Automatic setup of SCUBA-2 Detector Arrays

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ABSTRACT

The detector arrays for the SCUBA-2 instrument consist of TES bolometers with superconducting amplifier and multiplexing circuits based on Superconducting Quantum Interference Devices (SQUIDs). The SCUBA-2 TES arrays and their multiplexed SQUID readouts need to be set-up carefully to achieve correct performance. Algorithms have been developed and implemented based on the first available commissioning grade detector, enabling the array to be set up and optimized automatically.

Keywords: TES, superconducting detectors, submillimetre astronomy, SQUID, array, SCUBA-2, optimum algorithm, automatic, JCMT

1. INTRODUCTION

Bolometer detectors have been used for far–infrared, millimetre (mm) and sub-millimetre (sub-mm) wave astronomy for over 40 years, but it is only in recent years that imaging bolometer arrays have come into use on large sub-mm/mm telescopes. The move away from signal-pixel devices to multi-element cameras has led to a number of discoveries and the emergence of the sub-mm/mm as one of the most important wavelength regimes for astrophysics [1]. The discoveries made using instruments such as the SCUBA camera at the James Clerk Maxwell Telescope (JCMT) played a fundamental role in the advance of sub-mm/mm astronomy. The next major development will be the introduction of a new generation of detectors using superconducting Transition-edge Sensors (TES). Bolometer cameras based on TES [2][3] will provide the high sensitivity and high mapping speed needed to perform precision cosmic microwave background measurement and accurate characterisation of extra-galactic sub-mm galaxies [4].

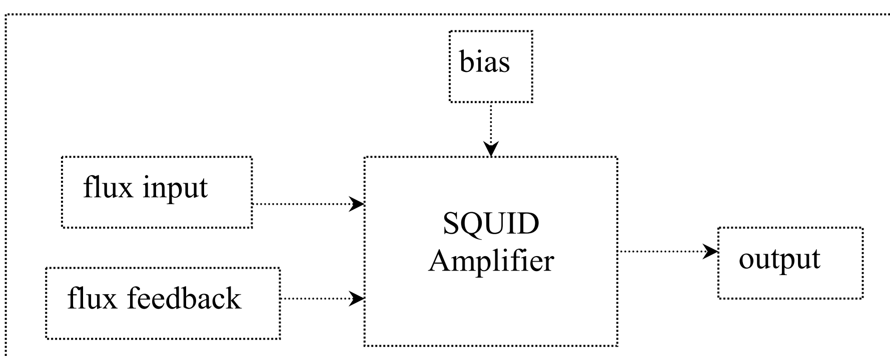

Fig. 1. Block diagram of a SQUID amplifier

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SCUBA-2 has two focal planes, one for working at a wavelength of 850um and the other at a wavelength of 450um[5]. Each focal plane holds a mosaic of four TES detector arrays each with a pattern of 32-by-40 bolometers. In addition each detector array has a "dark" row which has the full readout circuitry but no bolometers, providing for 1/f noise measurement. The resulting 1280 bolometers plus 32 dark pixels per array are readout with the help of an advanced superconducting multiplexing scheme [6], whereby each bolometer/dark pixel has a dedicated SQUID we call SQ1. All the SQ1s in a 41 element column have their output signals coupled by a superconducting DC transformer to a summing coil which provides the input to a single SQUID (SQ2). The multiplexing scheme operates by only having one row of SQ1s enabled at a given instant, the rest having their biases set to zero, so presenting each SQ2 with a selected input. The output from each of the 32 SQ2s is fed to each input of 32 SQUID Series Arrays (SSA) for further amplification before passing through the cables leading to the room temperature circuitry.

2. SQUID CHARACTERISTICS

SQUIDs are very sensitive, low noise magnetometers. They are used as amplifiers by feeding their electrical input signal through a coil whose magnetic field is detected by the SQUID as flux input. The result is a non-linear amplifier whose output varies like a cosinusoid as a function of input. The circuit is linearised by holding the SQUID near one of the inflection points on its characteristic by a suitable negative feedback scheme applied through a flux feedback coil.

