Detectors for the 10 000 pixel SCUBA-2 superconducting sub-mm camera for astronomy

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Sub-mm astronomy

- Sub-mm astronomy: wavelengths of a few hundred μm
  - Typically in “windows” around 450 and 850 μm (670 and 350 GHz)
- Lets us see cold things: peak in 10-K blackbody around 300μm
  - e.g. objects in formation (stars, planets…)
    - Also lets us see far away (red shifted) warmer objects: peak in 40 K blackbody at red shift Z=3 is at 300 μm
- Sub-mm emission usually “optically thin”; so we see the interior rather than just the surface of objects

Example: Eagle Nebula in visible light (Hubble Space Telescope):
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Example: sub-mm (850 μm) contours overlaid (SCUBA)
Instruments

• Instruments limited by small number of pixels
  • Gone from 1 pixel to 100s in a decade
  • Need more pixels!
  • But: can’t compromise on noise performance
• Aim is “BLIP” – background limited performance
  • Noise limit set by photon (shot) noise from sky

JCMT, Mauna Kea, Hawaii
UKT14
1986-1996
1 pixel
SCUBA
1997-2006
128 pixels
Detectors

- Most sensitive detection method is to use bolometers
  - Measure temperature rise due to absorbed radiation
  - Respond to wide wavelength range – define with filters
- Traditionally use NTD germanium thermistors
  - BUT: not background limited for best telescopes
  - Hard to make large arrays:
    - Ge chips have to be individually mounted on each pixel
    - Can’t multiplex without prohibitive noise penalty
    - Separate wiring and read-out electronics for each pixel required

SCUBA individual pixel  SCUBA focal plane  SPIRE array – multiple pixels on one silicon wafer
Solution

- Sensitive bolometer requires large $dR/dT$

- Very large $dR/dT$ through superconducting transition
- Basis of TES (transition edge sensor), operated in superconducting transition

- Other advantages:
  - TES sensors can be deposited on silicon wafer:
    - Entire array can be constructed with no operations at the level of a single pixel
  - Detectors can be multiplexed with acceptable performance
SCUBA-2

- Wide field TES imaging camera with up to 1000 x mapping speed of predecessor (SCUBA)
- Sensitivity limited by sky background (photon noise)
- Capable of carrying out large scale surveys
  - So far only area of about size of moon mapped to any depth in sub-mm

<table>
<thead>
<tr>
<th>SCUBA-2</th>
<th>SCUBA</th>
<th>UKT14</th>
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<tbody>
<tr>
<td>10240 pixels</td>
<td>128 pixels</td>
<td>1 pixel</td>
</tr>
</tbody>
</table>
Institutions

Instrument design, construction, testing, commissioning: ATC, Edinburgh

Multiplexer and TES devices: NIST, Boulder

Detector micromachining: University of Edinburgh

“1-K box” design and construction, detector test programme, filters/dichroic: Cardiff University

Warm electronics: University of British Columbia, MUX testing, University of Waterloo

Telescope infrastructure: Joint Astronomy Centre, Hawaii
Cryogenics

- Arrays must be operated from heat sink at 0.06 K
  - Cooling provided by dilution refrigerator (Leiden Cryogenics)
  - Operates from temperature of 4 K
    - Traditionally provided by bath of liquid helium
    - Instead use mechanical (pulse tube) cooler to reduce running costs
    - First commercial “dry” dilution refrigerator (?)
- Two more pulse tube coolers used for rest of instrument
Size

• Instrument size driven by need to cool large mirrors to below 10 K (to reduce thermal background on arrays)
**Multiplexing**

- Previous (much smaller) TES arrays have had separate detector and SQUID multiplexer chips.
- For arrays of this size, number of wires would be impractical.
- Instead, use new configuration: in-focal-plane multiplexer.
  - MUX wafer is bonded to detector wafer.
  - Indium bump bonds provide electrical connections.

