Performance Testing of the Astro-H Flight Model 3-stage ADR

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Astro-H Soft-X-ray Spectrometer

• 6x6 array of x-ray microcalorimeters cooled to 50 mK
• ADR is used to cool the detectors to 50 mK
  – 0.25 μW of conducted heat (leads)
• ADR rejects heat to either:
  – Superfluid helium at <1.3 K
    • <0.23 mW average (4 year lifetime)
  – Joule-Thomson cooler at ~4.5 K
    • <18 mW peak
• Detector housing stable to 1 mK (time scales of 10 min)
Astro-H Cryogenic System

Dewar Main Shell, 300K

Outer Vapor Cooled Shield, 155K

Inner Vapor Cooled Shield, 28K

JT Shield, 4.5K

Detector Assembly, 1.3K

Calorimeter Thermal Sink, 0.05K

15K 4.5K 1.3K 0.5K 0.05K
2-stage ADR operates by cascading heat from the detectors to the liquid helium.
Astro-H Cryogenic System

- 3rd stage transfers heat to JT cooler
- 2nd stage maintains helium tank temperature
- 1st stage cools detectors to 50 mK
Flight ADR

Heat Switch 1
Heat Switch 2
Stage 1
Stage 2
Stage 3
Heat Switch 4
Heat Switch 3
Thrust Tube
Operation with Liquid Helium

• Recycling sequence
  – Stage 1 and 2 are warmed to ~10% above the He bath
    • HS1 and HS2 turned ON
  – Stages 1 and 2 charge to full field (2 T and 3 T)
    • HS2 is turned off
  – Stage 2 cools Stage 1 (still at 2 T) to <0.8 K
    • HS1 is turned off
  – Stage 1 is demagnetized to 50 mK, and Stage 2 to 0.5 K
2-Stage ADR Cycling

• Recycle time <1 hour, including recovery time
  – Detector response stabilizes as detector and ADR components equilibrate
• Control setpoints are based on the He tank temperature (uses mounting plate T)
  – Control system automatically adjusts to conditions during flight
Stage 1 Hold

- Hold time of 32 hours
  - He bath at 1.25 K
  - On orbit expect <1.15 K, giving a hold time of 38 hours
- Current during demagnetization fits well to standard curve

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**Graph**

- $T_{salt} = 48.33 \text{ mK}$
- Heat load = 1.14 $\mu$W

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**Graph**

- S1 current (A)
- Time (hrs)
Temperature Stability

• Required stability: 2.5 μK rms
• Actual: 0.37 μK rms
Autonomous Operation (GSFC Testing)

- Recycling is triggered by Stage 1 current $< 5$ mA
- Control system operates autonomously based on preset parameters and real-time conditions (He tank temperature)
2-Stage ADR Operation Summary

• With He tank at ~1.25 K (cryocoolers at nominal power)
  – Heat load on S1 was 1.14 μW
  – Hold time at 50 mK is 32 hours
  – Recycle time (and recovery) <1 hour
  – Demonstrated observing efficiency of >97%

• Temperature stability <1 μK rms

• Issues
  – Heat load on S1 salt pill is higher than expected based on measurements at GSFC
    • With 1.25 K tank, expected <0.9 μW
  – Appears to be directly related to JT operation
Cryogen-Free Operation

- **3rd** stage transfers heat to JT cooler
- **2nd** stage maintains helium tank temperature
  - Builds up cooling capacity during hold time
- **1st** stage cools detectors to 50 mK, rejects heat to **2nd** stage

![Diagram of Cryogen-Free Operation]

- Dewar Main Shell, 300K
- Outer Vapor Cooled Shield, 155K
- Inner Vapor Cooled Shield, 28K
- JT Shield, 4.5K
- Detector Assembly, 1.3K
- 15K, 4.5K, 1.3K, 0.05K
- 3rd stage transfers heat to JT cooler
- 2nd stage maintains helium tank temperature
- Builds up cooling capacity during hold time
- 1st stage cools detectors to 50 mK, rejects heat to 2nd stage
3rd Stage Cycling

- Cycle period ~21 minutes
- Low temperature setpoint is continuously adjusted to match helium tank T
- Time average heat lift of 2-3 mW in range of 1.4-1.8 K

![Diagram showing temperature and current over time with peaks and troughs indicating cycling behavior.]
Full Cycle with He tank at 1.625 K

- 40 minute recycle
- 11.0 hour hold
- >94% observing efficiency

- S2 charges during hold time
- Some excess capability is evident
  - Can support 1.60 K operation
S1 Demag Curve Fit

• He tank at 1.625 K
  – S1 heat load = 2.98 µW
  – Salt temperature = 46.31 mK
DA Housing Stability

- Required stability is 1 mK over time scales of 0.2 s – 10 min
  - Brief periods in which fluctuation is ~2 mK
  - With current detector performance, this is acceptable
Warm Start

• ADR must handle the case of a warm start
  – He tank, ADR and detectors starting at 4.5 K
  – May be necessary after

• Control should be autonomous (i.e. no intervention via ground control)
Cooldown from 4.5 K
Starting Current at 50 mK

- Starting current from 0.80 K and 2 A is consistently 100 mA
  - +1, -2 mA
• ADR has demonstrated autonomous control in nominal operating modes
  – 2-stage with helium, and 3-stage cryogen-free
  – Warm start, automatic recycling

• 2-stage with helium
  – Hold times ~32 hours
  – Recycle times <1 hour
  – Observing efficiency >97%

• 3-stage cryogen-free
  – Hold times typically ~11 hours
    • Heat load dominated by HS1 and kevlar from He tank
  – Recycle times <45 minutes
  – Observing efficiency >93%