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Pulsenet – A Parallel Flash Sampler and Digital Processor IC for Optical SETI

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Abstract— PulseNet is a full-custom IC with parallel flash ADC and digital processing that enables an all-sky optical search for extraterrestrial intelligence. It integrates 448 sense amplifiers that digitize 32 analog signals at 1GS/s, and other circuits that filter samples, store candidate signals, and perform astronomical observations. Its ~250,000 CMOS transistors (TSMC 0.25µm) dissipate 1.1W at 400MHz and 2.5V.

I. INTRODUCTION

PulseNet is a full-custom flash ADC and digital processor chip designed for an all-sky optical search for extraterrestrial intelligence (SETI). It digitizes 32 analog signals at up to 1GS/s, and filters in real-time for intentional signals from other advanced civilizations. Thirty-two of these ICs form the computing core of our all-sky optical SETI instrument. Together they digitize and filter ~3.5Tb/s—roughly the contents of all books in print, every second. The strength of PulseNet is not optimization of a single parameter; rather, it is the experiment-driven on-chip integration of several demanding electronic components into an instrument that would otherwise be impossible to construct.

Astronomical searches for signals from other civilizations have been performed primarily in the microwave radio spectrum (sources whose spectral width is too narrow for physical processes) and in the visible optical spectrum (pulses whose short duration and brightness are incompatible with known astrophysical objects). The scope of these searches is frequently limited by technology—in radio SETI, the FFTs performed by ever expanding arrays of FPGAs, DSPs, and PCs have greatly increased the spectral coverage and sensitivity. Optical SETI before PulseNet was limited to observing candidate stars one at a time (~10^4 stars and ~10^{-5} of the sky area observed in several years) [1]. With PulseNet, we can survey the entire Northern sky for optical signals in less than a year.

Optical SETI is based on this remarkable fact: using today's technology, we could generate an optical signal that would be visible across much of the galaxy, and that would be distinguishable from astrophysical phenomena and noise. For example, a Helios laser (4.7MJ pulses lasting 3ns) coupled into a 10m Keck-class optical telescope would outshine the Sun by a factor of ~10^4 in broadband visible light during the brief pulse and in the narrow direction of the target. At a range of 10^3 lightyears (within which there are ~10^6 Sun-like stars), the signal would deliver ~1500 optical photons to a similar 10m telescope at the target [1]. Thus, optical communication between civilizations is plausible, and *searches* like ours are justified.

Our all-sky optical search scheme is shown schematically in Fig. 1. It uses a f/2.5 1.8m optical telescope that images a 1.6° x 0.2° patch of the sky on two identical arrays of photomultiplier tube (PMT) pixels through a beamsplitter. The telescope is fixed and the imaging beam drifts across the sky as the Earth rotates. To minimize noise, we require that a signal be seen *coincidentally* in a matched pair of pixels in the two PMT arrays. The PMTs are sensitive to single photons, which produce ~3-5ns voltage pulses (~10-50mV, depending on gain), and are approximately linear for larger signals.

