Tambo Sensor
Low Power Design Concepts

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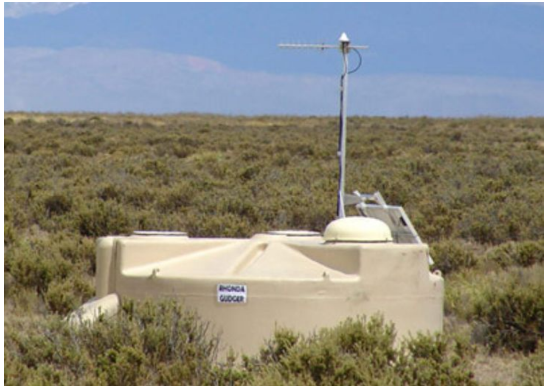
Tambo Collaboration Meeting,
PUCP, Lima, Peru
August 17-21, 2026

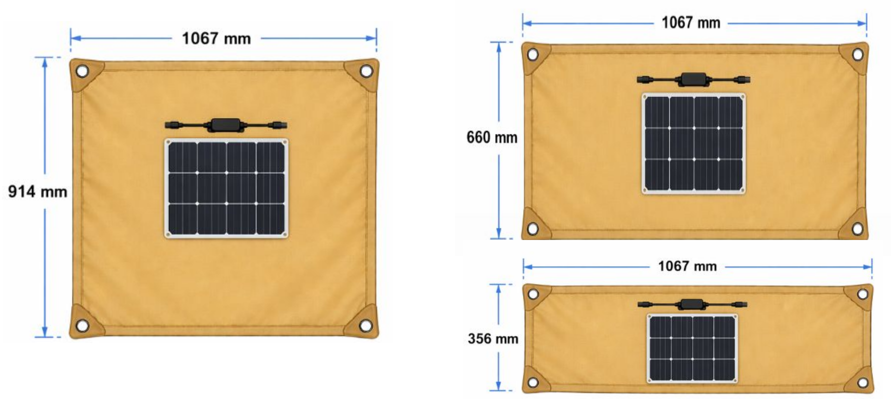
Low power helps with sensor integration & manufacturability

- Driven by scintillator area, solar array size, battery size, and antenna needs.
- Integrated “Sensors” may have lower overall cost and risk than “Stations”.
- Manufacturing, testing, and deployment favor smaller size and power consumption.
- It is often less costly to build a higher quantity of a more manufacturable item.
- Array spacing is relatively “easy” to adjust to accommodate the final sensor design.

Station - on-site assembly



Sensor - portable, self-contained



Tambo Sensor Power Consumption

- Drives solar array and battery size, strongly impacts integration and manufacturability
- Major driver on sensor size and expense of both R&D and installed array
- Power can likely be reduced by: data reduction, radio scheduling, and DAQ design

Preliminary Estimate (conservative)
From power case mount DSN

Component	Load power
uDAQ (NPX version)	~0.5 W
Data WiFi link	~10 W
GNSS timing system	1.000 W
SiPM, TIA and bias	0.400 W
Housekeeping/control	1.000 W
Subtotal	**~13 W**

Low-Power design Estimate (aspirational)
With data reduction and low-power DAQ

Component	Load power
DAQ w/ slow MCU	150 mW
Data Rx + Tx (Avg)	50 mW
GNSS timing system	300 mW
SiPM, TIA and bias	250 mW
Housekeeping/control	~30 mW
Subtotal	**<1 W**

Example Low-Power Sensor
<< 1W

Data reduction: “Shower-Triggered Lookback Readout”

1. Data from showers and single hits are continuously recorded at each sensor in a hit buffer.
2. Data from any sensors that detect a shower (“core hits”) are always sent to the central hub.
3. Central hub compiles list of showers seen by any individual sensors during the last interval
4. Central hub broadcasts all shower times to all sensors at the beginning of each readout interval
5. Sensors compare shower times to timestamps in hit buffer to create “infill data” of time - correlated hits
6. Infill data from previous interval is combined with lates shower hits and sent to central hub (-> step 2)

