actuator to validate low detent modifications and EVR interfaces. The ETU actuator is shown in Fig. 7.

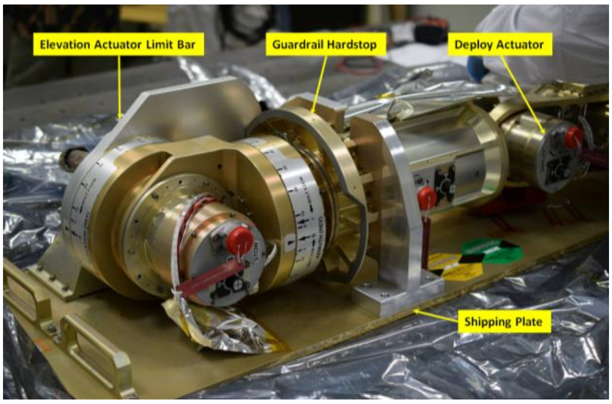

Figure 9. DAPS flight unit as delivered to the NICER/SEXTANT instrument.

As of this writing the DAPS has been delivered to GSFC and is undergoing performance testing as shown in Fig. 10. This is to be followed by integration into the NICER/SEXTANT instrument and environmental testing at the instrument level.

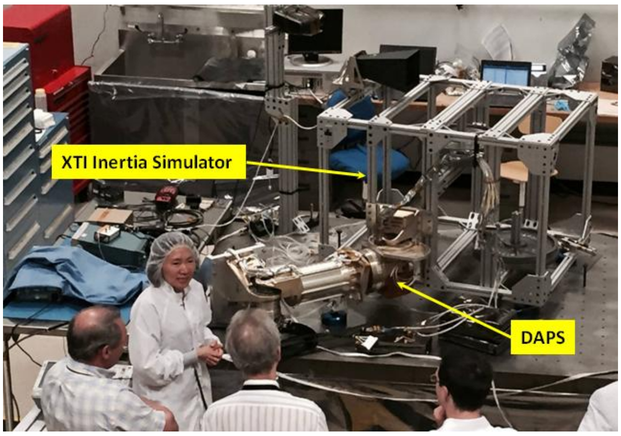

Figure 10. DAPS flight unit during performance testing with an XTI inertia simulator floating on air bearings.

7. References

1. Stevenson, J., Katsuyama, Y., Fukatsu, A., Kurihara, K., Saito, T., Zoren, M., Mallonee, S., (1999). Development of the JEM ICS Antenna Pointing System In Space Mechanisms and Tribology, Proceedings of the 8th European Symposium (Ed. D. Danesy), ESA SP-438, European Space Agency, Noordwijk, The Netherlands