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Characterization and locking squids with the Multi-Channel Electronics

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1 Introduction

We have developed a **closed loop** method to characterize the first and second stage squids in the *SCUBA2*multiplexors using the Multi-Channel Electronics. Starting from the squid series array modules (SSAM) and working on the second stage squids, and then the first stage squids, a squid is characterized by sweeping the associated feedback current across its full range while varying the lower stage feedback current in such a way as to keep the series array output voltage constant. This process results in $V\phi$ curves which are plots of Series Array Feedback current vs Second Stage Squid feedback current , or are Second Stage Squid feedback current vs First Stage Squid feedback current, and which do not contain any convolution of the various stages. The curves look similar to simple Series Array $V\phi$ curves.

From these data it is comparatively straightforward to choose operating points for running the full multiplexor closed loop. We choose operating points in the following order: Series Array bias current (sa_bias), then Second Stage squid bias current ($sq2\_bias$) and Series Array Feedback current (sa_fb), then First Stage Squid bias currents (rsN_select) and Second Stage Squid feedback current ($s2\_fb$). The bias current for the Series Array is chosen to be that which results in the largest slope in the $V\phi$ curve, and the target output value is chosen to be the Series Array output voltage at maximum slope. From a collection of second stage squid $V\phi$ curves, all of which have Series Array output equal to the target voltage at every point, the second stage squid bias current is chosen to correspond to maximum amplitude variation of the series array feedback current, and the operating point for the series array feedback current is chosen to correspond to maximum slope on the chosen Squid 2 $V\phi$ curve. First Stage Squid bias current and Second Stage Squid feedback are chosen in a similar way.

Decisions for the Series Array, and for the Second Stage Squid bias current are made for each individual element. First Stage Squid bias currents are chosen as a compromise for the possibly 32 First Stage Squids in a given row, and the Second Stage Squid feedback voltages are again a compromise among the 41 First Stage Squids in a given column.

We are very eager to get feedback on this technique from the rest of the *SCUBA2*team, particularly those parts with a lot more squid experience than we have.

2 The Series Array

Characteristics of all eight channels of a given Squid Series Array Module (SSAM) are measured with the bias and feedback currents of the first and second stage squids set to zero. The script `ramp_sa_fb` collects about 25 graphs like the one shown in Figure 1 with 25 different values for the bias current in about 40 seconds. In each graph we have chosen to measure 400 values of feedback current, from zero to full scale. This particular graph is near to IC_{max} for all eight channels, but no great care was taken to find a real optimum.

From the collection of data from which this graph has been drawn we have chosen to operate with Series Array bias DACs all set to 425000 and to choose 100,000 analog-to-digital converter units as our target output voltage. This provides a large slope dV_{out}/dI_{in} at the operating point.

The script `ramp_sa_fb` generates a batch file with about 10000 commands in it and this batch file is executed with a single call to the data aquisition software, das. In this way a 2D grid of output voltage vs feedback voltage for 25 different bias currents is collected in under one minute and plotted with an associated *idl* program. The individual $V\phi$ curves this way are collected in less than one second. We have noticed that these curves are of higher quality, freer of defects and drift, than $V\phi$ curves collected more slowly, say during one minute.

