Cryocoolers for Space Applications #4

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Topics

- Space Cryocooler Historical Overview and Applications
- Space Cryogenic Cooling System Design and Sizing
- Space Cryocooler Performance and How It's Measured
- Cryocooler-Specific Application and Integration Example: The AIRS Instrument
Session 4: Detailed Example
The AIRS Instrument

Topics

- Overview of AIRS Instrument
  - Example Application Ground Rules and Requirements
  - AIRS Cryosystem Conceptual Design
  - Cryosystem layout and cryo loads estimation
  - Important heatsinking considerations

- Sizing the Cryocooler for the Complete Mission Life Cycle
  - BOL/EOL performance margin analysis

- Temperature Stability Requirements and Control

- Cryocooler Structural Integration Considerations

- Electrical Interface Considerations
  - Meeting magnetic field requirements with shields
  - Meeting Inrush and reflected ripple current requirements
References


References (Con't)


- See the AIRS instrument web site for up-to-date descriptions of the science returns from the AIRS instrument and its science team members: [http://www-airs.jpl.nasa.gov/](http://www-airs.jpl.nasa.gov/)

- [http://www2.jpl.nasa.gov/adv_tech/](http://www2.jpl.nasa.gov/adv_tech/) JPL website with 103 JPL cryocooler references as PDFs (R. Ross, webmaster)
AIRS (Atmospheric Infrared Sounder) is a NASA Earth Science Instrument

- AIRS is an Atmospheric Infrared Sounder
  - **Design:** Highly stable IR spectrometer spanning visible to 15.4 μm bands with Focal Plane cooled to 58 K
  - **Launched:** May 2002
    - Still in orbit gathering data
  - **Science Output:**
    - Air Temperature Distributions
    - Atm Gas Concentrations (CO, CO₂, CH₄, H₂O) over Planet

Launched on NASA Aqua Spacecraft in May 2002

Water Vapor Transport

Global Patterns of Carbon Dioxide
The AIRS instrument was designed and built under JPL contract by BAE Systems, Lexington, MA.
AIRS Cryosystem Ground Rules and Requirements

- Totally redundant cryocoolers—for enhanced reliability
- No heat switches—to avoid increased complexity, cost and unreliability
- Ambient heat rejection to spacecraft-supplied cold plates operating between 10 and 25°C
- Cooler drive fixed at 44.625 Hz, synchronized to the instrument electronics
- Cold-end load (focalplane) mechanically mounted and aligned to the 150 K optical bench with a maximum vibration jitter on the order of 1 μm
- Focalplane calibration (for temperature, motion, etc.) every 2.67 sec (every Earth scan)
- Cooler input power goal of 100 watts (22 to 35 volts dc), and mass goal of 35 kg
- Cooler drive electronics fully isolated (dc-dc) from input power bus; EMI consistent with MIL STD 461.
<table>
<thead>
<tr>
<th>Radiation Type</th>
<th>Wavelength (microns)</th>
<th>Blackbody Temp. (K)</th>
<th>Detector Technology</th>
<th>Detector Oper. Temp. (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>γ-rays</td>
<td>10^{-5}</td>
<td>3 × 10^8 K</td>
<td>Ge Diodes</td>
<td>80 K</td>
</tr>
<tr>
<td>γ-rays</td>
<td>10^{-4}</td>
<td>3 × 10^7 K</td>
<td>Ge Diodes</td>
<td>80 K</td>
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<tr>
<td>x-rays</td>
<td>10^{-3}</td>
<td>3 × 10^6 K</td>
<td>micro calorimeters</td>
<td>0.050 K</td>
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<tr>
<td>x-rays</td>
<td>10^{-2}</td>
<td>3 × 10^5 K</td>
<td>micro calorimeters</td>
<td>0.050 K</td>
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<tr>
<td>UV</td>
<td>0.1</td>
<td>30,000 K</td>
<td>CCD/CMOS</td>
<td>200-300 K</td>
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<tr>
<td>visible</td>
<td>1</td>
<td>3000 K</td>
<td>CCD/CMOS</td>
<td>200-300 K</td>
</tr>
<tr>
<td>IR</td>
<td>2</td>
<td>1500 K</td>
<td>HgCdTe</td>
<td>55-130 K</td>
</tr>
<tr>
<td>IR</td>
<td>5</td>
<td>600 K</td>
<td>HgCdTe</td>
<td>55-120 K</td>
</tr>
<tr>
<td>LWIR</td>
<td>10</td>
<td>300 K</td>
<td>HgCdTe</td>
<td>35-80 K</td>
</tr>
<tr>
<td>LWIR</td>
<td>15</td>
<td>200 K</td>
<td>HgCdTe</td>
<td>35-60 K</td>
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<tr>
<td>LWIR</td>
<td>20</td>
<td>150 K</td>
<td>Si:As</td>
<td>6 -10 K</td>
</tr>
<tr>
<td>LWIR</td>
<td>50</td>
<td>60 K</td>
<td>Ge:Ga</td>
<td>2.0 K</td>
</tr>
<tr>
<td>LWIR/μwaves</td>
<td>100</td>
<td>30 K</td>
<td>Ge:Ga</td>
<td>1.5 K</td>
</tr>
<tr>
<td>microwaves</td>
<td>200</td>
<td>15 K</td>
<td>Bolometers</td>
<td>0.100 K</td>
</tr>
<tr>
<td>microwaves</td>
<td>500</td>
<td>6 K</td>
<td>Bolometers</td>
<td>0.100 K</td>
</tr>
</tbody>
</table>
Operating Regions of Cryocoolers vs Detector Cooling Requirements

