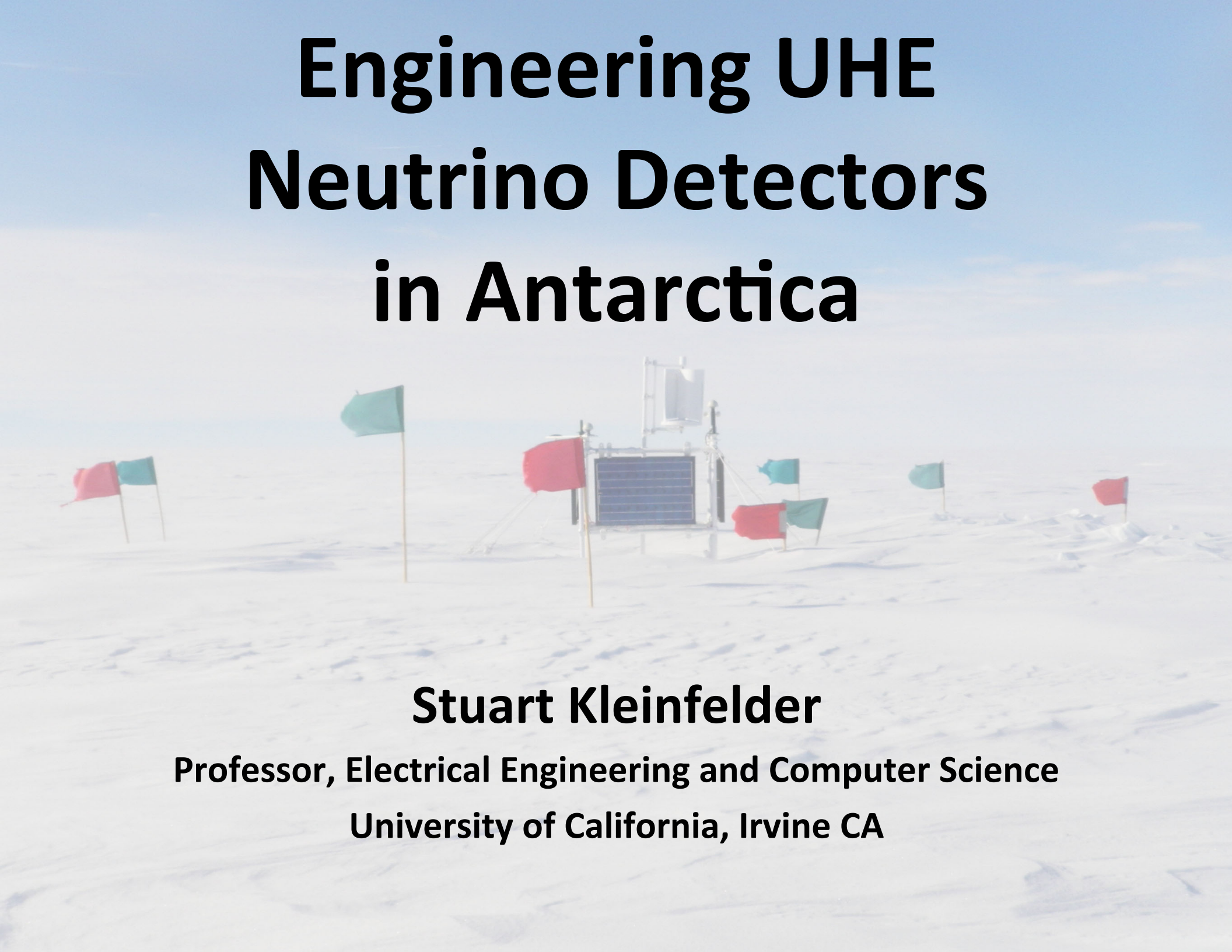
Engineering UHE Neutrino Detectors in Antarctica



Stuart Kleinfelder

Professor, Electrical Engineering and Computer Science

University of California, Irvine CA

New Solid State Devices for HEP - 1985

Proceedings of the Workshop on
New Solid State Devices for High Energy Physics

Lawrence Berkeley Laboratory
October 28-30, 1985

VLSI for Physics

Stuart A. Kleinfelder
Physics Division, Lawrence Berkeley Laboratory
Berkeley, CA. 94720 USA

From silicon detectors to super colliders, physicists need VLSI. Institutions and collaborations now recognize the feasibility and power of custom and semi-custom integration. Novel application specific architectures expressed in VLSI allow tremendous gains in speed and efficiency over systems of commercial components. An example of the flexibility of this medium is

Why Neutrinos? Why Antarctica?

Neutrinos are neutral sub-atomic particles that barely interact with matter. They can travel unimpeded through vast quantities of space, despite obscuring dust, etc.

Neutrinos can potentially be used as a telescope to see inside the obscured galactic core, etc. But because of how weakly neutrinos interact with matter, one needs an enormous amount of mass to detect rare extra-solar neutrinos.

Antarctica has lots of ice that can be used as a detector medium, and that ice is substantially transparent to the radiation that can be used to detect the interactions between neutrinos and ice nuclei.

The IceCube Experiment – South Pole

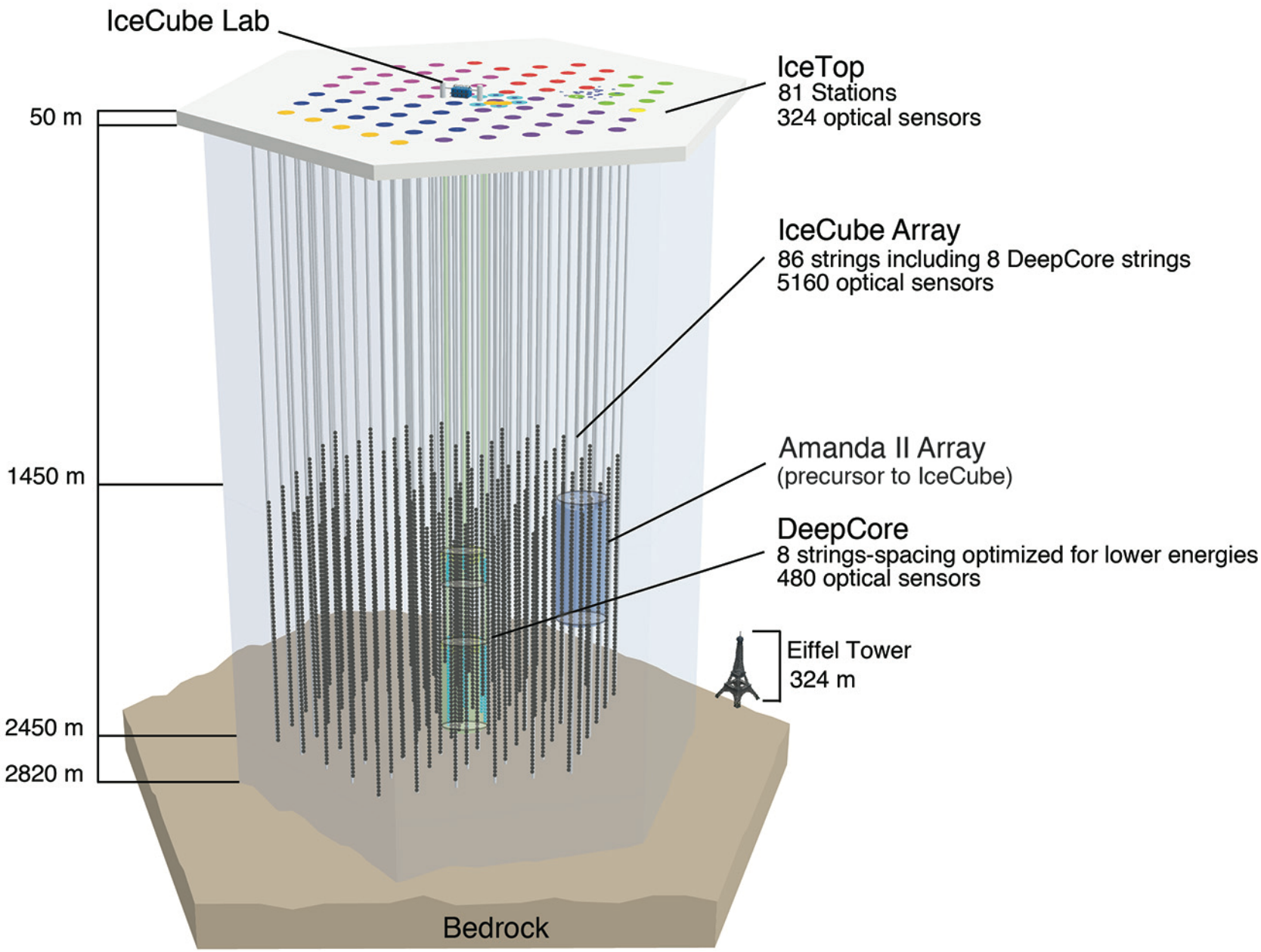
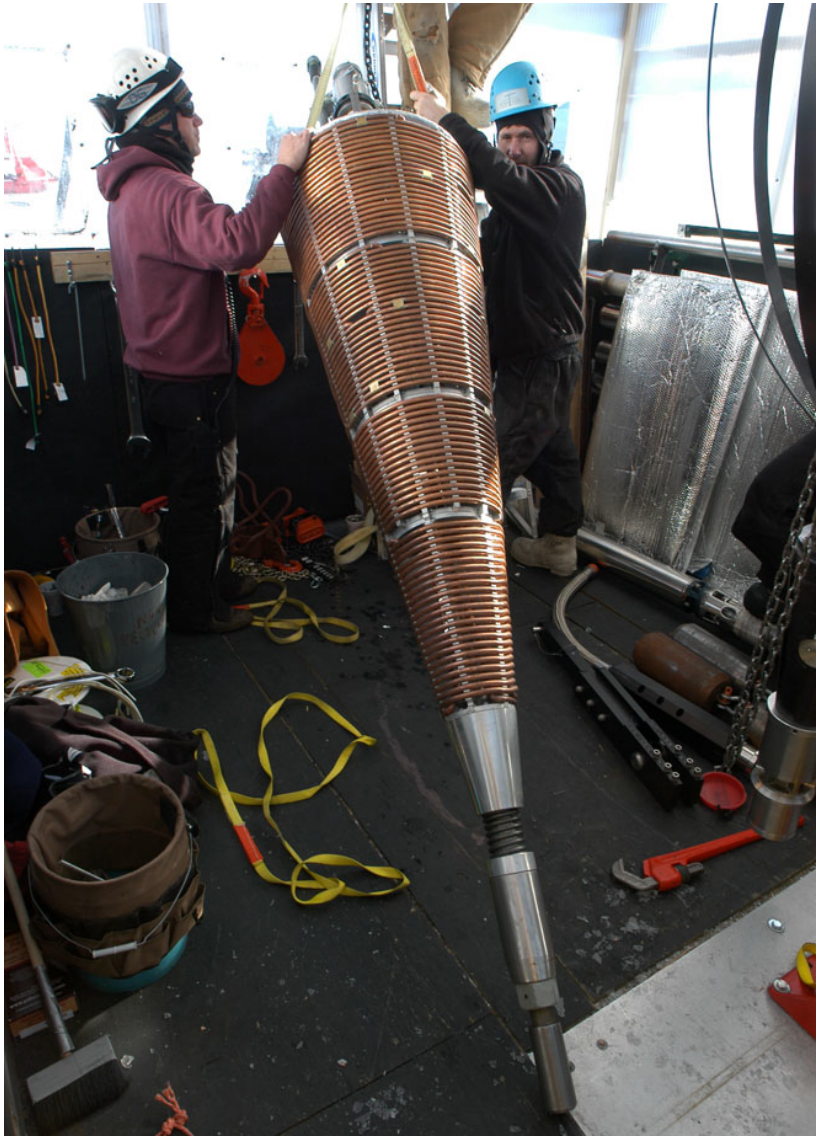
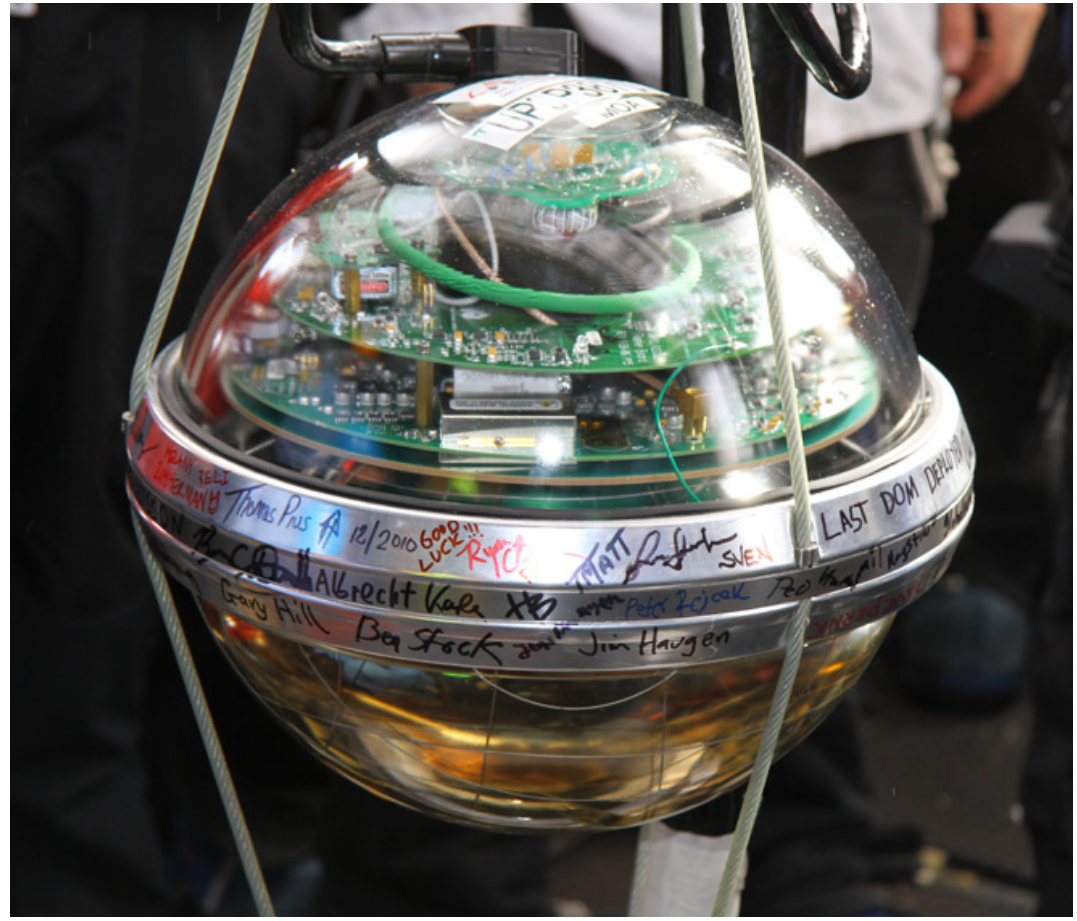


Figure: IceCube Collaboration.

The IceCube Experiment



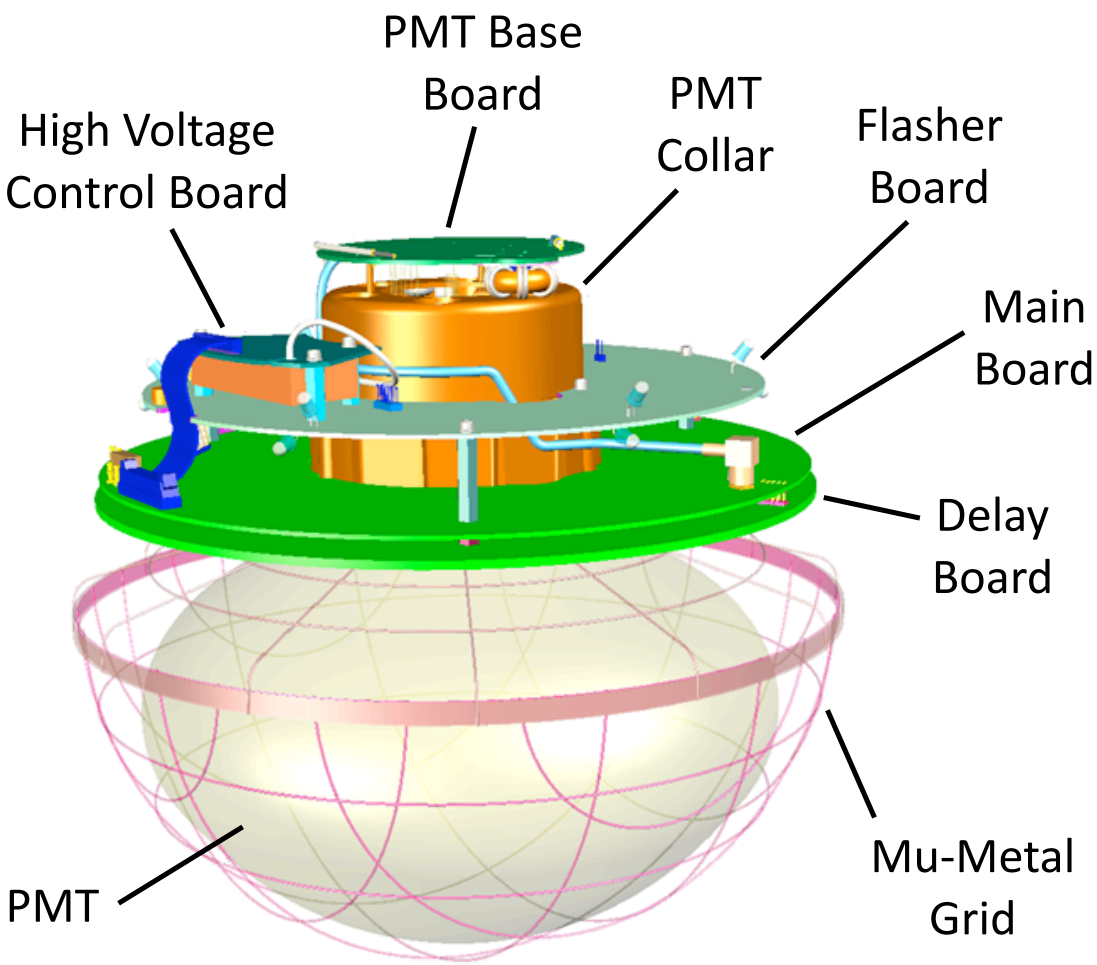
The hot-water “drill”

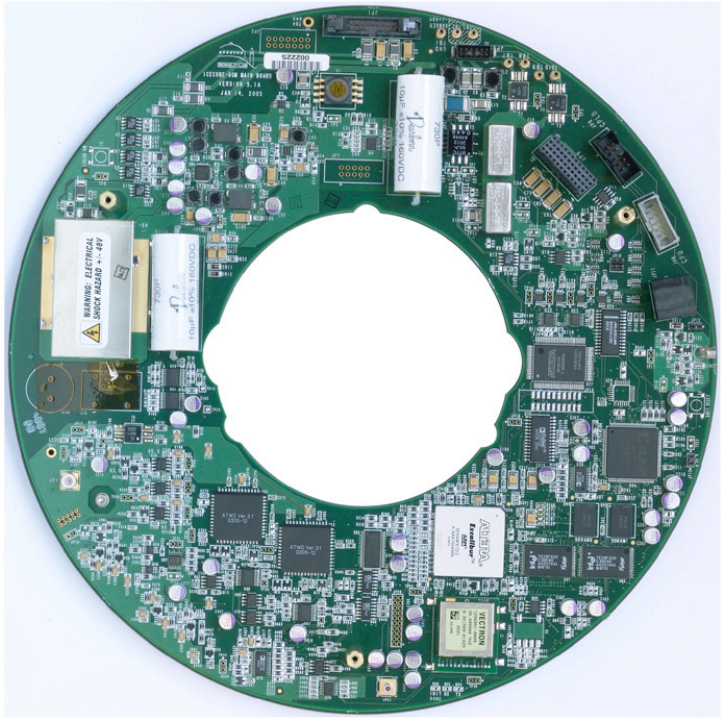


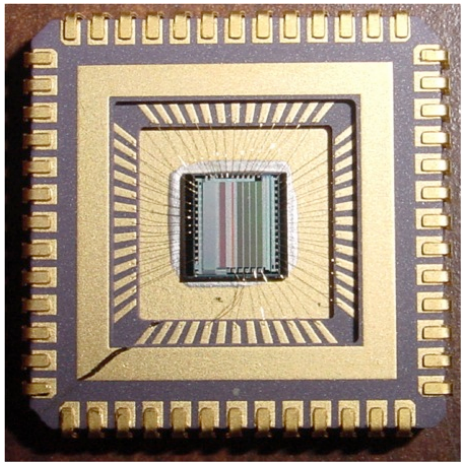
The last of over 5,000
Digital Optical Modules

Photos: IceCube Collaboration.

IceCube Digital Optical Module

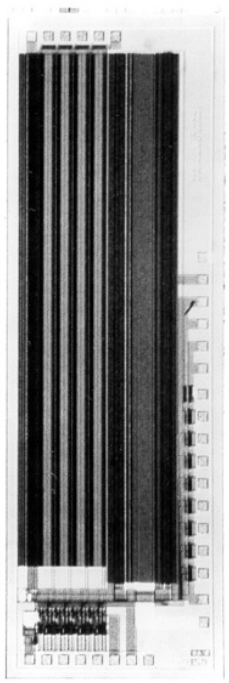


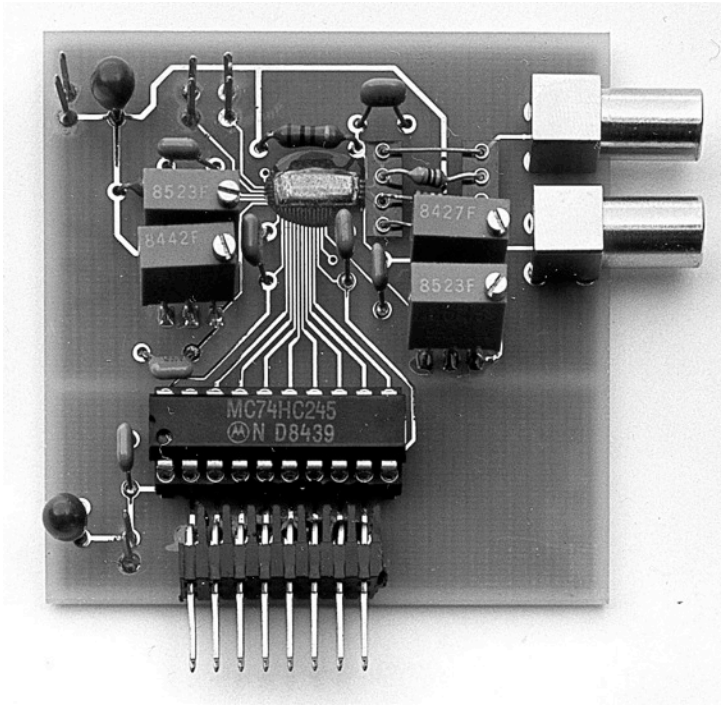




Credits: IceCube Collaboration.

