Bolometer Noise Calculation Memo

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This memo presents how to calulate the expected bolometer noise. It also presents the factors to apply to the predicted noise in order to compare with measured values due to the dependance of the transfer function on the source of the noise. An example of such calculation is shown in appendix.

1 Bolometer Noise

All of the following sections describe the different sources of noise present in the readout of the EBEX bolometers. Each source is described individually and table 1 summarizes all the non-neglected noise mentionned below.

1.1 SQUID Noise

The SQUID contributes to $i_{n\ SQ} = 2.5\frac{pA}{\sqrt{Hz}}$ of broad-band current noise at the SQUID coil from specifications. This noise is always present since a tuned SQUID is essential to read bolometers and is broad-band.

1.2 SQUID Controller Board

This section describes the noise produced by the components present on the SQUID controller board. This noise is always present since a tuned SQUID is essential to read bolometers and is broad-band.

1.2.1 Leadlag Filter

There is a RC voltage divider between the SQUID and the 1^{st} stage amplifier of the SQUID controller board as shown in figure 1. The transfer function for a signal going backwards (from the SQUID controller board to the SQUID) is $T_{LL}(f) = \left|\frac{100+R_w+Z_c}{R_w+Z_c}\right| = \sqrt{\frac{(100+R_w)^2+|Z_c|^2}{R_w^2+|Z_c|^2}}$ where $Z_c = \frac{1}{i2\pi f C_{1nF}} = \frac{1}{i2\pi f(10^{-9})}$ and R_w is the stray resistance of the Tekdata cable (typically 10Ω, can also be 20Ω for the initial version). So $T_{LL}(f)$ goes from $T_{LL}(0Hz) = 1.000$ to $T_{LL}(1MHz) = 1.213$ for the usual range of operations assuming $R_w = 10\Omega$.

1.2.2 1^{st} Stage Amplifier of the SQUID Controller Board Noise

The 1^{st} stage amplifier of the SQUID controller board contributes to $v_{n\ 1^{st}\ SQctrl} = 1\frac{nV}{\sqrt{Hz}}$ in the voltage noise at the input of the 1^{st} stage amplifier. Assuming a transimpedance from the coil to the SQUID of $Z_T = 500\Omega$ and considering the leadlag filter, we have a contribution of $i_{n\ 1^{st}\ SQctrl} = T_{LL}(f)\frac{v_{n\ 1^{st}}}{Z_T} = \frac{T_{LL}(f)}{500}\frac{nA}{\sqrt{Hz}} = 2T_{LL}(f)\frac{pA}{\sqrt{Hz}}$.

1.2.3 SQUID Controller Board 20Ω Resistor Noise

The 20Ω resistor ($R_{20\Omega}$) setting the gain of the 1^{st} stage amplifier of the SQUID controller board also has some voltage Johnson noise : $v_{n\ 20\Omega} = R_{20\Omega} \times \sqrt{\frac{4kT}{R_{20\Omega}}} = \sqrt{4kTR_{20\Omega}}$ where $k = 1.38 \times 10^{-23}\frac{J}{K}$ and T is the temperature of the resistor (ambient temperature assumed to be 300K). Assuming a transimpedance of $Z_T = 500\Omega$ from the SQUID to the SQUID coil and considering the leadlag filter, the noise at the SQUID coil is $i_{n\ 20\Omega} = T_{LL}(f)\frac{v_{n\ 20\Omega}}{Z_T} = T_{LL}(f)\frac{\sqrt{4kTR_{20\Omega}}}{Z_T} = T_{LL}(f)\frac{\sqrt{4(1.38\times10^{-23})(300)(20)}}{500} = 1.15T_{LL}(f)\frac{pA}{\sqrt{Hz}}$.

1.2.4 SQUID Controller Board Feedback Resistor Noise

The feedback resistor of the 1^{st} stage amplificator (R_{FB}) can be set either to $10k\Omega$, $5k\Omega$, both in parallel ($3.33k\Omega$), or both opened (then, no noise is present since no resistor is present). All of this Johnson noise goes directly in the SQUID coil. This noise is therefore $i_{n\ R_{FB}} = \sqrt{\frac{4kT}{R_{FB}}} = \sqrt{\frac{4(1.38\times10^{-23}(300)}{R_{FB}}} = \frac{4.069}{\sqrt{R_{FB}[k\Omega]}}\frac{pA}{\sqrt{Hz}}$ where $k = 1.38 \times 10^{-23}\frac{J}{K}$ and T is the temperature of the resistor (ambient temperature assumed to be 300K).