- **5% Carnot Refrigerator Specific Power, watts/watt**

- **Operating Regions**
  - **(INPUT POWER)**
  - **1000 watts**
  - **100 watts**
  - **10 watts**
  - **N₂/O₂ J-T**
  - **H₂ J-T**
  - **SH₂**
  - **He J-T**
  - **Extrin. IR**
  - **STIRLING & PULSE TUBE**
  - **REVERSE BRAYTON**
  - **IR**
  - **sub-mm preamps**
  - **MAGNETIC**
  - **DILUTION**
  - **Bolometers**
  - **SIS sub-mm**

- **Cooling Power, watts**
  - 0.1
  - 1
  - 10
  - 100
  - 1000
  - 60,000

- **Cooling Temperature, K**
  - 0.1
  - 1
  - 10
  - 100

*June 2015*
Candidate Stirling Cryocooler Redundancy Approaches

Single Cooler and Electronics
No Redundancy

AIRS

Dual Coolers and Dual Electronics
No Heat Switches

Single Cooler and Dual Electronics
with Electrical Switch

Dual Coolers and Dual Electronics
with Heat Switches
Possible Issues

- Displacer heatsinking
- Displacer vibration
- Displacer reliability
Hughes CSE Cryocooler Mounted in Heat Sink Assemblies
Incorporation of Inertance Tube at TRW

Specific Power at 58 K
Possible Issues

- Optics Contamination
- Pulse Tube Contamination
- Horizontal PTs
- PT/OB relative motion
Three Vacuum Level Issues: Gaseous Conduction, Cryopumping loads, Increased Emittance from contaminant films

Typical Vacuum Levels Achieved:
- $10^{-8}$ torr: Exterior to spacecraft sunlit surfaces (short term)
- $10^{-9}$ torr: Exterior to spacecraft sunlit surfaces (long term)
- $10^{-10}$ torr: Exterior to spacecraft shaded-side surfaces (long term)

Contamination Implications:

