AQUARIUS, the next generation mid-IR detector for ground based astronomy, an update.

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ABSTRACT

ESO has already published data from a preliminary laboratory analysis on the new mid-IR detector, AQUARIUS, at the previous SPIE conference of 2012, held in Amsterdam[2]. This data analysis indicated that this new mid-IR Si:As IBC detector, from Raytheon Vision Systems, was an excellent astronomical detector when compared to previous generations of this detector type, specifically in terms of stability, read noise and cosmetic quality. Since that time, the detector has been deployed into the VISIR[1] instrument at the VLT, with very mixed performance results, especially when used with the telescope secondary mirror, to chop between two areas of sky to do background subtraction and at the same time when many frames are co-added to improve the signal to noise performance. This is the typical mode of operation for a mid-IR instrument on a ground based telescope. Preliminary astronomical data analysis indicated that the new detector was a factor of two to three times less sensitive in terms of its signal to noise per unit time performance when directly compared to the old DRS detector that AQUARIUS was designed to replace. To determine the reason for this loss of sensitivity, the instrument was removed from the telescope and not offered to the ESO user community. A detector testing campaign was then initiated in our laboratory to determine the reasons for this loss of sensitivity, assuming that it was an issue with the new detector itself. This paper reports on our latest laboratory measurements to determine the reasons for this loss of sensitivity. We specifically report on indirect measurements made to measure the quantum efficiency of the detector, which can be difficult to measure directly. We also report on a little known source of noise, called Excess Low Frequency Noise (ELFN). Detailed analysis and testing has confirmed that this ELFN is the reason for the loss of instrument sensitivity. This has been proven by a re-commissioning phase at the telescope with the instrument and the detector. A new set of observing parameters and observational regime have been developed to help to mitigate the ELFN. We outline a possible explanation for the source of the EFLN, learnt from a literature search and discussion with the manufacturer.

Keywords: AQUARIUS, Si:As, Impurity Band Conduction Detector, Excess Low Frequency Noise

1. INTRODUCTION

The reader is referred to a previous SPIE paper [2] which details the specifics of the AQUARIUS detector. We summarise the main features of the detector here for completeness and then discuss the issues with the detector sensitivity.

Table 1 - AQUARIUS detector specification and performance summary.

Specification	Measured	Comment
Array size	1024 x 1024 pixels	Pixel size is 30 µm
Operating temperature	7-9 K	9K typically used
Frame Rate	> 100 Hz	> 150 Hz possible and also windowing
Spectral Response	3 – 28 µm	Our AR coating optimised at 6 µm
Quantum Efficiency	> 40%	Measured indirectly, see note later
Input referred noise	~ 200 e- rms	For single read, kTC noise not dominant
Power dissipation	~ 250 mW	For 64 outputs
Full well	~ 0.8Me	High gain mode
Dark current	1 e/pixel/second	Measured at 7K
Non-linearity	< 5%	Better than 0.1% over 2/3 full well (corrected)
Crosstalk	~ 6% to adjacent pixels	Measured using stochastic method

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We summarize the telescope chop and nod technique as this is important in understanding the way images are typically processed to increase sensitivity for a mid-IR detector. There are two possibilities for the reduced sensitivity in our detector, low quantum efficiency or high noise. We report here on our simple and indirect method to confirm that the detector quantum efficiency is as expected and that excess noise is the issue with the lack of instrument sensitivity. We show that the excess noise can be reduced by increasing the telescope chop frequency. We also show that this excess noise is a function of the detector material itself and not the silicon multiplexer. As a further point we show that the old DRS detector does not suffer from this excess noise to the same extent. We present some re-commissioning data from the telescope after system optimisation to minimise the excess noise. Finally we summarise some of the results presented in a past paper from the designers of this detector technology, describing their thoughts and ideas about the source of noise.

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2. TELESCOPE CHOPPING AND NODDING

Mid-IR astronomical sources are normally orders of magnitude fainter than the background emission which is very bright. The detectors must therefore be readout at very high speed to ensure that they do not saturate because of this very high sky background. To produce a final astronomical image of an object which is photon shot noise limited and has accurate background subtraction, requires the co-addition of multiple detector frames. The accuracy to which the background flux can be subtracted is limited by several sources of noise including the shot noise of the photon flux itself, "1/f" noise due to variations in the background caused by sky temperature drifts and noise in the detector itself. The technique used to achieve accurate background subtraction is implemented using the combination of chopping the telescope secondary mirror and nodding the telescope (the so called "chop and nod" technique). The 1/f sky noise is suppressed by the "chopping", in which the telescope's secondary mirror is oscillated in a square-wave pattern at a frequency of 0.1-10 Hz, dependent on the telescope implementation. At the VLT, the standard chop frequency is 0.25 Hz. By chopping the secondary mirror, the detector alternately views two fields on the sky, one field with the object and the other with a flat region of sky. However, because the optical path through the telescope optics is different for these two chop positions, the background level is also slightly different. Therefore to completely remove the background, the telescope is also "nodded" periodically, to ensure that the background is properly subtracted. At each of these chop and nod positions the detector must be read out at high frame rates to avoid saturation. Many frames are then co-added to achieve the required sensitivity. This method of detector readout and processing is important to understand in regard to the remaining discussion in this paper.

