(DRAFT) CMBpol Instrument Technologies Whitepaper

MHz Frequency Domain Multiplexed Readout

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***Abstract*— The MHz frequency domain multiplexed (fMUX) readout system for large format arrays of TES bolometers is described. Its benefits, challenges, and technical readiness level for a satellite platform CMB polarization experiment are summarized. The fMUX has being deployed on the APEX-SZ and South Pole Telescope instruments. A new version with a digital backend is being deployed on the EBEX balloon-borne CMB polarimeter and POLARBEAR instruments. There is modest funding in Canada to explore the development of the system for satellite applications.**

I. Introduction

A key technology for deploying large format Transition Edge Sensor (TES) bolometer arrays on satellite platforms is SQUID-based multiplexed readout systems. The Frequency domain multiplexed readout (fMUX) was developed for mm-wavelength observations using large arrays of TES bolometers by LBNL, U.C. Berkeley, and McGill. The system, with its original "analog" backend electronics [1,2,3], targeted ground based telescopes and is deployed on the APEX-SZ instrument [4] and the South Pole Telescope (SPT) [5]. These instruments have achieved unprecedented on-sky noise performance. The analog backend draws too much power for balloon or satellite applications. In the course of the analog system's development, fast ADCs and FPGAs with substantially increased gate-count and reduced power consumption became available. This allowed for the development of a new digital backend [6] for the fMUX system that dissipates an order of magnitude less power, making it amenable for stratospheric balloon payloads. This Digital fMUX (DfMUX) system is being deployed for the EBEX balloon-borne CMB polarimeter [8] and the ground-based POLARBEAR [9] instrument. The DfMUX also provides a path to further substantial power reductions by grouping many more bolometers together in a multiplexer module. With the digital fMUX system, the power consumption is roughly proportional to the number of multiplexer modules and not to the number of bolometer pixels.

The frequency domain multiplexer reads out many TES bolometers on a single set of wires without appreciably contributing to the system noise. The detectors are low impedance (≈½Ω) devices cooled to sub-Kelvin temperature. The sky signals are modulated in the bandwidth 0.05-100 Hz by the motion of the telescope or optics. The low frequency noise specification places strict requirements on all aspects of the system and distinguishes the firmware and digital algorithms employed in this system from other modulation/demodulation applications such as software defined radio. The electronics system also tunes the detectors to the optimum bias point by adjusting their voltage bias and tunes the SQUID pre-amplifiers using bias currents to obtain the best noise performance and dynamic range.

Advantages of the DfMUX system include: (1) bolometer signals are modulated above microphonic and low frequency noise, (2) there is no fundamental limit on the number of detectors that can be multiplexed in a module, (3) no heat dissipation on the sub-Kelvin stage, (4) the system is highly modular, and (5) individual bolometer biases and the detector readout bandwidth can be software configured.

The fMUX system is complementary to the time domain multiplexed system [9], [10] developed at NIST and UBC. Recently the NIST group began work on a system that frequency-multiplexes SQUIDs (rather than bolometers) at microwave frequencies [11]. The DfMUX electronics described here is a lower frequency version of what is needed for the backend of this future RF-SQUID multiplexing system.

II. Overview of Technology

A. System Description

The frequency domain multiplexer (DfMUX) is shown schematically in Fig. 1. For the EBEX system, the bolometer sensors R_{bolo} are biased with sinusoidal voltages in the frequency range from 300 kHz to 1 MHz. Each bolometer is biased at a different frequency. Intensity variations from the sky-signal change the bolometer resistance and amplitude modulate the bolometer current such that the sky-signal from each bolometer is transferred to a sideband adjacent to its carrier. Thus, the signals from different bolometers within a module are uniquely positioned in frequency space, so they can be summed and connected through a single wire to a SQUID preamplifier operating at 4K. Each bolometer is connected through a series resonant LC circuit* that defines the bias frequency. This allows the bias frequencies for all bolometers in a module to be applied through a single wire, as the tuned circuit selects the appropriate frequency for each bolometer. Only two wires are needed to connect the bolometers of a readout module on the sub-Kelvin stage to the 4K stage on which the SQUIDs are mounted. The tuned

* The first generation superconducting inductors for this system were fabricated at TRW which has closed its superconducting fab facility. The present generation is being fabricated at NIST. The capacitors are off-the-shelf ceramic chip devices.

circuits also limit the bandwidth of the bolometer Johnson noise, which would otherwise contribute to the noise in all other channels of the module. Refer to [3] for a detailed description of the readout system's cold circuits.