1.2.5 2^{nd} Stage Amplifier of the SQUID Controller Board Noise

The 2^{nd} stage amplifier of the SQUID controller board contributes to $v_{n\ 2^{nd}\ SQctrl} = 1.3\frac{nV}{\sqrt{Hz}}$ in the voltage noise at its input. Applying the transfer function to the SQUID coil, the current noise becomes $i_{n\ 2^{nd}\ SQctrl} = \frac{v_{n\ 2^{nd}\ SQctrl}}{R_{FB}} = \frac{1.3}{R_{FB}[k\Omega]}\frac{pA}{\sqrt{Hz}}$.

1.2.6 Flux Bias $50k\Omega$ Resistor Noise

The $50k\Omega$ resistor ($R_{50k\Omega}$) converting the voltage flux bias into current has some Johnson current noise that goes directly in the SQUID coil : $i_{n\ 50k\Omega} = \sqrt{\frac{4kT}{R_{50k\Omega}}} = \sqrt{\frac{4(1.38\times10^{-23})(300)}{50000}} = 0.58\frac{pA}{\sqrt{Hz}}$ where $k = 1.38\times10^{-23}\frac{J}{K}$ and T is the temperature of the resistor (ambient temperature assumed to be 300K).

1.3 Demodulator Noise

This section describes the noise produced by the components present on the demodulator line. This noise is always present since demodulating the dignal is essential to read bolometers and is broad-band.

Table 1: List of different types of noise present in the EBEX readout of bolometers system

Noise source	Value $\frac{pA}{\sqrt{Hz}}$
$i_{n\ SQ}$	2.5
$i_{n\ 1^{st}\ SQctrl}$	$2T_{LL}(f)$
$i_{n\ 20\Omega}$	$1.15T_{LL}(f)$
$i_{n\ R_{FB}}$	$\frac{4.069}{\sqrt{R_{FB}[k\Omega]}}$
$i_{n\ 2^{nd}\ SQctrl}$	$\frac{1.3}{R_{FB}[k\Omega]}$
$i_{n\ 50k\Omega}$	0.58
$i_{n\ digit\ D}$	$\frac{0.1911(100+Y)}{R_{FB}}$
$i_{n\ 1^{st}\ C}$	$\frac{357.1}{(100+X)R_{bolo}}$
$i_{n\ 2^{nd}\ C}$	$\frac{92.84}{(100+X)R_{bolo}}$
$i_{n\ 30m\Omega}$	$\frac{2.637}{R_{bolo}}$
$i_{n\ 50\Omega}$	0.52
$i_{n\ SN\ C}$	$22.47\sqrt{\frac{A_C}{(100+X)R_{bolo}}}$
$i_{n\ digit\ C}$	$\frac{93.43}{(100+X)R_{bolo}}$
$i_{n\ 1^{st}\ N}$	$\frac{762.2}{100+X}$
$i_{n\ 2^{nd}\ N}$	$\frac{198.2}{100+X}$
$i_{n\ 4\times 820\Omega}$	2.2
$i_{n\ SN\ N}$	$32.83\sqrt{\frac{A_N}{(100+X)}}$
$i_{n\ digit\ N}$	$\frac{189.92}{(100+X)}$
$i_{n\ Johnson}$	$\sqrt{\frac{4kT_{bolo}}{R_{bolo}}}$
$i_{n\ Phonon}$	$\frac{\sqrt{\gamma 4kT_{bolo}^2 G}}{V_{bias}}$
$i_{n\ Photon}$	$\frac{\sqrt{2P_{optical}h\nu}}{V_{bias}}$

1.3.1 1^{st} Stage Amplifier of the Demodulator Noise

The 1^{st} stage amplifier of the demodulator produces $1.3\frac{nV}{\sqrt{Hz}}$ of voltage noise at its input. Applying the transfer function to the SQUID coil, the current noise in the SQUID coil is $i_{n\ 1^{st}\ D} = 1.3\frac{nV}{\sqrt{Hz}} \times \left(\frac{100+82.5+\frac{1}{\frac{1}{10}+\frac{1}{121}}}{500+500}\right) \times \frac{1}{R_{FB}} = \frac{0.2493}{R_{FB}[k\Omega]}\frac{pA}{\sqrt{Hz}}$. Since $i_{n\ 1^{st}\ D}$ is at most $0.07\frac{pA}{\sqrt{Hz}}$ (when R_{FB} is $3.33k\Omega$) and since it adds in quadrature with the other sources of noise, this noise source is neglected.