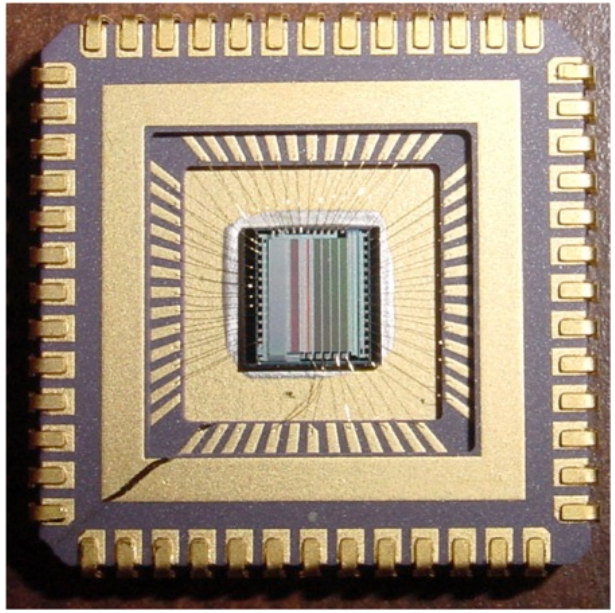
SCA to ATWR to ATWD: IceCube





Advanced Transient Waveform Recorder (Kleinfelder, 1992)

- First multi-GHz Switched Capacitor Array.
- 5 G-samples/s acquisition speed,
- 4 Channels of 512 samples/channel.
- 1.2 μm 2-metal CMOS.
- 350+ MHz B.W.
- 11+ bits RMS dynamic range.



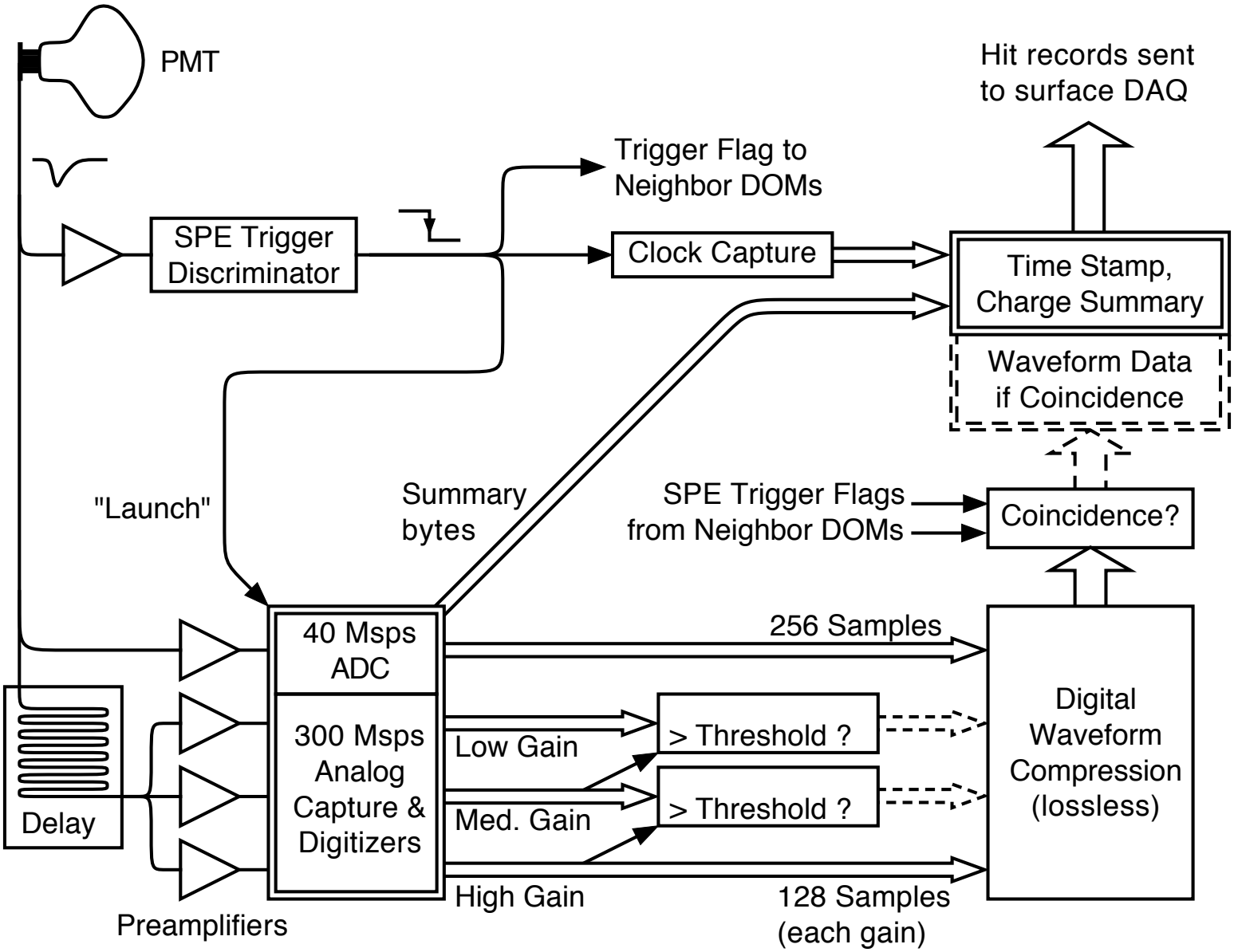
Advanced Transient Waveform Digitizer with on-chip channel-parallel digitization.

Used in AMANDA, IceCube, KamLAND

In IceCube:

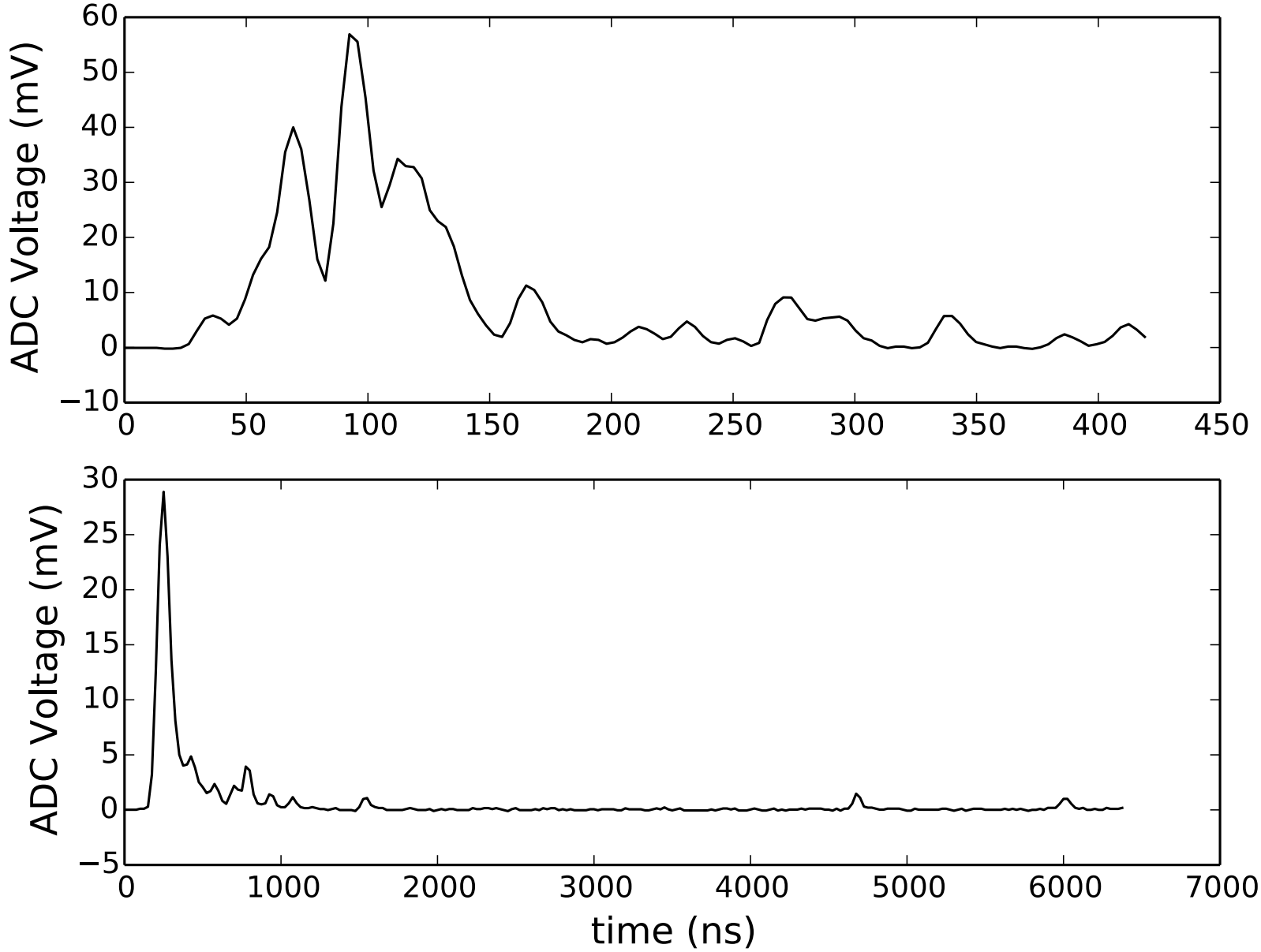
- Four channels combined to create equivalent of 14-bit ADC.
- Two chips used per photomultiplier tube for dead-time reduction.

IceCube Main Board



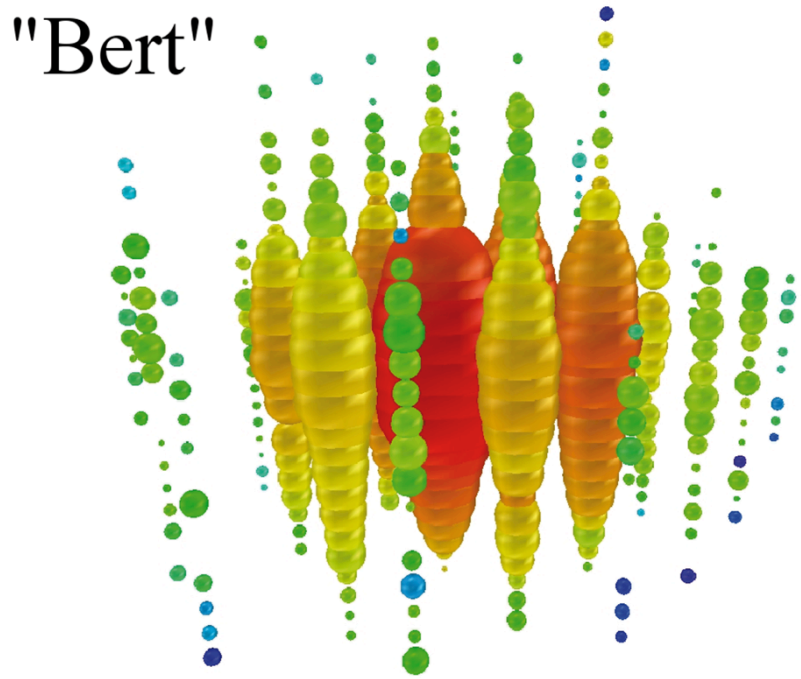
Credits: IceCube Collaboration.

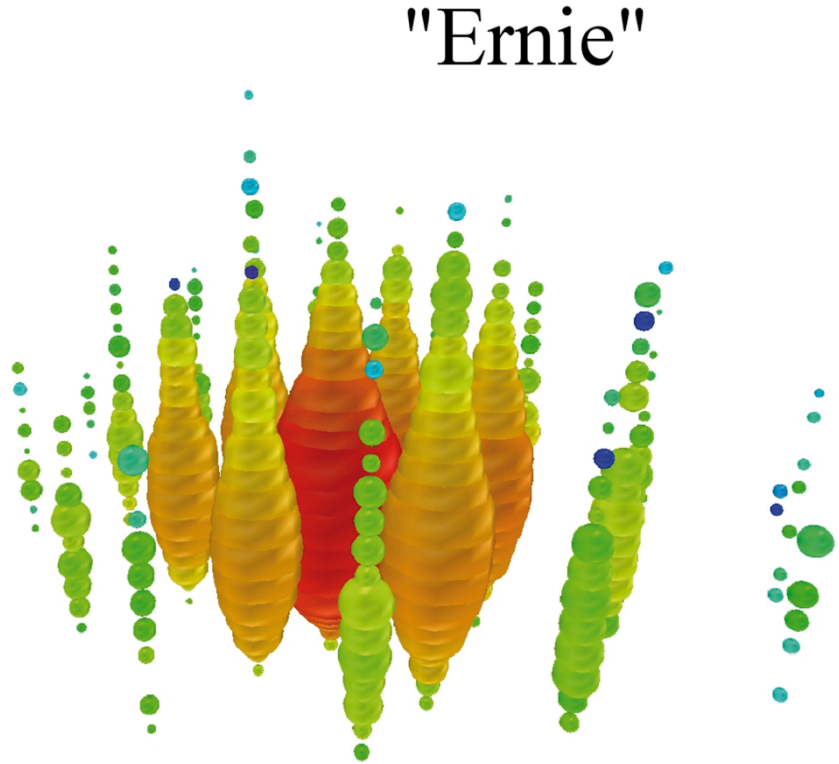
Example Waveforms



Credits: IceCube Collaboration.

IceCube Experiment: Events





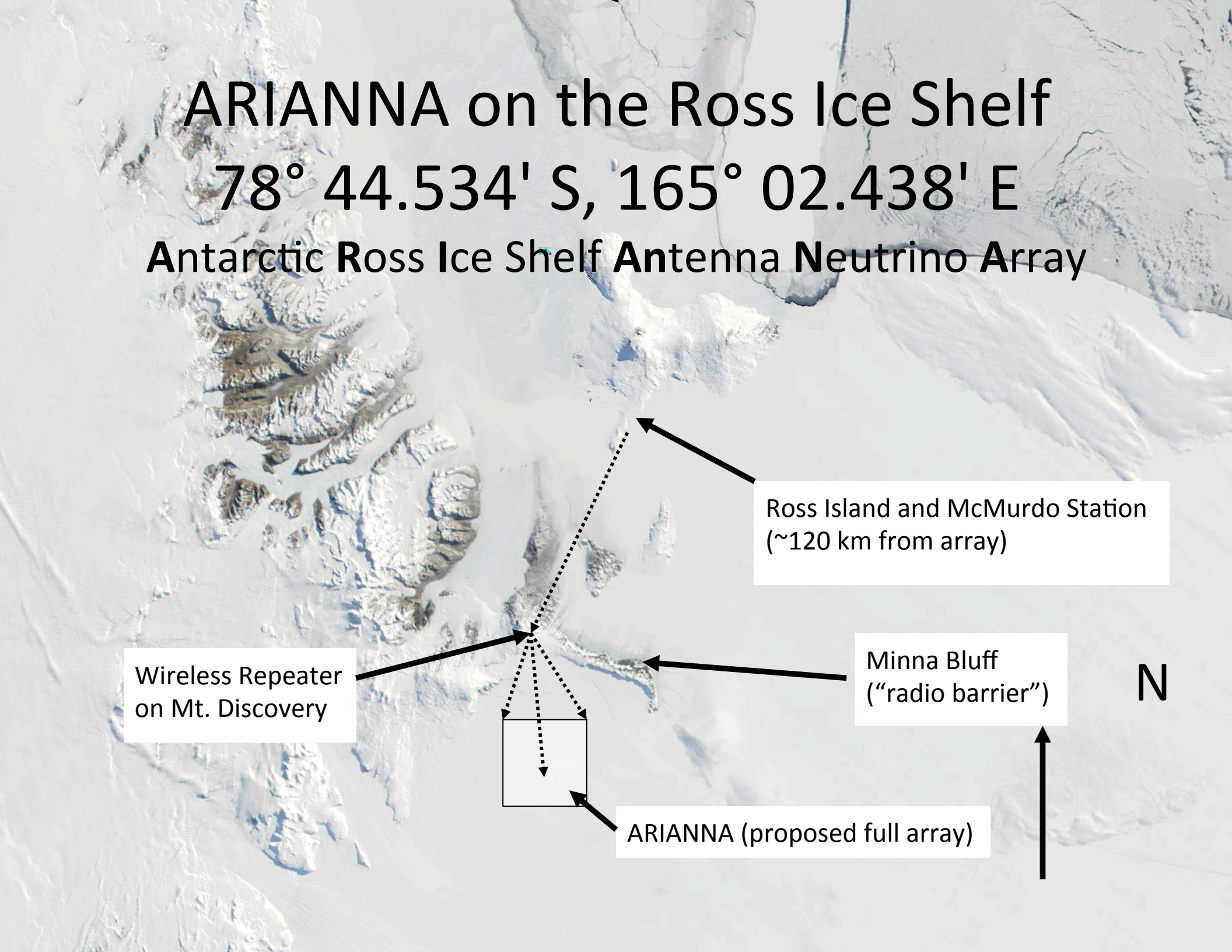
Two of the most powerful neutrino events recorded by IceCube:
Peta electron volts (10^{15} eV = 1.6×10^{-4} Joules).
Spheres indicate triggered Digital Optical Module outputs.
Size of spheres indicates the number of photons collected.
Color indicates photon arrival time (red = earlier, blue = later).

Figures: IceCube Collaboration.

ARIANNA on the Ross Ice Shelf

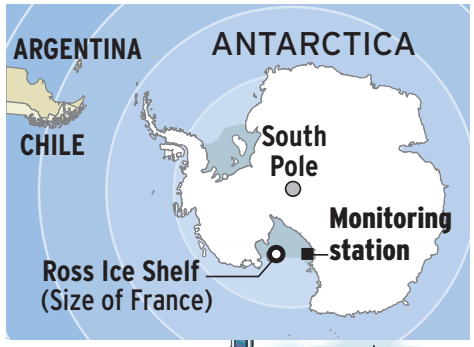
78° 44.534' S, 165° 02.438' E

Antarctic **R**oss **I**ce Shelf **An**tenna **N**eutrino **A**rray



Counting neutrinos

High-energy neutrinos constantly stream through all objects on Earth. Occasionally, a neutrino hits the nucleus of atoms and generates a blast of particles, creating a pulse of radio emissions that can be recorded. Here is a look at why the Antarctic is a good place to monitor those radio emissions:



NEUTRINOS ENTER ICE

1 Countless neutrinos enter the ice; a few occasionally strike hydrogen and oxygen atoms in the ice.

COLLISION IN ICE

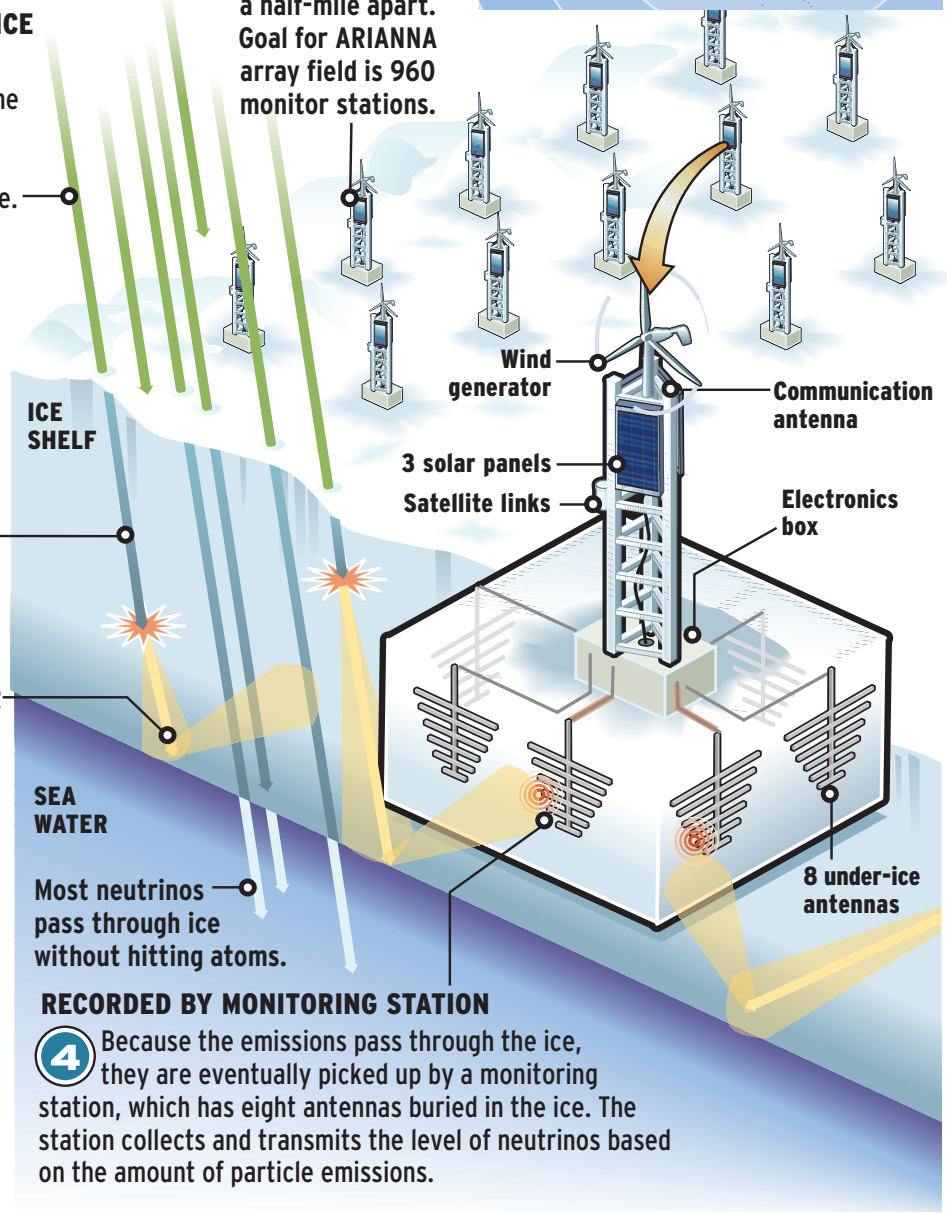
2 The force of the collision blasts particles from the nucleus of the atoms. The spray of particles emits radio waves in the form of a "cone" that points in the same direction that the neutrino was moving.

BLOCKED BY WATER

3 The Ross Ice Shelf is ideal for monitoring these emissions because the water below the ice blocks the radio emissions. They bounce off the water and travel back through the ice.