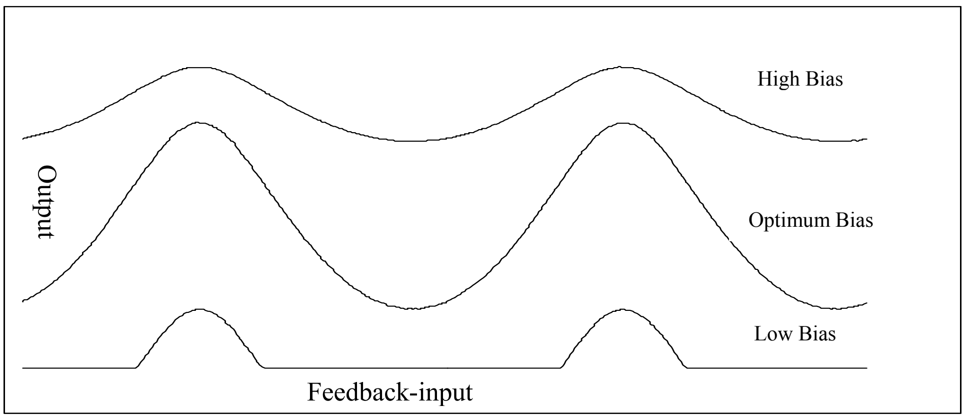

Fig. 2. The typical SQUID characteristics for low, optimum and high bias

We use SQUIDS in one of two modes, open-loop and closed-loop. In open-loop, the input to the SQUID is "arranged" so that it only changes by a small amount, and the feedback is held constant - in other words the SQUID is used as a DC amplifier with very small dynamic range. In closed-loop mode the input is allowed to change over a much wider range, and the feedback is continually updated to maintain the total input to the SQUID at a fixed level. In closed-loop, the "measurement" taken by the system is equal to the required feedback level

3. SETTING UP SQUIDS IN SERIES

The performance of a single SQUID can be optimised by experimentally determining the bias setting which gives the best response characteristic. For SCUBA-2 we have the problem that we have three sets of SQUIDs in series. This means that, although we can optimise the SSAs directly, the SQ2 outputs are measured via the SSAs, and the SQ1 outputs go via both the SQ2s and the SSAs (Fig.3).

The procedure is to start by setting the circuit so that the output from SQ2 is constant. SSA can then be characterised by recording its output for various settings of its flux feedback and its bias. Once its optimum bias has been chosen, the output it generates when its total input puts it on the preferred point of its characteristic is known (SSA-OPEN, Fig. 8). It can then be used in closed-loop mode (SSA-CLOSE) to characterise SQ2.

SQ1 is set up to provide a constant input to SQ2. SQ2 is then characterised in SSA-CLOSE mode (Fig 4) by recording the required SSA feedback for various settings of SQ2 flux feedback and bias. Once its optimum bias has been chosen, the output it generates when its total input puts it on the preferred point of its characteristic is known (SSA-OPEN,SQ2-OPEN, Fig. 5). It can then be used in closed-loop mode (SQ2-CLOSE) to characterise SQ1.