1.3.2 2^{nd} Stage Amplifier of the Demodulator Noise

The 2^{nd} stage amplifier of the demodulator produces $1.3\frac{nV}{\sqrt{Hz}}$ of voltage noise at its input. Applying the transfer function to the SQUID coil, the current noise in the SQUID coil is $i_{n\ 2^{nd}\ D} = 1.3\frac{nV}{\sqrt{Hz}} \times \frac{1}{2} \times \left(\frac{100+82.5+\frac{1}{\frac{1}{10}+\frac{1}{121}}}{500+500}\right) \times \frac{1}{R_{FB}} = \frac{0.1246}{R_{FB}[k\Omega]}\frac{pA}{\sqrt{Hz}}$. Since $i_{n\ 2^{nd}\ D}$ is at most $0.04\frac{pA}{\sqrt{Hz}}$ (when R_{FB} is $3.33k\Omega$) and since it adds in quadrature with the other sources of noise, this noise source is neglected.

1.3.3 Demodulator Digitization Noise

The digitization noise at the ADC is simply $\frac{1\ LSB}{\sqrt{12}\times\sqrt{Bandwidth}}$. Applying the transfer function to the SQUID coil, it is $i_{n\ digit\ D} = \frac{1\ LSB}{\sqrt{12}\times\sqrt{\frac{1}{2}\times 25MHz}} \times \frac{2V}{2^{14}\ LSB} \times 2 \times \frac{100+Y}{10000} \times \frac{1}{2} \times \left(\frac{100+82.5+\frac{1}{\frac{1}{10}+\frac{1}{121}}}{500+500}\right) \times \frac{1}{R_{FB}} = \frac{191.1(100+Y)}{R_{FB}[k\Omega]}\frac{pA}{\sqrt{Hz}}$ where Y is 10000, 2000, 200 and 0 for demodulator gain 0, 1, 2 and 3.

1.4 Carrier Noise

Thise section describes the noise produced by the components present on the carrier line. This noise is only measured when bolometers are attached to the SQUIDs. The noise has to go through the bolometer LC filters. Therefore, the noise described in this section is narrow-band and only present near the bias frequencies of the bolometers (except the bolometer 50Ω termination that does dot have an LC filter and which is broad-band). The digitization of the carrier is obviously only measured when a carrier is produced.

1.4.1 1^{st} Stage Amplifier of the Carrier Noise

The 1^{st} stage amplifier of the carrier produces $2.5\frac{nV}{\sqrt{Hz}}$ of voltage noise at its input. Applying the transfer function to the SQUID coil, the current noise in the SQUID coil is $i_{n\ 1^{st}\ C} = 2.5\frac{nV}{\sqrt{Hz}} \times 2 \times \frac{1000}{100+X} \times \frac{1}{2} \times \frac{0.03}{210.03} \times \frac{1}{R_{bolo}} = \frac{357.1}{(100+X)R_{bolo}}\frac{pA}{\sqrt{Hz}}$ where X is 2000, 820, 200 and 0 for carrier gain 0, 1, 2 and 3.

1.4.2 2^{nd} Stage Amplifier of the Carrier Noise

The 2^{nd} stage amplifier of the carrier produces $1.3\frac{nV}{\sqrt{Hz}}$ of voltage noise at its input. Applying the transfer function to the SQUID coil, the current noise in the SQUID coil is $i_{n\ 2^{nd}\ C} = 1.3\frac{nV}{\sqrt{Hz}} \times \frac{1000}{100+X} \times \frac{1}{2} \times \frac{0.03}{210.03} \times \frac{1}{R_{bolo}} = \frac{92.84}{(100+X)R_{bolo}}\frac{pA}{\sqrt{Hz}}$ where X is 2000, 820, 200 and 0 for carrier gain 0, 1, 2 and 3.

1.4.3 Carrier Voltage Bias Resistor Noise

A $30m\Omega$ resistor ($R_{30m\Omega}$) converts the carrier current into a voltage bias across the bolometers. It contributes to a voltage noise of $v_{n\ 30m\Omega} = R_{30m\Omega} \times \sqrt{\frac{4kT}{R_{30m\Omega}}} = \sqrt{4kTR_{30m\Omega}}$ across te bolometers where $k = 1.38 \times 10^{-23}\frac{J}{K}$ and T is the temperature of the resistor (assumed to be 4.2K). To get the current noise in the SQUID coil, the resistance of the bolometer is required : $i_{n\ 30m\Omega} = \frac{\sqrt{4kTR_{30m\Omega}}}{R_{bolo}} = \frac{\sqrt{4(1.38\times10^{-23})(4.2)(0.03)}}{R_{bolo}} = \frac{2.637}{R_{bolo}}\frac{pA}{\sqrt{Hz}}$.