Source: UCI professor Steven Barwick

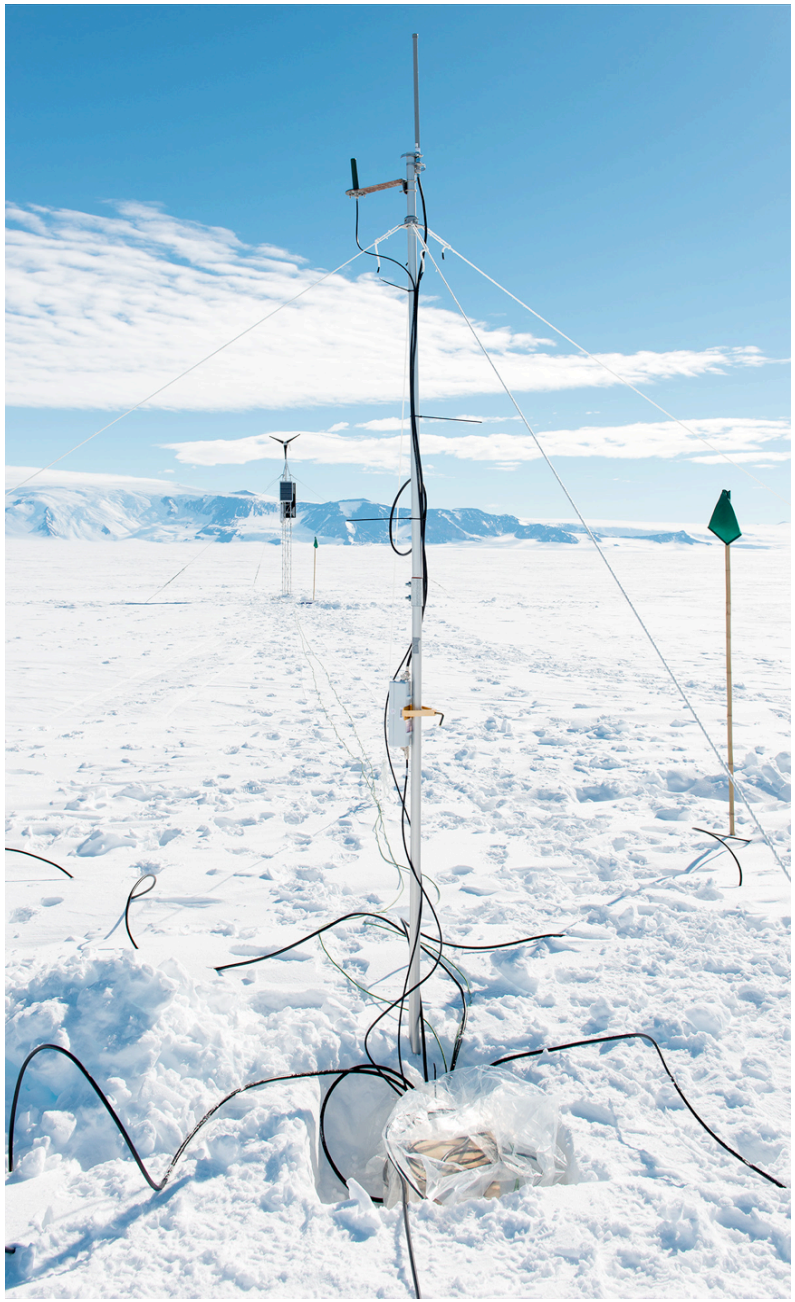
Graphic by Scott Brown / The Register

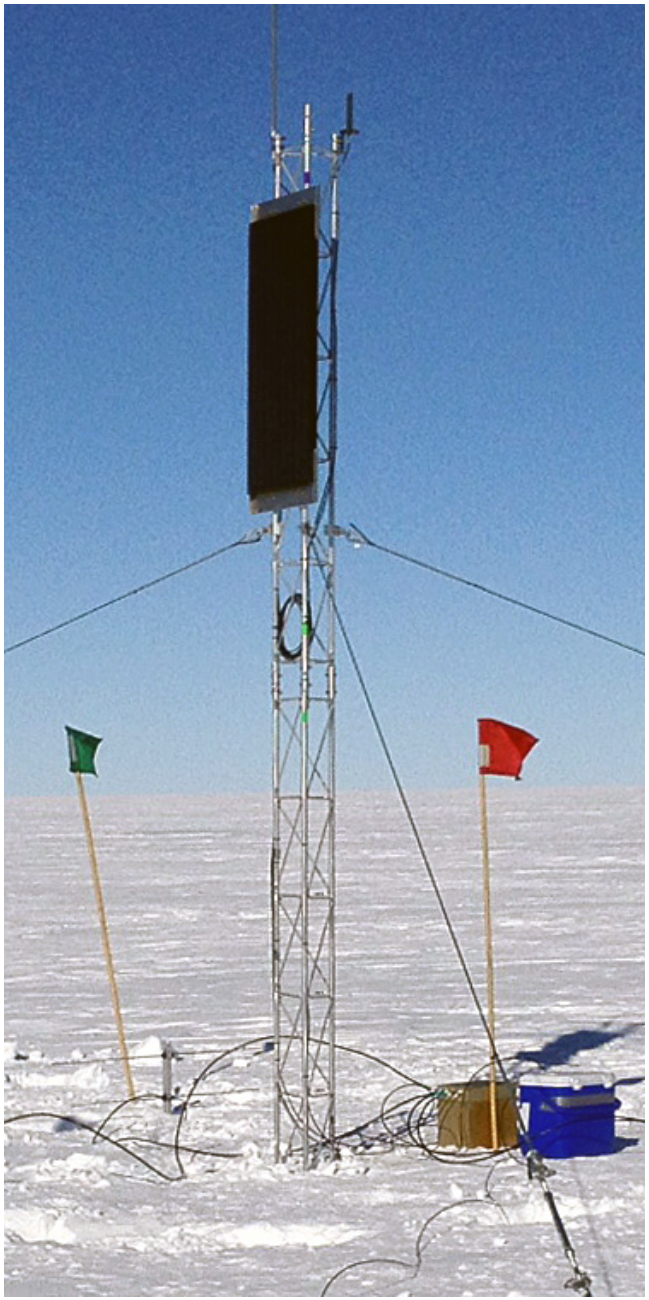


RECORDED BY MONITORING STATION

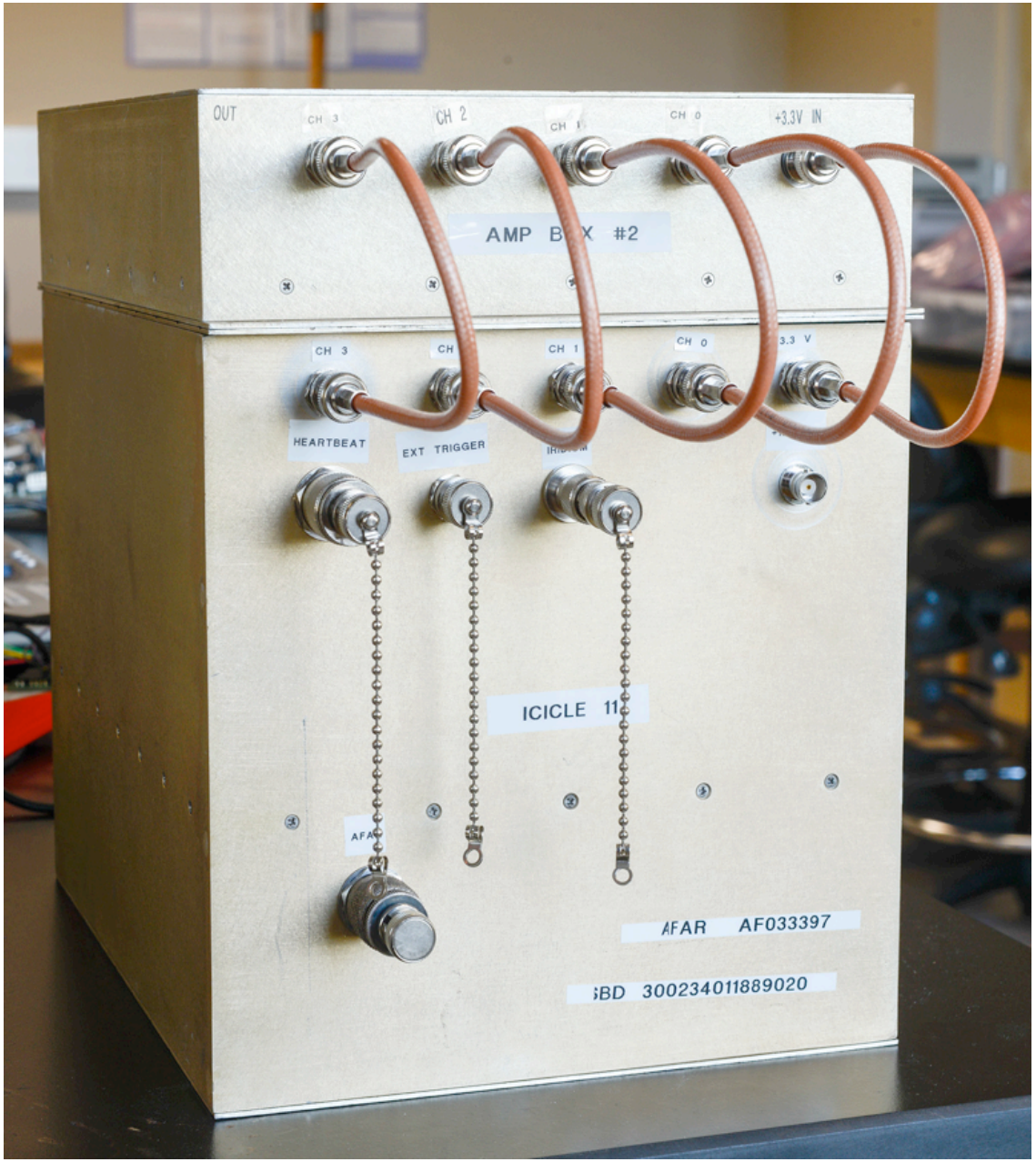
4 Because the emissions pass through the ice, they are eventually picked up by a monitoring station, which has eight antennas buried in the ice. The station collects and transmits the level of neutrinos based on the amount of particle emissions.

Power Tower and Communications





Amplification and System Boxes

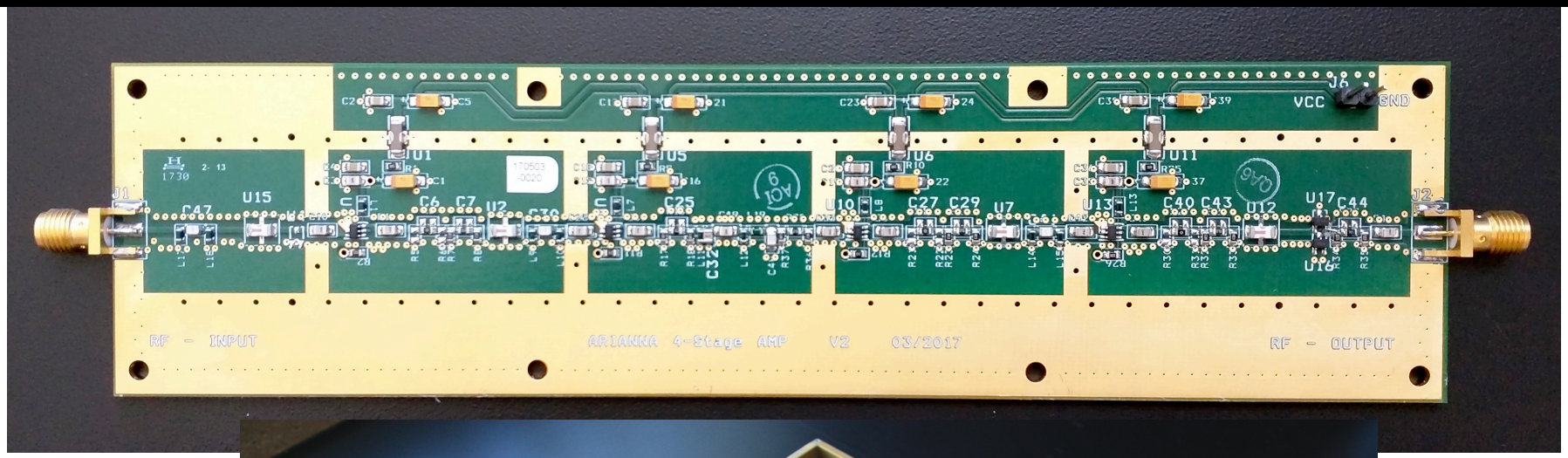


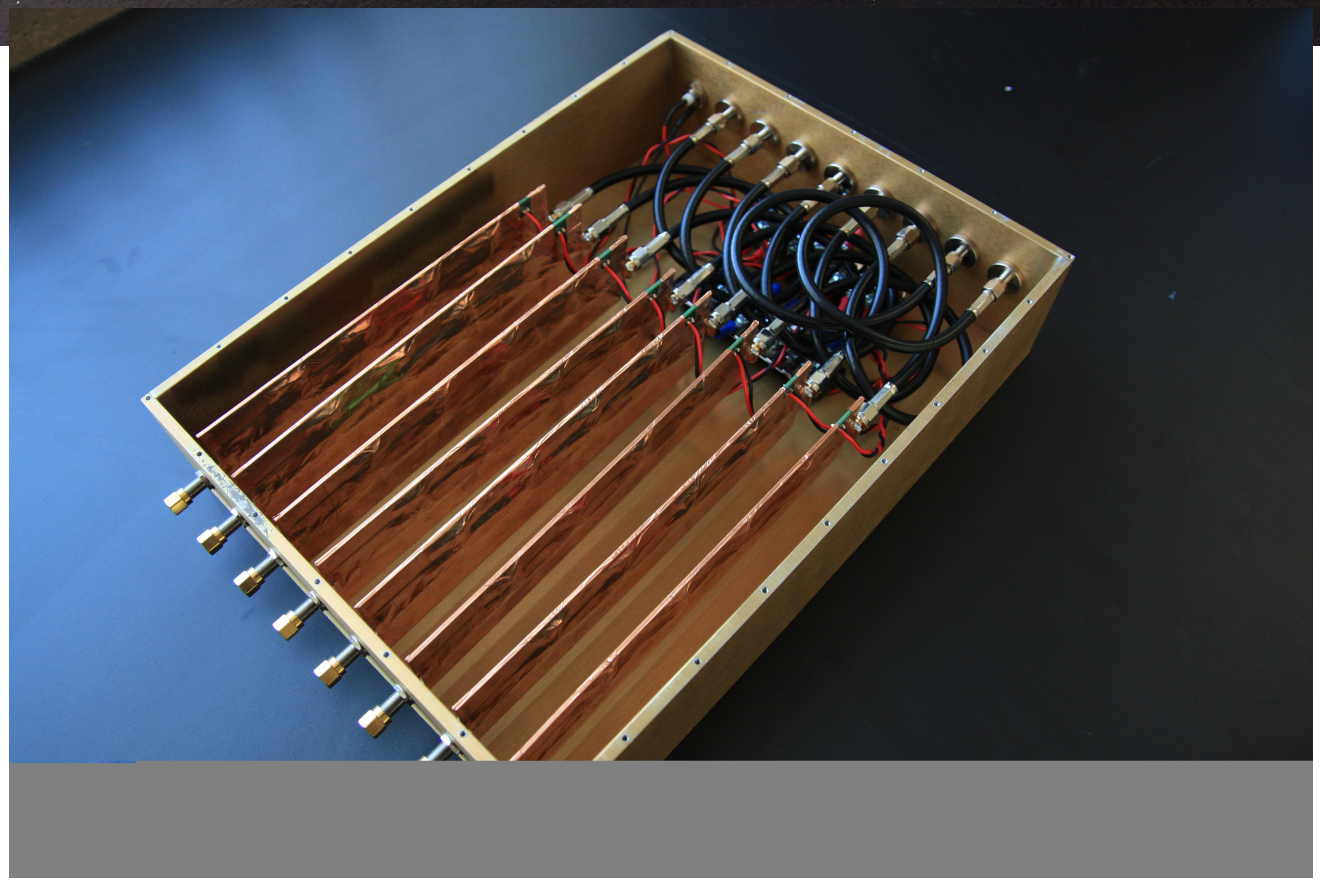
Amplifier box contains 4 channels, N-type inputs, BNC outputs.

System box encloses all DAQ electronics, WiFi and Iridium modules, 20 Ah LiFePO4 batteries and battery management unit, “heartbeat” output, external trigger input, power control and conditioning, etc.

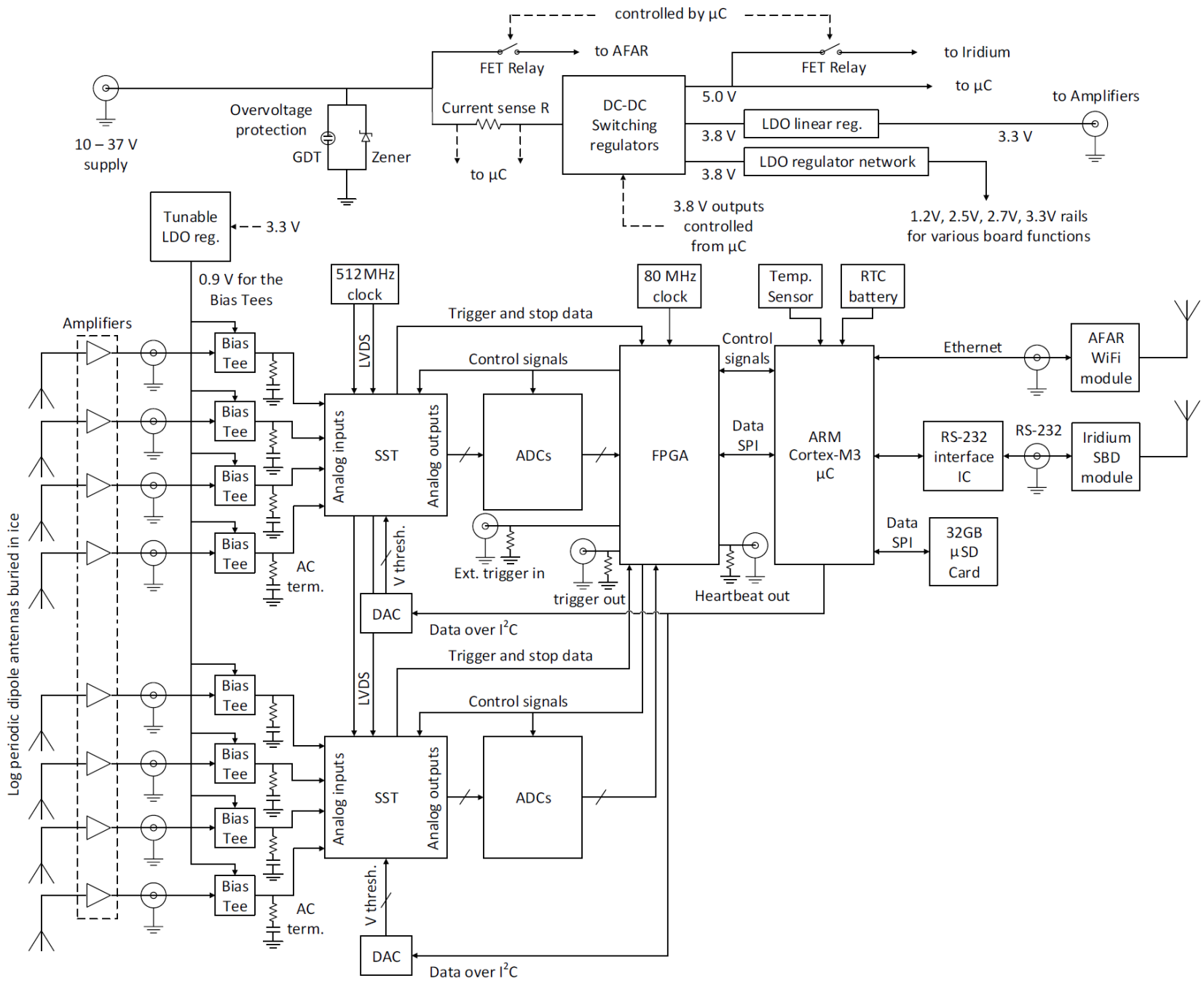
Boxes can be bolted together or kept separate.

