SQUID-based multiplexing by slope inversion and binary-to-Hadamard address translation[1]

Mikko Kiviranta and Nikolai Beev.
VTT, Tietotie 3, 02150 Espoo, Finland

E-mail: Mikko.Kiviranta@vtt.fi

Abstract. We have demonstrated multiplexing and demultiplexing of 7 test signals using the Hadamard-Walsh basis set. The encoding utilizes the sign change of the SQUID gain when a $\Phi_0/2$ flux shift occurs. The periodicity of the SQUID response allows recursive construction of in principle arbitrarily high order Hadamard matrices out of binary addresses and hence makes it possible to access N channels by $\log_2 N$ address lines.

1. Introduction

There is an infinite number of orthogonal basis sets which could be used in SQUID-based multiplexing of cryogenic detector matrices or multichannel magnetometers [1]. The functions taken from the basis set 'fingerprint' the signals so that they can be resolved at the decoding stage. Three basis sets provide certain technical advantages and have hence been favored in the past. (i) The time domain basis set (TDM) was pioneered at National Institute of Standards and Technology [2]. Because the basis set comprises of two-level functions, the encoding can be performed with a simple on-off cryogenic switch. The main disadvantage of TDM is the noise penalty [3] which prevents large multiplexing factors.

The frequency domain basis set (FDM) was originally pursued by Berkeley [4] and by the VTT-SRON collaboration [1, 5]. Because the FDM basis functions are continuous, a continuous cryogenic multiplication is required for encoding. Transition edge sensors (TESes) can function as continuous multipliers via Ohm's law [1], and they tend to work well in the bolometric mode where the TES remains close to the thermal equilibrium. However, in calorimetric mode where non-equilibrium excursions occur, excess noise is often observed [6]. The important advantages of FDM are related to its compact spectral representation and lack of the dc component in the encoded signals. The consequent possibility of reactive detector biasing and non-galvanic signal coupling helps in reducing the heat generation which is important when the cooling budget is limited, eg. in the SAFARI instrument [7]. The amplifier 1/f noise is also avoided and the cable dispersion can be compensated effectively at narrowband spot frequencies.

The third, Hadamard basis set was proposed in [8] and demonstrated in practice at NIST [9], [10]. The CDM basis functions are two-level and thus allow encoding by commutating (on-on) cryogenic switches. This basis set does not suffer from the noise penalty and does not have other obvious shortcomings either. When the lowest-order modulating function is discarded, the remaining signals lack the dc component and many of the advantages of FDM become applicable. We suspect that the long delay between the proposal of the Hadamard basis set and its first practical demonstration was due to the misconception that the method would alias noise from many detectors into a single readout channel. However, if the detector signals are low-pass filtered before the encoding takes place, the random part of the signal does not change significantly during the frame and hence gets fingerprinted. This makes it possible to resolve the noise, too, into the different output channels during the demultiplexing process, and no aliasing takes place.

2. Experiment

In the experiment we perform the signal encoding by switching each readout SQUID between the positive and negative slopes of the flux response. The experiment at hand utilizes the mechanism, proposed by Irwin et. al. [9], that successive *multiplications* by -1 inherent in the construction of

[1] This slope-switching approach suffers from summing of the noise currents of the SQUIDs, which lead to similar sqrt(N) proportional noise penalty as the classical TDM approach.