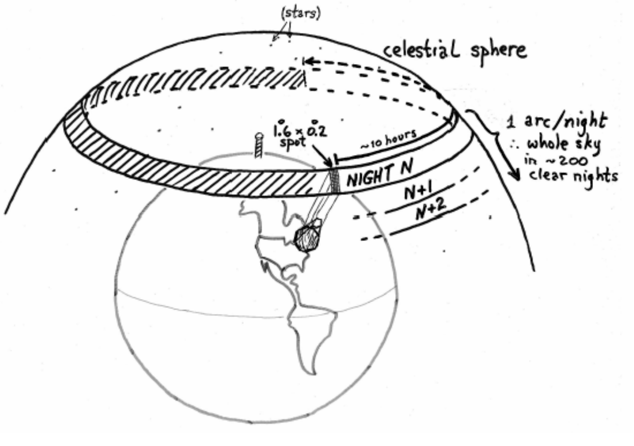


Figure 1. All-sky optical search scheme

II. PULSENET DESIGN

Each PulseNet handles analog signals from 32 PMT pixels (16 matched pairs) as shown in Fig. 2. These signals are digitized at 1GS/s by comparing each to seven external voltages ($V_{REF}[6:0]$) on the rising edges of two interleaved clocks (clka/clkb; 500MHz). The resulting 7-bits/pixel/clock of thermometer code are encoded to 3-bits/pixel/clock and are delayed by an 8-bit deep array of 2-phase shift registers. Meanwhile, a coincidence trigger circuit selects one thermometer code bit from all 32 pixels (and both clocks) and looks for instances when a matched input pair simultaneously exceed a given threshold—a "coincidence", e.g., pixels 14A and 14B both exceed $V_{REF}[3]$ on a rising edge of clka. Coincidences trigger switches that steer streaming data from the input pair into 256-bit long shift

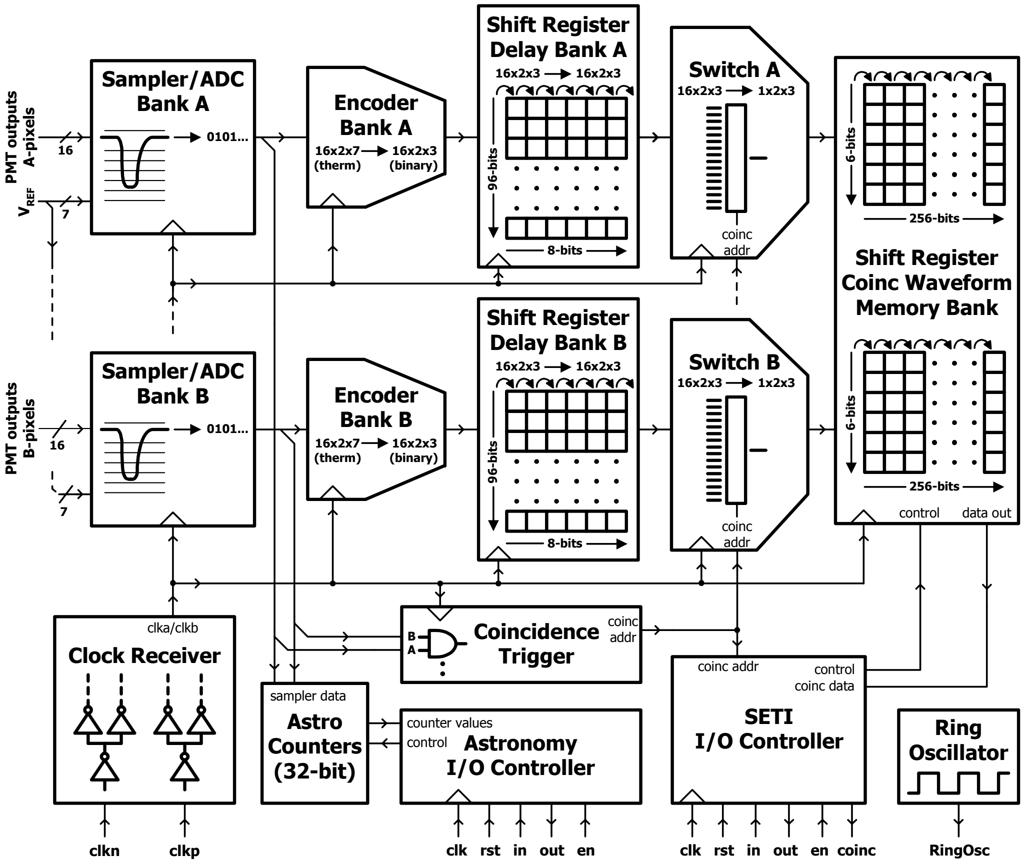


Figure 2. PulseNet top level block diagram

registers. The SETI I/O controller then passes the waveforms and coincident pixel address off chip.

PulseNet's parallel and independent function is to measure "countrates"—the number of pulses exceeding a certain V_{REF} in a time interval. With the proper V_{REF}, this is proportional to the photon flux on the PMT pixel, i.e. it measures the brightness of the star seen by that pixel. These measurements are orchestrated by the astronomy I/O controller, which steers streams from particular pixels and thermometer-codes, starts and stops four 32-bit counters, and transmits the data off chip.

