Outline

➔AURA/NARC - RF enhanced IceCube (Neutrino Array Radio Calibration)
(Askaryan Underice Radio Array)

– 5 clusters In the Ice –taking data [2007-2008] .
Calibration using surface and inice (RICE) pulsers.
Goal: Noise levels measurement; Coincidence with IceCube/IceTop;
Ice Attenuation; Feasibility of IceCube-based GZK array

➔ Exploring new technologies for next generation inice detectors
Goal: On the way to Sub GZK detector

➔ Surface Detector for CR and astronomy
Goal: Noise measurement; Coincidence with Other detectors;

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NARC Radio Cluster

Neutrino Array Radio Calibration

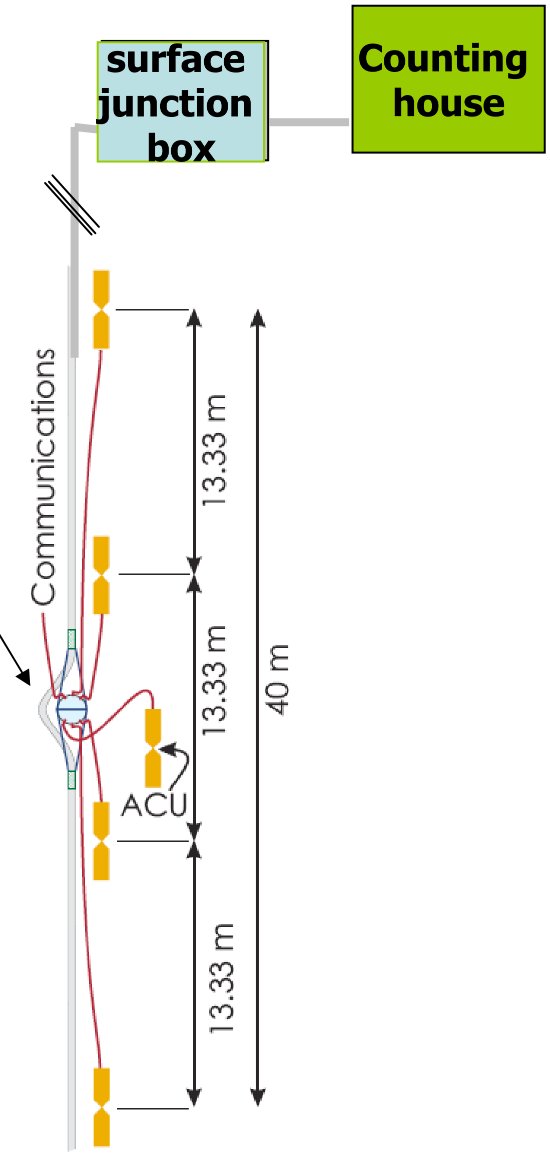
Use IceCube's resources: holes, comm. and power

- Each Cluster contains:
  - Digital Radio Module (DRM) – Electronics
  - 4 Antennas
  - 1 Antenna Calibration Unit (ACU)

- Signal conditioning and amplification happen at the front end

- Signal is digitized and triggers formed in DRM

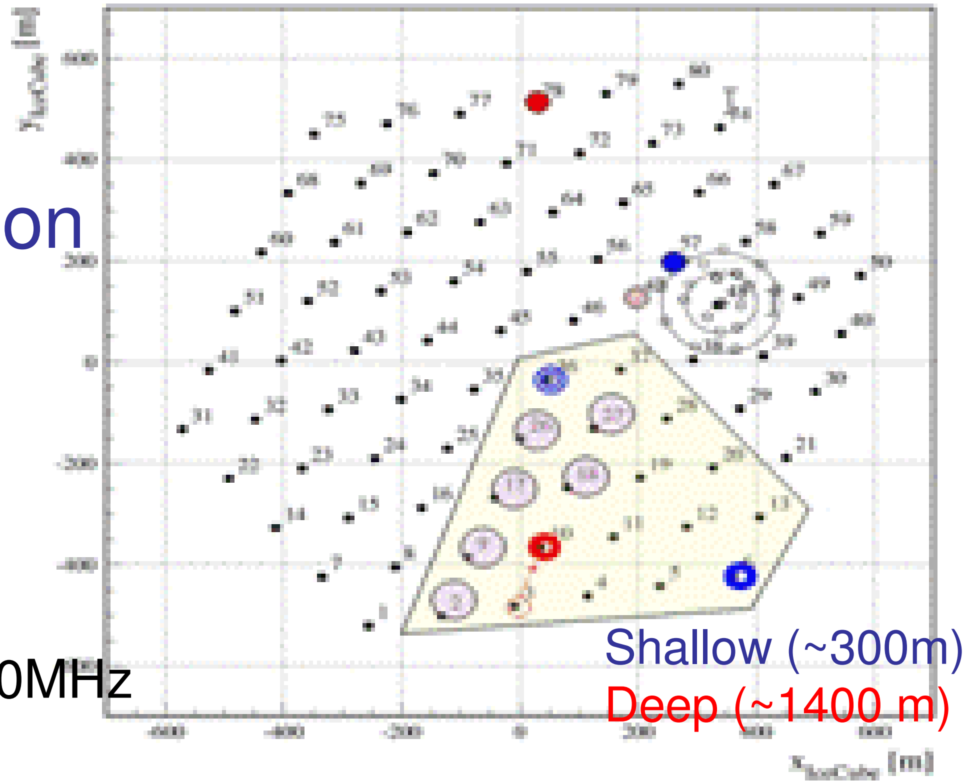
- A cluster uses standard IceCube sphere, DOM main board and surface cable lines.



