UK Astronomy Technology Centre
Royal Observatory Edinburgh
SCUBA-2 Project

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SC2/ANA/S100/41
Version 2

SCUBA-2 Digitisation Scheme

1. Summary

The principles behind the NIST scheme for digitising the multiplexed readout from the arrays are described.

Version 2 updates the timing and sampling frequencies.

2. References

"Superconducting multiplexer for arrays of transition edge sensors", J.A.Chervenak, K.D.Irwin, E.N.Grossman, John M.Martinis and C.D.Reintsema, Applied Physics Letters, 74, p.4043, 1999

"SCUBA 2 Relative Pixel Calibration", B.D.Kelly, 2001, SC2/ANA/S100/35

"SCUBA 2 Pixel Bandwidth and Multiplexing", B.D.Kelly, 2002, SC2/ANA/S100/36

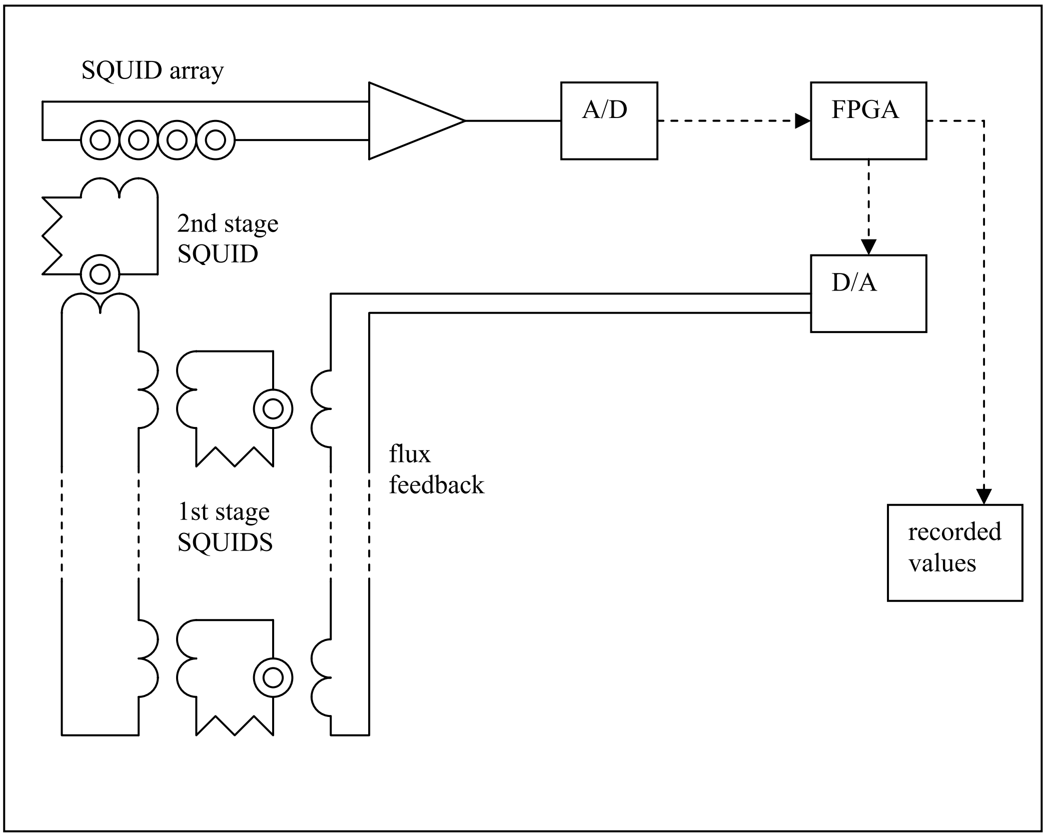
3. Introduction

This document describes the practical details of the NIST multiplexed digitisation scheme for reading out the SCUBA-2 arrays, which they developed following the Chervenak et al. paper. Background on the overall readout scheme is provided by SC2/ANA/S100/35 and SC2/ANA/S100/36.

There are some slight descriptive difficulties where it is known that the actual system used by NIST will be modified for SCUBA-2 (eg. the NIST circuit used 12-bit A/Ds, SCUBA-2 will use 14-bit A/Ds). Where a clear decision has been taken, the SCUBA-2 variant is described.