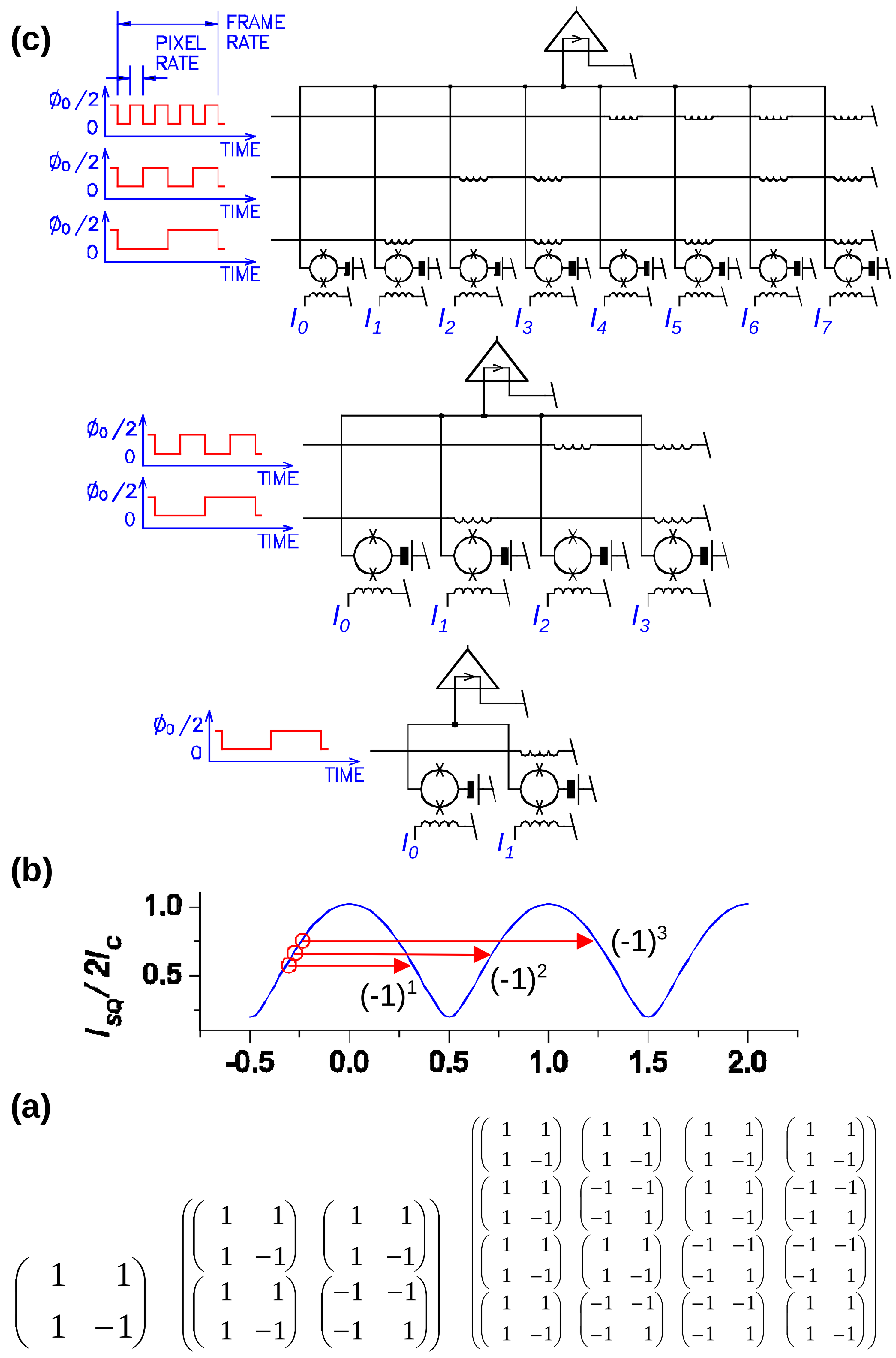

Figure 1: (a) Hadamard matrices can be generated by taking the primitive 2 x 2 matrix and recursively replacing its elements by copies of the primitive matrix. In the multiplexing context the rows correspond to signal channels and columns correspond to time slots. (b) The inherent multiplications by *(-1)*^{N} can be replaced by $N\times\Phi_0/2$ flux shifts. (c) The Hadamard matrix procedure is equivalent to repeated doubling of the primitive 2-SQUID cell when an additional double-rate $\Phi_0/2$ flux shift is summed to the lower half of the new cell .

Hadamard matrices can be replaced by successive *summations* of $\Phi_0/2$ flux shifts, see Fig. 1. This enables one to use ordinary binary code when addressing the SQUIDs.