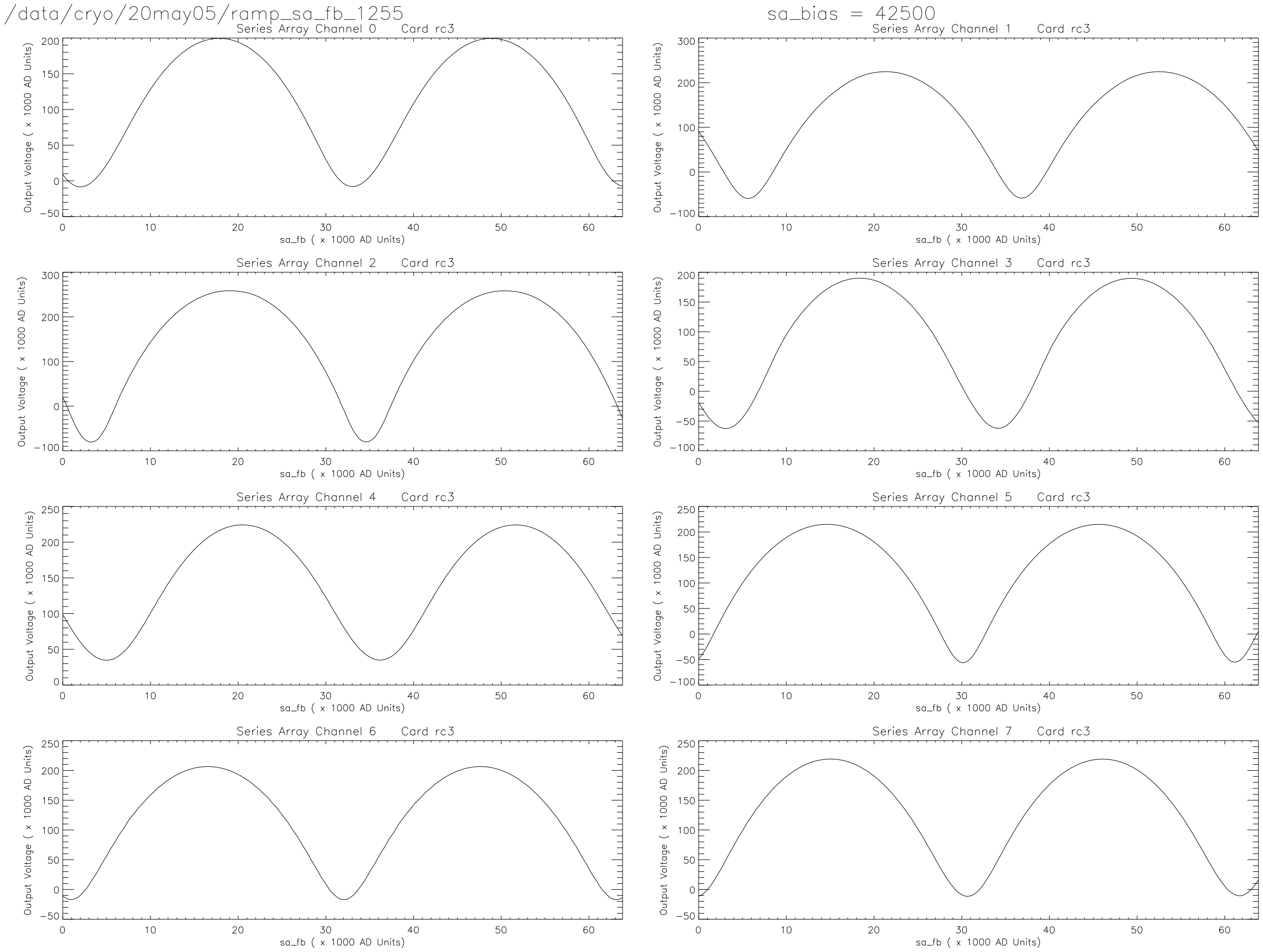

Figure 1: **Series Array $V\phi$ curves** for all eight channels of SSAM-006, at a bias current DAC setting of 42500. (65536 is full scale.) This is near enough to IC_{max} for all channels. The Offset voltage on the readout card has been adjusted separately for each channel so that the maximum slope occurs near to ADC readings of 100,000. The output readings are the *sum* of 48 successive readings at each address step, and the values shown here are the average of the values of each of the 41 rows. On the vertical axis, 392,000 corresponds to 5.5 mv and full scale on the horizontal axis is 167 μA.

3 Second Stage Squids

If the second stage squids are biased on and their feedback currents swept across their full range with the series array bias current and feedback current held fixed the resulting curve is not really a convolution of the two $V\phi$ curves, but it is complicated. Experience is required to interpret it well. This experience is in short supply at UBC, so we have measured the second stage squids *closed loop.* For a given value of the second stage squid bias current, wee sweep the secons stage squid feedback current from zero to full scale. At each value of the second stage feedback current we adjust the series array feedback current to null the effect of the second stage squid and bring the series array output voltage back to the target output voltage, chosen above.

Calculation of the correct series array feedback current is done in a C program `sq2servo`, which uses a simple proportional feedback term and repeats the cycle twice at each second stage squid feedback value to assure the system has converged. The values of both iterations are shown in the Figure 2, and their similarity lends confidence that the intrinsic $V\phi$ curve is measured well enough. Notice that everywhere that the series array feedback crosses full scale, 65,536, there is a discontinuity. This arises because the DAC expresses values of sa_fb = (Full Scale + η) as sa_fb=η, and the servo must re-lock. The size of the discontinuity is small because full scale variation of the series array feedback corresponds very closely to an integer number of flux quanta, 2. See Figure 1.