"R&D Results Radio and future options", Hagar Landsman;
IceCube Science Advisory Committee,May 13 09;

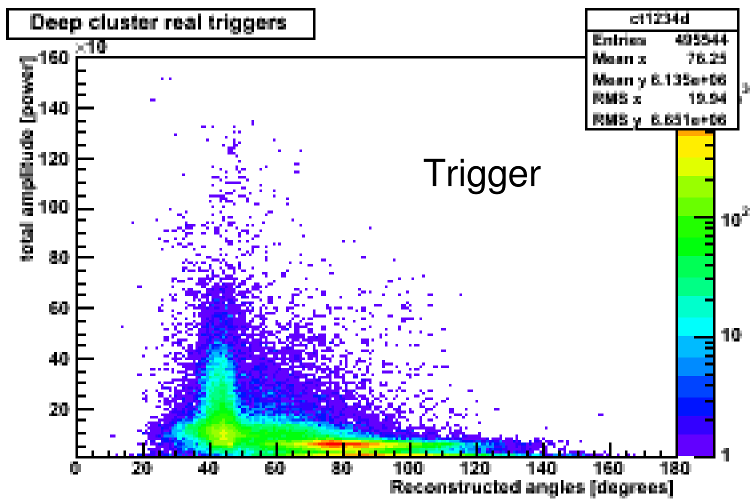
NARC Radio Cluster

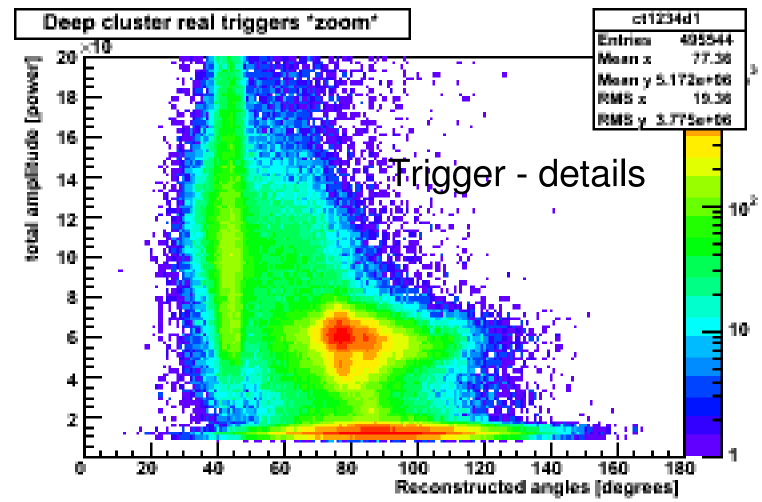
What’s new in the last season

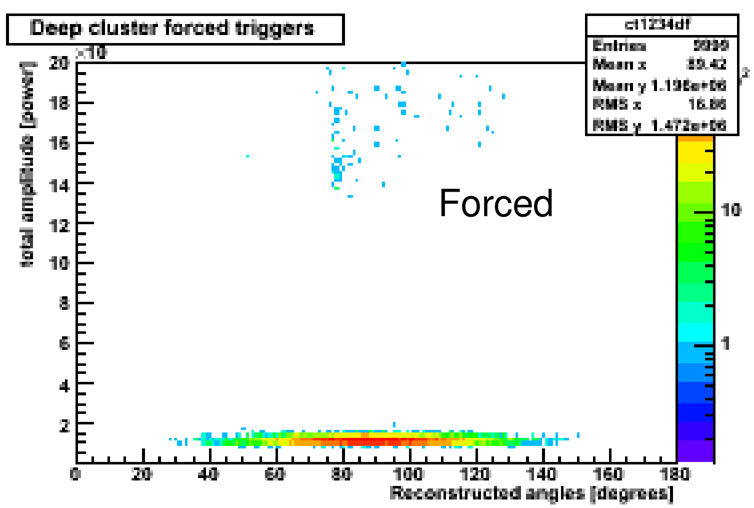


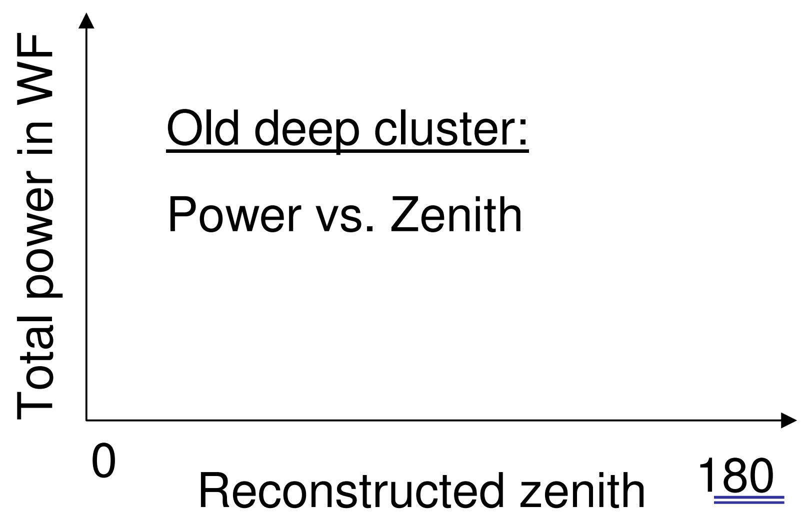
- An array of 5 clusters:
  2 clusters 2006-2007
  +3 clusters 2008-2009
- 2 channels (“antennas”) down to 100MHz
- 15/20 channels are working
- Stronger and/or more sophisticated in ice pulsers (support CW and pulses)
- IceCube-like DAQ (based on pdaq)
- Strong surface pulser