To summarize, in the mid-IR, many consecutive detector frames are typically co-added to improve the signal to noise performance and also ensure that the detector does not saturate.

3. AQUARIUS DETECTOR COMMISSIONING ISSUES

The new AQUARIUS detector was specifically developed to be installed as an upgrade to the old DRS detector into the ESO VISIR[1] instrument, to increase its field of view and improve system performance because the old device was cosmetically very poor. After commissioning of the instrument with the new detector it went through an on-sky re-commissioning phase to check its performance. Very early on it was obvious that the upgraded instrument was less sensitive than before and the issue had to do with the new detector itself since no other relevant changes were made. A simple plot of instrument sensitivity versus exposure time summarises this in Figure 1. The plot shows that the instrument sensitivity (measured as milli-Jansky/10 sigma/hour) is approximately a factor of 2 less than when compared to the original setup with the older DRS detector type. The "star" in the plot gives the sensitivity of VISIR with the DRS at a chop frequency of 0.25 Hz. The second white square gives the equivalent value for the new AQUARIUS detector, lower values are better. The plot also indicates that there is a relationship between sensitivity and chop frequency. This result implies that an exposure that typically took 1 hour with the DRS detector would now require at least 4 hours with the new detector, a very disappointing result and making the instrument virtually unusable.

Laboratory measurements, which have already been reported[2] previously, indicated that the detector performance in terms of read noise, conversion gain and linearity were as expected and should not have been the cause of the instrument insensitivity. The instrument was therefore removed from the telescope, not offered to the astronomical community and a period of detector characterization took place to track down the problem.

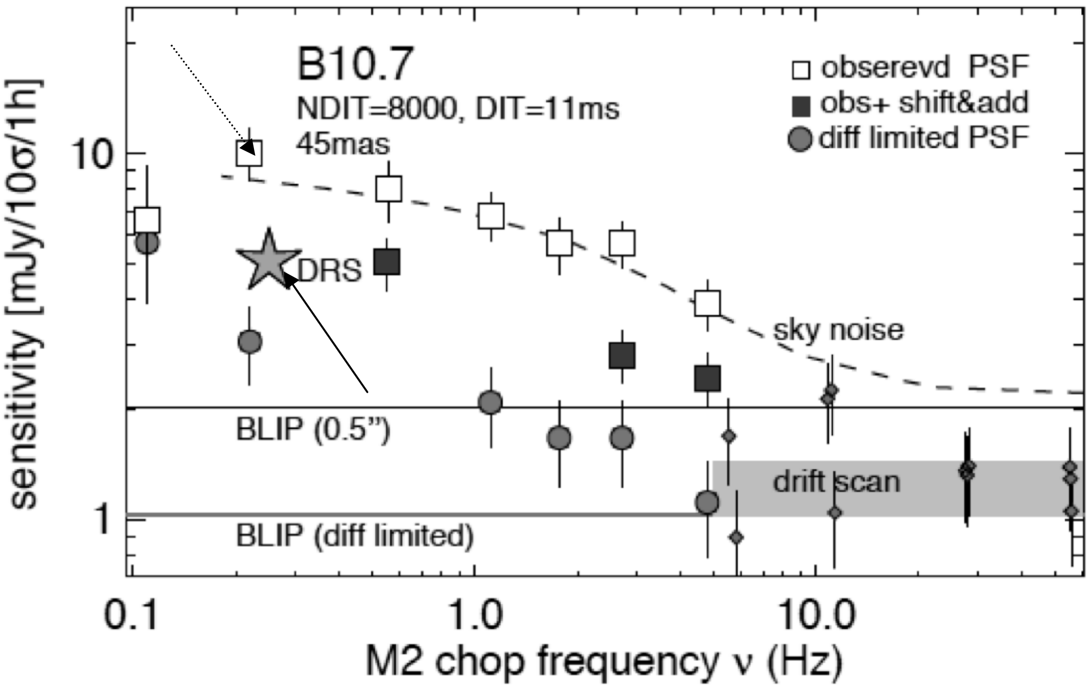

Figure 1- VISIR sensitivities as a function of telescope chop frequency. Observations obtained with B10.7 filter on standard star HD198048. Star point and straight arrow indicates sensitivity of VISIR with old DRS detector at chop frequency of 0.25Hz. White square with dotted arrow shows sensitivity with the new AQUARIUS detector versus telescope chop frequency, at 0.25Hz it is almost twice as bad. Other points not relevant to this paper.

There were two detector characteristics which had not been tested before commissioning because of the haste to install the new detector and offer the instrument back to the community. The detector quantum efficiency was not tested because this can be quite difficult to do precisely in the mid-IR bands. The noise as a function of telescope chop frequency was not tested, again because this is difficult to mimic in the laboratory and it was not a known effect at the time of instrument commissioning.

4. QUANTUM EFFICIENCY ISSUES

It was believed that detector quantum efficiency was not the source of the detector insensitivity, because it would have meant that the quantum efficiency of the detector would had to have been much lower than 10%, to give the reported insensitivity issues, since sensitivity is proportional to the square root of the quantum efficiency. However a test was performed to confirm this.