A data set like the one displayed in Figure 2 is collected in under one minute. The data collection does the folowing:

- Write new SQ2 Feedback value (32 identical numbers).
- Read voltages, V, from Series Array (eight voltages for one SA).
- Calculate new SAFB' = SAFB + P(V-target) (Eight values/SA).
- Apply new SA Feedback (32 values, but only eight are new.)
-
- Read voltages, V, from Series Array (eight voltages for one SA).
- Calculate new SAFB' = SAFB + P(V-target) (Eight values/SA).
- Loop.

This algorithm requires $6 \times 400 = 2400$ instructions to collect the data in Figure 2, and could take place in as little as two seconds. However, in practice our approach requires starting and stopping the data aquisition program 800 times, and one data set requires near to one minute to collect. Collecting a 25 bias current 2D grid, like the 2D grid we collect for the series array, would require half an hour. Instead, we use our judgement, and collect a few curves near to IC_{max} for the given SQ2's under consideration. In practice it often takes us longer to understand the data than to collect it.

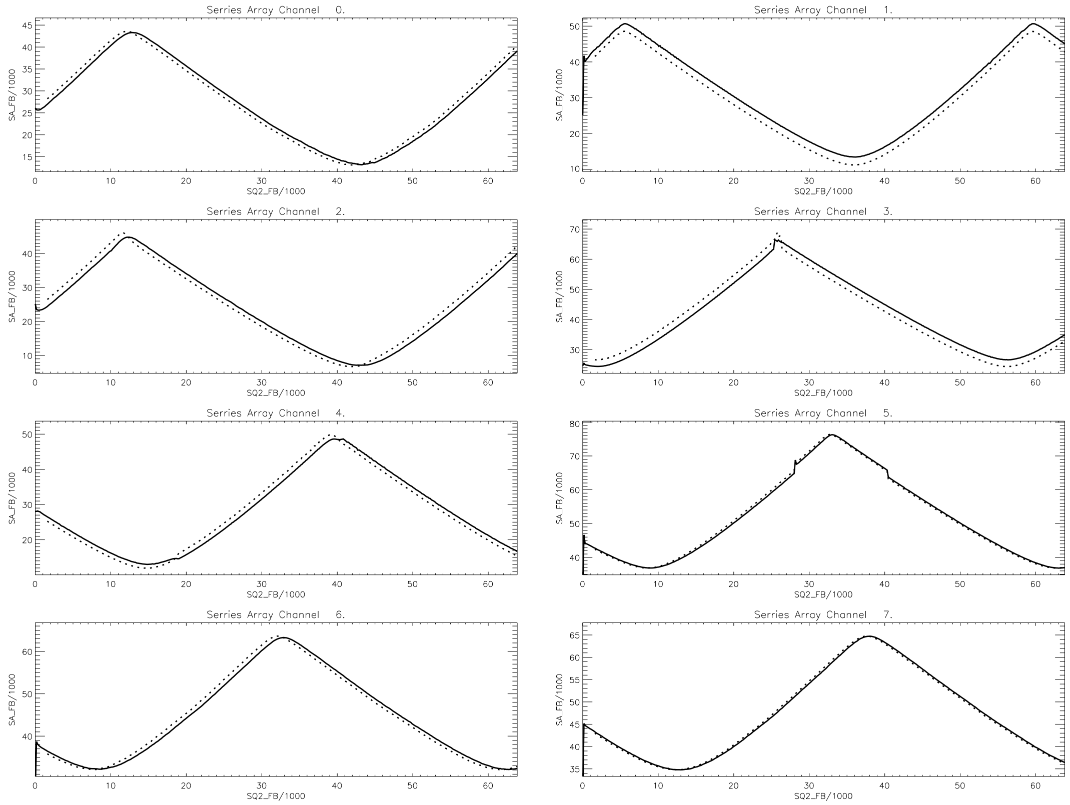

Figure 2: **Second Stage Squid $V\phi$ curves** for all eight channels connected to a given Readout Card. These particular data were collected on 1 June 2005 in Cardiff. All Second Stage Squids were set to the same bias current. In this case it is a DAC reading of 25000, chosen to be near IC_{max}. The horizontal axis is the second stage squid feedback current running from zero to full scale. The vertical axis is the value of the Series Array Feedback current which is required at each point to hold the system output voltage at the target value. Notice that there are discontinuities wherever the SA_FB value crosses the DAC maximum of 64,000. See the text. The solid and dashed lines are the first and second iterations of the closed loop servo at each value of the SQ2 feedback current.