<table>
<thead>
<tr>
<th>Vacuum Level</th>
<th>Time for $1,\mu\text{m} \text{H}_2\text{O}$</th>
<th>$\text{H}_2\text{O}$ Cryopumping Heat Transfer</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{-6}$ torr</td>
<td>1.7 hours</td>
<td>340 mW/m$^2$</td>
</tr>
<tr>
<td>$10^{-8}$ torr</td>
<td>7 days</td>
<td>3.4 mW/m$^2$</td>
</tr>
<tr>
<td>$10^{-9}$ torr</td>
<td>70 days</td>
<td>0.34 mW/m$^2$</td>
</tr>
<tr>
<td>$10^{-10}$ torr</td>
<td>2 years</td>
<td>0.034 mW/m$^2$</td>
</tr>
</tbody>
</table>
AIRS Optical Bench
Contamination Risk Assessment

Optical Bench BOL Design: 145 K (10^{-8.5} torr): Contamination Likely
Optical Bench EOL Design: 160 K (10^{-6} torr): Looks Good
Pulse Tube Design: 55 K (10^{-50} torr): Contamination Very Likely

![Graph showing vapor pressure vs. temperature for different gases and pulse tubes at various temperatures and pressures.]

- He
- Hydrogen
- Neon
- Nitrogen
- Oxygen
- CH₄
- CO₂

Space Vacuum

145K < 10^{-8} torr

160K
145K
14K
Pulse Tubes

Temperature, K

 Vapor Pressure, torr

He = Triple Point
Massive Heat Sinks Added to AIRS Pulse Tubes
Summary of AIRS Cooler System Thermal Gradients

- ORIFICE TEMPERATURE
- REGENERATOR TEMPERATURE
- COMPRESSOR TEMPERATURE
- COLDPLATE TEMPERATURE

Graph showing temperature rise above coldplate vs. compressor power.
AIRS Cryosystem Cold Link Design with Pulse Tube Coolers

- 58 K Focal Plane
- 150 K Optical Bench
- Electrical Connectors
- Vacuum Pinch-Off
- Sapphire Cold Link
- Flex-Braid Assembly
- Pulse Tube
- Capacitive Position Sensor
- Linear Motor Coil
- Flexure Bearings
- Piston
- Heat Rejection Coldplate
- Motor Magnet Assembly

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AIRS Cold Link Assembly

- Copper Flex Braid
- Gold Plated Sapphire Rod
Cryogenic Conductivity of High Conductivity Materials

CONDUCTIVITY, watts/cm·K

TEMPERATURE, K

Alum RRR=3000
Silver
platinum
gold
Cu RRR=20
Alum 6063-T6
& MLI
BrO
alumina
Alum 2024-T4
Diamond
APG
K-core
AirS Cold Link
### Breakdown of AIRS Coldlink Assembly Thermal Resistances

<table>
<thead>
<tr>
<th>ITEM</th>
<th>Resistance (K/W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Focal plane to Sapphire rod</td>
<td>1.57</td>
</tr>
<tr>
<td>Conduction down Sapphire rod</td>
<td>0.16</td>
</tr>
<tr>
<td>Sapphire rod to moly coupling</td>
<td>0.34</td>
</tr>
<tr>
<td>Resistance across shrink-fit joint</td>
<td>0.40</td>
</tr>
<tr>
<td>Resistance across flex braid</td>
<td>1.35</td>
</tr>
<tr>
<td>Coldblock contact resistance</td>
<td>0.30</td>
</tr>
<tr>
<td><strong>Total focal plane/pulse tube thermal resistance</strong></td>
<td><strong>4.12 K/W</strong></td>
</tr>
</tbody>
</table>
## Summary of AIRS Instrument Cryocooler Loads