4. Multiplexing

4.1 Multiplexer Circuit Elements



The first stage SQUIDs are turned on and off in sequence at the multiplexing rate. The multiplexer circuit includes the output coupling from the first stage SQUIDS, the second stage SQUID, the SQUID array, the room temperature amplifier, the A/D, the FPGA system and software, the D/A and the flux feedback circuit. This whole analogue-digital circuit has to run at 40 times the rate needed to read-out a single TES circuit (assuming 40 pixels to a column). This turns into a bandwidth about 120 times the bandwidth of the "Johnson noise envelope" (allowing a factor three to ensure the Johnson noise is fully sampled). There is no possibility of having an analogue low-pass filter to remove the Johnson noise, so this filter has to be applied to the "recorded values" using software.

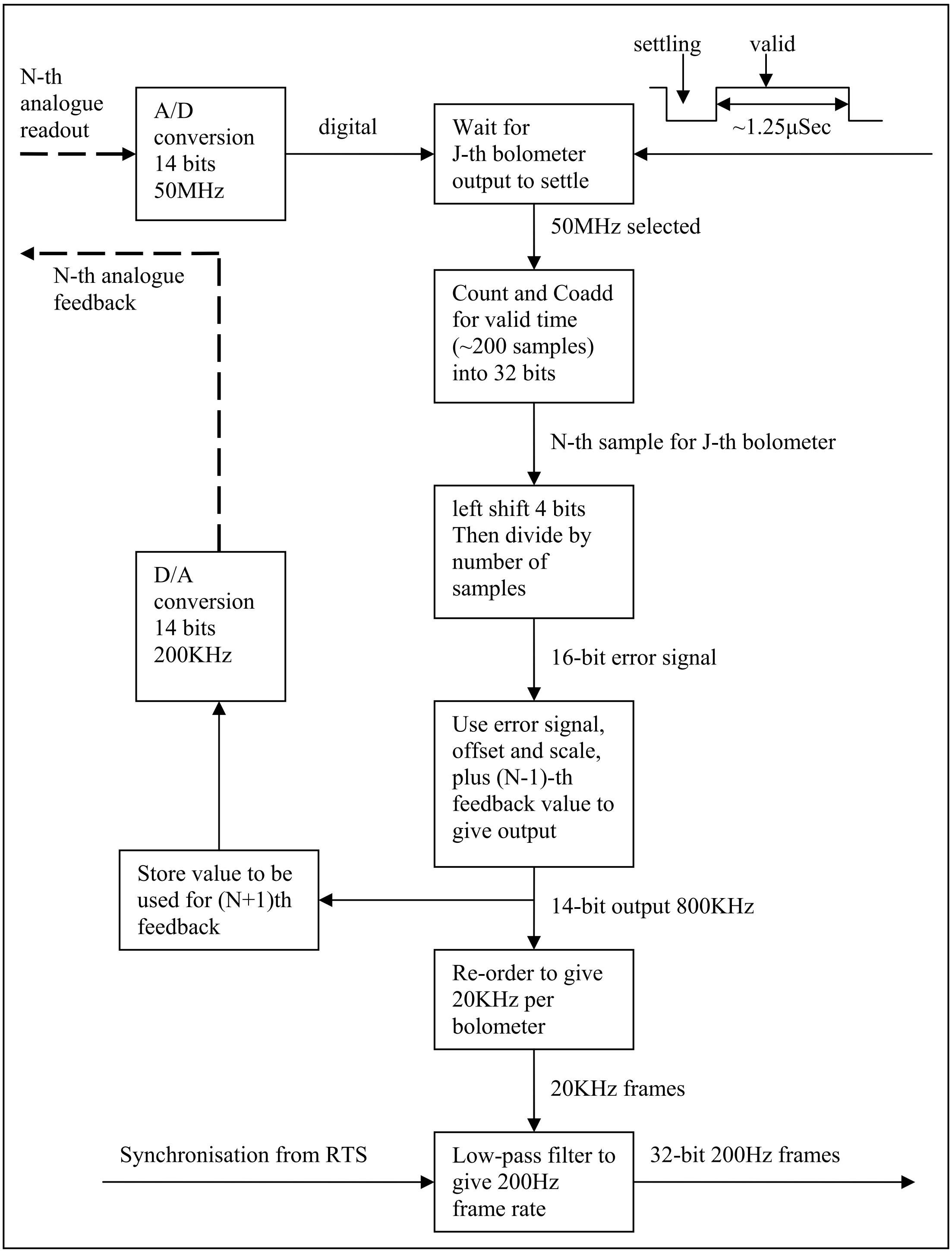
Any noise arising in the multiplexer circuit itself is unavoidably very undersampled, and so this noise has to be kept very low in comparison with the TES circuit noise.