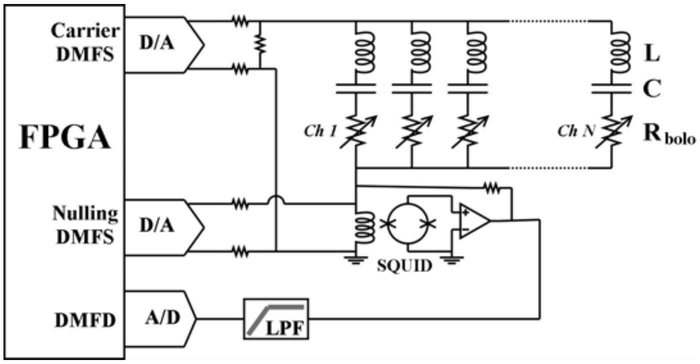

Fig. 1: The digital frequency domain multiplexer system is shown schematically.

The comb of bias carriers is synthesized with a *Digital Multi-Frequency Synthesizer* (DMFS). It produces a comb of sine waves using an algorithm implemented in firmware. It converts the signal to analog using a 16-bit D/A operating at 25 MHz. The DMFS firmware is shown schematically in Fig. 2. Each sinusoidal carrier is synthesized using a Direct Digital Synthesizer algorithm [11]. A 'comb' of carriers it created by multiply-and-accumulating the DDS outputs with an amplitude control register for each sine wave. The comb is sent to the cryostat as a differential signal on a shielded twisted pair cable.

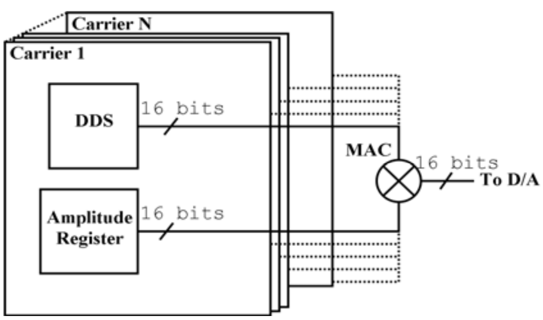

Fig. 2: The Digital Multi-Frequency Synthesizer algorithm is shown schematically.

The sky-modulated signals from the bolometers are pre-amplified with a SQUID as it has the necessary noise temperature and has low input impedance. To maintain constant voltage bias across the TES, the input resistance of the SQUID must be small compared with the TES resistance. This is achieved by operating the SQUID with shunt feedback from the output of the room-temperature amplifier that follows. The feedback amplifier has a high gain × bandwidth product, so connections between the SQUID and the room temperature electronics must be short. Negative feedback also linearizes the SQUID response, reducing intermodulation between the bias carriers.

Since the carrier amplitudes are orders of magnitude larger than the sky signals, we cancel the carriers at the SQUID input with a second comb (synthesized with a second DMFS), referred to as the nulling signal. The nulling comb is an inverted version of the original carrier comb, and serves to remove the large carrier signals. It does not affect the carrier sidebands, which contain the information of the sky-signals. The use of the nulling signal dramatically reduces the dynamic range requirements of the system. Nulling factors of 10^3 are routinely achieved.

The SQUID amplifiers are 100 element series array devices [12] manufactured by NIST in Colorado. Each SQUID device is operated in shunt-feedback with a low-noise bipolar transistor op-amp located on a custom room temperature SQUID controller circuit board. These boards also include digital control electronics and DACs to provide the bias currents and tuning functionality to operate the SQUID devices.

After amplification, the comb of sky-signal modulated carriers output by the SQUID controller is transmitted to the Digital Multi-Frequency Demodulator (DMFD) on a twisted pair cable. The comb is directly digitized with a 14-bit A/D converter operating at 25 MHz. The over-sampling improves the resolution beyond 14 bits. Since the sky-signals occupy only a small fraction of the waveform's total bandwidth, it is not feasible to store the entire waveform on disk. The signals are processed in real time.

Inside the FPGA, the DMFD input data is sent down a set of parallel algorithm pipelines, each of which consists of a quadrature mixer, Cascade Integrator-Comb (CIC) [14] low pass filter, and a chain of band defining FIR filters. There is one pipeline for each detector channel in the comb. A basic schematic of the configuration is shown in Fig. 5.