Fig. 3 shows the sampling scheme in greater detail. An analog input (V_{PMT}) is compared with $V_{REF}[6:0]$ on the rising edges of the interleaved clka and clkb, producing the 7-bit thermometer code for each sample. Note that $V_{REF}[6:1]$ is less than V_{PMT} since PMTs produce negative pulses; in order to detect V_{PMT} samples that exceed its bias voltage (an artifact of spurious PMT signals), we set $V_{REF}[0] > V_{PMT}$. Fig. 4 shows V_{PMT} and $V_{REF}[6:0]$ wired to comparators that produce the thermometer-coded samples. Fig 5 illustrates one of these comparators in greater detail; V_{PMT} is compared to V_{REF} on the rising edges of clka and clkb in modified StrongArm sense amplifiers (SAs), whose outputs drive a second stage of reduced-size SAs (improving gain and reducing hysteresis), followed by RS latches. The SA (see [2] and references therein) is a simple clocked, regenerative, differential amplifier shown in Fig. 6. The design provides good input isolation and a small aperture time (tens of ps) that can resolve small voltage differences (tens of mV). The 448 SAs on PulseNet are grouped in four blocks with staggered clocking to mitigate power supply noise. Fig. 7 shows a measured signal reconstruction for one PMT signal.

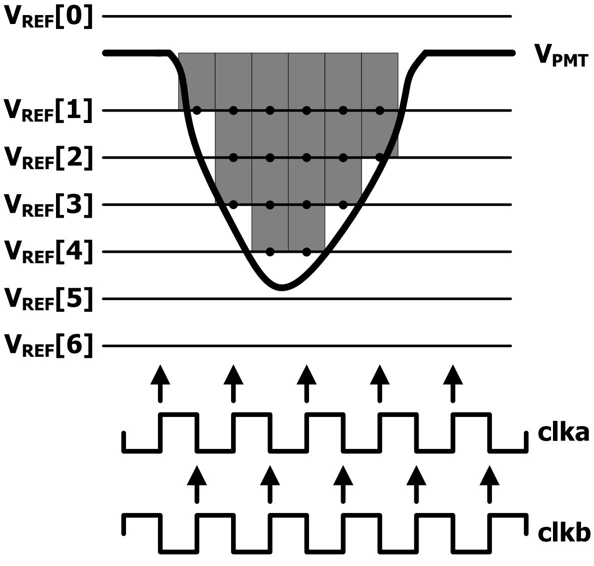


Figure 3. PMT signal sampling scheme

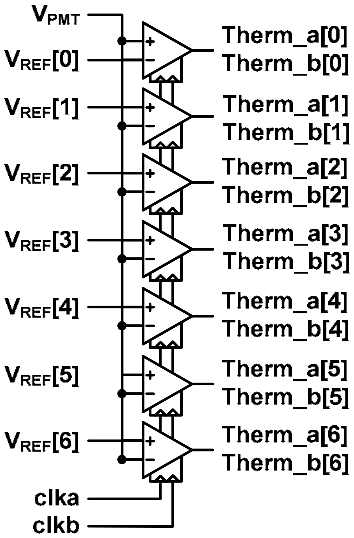


Figure 4. Thermometer-coded sampler bank.

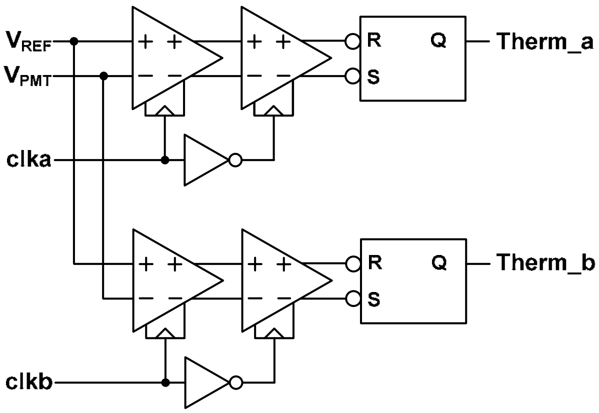


Figure 5. Detailed sampler path.