The absolute QE was not actually measured because it is difficult to do at 10 µm. This is because it is difficult to obtain a calibrated detector or photo-diode reference to measure against and thus determine the absolute value, simple testing is usually performed using a calibrated blackbody and knowledge of the optical geometry. However a simple test was performed to mount a calibrated blackbody source in front of our test cryostat and then use this to measure the throughput of both the cryostat optical chain and the detector together. The blackbody temperature is increased and the corresponding signal is measured on the detector. With prior knowledge of the cryostat geometry, filter profile and detector conversion gain then the overall system throughput can be measured. The outcome of this test is given in Figure 2, which is a plot of expected signal from the temperature of the blackbody versus measured signal. The slope of the plot gives the throughput which at 20%, seems low. This value is for both test cryostat and detector together, which implies that the detector must be higher than this value. This implied value is already too high to explain the insensitivity issues we saw at the telescope. A final test was performed to measure the throughput of the test cryostat alone, without the detector. In this test a pryo-electric detector is used which is sensitive to 10 µm radiation at room temperature. The optical setup is as shown in Figure 3.

A slow optical beam is generated using a black-body source, a pinhole and some optics. This was done to ensure that the spot produced was much smaller than the size of the active area of the pryo-electric detector. A relative measurement was then carried out by placing the detector at the entrance window of the test cryostat and at the normal position of the AQUARIUS detector. The relative strength of the photocurrent at the two positions then gave a measure of the throughput of the test cryostat. These measurements were carried out at room temperature. However as a final check the AQUARIUS detector was inserted into the cryostat and the size of the spot was measured as a confirmation that the optics produced the required spot size.

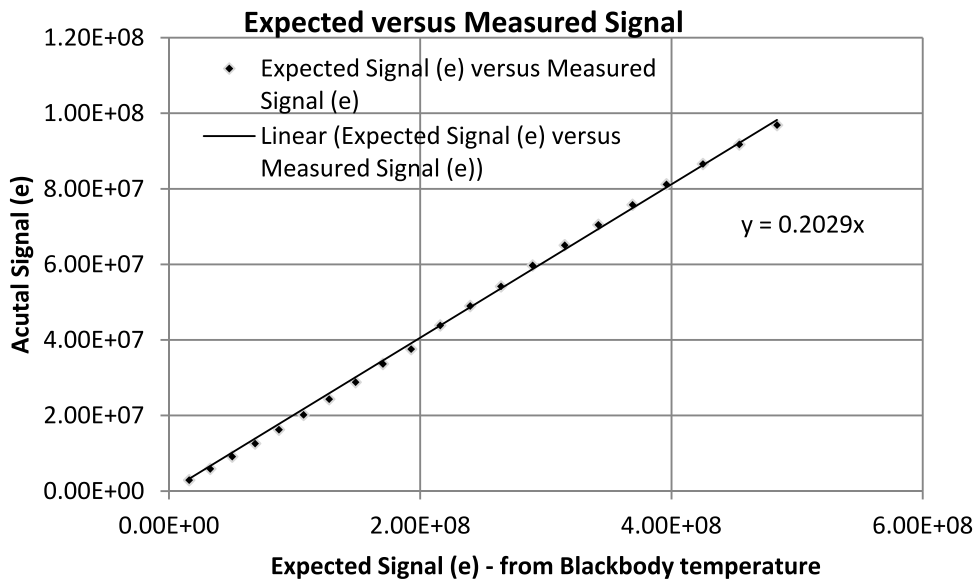

Figure 2 - System throughput measured, expected signal versus measured signal for increasing blackbody temperature.

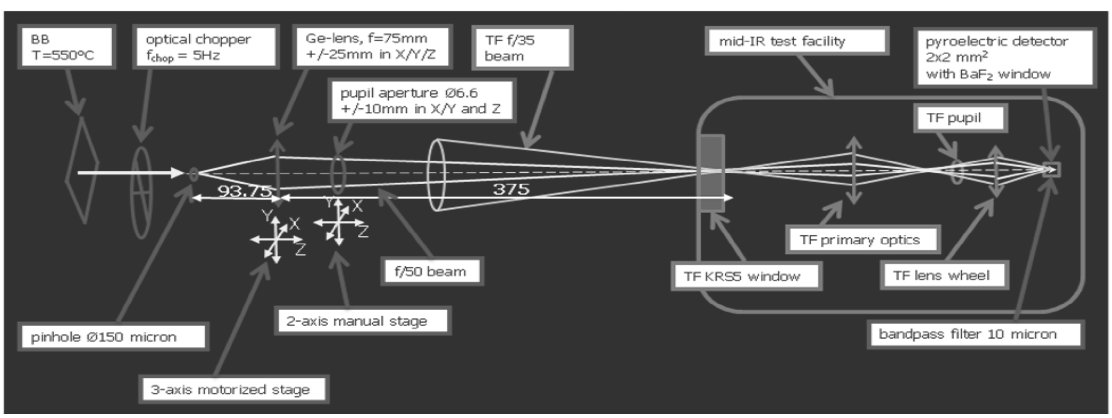

Figure 3 – Optical test setup to determine system optical throughput of test cryostat at room temperature

This optical test, with pryo-electric detector, indicated that the throughput of our test cryostat is only of the order of 50%. This result seems very low for such a simple optical system as our test cryostat which only has 4 optical surfaces, however we have no reason to believe that this number is wrong. This then implies that the quantum efficiency of the detector is greater than 40%, which is approximately the expected value for this detector technology. This test confirmed our hypothesis that detector quantum efficiency was not the problem causing the insensitivity but that some form of excess noise in the detector itself was the problem. However the read noise of the detector, conversion gain and dark current were shown to be close to their design value, so there had to be some other source of noise.