**FOCAL PLANE: 58 K, OPTICAL BENCH: 145 K BOL, 160 K EOL**

<table>
<thead>
<tr>
<th>ITEM</th>
<th>Load (mW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Focal Plane Radiation Load from OB</td>
<td>73</td>
</tr>
<tr>
<td></td>
<td>108</td>
</tr>
<tr>
<td>Focal Plane Electrical Dissipation</td>
<td>193</td>
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<tr>
<td></td>
<td>193</td>
</tr>
<tr>
<td>Focal plane Lead Wire Conduction</td>
<td>98</td>
</tr>
<tr>
<td></td>
<td>118</td>
</tr>
<tr>
<td>Focal plane Structural Support Conduction</td>
<td>129</td>
</tr>
<tr>
<td></td>
<td>158</td>
</tr>
<tr>
<td>Radiation to Coldlink from Optical Bench</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>24</td>
</tr>
<tr>
<td>Radiation to Coldlink from Vacuum Housing</td>
<td>177</td>
</tr>
<tr>
<td></td>
<td>195</td>
</tr>
<tr>
<td>Off-state Conduction of Redundant Cryocooler</td>
<td>486</td>
</tr>
<tr>
<td></td>
<td>496</td>
</tr>
<tr>
<td>Total Cryocooler Load</td>
<td>1173</td>
</tr>
<tr>
<td></td>
<td>1292</td>
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</table>
AIRS Predicted Cryocooler Thermal Performance

![Graph showing predicted cryocooler thermal performance](image)
AIRS Cryocooler Electronics Efficiency

$Ps = \frac{Pc}{0.81} + 2.2$

$Ps = \frac{Pc}{0.85} + 4.5$

SYSTEM INPUT POWER, watts

COMPRESSOR INPUT POWER, watts
## AIRS BOL/EOL Performance Margin Analysis

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>Unit</th>
<th>BOL Performance</th>
<th>200 mW Load Increase</th>
<th>15°C Heatsink Increase</th>
<th>Cooler Wearout Degrad.</th>
<th>EOL Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Focalplane Temperature</td>
<td>K</td>
<td>58</td>
<td>58</td>
<td>58</td>
<td>58</td>
<td>58</td>
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<tr>
<td>Total Cooler Cold-End Load</td>
<td>W</td>
<td>1.07</td>
<td>1.27</td>
<td>1.07</td>
<td>1.07</td>
<td>1.27</td>
</tr>
<tr>
<td>Cooler Cold-tip ΔT to FP (3 K/W)</td>
<td>K</td>
<td>3</td>
<td>3.4</td>
<td>3</td>
<td>3</td>
<td>3.4</td>
</tr>
<tr>
<td>Cooler Cold-tip Temperature (T_c)</td>
<td>K</td>
<td>55</td>
<td>54.6</td>
<td>55</td>
<td>55</td>
<td>54.6</td>
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<tr>
<td>Heat Rejection Coldplate Temp</td>
<td>K</td>
<td>290</td>
<td>290</td>
<td>305</td>
<td>290</td>
<td>305</td>
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<td>Expander to Coldplate ΔT (0.16 K/W)</td>
<td>K</td>
<td>9.8</td>
<td>11.2</td>
<td>10.6</td>
<td>12.0</td>
<td>16.8</td>
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<tr>
<td>Comp. to Coldplate ΔT (0.05 K/W)</td>
<td>K</td>
<td>3.0</td>
<td>3.5</td>
<td>3.3</td>
<td>3.8</td>
<td>5.3</td>
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<tr>
<td>Avg. Cooler Rejection Temp (T_R)</td>
<td>K</td>
<td>296</td>
<td>297</td>
<td>312</td>
<td>298</td>
<td>316</td>
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<tr>
<td>T_c Correction for T_R ≠ 300K (0.17 K/K)</td>
<td>K</td>
<td>+0.7</td>
<td>+0.5</td>
<td>-2.0</td>
<td>+0.3</td>
<td>-2.7</td>
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<tr>
<td>T_c Correction for Cooler Wearout</td>
<td>K</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-5.0</td>
<td>-5.0</td>
</tr>
<tr>
<td>Total Cold-tip Temp Correction</td>
<td>K</td>
<td>+0.7</td>
<td>+0.5</td>
<td>-2.0</td>
<td>-4.7</td>
<td>-7.7</td>
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<tr>
<td>Effective 300K Cold-tip Temp (T_EC)</td>
<td>K</td>
<td>55.7</td>
<td>55.1</td>
<td>53.0</td>
<td>50.3</td>
<td>46.9</td>
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<tr>
<td>Cooler Specific Power at T_EC</td>
<td>W/W</td>
<td>57</td>
<td>55</td>
<td>62</td>
<td>72</td>
<td>83</td>
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<tr>
<td>Cooler Compressor Power (P)</td>
<td>W</td>
<td>57</td>
<td>67</td>
<td>65</td>
<td>75</td>
<td>101</td>
</tr>
<tr>
<td>Total Input Power (P/0.9 + 10)</td>
<td>W</td>
<td>73</td>
<td>84</td>
<td>82</td>
<td>93</td>
<td>122</td>
</tr>
<tr>
<td>Compressor Stroke</td>
<td>%</td>
<td>64</td>
<td>68</td>
<td>67</td>
<td>70</td>
<td>80</td>
</tr>
</tbody>
</table>
AIRS BOL/EOL Operating State Verification Analysis