For the experiment, we built a module out of four chips each containing two 60-series SQUID arrays [11]. The arrays were read out by a simple transimpedance amplifier built around an AD797 operational amplifier. The opamp creates a cryogenic virtual ground (Fig. 2) into which the SQUID currents are summed. SQUIDs are voltage biased by a forced potential difference between the inverting and non-inverting inputs of the opamp. The offset adjustment pins of the opamp could be used, but in order to facilitate bias sweeps we use a

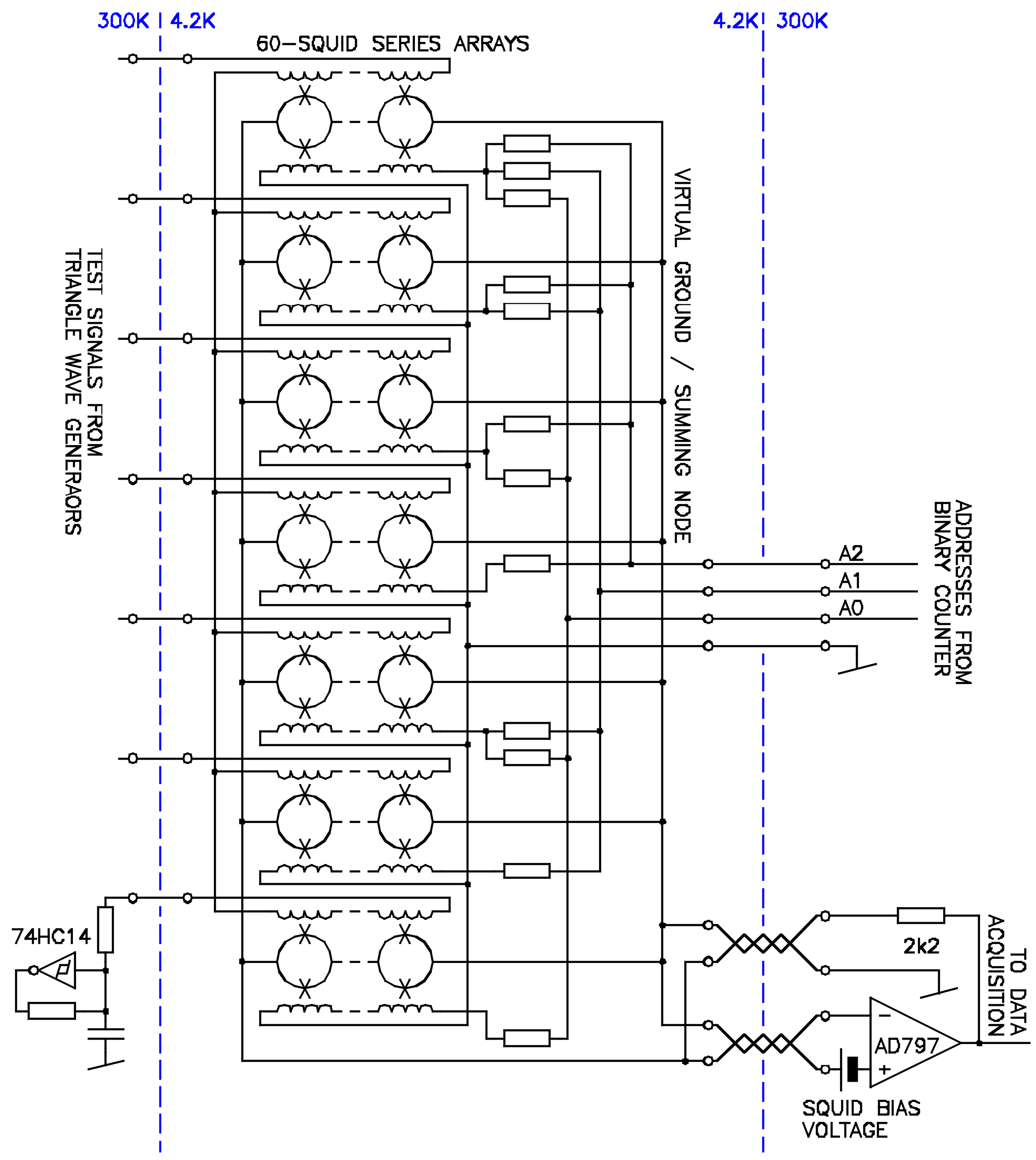

Figure 2: Simplified schematic of the readout circuitry.

small resistor in series with the non-inverting input and pass current through it to create the bias voltage. Addresses are created by a simple CMOS binary counter. The opamp output is Nyquist filtered with 150 kHz frequency corner and digitized by a National Instruments USB-6363 acquisition unit.

