Herschel/Planck

HFI Bolometer Detectors
Programmatic CDR

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2001

Andrew Lange, PI
Timothy Koch, PEM
Overview: Scientific Requirements and Goals

- HFI contains 9 types of bolometric detector
  - 6 photometric bands
    (100, 143, 217, 345, 545, 850 GHz)
  - 3 polarization-sensitive bands
    (143, 217, 354 GHz)

- Ultimate Scientific Requirement is NET ($\Delta T_{cmb}$ sec $^{1/2}$) on-orbit
  - Function of bolometer properties + (photon background + optical efficiency + amplifier noise + other sources of system noise)

- Philosophy:
  - Well-defined budget for each contribution to noise
  - Well-defined specifications on specific, easily measured bolometer properties (dark electrical NEP, tau, G) that ensure that bolometer contribution to noise not exceed budget
  - Well-defined Requirements and Goals, with large margins to meet Requirements

  • Required performance ensures that precision of CMB power spectrum is limited by fundamental confusion by astrophysical foregrounds. Goal performance enhances secondary scientific goals.
Silicon Nitride Micromesh ‘Spider-web’ Bolometers

Spider-web architecture provides
• low absorber heat capacity
• minimal suspended mass
• low-cosmic ray cross-section
• low thermal conductivity = high sensitivity

Sensitivities and heat capacities achieved to date:
• NEP = 1.5 x 10^{-17} W/√Hz, C = 1pJ/K at 300 mK
• NEP = 1.5 x 10^{-18} W/√Hz, C = 0.4 pJ/K at 100mK

Operating in numerous sub-orbital experiments:

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Institution</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>BOOMERANG</td>
<td>Caltech</td>
<td>Antarctic balloon CMB instrument</td>
</tr>
<tr>
<td>SuZIE</td>
<td>Stanford</td>
<td>S-Z instrument for the CSO</td>
</tr>
<tr>
<td>MAXIMA</td>
<td>UC Berkeley</td>
<td>North America balloon CMB instrument</td>
</tr>
<tr>
<td>BOLOCAM</td>
<td>UMass</td>
<td>Bolometer camera for the CSO</td>
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<tr>
<td>ACBAR</td>
<td>UC Berkeley</td>
<td>Antarctic S-Z survey instrument</td>
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<tr>
<td>MAT</td>
<td>UPenn</td>
<td>CMB experiment for Chile</td>
</tr>
<tr>
<td>POLATRON</td>
<td>Caltech</td>
<td>CMB polarimeter for OVRO</td>
</tr>
<tr>
<td>Archeops</td>
<td>CNRS, France</td>
<td>CMB balloon experiment</td>
</tr>
<tr>
<td>PRONAOs</td>
<td>IAS, France</td>
<td>Submillimeter balloon experiment</td>
</tr>
</tbody>
</table>
Sub-Orbital Heritage: BOOMERANG

High cosmic ray flux
High and time-varying temperature gradients
Challenging EMI / RFI environment

- 18 detectors in focal plane
- NEPs $\sim 2 \times 10^{-17}$ W/Hz$^{-1/2}$ @ 300 mK
- Time constants $\tau \sim 10$ msec
- Feedhorn coupled
- AC-biased with 20 Hz post-demodulation bandwidth
- $1/f$ knee @ $\sim 30$ mHz
BOOMERANG: Map of CMB anisotropy

Temperature control

Measured noise stability in lab without

Boomerang PSD

Boomerang noise stability demonstrated in BOOMERANG
Overview:

Instrument Partners

- **CNES/IAS**
  - Centre National d'Etudes Spatiales
  - Institut d'Astrophysique Spatiale, Orsay, France
    - Jean-Loup Puget, HFI Principal Investigator
    - Jacques Charra, HFI Project Manager
    - Jean-Michel Lamarre, HFI Instrument Scientist

- **PPARC/Cardiff**
  - Particle Physics and Astronomy Research Council
    - Ray Carvell, UK HFI Project Manager
  - University of Wales, Cardiff (QMC group), UK
    - Peter A.R. Ade, UK HFI PI and Local Project Element Manager

- **NASA/Caltech/JPL**
  - Jet Propulsion Laboratory, Pasadena, USA
    - Gary Parks, US Herschel/Planck Project Manager
  - California Institute of Technology, Pasadena, USA
    - Andrew E. Lange, US HFI Principal Investigator
Overview:
Bolometer Environment on Planck/HFI