GaAs Amps, 0.05-0.5 or 1.0 GHz

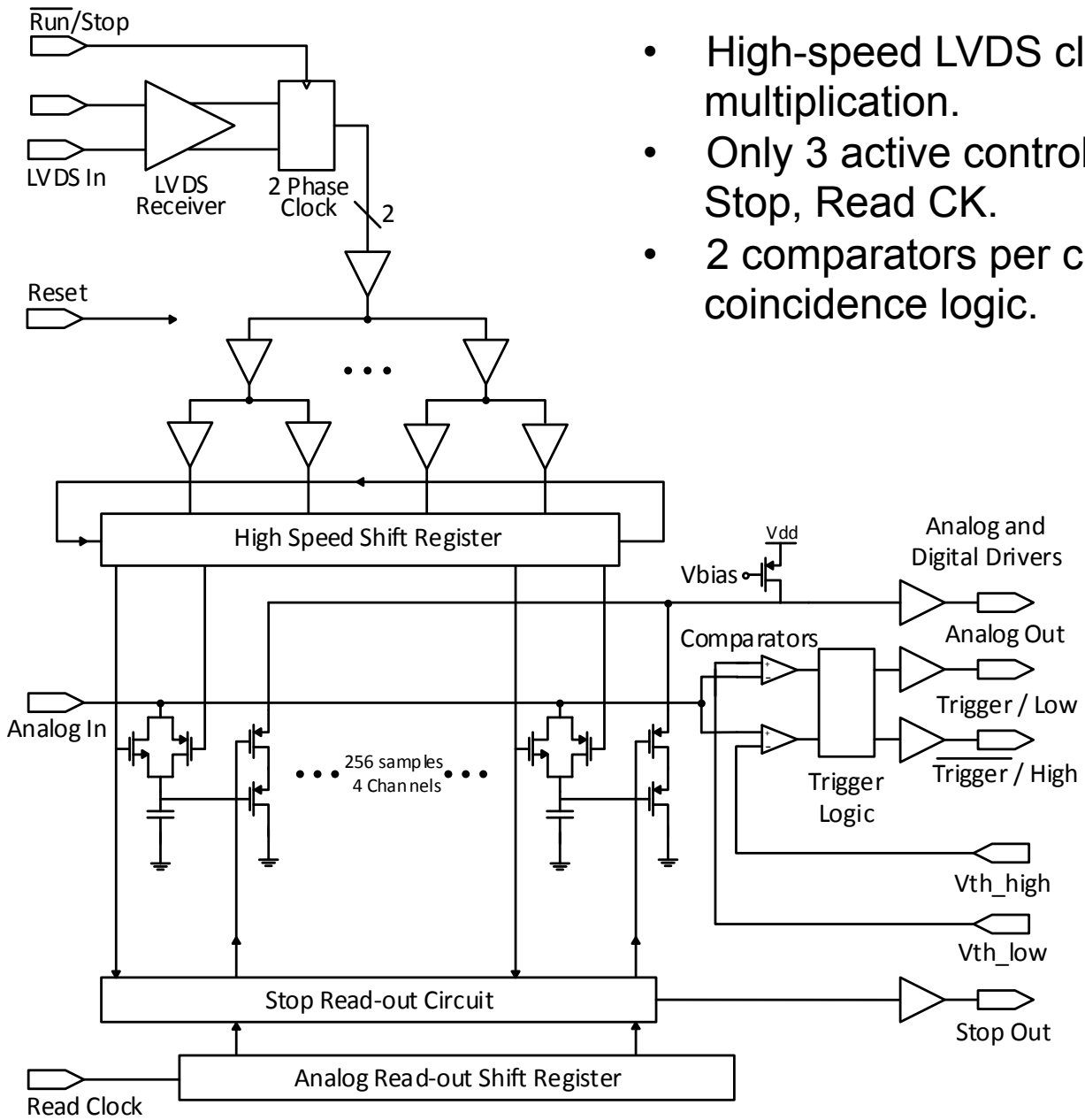




ARIANNA Electronics System Diagram



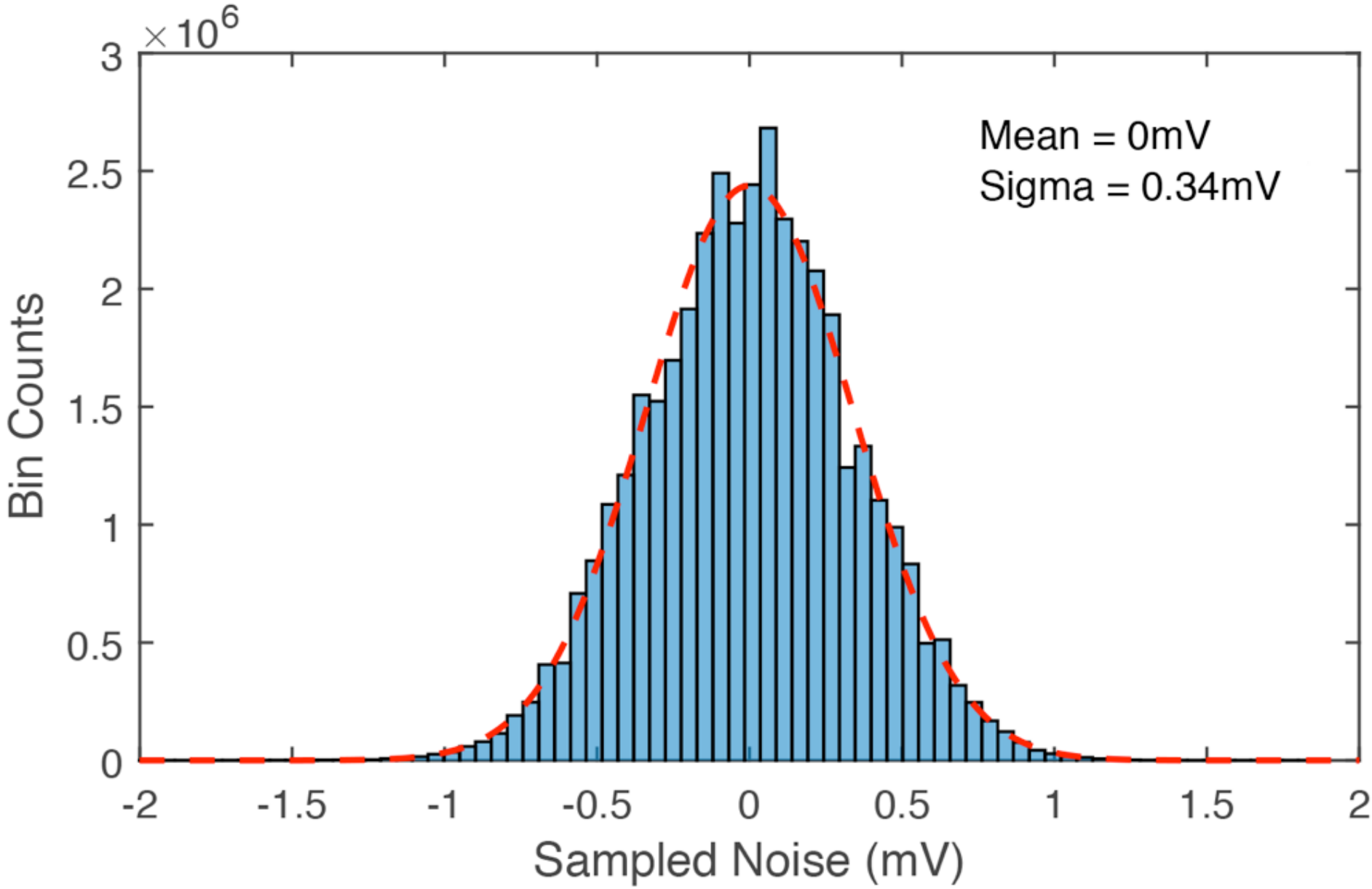
SST Overview



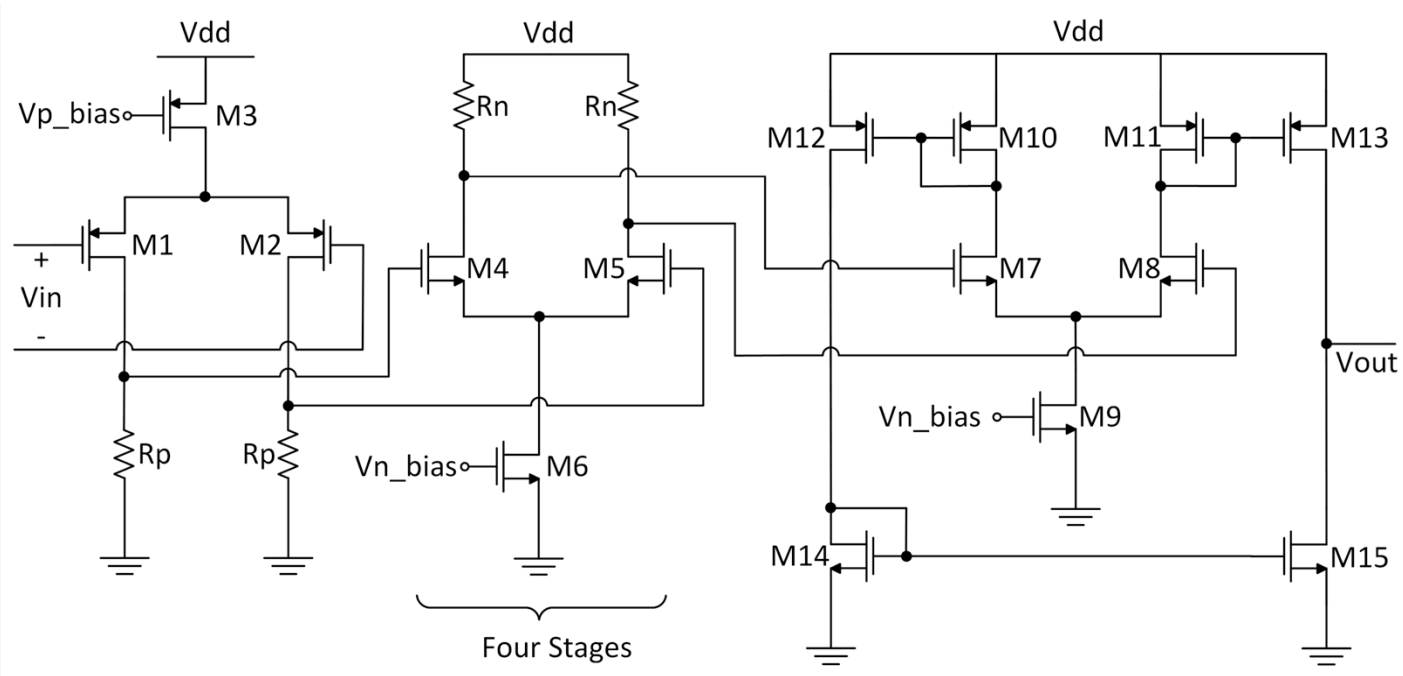
- High-speed LVDS clock input with on-chip 2x clock multiplication.
- Only 3 active controls for operation : Reset, Run/ Stop, Read CK.
- 2 comparators per channel plus flexible trigger coincidence logic.

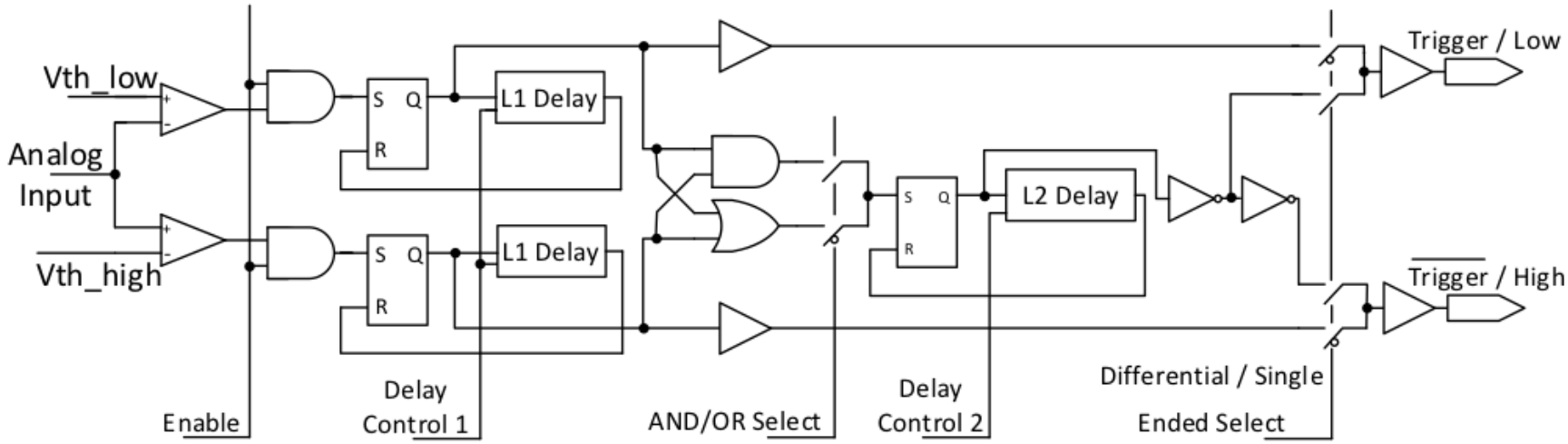
- 0.25 µm CMOS.
- Dynamic fast S.R.
- CMOS sample switches.
- M-I-M capacitors (80 fF).
- APS-style readout.
- Stop position readout.
- 6-stage comparators.
- Trigger pulse-stretching.
- Differential or single-ended trigger outputs with flexible output voltages.
- 1.9V input range.
- 12 bits dynamic range

SST Noise = 0.34 mV RMS (12 bits S/N)



SST Comparator and Trigger Circuitry



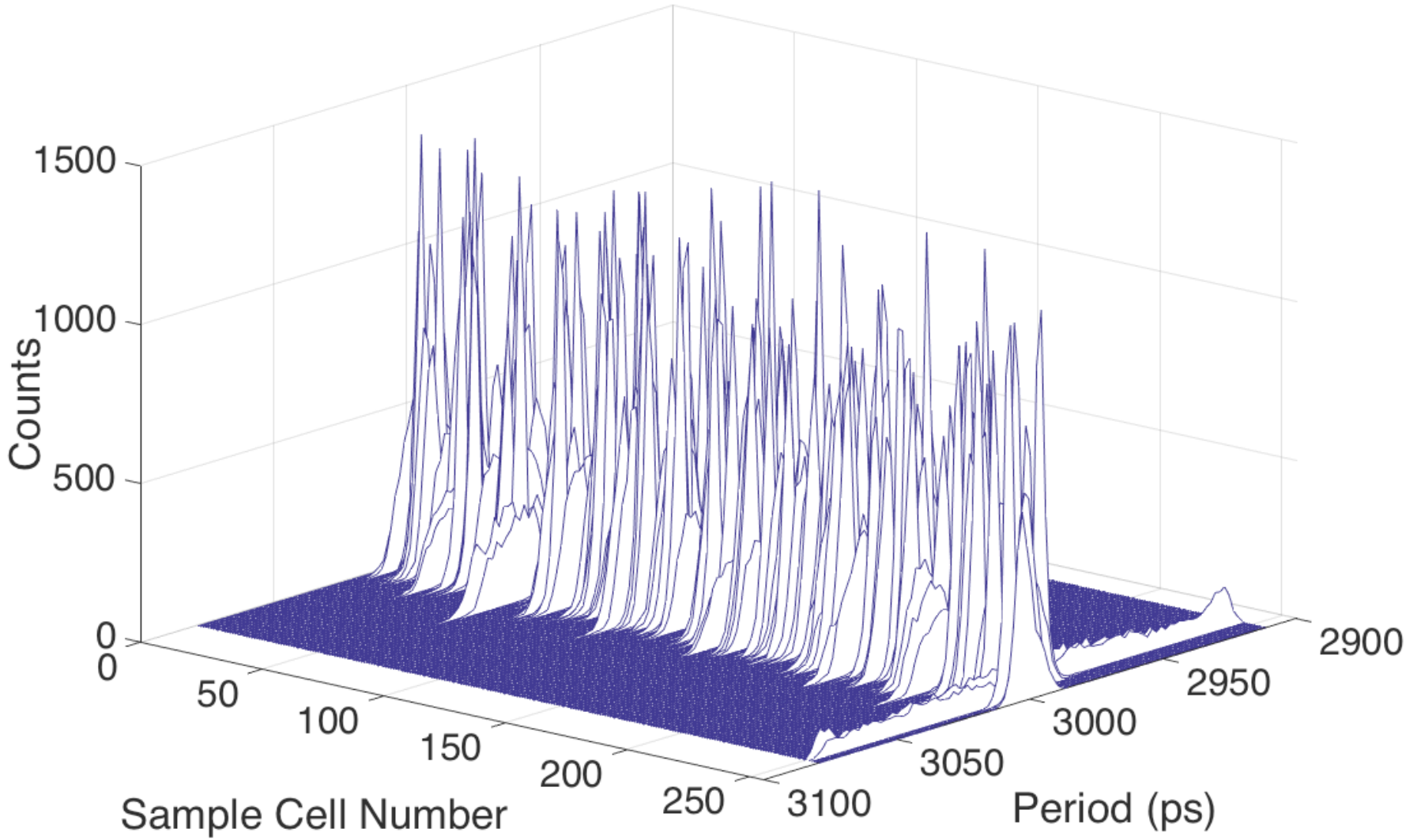


Example SST Trigger Performance

Calibration by Simulated Annealing

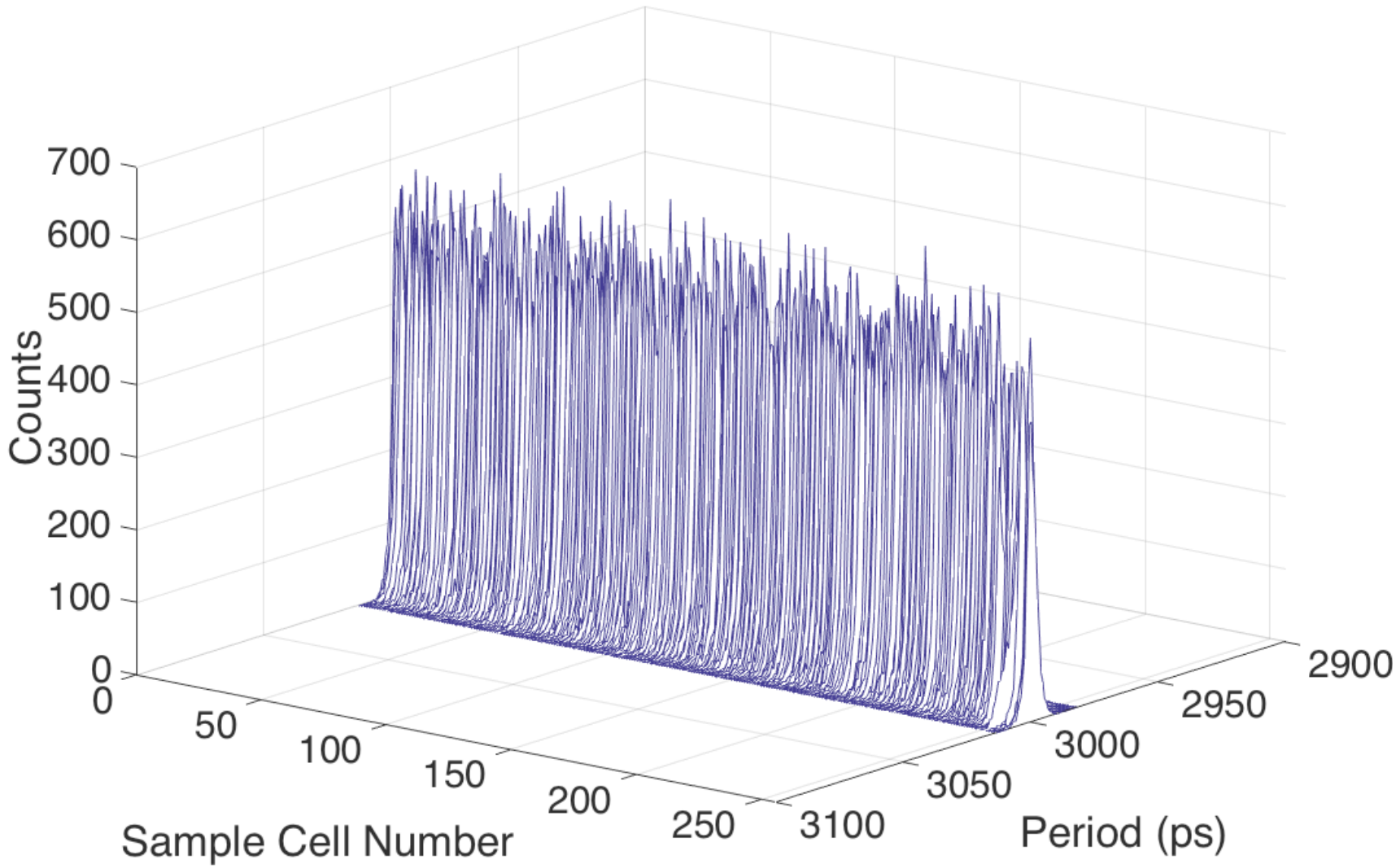
- Start with an assumption about the timing FPN, e.g. from simulation or by assuming that every sample is the same width (e.g. 500 ps at 2 GHz).
- Add Gaussian noise to each bin width − this is a tentative new calibration.
- Compute the net timing error using a set of calibration data, e.g. sine waves, neutrino templates, etc.
- If timing error is greater than the previous best calibration, discard it.
- If better than the last best calibration, the tentative calibration becomes the new one. This is the “greedy” option, in which *every* time a better calibration is obtained, that one is used. This does not work if the timing is not monotonic!
- Lower the temperature, here meaning how much noise is added. An adaptive temperature reduction lowers the temperature in an asymptotic fashion towards zero (smaller delta-t’s at every step).
- Stop when some arbitrarily-low temperature is reached.

Uncorrected Intra-Channel Timing



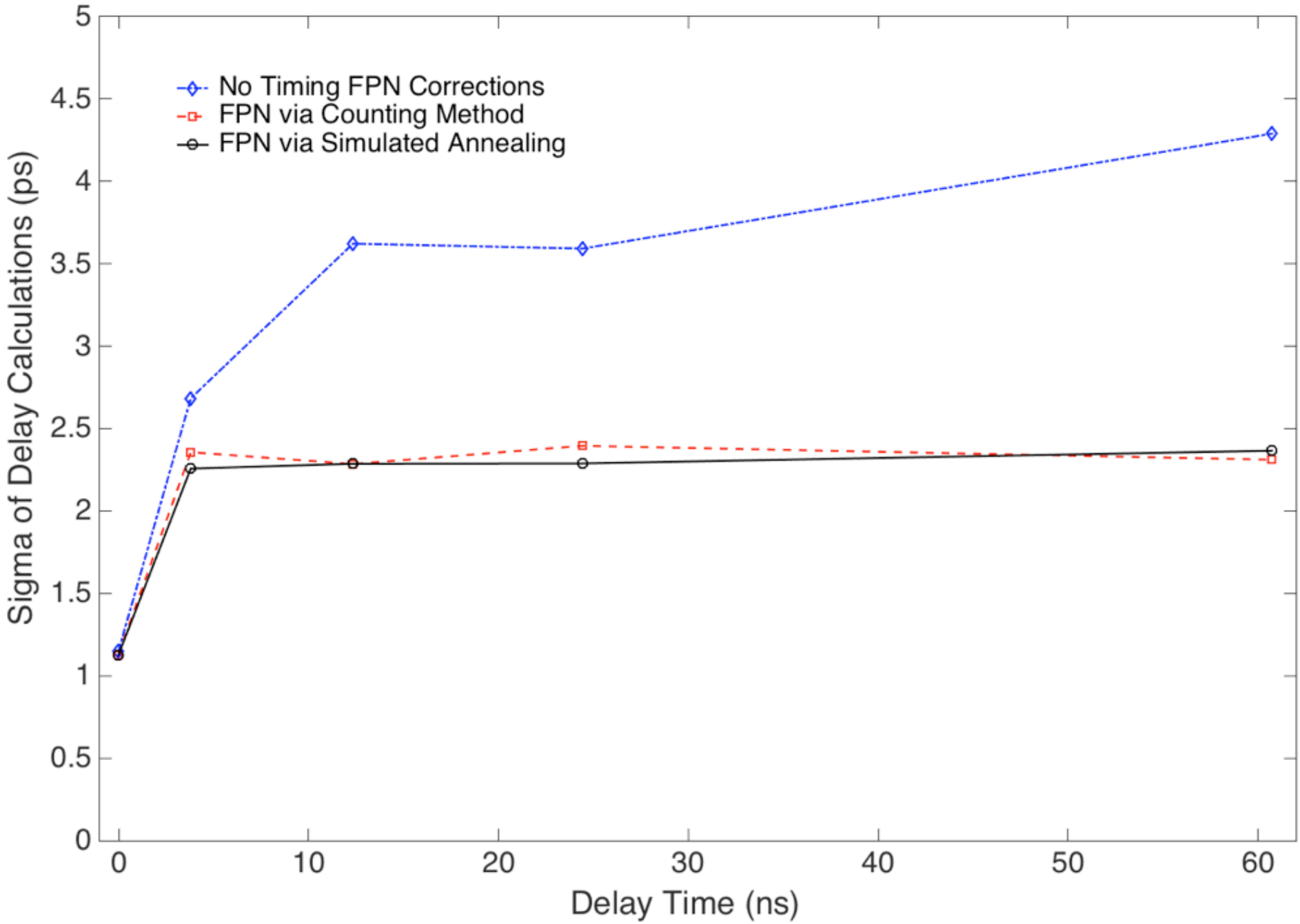
- Uncorrected timing FPN (every cell = 500 ps).
- Average sigma (errors in period measurements) = 8.4 ps.

Corrected via Simulated Annealing

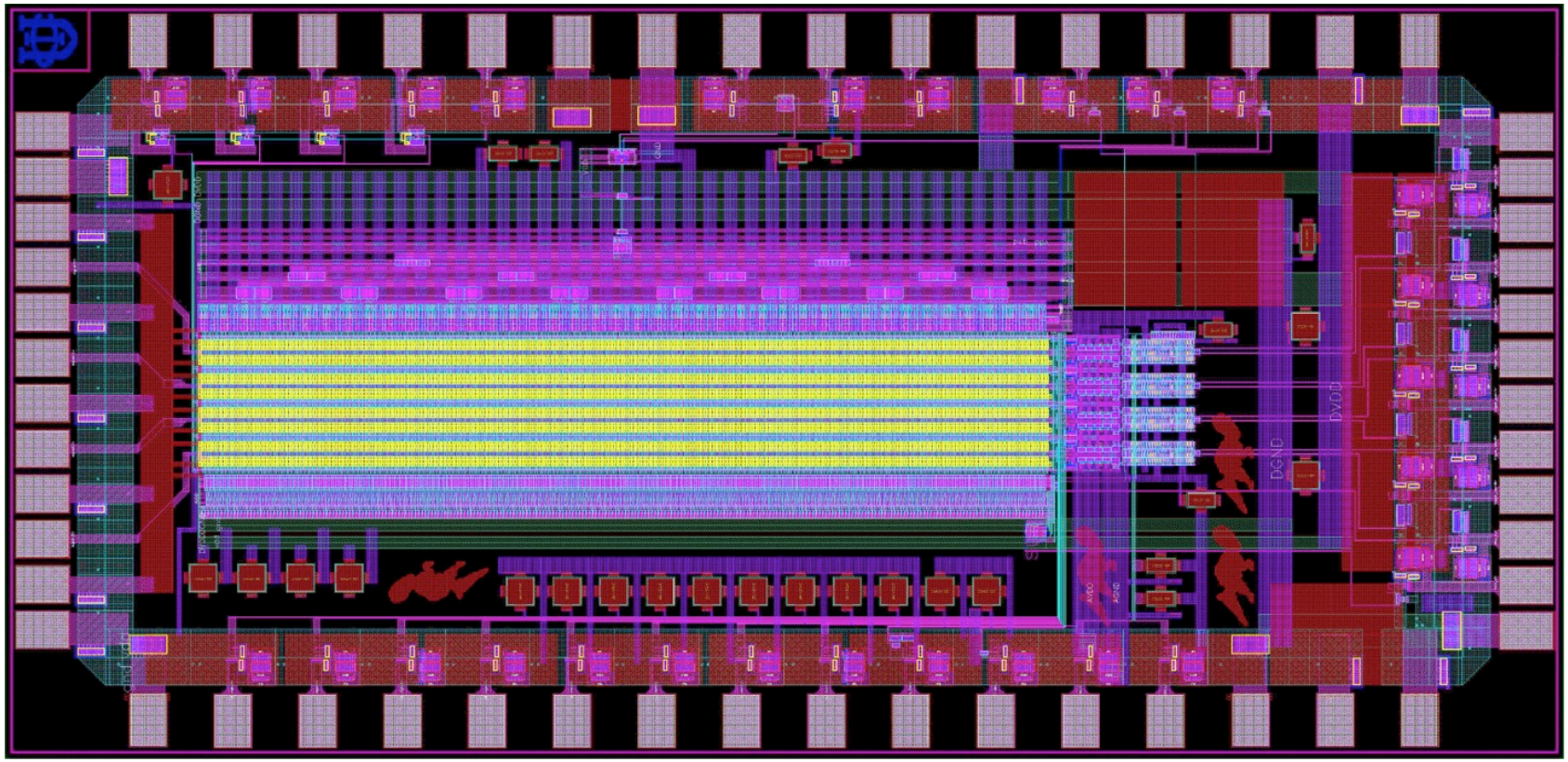


- Average sigma reduced from 8.41 ps to 2.16 ps.