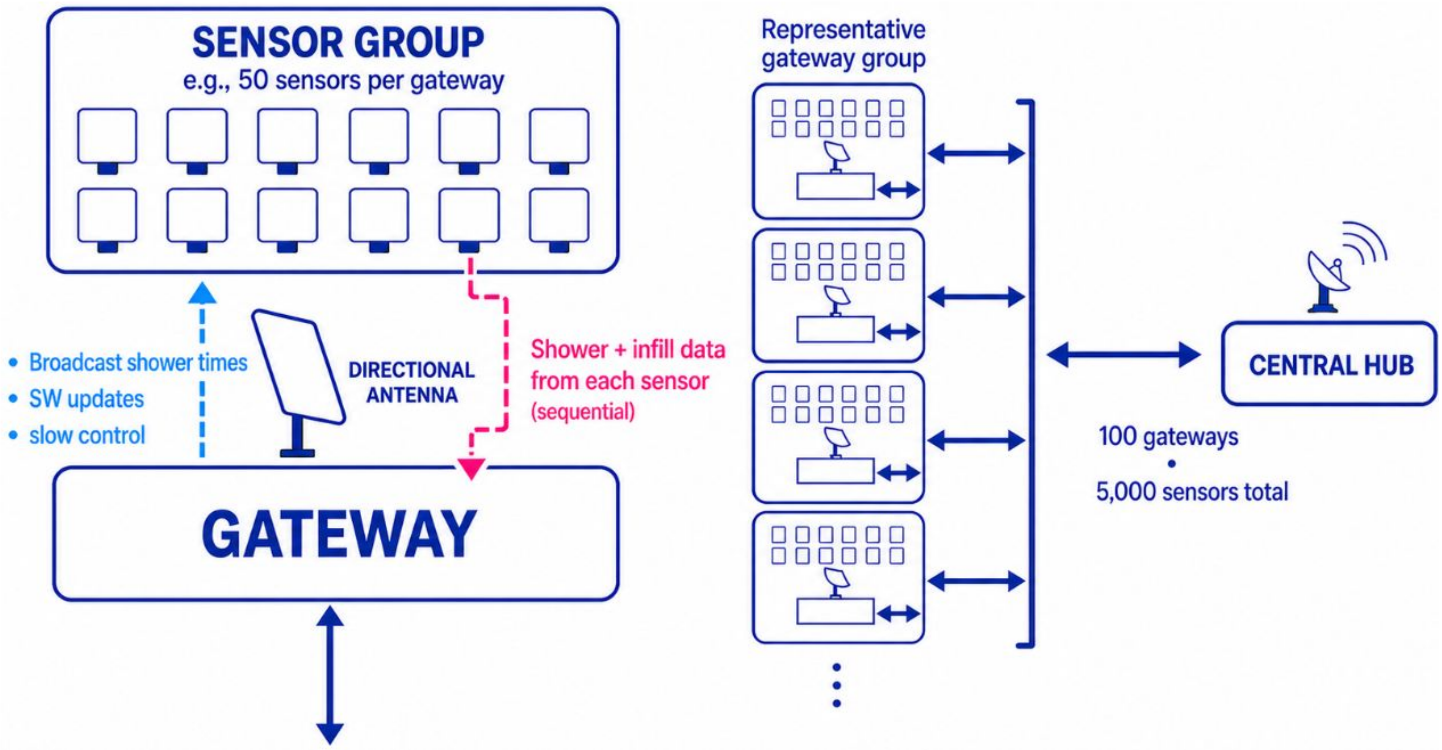
Sensor data transmitted in each 1-minute interval
(a few thousand bits every *minute*)

Shower (core) Hits From interval “N” ~1-2 kbit	**“Shower-Correlated” Lookback Hits** From interval “N-1” ~1-2 kbit	**Sensor ID** Header info ~48 bits

Shower-Triggered Lookback (STL) Readout - Data Flow

Shower data + infill data for a given sensor: (small payloads sequentially read by each gateway)

- **Shower data** = Near-core multi-hits seen by the sensor in the most recent readout interval
- **Infill data** = Singles that are time-correlated to any showers seen by all sensors in the previous interval



Lookback readout scheme likely reduces sensor data

Data-Rate (all singles sent)

Assumptions: 5,000 sensors; 120 hits/s/sensor; 200 bits/hit.

Calculation	Expression	Result
Data per hit	$b_{hit} = 200$	200 bits/hit
Hit rate per sensor	$r_s = 120$ hits/s/sensor	120 hits/s/sensor
Data rate per sensor	$D_{sensor} = (120 \text{ hits/s/sensor})(200 \text{ bits/hit})$	24.0 kbit/s/sensor
Hit rate per array	$R_{hits,array} = (5{,}000)(120 \text{ hits/s/sensor})$	600,000 hits/s
Data rate per array	$D_{array} = (600{,}000 \text{ hits/s})(200 \text{ bits/hit})$	120 Mbit/s
Byte rate per array	$120 \text{ Mbit/s} \div 8$	15.0 MB/s
Daily data volume per array	$(15.0 \text{ MB/s})(86{,}400 \text{ s/day})$	1.296 TB/day

Data-Rate (Shower-Triggered Lookback Readout)

Assumptions: $N = 5{,}000$; $r_s = 120$ hits/s/sensor; $R_{sh} = 33$ showers/s; $\Delta t = 33.36\ \mu s$; $b_{hit} = 200$ bits/hit; $M_{sh} = 15$.
M_{sh} = average sensors with true shower hits per array shower.