Finding the closed loop second stage squid $V\phi$ curve which has the largest amplitude, one has determined a good operating bias current for each second stage squid. The values of the series array feedback current which lie in the region of maximum slope dI_{sa_fb}/dI_{sq2_fb} on the optimal graph give the acceptable operating range for each channel of series Array Feedback.

By the end of examining the second stage squids we have determined the optimal DC output voltage, the series array bias and feedback and the optimal second stage squid bias current.

4 First Stage Squids

A single, eight-channel readout card addresses $8 \times 41 = 328$ pixels, and therefore 328 first stage squids. However, there are *not* 328 operating points to determine. All of the 32 first stage squids in a given row take the same bias current, supplied by the address card. (The nomenclature is that the bias current for row N is supplied by the Row Select DAC value rs$N$ on the address card.) The address card turns one row at a time from some nominal off-bias to the value rs$N$, and turns the previous row to its off value. The time spent at each row is commandable, but the target is 1.2μs, in which case the full set of 41 rows is cycled through at 20 kHz.

Ideally, one might choose a new value of second stage feedback for every first stage squid. In practice, we have not made circuitry which can switch `sq2_fb` this rapidly, and a single value of second stage squid feedback has to be chosen for a full *column* of 41 first stage squids. Therefore, instead of choosing first stage squid bias and second stage squid feedback at each of 328 pixels, for 656 parameters, we need only choose 41 biases and eight feedback values, or 49 parameters.

Especially in these early days, when many of the rows in our multiplexors do not have interesting first stage squids, it is too slow for a first glance to collect a full set of a few closed loop first stage squid curves for each row of the multiplexor. This would take a few hours. As a first glance at the multiplexor, we collect open loop curves of the first stage squids. For *fixed* values of all other currents, and for a we collect and plot $v\phi$ curves for every first stage squid. The result is a single file of 41 pages of graphs of output voltage versus first stage squid feedback current. Every curve is a convolution with lower stages, but the main features of the squids can be almost seen and one gets a sense of which values of first stage squid bias current (rs$N$) are likely to be worth investigating and certainly a very good idea of which rows work at all. See Figure 3 We almost never print these graphs onto paper. In Ghostview, where page numbers start at page 0, pages in the graph correspond to rows in the multiplexors.