NARC Radio Cluster – Results: EMI and Stability tests
Source reconstruction



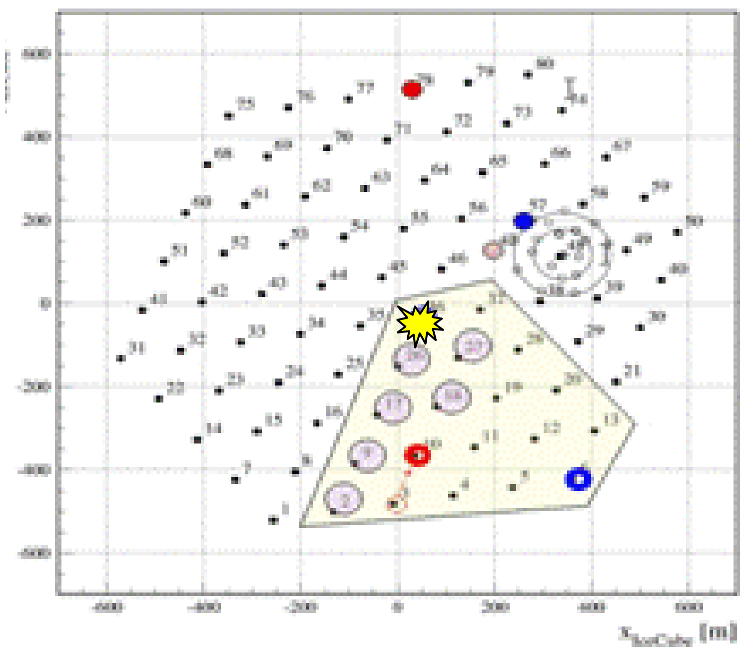




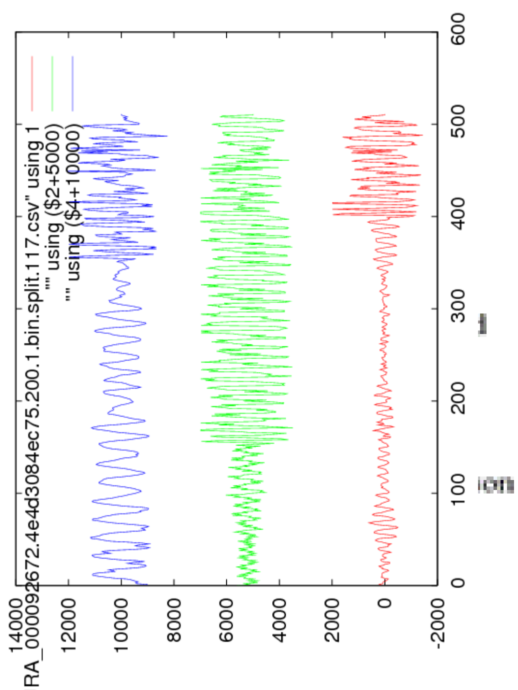


"R&D Results Radio and future options", Hagar Landsman; IceCube Science Advisory Committee,May 13 09;

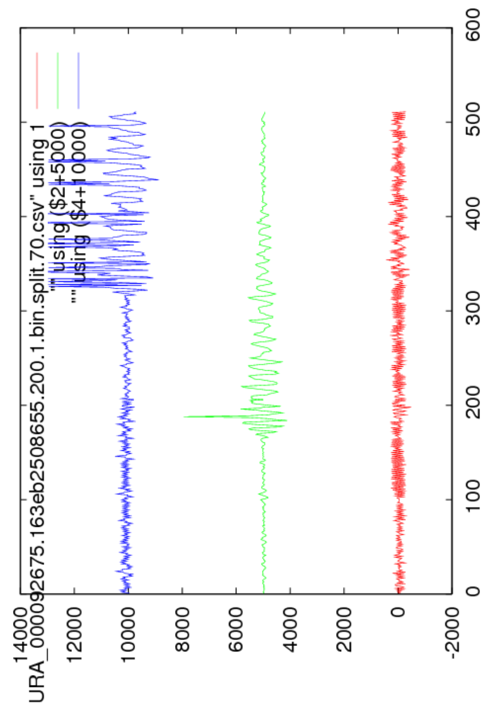
NARC Radio Cluster – Results: EMI and Stability tests
New in ice transmitters



Hole 36, -250 m



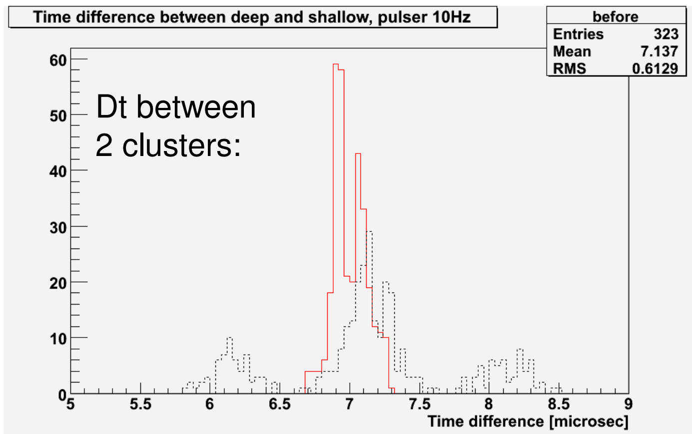
Hole 57, -288 m

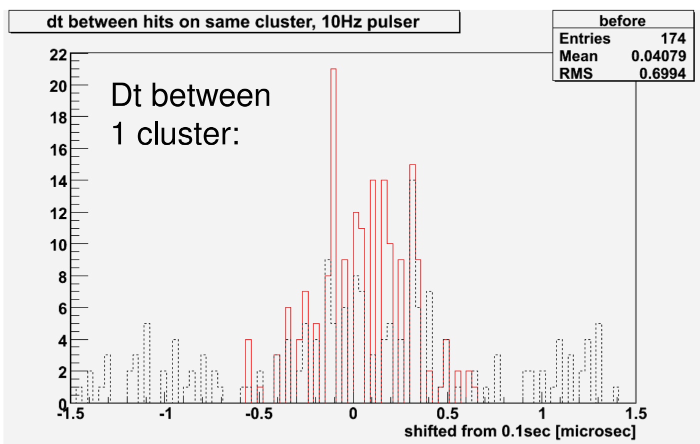


NARC Radio Cluster – Results: EMI and Stability tests

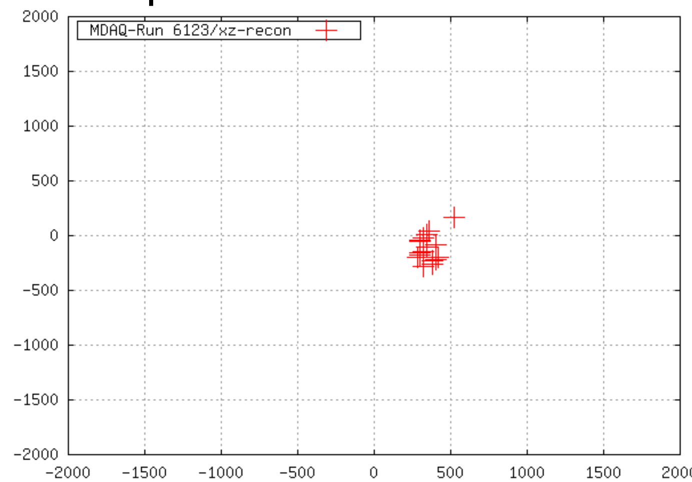
Surface transmitter – repetition rate of 10Hz