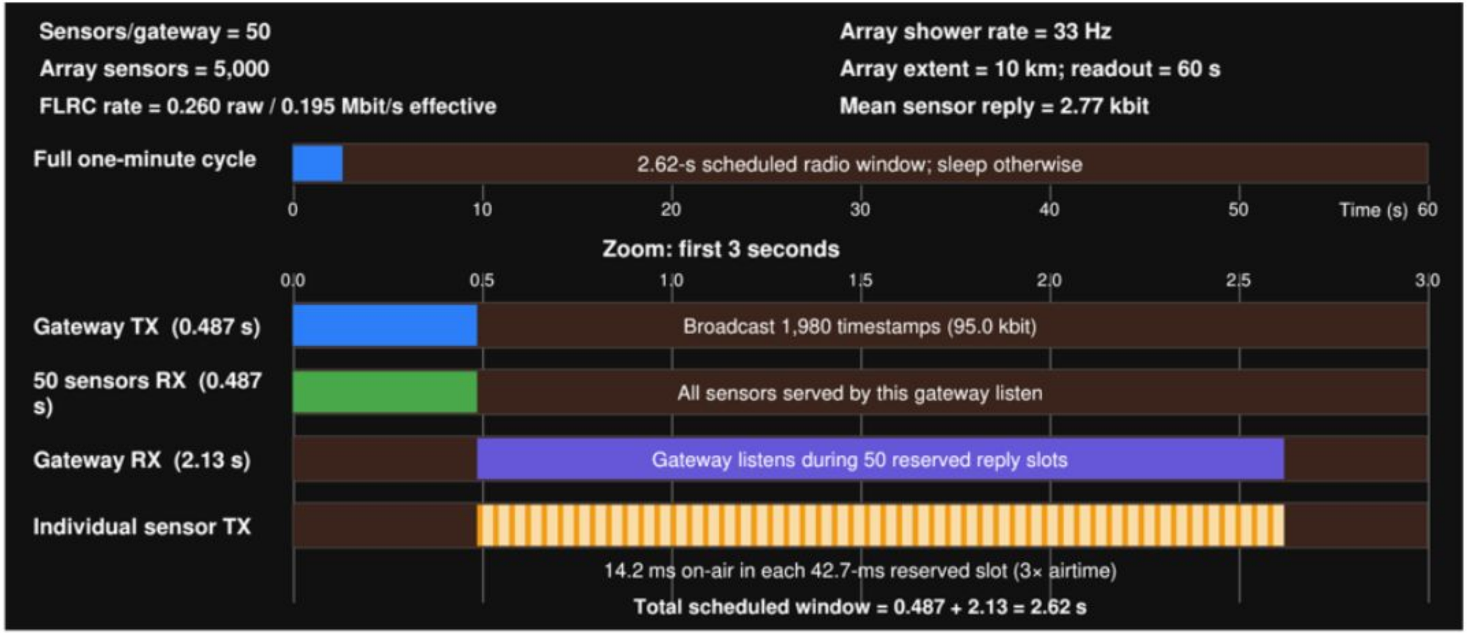
Calculation	Expression	Result
Coincidence-window time per second	$f = R_{sh}\Delta t = (33 \text{ showers/s})(33.36\ \mu s/\text{shower})$	0.0011009 = 0.1101%
Accidental time-correlated singles rate	$r_{acc} = r_s f = (120 \text{ hits/s})(0.0011009)$	0.1321 hits/s/sensor = 7.93 hits/minute/sensor
Accidental hits per array trigger	$n_{acc} = N r_s \Delta t = (5{,}000)(120)(33.36\ \mu s)$	20.016 hits/trigger
Accidental data per array trigger	$B_{acc} = n_{acc} b_{hit} = (20.016)(200 \text{ bits/hit})$	4.0032 kbit/trigger
Accidental hit rate per array	$R_{acc} = R_{sh} n_{acc} = (33)(20.016)$	660.528 hits/s
Accidental infill data rate per array	$D_{acc} = R_{acc} b_{hit} = (660.528)(200 \text{ bits/hit})$	132.1 kbit/s
True shower data rate per array	$D_{sh} = R_{sh} M_{sh} b_{hit} = (33)(15)(200 \text{ bits/hit})$	99.0 kbit/s
Total shower + infill data rate per array	$D_{total} = D_{acc} + D_{sh} = 132.1 + 99.0$	231.1 kbit/s
Daily total data volume per array	$V_{total} = (231.1 \text{ kbit/s} \div 8)(86{,}400 \text{ s/day})$	2.496 GB/day

Data ratio-array = 120 Mbit/s / 231 kbit/s = **520:1**

Headers, retransmissions, acknowledgements, etc. not included

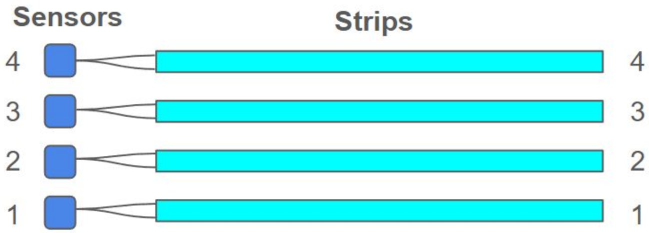
Radio Scheduling is likely a good fit for TAMBO

- GNSS makes scheduled transmission-reception “easy”
- Scheduling combined with data reduction can save a lot of power!
- Scheduling and sleep compatible with FLRC and HaLow WiFi
- Sensor Tx can be scheduled (e.g. by sensor ID) to avoid collisions



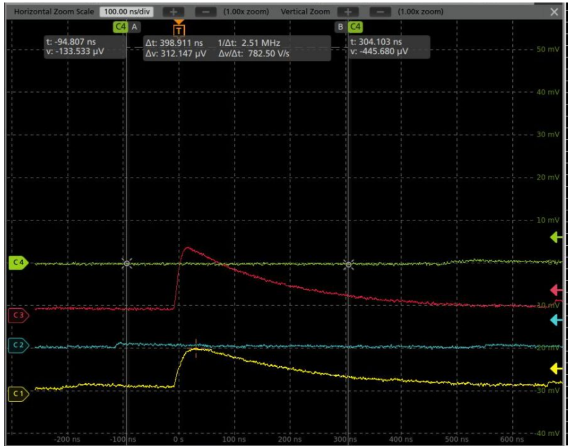
How can a single sensor *detect* a shower (near core)?

- **By threshold:** Set V_{th} > 3 VEM in a single channel sensor (false triggers with low inclination muons)
- **By multi-channel coincidence:** Using a multi-channel sensor (4-channel example shown below)

