Pulse waveform data processing for preclinical PET scanners using discrete frontend electronics and FPGA

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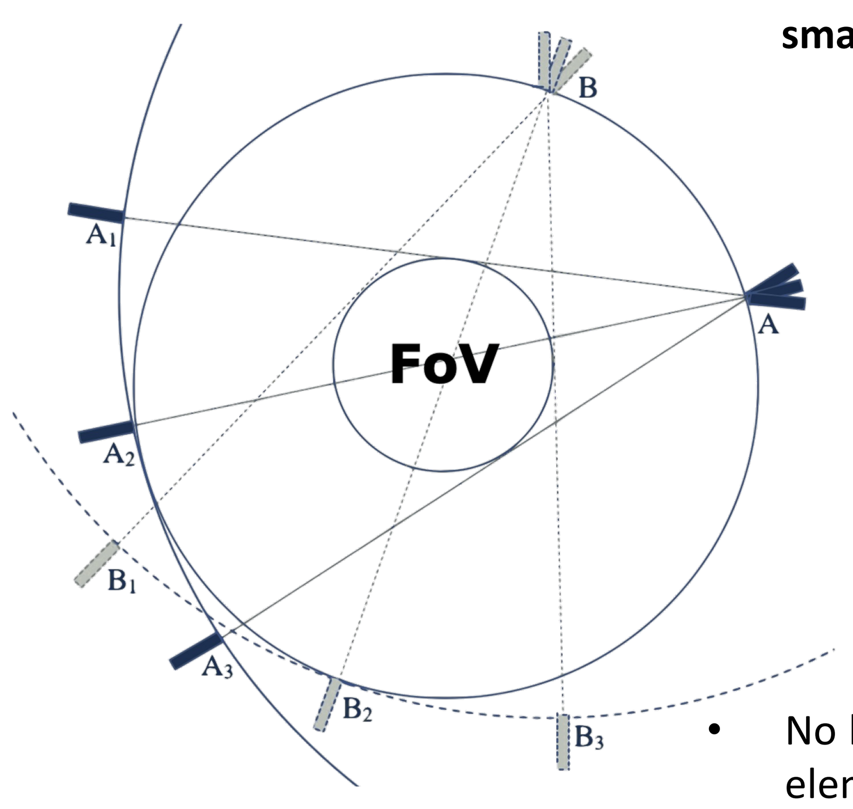
The iPET is a preclinical PET system based on the easyPET scanning method, an affordable PET technology capable of acquiring real-time high-quality in-vivo images with only two detector heads, at a reduced cost without compromising image quality. Full body mouse imaging is possible using a small number of detector elements, scanning billions of lines of response (LoRs) in few minutes, covering a FoV of up to 100 mm diameter × 80 mm long. The electronic readout of each detector block consists of discrete electronics (preamplifier and fast ADC – 80 MSPS) and a dedicated FPGA. Each detector block is multiplexed using a chain of resistors – 25 SiPMs per chain. Using Anger logic allows identifying in which detector cell the radiation interacted. Algorithms for digital filtering can be applied to the digitized pulses directly on the FPGA, to enhance the pulse height measurement. Flood maps comparing the use of the original signal and the filtered one indicate promising results to better identify the position of the radiation interaction in the detector arrays, and therefore improve data analysis and contribute for a better PET image through the identification of more accurate LoRs. An overview of the iPET scanner, prospects and results will be presented, as well as examples of simulated preclinical images.