5. DETECTOR NOISE AS A FUNCTION OF NUMBER OF READ FRAMES AND FREQUENCY

It has been reported[3] that the previous generation of the Si:As Impurity Band Conduction detectors had suffered an effect know as "Excess Low Frequency Noise" (ELFN). However, it was thought that this issue was well understood and the problem had been fixed in the previous generations of detectors. A campaign was instigated to look for this noise to try to characterize it.

A very simple way to do this is to project a known stable flux from a blackbody onto the detector and then readout many thousands of frames for analysis. Figure 4 is a plot of noise versus the averaged number of reads for both the dark and high flux regimes, both available on the detector because of the use of masked regions. It is obvious that the noise does not reduce as expected by the square root of the number of reads in the high flux regime but does so in the dark regime. The high flux regime is the typical operating regime for mid-IR detectors, where photon shot noise should always the dominant noise source. This test was not performed before on sky testing which was the simple mistake made during the haste to go to the telescope, the testing was done in the dark regime but not the shot noise regime, the thought being that this dark regime which is read noise limited is always the most difficult regime to operate it.

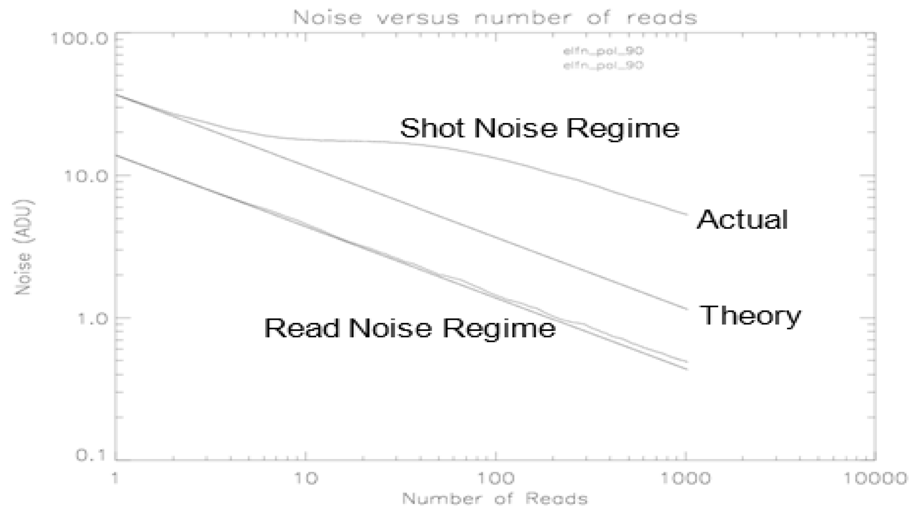

Figure 4 - plots of measured noise versus number of co-added reads for both the low flux and high flux regimes. The straight lines indicate the corresponding theoretical values.

This same data cube can also be processed to measure detector noise versus chop frequency. For example, for a 1024 frame data cube, the Lowest Frequency (LF) noise measurement is given by the form shown to the left of Equation 1 and the Highest Frequency (HF) noise is given by the form shown to the right of Equation 1.

$$\sigma_{LF} = std\left(\sum_{1}^{512} I_n - \sum_{513}^{1024} I_n\right) \text{ and } \sigma_{HF} = std\left(\sum_{1}^{1023} (I_n - I_{n+1})\right) \quad Eq.1$$

All intermediate frequencies are a subset of these two forms of the equations given. The outcome of such a frequency analysis is given in Figure 5, a plot of detector noise versus chop frequency for different increasing flux levels. The chop frequency is calculated as the time taken for each set of co-added frames. This plot clearly shows why the VISIR instrument, after the upgrade to a new detector, is less sensitive than with the older detector. The most important highlight of the plot is the noise factor, which is the ratio of the noise at the highest frequency (100 Hz), where the detector is shot noise limited, to the noise at 0.25 Hz, which is the chopping frequency for the VLT. For the AQUARIUS detector, this noise factor is approximately four, that is, the noise is four times higher than expected for the number of co-added frames used to produce the final data product.

Typically at the telescope with a secondary mirror chop frequency of 0.25 Hz and with a 10 ms detector readout time then approximately 400 frames can be readout and co-added for each chop position. The noise should then reduce by a factor of twenty but in fact only reduces by a factor of five for the new detector at this telescope chop frequency, accordingly to the results of this plot. The figure also clearly shows that the bottom line of the plot, which is for no flux on the detector, there is no relationship between noise and frequency such that the noise is flat across the measured frequency bands and is read noise limited.

This function of noise with frequency is more clearly shown in the images of Figure 6, which are the resultant co-added images, produced in the laboratory environment, when using a real chopping wheel and pinhole source to mimic on sky data taking. The top image is for a 1 Hz chop frequency and the bottom image for a 10 Hz chop frequency. The noise is better by more than a factor of two for the 10 Hz image compared to the 1 Hz image when all else is the same, the only difference is the frequency of the chopper wheel. More Airy rings are clearly visible, as well as the low level cross talk to the other channels and likewise the noise seems less "speckled" and more random in the bottom image.