Collecting data like that in Figure 3 for all 328 first stage squids associated

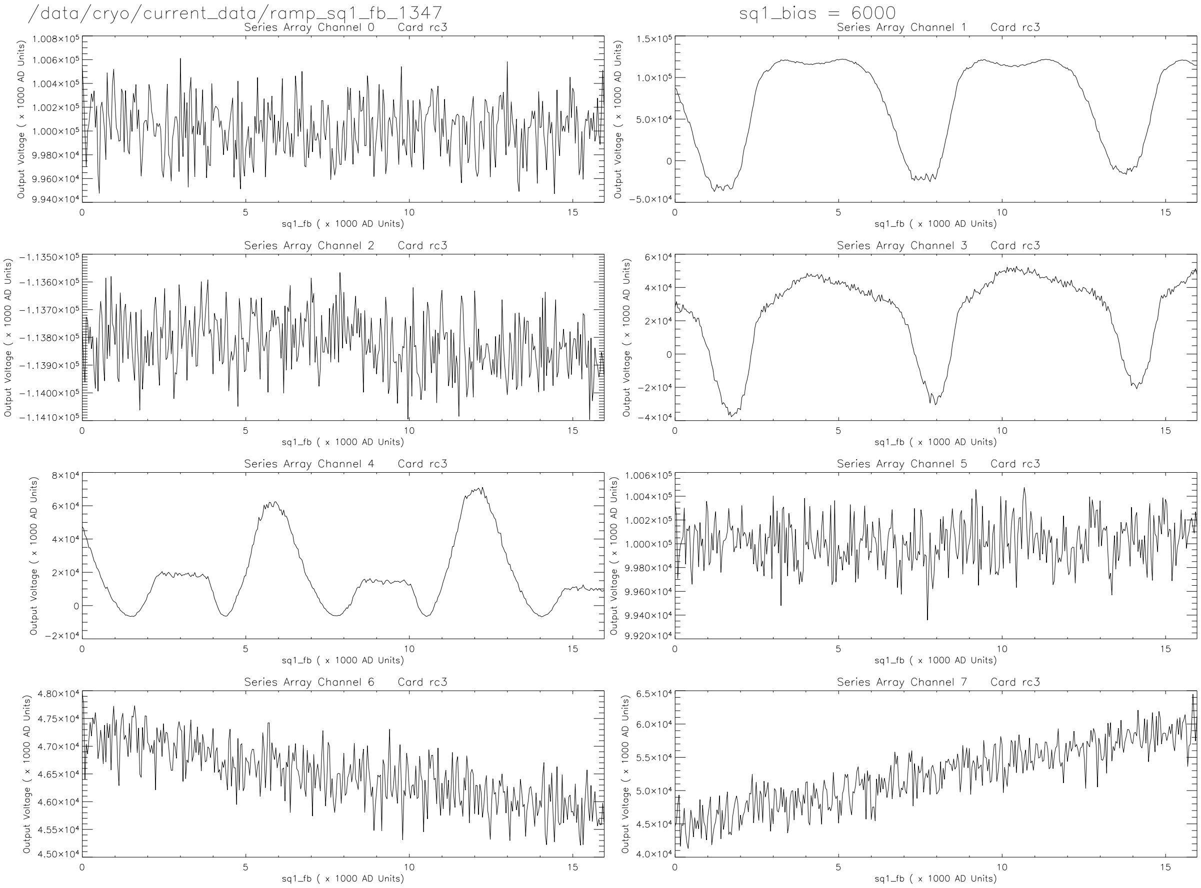

Figure 3: **First Stage Squid Open Loop** $V\phi$ **curves** for all eight channels of row 31 of the 'UBC' multiplexor at 4 Kelvin. These data were collected at bias current DAC = 6000 da units, and were collected via readout card RC3. Therefore channels 0-7 correspond to multiplexor columns 24-31. (These are pixels 31-24 through 31-31) Notice that only columns RC3-1,3, and 4 appear to be healthy. All curves are heavily 'convolved', but it is apparent from the very flat sections in channels 1 and 4 that those pixels are not yet at IC_{max}. These data were collected 20 May 2005 at UBC looking at a 4K system.

with a given readout card takes only a second or so. Understanding it takes a lot longer, typically. These curves are what is commonly referred to as convolutions of $V\phi$ curves. The current modulation has carried the flux into the series array across several flux quanta, producing nulls and slope reversals which are not properties of the first stage squids themselves. Once you get a bit used to how these should look, the flat portions of panels 1 and 4 indicate clearly that those squids are not yet at IC_{max}.

We use curves like these to determine which portions of the array to examine more closely and which values of first stage squid bias current are likely to be useful. Notice that there is no way to tell from this graph what values of second stage squid feedback current would be appropriate. It is worth mentioning that the amplitude of the modulation seen here is not directly an indicator of quality since the slopes of the underlying $V\phi$ curves is not known or controlled.

The real amplitude of the first stage squid $V\phi$ curves can be read directly from a *closed loop* measurement. Using the same algorithm as for second stage squids, we bias the first stage squids, sweep the feedback current from 0 to full scale and adjust the second stage feedback current at each step to null the effects of the first stage squid and return the series array output voltage to its target value. A typical closed loop squid measurement is shown in Figure 4. Although data are automatically collected for all pixels at once by the MCE, the calculation of the appropriate values of second stage feedback are only carried out for one row in a given 30 second measurement.

A couple of curves are collected for nearby values of the squid bias to choose IC_{max}. As was done at lower stages, the second stage squid feedback current is chosen to correspond to the maximum slope in Figure 4.

At this stage one has, in principle, chosen the optimal values of first stage squid bias currents, second stage squid feedback and bias currents and series array feedback and bias currents. It seems that iteration is not required to set up the squid amplifier. In practice, we have chosen plausible values with no real attempt at optimization.