HEATSINK TEMPERATURE = 300 K

BOL/EOL Operating State

COLDTIP TEMPERATURE, K

COMPRRESSOR INPUT POWER, watts

SPECIFIC POWER, watts/watt

COLDTIP LOAD, watts

35K 40K 45K 50K 55K 60K 65K 70K 75K 80K

90% stroke
79% stroke
70% stroke
55% stroke
57% stroke

1.07 1.27

0 1 2 3 4 5 6 7
• Meet inrush and reflected *ripple current* requirements

• Accommodate broad *input voltage ranges* as compounded by high ripple current of cooler

• **Suppress EMI** to low levels consistent with MIL-Std 461 and accommodate MIL-Std 461 susceptibility levels

• Provide high *isolation from ground* loops: case isolated from ground; possible dc-dc isolation from power bus

• **Provide digital data interface** for communication of commands and transmission of measured parameters & performance data
AIRS Cryocooler Electronics
Conducted Ripple Current

28V Bus

Ripple Filter
Cooler Elect.

TIME, msec

COOLER SYSTEM INPUT POWER, watts

CURRENT, A

RIPPLE (I_{pp}/I_{Ave}), %

S/N 301
S/N 302

PEAK
AVE.
Prototype Magnetic Shields Used in Magnetic Shielding Studies
AIRS Compressor AC Magnetic Fields (With and Without Mag Shields)

AIRS coolers with mag shields

dB picoTesla at 7 cm

FREQUENCY, Hz

MIL-RE01

WITHOUT SHIELDS

WITH SHIELDS
AIRS Flight Pulse Tube Coolers

TRW (NGAS) AIRS PT Coolers

Launched on NASA Aqua Spacecraft in May 2002
Cooler Drive Level During First 50 Days of Mission

Time from Launch, Days

Cooler Drive Level, %

- 0.63 %/wk
- 1.02 %/wk

June 2002 July 2002 August 2002

6 7 8 9 10 11 12 13 14
Cooler Drive Level During First 120 Days of Mission
Cooler Load Point for 2-Cooler vs 1+Standby Operation

Operating Point with one-cooler operation

Operating Point with two-cooler operation

REJECT TEMPERATURE = 25°C
Cooler Drive Level Summary for 12 Years of Operation

Cryocooler drive level has remained relatively constant over past 12 years.
Operating Point with one-cooler in operation

BOL Operating Points with two-coolers in operation

12-year Operating Points with two-coolers in operation
AIRS was the first space instrument to commit to a pulse tube cryocooler and served as a very successful example

- Cooler performance characterization
- Dealing with Heat Rejection and Coldlink design
- Achieving tolerable generated vibration and EMI levels

During the 20 years since the AIRS conceptual design was developed, we've learned a great deal more about a number of integration challenges:

- Two-cooler operational redundancy trade-offs
- Space vacuum levels and contamination sensitivity
- Cryo MLI performance
- Internal ripple current suppression
- Lighter and more efficient 2-stage coolers that can accommodate both the 150K optical bench load and the 58 K focal plane load

Bottom Line: Space cryocoolers continue to evolve and we continue to learn how to improve their system performance