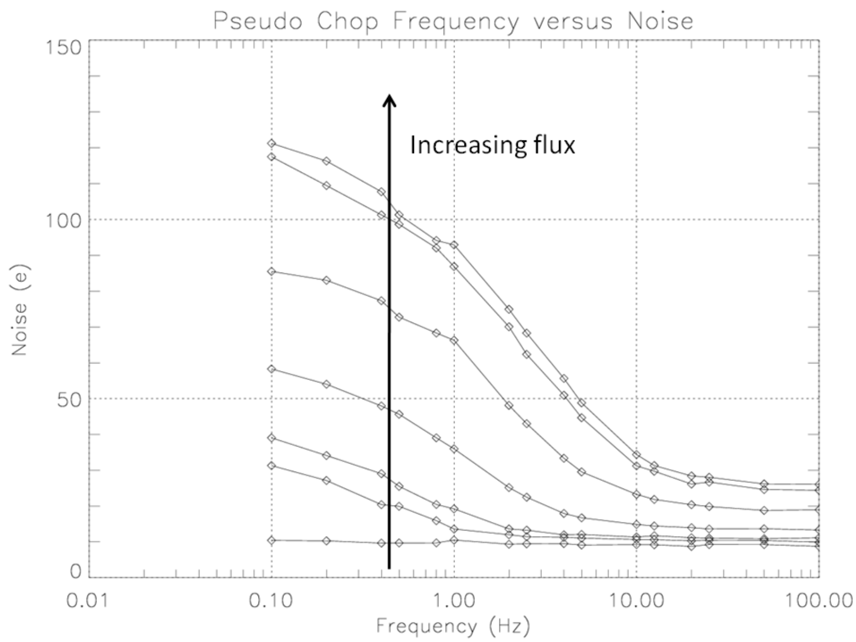

Figure 5 - Detector noise versus "pseudo" chop frequency (chop is produced in software) for increasing flux levels

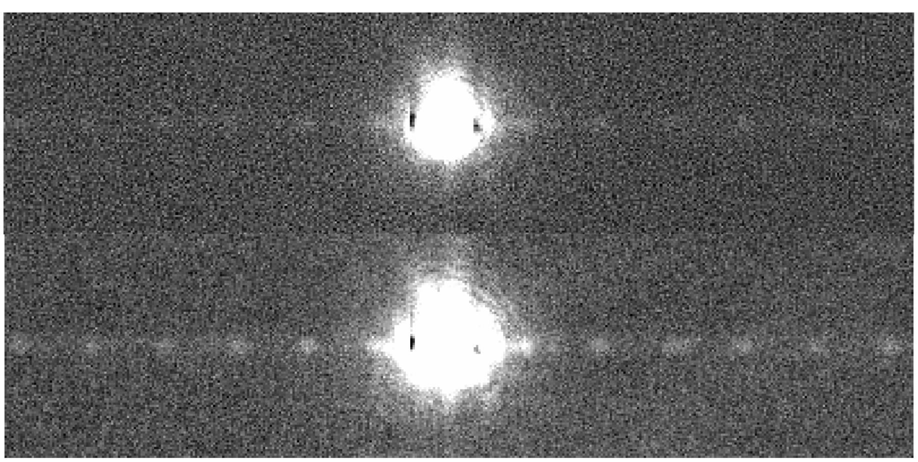

Figure 6 - Top frame is the 1 Hz frequency chopped image and the bottom frame is the 10 Hz chopped image, for a pinhole image projected onto the detector and with the use of a chopper wheel to mimic the telescope chopping.

The noise characteristics of the original DRS detector with telescope were also analysed because a previous paper[4] reported that this detector also had this source of excess noise. However for the 0.25 Hz chop frequency used at our telescope this noise does not seem to have been an issue because the VISIR instrument sensitivity was much better with the DRS detector compared to the new AQUARIUS detector. To confirm this, we analysed some old DRS detector data in the previous manner, using the algorithm as already described. The graph in Figure 7 shows two plots, the “No settling – Plot 1” result and the “with settling – Plot 2” result. For normal operation we operate all our detectors continuously reading out without stopping and starting the read sequence. However to acquire data for this analysis required a burst of many thousands of frames to be stored in a data-cube, which meant stopping the detector then starting and storing a sequence of 1200 frames. This was an unwanted feature of the detector acquisition system in use at that time. Plot 1 is the frame sequence from frame 1 to frame 1000, whereas Plot 2 is the frame sequence from frame 101 to frame 1101.