Cross-Correlation Timing Imprecision



3 GHz SST Layout



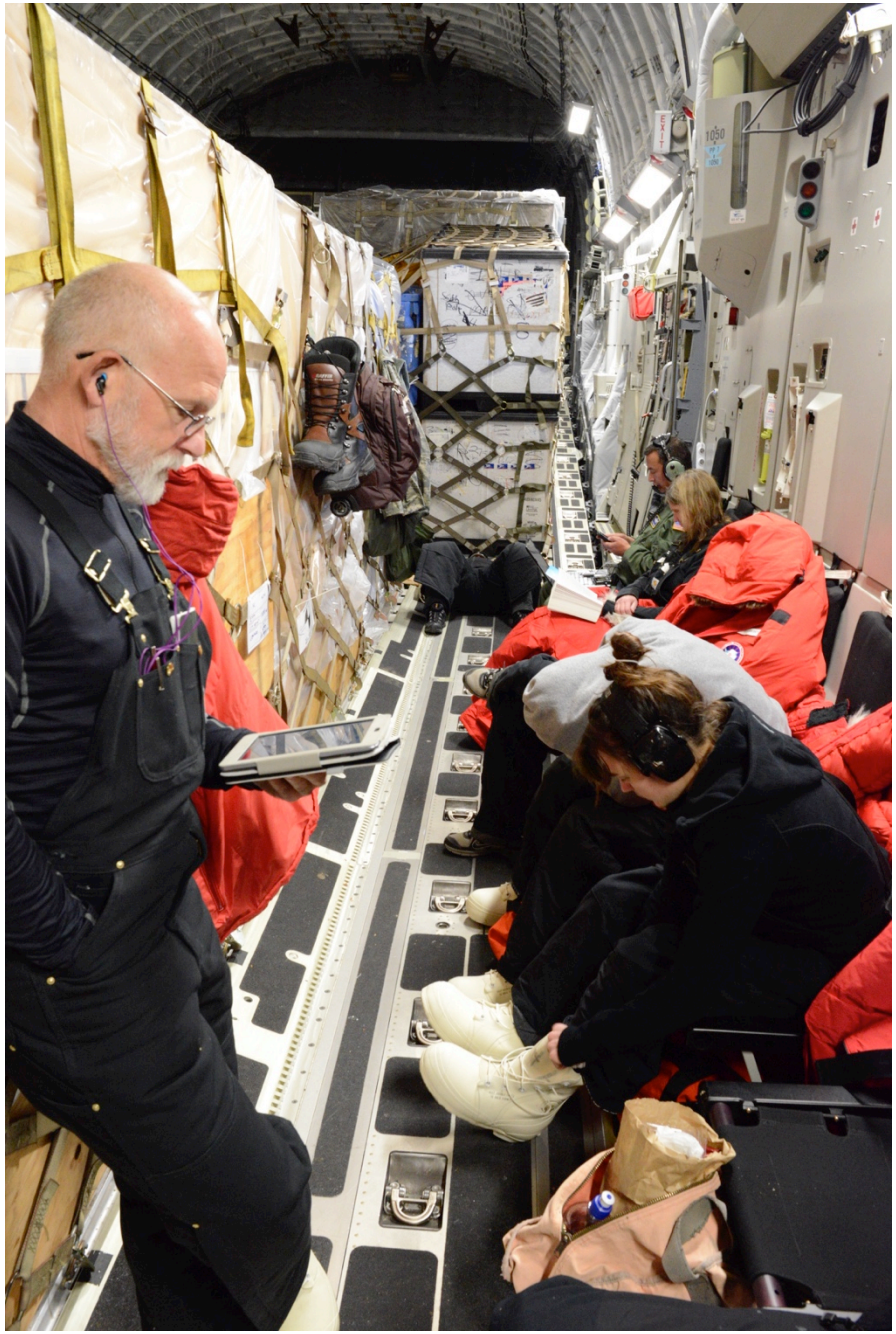
- 4 channels of 512 samples per channel in 0.18 μm CMOS.
- Synchronous 3 GHz sampling, common-start or common stop with 0.66 ps start/stop time. Fast (<500 ps) trigger + trigger logic.
- Research goal is to substantially reduce timing FPN errors and to reduce or eliminate the need for FPN corrections.

Travel to Antarctica from N.Z.

U.S. AIR FORCE
9212
62ND AW
446TH AW
AIR MOBILITY COMMAND
AIR FORCE RESERVE COMMAND

Securing Cargo

Flying – About 5 Hours



The Cockpit

Mts. Terror and Erebus.

