Timing jitter in *SCUBA2* array readout

<u>The problem:</u> There is a request that we read out the *SCUBA2* arrays with very little timing jitter upon receipt of a Data Valid (DV) pulse from the real time controller. The request is that we return a filtered array image within a few μs of receipt of the DV pulse. This is awkward since we read the full array only at 20 KHz, ie every 50μs. It is the purpose of this note to estimate the effect which timing jitter of this magnitude might have on anticipated data. We will look at equivalent voltage noise and at equivalent pointing errors separately.

Timing details The *SCUBA2* arrays are read out by multichannel electronics which read all 32 detectors in a given row simultaneously, and step from row to row at just over 800 kHz. There are 40 illuminated rows and one dark one, so the entire array is read out at 20kHz. In fact, the A/D converters employed run at 50 MHz, and a given detector reading is the appropriate sum of nearly fifty very fast readings. The FPGAs controlling readout will perform filtering of the 20kHz data with a bandwidth not to exceed 200 Hz, and array images will be sent to the data acquisition system in response to DV pulses at a rate not to exceed 400 Hz.

Options It would be straightforward to return a filtered full array image the first time the address card returns to address 0 after receipt of a DV pulse. This would result in a timing jitter uniformly distributed from 0 to 50μs, ie the mean delay would be 25μs, and the rms scatter about that mean is $25/\sqrt{3} = 14.\mu$s. In addition, there would be a guaranteed timing gradient across the array; all bolometers at address 0 will have been read 50μs prior to all bolometers at address 41. The advantages of this approach, beyond simplicity, are that the filtering and relative timing of the various bolometers are identical in every sample, aiding subsequent analysis.

There are two proposals to report array images with less timing jitter. One option is to report the full filtered array image promptly upon receipt of a DV pulse, no matter which address the card is asserting. In this context, promptly means within the current address period, roughly 1.2μs. The disadvantages of this proposal are that there is still a guaranteed 50μs gradient across the array and the relative timing of the various rows is no longer stable. The 14μs rms jitter will have been removed.

A second option is to report the full filtered array only one full array cycle later, but to *interpolate* all readings to the precise time of the DV pulse. This method produces very little effective timing jitter. However, in this mode some rows have been interpolated and some have not, and it is not at all stable which row is which. Thus the filtering of the various bolometers is different in every sample.

We will estimate the largest possible signal difference in two samples which occur 50μs apart, and compare that to the anticipated noise in a 400 Hz single sample in order to evaluate if the third method could possibly provide a benefit which outweighs the complexity it introduces.

Equivalent Voltage Noise: Imagine that the array is scanning across the sky at the fastest useful rate, so that a source moves from the beam center to the half power point in one sample, ie $\delta t = 1/400$ seconds. (This is 49 arc minutes per second.) Imagine that the bolometer in question has been scanning across a uniform region of S mJ/beam and at the moment in question has just entered a region of zero flux. That is, let's consider a step function in flux since that produces the largest change in detector voltage.

Since we are at the 3db point of *both* the audio filter and the optical beam, the time rate of change of the signal in this extreme case is

$$\frac{\mathrm{d}S}{\mathrm{d}t} = \frac{1}{4}\frac{S}{\delta t} = 100S\mathrm{mJ/s}$$

and the signal difference associated with two measurements 50μs apart is

$$\Delta S = 50\mu\mathrm{s} \times \frac{\mathrm{d}S}{\mathrm{d}t} = \frac{S}{200}\mathrm{mJ}.$$

This is the largest signal error due to timing jitter which *SCUBA2* can reasonably produce.

To estimate the noise in a single sample, I start with the estimate that the noise of *SCUBA2*is likely to be 5 mJ$\sqrt{\mathrm{seconds}}$. This is ten times better than SCUBA is at 850 μm. At this level, the variance of a 1/400 s observation is

$$\delta S = \frac{5\mathrm{mJ}}{\sqrt{\mathrm{seconds}}} \times \frac{1}{\sqrt{1./400}} = 100\mathrm{mJ}.$$

The source strength, S_{match}, which produces this much noise from timing jitter is

$$S_{match} = 100\mathrm{mJ} \times 200 = 20 \text{ Janskies}.$$

For sources less bright than this, or for observing strategies which are less aggressive (ie for nearly all sources and nearly all strategies) the voltage errors associated with 50μs timing jitter are not a serious issue.

Equivalent pointing errors: The noise level per sample is not the whole story. It is common to perform an experiment in which the signal-to-noise ratio per sample is very low, and to accumulate a high fidelity signal over time. In this context, it is important that the pointing associated with every data sample is well enough known that the final map is useful. This pointing requirement is independant of signal level and in the low signal situations we should expect from *SCUBA2* this requirement will impose a tighter timing requirement than the noise considerations above.

As the mirror moves across the sky, a timing uncertainty translates into a position uncertainty. It is important that these uncertainties be less than the beam width by some factor, F. For a mirror to provide diffraction limited performance it is common to require that the surface *rms* be less than $\lambda/70$. This gives rise to phase errors in the electromagnetic field of $\delta x = \lambda/35$. Let's take $F = 1/35$ to be a reasonable requirement pointing accuracy. Again, assume that the mirror is moving at the half-width-half-max per $\delta t = 1/400$s. We must know the effective time of every data sample with a precision

$$\Delta t \leq 2. \times \frac{1}{35.} \times \frac{1\ \mathrm{s}}{400.} = 143.\mu\mathrm{s}.$$

If the timing errors associated with finishing an array scan are incoherent with respect to errors arising in the rest of the system, the allowance for the rest of the system is the quadrature difference

$$\Delta_{RTS} = \sqrt{(\Delta t)^2 - (14.\mu\mathrm{s})^2} = 143.\mu\mathrm{s}.$$

If we cut the requirement for Δt in half, *and* calculate variance from the time of the DV pulse rather than from the mean delay time, the allowance becomes

$$\Delta_{RTS} = \sqrt{(71.4\mu\mathrm{s})^2 - (28.\mu\mathrm{s})^2} = 65.\mu\mathrm{s}.$$

which is tolerable.

The 50mus delay gradient across the array corresponds to misaligning the two edges of the array by 0.15 arc seconds, more than an order of magnitude below the most ambitious pointing claims ever made for the JCMT.

Conclusion: The simplest response to a DV pulse results in a mean delay of 25μs, an rms variation about that mean of 14μs and a 50μs delay gradient across the array. All of these numbers appear to be well within the range of the requirements imposed by subsequent data analysis.