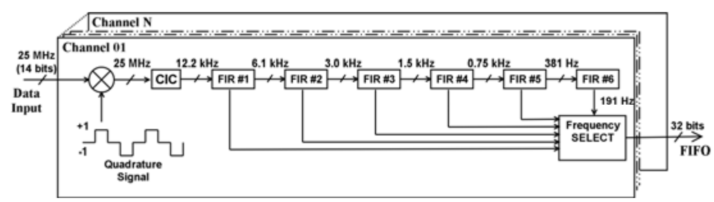

Fig. 3: The Digital Multi-Frequency Demodulator algorithm is shown schematically.

The low pass filtering of the waveform is challenging. Low frequency (typically 0.05-100~Hz) signals need to be maintained while filtering and sub-sampling the waveforms by a factor of roughly 10^5 to reduce the 25 MHz sampling rate to the ~200 Hz data rate that will be recorded on disk. The user can easily change the output data rate and hence the bandwidth of the system by bypassing some of the FIR filters with software commands. This is a powerful tool for debugging during the integration phase of the instrument's commissioning, where typically a larger bandwidth is desired to measure detector properties such as electrical and thermal time constants.

Four DfMUX modules are contained on a single 6U VME board, shown in Fig. 4. Each motherboard can handle 4 multiplexer modules. The digital circuits, including a powerful Xilinx Virtex4 LX160 FPGA, reside on this FPGA motherboard, while the low noise analog converters, amplifiers, and filters ride 'piggy-back' on two mezzanine boards. The total number of detectors that can be demodulated by a single FPGA is determined by its gate count, but this gate count has been increasing faster than Moore's law over the last decade.

A SQUID controller board, capable of handling 8 SQUID modules, forms an intermediary between the cold SQUIDs and the analog signals coming from the DfMUX backend.

The electronics attaches timestamps to the bolometer data from either an IRIG-B encoded GPS signal or Manchester encoded system clock. High-level commands ("set up squids", "set up bolometers") are encoded as TCP/IP packets and sent to the boards over standard Ethernet. Bolometer data is streamed off the board as UDP Ethernet packets. Each board has an embedded processor running μCLinux allowing it to run autonomously. It has its own watchdog circuit and temperature monitors. A monitoring system is being developed which will recognize configuration bit-flips due to single event upsets and correct for them.

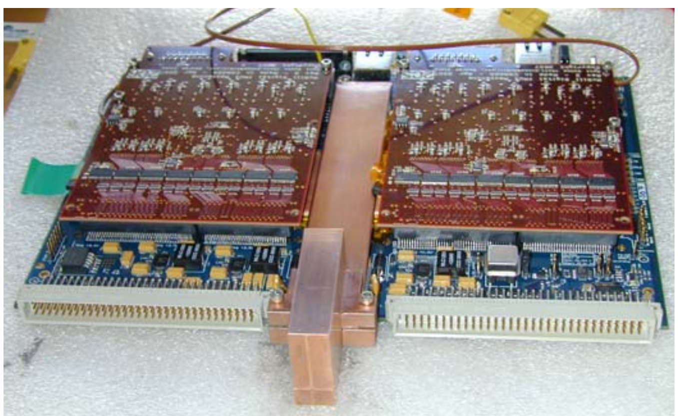

Fig. 4: The digital fMUX backend electronics. An FPGA motherboard is shown (large lower blue board) with two of its analog converter mezzanine boards attached (smaller upper red boards) and the copper convective heat pipe and conductive heat sink.

The SQUID controller and cold components of the system were developed at LBNL/UC Berkeley and are described in [4], [5]. The room temperature digital backend electronics developed at McGill are described in [6]. The heat dissipation scheme being employed for EBEX was developed at U. Minnesota. Performance validation of the digital system in the laboratory can be found in [6] and [15].

B. Channel spacing

The number of detectors that can be grouped together in a multiplexer comb is defined by the SQUID pre-amplifier system bandwidth divided by the carrier spacing.

Our present SQUID system has a bandwidth of just above 1 MHz, limited by phase shifts along the wires that connect the 4K SQUID to the room temperature amplifier which forms part of the flux locked loop. There are several suggestions for SQUID systems that could greatly improve this bandwidth while maintaining the necessary system loop gain and linearity. One example is the Linearized SQUID Array (LISA) that is outlined in [3] and has recently been further developed. Bandwidths of 5-10 MHz have been achieved with LISA.