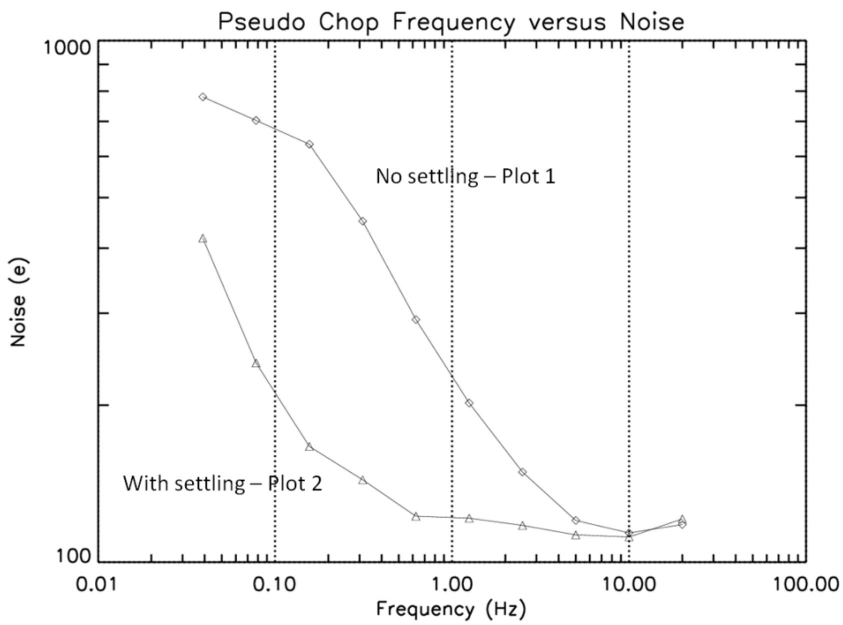

Figure 7 – DRS detector noise versus chop frequency, diamonds shows without settling and triangles with settling

This second sequence allows for settling in the detector before image processing. Without settling then the DRS detector seems to have something equivalent to the excess noise, whereas with the settling then the noise moves to much lower frequencies and out of the chopping frequency range of the telescope. The DRS detector probably requires a long time to thermally stabilize after starting the readout sequence. The conclusion is that the DRS detector might indeed suffer from the same noise source as the AQUARIUS detector but the onset of this noise occurs at a much lower frequency than the AQUARIUS detector. It should be noted that both types of detectors are not normally run in this stop-start mode so no settling is typically required, but it was needed for this test for the operational reasons described. This result therefore explains why the DRS detector is more sensitive than AQUARIUS when used in the VISIR instrument at the VLT with a 0.25 Hz telescope chopping frequency. It also indicates that there is a difference in the technology or process steps between the two detector types which manifests itself as low frequency noise at different frequencies.

6. DETERMINATION OF SOURCE OF THE EXCESS NOISE

It was already known that the excess noise source is a function of the flux on the detector. Figure 5 clearly shows this, where no flux gives the expected noise performance and the highest flux gives the worst noise performance over and above the expected shot noise with a shift in the noise to higher frequencies as well. The main task then was to determine if the noise was a function of the silicon multiplexer in the hybridised circuit or the Si:As detection material. A multiplexer without detection material hybridized to it was therefore cooled and tested in a similar fashion to the real hybridised detectors. This multiplexer is not responsive to radiation, therefore the different signal levels were mimicked by adjusting some of the detector biases. This is clearly shown in Figure 8, for a "signal" level of a third (15k DN) and two thirds full well (33k DN). The noise profile is the same for both levels and flat with no effect of frequency on the noise. This result clearly indicates that the excess noise is a function of the Si:As material and the flux on the material and not a function of the silicon read out circuit. Further laboratory testing shows that the noise of the silicon multiplexer and our readout electronics comes down as the square root of the number of co-added images for many thousands of images, as would be expected for a shot noise limited detector and indicates also that our read out electronics are performing as expected.

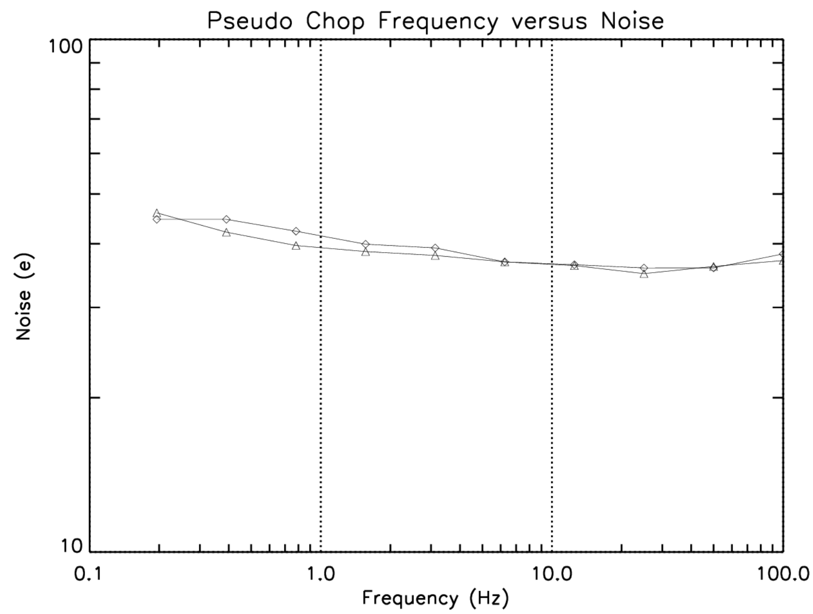

Figure 8 - Noise as a function of frequency for the AQUARIUS MUX when at operational temperature, plots given for two d.c. levels to mimic different signal levels (triangle is low signal level and diamond is high signal level).