1.4.4 Bolometer 50Ω Termination

A 50Ω resistor ($R_{50\Omega}$) terminates the bolometers (a 50Ω resistor is in parallel with all the bolometers). It contributes to a current Johnson noise of $i_{n\ 50\Omega} = \sqrt{\frac{4kT}{R_{50\Omega}}} = \sqrt{\frac{4(1.38\times10^{-23})(0.250)}{50}} = 0.52\frac{pA}{\sqrt{Hz}}$.

1.4.5 Bolometer Voltage Bias Current Shot Noise

The current shot noise is given by $i_n = \sqrt{2eI}$, where I is the current and e is the charge quanta ($1.6\times10^{-19}C$). The current going through the SQUID coil generated by the carrier line is given by $I_C = A_C \times \frac{0.01A^{PP}}{N} \times 50\Omega \times 2 \times \frac{1000}{(100+X)} \times \frac{1}{2} \times \frac{0.03}{210.03} \times \frac{1}{R_{bolo}} \times \frac{A^{RMS}}{2\sqrt{2}A^{PP}} = \frac{1.5781\times A_C}{(100+X)R_{bolo}}mA^{RMS}$ where A_C is the fractionnal amplitude of the carrier, N is the multiplexing factor (usually 16) and X is 2000, 820, 200 and 0 for carrier gain 0, 1, 2, and 3. The corresponding shot noise is therefore $i_{n\ SN\ C} = \sqrt{2(1.6\times10^{-19})\left(\frac{1.5781^{-3}\times A_C}{(100+X)R_{bolo}}\right)} = 22.47\sqrt{\frac{A_C}{(100+X)R_{bolo}}}\frac{pA}{\sqrt{Hz}}$.

1.4.6 Carrier Digitization Noise

The digitization noise at the DAC is simply $\frac{1\ LSB}{\sqrt{12}\times\sqrt{Bandwidth}}$. Applying the transfer function to the SQUID coil, it is $i_{n\ digit\ C} = \frac{1\ LSB}{\sqrt{12}\times\sqrt{\frac{1}{2}\times25MHz}} \times \frac{0.01A\times50\Omega}{2^{16}\ LSB} \times 2 \times \frac{1000}{100+X} \times \frac{1}{2} \times \frac{0.03}{200.03} \times \frac{1}{R_{bolo}} = \frac{93.43}{R_{bolo}\times(100+X)}\frac{pA}{\sqrt{Hz}}$ where X is 2000, 820, 200 and 0 for nuller gain 0, 1, 2 and 3.

1.5 Nuller Noise

Thise section describes the noise produced by the components present on the nuller line. This noise is always present except for the digitization noise that requires a nuller to be on. This noise is broad-band.

1.5.1 1^{st} Stage Amplifier of the Nuller Noise

The 1^{st} stage amplifier of the nuller produces $2.5\frac{nV}{\sqrt{Hz}}$ of voltage noise at its input. Applying the transfer function to the SQUID coil, the current noise in the SQUID coil is $i_{n\ 1^{st}\ N} =$

$2.5\frac{nV}{\sqrt{Hz}} \times 2 \times \frac{1000}{100+X} \times \frac{1}{2} \times \frac{1}{4\times 820\Omega} = \frac{762.2}{100+X}\frac{pA}{\sqrt{Hz}}$ where X is 2000, 820, 200 and 0 for nuller gain 0, 1, 2 and 3.

1.5.2 2^{nd} Stage Amplifier of the Nuller Noise

The 2^{nd} stage amplifier of the nuller produces $1.3\frac{nV}{\sqrt{Hz}}$ of voltage noise at its input. Applying the transfer function to the SQUID coil, the current noise in the SQUID coil is $i_{n\ 2^{nd}\ N} = 1.3\frac{nV}{\sqrt{Hz}} \times \frac{1000}{100+X} \times \frac{1}{2} \times \frac{1}{4\times 820\Omega} = \frac{198.2}{100+X}\frac{pA}{\sqrt{Hz}}$ where X is 2000, 820, 200 and 0 for nuller gain 0, 1, 2 and 3.

1.5.3 Nuller Voltage to Current Converter Resistors Noise

Four 820Ω resistors in series ($R_{4\times 820\Omega}$) converts the voltage of the nuller into a current that goes through the SQUID coil. Their Johnson noise in the SQUID coil is simply $i_{n\ 4\times 820\Omega} = \sqrt{\frac{4kT}{R_{4\times 820\Omega}}} = \sqrt{\frac{4(1.38\times 10^{-23})(300)}{4\times 820\Omega}} = 2.2\frac{pA}{\sqrt{Hz}}$ where $k = 1.38 \times 10^{-23}\frac{J}{K}$ and T is the temperature of the resistor (ambient temperature assumed to be 300K).