5 Closing the Loop

We have implemented an operating mode in the readout cards in which signed 8-bit numbers are collected at the full rate of the 50 MHz a-to-d converters. There is only room to store 8192 numbers per channel. If the address card moves from one address to the next every 64 clock cycles, the nominal rate,

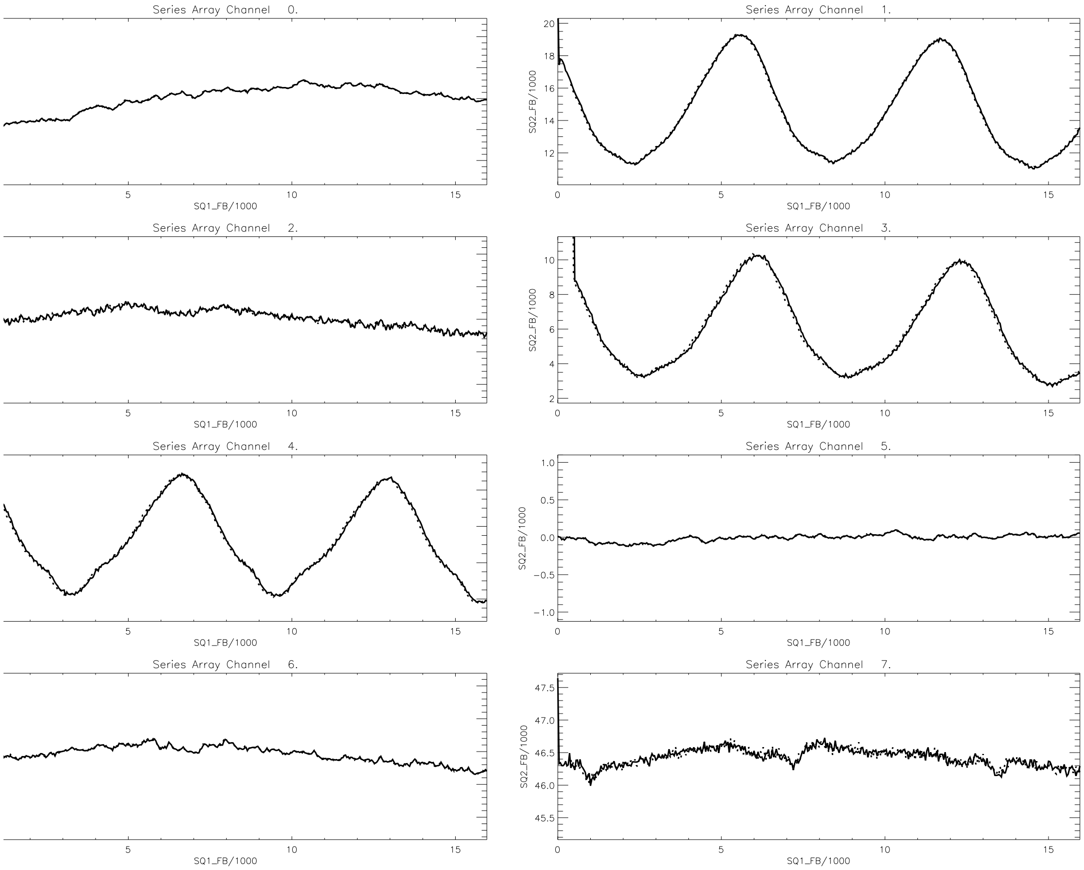

Figure 4: **First Stage Squids, Closed Loop** $V\phi$ **curves** for all eight channels of row 3 of the 'UBC' multiplexor. These data were collected at bias current DAC = 6000 da units, and were collected via readout card RC3. . These data were collected 20 May 2005 at UBC looking at a 4K system. The DAC values of second stage squid feedback current corresponding to the maximum slope for each column can be read directly from the graphs. Ideally, a single value of first stage squid bias current can be chosen for all 32 pixels in a row, and ideally the second stage squid feedback values determined for each column for this particular row will work well at other rows.

we can store a bit over two full cycles through all first stage squids. In Figure 6 we have slowed the address card to 128 cycles per address, and we display one full address cycle. (This address rate is slower than desired, but our current setup incorporates large wiring harnesses and has time constants of many hundreds on nano seconds. Notice in particular how slow channel 3 appears to be.)