Field Survival Training

Helo flight to the Ross Ice Shelf
EMERGENCY EXIT

Panoramas on the Ross Ice Shelf Camp

Cook Tent and Sleeping Tents

Life Inside the Cook Tent

In the Science Tent

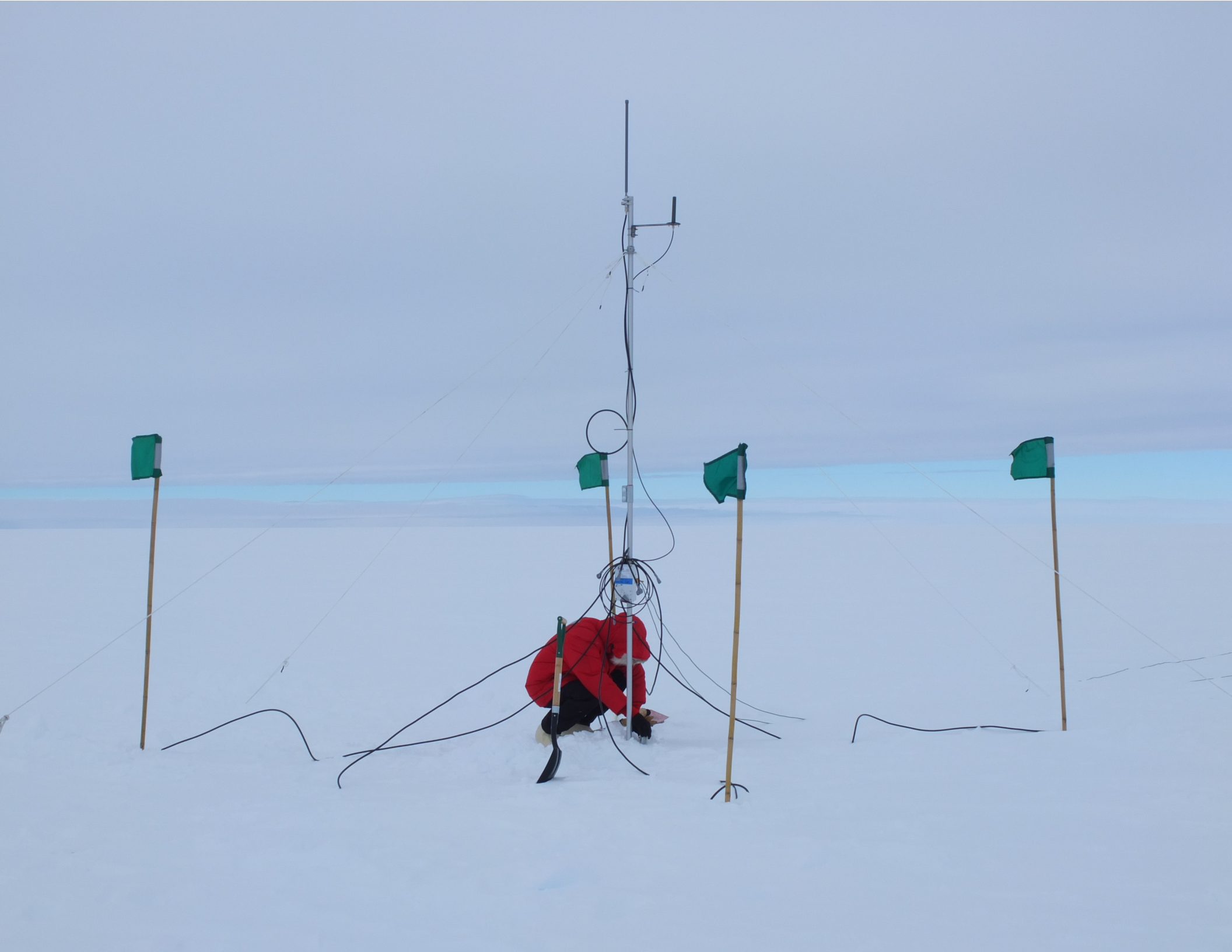
Comfort
BIG Buddy

Yes, it's Cold in Antarctica

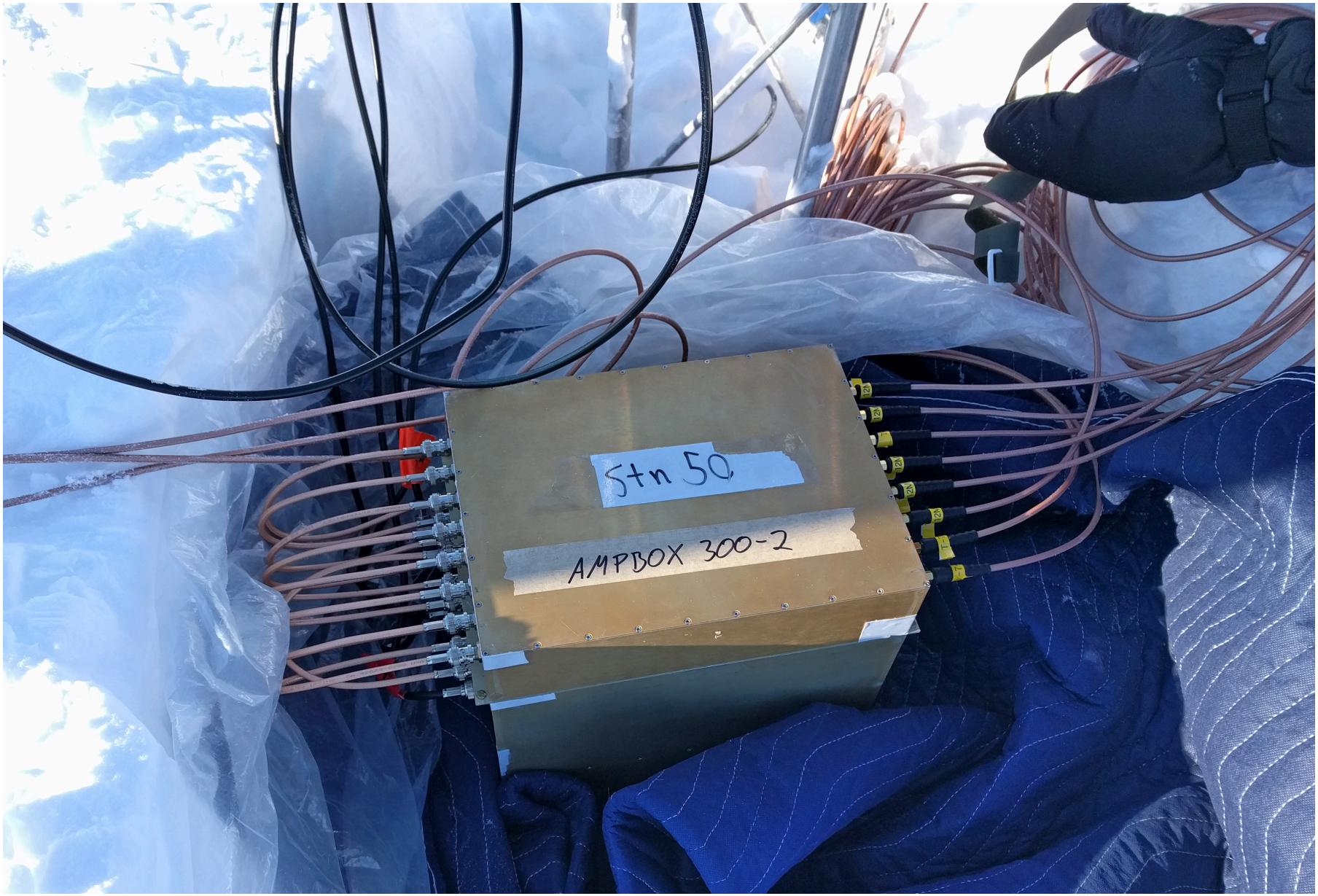
Photo Credit Chris Persichilli

Working on the Ice

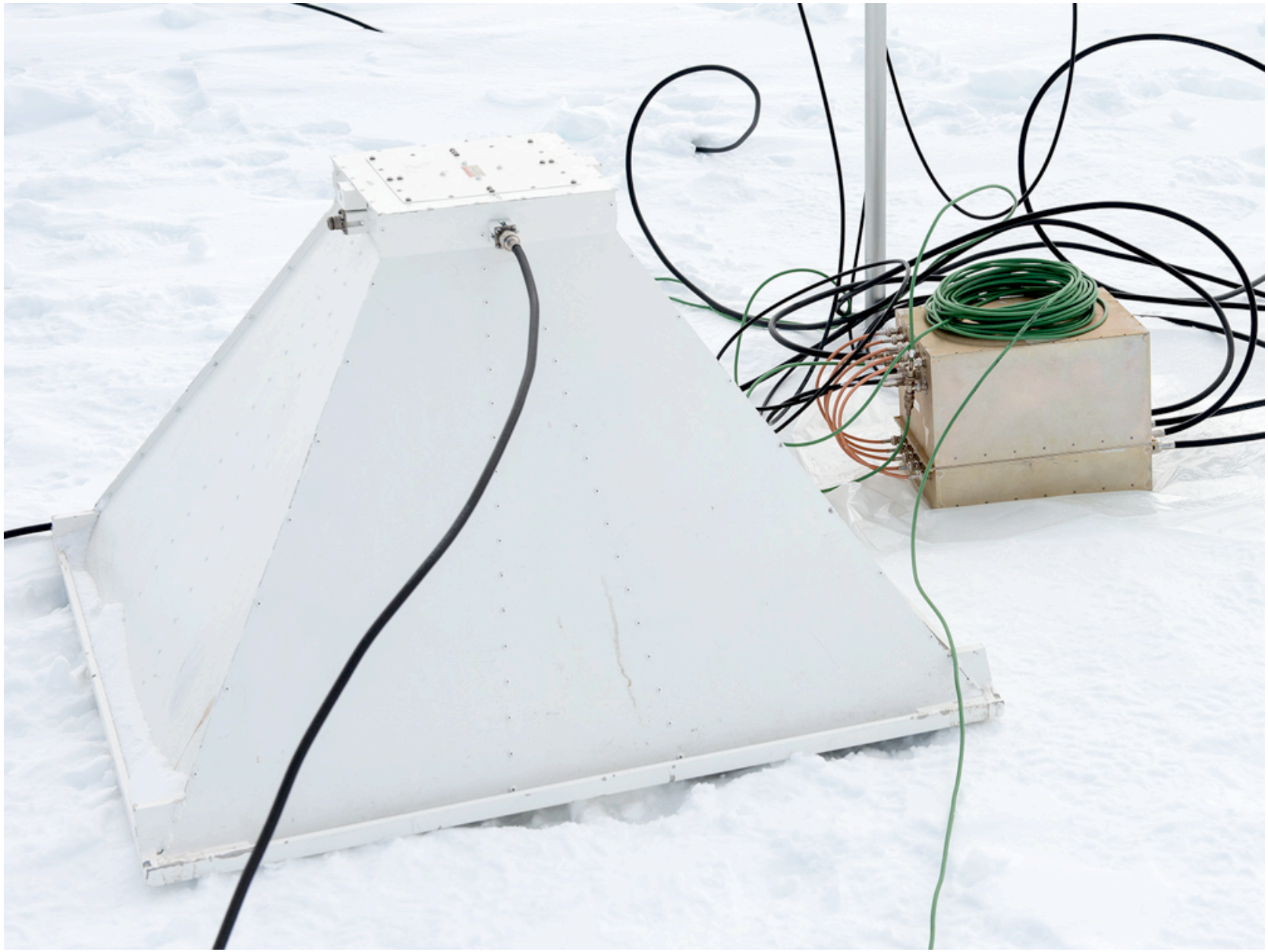
DR1
24737



“Station 50” Under Deployment

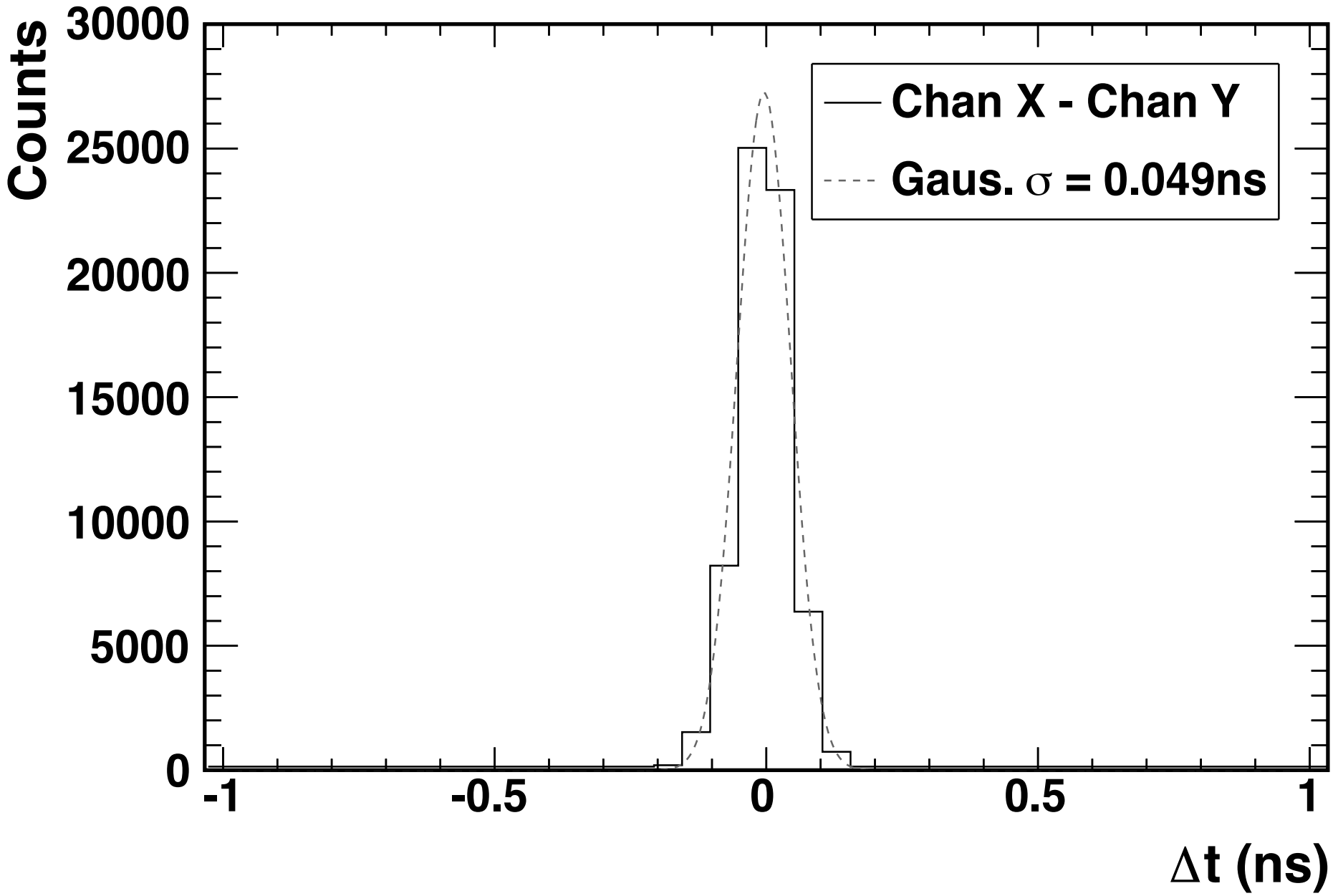


Reflection Studies Transmitter Horn

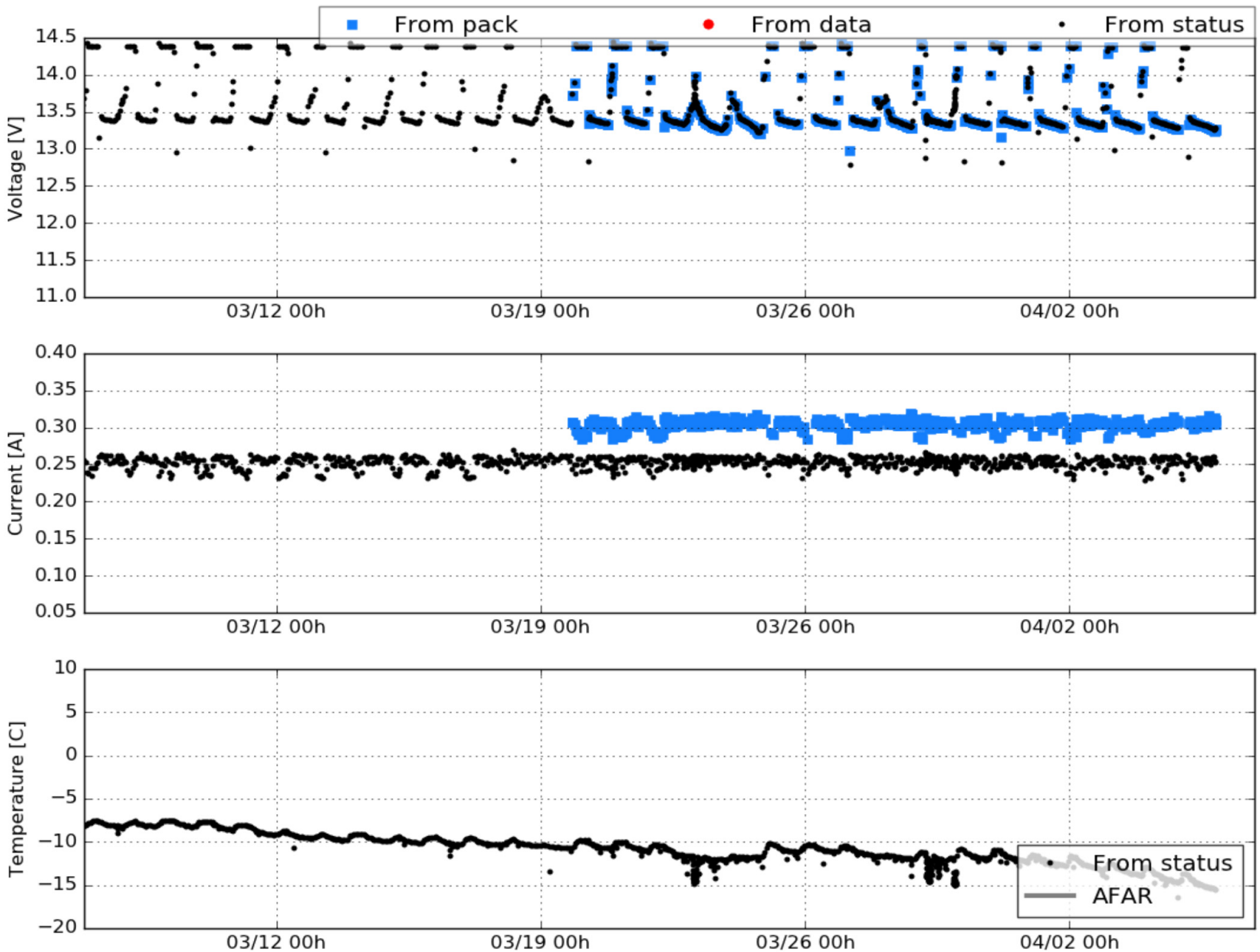


Prof. Stuart Kleinfelder, U.C. Irvine

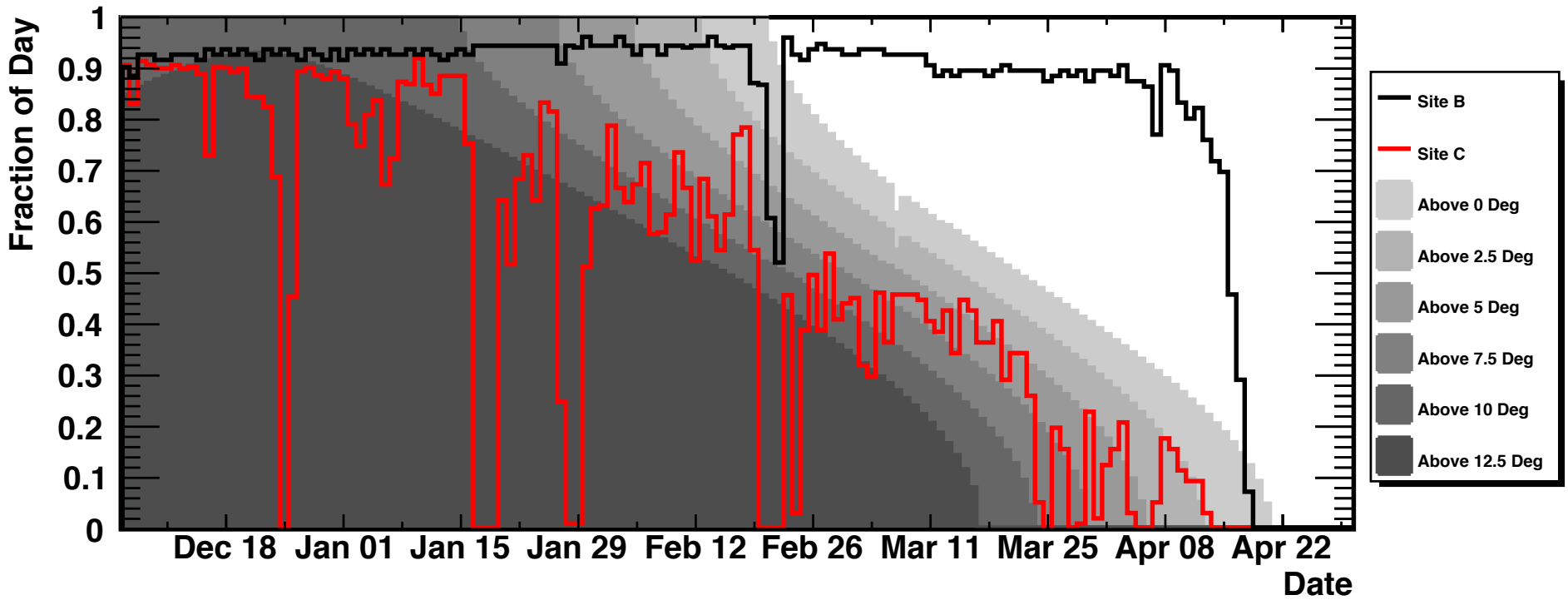
Bounce Study Precision



Example On-Line Status Charts

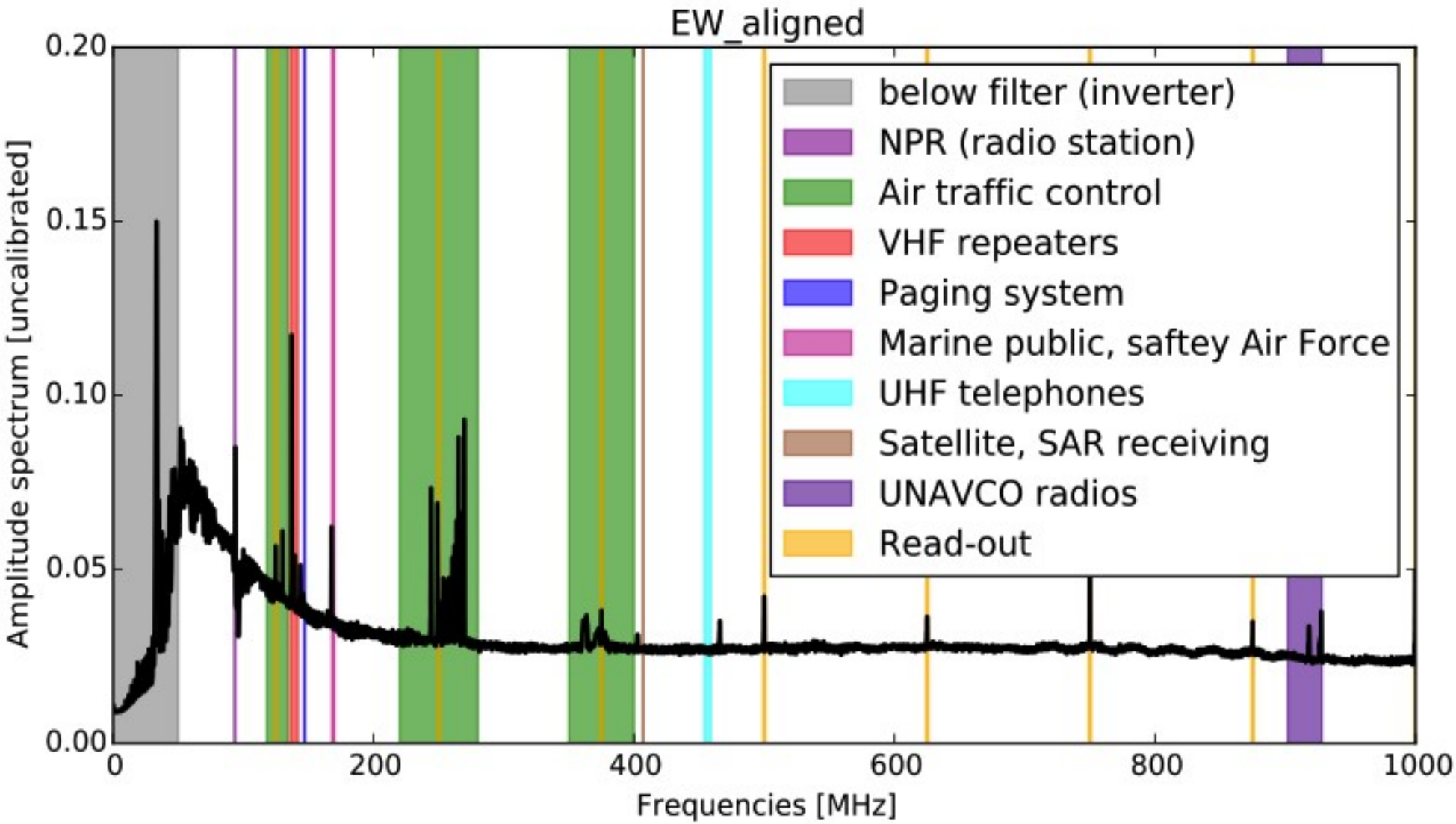


Live-time vs. Calendar Time

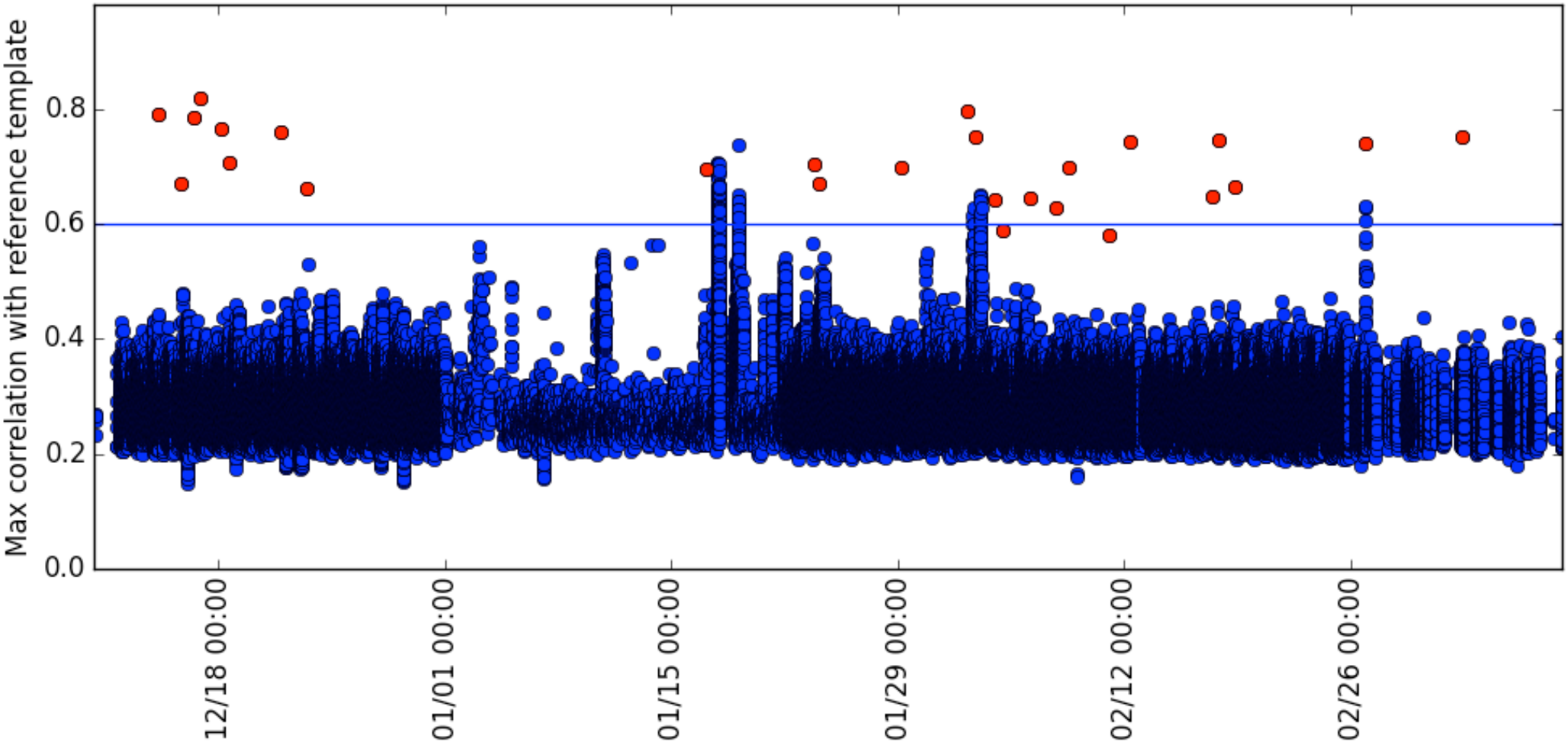


Red: A station without a battery, operating on solar power only.
Black: A station with a 20 Ah battery (nominal at room temperature).

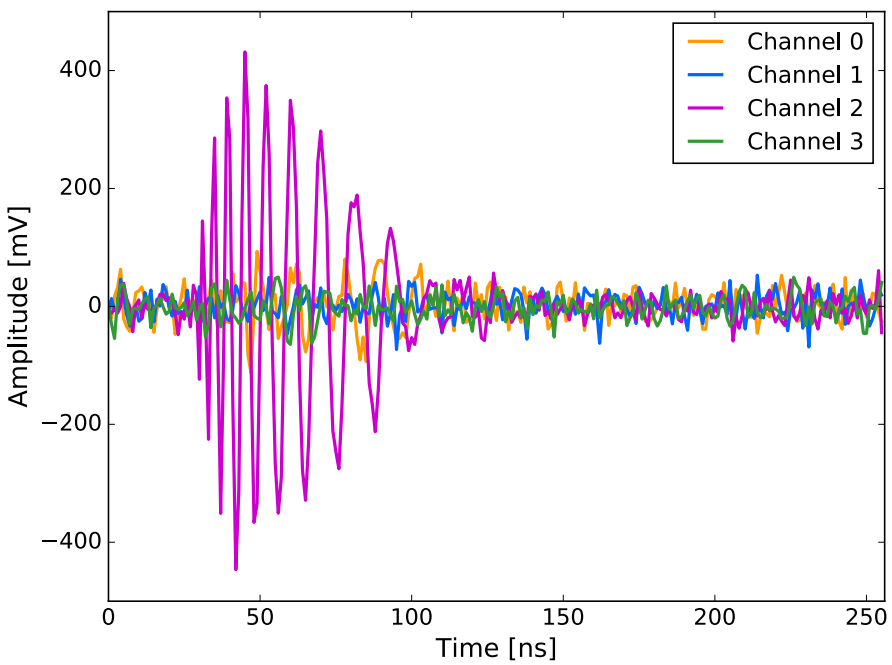
R.F. Environment on the Ross Ice Shelf

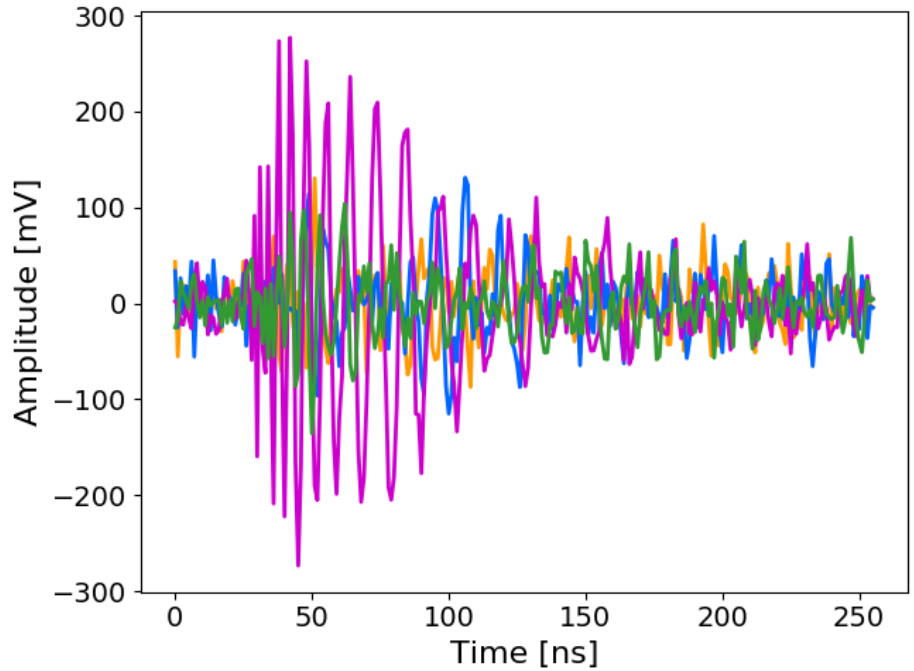


Cosmic Ray Search

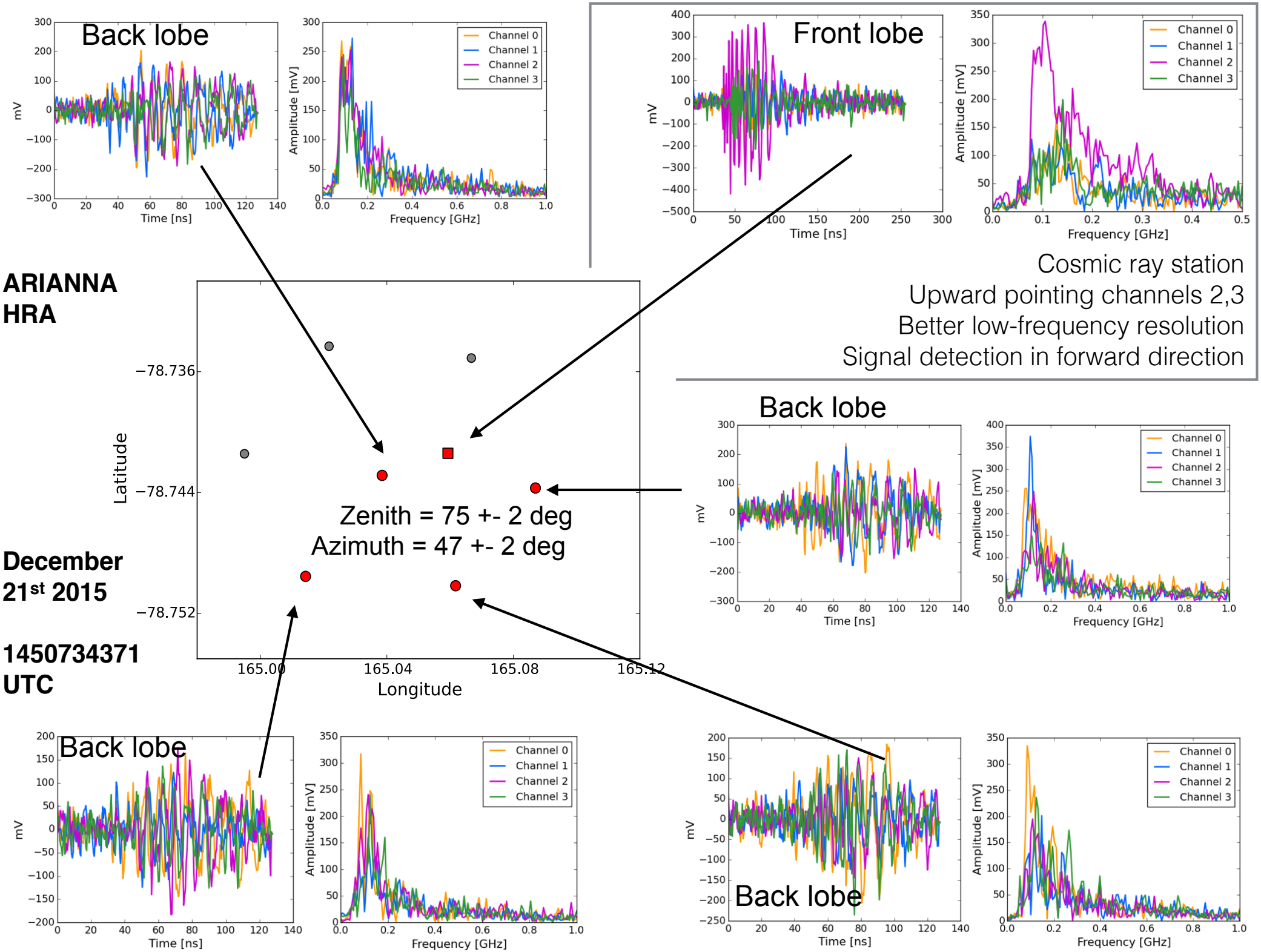


Simulated vs. Real Air Shower Event

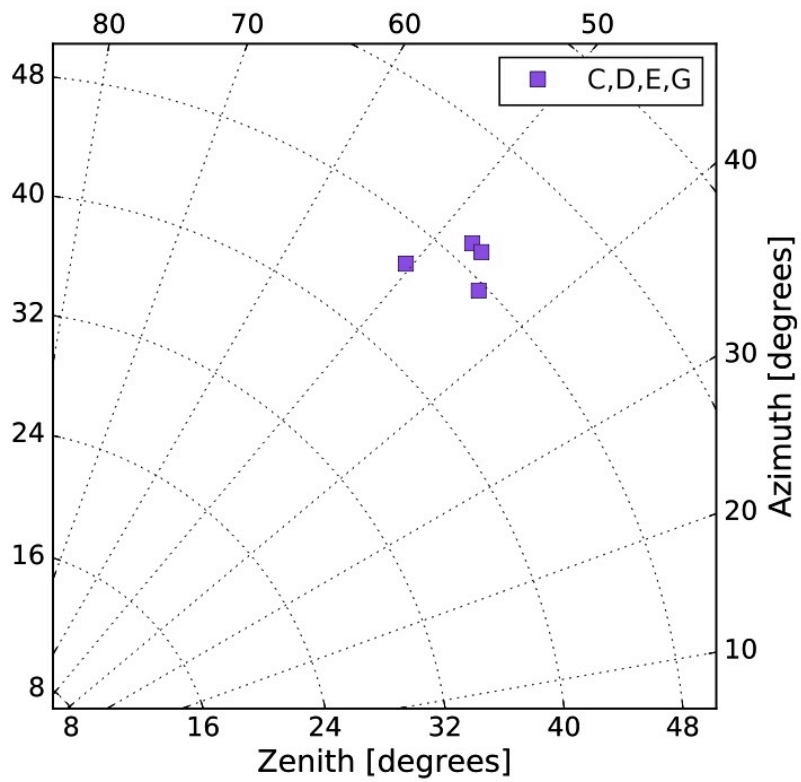


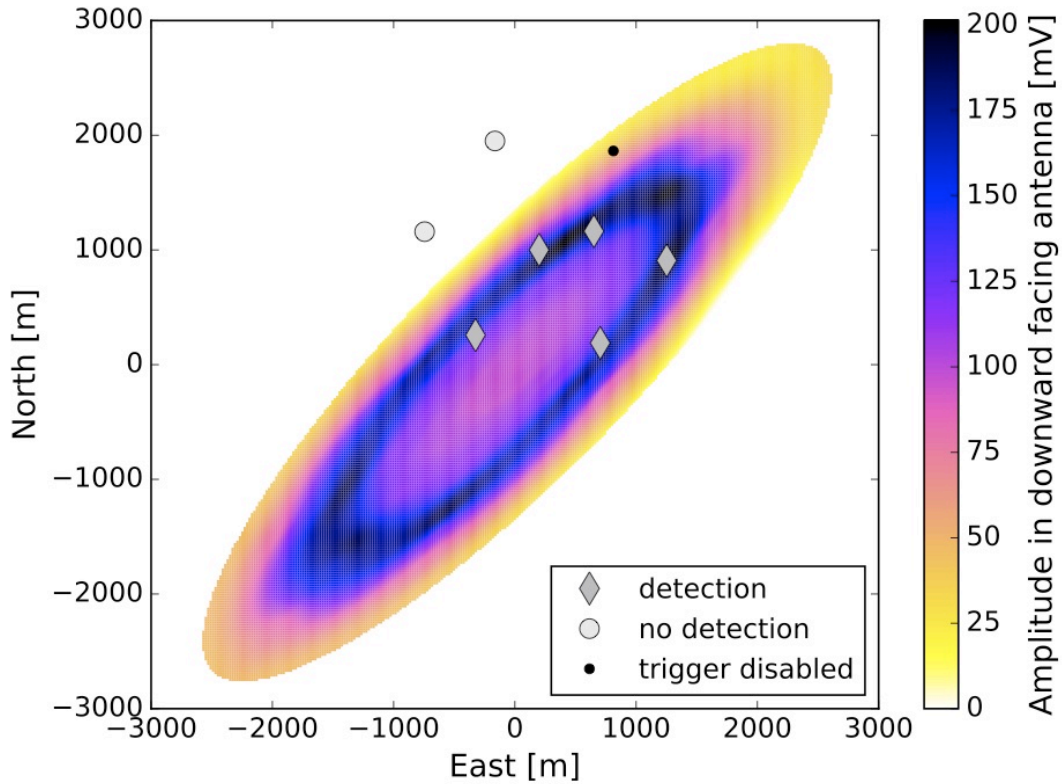


Left: A typical simulated cosmic ray template.
Right: A typical acquired cosmic ray candidate event.