1.5.4 Nulling Current Shot Noise

The current shot noise is given by $i_n = \sqrt{2eI}$, where I is the current and e is the charge quanta ($1.6 \times 10^{-19}C$). The current going through the SQUID coil generated by the nuller line is given by $I_N = A_N \times \frac{0.01A_{PP}}{N} \times 50\Omega \times 2 \times \frac{1000}{(100+X)} \times \frac{1}{2} \times \frac{1}{4\times 820\Omega} \times \frac{A^{RMS}}{2\sqrt{2}A^{PP}} = \frac{3368\times A_N}{100+X}\frac{\mu A}{\sqrt{Hz}}$ where A_N is the fractionnal amplitude of the nuller, N is the multiplexing factor (usually 16) and X is 2000, 820, 200 and 0 for nuller gain 0, 1, 2, and 3. The corresponding shot noise is therefore $i_{n\ SN\ N} = \sqrt{2(1.6 \times 10^{-19})\left(\frac{3368\times 10^{-6}\times A_N}{100+X}\right)} = 32.83\sqrt{\frac{A_N}{(100+X)}}\frac{pA}{\sqrt{Hz}}$.

1.5.5 Nuller Digitization Noise

The digitization noise at the DAC is simply $\frac{1\ LSB}{\sqrt{12}\times\sqrt{Bandwidth}}$. Applying the transfer function to the SQUID coil, it is $i_{n\ digit\ N} = \frac{1\ LSB}{\sqrt{12}\times\sqrt{\frac{1}{2}\times 25MHz}} \times \frac{0.01A\times 50\Omega}{2^{16}\ LSB} \times 2 \times \frac{1000}{100+X} \times \frac{1}{2} \times \frac{1}{4\times 820\Omega} = \frac{189.92}{(100+X)}\frac{pA}{\sqrt{Hz}}$ where X is 2000, 820, 200 and 0 for nuller gain 0, 1, 2 and 3.

1.6 Bolometer Johnson Noise

The Johnson noise of the bolometer is given by $i_{n\ Johnson} = \sqrt{\frac{4kT_{bolo}}{R_{bolo}}}$ where $k = 1.38 \times 10^{-23}\frac{J}{K}$, T_{bolo} is the temperature of the bolometer and R_{bolo} is the resistance of the detector. T_{bolo} is T_{wafer}, the temperature of the bolometer wafer, if $T_{wafer} > T_c$, the temperature at which the detector goes superconducting, or T_c if $T_{wafer} < T_c$. Since this noise modulates the carrier, it is narrow-band.

1.7 Bolometer Phonon noise

The phonon noise in the current is given by $i_{n\ phonon} = \frac{\sqrt{\gamma 4kT_{bolo}^2 G}}{V_{bias}}$ where $\gamma = 0.498$ is an attenuation factor accounting for the temperature gradient along the thermal link, $k = 1.38 \times 10^{-23} \frac{J}{K}$, T_{bolo} is the temperature of the bolometer, G is the dynamic thermal conductance of the bolometer and V_{bias} is the voltage bias of the detector. $\overline{G}$, the average thermal conductance, can be approximated by $\overline{G} = \frac{P_{turnaround\ dark}}{T_c - T_{bath}}$. The relation between G and $\overline{G}$ is $G/\overline{G} = (n+1)\frac{1-T_{bath}/T_c}{1-(T_{bath}/T_c)^{n+1}}$ where n=3 typically for EBEX. The phonon noise is seen as signal since it causes the bolometer to change resistance.

1.8 Bolometer Photon noise

The photon noise is given by $i_{n\ photon} = \frac{\sqrt{2P_{optical}h\nu}}{V_{bias}}$ where $h = 6.63 \times 10^{-34} Js$, ν is the mean frequency of the oberved frequency band in Hz and V_{bias} is the voltage bias of the detector. An estimate of the optical power $P_{optical}$ is required to evaluate this term. The photon noise is seen as signal since the photons are the signal.

2 Demodulation Factors

The transfer function is different for signal and for the different types of noise (broad-band and narrowband). For simplicity, only one transfer function is used in all analysis. Correction factors have therefore to be applied to compare the predicted and measured noise values. The choice has been made to apply those factors to the predicted values and compare directly to the measured values afterwards.