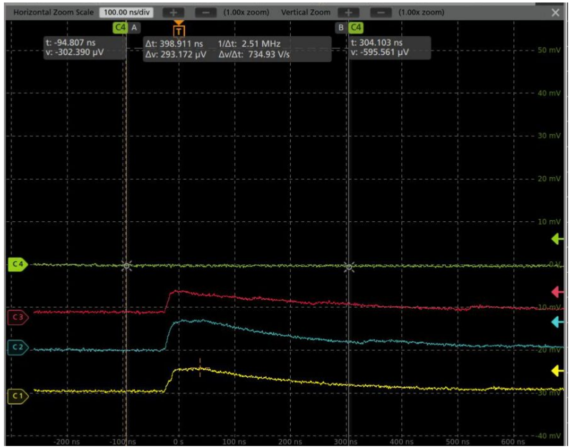


Global trigger by single sensors
May improve Tambo sensitivity

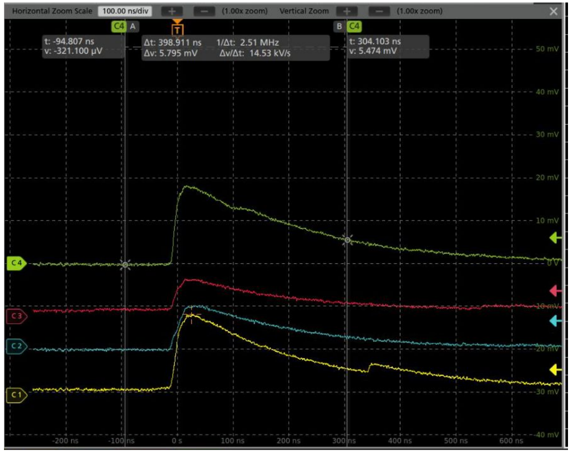
2 of 4 Hit



3 of 4 Hit

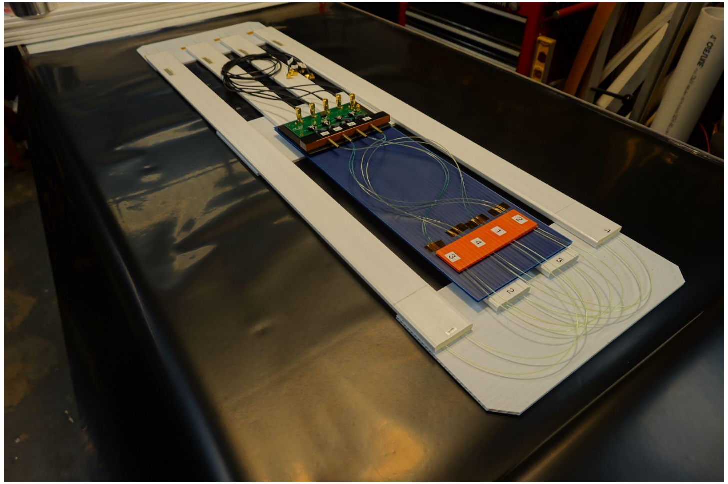


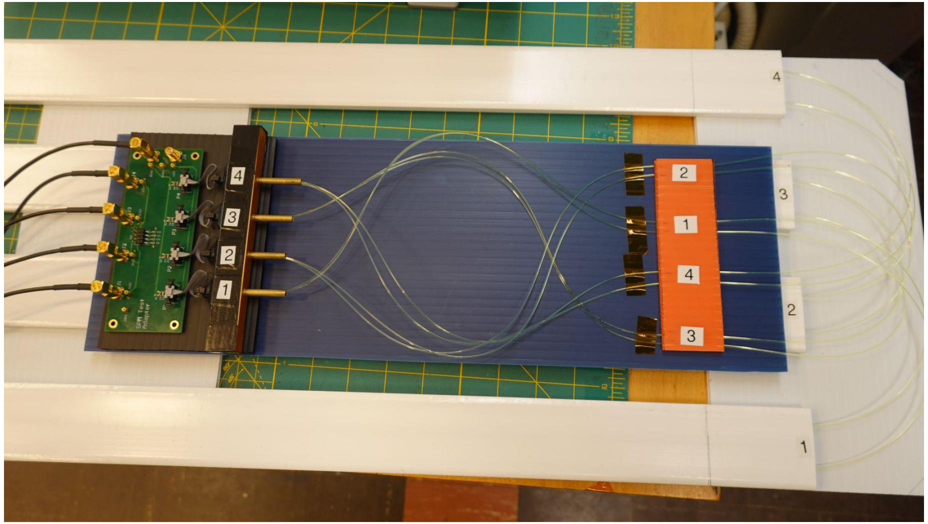
4 of 4 Hit



Mini-Panel Construction

- Four strips (1cmx5cmx85cm) =1700 cm^2 total area
- Two FO each strip (no end loops)
- Four sensors (roughly matched)
- Spring-loaded FO coupling into optical receptacles
- Light-tight hatch for access
- “Strips are the structure” plasticore + VHB tape





Coincidence Arrangements for shower detection

Each SiPM channel combines up to four strips by *fiber routing*

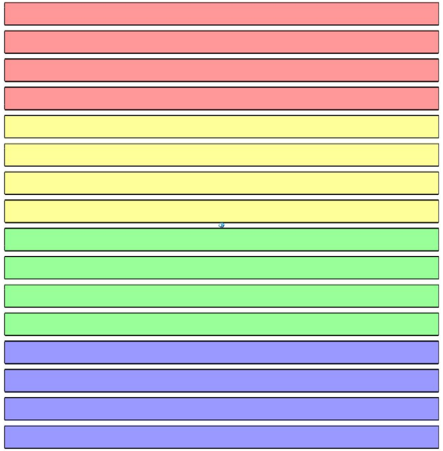
Ch “A”

Ch “B”

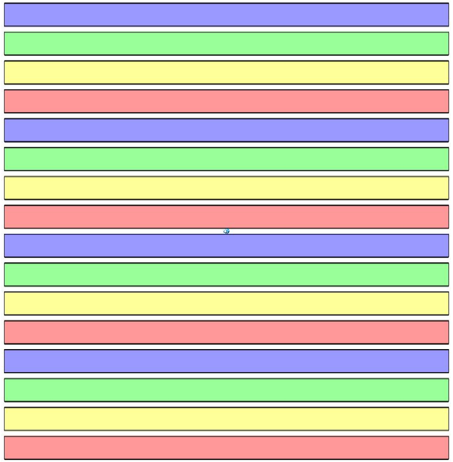
Ch“C”