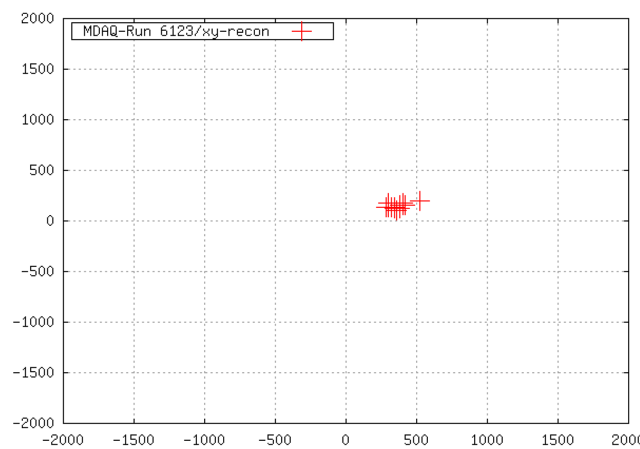
Time Resolution





Spatial Reconstruction





NARC/AURA – To-Do list:
With the 5-clusters array and stronger calibration source

Analyses:

- Time resolution
- Ice attenuation
- Coincidences with icecube/icetop
- Noise source vertexing and South pole EMI map vs. time
- Lower limit on GZK neutrinos:
  - Sensitivity calibration (thresholds to field calibration)
  - Detector Life time
  - Simulation

Hardware:

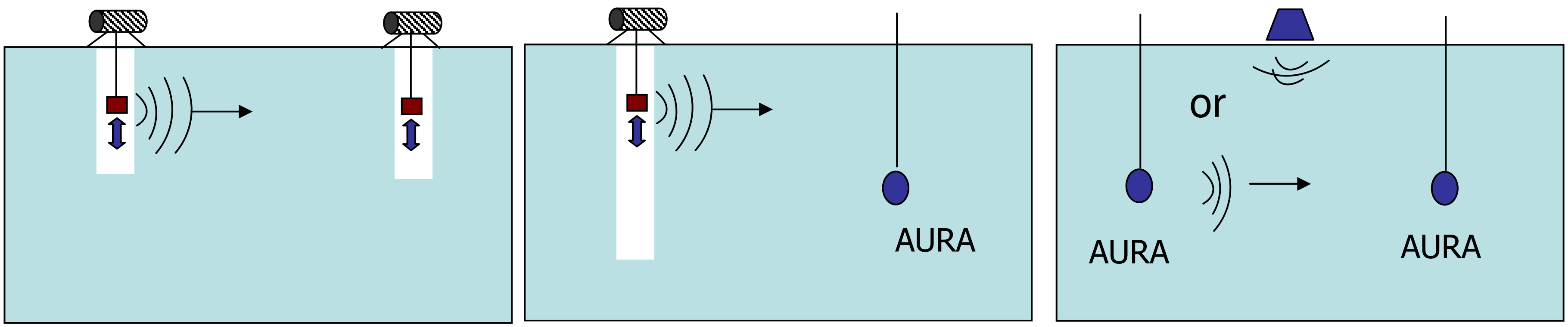
- 1 additional cluster left at north.
- Seasonal measurement of ice attenuation

Ice Properties Measurements

Good ice understanding is needed for optimization of detector geometry (depth and spacing), And for estimating effective volume and efficiencies.

➔ Additional direct on site attenuation length measurements.
➔ More data points on n(z) below 200 meters

<u>Some scenarios for direct point to point surveys below 300 m</u>:
1. Use Froze-in Tx an Rx (+ good coupling, – froze in)
2. Use IceCube holes pre-deployment (+many depths, – water)



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Future detector design

Some considerations:

- Frequency range and band width.
- Antennas type

Unique signature of Askaryan:
 short pulse, linearly polarized
 - Capture polarization?
 - Low freq has wider energy spread
   but more noise
 - Narrow holes effect design

Geometry (depth and spacing):

- Space detectors
- Shadowing effect → Deeper is better
- Ice Temperature → Shallower is better
- Drilling cost and time– Deep=expensive
- Hole diameter can limits design of antennas
- Wet/dry hole

Data type:

- Full digitized WF
- Transient array

Future detector design

Some considerations:

- Frequency range and band width.
- Antennas type

Geometry (depth and spacing):

- Space detectors (outer ring better as ring, and not as pile)
- Shadowing effect → Deeper is better
- Ice Temperature → Shallower is better
- Drilling cost and time– Deep=expensive
- Hole diameter can limits design of antennas
- Wet/dry hole

Data type:

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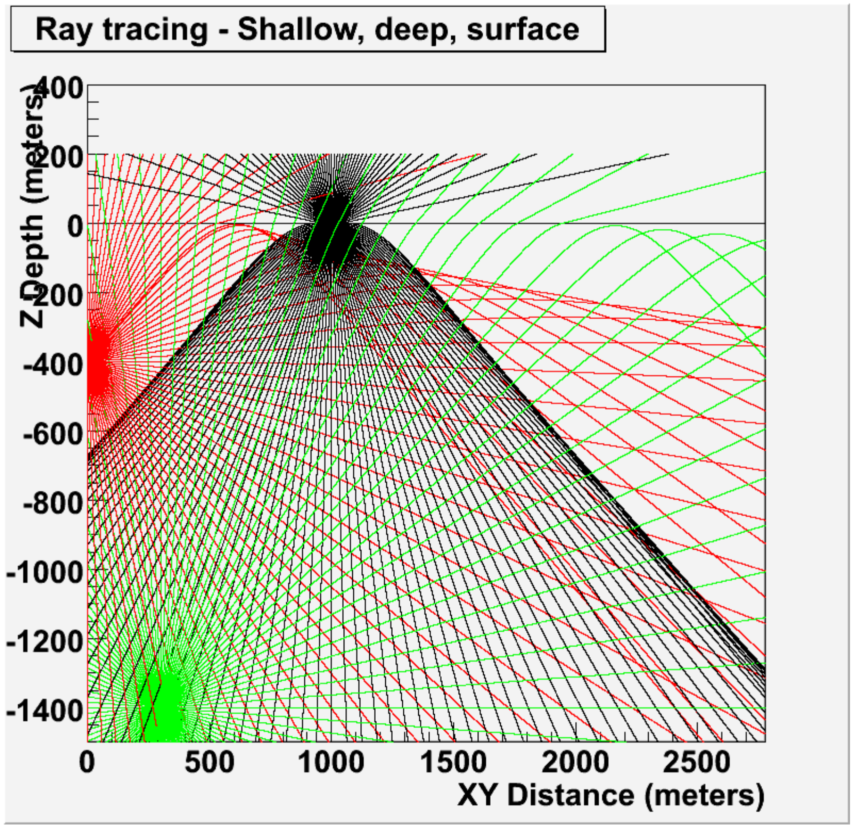