The SQUID module was immersed in LHe and magnetically shielded by a Pb + Cryoperm can. We rely on flux trap resistance of the SQUIDs [11] which allows us to use one flux setpoint line common to the 7 channels.

The SQUIDs were driven from seven triangle wave generators, constructed out of simple CMOS Schmitt triggers. The ± 2.5 $\mu A_{p\text{-}p}$ amplitude triangle waves whose frequencies ranged from 0.25 Hz to 4 Hz were fed to the SQUID input coils, encoded, digitized and decoded. The waveforms are shown in Fig. 3, when decoded with the uncorrected Hadamard matrix. At high frame rates the system begins to suffer from glitches related with the binary address transitions (Fig. 3a), which are not as easy to decimate away as at lower frame rates (Fig. 3b). We believe the glitches are due to ground bounce in our particular setup. The average SQUID noise was measured as roughly 0.6 $\mu\Phi_0/Hz^{1/2}$ which corresponds to 15 $pA/Hz^{1/2}$ input referred current noise.

Another set of test signals was produced by a two-level burst generator, which was devised for the purpose of measuring the true encoding matrix. Use of the true inverse matrix for decoding would then allow crosstalk and gain differences to be largely calibrated away. These test signals, shown in Fig. 3c, give an indication of the performance of the uncalibrated bare system. In particular, channel-to-channel gain variation of ±15% is evident, which is due to difficulties in the critical current control in the SQUID fabrication round [11]. Some amount of crosstalk, particularly to the unused zero channel, is also visible.

3. Discussion and conclusion

The primary disadvantage of the slope switching technique is the difficulty to arrange the linearizing feedback. Without feedback the SQUID power dissipation is proportional to the square of the dynamic range [12], which makes the approach unattractive for 100 mK applications such as Transition Edge Sensor arrays. More promising are the 4.2 K applications such as magnetometers and microbolometer arrays [13] where more dissipation can be tolerated. We also study the possibility to use the technique for readout of Superconducting Tunnel Junction (STJ) detectors at 300 mK. The binary-to-Hadamard address translation is also applicable in the current steering CDM variant [9], which we are pursuing in parallel with the slope switching variant. Regardless of its limitations, we find the slope switching method to be a very simple and robust way to perform cryogenic multiplexing.

Acknowledgement
This work has received funding from the grant no. 262947 of the European Community's seventh framework programme (FP7/2007-2013). We thank J. van der Kuur for the valuable insights presented in many related discussions.