EasyPET Concept

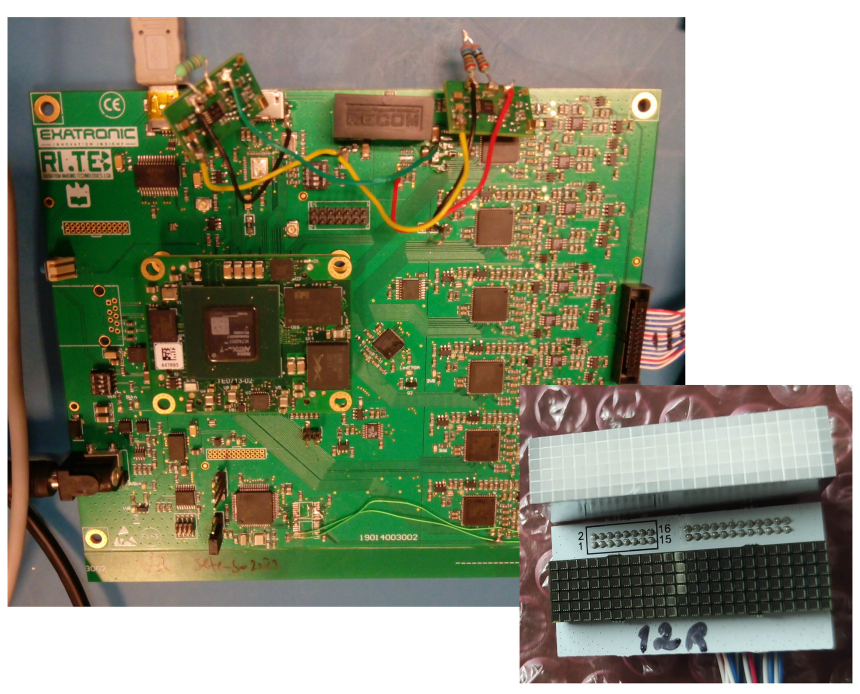
2 rotation axes for the movement of detector modules[1,2], FoV is defined by the angular aperture of the fan beam scan - can be tuned and adapted to specific regions of interest.

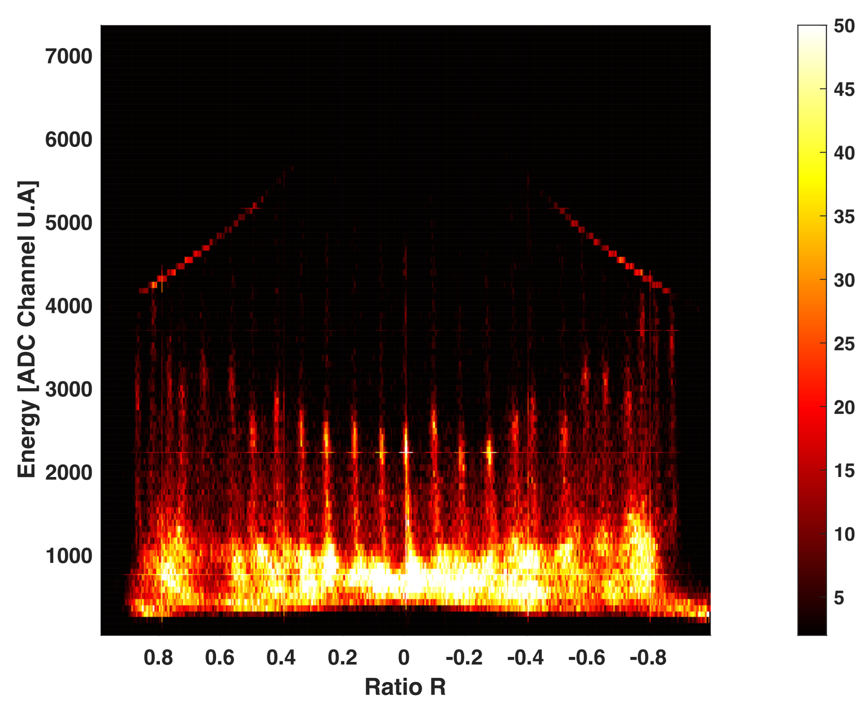


- Full axial imaging (full animal body) with a **small** number of crystals.
- High spatial resolution (up to **1 mm FWHM**) and **uniformity** over the FOV
- Scans up to **2600 millions** of LoRs in few minutes.
- Eliminates **parallax error** by keeping detectors aligned
- No limitations on the proximity of the detector elements to the FoV and adjustable during scanning – **intelligent scanning.**