Denser Shallow holes

≈

Spaced deep holes

"R&D Results Radio and future options", Hagar Landsman;
IceCube Science Advisory Committee,May 13 09;

Drill options for large array

- Drill options exist and are being studied. Down to 200 meters.

See Klaus's talk

A summary table from PSL showing different drills

Future detector design

Some considerations:

- Frequency range and band width.
- Antennas type

Geometry (depth and spacing):

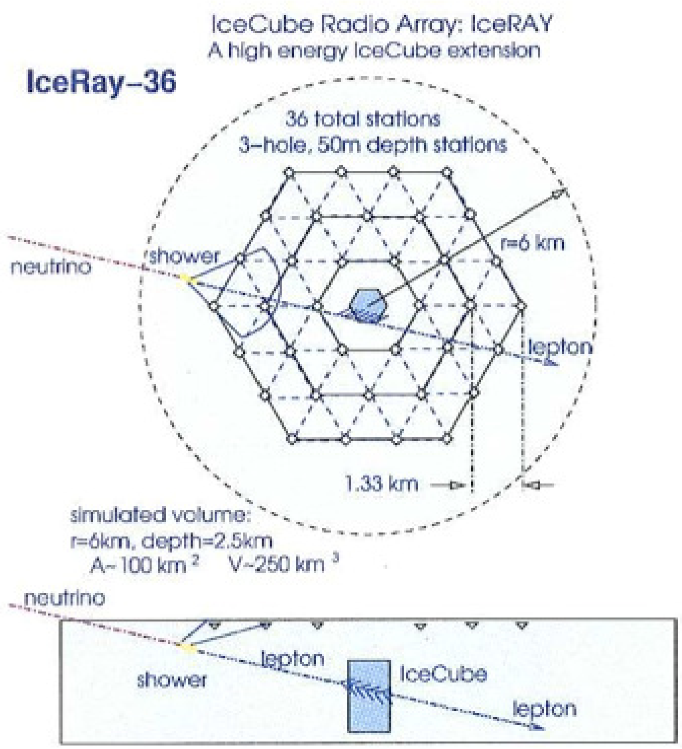
- Space detectors
- Shadowing effect → Deeper is better
- Ice Temperature → Shallower is better
- Drilling cost and time– Deep=expensive
- Hole diameter can limits design of antennas
- Wet/dry hole

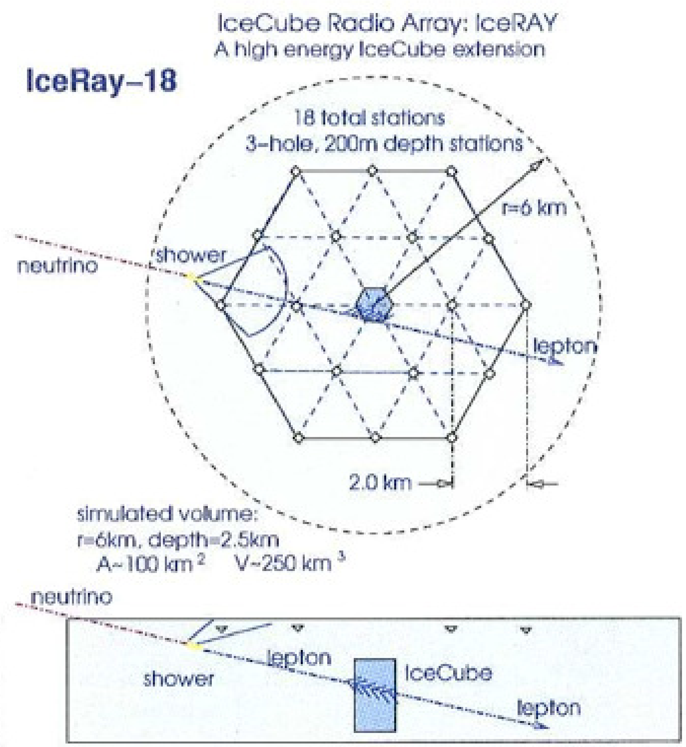
Data acquisition method:

- Full digitized Wave Form
- Transient array

→ Full WFs give good timing and frequency content, But require more sophisticated DAQ and electronics (power, noise) and larger data volumes