Ch “D”

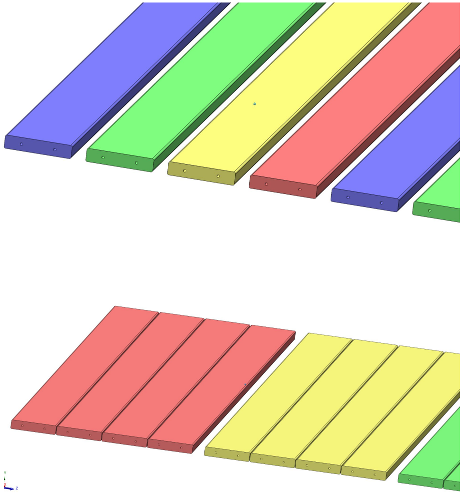
Adjacent Channels



Interspersed Channels



Gaps to minimize corner-clipping



How multi-channel coincidence may add value:

1. High confidence “shower core” data trigger for data reduction
2. Low data rate and power may enable “IOT”- style sensors with low-power comms
3. Possible means of calibrating VEM by comparison of channel hits with identical AOI
4. May provide fit to time-of-arrival AOI from amplitude data at a single sensor

Bits/Sensor/Hit with four-channel sensor ~200b/s

Ch1	Ch2	Ch3	Ch4	Time Stamp	Sensor ID
16b	16b	16b	16b	48b	48b

Avg Power/Sensor <1W

DAQ (Peak Det). ~500mW

GPS Module ~300mW

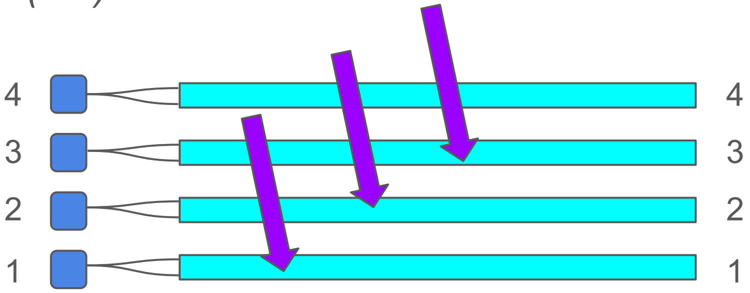
FLRC Comms ~10mW

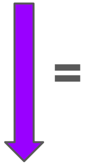
**Infill methods can acquire correlated single muon hits*

Possible VEM Calibration with multi-channel (shower) hits ?

Similar to concept (M4) shown by Will

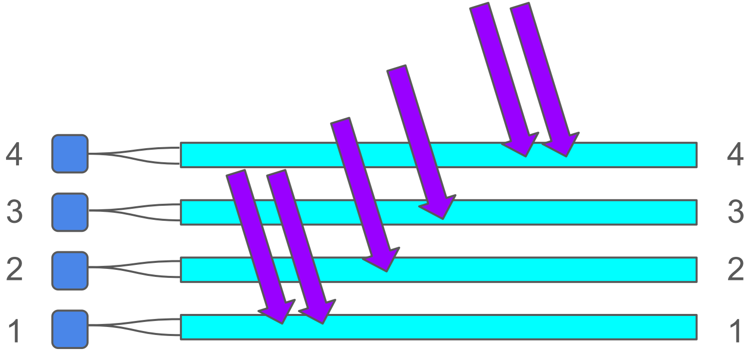
Shower 1, ϴ1

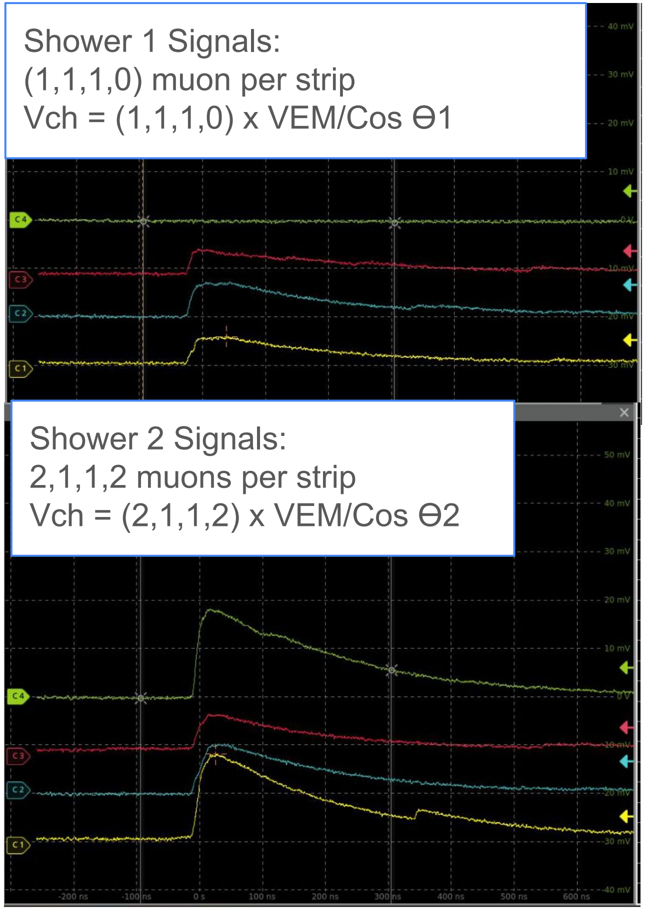




= Single Muon (VEM)