100 mK heat sink provided by 4 stages of cooling:
- Passive cooling to 50 K
- H sorption cooling to 18K
- JT cooling to 4K
- 3He/4He dilution to 0.1K

Optical backgrounds dominated by loading from instrument

Signal band of 0.016 to 90 Hz determined by 1 rpm rotation of satellite
Bolometer Modules

- Define interface
- Control all aspects of bolometer environment:
  - Optical
    - Stray light
    - Tuned backshort
  - Electrical
    - Electrical connection
    - RFI/EMI filter
  - Thermal
    - Heat sink via cover plate
  - Mechanical
    - Close packing in focal plane
    - XYZ and rotational position
- EM Modules deployed on ARCHEOPS: 0/24 failures
HFI Scientific Requirements and Goals:

Current Performance Estimates Meet Requirements in All Bands

<table>
<thead>
<tr>
<th>Detector Chain</th>
<th>Requirement [GHz]</th>
<th>Goal (T_{\text{cmb}} \text{sec}^{1/2} \text{uK})</th>
<th>Current Estimate*</th>
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<tbody>
<tr>
<td>100</td>
<td>99</td>
<td>47</td>
<td>70</td>
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<tr>
<td>143</td>
<td>123</td>
<td>51</td>
<td>77</td>
</tr>
<tr>
<td>217</td>
<td>182</td>
<td>74</td>
<td>112</td>
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<tr>
<td>354</td>
<td>553</td>
<td>231</td>
<td>350</td>
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<tr>
<td>545</td>
<td>4,000</td>
<td>900</td>
<td>1400</td>
</tr>
<tr>
<td>850</td>
<td>180,000</td>
<td>33,000</td>
<td>50,000</td>
</tr>
<tr>
<td>143P</td>
<td>161</td>
<td>72</td>
<td>110</td>
</tr>
<tr>
<td>217P</td>
<td>266</td>
<td>105</td>
<td>159</td>
</tr>
<tr>
<td>354P</td>
<td>810</td>
<td>326</td>
<td>492</td>
</tr>
</tbody>
</table>

* includes contributions from photon noise, bolometer noise, amplifier noise, and 10 identified sources of additional system noise
All Requirements Explicitly Stated in Business Agreement:

- Requirements on Bolometers:
  - Dark electrical $\text{NEP}_{\text{bolo}} < 0.88 \text{NEP}_{\text{BLIP}}$
  - Dark optical time constant $\tau_{\text{bolo}} < \frac{t_{\text{beam}}}{\pi}$
  - Responsivity under assumed optical load adequate to give $V_n > 7 \text{nV/Hz}^{1/2}$ load
  - Thermal conductivity adequate to maintain BLIP limited performance under 2 x higher than expected loading
  - Optical efficiency $> 25\%$ end-to-end, including all filters and focal plane feeds

- Requirements on System
  - Amplifier noise $< 7 \text{nV/Hz}^{1/2}$
  - Heat sink $< 110 \text{mK}$
  - Limits on following sources of excess noise:
    - Amplifier chain and CR deglitch
    - Straylight from payload
    - Straylight from sidelobe response to astrophysical sources
    - Temperature fluctuations of 4K, 1.6K and 0.1K stage
    - EMI
    - Microphonics
    - Data compression
Summary of Performance of P04 Engineering Prototype

Measured P04 Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G$</td>
<td>$122(T/0.1)^{1.34}$ pW/K</td>
</tr>
<tr>
<td>$C$</td>
<td>$0.17(T/0.1)^{1.34}$ pJ/K</td>
</tr>
<tr>
<td>$R_0$</td>
<td>77 $\Omega$</td>
</tr>
<tr>
<td>$\Delta$</td>
<td>15 K</td>
</tr>
<tr>
<td>$R_{op}(120 \text{ mK})$</td>
<td>5 M$\Omega$</td>
</tr>
<tr>
<td>$V_{nop}(120 \text{ mK})$</td>
<td>7.0 nV/(Hz)$^{1/2}$</td>
</tr>
<tr>
<td>$\tau$</td>
<td>1.0 ms</td>
</tr>
<tr>
<td>$\text{NEP}_{e,bol}$</td>
<td>1.43 e-17 W/(Hz)$^{1/2}$</td>
</tr>
</tbody>
</table>

Optical Speed of Response at $T_0 = 120 \text{ mK}$

Satisfies speed and sensitivity goals for 143 GHz channel
Worst-Case (100 GHz) Detector Noise Budget:

- Assumes 25% optical efficiency
- Assumes conservative CBE for BLIP
- Assumes worst-case for amplifier noise