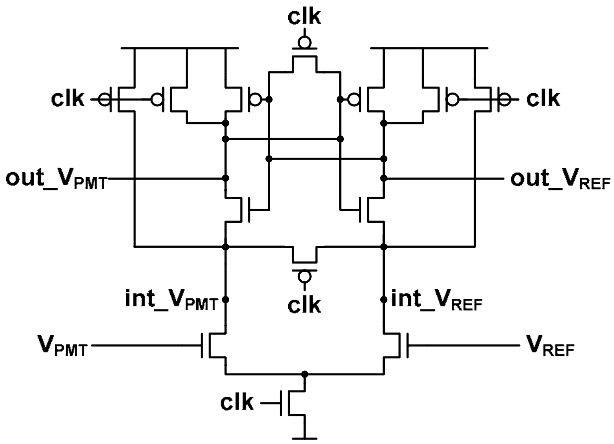


Figure 6. Modified StrongArm sense amplifier [2].

III. SAMPLER OFFSET VOLTAGE MEASUREMENTS

PulseNet's sensitivity depends on variations in input sampler offset voltage (among other things). We measured this offset on 42 chips (448 SAs per chip) and found a 1-σ variation of 12mV. This is consistent with the ~15mV offset for the SA input pair predicted by the model in [3]. The full offset distribution is shown in Fig. 8; note the narrower distribution resulting from calibrating out pixel-dependent off-chip static offsets in the test setup. Fig. 9 shows offset voltage variation away from the nominal parameters used in Fig. 8: supply voltage = 2.5V and input bias voltage = 1.5V.

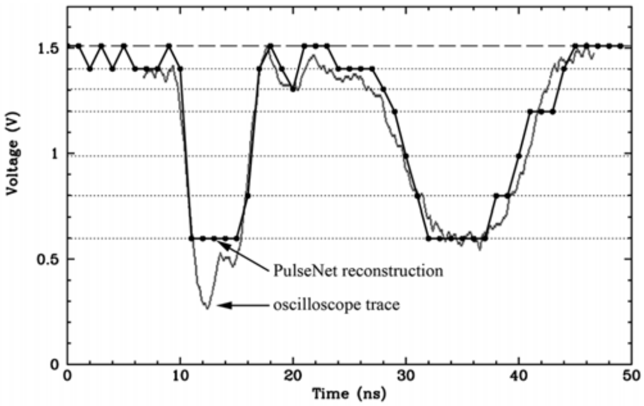


Figure 7. Waveform reconstruction of one of two analog channels (first 46 of 256 samples), sampled at 1GS/s, with oscilloscope trace for comparison.

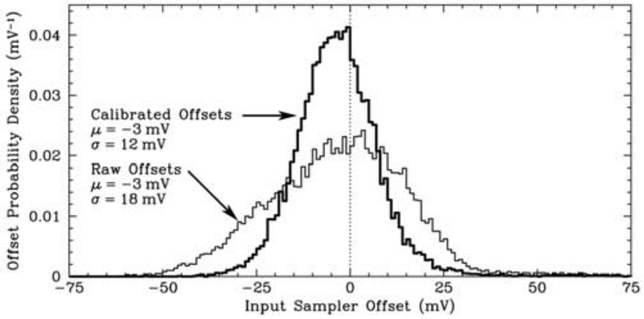


Figure 8. Histograms of input offset voltages for 42 chips (448 SAs). Note the narrower distribution after test setup calibration.