Electronic Readout

- Frontend boards with discrete preamplifiers. Each channel contains a dual-stage gain preamplifier (LTC6229), a high-speed comparator (LTC6752) for signal triggering, and a fast dual channel analog-to-digital converter (AD9231) with digitalization's rates up to 80 MSPS (12.5 ns per capture) – for pulse waveform digitalization.
- An FPGA (Xilinx Artix-7 200T-2C) is responsible for reading the 6 ADCs (12 channels) for each block and transmit data (USB3.0).
- Array of 300 detectors are grouped into smaller blocks of 25 SiPM each, with anodes connected together into a resistor line readout.
- 25:2 multiplexer by charge division allows the use of only 2 electronic channels for signal amplification and event reconstruction using Anger logic methods.





Left - Frontend board, including the FPGA, 6 ADC (dual channel) and 12 preamplifier circuits and a Close view of the detectors: LYSO array (150 crystals 1.5 x 1.5 x 20 mm³) and the photodetectors array (6x25 KETEK SiPM 1x1 mm²). Custom made boards designed and fabricated by **RI-TE, LDA** and **Exatronic.**
Rigth - Experimental bivariate histogram (flood map) in optimal conditions, allowing clear separation of the 25 detectors and identification of the photopeak (511 keV annihilation photons from Na^{22}) between ADC channels 2000 – 3000.