Depending on the form of the mixer used to demodulate the signal, the factors vary. For the EBEX engineering flight of June 2009, a quasi-sine mixer (refered as sine mixer) was in use (as a square mixer was used for the firmware releases previous to March 3^{rd} 2009). Values for the sine mixer will be discussed as the values in square brackets are shown for consistency with previous calculation that could have been made. For a complete derivation of the following values, refer the the McGill Wiki : http://kingspeak.physics.mcgill.ca/twiki/bin/view/DigitalFMux/DMFDMixerTra

The signal sent through the bolometer gets multiplied by $\frac{1}{2}\left[\frac{2}{\pi}\right]$ while being demodulated. This factor is included in the digital gain factor in the transfer function applied to the data. For the electronic noise, this factor of $\frac{1}{2}\left[\frac{2}{\pi}\right]$ is instead $\frac{1}{\sqrt{2}}$ [1] because it is broad-band. The predicted noise has to be multiplied by $\sqrt{2}\left[\frac{\pi}{2}\right]$ to be compared with the measured noise.

The Johnson noise is a broad-band source of noise, but only the band near the carrier frequency makes it through the LC band filter near the bolometer. It becomes, from the output point of view, a narrowand source of noise. A factor of $\frac{1}{\sqrt{2}}\left[\frac{2\sqrt{2}}{\pi}\right]$ is applied to the Johnson noise in the digital filters. Consequently, a factor of $\sqrt{2}\left[\sqrt{2}\right]$ must be applied to the predicted noise to compare with measurements.

The phonon noise causes the resistance of the bolometer to change when it is in its transition and appears as an amplitude modulation on the carrier. The phonon noise is therefore treated like the signal by the digital filter and the factor to apply is simply 1 [1].

The photon noise is a variation of the signal and is treated as signal by the digital filter. The factor to apply is therefore also simply 1 [1].

Table 1 summarizes the demodulation factors for the different types of noise for a square and a sine mixer.

Table 2: Predicted noise correction factors for different sources of noise

Noise Type	Correction Factor (sine mixer)	Correction Factor (square mixer)
Broad-band (BB)	$\sqrt{2}$	$\frac{\pi}{2}$
Narrow-band (NB)	$\sqrt{2}$	$\sqrt{2}$
Signal (S)	1	1

3 The Expected Noise

The electronic noise from the SQUID, SQUID controller board, demodulator and nuller (except nuller digitization and shor noise) are always measured in the system as well as the shot noise from the SQUID flux bias and current bias. When demodulating at bolometer bias frequencies while bolometers are connected, the noise components from carrier (except carrier digitization) are measured as well as the Johnson noise from the bolometers. Overbiasing the bolometers adds the digitization noise from the carrier and nuller as well as the shot noise from the carrier and nuller current. Dropping the bolometer in its transition adds phonon noise. If the bolometer is opened to light, some photon noise also adds up.

Table 3 summarizes which noise is present for dark SQUIDs, SQUIDs attached to unbiased bolometers demodulated at arbitrary frequencies, SQUIDs attached to unbiased bolometers demodulated at bolometer bias frequencies, overbiased bolometers, dark bolometers in their transition and light bolometers in their transition.

4 Conclusion

The expected noise present in the system can be calculated using table 1. The demodulation factor to apply to each source of noise are taken from table 2 and the sources to consider are listed in table 3. The noise equivalent power at the bolometers obtained at first order by multiplying by the voltage bias applied to the detectors : $NEP = V_{bias} \times i_n$

Table 3: Presence of different types of noise for different situations. BB stands for broad-band, NB for narrow-band and S for signal, the different types of noise.

Source	Dark SQUID	SQUID bolo attached arbitrary f	SQUID bolo attached bolo f	Bolo overbiased	Dark bolo in transition	Light bolo in transition
$i_{n\ SQ}$	BB	BB	BB	BB	BB	BB
$i_{n\ 1^{st}\ SQctrl}$	BB	BB	BB	BB	BB	BB
$i_{n\ 20\Omega}$	BB	BB	BB	BB	BB	BB
$i_{n\ R_{FB}}$	BB	BB	BB	BB	BB	BB
$i_{n\ 2^{nd}\ SQctrl}$	BB	BB	BB	BB	BB	BB
$i_{n\ 50k\Omega}$	BB	BB	BB	BB	BB	BB
$i_{n\ digit\ D}$	BB	BB	BB	BB	BB	BB
$i_{n\ 1^{st}\ C}$			NB	NB	NB	NB
$i_{n\ 2^{nd}\ C}$			NB	NB	NB	NB
$i_{n\ 30m\Omega}$			NB	NB	NB	NB
$i_{n\ 50\Omega}$			BB	BB	BB	BB
$i_{n\ SN\ C}$				BB	BB	BB
$i_{n\ digit\ C}$				NB	NB	NB
$i_{n\ 1^{st}\ N}$	BB	BB	BB	BB	BB	BB
$i_{n\ 2^{nd}\ N}$	BB	BB	BB	BB	BB	BB
$i_{n\ 4\oplus 820\Omega}$	BB	BB	BB	BB	BB	BB
$i_{n\ SN\ N}$				BB	BB	BB
$i_{n\ digit\ N}$				BB	BB	BB
$i_{n\ Johnson}$			NB	NB	NB	NB
$i_{n\ Phonon}$					S	S
$i_{n\ Photon}$						S