Case study: A Fully Digitized Wave Form Detector
IceRay:50 km^2 Baseline Studies



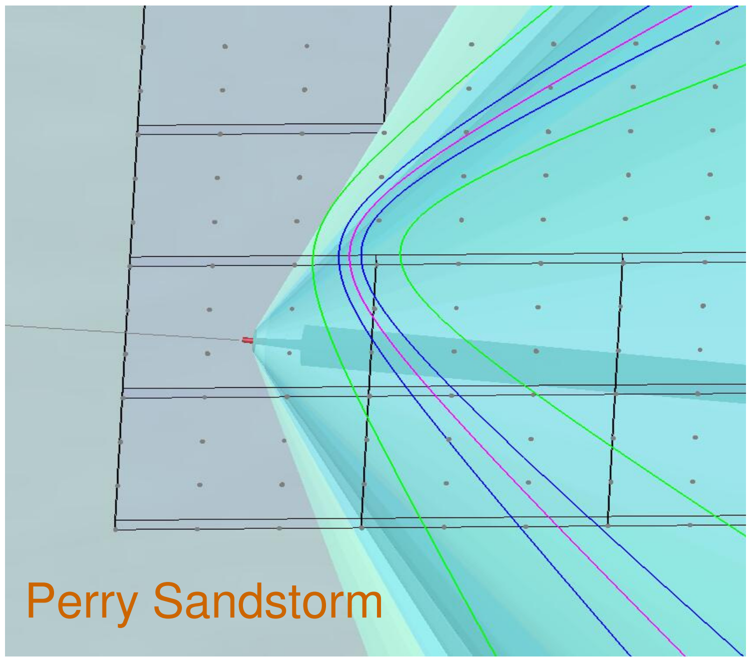


Higher density, shallow (50m) vs. sparse, deep (200m
➔Estimate to get 3-9 events/year using "Standard fluxes"
➔0.3-2 events/year with IceCube coincidence

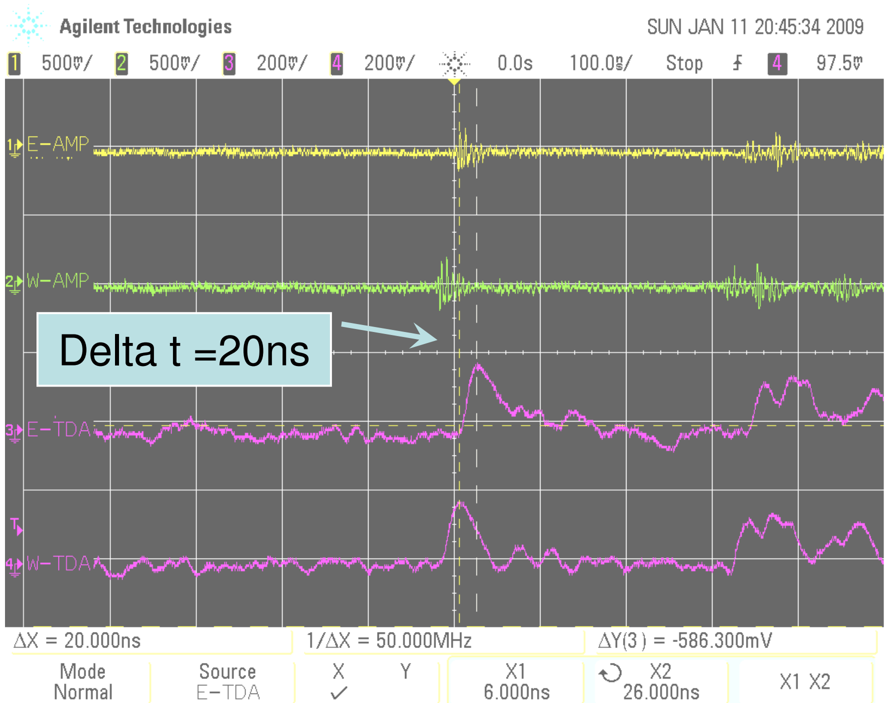
"R&D Results Radio and future options", Hagar Landsman;
IceCube Science Advisory Committee,May 13 09;

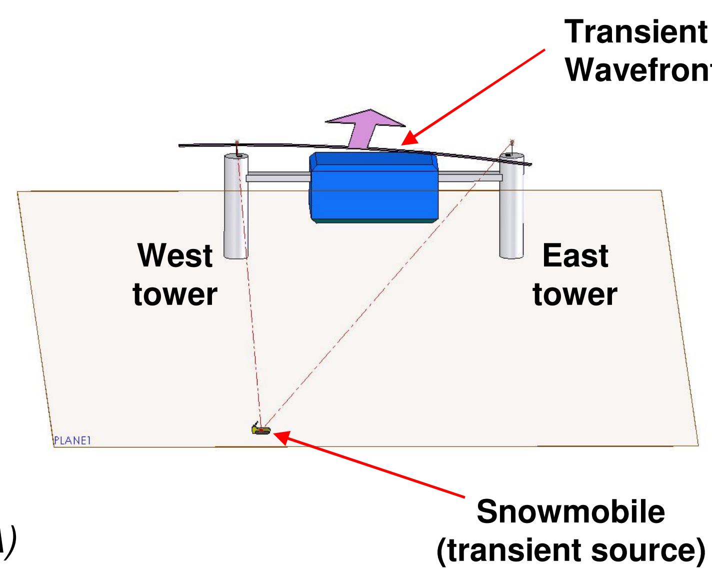
Transient sensor array

Many “simple” sensors to provide a snap shot of an Askaryan pulse.
Wide dynamic range, low power, simple output



Example Transient (from snowmobile ignition)