• "System" = maximum allowed contributions to NET from:
  - Signal processing efficiency
  - Payload straylight
  - Sidelobes straylight
  - Temperature fluctuations of 0.1K, 1.6K, and 4K stages
  - EMI/RFI
  - Microphonics
  - Data compression

Summary of Contingency NET/ Bolometer NET:

<table>
<thead>
<tr>
<th></th>
<th>100</th>
<th>143</th>
<th>217</th>
<th>353</th>
<th>545</th>
<th>857</th>
<th>143P</th>
<th>217P</th>
<th>353P</th>
</tr>
</thead>
<tbody>
<tr>
<td>NET</td>
<td>99%</td>
<td>162%</td>
<td>177%</td>
<td>162%</td>
<td>450%</td>
<td>580%</td>
<td>124%</td>
<td>192%</td>
<td>183%</td>
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</tbody>
</table>
Margins Analysis

- Analysis of worst-case 143 GHz polarized channel
- Choose bias point to satisfy goal criteria with $R \leq 10 \, \text{M}\Omega$
- Otherwise satisfy specification with $R \leq 10 \, \text{M}\Omega$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Nominal Value</th>
<th>Satisfies Goal</th>
<th>Satisfies Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G_0$</td>
<td>pW/K</td>
<td>46</td>
<td>$33 &lt; G_0 &lt; 87$</td>
<td>$17 &lt; G_0 &lt; 87$</td>
</tr>
<tr>
<td>$C_0$</td>
<td>pJ/K</td>
<td>0.2</td>
<td>$C_0 &lt; 0.27$</td>
<td>$C_0 &lt; 0.55$</td>
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<tr>
<td>$R_0$</td>
<td>Ohms</td>
<td>155</td>
<td>$R_0 &gt; 50$</td>
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<tr>
<td>$Q$</td>
<td>pW</td>
<td>0.57</td>
<td>$Q &lt; 1.25^*$</td>
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<tr>
<td>$V_n$ (amp)</td>
<td>nV/rtHz</td>
<td>5</td>
<td>$V_n &lt; 9$</td>
<td></td>
</tr>
<tr>
<td>$T_0$</td>
<td>mK</td>
<td>100</td>
<td>$T_0 &lt; 113$</td>
<td></td>
</tr>
</tbody>
</table>

* In order that $\text{NEP}_{\text{det}} < (2hvQ_{\text{nom}})^{1/2}$; $\text{NEP}_{\text{det}} < (2hvQ)^{1/2}$ for $0.33 < Q < 5$

- Large margins in $G_0$, $R_0$, $V_n$, and $Q$, small margins in $C_0$, $T_0$
- Decreasing $V_n$ and/or increasing $R_0$ can provide more margin in $T_0$
- Need to include $\tau_{\text{elec}}(RC)$, $V_n(RC)$ in this analysis!
Model Philosophy

• Engineering Models
  – ARCHEOPS
    • Full-up balloon-borne technical and scientific demonstrator
    • Telescope, Focal plane optics, 0.1K cooler, and readout electronics all mimic Planck HFI
    • 24 EM detectors delivered in November 2000
    • In-flight performance verifies that end-to-end system can meet HFI requirements (optical efficiency of 30% achieved)
  – EBB
    • Laboratory simulator: first test of cooler chain including 4K compressors

• Flight Models
  – "Cryogenic Qualification Model"
    • First chance to test full Planck HFI + LFI focal plane and cooler chain
  – "Proto Flight Model"
    • Flight model

• JPL Qualification Models
  – Taken from CQM build
    • Qualification tests on these detectors prove reliability of detectors, but invalidate them as flight deliverables
## Total of 114 Bolometers to be delivered to HFI:

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>EBB Spare</th>
<th>EBB Spare</th>
<th>CQM Spare</th>
<th>CQM Spare</th>
<th>Flight Model</th>
<th>Flight Spares</th>
<th>Quantity Requirement</th>
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</thead>
<tbody>
<tr>
<td>100</td>
<td>0</td>
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<td>4</td>
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<td>1</td>
<td>4</td>
<td>2</td>
<td>8</td>
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<tr>
<td>217</td>
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<td>1</td>
<td>1</td>
<td>1</td>
<td>4</td>
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<td>545</td>
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<td>4</td>
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<td>857</td>
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<td>0</td>
<td>1</td>
<td>1</td>
<td>4</td>
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<td>8</td>
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<tr>
<td>143P</td>
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<td>0</td>
<td>2</td>
<td>2</td>
<td>8</td>
<td>4</td>
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<tr>
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<td>2</td>
<td>2</td>
<td>8</td>
<td>4</td>
<td>16</td>
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<td>0</td>
<td>2</td>
<td>2</td>
<td>8</td>
<td>4</td>
<td>16</td>
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<tr>
<td>217 Blanked</td>
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<td>0</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>6</td>
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<td>217 Resistor</td>
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<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>4</td>
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<tr>
<td>217 Capacitor</td>
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<td>1</td>
<td>2</td>
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<td><strong>TOTAL</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>114</td>
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</table>
European Instrument: Test Plans