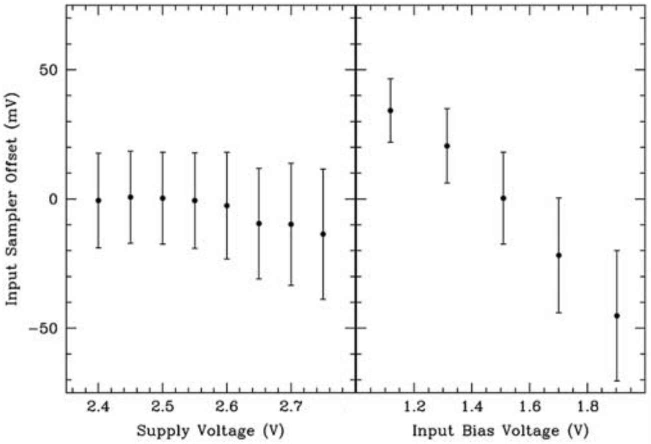
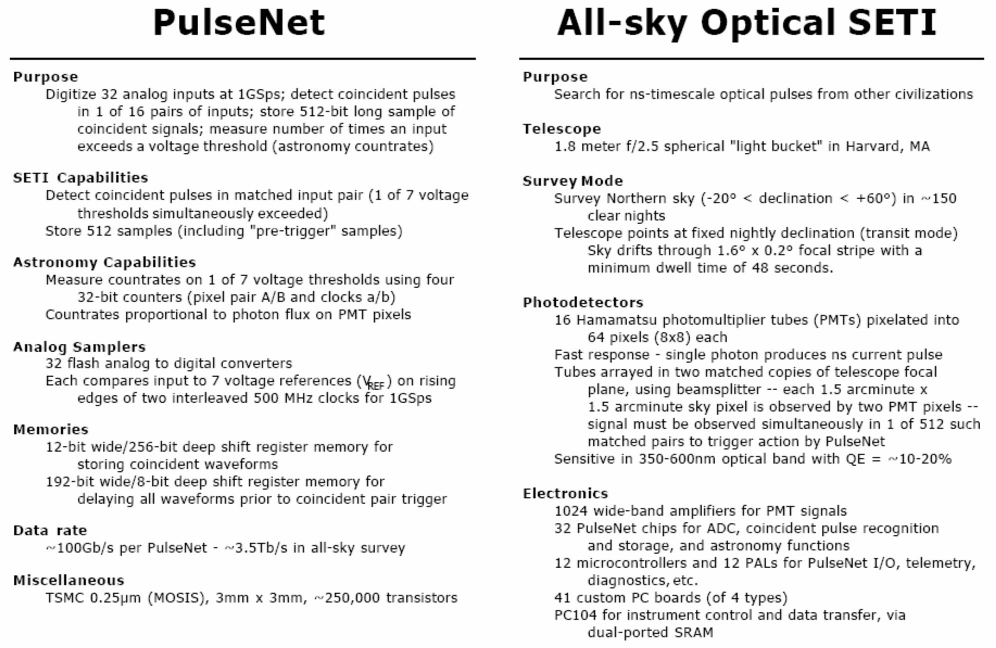


Figure 9. Offset voltage vs. V_{dd} and input bias. Each point is the mean, and the error bars are the 1-σ variation, for 448 SAs on one chip.



PulseNet

Purpose
Digitize 32 analog inputs at 1GSps; detect coincident pulses in 1 of 16 pairs of inputs; store 512-bit long sample of coincident signals; measure number of times an input exceeds a voltage threshold (astronomy countrates)

SETI Capabilities
Detect coincident pulses in matched input pair (1 of 7 voltage thresholds simultaneously exceeded)
Store 512 samples (including "pre-trigger" samples)

Astronomy Capabilities
Measure countrates on 1 of 7 voltage thresholds using four 32-bit counters (pixel pair A/B and clocks a/b)
Countrates proportional to photon flux on PMT pixels

Analog Samplers
32 flash analog to digital converters
Each compares input to 7 voltage references (V_{REF}) on rising edges of two interleaved 500 MHz clocks for 1GSps

Memories
12-bit wide/256-bit deep shift register memory for storing coincident waveforms
192-bit wide/8-bit deep shift register memory for delaying all waveforms prior to coincident pair trigger

Data rate
~100Gb/s per PulseNet - ~3.5Tb/s in all-sky survey

Miscellaneous
TSMC 0.25μm (MOSIS), 3mm x 3mm, ~250,000 transistors

All-sky Optical SETI

Purpose
Search for ns-timescale optical pulses from other civilizations

Telescope
1.8 meter f/2.5 spherical "light bucket" in Harvard, MA

Survey Mode
Survey Northern sky (-20° < declination < +60°) in ~150 clear nights
Telescope points at fixed nightly declination (transit mode)
Sky drifts through 1.6° x 0.2° focal stripe with a minimum dwell time of 48 seconds.