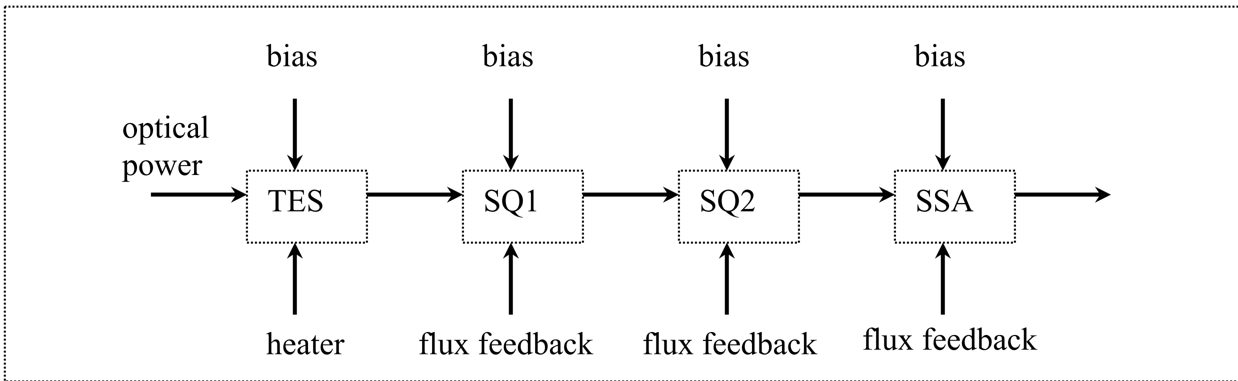

Fig. 3. The overall measurement circuit

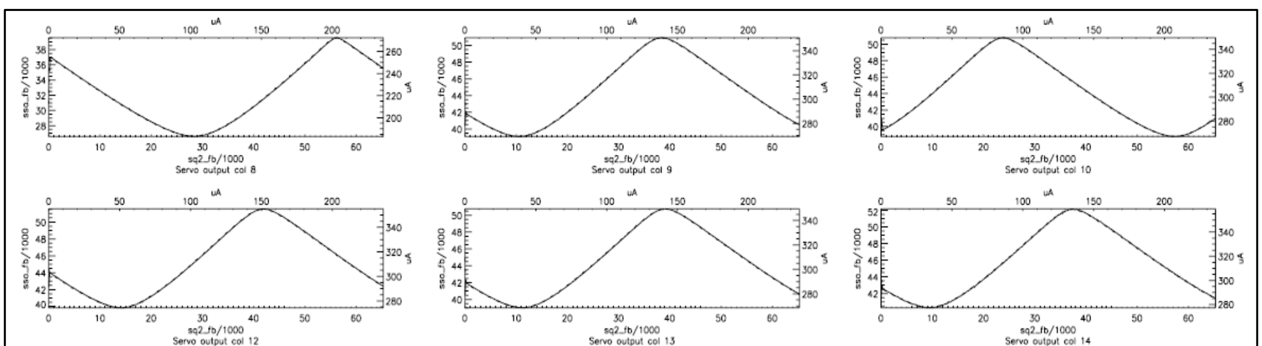

Fig. 4. Example SQ2 responses at optimum bias using SSA-CLOSE. Y-axis=SSA feedback, X-axis=SQ2 feedback

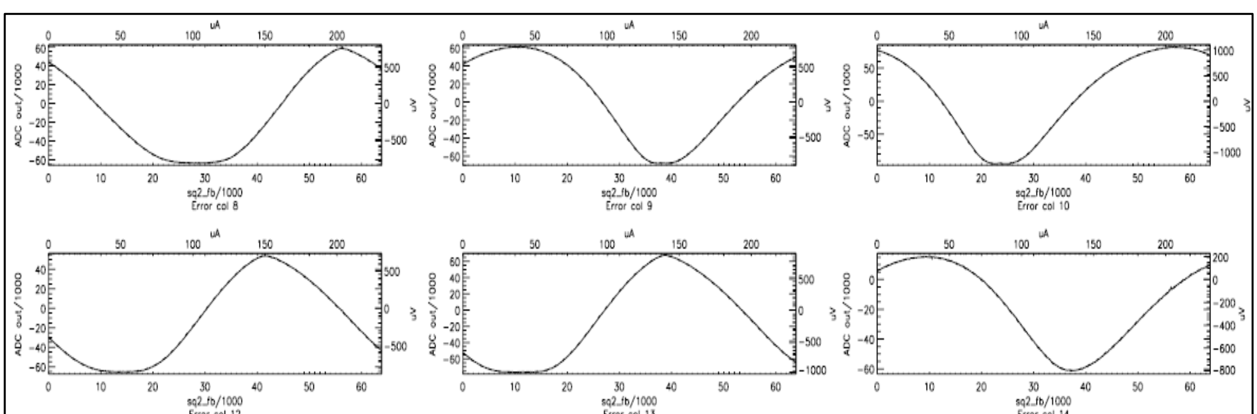

Fig. 5. Example SQ2 responses at optimum bias using SSA-OPEN. Y-axis=SSA output, X-axis=SQ2 feedback

The final stage of SQUID setup involves operating SSA in open loop mode and SQ2 in closed-loop mode (Fig.6). The TES is set-up so that its output is fixed. SQ1 is then characterised by recording SQ2 feedback for various settings of SQ1 flux feedback and SQ1 bias. Once its optimum bias has been chosen, the output it generates when its total input puts it on the preferred point of its characteristic is known (Fig.7).