- Bolometers delivered to Cardiff, UK
  - Cardiff integrate detectors with horns and filters.
  - Cardiff test one detector from each wafer for conformance check of end-to-end performance
  - Cardiff maintain one set of horns and filters from each CQM channel as a performance standard
  - Cardiff integrate detectors horns and filters into focal plane support plates
  - Cardiff characterize focal plane units in dilution test facility
  - Cardiff vibrate focal plane units to qualification levels and retest

- Focal Plane Units delivered to IAS, France
  - IAS integrate focal plane units into HFI
  - IAS mount HFI into large 4K cryostat and characterize instrument
  - IAS vibrate HFI to qualification levels and retest
European Instrument Status

- Cardiff, UK
  - Cardiff have experience from characterising engineering devices and from integrating and testing of 22 channels flown in Archeops.
  - Dilution fridge installed and is being modified for focal plane unit testing.
  - Horn procurement in progress
  - Filter production in progress

- IAS, France
  - IAS have experience from flight dilution system testing and Pronaues experiment with bolometer instrument
  - IAS are modifying the ISO test cryostat to install HFI for instrument characterisation

- Alcatel, France
  - Late start but now being integrated into programme
Business Agreement Status:
Requirements Documents

- "Requirements complete and stable" and "no changes in scope"
- Business Agreement updated in response to August 2001 Peer Review
  - Explicit Statement of Total System Noise Budget
  - Requirements on Optical Efficiency
  - Plan for Confirming Optical Efficiency
  - Requirement on Cross-Polarization of PSBs
  - Vibration Requirement
  - Agreed to by all parties, signed off
- Handling and Storage Requirements Document created in response to Peer Review includes:
  - Bakeout time and temperature
  - ESD, Cleaning, Venting, Thermal Cycling, Electrical
  - Shipping Containers and Receiving Inspection
  - Other handling requirements imposed on Instrument
  - Agreed to by all parties, sign off in process
- ICD updated
  - Mechanical and Electrical Interfaces
  - Agreed to by all parties, signed off
Rec / Del Plans and Status (With Europe)

- **Deliverables** (all detectors include data package with fabrication and test data):
  - EBB: 2 detectors
  - CQM: 24 detectors + 6 diagnostic loads
  - PFM: 72 detectors + 10 diagnostic loads

- **Receiveables**
  - Test data on opt efficiencies of detectors (from Cardiff)
  - CQM detectors for refurbishment to flight spares (from IAS)
Spider Web detectors demonstrated to meet all requirements at 143, 217 GHz
  - Most difficult channels to meet specs -> high confidence in all channels
New design tool (HFSS) allows optical and thermal performance of absorber geometry to be accurately modeled
  - Simulations show opportunity for significant (~ 15%) improvement in optical coupling
Low yield of 100 GHz devices will be improved by better mechanical design of web and legs
PSBs still in EM phase
  - Prototypes to date have failed to meet optical efficiency requirement
  - HFSS analysis confirmed that problem was in absorber impedance AND that high optical efficiency can be achieved with proper impedance match
  - EM/CQM wafer in fab now / optical tests complete before delta-CDR end of 11/01
Design of PFM detector masks will be finalized in December
  - Anticipate modest evolution in detailed design parameters from CQM devices
  - Goal: increased mechanical and electrical yield to minimize program cost and maximize performance of FM detectors
- Cryogenics working reliably
- Measurement electronics characterized:
  - 20/24 channels of bolometer signal acquisition functional
  - Well characterized transfer function allows $\tau_{\text{bolo}}$ to be measured
  - Excess noise < detector noise but needs more work!
- Optical modulation implemented
  - Low level optical signal injection demonstrated - allows $\tau_{\text{bolo}}$ to be measured optically
- Thermal stabilization plan in implementation
  - electronics characterized
  - thermometry sensitivity sufficient for evaluation
- Additional signal collection electronics (in process) will improve throughput, enhance automation of data collection