References

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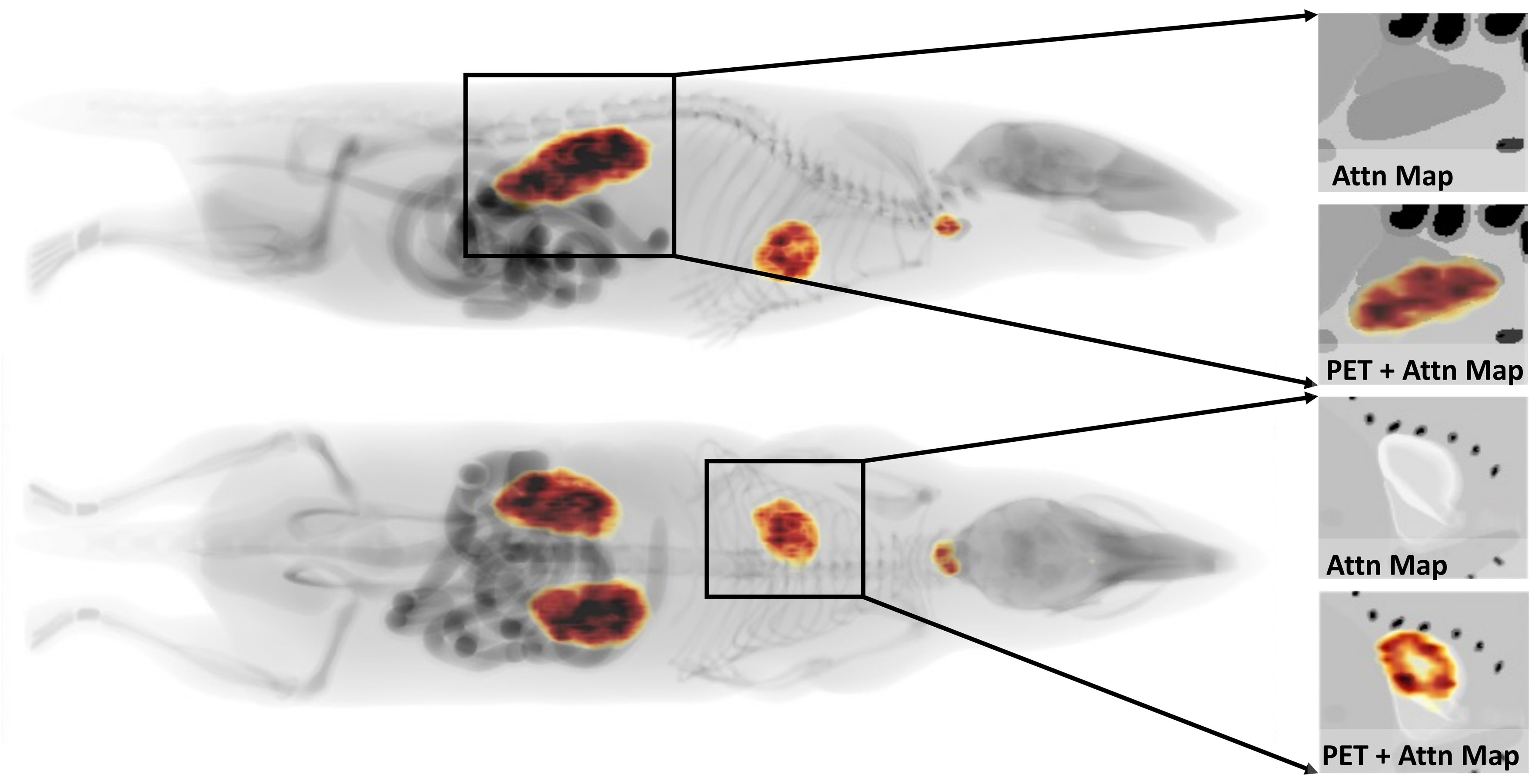
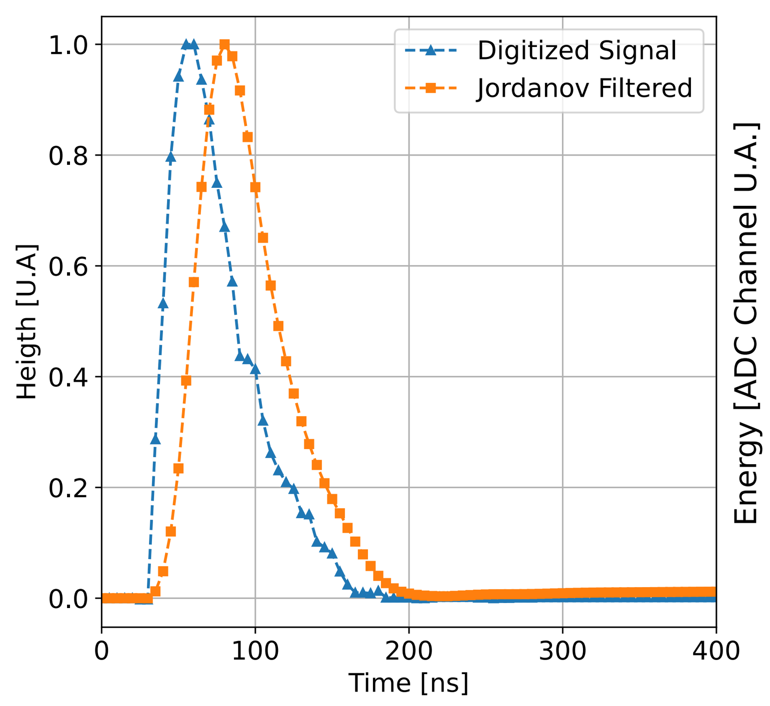
GATE Simulations