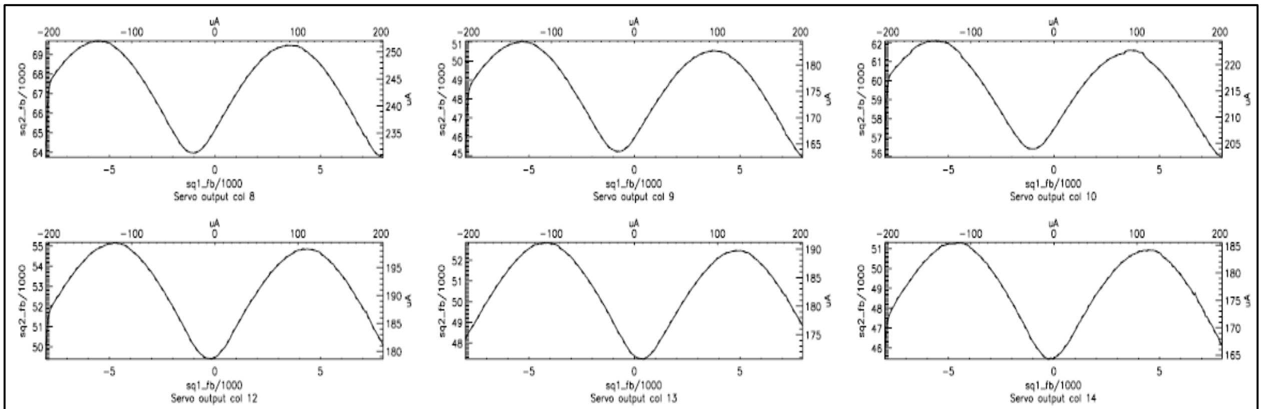

Fig. 6. Example SQ1 responses at optimum bias using SSA-OPEN and SQ2-CLOSE. Y-axis=SQ2 feedback, X-axis=SQ1 feedback

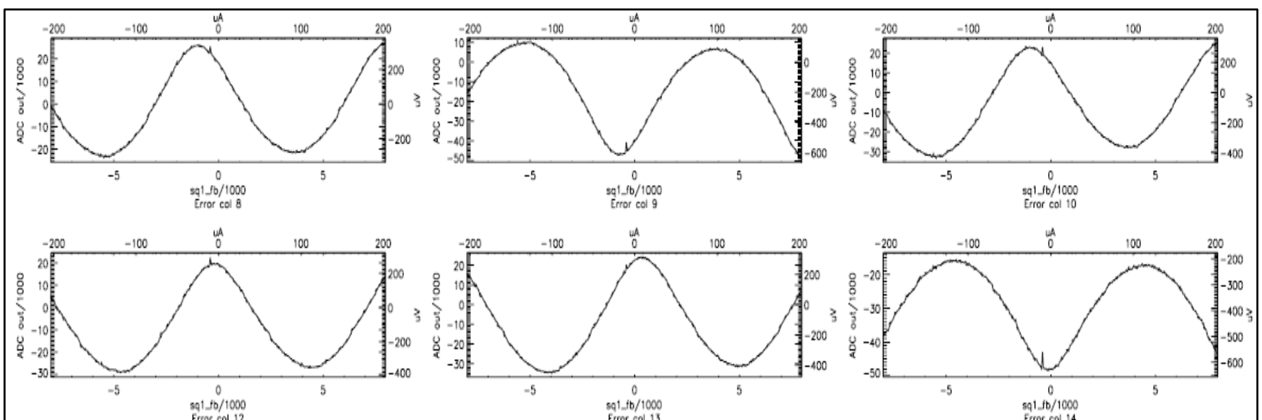

Fig. 7. Example SQ1 responses at optimum bias using SSA-OPEN and SQ2-OPEN. Y-axis=SSA output, X-axis=SQ1 feedback

4. CLOSED-LOOP ALGORITHM

Assume that a working point L is chosen near the inflection on the positive slope in the SQUID characteristic curve (see Fig. 8). The amplifier gain near the working point is approximately:

$$\text{gain} = \frac{NP}{MP} \tag{1}$$

Suppose at the i-th instant feedback(i) is applied to the SQUID, and the resulting output from SSA is ssaOut(i). In the next step, in order to adjust the SQUID back to its working point the feedback is updated by

$$\text{feedback}(i+1) = \text{feedback}(i) - (\text{ssaOut}(i)-\text{ssaoutL}) / \text{gain} \quad (2)$$

where ssaoutL is the value of ssaOut at L. (Fig. 8)