Shower 2, ϴ2





Shower 1 Signals:
(1,1,1,0) muon per strip
Vch = (1,1,1,0) x VEM/Cos ϴ1

Shower 2 Signals:
2,1,1,2 muons per strip
Vch = (2,1,1,2) x VEM/Cos ϴ2

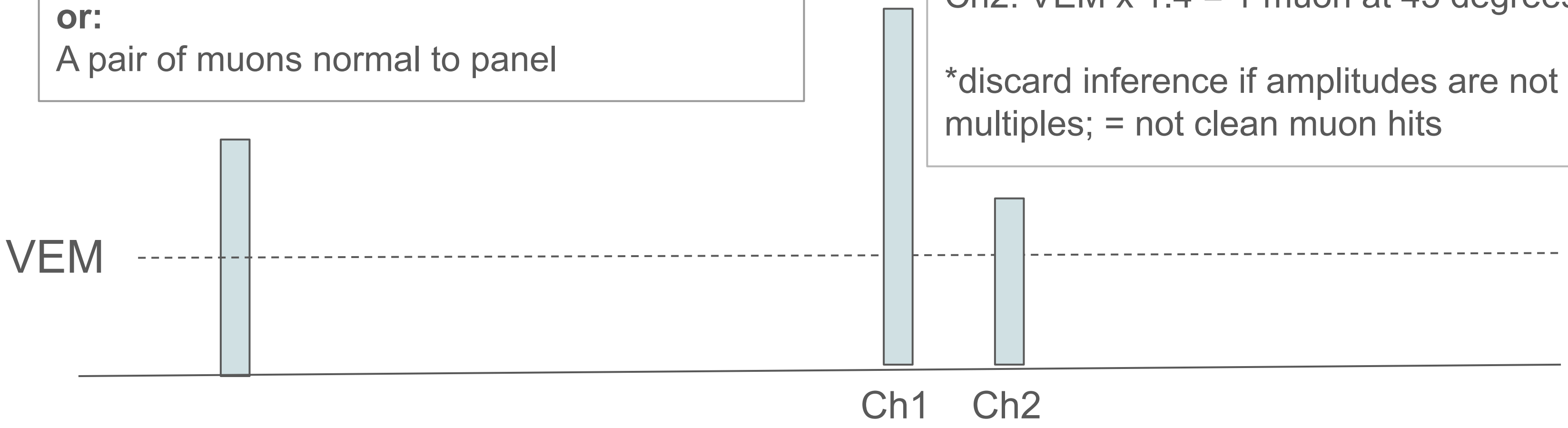
Possible angle-of-incidence (AOI) inference with multi-channel data

- Can remove ambiguity between AOI vs qty of particles hitting a single channel
- Coincident hits can be assumed to be from the **same shower and will therefore have the same AOI**
- Comparison of hit amplitudes allows distinction between 0,1,2,3 muon hits/channel
- Quantized channel **amplitudes** from a shower can indicate AOI during operation

This (single channel) hit could be either:
A single muon at 60° from normal
or:
A pair of muons normal to panel

These (coincident) hits are ~ unambiguous*
Ch1: VEM x 2.8 = 2 muons at 45 degrees
Ch2: VEM x 1.4 = 1 muon at 45 degrees

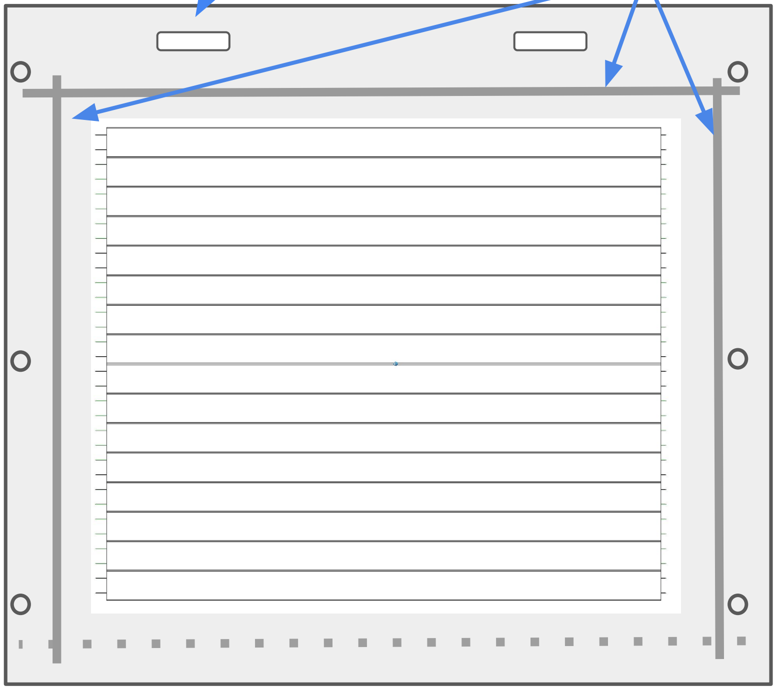
*discard inference if amplitudes are not integer multiples; = not clean muon hits



Single-Channel Amplitude **Multi-Channel Amplitudes**

Consider: smaller panels & geomembrane cover

- Opaque envelope
- UV proof
- Waterproof
- Light weight
- Low parts count
- RF transparent (allows internal antennas)
- Available in tan color in qty
- Animal nibble-proof?