4.2 Digitisation

For any individual TES circuit, the "recorded value" is the D/A setting plus a constant times the A/D value read back. The next time around, the D/A setting is set to the previous "recorded value". The A/D value is normally expected to be a small correction to the D/A setting.

5. Digitisation Details

5.1 Principle of Processing Chain



5.2 50 MHz Gating and Generation of 16-bit Error Signal

The analogue signal changes suddenly as the input is switched from one pixel to another. The signal from a particular bolometer needs to be generated by ignoring an initial settling time and then taking an average of the settled level before the switch to the next pixel occurs. This is achieved digitally by sampling the analogue signal at 50MHz, which is a rate much higher than the pixel switching rate, then ignoring the samples taken during the settling time. The samples taken during the steady period can then be averaged. If there is very broad band noise present in the signal at greater than one bit digitisation, then the averaging also increases the effective number of digitisation bits.

The NIST algorithm for "averaging" within the FPGA environment is complex (in fact because of limited processing power it avoids performing the actual division, instead it assumes the number of samples taken is the same when taking data and when performing the initial setup so that the calibration constants have the scale factor built in) and is not described here. A simple alternative follows.

A reasonable integer algorithm produces a 32-bit sum with some spare least-significant bits, and then divides to produce the average in 16 bits

$d_{32} = \left(\sum d_{14}\right) * 2^4$

$d_{16} = d_{32} / M.$

Where M = number of samples coadded.

5.3 Calculate Output and Next Feedback Value

These values are all specific to the J-th bolometer.

A_N = the 16-bit measurement for the N-th readout of this bolometer

F_N = the 14-bit feedback value which was applied before taking the N-th measurement

F_{N+1} = the 14-bit feedback value which will be remembered for use in the (N+1)-th measurement

Offset and K provide the linear relation between the small measured error signal and the feedback signal.

Then:

$A_N = (F_N * 4) + (d_{16} - \text{Offset}) * K$

$F_{N+1} = A_N / 4$

Note that the measured error is relative to the value fed back, so the final answer is computed from the F_N, not from the previous answer (A_{N-1}).

Note also that "(F_N * 4)" is a 16-bit number. "(d_{16} - Offset) * K" is positive or negative, and so adding them, formally, can result in the 16-bit sum over- or under-flowing. This is physically meaningful (the demand for F_N has actually gone out of range), and should be handled in a way which allows for easy recovery. Relevant items might be marking bad values and deliberate flux jumping.

Note that again the NIST implementation does not use precisely this algorithm. Instead it performs something like

$A_N = P*new\_d_{16} + I*sum\_of\_old\_d_{16} + constant$

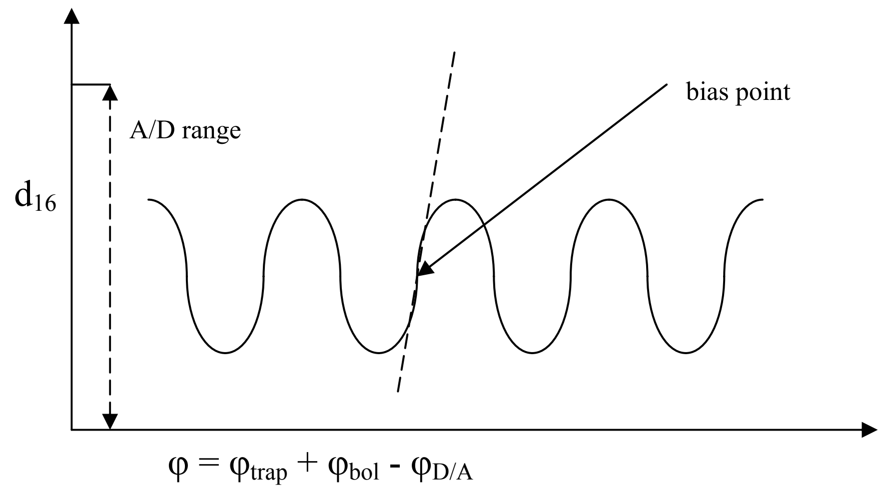
Where P and I are constants set from outside and are approximately equal to one another. If Pand I are exactly equal, then this is equivalent to the above algorithm (ignoring the precise techniques for generating the correct number of bits).