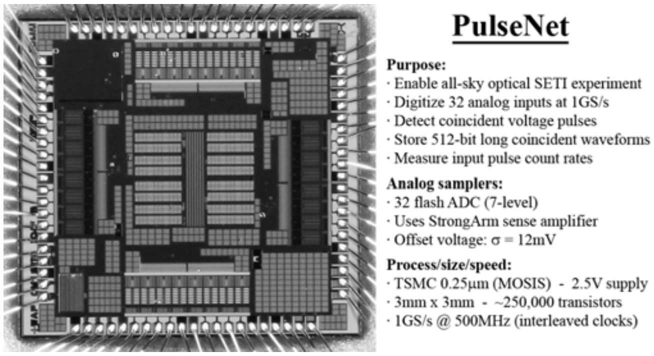
Photodetectors
16 Hamamatsu photomultiplier tubes (PMTs) pixelated into 64 pixels (8x8) each
Fast response - single photon produces ns current pulse
Tubes arrayed in two matched copies of telescope focal plane, using beamsplitter -- each 1.5 arcminute x 1.5 arcminute sky pixel is observed by two PMT pixels -- signal must be observed simultaneously in 1 of 512 such matched pairs to trigger action by PulseNet
Sensitive in 350-600nm optical band with QE = ~10-20%

Electronics
1024 wide-band amplifiers for PMT signals
32 PulseNet chips for ADC, coincident pulse recognition and storage, and astronomy functions
12 microcontrollers and 12 PALs for PulseNet I/O, telemetry, diagnostics, etc.
41 custom PC boards (of 4 types)
PC104 for instrument control and data transfer, via dual-ported SRAM

Figure 11 PulsetNet and All-sky optical SETI – table of characteristics

IV. PERFORMANCE

PulseNet contains ~250,000 transistors, is 3.1mm x 3.1mm, and was fabricated through MOSIS on TSMC's 0.25μm CMOS process. Fig. 10 shows a die photo and gives a performance summary. All circuits were full-custom designs, with the exception of the three synthesized state machines. At 400MHz and 2.5V (standard operation) PulseNet dissipates 1.1W, but has been shown to work as high as 500MHz and 2.87V. Fig. 11 presents an overall summary of characteristics of both PulseNet and All-sky optical SETI. PulseNet is fully functional and is being deployed in the all-sky optical SETI experiment as a part of the camera system shown in Fig. 12. We should see "first light" in April 2006.



PulseNet

Purpose:
- Enable all-sky optical SETI experiment
- Digitize 32 analog inputs at 1GS/s
- Detect coincident voltage pulses
- Store 512-bit long coincident waveforms
- Measure input pulse count rates

Analog samplers:
- 32 flash ADC (7-level)
- Uses StrongArm sense amplifier
- Offset voltage: $\sigma = 12$mV

Process/size/speed:
- TSMC 0.25μm (MOSIS) - 2.5V supply
- 3mm x 3mm - ~250,000 transistors
- 1GS/s @ 500MHz (interleaved clocks)

Figure 10. PulseNet die photograph and performance summary.

ACKNOWLEDGEMENTS

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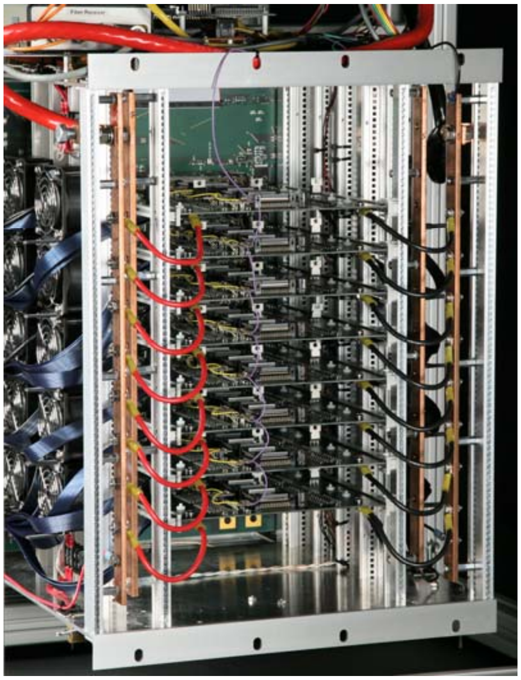

Figure 12. Camera system with 32 PulseNet chips

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