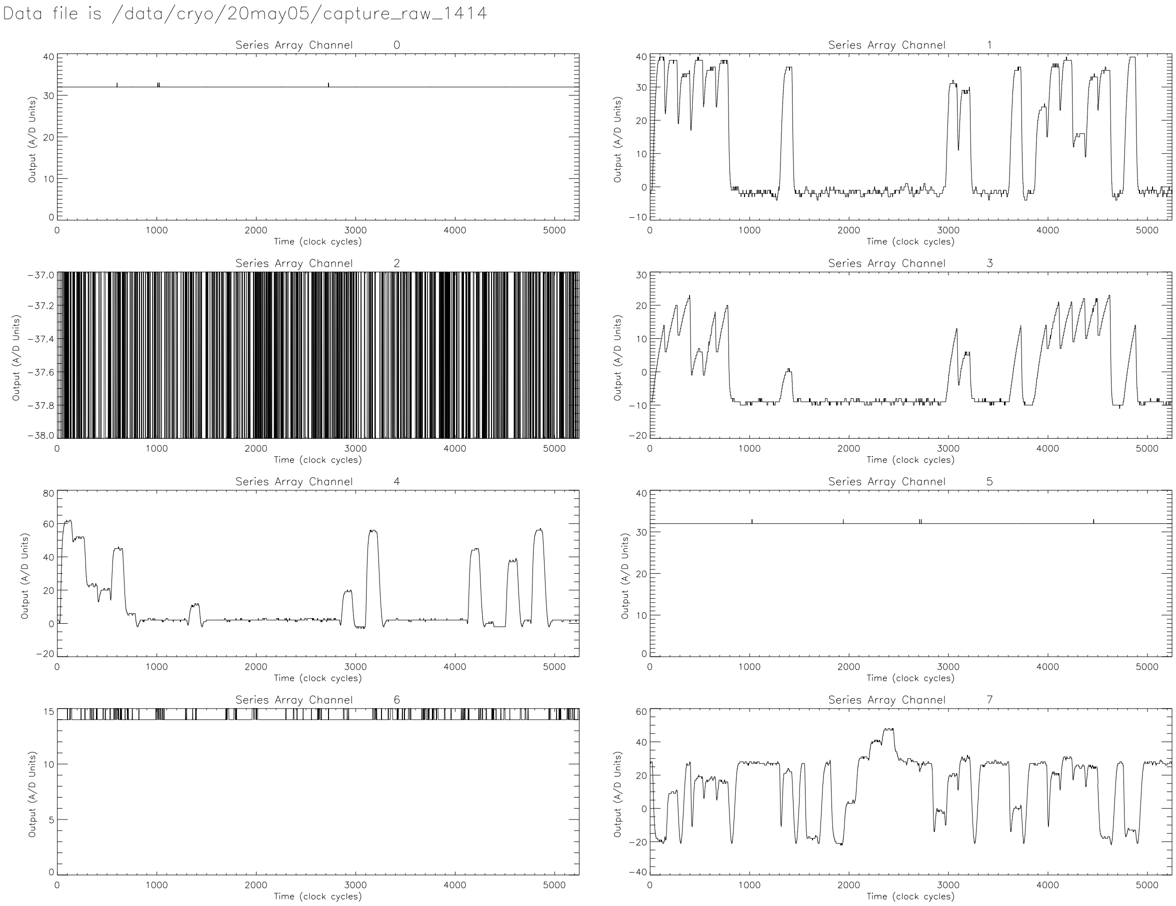

Figure 5: **Raw data,, Running Open Loop** for all eight channels of row 3 of the ‘UBC’ multiplexor. These data were collected at bias current DAC = 6000 da units, and were collected via readout card RC3 on 20 May 2005 at UBC looking at a 4K system. One can easily see the pattern of valid first stage squids by counting the trapezoids in channels one, three or four. Rows 0 to 5 are healthy, 6,7,8 and 9 are not. Row 10 is healthy, and so on.

The pattern of valid first stage squids is apparent in any of the healthy columns– in this case columns one, three and four of Readout Card 3. Rows 0 to 5 are healthy. So is row 10, and so on. Notice that the pattern is slightly different in the three healthy columns. It surprised us to see structure in the column attached to channel 7. The $V\phi$ curves of this channel had shown weak signals for some pixels, but nothing as promising as in the three healthy columns.