Back lobe
Front lobe
Back lobe
Back lobe
Back lobe
Channel 0
Channel 1
Channel 2
Channel 3
mV
Time [ns]
Amplitude [mV]
Frequency [GHz]
Cosmic ray station
Upward pointing channels 2,3
Better low-frequency resolution
Signal detection in forward direction
ARIANNA
HRA
Latitude
Longitude
Zenith = 75 +- 2 deg
Azimuth = 47 +- 2 deg
December
21st 2015
1450734371
UTC

Multi-Station Reconstruction

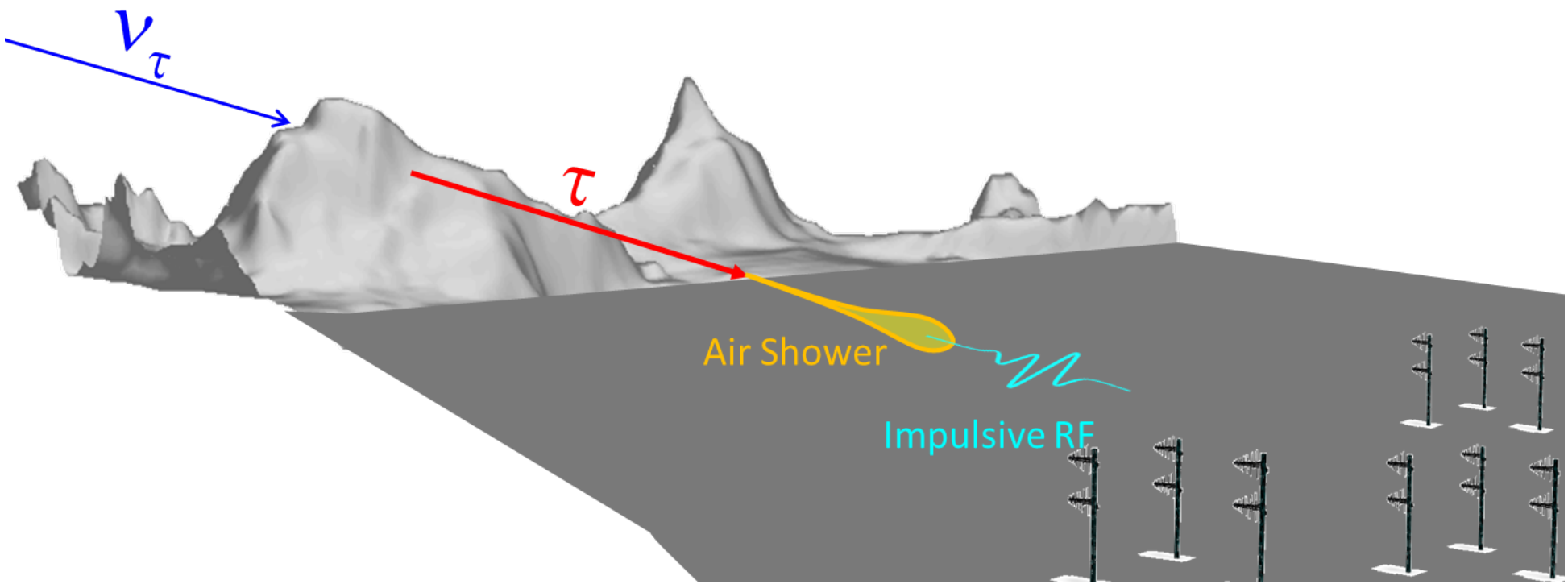




Left: reconstructed signal source from stations C,D,E and G in zenith and azimuth, showing all independently-recorded events clustered in the same direction in the sky.

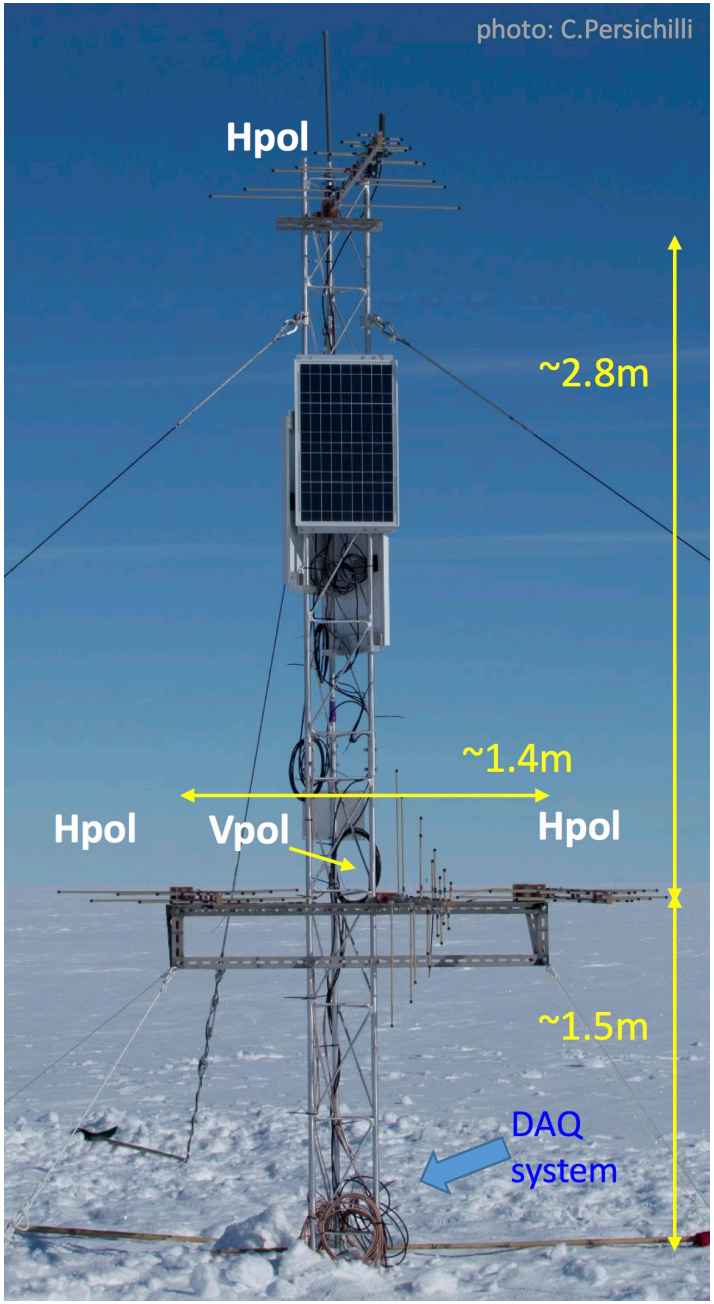
Right: best fit of a simulated event leading to such a cluster.

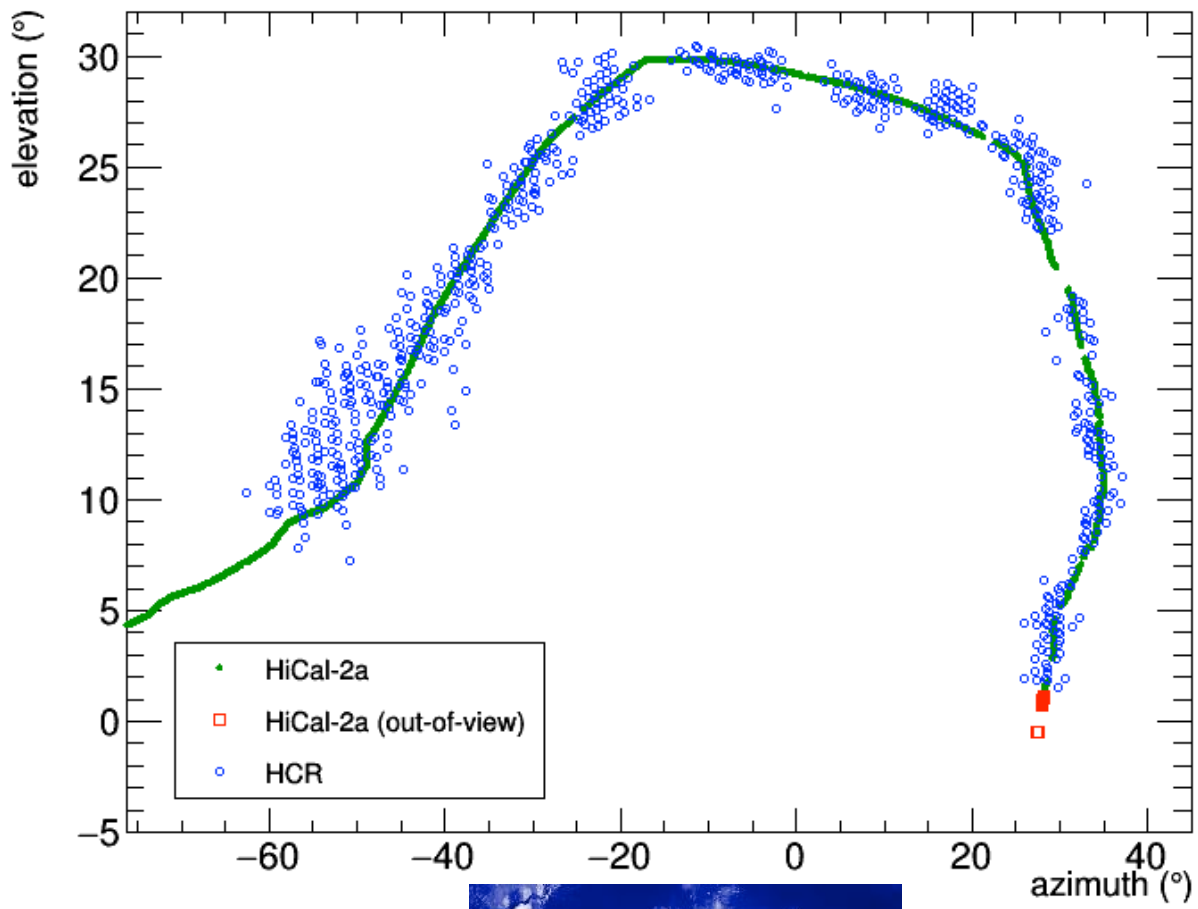
Horizontal Tau Neutrino Detector

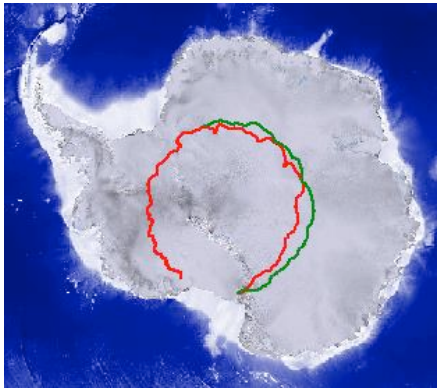


"Earth skimming" array concept using nearby Minna Bluff Mountain range.
Strongly benefits from low background RF noise conditions found on the Ross Ice Shelf.

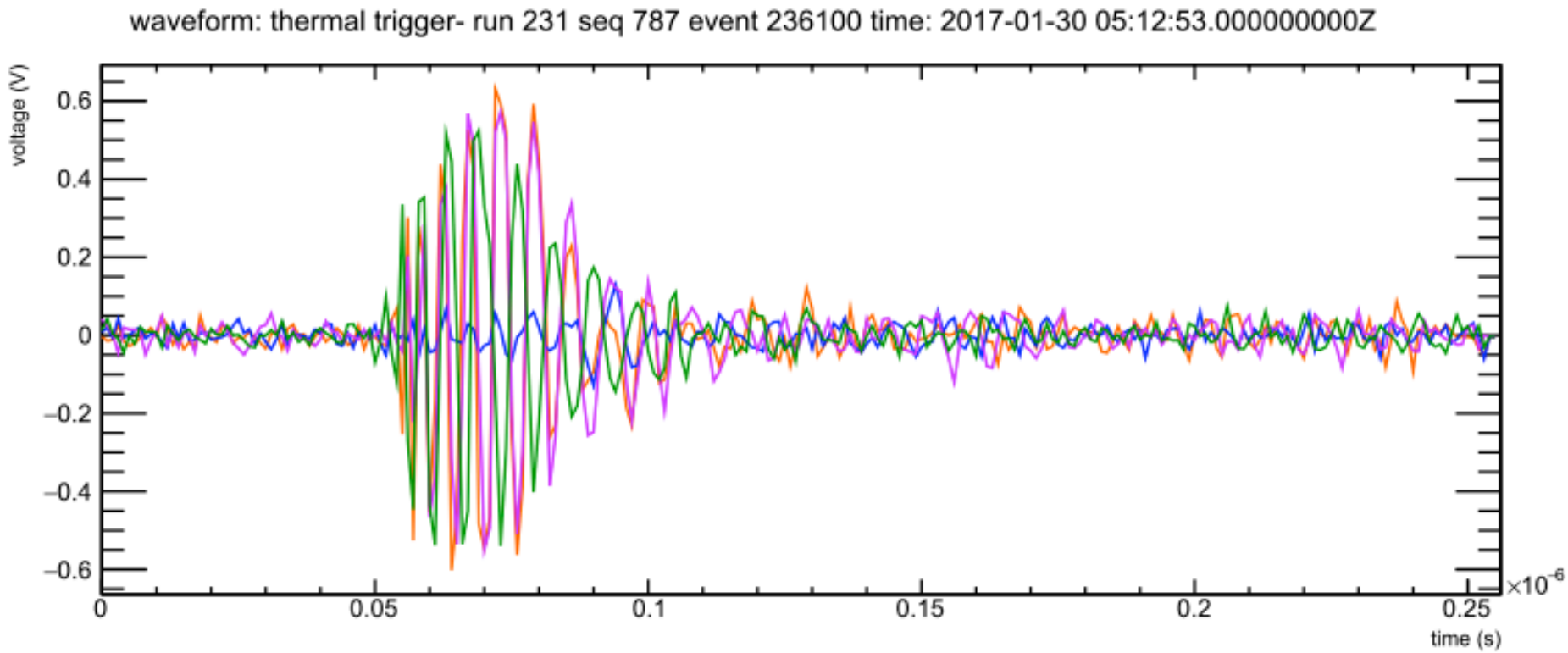
4-Channel Horizontal Cosmic Ray Array







4-Channel Horizontal Cosmic Ray Array



Example candidate cosmic ray event picked up by the 4-channel Horizontal Cosmic Ray instrument.

8-Channel Horizontal Cosmic Ray Array

Photo Credit Chris Persichilli

8-Channel Horizontal Cosmic Ray Array

Photo Credit Chris Persichilli

Cold Temperature Precautions

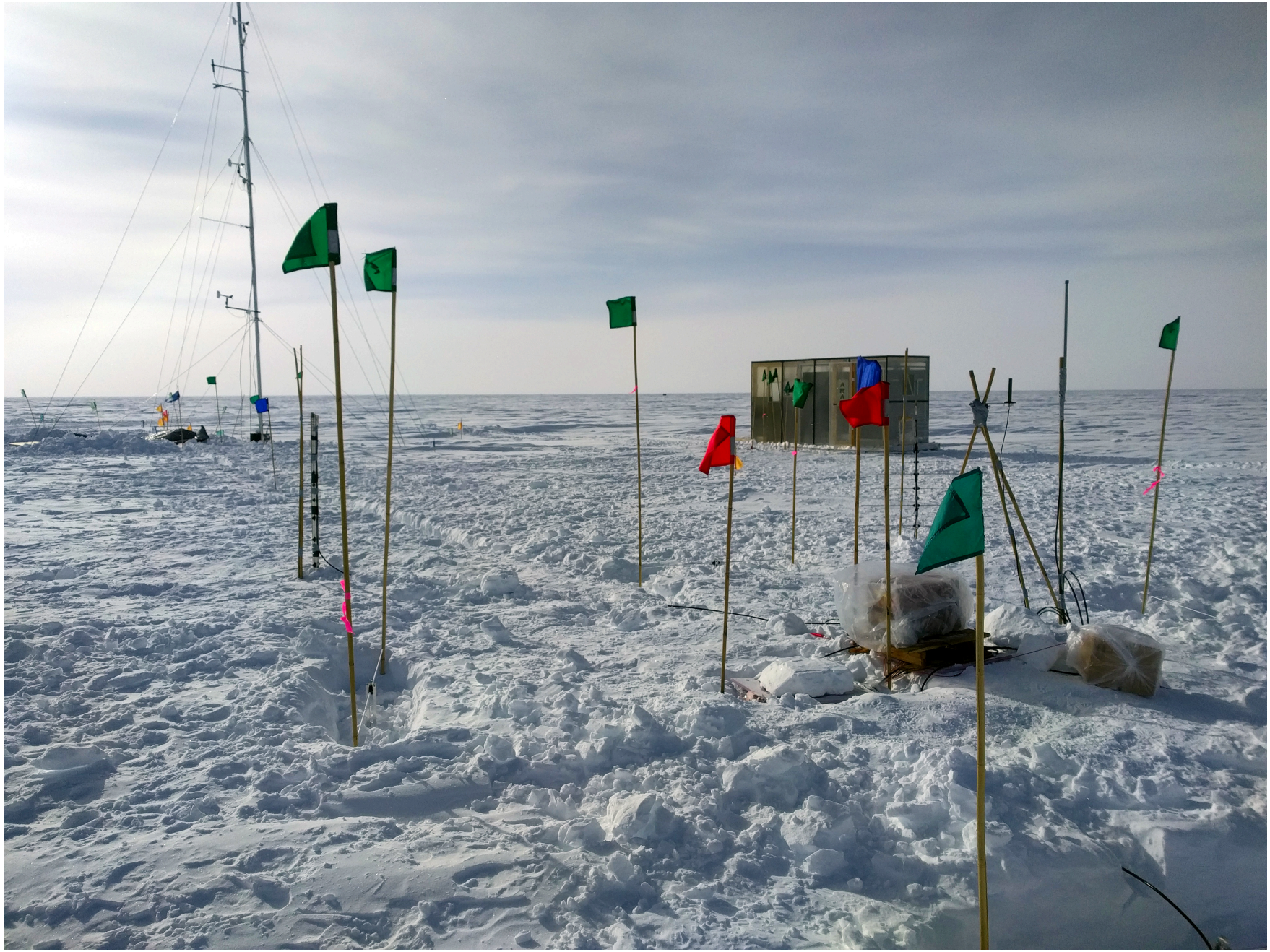
- Few circuit components are rated to below -40C; we must accept this. Lots of testing at temperatures as low as -60C!
- Integrated circuits rated to -40C have performed well down to -60C, including so far at the pole.
- So far there have been no problems with PCBs and soldering (we do use lead-based solder rather than tin-based), including during torture-tests at -60C.
- Avoid electrolytic capacitors, and use tantalum, ceramic or film capacitors, etc.
- Be careful about what sort of plastics are used, e.g. in cheaper connectors and cables − we have had connector insulation components fall apart. Teflon works very well.
- Cabling must also use insulation and jacket materials suitable for cold temperatures. We used Teflon insulated and jacketed cabling for our long-distance power distribution at the pole, as this is rated to -70 and remains flexible in the cold (but it's expensive!).

Cold Temperature Precautions

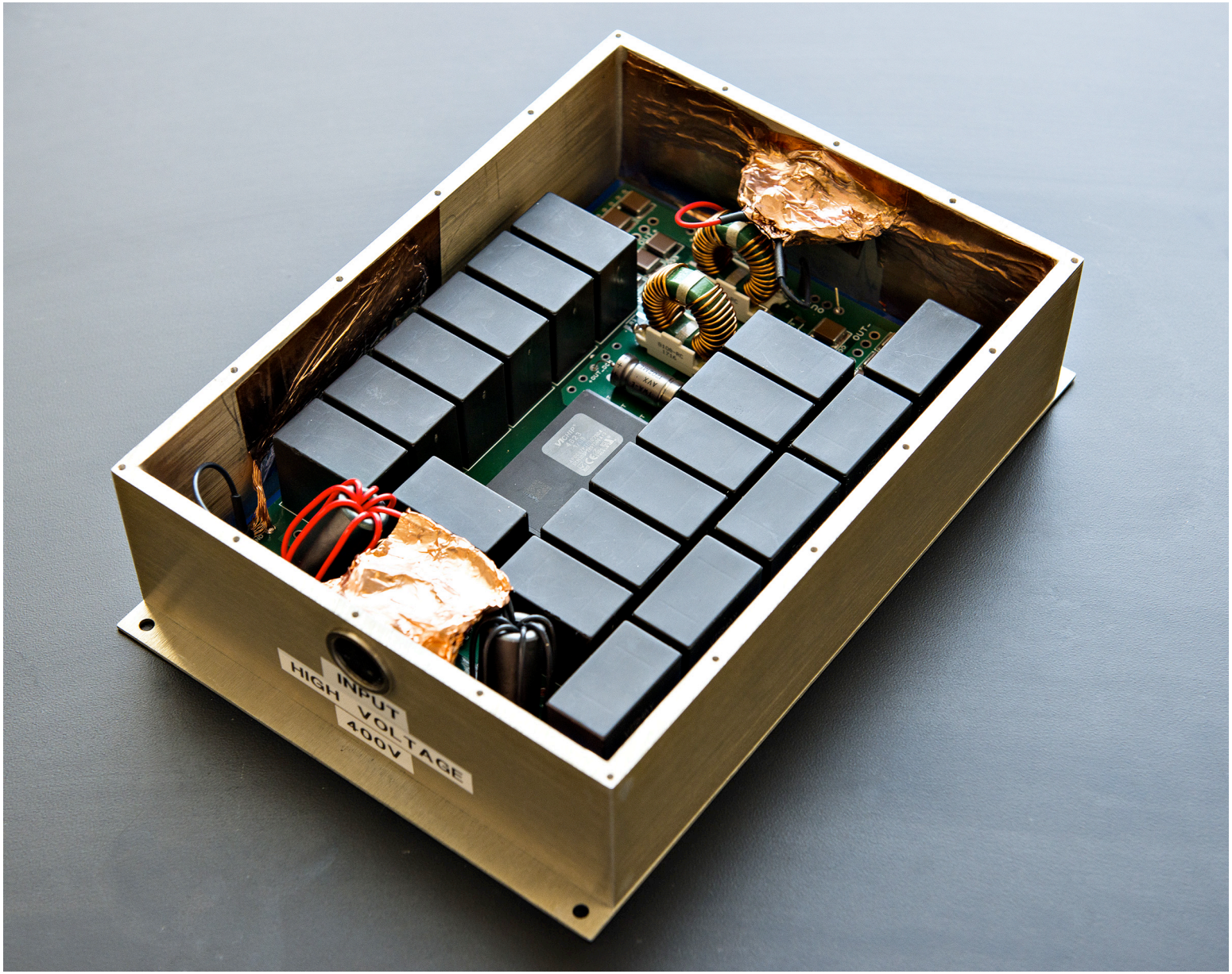
- Solar power works very well (better!) in the cold, e.g. due to lower recombination and leakage.
- Thus far wind power has remained consistently problematic. We've had multiple mechanical failures and excess R.F. noise picked up by stations, even from turbines that were found to be R.F. quiet during lab tests.
- Batteries have been a significant problem at -30C:
  - Lead-acid batteries cannot be charged once drained.
  - LiPo batteries have poor performance.
  - Low-quality LiFePO4 batteries have had catastrophic (complete!) failures, e.g. inert or open-circuited packs.
  - High-quality LiFePO4 batteries have proven to be reliable, though their capacity drops to under 50% and one must be careful not to charge or discharge them too fast: About 0.1C charge/discharge rates are OK.