The detector time constants define the minimum LCR filter width and ultimately the channel spacing. While detectors employed with this system typically have optical time constants >1 ms, the TES sensor itself can respond to much faster thermal signals and the filter needs to be wide enough to allow stability across the full TES bandwidth. A careful reduction of the TES time constant to just wider than the optical time constant would allow closer channel spacing. The system presently uses 16μH inductors with ½Ω bolometers, resulting in an L/R bandwidth of 5 kHz.

Once the L/R bandwidth is defined, the frequency spacing of adjacent carriers in the bias comb is specified by the requirement that Johnson noise from neighboring channels be attenuated to a negligible level.

For EBEX, the carriers occupy the bandwidth from 0.3-1 MHz with a spacing of ~50 KHz, resulting in 12 detectors per multiplexer module.

It should be emphasized that there is nothing fundamental limiting the module channel count—by optimizing the detector time constants and implementing new SQUID technology, a factor of many should be achievable without the development of any new technology. A commiserate reduction in power consumption and sub-Kelvin heat load would be achieved. If the SQUID to room temperature feedback loop can be eliminated, the 4K-300K wire length could be greatly increased, greatly reducing the heat load there as well.

C. System Configuration for EBEX

For the EBEX science flight, 12 detectors will be multiplexed per module. The 1536 bolometer system has 32 DfMUX backend boards, 16 SQUID controller boards, and 128 SQUIDs. The SQUID controllers are mounted in a Faraday cage directly on the receiver cryostat. The DfMUX boards are housed in two 6U VME racks.

D. Power and thermal considerations

The power consumption is about 4W per multiplexed module. For EBEX (12 detectors per multiplexer module) the power dissipation is ~500W for 1536 channels. By increasing the number of multiplexed detectors per module as described in the channel spacing section, this power consumption could be substantially decreased.†

Heat dissipated on the boards is removed through a two stage system designed by the Hanany group at U. Minnesota.

† As the detector count goes up, FPGAs with larger gate-counts are needed to handle the demodulation. Fortunately the density of this technology is increasing very rapidly. We feel that much more efficient demodulation algorithms are possible as well.

Heat is conducted from the board and ICs through thermal grease to a pair of crossed rectangular heat pipes made of copper and a convective fluid (Tradename: "Nano Spreader", developed for laptop computers by Celsia Technologies). The heat pipes, visible in Fig. 4, are terminated in a copper plug that brings the heat through the backplane to the gondola frame. The system has been thermally modeled and the results verified with a thermal-vacuum chamber at NASA's Palestine balloon facility. The heat is radiated away from the instrument using panels mounted on the bottom of the gondola.

III. Benefits / Challenges for this System

A. Advantages

Sky signals modulated above microphonics and low frequency electronic noise: With frequency multiplexing, all detectors are continuously read out without interruption or switching transients. Sky-signals are modulated at ~MHz frequencies, greatly reducing susceptibility to microphonic pickup and amplifier/SQUID low-frequency noise.

No power dissipation on sub-Kelvin stage: In the fMUX system, there is one 4K SQUID per multiplexed module (rather than one SQUID per detector) and there is no power dissipation from the readout system on the sub-Kelvin stage.

No fundamental limit in the multiplexing factor: While existing fMUX systems use multiplexing factors of just 8 or 12 channels, there is no fundamental limit on this number. This number reflects the relatively small investment that has been made in this technology to date. A path to substantially larger channel counts using existing technology exists.

Modularity: For the DfMux system, the bias and demodulation functions for a multiplexer module of detectors are provided by the same electronics board (e.g. there are no rows of bias and columns of demodulation). This provides modularity, such that if an electronics board or cryogenic wire fails, it brings down only those combs. Each board is autonomous in its execution of setup scripts, and needs only high level commands from a control computer.

Configurable bandwidth: The configurable firmware demodulator allows the bandwidth of bolometer data recorded to disk to be changed by factors of 2 with a simple software command. For EBEX, we plan to record sky data with a bandwidth of 180 Hz (381 Hz sampling), but can command the system to record data with a bandwidth up to 6 kHz anytime without changing the system tuning. This is useful for mapping out the bolometer response functions or debugging the system.

Other advantages of the fMUX system include:

- bias voltage can be configured for each bolometer separately,
- the bolometer to SQUID wiring can be interrupted with small resistances ($R \ll R_{bolo}$) allowing the use of connectors with copper contacts,
- low power dissipation on the 4K stage (one SQUID per multiplexer module).
- FPGA Vendors such as Xilinx are actively pursing satellite applications and large gate count devices, similar to the ones used for this system, are already space qualified.
- DSP power in FPGAs is increasing quickly—faster than Moore's law by some estimates—this will result in even lower power consumption and make processing of drastically higher channel counts possible.