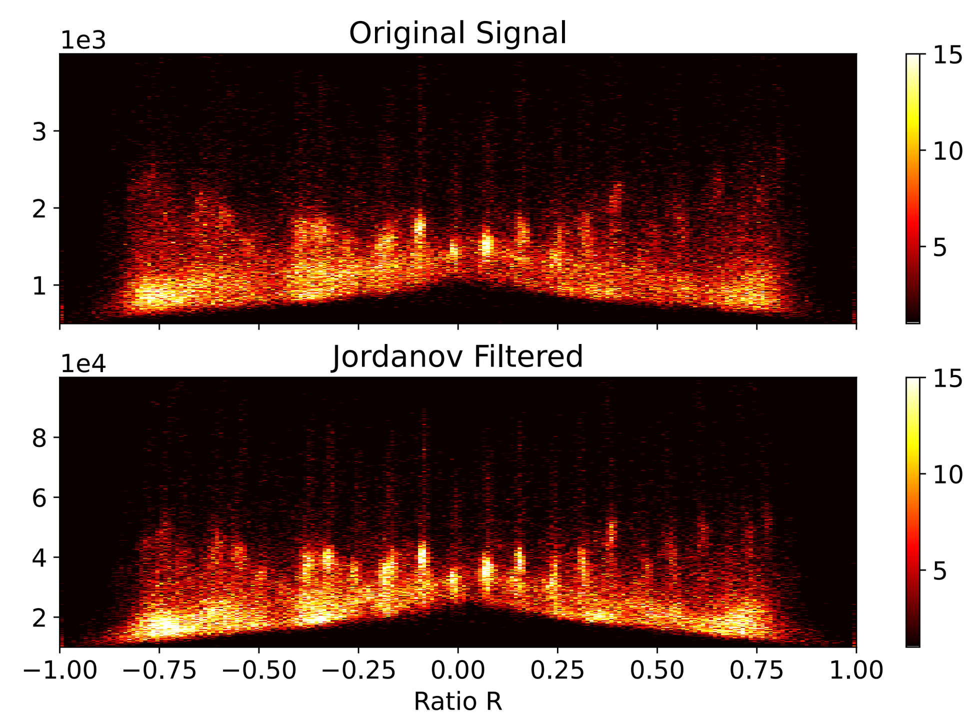


Mouse Moby[3] Phantom – 18-FDG full body image, GATE simulation[4] by iPET model and reconstructed with proprietary GPU-accelerated MLEM algorithm. Reconstruction parameters: LM-MRP algorithm, β=0.3, kernel size 3, 40 iterations and without decay correction, 30 mm slices. Only kidneys, heart and thyroid are filled with 3280 Bq/mm³, while body background of 32.8 Bq/mm³ . Zoom images (right plots) are 0.145 mm thickness slices, comparing attenuation map (phantom) with PET reconstructed image of kidneys and heart.

Signal Filters and Results

- A Digital signal processing (DSP) using a Jordanov Trapezoidal filter[4,5] was applied to our data using short time parameters (decay time 100 ns, sampling time 5 ns, l=k=5 sampling units). This results not exactly in a trapezoidal output signal but acts as a high-frequency filter.





Left - Original digitized pulse compared with the fast integrated signal from a Jordanov-like filter. High-frequency noise is attenuated, contributing to a smoother signal. **Right** - Experimental bivariate histogram of Energy and R under low electronic gain to evaluate the performance of the system in a more demanding (non-optimal) situation. Comparison of using the original pulse height (top) and the filtered one (bottom). 25 cells are still visible (vertical groups) and the 511 keV photopeak is enhanced at higher energies, although noise deteriorates neighbor group separation at lower energies, being visible the better separation achieved after applying the digital filter.

Conclusions

- The iPET prototype will use detector blocks with hundreds of detector cells, multiplexed using resistors chains and Anger logic. Each block is read by 6 dual-channel ADCs and an FPGA.
- Frontend electronics using signal digitalization and posterior processing allowed the reduction of the detector dead time and better location of the gamma rays interactions
- The use of DSP filters on the FPGA shows that an improvement of the detector cell identification on the flood maps, with positive implications for the reconstructed PET images.
- Future development of affordable organ-specific clinical PET scanners for applications such as brain and breast imaging are possible using this technology. Furthermore, this technology can be seamlessly integrated with CT or optical imaging to build hybrid scanners.