APPENDIX : Example

We consider bolometer 12-01 on the 410 GHz wafer G18 read out by DfMUX 54 on Mux 1 and Channel 1 (b54_w0_c0) at EBEX time 1015350s during the engineering flight of June 11^{th} 2009. The bolometer is 70% in its transition at that point. Table 4 shows the parameters used to predict noise.

Table 4: Parameters used to predict noise for bolometer 12-01 on the 410 GHz wafer G18

Parameter	Value
Demodulator gain	2
Demodulator frequency	292968 Hz
Carrier gain	2
A_C	0.60
Nuller gain	2
A_N	0.41
V_{bias}	3.19 μV_{RMS}
R_{normal}	1.57 Ω
R_{bolo}	1.099Ω
T_c	0.485 K
T_{bath}	0.270 K
$P_{turnaround\ dark}$	11.36 pW
$P_{turnaround\ at\ float}$	10.85 pW
R_w	10Ω
SQUID flux bias	-34.0mV
current bias	5.67V
$R_{feedback}$	$5k\Omega$
Frequency band	150GHz
R_{bolo}	1.57Ω

From those parameter, we get $\overline{G} = \frac{P_{turnaround\ dark}}{T_c - T_{bath}} = \frac{11.36\times10^{-12}}{(0.485)-(0.270)} = 52.84\frac{pW}{K}$ and $G = \overline{G}(n+1)\frac{1-T_{bath}/T_c}{1-(T_{bath}/T_c)^{n+1}} = \left(52.84\frac{pW}{K}\right)((3)+1)\frac{1-(0.270)/(0.485)}{1-((0.270)/(0.485))^{(3)+1}} = 103.7\frac{pW}{K}$. Also, we estimate P_{sky}=$P_{turnaround\ dark}$-$P_{turnaround\ at\ float}$=11.36- 10.85=0.51pW. We can calcultate from there each component of the noise as shown in table 5 :

And applying the demodulating factor to each of the noise sources and adding in quadrature, the value to compare with measured noise is $i_n = 15.1\frac{pA}{\sqrt{Hz}}$.

Table 5: Types and values of noise

Source	Noise $\frac{pA}{\sqrt{Hz}}$	Value $\frac{pA}{\sqrt{Hz}}$
$i_{n\ SQ}$	2.5	2.50
$i_{n\ 1^{st}\ SQctrl}$	$2T_{LL}(f)$	2.04
$i_{n\ 20\Omega}$	$1.15T_{LL}(f)$	1.17
$i_{n\ R_{FB}}$	$\frac{4.069}{\sqrt{R_{FB}[k\Omega]}}$	1.82
$i_{n\ 2^{nd}\ SQctrl}$	$\frac{1.3}{R_{FB}[k\Omega]}$	0.26
$i_{n\ 50k\Omega}$	0.58	0.58
$i_{n\ digit\ D}$	$\frac{0.1911(100+Y)}{R_{FB}}$	0.01
$i_{n\ 1^{st}\ C}$	$\frac{357.1}{(100+X)R_{bolo}}$	1.08
$i_{n\ 2^{nd}\ C}$	$\frac{92.84}{(100+X)R_{bolo}}$	0.28
$i_{n\ 30m\Omega}$	$\frac{2.637}{R_{bolo}}$	2.40
$i_{n\ 50\Omega}$	0.52	0.52
$i_{n\ SN\ C}$	$22.47\sqrt{\frac{A_C}{(100+X)R_{bolo}}}$	0.96
$i_{n\ digit\ C}$	$\frac{93.43}{R_{bolo}\times(100+X)}$	0.28
$i_{n\ 1^{st}\ N}$	$\frac{762.2}{100+X}$	2.54
$i_{n\ 2^{nd}\ N}$	$\frac{198.2}{100+X}$	0.66
$i_{n\ 4\times820\Omega}$	2.2	2.20
$i_{n\ SN\ N}$	$32.83\sqrt{\frac{A_N}{(100+X)}}$	1.21
$i_{n\ digit\ N}$	$\frac{189.92}{(100+X)}$	0.63
$i_{n\ Johnson}$	$\sqrt{\frac{4kT_{bolo}}{R_{bolo}}}$	4.94
$i_{n\ Phonon}$	$\frac{\sqrt{\gamma 4kT_{bolo}^2 G}}{V_{bias}}$	8.11
$i_{n\ Photon}$	$\frac{\sqrt{2P_{optical}h\nu}}{V_{bias}}$	5.22

