SCUBA-2: a 10 000-pixel submillimetre camera for astronomy

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***Abstract*—We describe the current status of the SCUBA-2 sub-mm camera for astronomy. We describe the first measurements made while operating an entire sub-array, rather than small subsections as has previously been the case. These results demonstrate that the procedure required to set up the multiplexer for full sub-array operation can be carried out entirely automatically, and that the pixels are sufficiently uniform for the whole sub-array to be usefully operated simultaneously.**

SCUBA-2 is the first wide-field, ultra-sensitive camera for sub-millimetre astronomy. With over 10 000 pixels, and operating in two frequency bands centred at 450 and 850 μm (670 and 350 GHz), it will enable research which addresses many of the fundamental questions in modern-day astronomy.

There has been a huge revolution in sub-millimetre astronomy (wavelengths of a few hundred μm to a few mm) in the past decade. The SCUBA [1] instrument on the James Clerk Maxwell Telescope in Hawaii was largely responsible for this. With over 100 pixels, and (for its time) state-of-the-art germanium semiconductor detectors, it enabled the sky to be mapped much more quickly and with improved fidelity when compared to the single pixel instrument which preceded it. However, with less than 1% of the sub-millimetre sky having been studied in any detail, there is a need for instruments with greatly increased mapping capability.

This requires a large increase in number of pixels over SCUBA. In addition, the overall noise performance of SCUBA was limited by the detectors. Ideally, detectors will achieve background limited performance (BLIP), in which photon noise from background radiation dominates.

Achieving the twin goals of improved noise performance and substantially increased pixel count has required a change in detector technology. Semiconductor detectors are not background noise limited for the best ground based telescopes, and have reached fundamental noise limits. In addition, extending the SCUBA design to large pixel counts is not feasible for two reasons. Firstly, it is not possible to use a multiplexed readout without an unacceptable noise penalty. Without multiplexing, an instrument such as SCUBA-2 would require an unworkable size of readout electronics, as well as number of wires to the detectors. Secondly, the germanium thermistor chips must be individually glued and wired to each pixel.

SCUBA-2 uses superconducting detectors (transition edge sensors). These have several advantages over semiconductor bolometers. As well as being able to achieve better signal to noise, all the fabrication stages are carried out on the array as a whole using standard micromachining techniques rather than separately on individual pixels. Finally, it is possible to constructed a multiplexed readout using superconducting electronics with only a small degradation in noise properties compared to individual readouts.

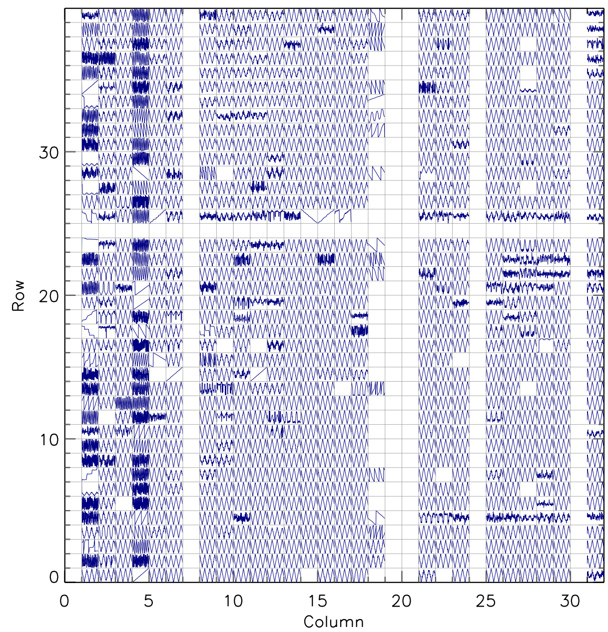

Fig. 1. The response to a bias modulation measured simultaneously by all pixels in one sub-array. For each pixel, the x-axis shows time, and the y-axis shows detector current.