A full-sized (40 × 32 pixel) multiplexer wafer.
Detectors

- Simultaneous dual colour imaging (450 and 850 µm)
- Each focal plane made up of four 1280 pixel sub-arrays
Detectors

• Time division multiplexing scheme
  • Separate readout box for each sub-array

• Pixels use Mo/Cu bi-layer superconductors
  • Weak thermal link provided by silicon nitride membrane
  • Pixel heaters used for sky background compensation

100 μm
Sub-array module

- Sub-array
- Niobium flex cables
- Shielded SQUID Series arrays
- Folded sub-array module
- Fully populated detector unit
- Detector unit with one prototype array installed

45mm

60 mK

1 K
Detector testing

• Tests carried out on prototype 450 and 850 µm arrays
  • First tests of in-focal-plane MUX detector
  • First tests of arrayed SCUBA-2 style pixels
    • (Previous tests on single pixels only)
• Tests validate in-focal-plane concept as well as this implementation

• Tests carried out:
  • In dedicated testbed (Cardiff University)
    • Contains calibrated illuminator for optical measurements
  • In SCUBA-2 instrument (ATC, Edinburgh)

• With test readout electronics
• With prototype of final electronics
Multiplexing

• Worked on small blocks of up to 72 pixels
  • All pixels read out simultaneously using multiplexer
  • Shown here responding to modulation of detector bias (6 columns, 12 pixels in each row)

• Readout chain (through three series of SQUID) is complex, and requires tuning of several parameters
  • Automatic tuning not available yet
Load curves

• Measure detector current as a function of bias current in multiplexed mode

• Basic characterization method

• Curves have expected shape

• Good agreement between two readout systems
Load curves

• Take set of load curves at different pixel heater settings

• Normal state resistance in agreement with design values √
Load curves

• Also plot as power in detector vs voltage
• Power constant in superconducting transition ✓
• Power proportional to $V^2$ in normal state ✓
• Responsivity ($S$) in transition proportional to $1/V$ ✓
• $S = 5e5$ to $8e6$ A/W. Values agree with those from modulating bias
Power measurements

- Three ways of applying power to a pixel:
  - Bias
  - Pixel heater
  - Optical signal
    - Calculate power using calibration for illuminator power and measured filter profiles

- Good agreement when power is applied all three ways
  - Calibration is well understood
    - We can have confidence in Noise Equivalent Power (NEP) values
Example

- For each load curve, plot electrical (heater+bias) power in transition
- Electrical power constant as heater power varies √
- Difference in power for shutter open and closed same for different pixels (NO calibration factor!) √
# Performance

<table>
<thead>
<tr>
<th>Parameter</th>
<th>450µm</th>
<th></th>
<th>850µm</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Spec</td>
<td>Single pixel</td>
<td>Proto array testing</td>
<td>Spec</td>
</tr>
<tr>
<td>$T_c$ (mK)</td>
<td>150 - 170</td>
<td>193</td>
<td>175</td>
<td>120 - 140</td>
</tr>
<tr>
<td>Total power (pW)</td>
<td>200 - 250</td>
<td>267</td>
<td>460</td>
<td>40 - 60</td>
</tr>
<tr>
<td>$G$ (nW/K)</td>
<td>~5</td>
<td>5.2</td>
<td>9.0</td>
<td>~1.5</td>
</tr>
<tr>
<td>Optical NEP (W/√Hz)</td>
<td>$&lt;29 \times 10^{-17}$</td>
<td>$9.7 \times 10^{-17}$</td>
<td>$14 \times 10^{-17}$</td>
<td>$&lt;7 \times 10^{-17}$</td>
</tr>
<tr>
<td>$\tau_e$ (msec)</td>
<td>&lt;1.5</td>
<td>0.2</td>
<td>0.6</td>
<td>&lt;2.8</td>
</tr>
</tbody>
</table>
Conclusions

• Detectors and read-outs operate in a stable and reproducible fashion

• Basic concept of in-focal-plane multiplexer works

• Array design has been proven with performance parameters met

• *Instrument* performance has been verified using prototype array

• Results have enabled us to go ahead with science grade array production