5.4 Sorting and Low-Pass Filtering

The 800KHz output values are stored in a sorted order to give 20KHz time sequences for each bolometer. These are low-pass filtered and subsampled at times indicated by the RTS to give the final output of 200 frames/sec.

6. Relationship Between Feedback and Error

If the signal input to the first-stage SQUID is constant, then the function obtained by recording the A/D output as a function of the value fed into the D/A is, essentially, the V-φ curve of the first-stage SQUID.



φ_{trap} is the flux trapped in the SQUID.

φ_{bol} is the flux generated by the signal current coming from the bolometer.

$\varphi_{D/A}$ is the flux generated by the current issued from the flux feedback D/A.

Assuming the D/A setting is linearly related to the flux it generates, then close to the bias point there will be an approximately linear relationship between changes in D/A setting and the resultant change in the A/D measurement.

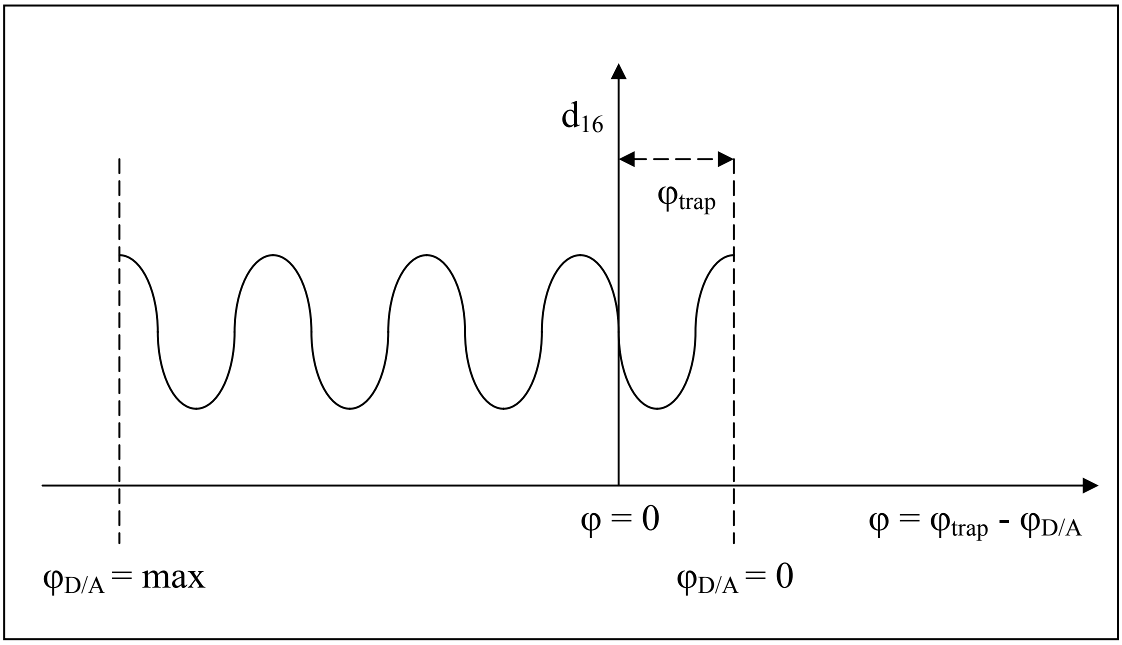
This results in the relationship

$\Delta F_N = (d_{16} - \text{Offset}) * K$

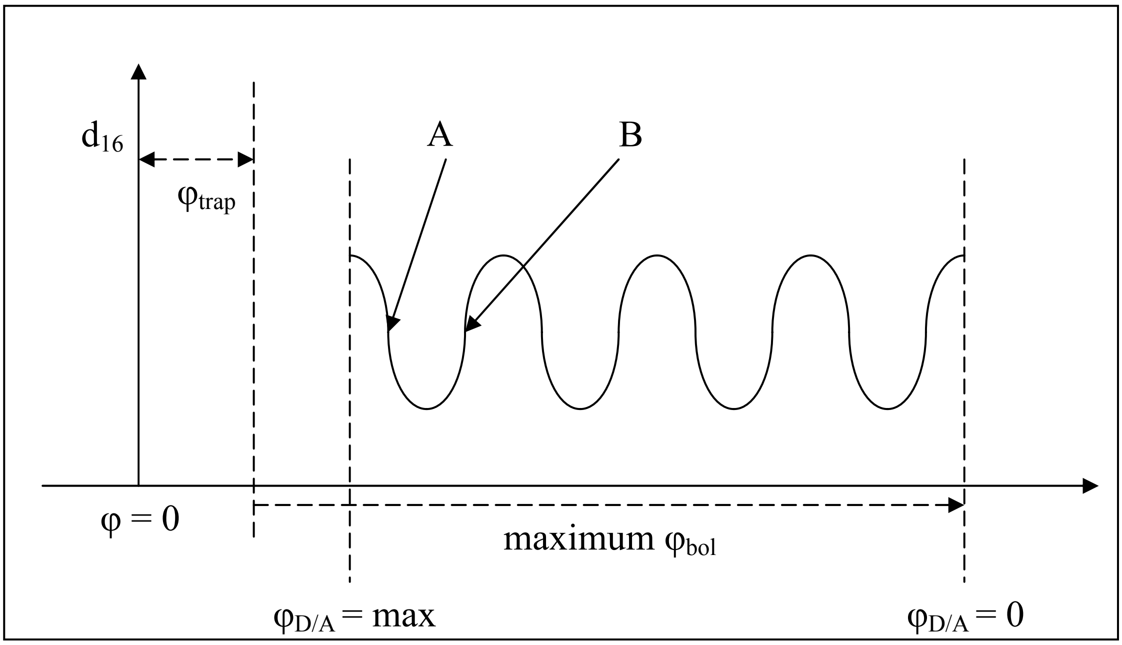
where Offset is the value of d_{16} at the bias point. This is used in the calculation of the output value presented in a previous section.

7. Operational Issues

7.1 Basic Principles



Initial set-up of the first stage SQUID is performed with zero input from the bolometer. This means that the operation is carried out on a completely different part of the V-φ curve from that used in normal operation.



The diagram shows the range of possible feedback values from the maximum bolometer signal.

In normal operation, the feedback flux is used to cancel out part of the combined trapped and signal flux, to arrive at the chosen bias point. Strictly, Offset and K should be determined for this point, rather than the part of the characteristic which is available when the bolometer signal is zero.