B. Challenges

Stray inductance: To maintain good voltage bias across the TES, the loop that includes the LC filter, SQUID input, and bolometer should be dominated by the bolometer impedance. Stray inductance between the sub-Kelvin and 4K stages spoils this voltage bias. For the analog system, low-inductance lead-coated copper strip-lines are used for the majority of the distance from the SQUIDs to detectors, with a heat-gap created by several inches of Nb twisted pairs. The inductance is dominated by the twisted pair. While this inductance is low enough for sub-MHz operation, it would not work at substantially higher frequency. The short length of twisted pair adds extra heat loading to the sub-Kelvin stage. The Hanany group at U. Minnesota are developing Nb superconducting strip-lines for EBEX by rolling thin Nb wire flat and suspending the traces between Kapton films. This is expected to provide a simple and cost effective solution that is both low inductance and low thermal conductivity.

4K–room temperature wire lengths: The SQUID flux locked loop, as it is presently implemented, includes a room temperature amplifier in the feedback loop. To maintain stability at high loop gain, the wire length between these devices must be kept short (<20cm), loading the 4 K stage. We note that a system with cold feedback, like the LISA pre-amplifier described above, would remove this constraint.

Readout white noise: white noise sources that do not modulate the carrier (such as SQUID and readout electronics noise) are enhance by a factor $\sqrt{2}$ post-demodulation. This is true of any AC-biased bolometer system. For a system with carefully optimized bolometer parameters, this is usually not an issue, as this noise is, even after the enhancement, small compared to other noise sources.

Low frequency D/A noise: The stability of the DMFS waveforms is extremely important to maintain good low frequency performance for temperature anisotropy measurements. The DMFS carrier, DMFS nuller, and DMFD are all clocked with the same crystal oscillator such that clock jitter cancels out to first order. The largest contributor is the low frequency noise from the transistors in the D/A converter output ladder. This low frequency transistor noise is modulated up to the carrier tone frequency by the D/A switching and appears as sidebands on the tones. While the older analog fMUX system suffered from low frequency noise with a low frequency knee typically at 1 Hz, this has been greatly improved for the digital system, where the knee sits at ~0.1 Hz. The location of the knee is determined by the amplitude of the bolometer bias, and so will be lower yet for low thermal conductivity bolometers such as those that will be used on satellite platforms.

Inter-modulation distortion: Any SQUID system is inherently non-linear. Since the SQUIDs in the fMUX system must handle many large carriers, inter-modulation distortion products are produced. Accurate nulling greatly reduces this effect. If the carriers were located at arbitrary frequencies, this distortion would create a forest of inter-modulation distortion products from these tones. Fortunately, there is some flexibility in the specification of the carrier frequency for each LCR resonance. By specifying that every carrier frequency is a multiple of (i.e.) 117 Hz, these distortion products are forced to live post-demodulation at either DC or a 117 Hz. It is easy to notch out this frequency off line.

IV. Technical Readiness

The DfMUX system is presently at Technical Readiness Level 4. Components have been prototyped and strung together end-to-end in the laboratory with TES bolometers to demonstrate performance, including noise [6,15].

Two areas need more attention and investment.

Space qualification for FPGAs: The system makes heavy use of DSP implemented with Xilinx Virtex-4 FPGAs. The vendor has identified satellite and aerospace applications as an important market, and has an active program of space qualification. Recently Xilinx announced a new space grade version of the Virtex-4 line called Virtex-4QV [16]. This line includes a model that has 25% more processing power than the device presently used in the digital backed.

The McGill team has modest funding from the Canadian Space Agency and NSERC to work with an industrial partner (COM DEV) to explore technology that corrects configuration bits in FPGAs that have been flipped by single event upsets (SEUs). The strategy is to allow and expect SEUs, but recognize and correct them quickly. COM DEV has experience in this regime from systems it flew on the MAESTRO payload.

Pre-amplifier Bandwidth: presently the number of multiplexed detectors and hence the power consumption and heat load on the sub-Kelvin stage is limited by the bandwidth of the SQUID pre-amplifier system. Very little research, time, or funding has been invested to improve this bandwidth. A relatively small investment here will likely provide substantial returns. The goal is to produce a high-bandwidth (>~10 MHz) SQUID pre-amplifier system that does not use warm components inside the feedback loop.