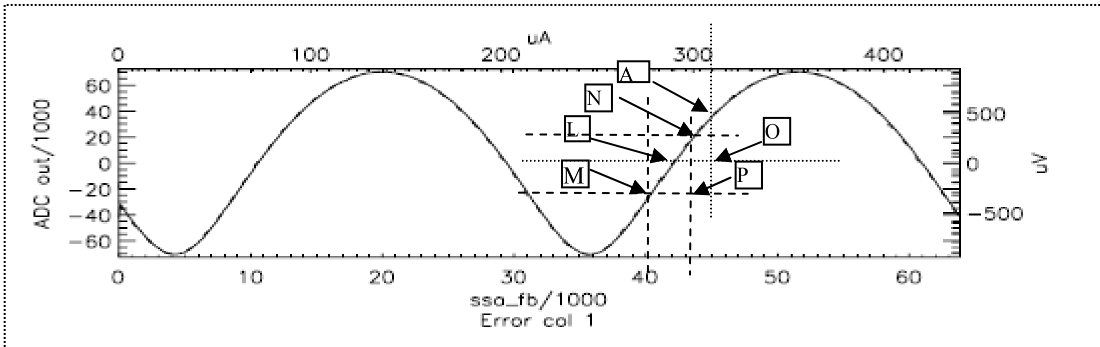

Fig. 8. A typical SSA characteristic curve, SSA output (Y-axis) versus SSA feedback (X-axis).

5. SQ1/SQ2 OPTIMISATION ALGORITHM

Each pixel's SQ1 has an optimum bias which maximises its usefulness as an amplifier, but a single bias setting is used to activate an entire row of 32 SQ1s, meaning a compromise bias has to be chosen for each row.

When an SQ1 is at this bias, the best closed-loop operating point on the resulting response curve implies that the SQ1 will deliver a certain current to the SQ2 handling that column. The SQ2 should be set onto a good working point by adjusting its flux feedback to match the SQ1 output, but in practice the SQ2 feedback is held constant as different SQ1s in a column are switched on and off. This means a compromise SQ2 feedback has to be selected to handle all the SQ1s in a column.

Measurements from experiment indicate that, provided the change in SQ1 bias is not too large, then a linear relationship can be expected describing how SQ2 feedback should change to match changing the bias on a SQ1.

Let
F_i = compromise SQ2 feedback for i-th column
B_j = compromise SQ1 bias for j-th row
b^{max}_{ij} = optimum bias for an SQ1
s_{ij} = constant for each SQ1
α_{ij} = optimised SQ2 feedback for given SQ1 at b^{max}_{ij}

The linear SQ1 bias versus SQ2 feedback relationship is

$$\alpha_{ij} - F_i = s_{ij} \, (b^{max}_{ij} - B_j) \quad (3)$$

Take a second measured "reference" bias at a higher level

b^{ref}_{ij} = reference bias for an SQ1
β_{ij} = optimised SQ2 feedback for given SQ1 at b^{ref}_{ij}

i.e. $\alpha_{ij} - \beta_{ij} = s_{ij} (b^{max}_{ij} - b^{ref}_{ij})$

Hence
$s_{ij} = (\alpha_{ij} - \beta_{ij}) / (b^{max}_{ij} - b^{ref}_{ij})$ (known variables)
$\alpha_{ij} - s_{ij} b^{max}_{ij} = F_i - s_{ij} B_j$

define $\Delta_{ij} = \alpha_{ij} - s_{ij} b^{max}_{ij}$ thus $\Delta_{ij} = F_i - s_{ij} B_j$

define $\delta_{ij} = 1$ for $i = j$; $\delta_{ij} = 0$ otherwise

we have

$$\Delta_{ij} = \Sigma_m \delta_{im} F_m - \Sigma_k \delta_{jk} s_{ik} B_k \qquad (4)$$

These can be used for a least-squares solution, but note that adding a constant ε to all F_i and ε / s_{jk} to all B_k would also satisfy the equations, so an additional constraint is required. An obvious constraint is to set the mean B_k to be equal to an acceptable average b^{max}_{ij}.

6. OPERATING A FULL ARRAY

Once the compromise B_j, and F_i are found, all the SQUID characteristics are known. SSA and SQ2 can then be operated open-loop acting as a high-gain small dynamic range amplifier, and SQ1 is operated closed loop with real-time control provided by an FPGA-based Multi-Channel-Electronics[4] to allow the system to deal with the actual output from the TES.

7. CONCLUSION

Optimum algorithms implemented for the first available commissioning grade sub-millimeter CCD-style detector array have been presented with real response data diagrams. Automatic setup, which takes less than 10 minutes to complete, has greatly smoothed the array testing program, giving the SCUBA-2 project better understanding of the array's behaviour leading to further improvements in the array design preparatory to the production of science grade detectors.

8. ACKNOWLEDGEMENTS

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