To understand the source of the excess noise then one needs to understand the structure of a typical IBC detector such as AQUARIUS. A pictorial representation of the detector build is given in Figure 9 and which is copied directly from the user manual.

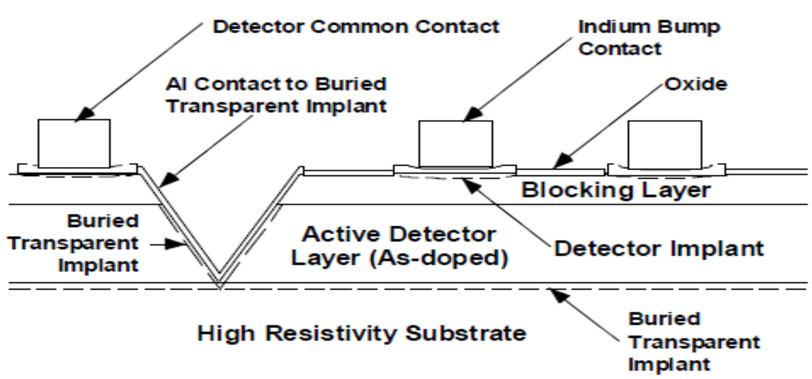

Figure 9 - Basic architecture of a back illuminated IBC detector, from the AQUARIUS detector user manual.

IBC detectors can deliver higher quantum efficiency in a volume much smaller than in conventional photo-conductors because of their much higher primary doping. As a reference, an infra-red photo-conductor made of extrinsic silicon or germanium would need to be very thick, of the order of 1mm or more in length through the detection volume, to absorb most of the incident IR radiation. To increase the sensitivity of a photo-conductor and minimize its thickness means increasing the doping of the material. The more heavily doped the material it is then the closer the doping impurities become on average. This increased impurity doping aids the hopping conduction mechanism where the shallow impurities become the most important provider for free carriers as their ionization energy is much lower than the intrinsic material's band-gap. However this increased doping increases the chance of trapped carriers to tunnel from one impurity to another without the need for photo-ionisation. This tunneling current is unwanted dark current and is minimised in an IBC detector by the use of a special very lightly doped or un-doped layer called the *Blocking Layer*. The use of this blocking layer means that the doping can be at least two orders of magnitude greater than in a bulk photo-conductor without such a layer.

However Stapelbroek[3] has shown that the blocking layer is the source of the excess noise. In fact he was first to notice this noise and give it the name, Excess Low Frequency Noise (ELFN). This noise is believed to occur because of fluctuations in the space charge which can occur from the generation and recombination in the IBC blocking layer which then results in a fluctuating potential appearing across the IR active layer, which then results in randomly modulated photo-response of this layer which produces the excess noise. That is, photocurrent is not only generated in the IR layer but also due to photon absorption in the blocking layer, it is generated there as well. It is also believed that long time constants are associated with these fluctuations. Furthermore in this paper he suggested than thinning the blocking layer would minimize the excess noise. His paper reports that this thinning of the blocking layer was tried in different batches of detector material with different blocking layer thicknesses and this seems to have had a large effect in minimizing the noise. However for AQUARIUS this is not an option because the detector has already been manufactured. It does mean that any future manufacturing run should consider thinning the blocking layer compared to the thickness it is at present. Because of ITAR regulations we do not have a detailed understanding of the build and structure of the AQUARIUS detector.

7. EXCESS LOW FREQUENCY NOISE CHARACTERISTICS

Once it was understood that the AQUARIUS detector suffered from this low frequency noise, a full characterization program was instigated to determine the operational parameters for this noise and how our instrument could be optimized when operating in the EFLN regime. It is already known that the noise is a function of flux level, detection material and to a lesser extent integration time. It also seems obvious that there is some sort of temporal issue with the detector material.

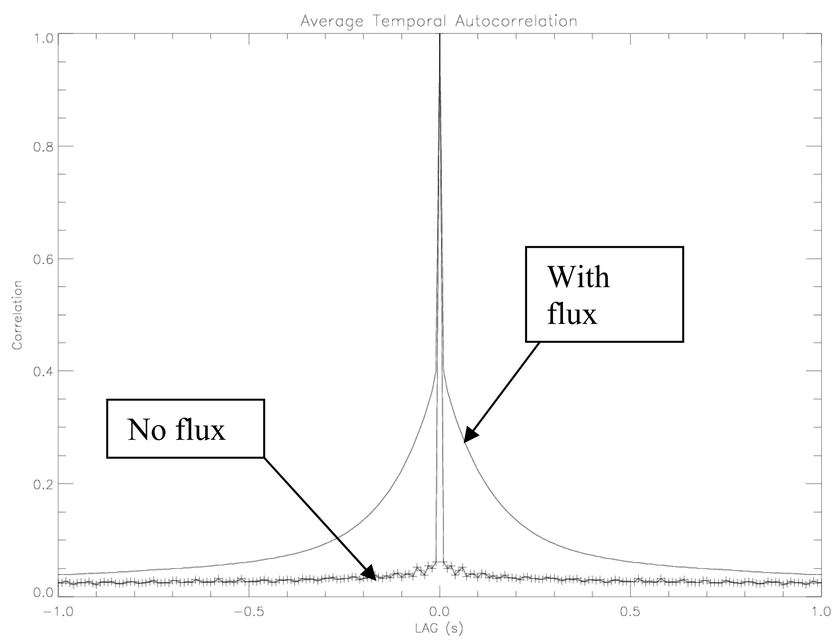

Figure 10 - Temporal auto-correlation measurement for detector showing correlation as a function of time, for high flux the correlation is clearly seen and for no flux (+), there is no correlation seen and thus no ELFN.