The data in FIgure 6 were collected in a mode in which the first stage squid feedback signal is zero and one reads out raw analog-to-digital converter values. There is a mode in which one sums `sample_num` (here set to 48) AD readings from each pixel, compares that to the target value which was set after examining the series array curves, and calculates the first stage feedback signal required to return the series array output signal to the target value. We use a simple PID loop for the first stage squid feedback calculation, with P=-I and D=0. In this mode, all healthy channels ought to have the same values.

Notice that all the valid rows in channels 1, 3, and 4 of Figure **??** are at V=28. This constitutes closed loop operation of 54 squids simultaneously. The data in Figure **??** were collected on 20 May 2005 at UBC.

6 Acknowledgments:

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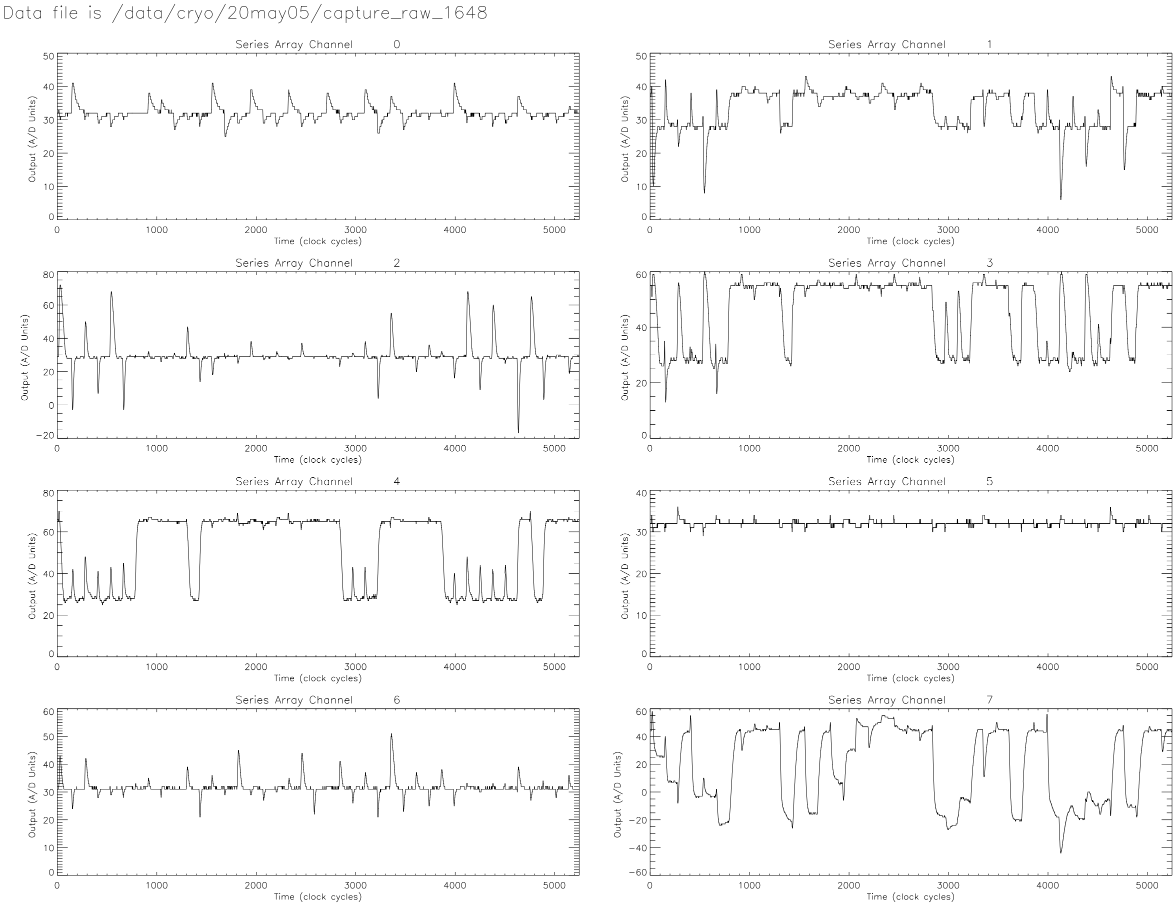

Figure 6: **Raw data, Closed Loop** for all eight channels of row 3 of the 'UBC' multiplexor. Notice that all healthy pixels have converged to a single value, as one would expect in successful closed loop operation. There are 54 locked pixels in this plot in channels one, three and four. Notice that the relatively poor time constant in channel three is not as much of a problem when the system is locked.