Ignition noise transients from idling snowmobile

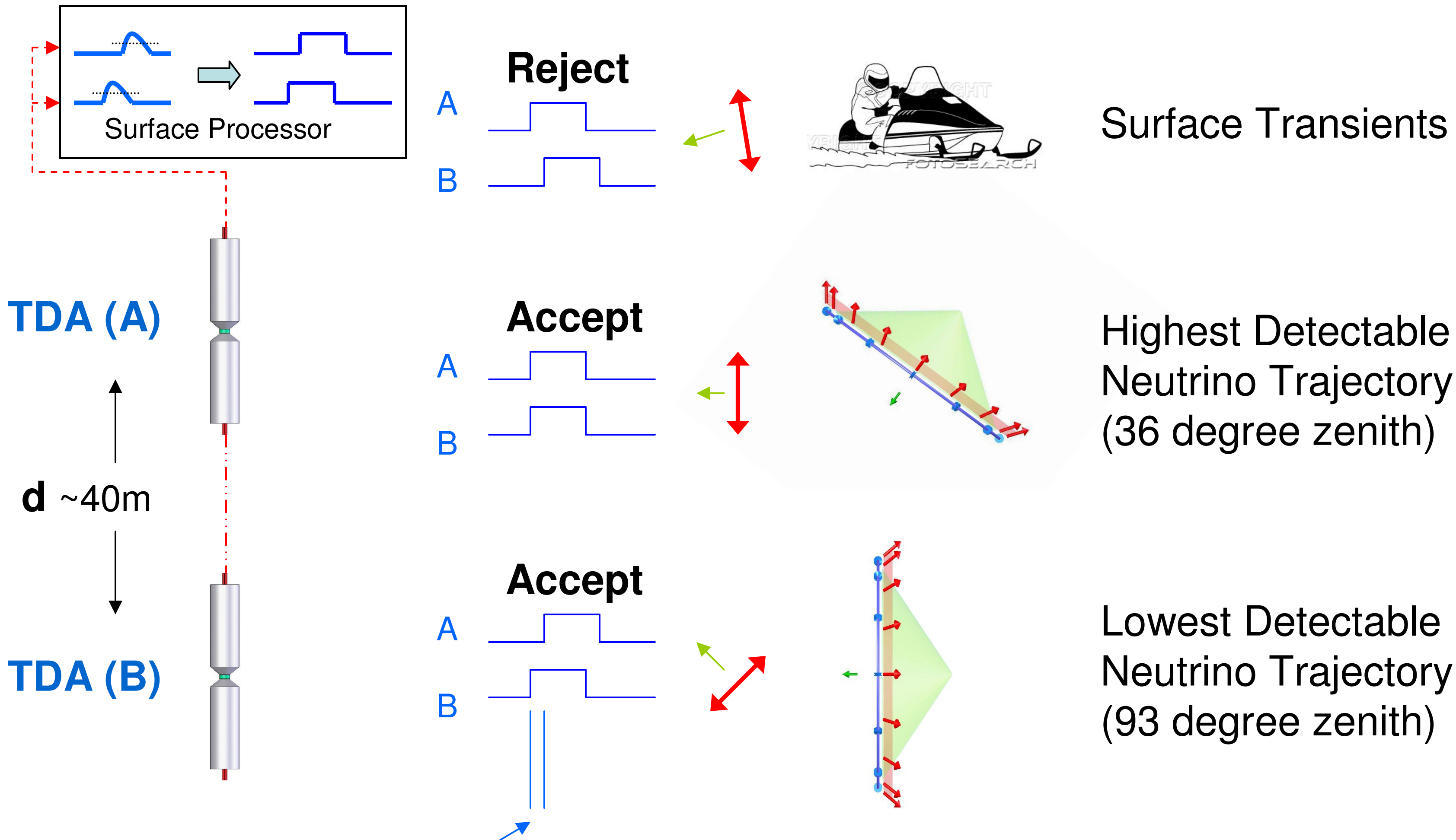
Snowmobile was approximately 100m distance from ICL.
Snowmobile was perpendicular with West tower.
Signals as acquired by ic-scope-ag1
Time Delay=20ns W-E, consistent with Angle-of-Arrival (AOA)

"R&D Results Radio and future options", Hagar Landsman;
IceCube Science Advisory Committee,May 13 09;

Downward Rejection

via Priority, Coincidence

Real-Time, Simplest "Elevation Gating"



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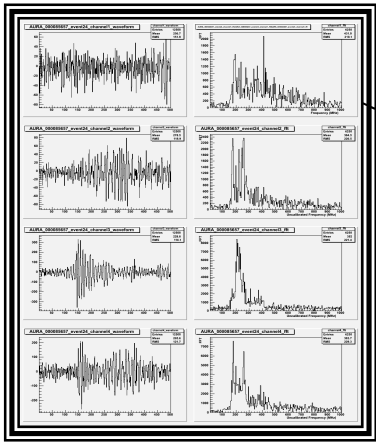
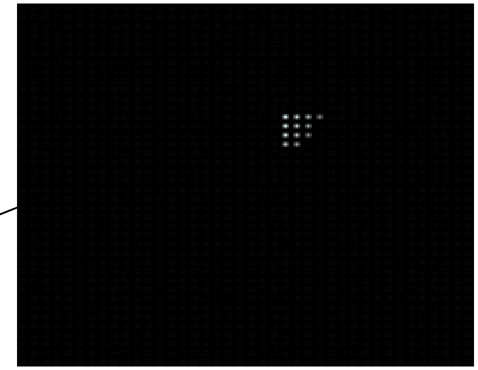
Future directions- Data acquisition methods:





Full digitized Wave-Form array

Pros:
+ Full WF
+ Method proven by ANITA and RICE

Cons:
- Expensive and m

Challenges:
- Handling large amount of data

Transient array

Pros:
+ cheaper units ➔ large array
+ Simpler detector

s:
nited information

Challenges:
-Is the information sufficient to reject background and detect GZK neutrinos

Large arrays challenges:
-Power distribution
- Communication
- Accurate timing

3 years In Ice Todo List:

- 2008-2009:
  AURA/NARC :
    - Deployment of new modified AURA clusters (total of 5)
    - Strong Transmitters (both inice and surface)

  en route GZK detector:
    - Two TDAs connected to Horizontally-separated antennas on ICL Towers.
    - Simulation
    - Drills survey

- 2009-2010:
  AURA/NARC:
    - Analyses of AURA data: coincidences with IceCube; Transients; Attenuation; GZK limit
    - Special Seasonal attenuation length tests (point2point)
    - Deployment of additional hardware - last chance to deploy deep