As a final proof of this, a temporal auto-correlation was calculated by taking a long data cube with constant flux and fixed exposure time. This data cube was then processed to measure the temporal auto-correlation for each pixel, an average value was then determined for all the pixels. The result of this is shown in Figure 10. This plot indicates that for any pixel with flux on it then the next read of the same pixel, even after reset, will have a correlation of nearly 40% with the previous read value and that this correlation slowly decreases until completely gone, but only after a few hundred milliseconds. The plot also confirms that for no flux on the detector then the temporal auto-correlation is a "delta" function with no correlation as expected, confirming the fact that for no flux on the detector then there is no measured excess noise. This correlation between consecutive reads explains the reason why co-adding frames does not reduce the noise by the square root of the number of reads as expected. Early testing of algorithms to de-correlate the images and remove the ELFN have not been successful and the reasons for this are not yet understood. De-correlation is also very processor intensive and not suited to real time observing with our present setup.

8. PRACTICAL REDUCTION OF ELFN AT THE TELESCOPE

The simplest way to minimise the ELFN is to chop the telescope secondary mirror at higher frequencies and also minimize the flux to the detector. Recent testing at the VLT has confirmed that higher chopping frequencies gives near expected shot noise limited performance, dependent on the flux and integration time. The VLT secondary mirror was in the past always chopped at a fixed 0.25 Hz but testing has shown that 5 Hz chopping is possible. Some issues remain in terms of commissioning the telescope to chop at this higher frequency but these are not AQAURIUS detector related but to do with the secondary guiding camera performance. Re-visiting Figure 1 shows this recent testing with increased chopping frequency. The white squares are the instrument plus AQUARIUS sensitivity as a function of secondary mirror chop frequency and clearly show that chopping at 3 Hz should give the instrument the same sensitivity as with the old detector and higher frequencies should give still further improvements. It is therefore the plan to re-commission the instrument with a default chop frequency of approximately 5 Hz, once the guiding issues are fixed.

Analysis of previous generations of instruments such as MIDI at the VLTI and TIMMI2 at the La Silla 3.6m telescope, confirm that noise is also seen in the previous generation of this detector, the CRC-774, 320 x 240 pixel device. However the noise was not noticed in this detector because they were typically operated at much higher telescope chop frequencies, for example the NTT routinely chopped at 6 Hz.

Constraining some of the instrument operational parameters can also help to minimize ELFN, for example, minimizing the flux, increasing the integration time and inserting some dead time between frames will all help. However for observations at 20 μm with wideband filters then this is not possible since the shortest exposures will be required and the flux levels will be highest.

9. CONCLUSIONS

In some types of Si:As IBC detectors, where co-adding of frames in high flux regimes is typically used, then the noise does not reduce as the square root of the number of reads because of Excess Low Frequency Noise. This noise is a strong function of flux levels. It has also been confirmed that this noise was seen in the previous generation of these detectors from the same manufacturer. Stapelbroek showed that for the Rockwell BIB detectors, the source of the excess noise was in the blocking layer or at its interface to the IR active layer. It was stated that the excess noise was probably due to the fact that the blocking layer acts as a high gain, low quantum efficiency photo-conductor in series with the normal detector material. The influence of charge in the blocking layer acts on the potential across the IR active layer. It has likewise been confirmed that the Si:As material of the AQUARIUS detector is the source of this excess low frequency noise. However until a further development and manufacturing runs takes place with different blocking layer thicknesses then the conclusion that the issue is with the blocking layer cannot be confirmed for the AQUARIUS detector.

Chopping at higher telescope frequencies minimizes the noise such that in some operational regimes photon shot noise limited performance can be reached. Post processing algorithms such as drift scan with shift and add processing can also help but the issue here is that for the mid-IR, huge amounts of raw data are produced which must then be stored and processed. For example, the AQUARIUS generates data at greater than 210 Mbytes/second continuously for the required integration time; the required computing power is not usually available at the telescope to process this data rate in real time.

In most other ways, the new AQUARIUS detector is almost a perfect device, with low read noise, good stability and excellent cosmetic quality. However the ELFN ultimately limits its performance.

10. ACKNOWLEDGEMENTS

We thank the design and test staff, past and present, at Raytheon for development of the AQUARIUS detector. The development of the NGC detector control system at ESO has allowed us to operate the detector at its maximum potential and has been made possible by the highly skilled electronics and software engineers in the Detector Group at ESO. We also acknowledge the astronomical assistance of ESO staff astronomers Florian Kerber, Hans Uli Kaufl and Ralf Siebenmorgen who did the astronomical data analysis associated with Figure 1. A final mention should also be made of Udo Beckmann and his group at the MPIA, Bonn who have been intimately involved in the detector use and testing for the VLTI MATISSE project.

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