ARIANNA at the South Pole

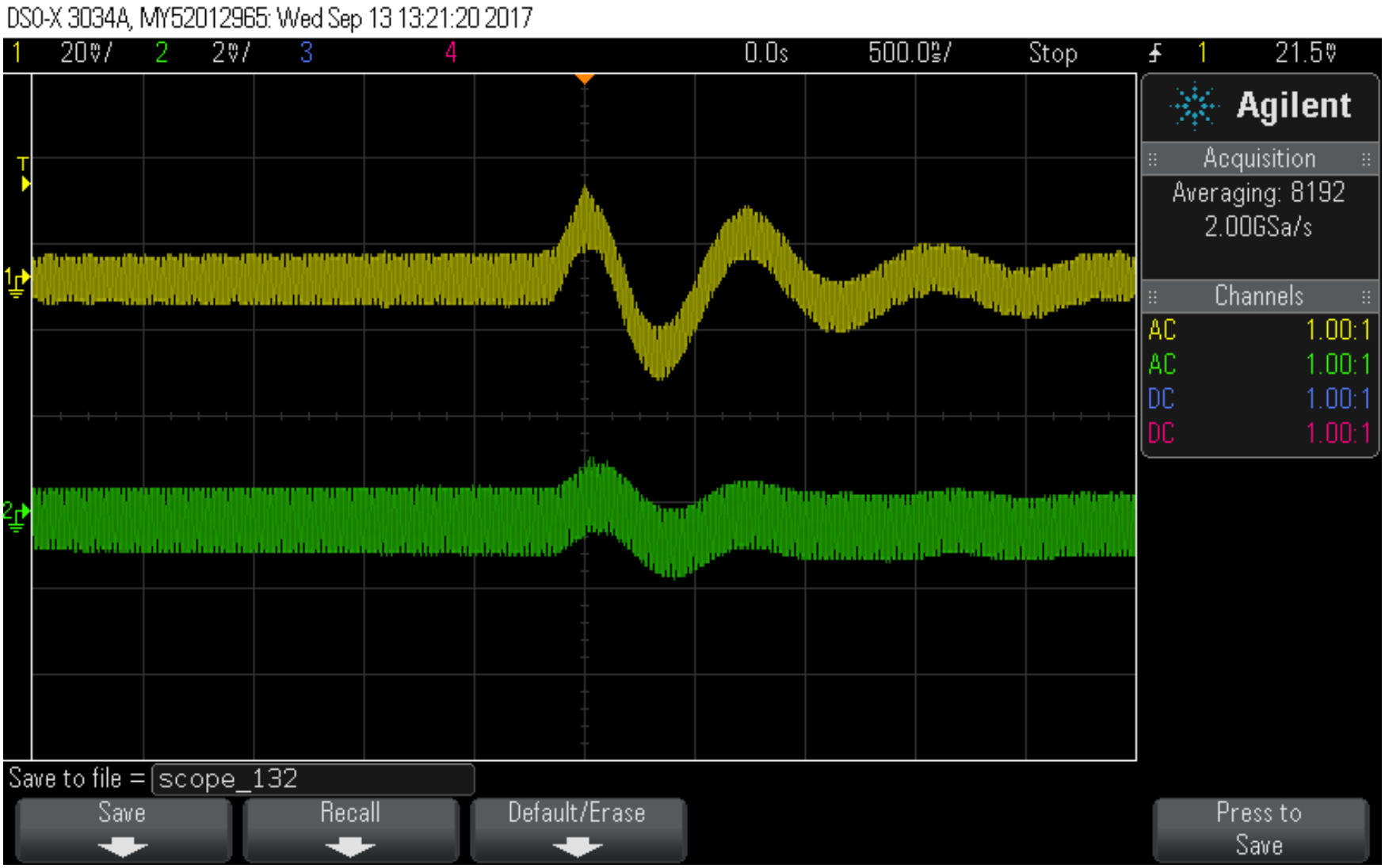
ARIANNA at the South Pole



400V to 28V at Polar Temperatures



DC-DC Output and Input Noise



Input-side noise = ~2mV, output-side noise = ~40mV, both at ~1.3 MHz (~89 MHz noise is from the local KUCI radio station).

Under Deployment at the South Pole

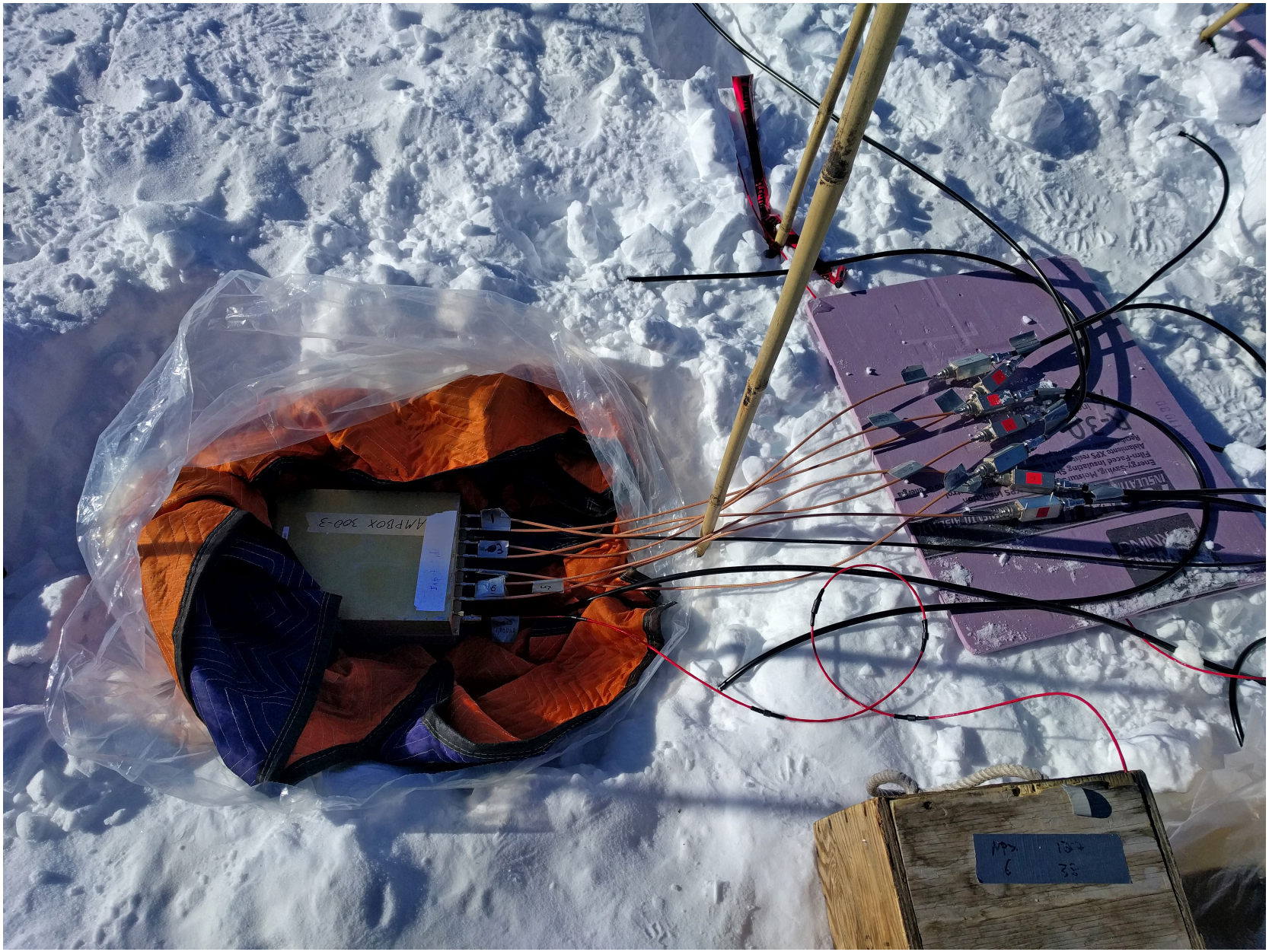


Photo Credit Chris Persichilli

Testing the South Pole Instrument

Photo Credit Chris Persichilli

Next Generation Systems

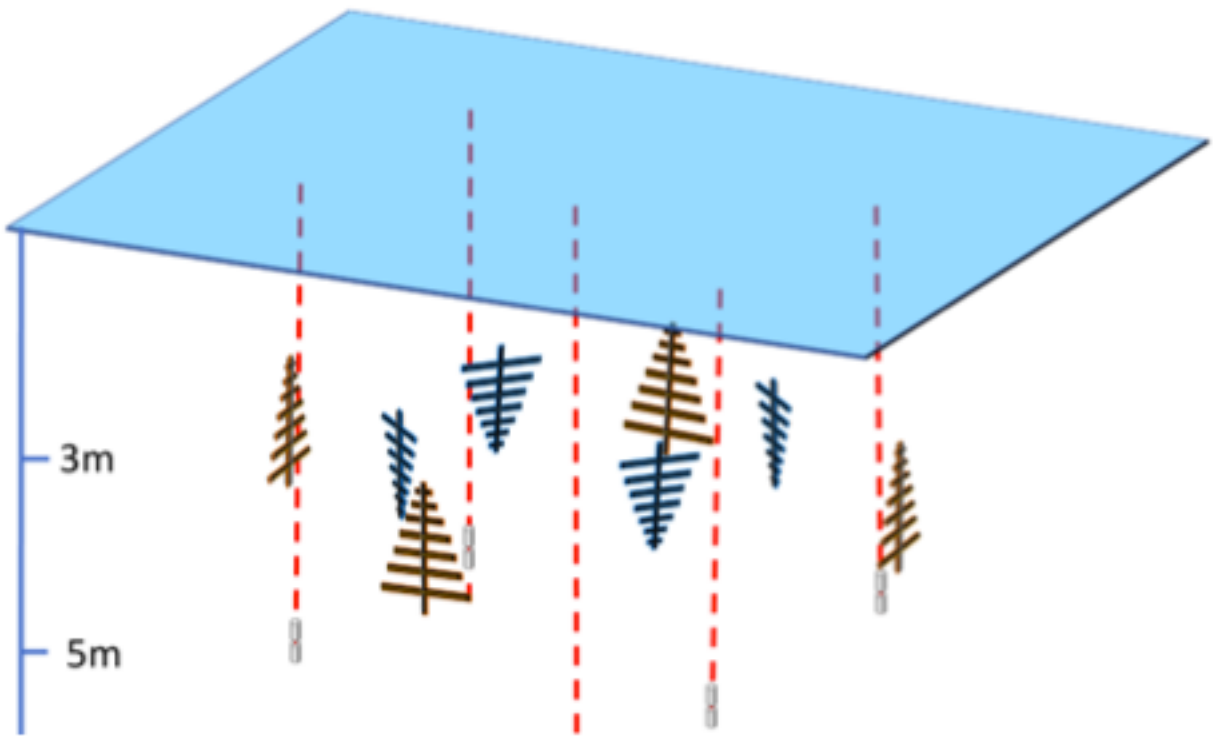
- New SST chip with 1024 samples per channel, etc.
- 16 channels per station, e.g. 8 down, 4 up, 4 dipoles.
- Upgraded FPGA for fast multiple event buffering, etc.
- Upgraded microcontroller − faster, more memory...
- Automated in-situ fast self-calibration of thresholds (now automated but performed via remote control).
- Read out which channels fired their comparators.
- Improved dynamic range.
- Single-board multiple-channel amplification system.
- Replace WiFi with low-power mesh connectivity.
- Can we filter WiFi antenna to allow simultaneous data acquisition and full-time communications?
- Keep working on wind power...

Polar Neutrino Experiment Tea Leaves

- Distributing power at the pole is turning out to be very expensive: $40k per station, about 4x the cost per autonomous ARIANNA station!
- Latest “tea leaves” point to large new polar power distribution grids being unacceptable, and current thought is to continue autonomous (e.g. solar) power.
- Autonomy allows a free choice of polar site (better ice) or Moore’s Bay (quieter RF environment).
- Current plan is to deploy an 8-channel autonomous ARIANNA station at a more remote polar site to compare against current powered station and against Moore’s Bay site.
- The big question: Can ARIANNA and ARA finally team up on a compromise experiment?

ARIANNA + ARA = ARIA

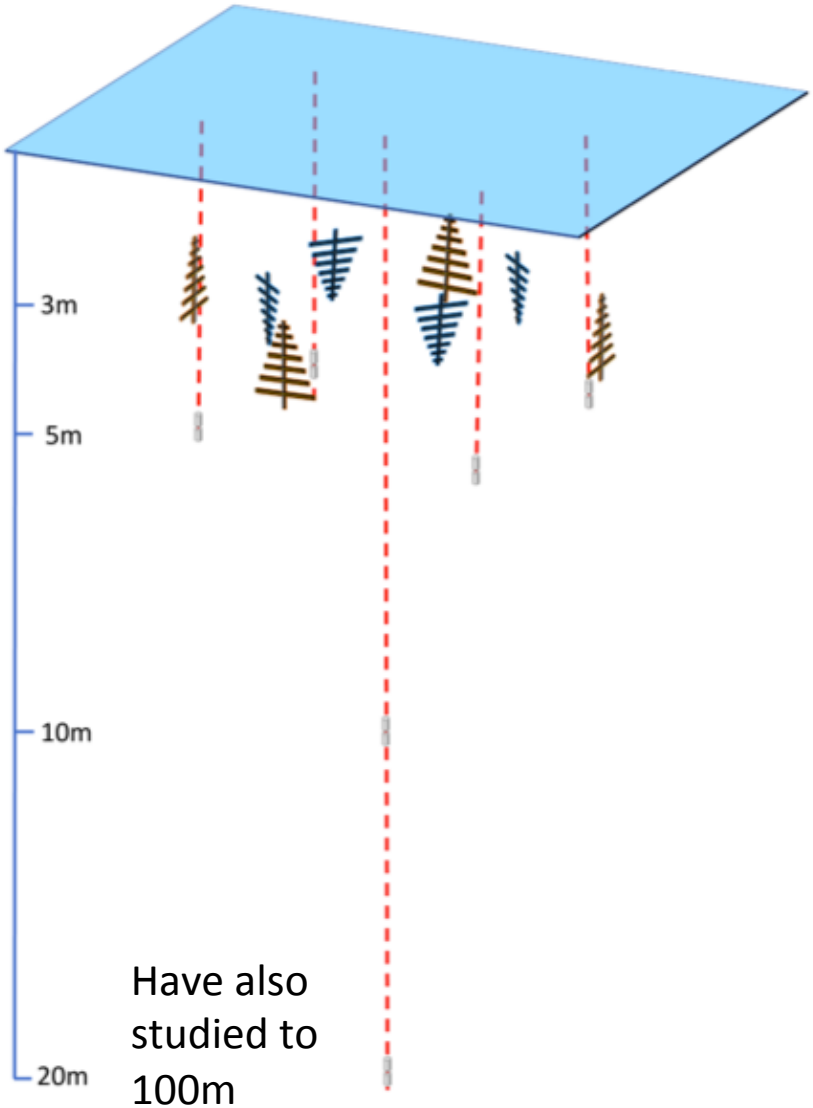
Strawman for ARIA -1st iteration



Combines elements of ARIANNA and ARA:
-South Pole
-dipoles
-subsurface elements
-LPDA
-ARIANNA DAQ
-Cosmic Ray observation
-polarization, nu-direction
-nearby vertex

ARIA with Deeper Dipoles

Strawman – 2nd Iteration



Have also studied to 100m

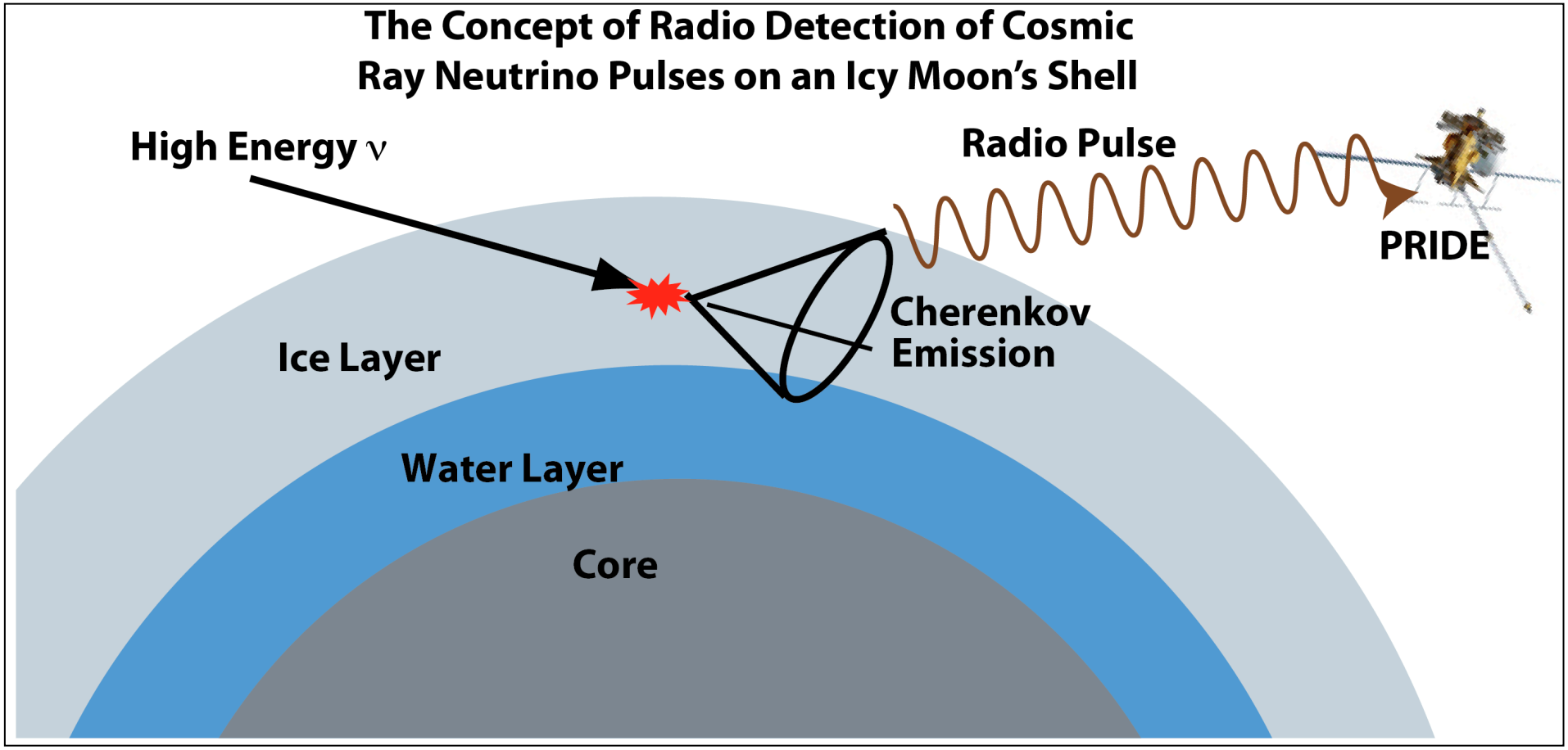
Replace 4 of 8 downward LPDA with 4 subsurface dipoles in single hole

Use full power of event reconstruction to deconvolve E-field

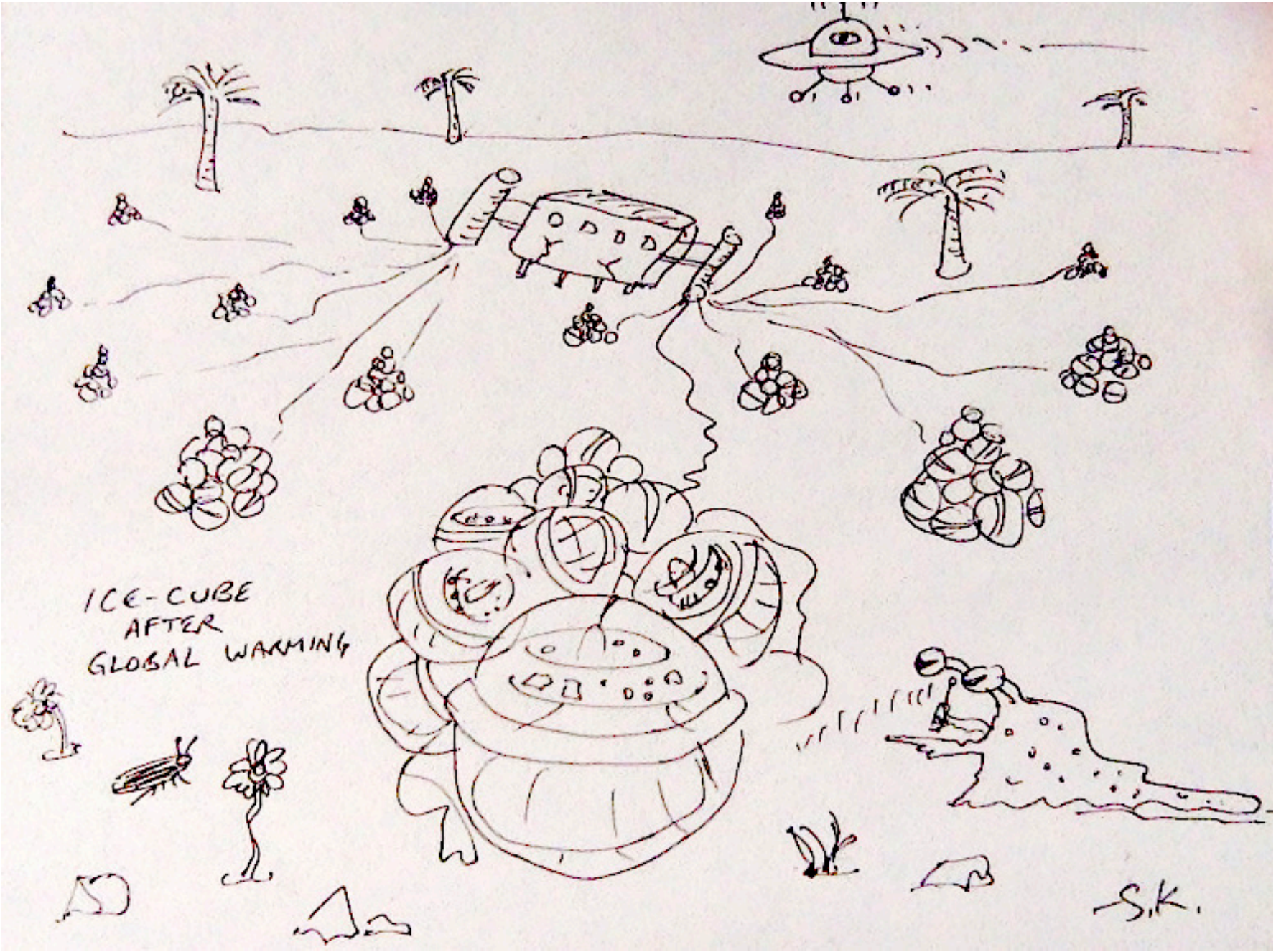
Obtain C-cone viewing angles. Christian estimates that 2-3 deg variation is minimum. But measurement of more than 3 deg is difficult

The Trip Home: C-130, ~9 Hours

Neutrinos to Probe Icy Moons?



Enceladus (moon of Jupiter) has an ocean under a layer of ice.

Using similar concepts as ARIANNA, we can explore this layer and those of other icy moons via the use of cosmic neutrinos.

IceCube after Global Warming