Previous TES arrays have operated with a multiplexer which is separate from the detectors. While multiplexing reduces the wire count for large arrays to a manageable size, it is still of course necessary to wire each pixel to the multiplexer. This limits the practical size of an array. SCUBA-2 uses a new configuration, in which the silicon wafer carrying the multiplexing circuitry is bonded directly to the detector wafer by indium bump bonds. These provide superconducting electrical connections between each pixel and the multiplexer, as well as bonding the two wafers together. This enables arrays of over 1000 pixels to be constructed, with the size only limited by the size of wafer which can be handled. These arrays can be butted on two sides, to form focal planes of over 5000 pixels. They are thus often referred to as sub-arrays, with the SCUBA-2 focal plane containing a set of four sub-arrays

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at each frequency.

The detectors are not the only challenging part of the instrument. In order to reduce operating costs, the instrument uses mechanical (pulse-tube) coolers rather than the conventional approach of using liquid cryogens for cooling. The low temperature thermal design [2] is highly complex. The detector arrays operate at temperatures below 100 mK, and are located approximately 1 metre away from the dilution fridge which provides the cooling power. A complex system of thermal links is therefore required. Making good thermal contact to the silicon multiplexer wafer without damage being caused on cooling down due to differential thermal contraction was also challenging [3]. Other difficulties include cooling 300 kg of mirrors inside the instrument to 4 K and providing sufficiently good magnetic shielding around the SQUID circuitry to prevent magnetic interference from disrupting operation. Tests on the instrument with prototype arrays have shown that all these areas function according to the requirements.

The detectors [4] consist of Mo/Cu bi-layer thermistors, with weak thermal linking provided by a silicon nitride membrane. Fabrication is carried out at NIST (Boulder, Colorado) and at the Scottish Microelectronics Centre, Edinburgh. The multiplexer [5], designed and fabricated at NIST, operates using a time division multiplexing scheme.

Operating TES detectors requires sophisticated electronics. The current through each pixel is measured using a SQUID [6]. A SQUID has a periodic response to the input, and each SQUID is therefore used as a null detector, with a feedback signal being applied to null out the detector signal. The readout chain consists of three SQUID stages in series. For successful operation each SQUID stage has to be set up appropriately, and correct parameters chosen for the feedback for each pixel.

Until recently, tests on SCUBA-2 arrays have required these operations to be carried out manually. Therefore, we have previously only been able to report on tests of small numbers of pixels [3], [7], [8]. However, the readout system which will be used at the telescope is now available. This was developed by the University of British Columbia, NIST and the UK Astronomy Technology Centre. As well as being able to address a full sub-array at once (the previous readout system could only address one quarter), it can automatically set up the parameters to operate the entire array, enabling simultaneous measurements of all pixels to be made for the first time. An example is shown in Fig. 1; this shows the response of each pixel to a modulation in the bias current.

From these measurements, we can determine the yield of good pixels. This was approximately 70% and 40% for the 850 μm and 450 μm arrays respectively. Flaws in the multiplexer wafer were responsible for almost all the failed pixels. The multiplexers for the science grade sub-arrays have already been produced and screened, with yields of over 90% measured. We therefore have confidence that the science grade arrays will have acceptable yields.

The bias supply to all the pixels in a single sub-array is wired in series. Operating a whole sub-array is only possible if the pixels have sufficiently uniform properties (such as the superconducting transition temperature, the thermal conductance to the absorber in each pixel and the detector resistance). If the variation in properties is too large, it will not be possible to choose a value of the detector bias which permits simultaneous operation of all the pixels. Our tests show that both sub-arrays are indeed operable simultaneously, confirming earlier measurements on small numbers of pixels distributed across arrays.

The instrument is now essentially complete, and is nearing delivery standard. Currently there is one commissioning grade sub-array installed for each wavelength (full operation will require eight sub-arrays). The presence of these arrays enables verification measurements to be carried out on the instrument itself as well as the arrays themselves.

Instrument verification is currently underway; this includes optical tests and operational modes. Delivery to the JCMT is planned for late summer 2007, with one science grade sub-array installed for each frequency in addition to the two commissioning grade sub-arrays. The remaining science grade sub-arrays will be installed at a later date once they have been completed and characterised.

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