Conclusions

- Low power design may facilitate sensor manufacturability
  - Smaller components = tighter integration = lower cost and easier deployment
- Sensor power can likely be reduced by:
  - Data communications reduction using “Shower-Triggered Lookback Readout”
  - Use scheduled radion sleep and transmission
  - Lower clock rate in DAQ, eliminate LVDS line drivers
- Having GNSS at each node allows flexible radio scheduling
  - This would be somewhat hard to do otherwise
- Multichannel architecture may be worth investigating:
  - Shower trigger sensitivity may be enhanced over amplitude threshold
  - VEM calibration (likely an operational complexity tradeoff with multiple channels)
  - Additional AOI fit to timing data using amplitude profiles from a single sensor

Extra slides for discussion

“Shower triggered lookback readout”: Assumptions

1. Every shower of interest results in at least one sensor being hit by multiple simultaneous muons (e.g. near the core).
2. Most single hits in a sensor are unlikely to be time-correlated with any shower of interest.
3. Any singles that are truly part of a shower will occur during a time window surrounding the shower timestamp.
4. Any singles that are accidentally in the time window can be later discarded because of non-physical geometry

Going Further

- Check rate assumptions for various sensor sizes and array spacings.
- Find minimum sensor size and maximum spacing that ensures multiple hits (for shower trigger) on at least one sensor for smallest showers of interest.
- Check MC reconstruction performance using single-sensor trigger.
- Review power and scheduling assumptions for real radio modules

Low Data Rates + Sleep -> Tiny Power Consumption

- *Includes accidental hits + mean true shower hits assuming (15) sensors hit in each shower*
- *Coincidence window of 33us corresponds to maximum array extent of ~5km*
- *Radio wake-up overhead, headers, retransmissions, etc, not considered below*

Data Rates

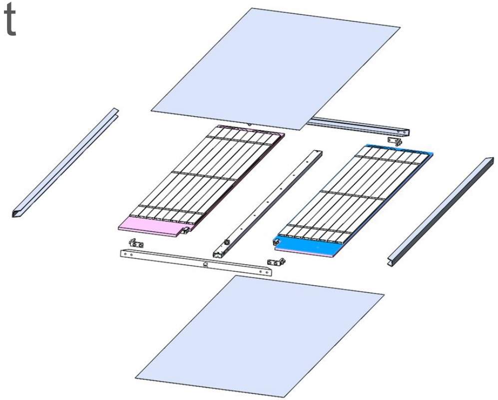
Parameter	Value
Sensors / gateway	50
Sensors / whole array	5,000
Singles rate / sensor	120 Hz
Shower rate / whole array	33 Hz
Array extent / total coincidence window	10 km / 33.36 µs
Readout period / shower triggers	60 s / 1,980
Coincidence-time fraction	0.1101%
Accidental hits / sensor / minute	7.93
True shower records / sensor / minute (mean)	5.94
Accidental infill payload	1.59 kbit / readout
True-shower payload (mean)	1.19 kbit / readout
Mean total sensor reply	2.77 kbit / readout

Power Consumption

Parameter	Value
Radio / mode	SX1280 FLRC, CR 3/4
Raw / effective link rate	260 / 195 kbit/s
Radio supply	3.3 V
RX active current / power	6.5 mA / 21.45 mW
TX operating point	+12.5 dBm RF
TX active current / power	24 mA / 79.2 mW
Broadcast RX time / readout	0.487 s
Mean sensor TX time / readout	14.2 ms
Sensor RX Pavg (0.812%)	0.174 mW
Sensor TX Pavg (0.0237%)	0.0188 mW
Total sensor radio Pavg	0.193 mW

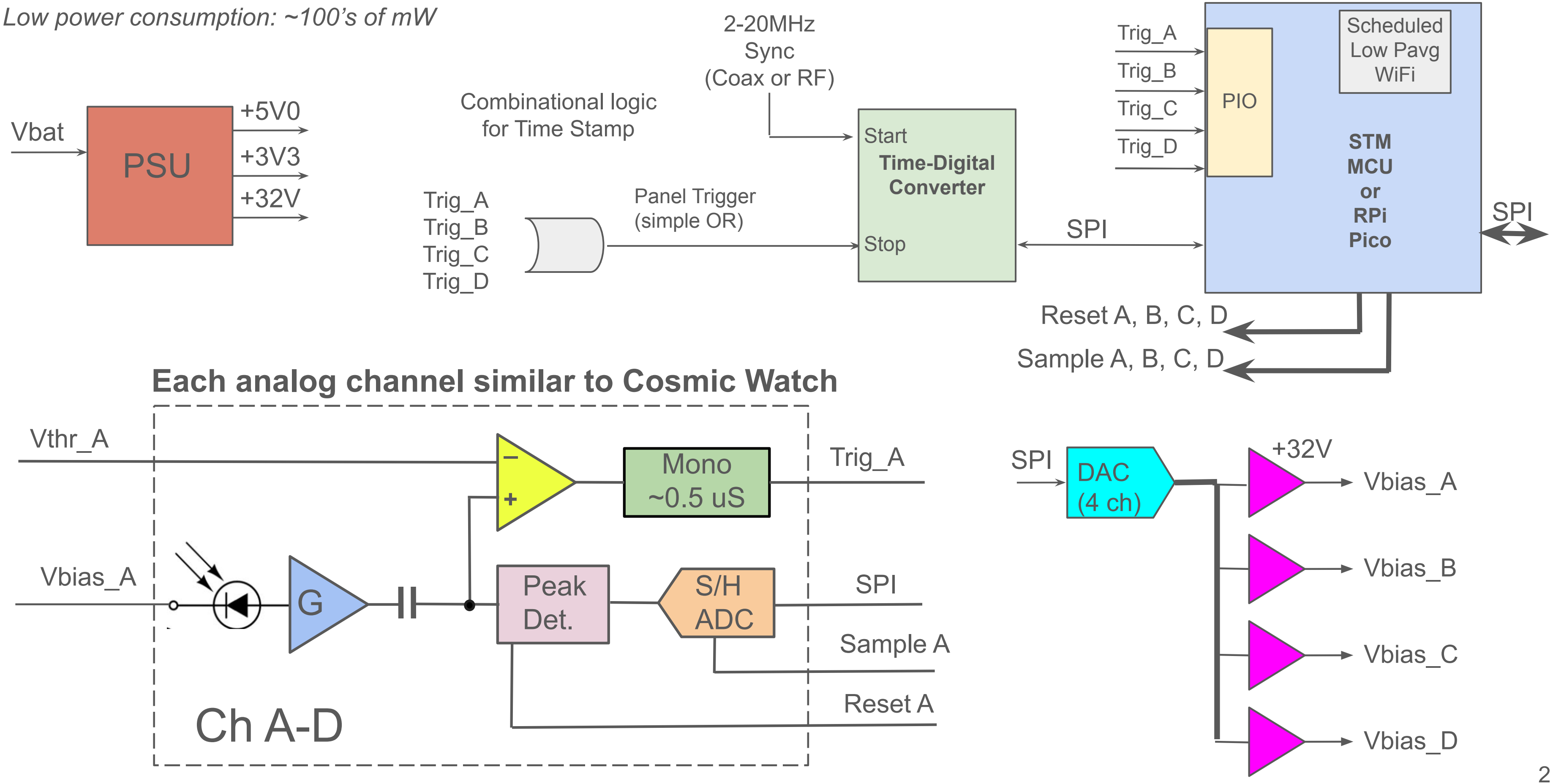
Door-sized panels installed at south pole