V. Summary and Future Prospects

Recent developments in the processing power of FPGAs have allowed for the development of digital backend electronics for a SQUID-based frequency domain multiplexer system that operates with large arrays of sub-Kelvin Transition Edge Sensor bolometers. This new technology has sufficiently low power consumption to allow for the readout of large focal plane arrays on stratospheric balloon platforms. The system will be deployed on the EBEX instrument in 2008/9.

A number of important advantages, discussed above, makes this system attractive—while its primary disadvantages are addressable with existing technology.

Substantial reductions in power consumption could be achieved by improving the bandwidth of the SQUID pre-amplifier flux-locked loop. An increase in bandwidth of a few MHz would result in power reduction by a factor of many. Space qualification of the large gate-count Virtex-4 FPGAs employed in the system has already been undertaken the vendor, Xilinx.

To bring the system up to the maturity level necessary for satellite platforms, an investment similar to that made for the UBC TDM electronics is probably necessary. Fortunately, there are no fundamental limits or boundaries that stand in the way of this development—in principle the number of detectors grouped together in a multiplexed module is limited only by the bandwidth of the analog electronics so large advances are in principle possible.

References

[1] H. Spieler, “Frequency Domain Multiplexing for Large Scale Bolometer Arrays”, *Monterey Far-IR, Sub-mm and mm Detector Technology Workshop proceedings*, 2002, pp. 243-249.

[2] T.M. Lanting *et al.*, “Frequency domain multiplexing for bolometer arrays”, *Nuclear Instruments and Methods in Physics Research A* vol. 520, 2004, pp. 548-550.

[3] T.M. Lanting, “MUX Readout of Superconducting Bolometers”, 2007 UC Berkeley Ph.D Thesis.

[4] M. Dobbs, N. Halverson *et. al.,* “APEX-SZ first-light and instrument status”, *New Astronomy Reviews* vol. 50, 2006, pp. 960-968.

[5] John E. Ruhl *et al.*, “The South Pole Telescope”, *Proc. SPIE Int. Soc. Opt. Eng*. Vol. 5543, 2004. [astro-ph/0411122]

[6] M. Dobbs, E. Bissonnette, and H. Spieler, "Digital Frequency Domain Multiplexer for mm-Wavelength Telescopes", IEEE Transactions on Nuclear Science, TNS-00230-2007.R2, 2008 [arXiv:0708.2762v1].

[7] P. Oxley *et al.*, “The EBEX Experiment”, *Proc. SPIE Int. Soc. Opt. Eng*. Vol. 5543, 2004, pp. 320-331 [astro-ph/0501111v1]

[8] POLARBEAR Experiment [Online]. Available: http://bolo.berkeley.edu/polarbear/

[9] J.A. Chervenak, K.D. Irwin, E.N. Grossman, J.M. Martinis, C.D. Reintsema, and M.E. Huber, “Superconducting Multiplexer for Arrays of Transition Edge Sensors”, *Applied Physics Letters*, vol. 74, 1999, pp. 4043-4045.

[10] W. Holland *et al.*, “SCUBA-2: a 10,000 pixel submillimeter camera for the James Clerk Maxwell Telescope”, *Proceedings of the SPIE*, vol. 6275, pp. 62751E (2006).

[11] K.D. Irwin, KW Lehnert, “Microwave SQUID multiplexer“, Applied Physics Letters 85, 2107 (2004).

[12] M.E. Huber et al., ”DC SQUID Series Array Amplifiers with 120 MHz Bandwidth (Corrected)”, IEEE Transactions on Applied Superconductivity, vol. 11 (2), 2001, pp. 4048-4053.

[13] Xilinx Logicore DDS v5.0 Product Specification, 2005 [Online]. Available: http://www.xilinx.com/ipcenter/catalog/logicore/docs/dds.pdf

[14] E. B. Hogenauer. “An economical class of digital filters for decimation and interpolation”, *IEEE Transactions on Acoustics, Speech and Signal Processing*, ASSP-29(2) vol. 155, 1981.

[15] J. Hubmayr *et al.*, (EBEX), “Design and characterization of TES bolometers and SQUID readout electronics for a balloon-borne application”, submitted to the proceedings of SPIE, 2008.

[16] http://www.xilinx.com/publications/prod_mktg/virtex4qv_flyer.pdf