Possible bias points are shown marked A and B. This demonstrates that the bias point can equally well be on a rising or falling section of the characteristic, the slope constant K having a different sign in the two cases.

7.2 Initialisation

The system has to be initialised by first operating without the feedback loop. The signal from the bolometer and the feedback signal have both to be set to a known value (this means closing the shutter and setting the heaters to put the right amount of power into the bolometers). This gets all the first stage SQUIDs close to the selected bias point. F_1 is set explicitly for each pixel, and then the feedback loop is started:

$A_1 = (F_1 * 4) + (d_{16} - \text{Offset}) * K$

$F_2 = A_1 / 4$

and so on.

7.3 Flux Jumping

When the feedback loop is running it is possible for any pixel to jump and lock onto an alternative point on the characteristic. This happens if the bolometer flux changes too quickly for the feedback loop to follow, or if the bolometer flux goes outside the range which can be cancelled by the feedback flux. In either case, the new lock point is an integer number of cycles of the (approximately periodic) characteristic away from the intended bias point. This results in a jump in the measurement zero point for the pixel in question.

8. Conclusion

The array digitisation scheme is quite complex, both in its initial set up and its standard recording condition. The detection of zero point shifts due to flux jumping is a problem - the only obvious resolution of which is to move smoothly to a standard bolometer input signal (eg. closing the shutter slowly while increasing the heater power) and comparing the measured values with those expected. This could be a serious problem if cosmic ray hits on bolometers cause flux jumping.