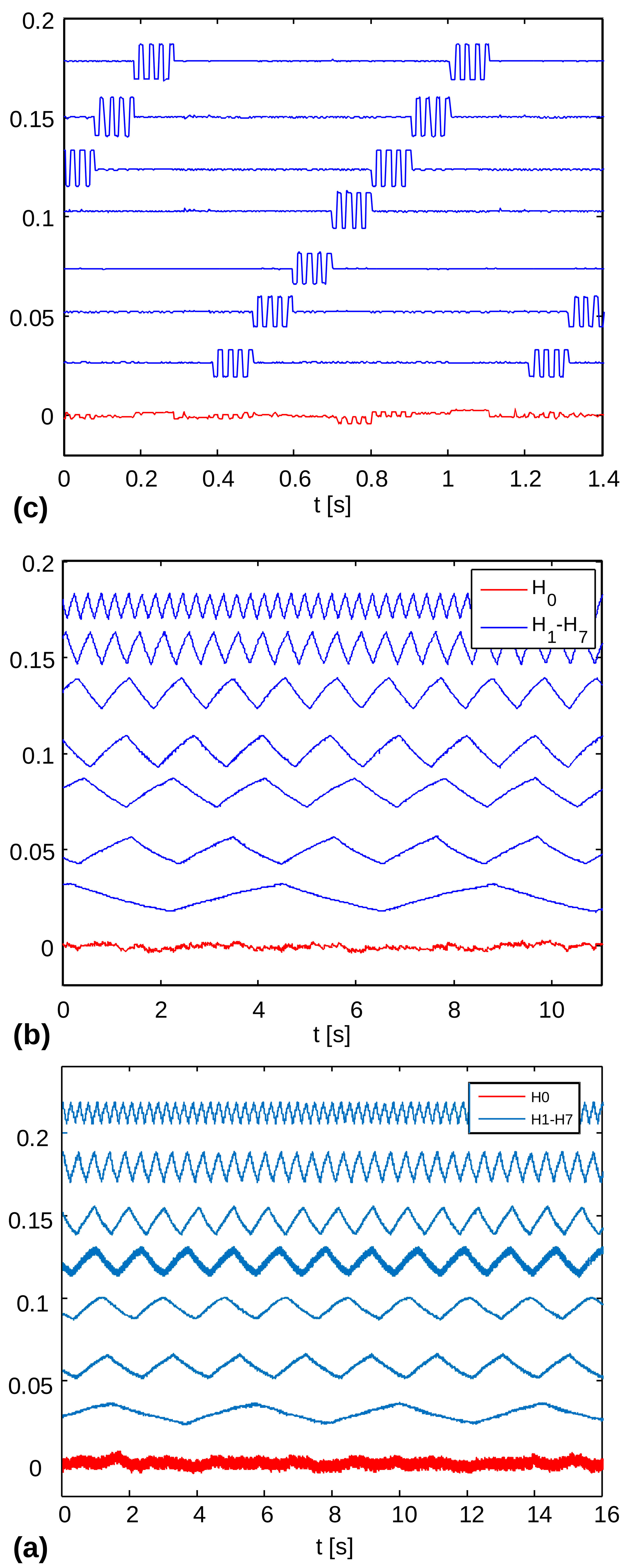

Figure 3: Encoded, digitized and decoded test signals: sawtooth signals encoded (a) at 3900 frames per second and (b) at 310 frames per second, and (c) two-level calibration bursts encoded at 310 frames per second. Arbitrary units are used in the vertical axis. The H_0 channel is not used for signals although it is decoded and included in the plots

References

[1] Kiviranta M et al 2002 SQUID-based readout schemes for microcalorimeter arrays *AIP Conf. Proc.* **605** 295-304 .

[2] Chervenak J et al 1999 Superconducting multiplexer for arrays of transition edge sensors *Appl. Phys. Lett.* **74** 4043-5 .

[3] Irwin K D 2002 SQUID multiplexers for transition-edge sensors *Physica C* **368** 203-10 .

[4] Yoon J et al 2001 Single superconducting quantum interference device multiplexer for arrays of low-temperature sensors *Appl. Phys. Lett.* **78** 371-3 .

[5] van der Kuur J et al 2002 Performance of an x-ray microcalorimeter under ac biasing *Appl. Phys. Lett.* **81** 4467-9 .

[6] Gottardi L et al 2002 AC read-out circuits for single pixel characterization of TES microcalorimeters and bolometers *IEEE Tran. Appl. Supercond.* **21** 272-5 .

[7] Jackson B D 2012 The SPICA-SAFARI detector system: TES detector arrays with frequency-division multiplexed SQUID readout *IEEE Tran. THz Sci. Tech.* **2** 12-21.

[8] Karasik B S and McGrath W R 2001 Novel multiplexing technique for detector and mixer arrays *12th Intl. Symposium on Space Terahertz Technology, San Diego, CA, USA 14-16 Feb. 2001*.

[9] Irwin K D et al 2010 Code-division multiplexing of superconducting transition edge sensor arrays *SuST* **23** 034004.

[10] Niemack M D et al 2010 Code-division SQUID multiplexing *Appl. Phys. Lett.* **96**, 163509.

[11] Kiviranta M, Grönberg L and Hassel J 2012 A multiloop SQUID and a SQUID array with one-um and sub-um input coils, accepted to *IEEE Tran. Appl. Supercond.*

[12] Kiviranta M et al 2003 Dc and un SQUIDs for readout of ac-biased transition edge sensors *IEEE Tran. Appl. Supercond.* **13** 614-7.

[13] Luukanen A et al 2010 Realtime passive terahertz imaging system for standoff concealed weapons imaging *Proc. SPIE* **7670** 767004.