Design was tailored for unique South Pole environment

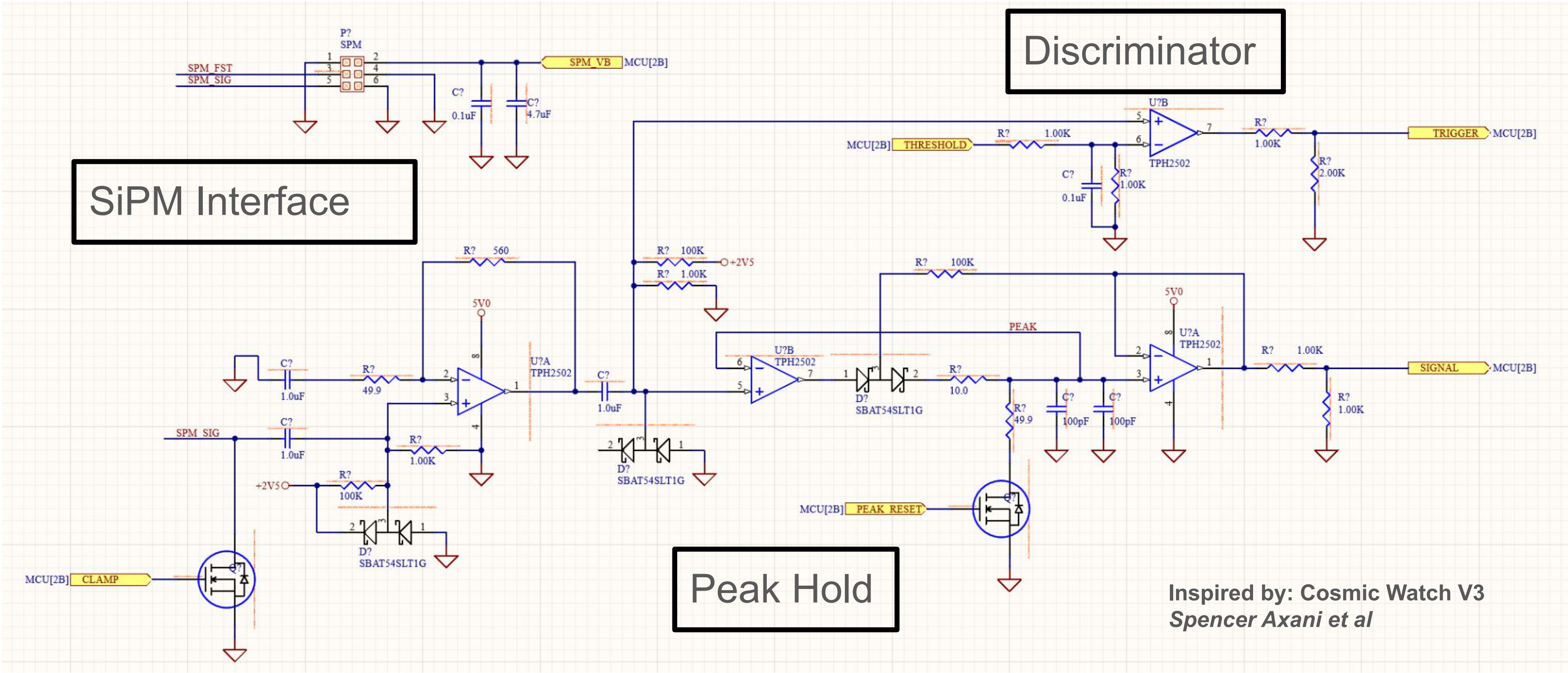


Block Diagram for example multi-channel low-power DAQ

Low power consumption: ~100's of mW



Example low-power DAQ analog channel



Inspired by: **Cosmic Watch V3**
Spencer Axani et al

Amanda Deconstruction and Packing, Dec. 2009

References and links

Cosmic Watch Desktop Muon Detector (v3x)
Wireless TDAQ Upgrades for PEP Array
Semtech SX1280/SX1281 FLRC with TOF ranging
Powerfilm Solar
TDC7200

Optical System DSN
Power Case Mount DSN
Communication System DSN
Timing System DSN

uDAQ DSN
MicroDaq 5.0 and fanout