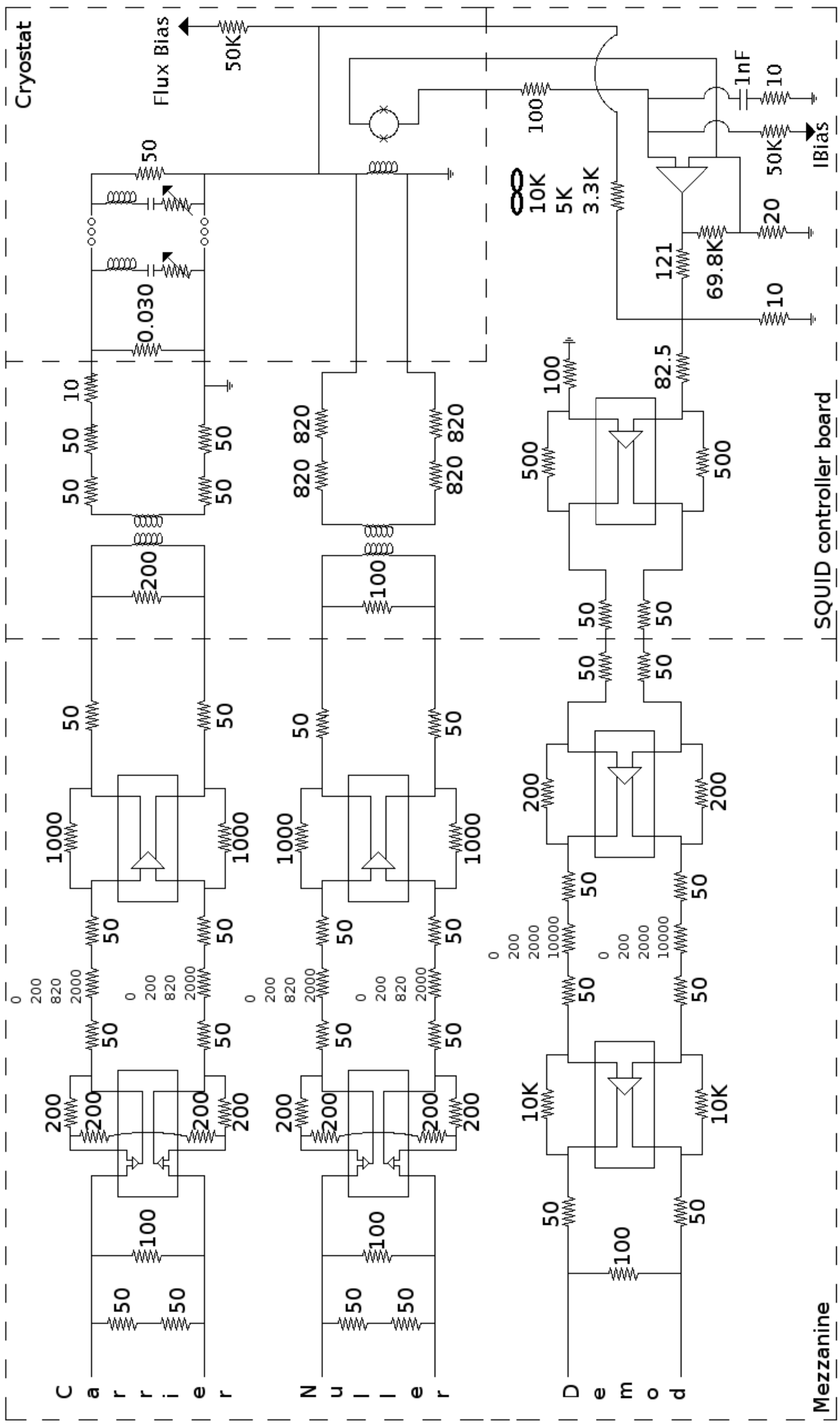

Figure 1: Schematic of the whole readout system with detectors