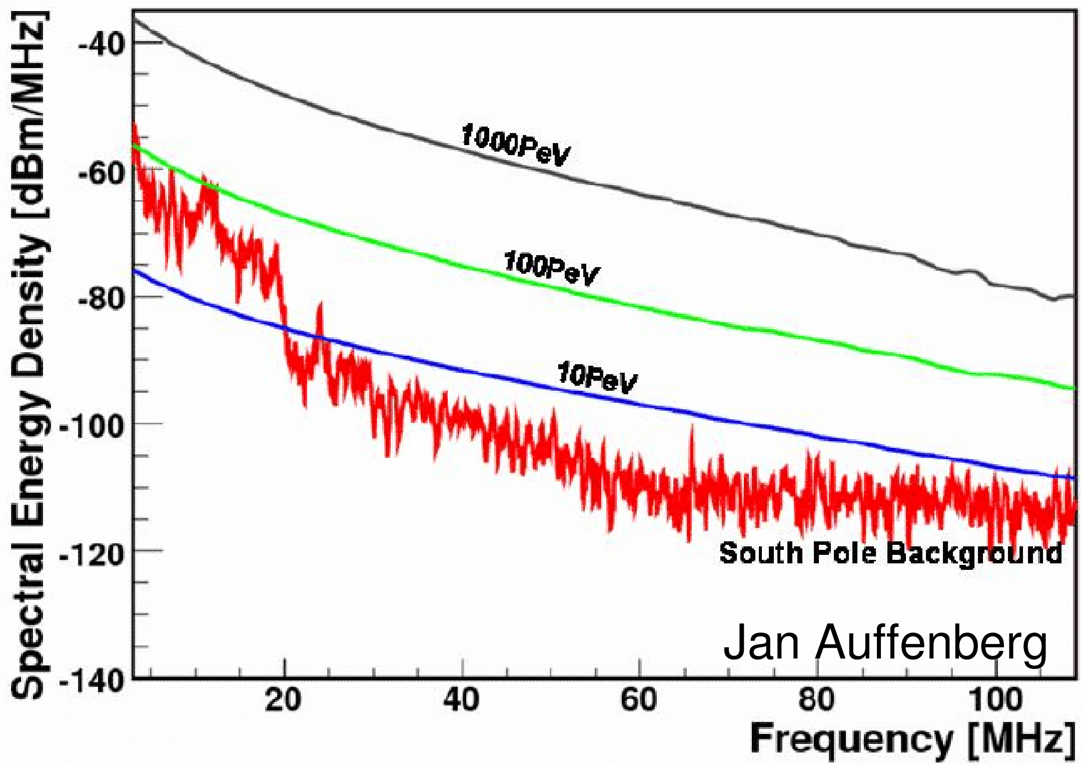
  en route GZK detector:
    - 3 transient clusters – Using IceCube holes ~200 meters: study results – background and pulse reconstruction
    - Studies of power and comm distribution
    - Deployment of strong transmitter for future use – last chance to deploy deep
    - Prepare proposal

- 2010-…
  AURA/NARC:
    - Continue data taking
    - Merge with IceCube data stream and DAQ.

  en route GZK detector
    - Small test array: Additional clusters in improved design. Full DAQ, inter string timing and triggering.
    - Improve stand-alone drill
    - Finalize geometry based on simulation

Backup

Muon bundle
Energy dependence of air showers signals



Air shower in 125m distance with 45° inclination angle simulated with Reas2

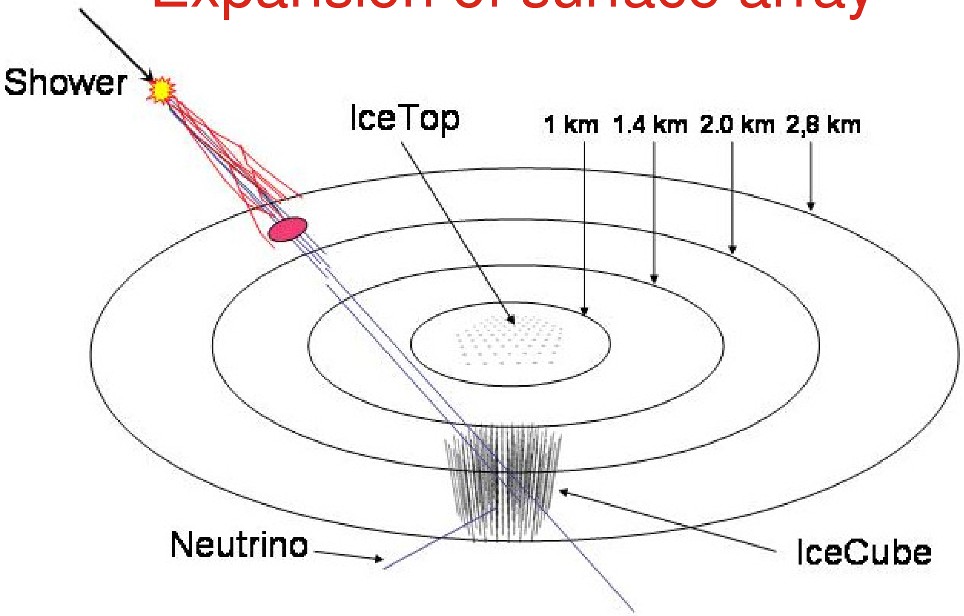
Based on south pole RF surface survey 1 MHz-500MHz (red curve)

RF Content for Muon bundles can get above background

coincidences with IceCube are possible

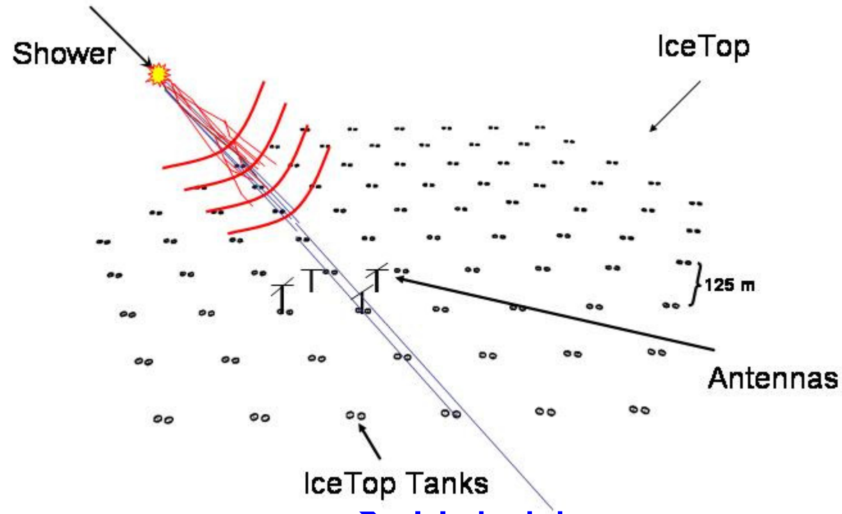
Options for IceTop Radio Extension

Expansion of surface array



➔ Veto for UHE neutrino detection InIce

Infill surface array



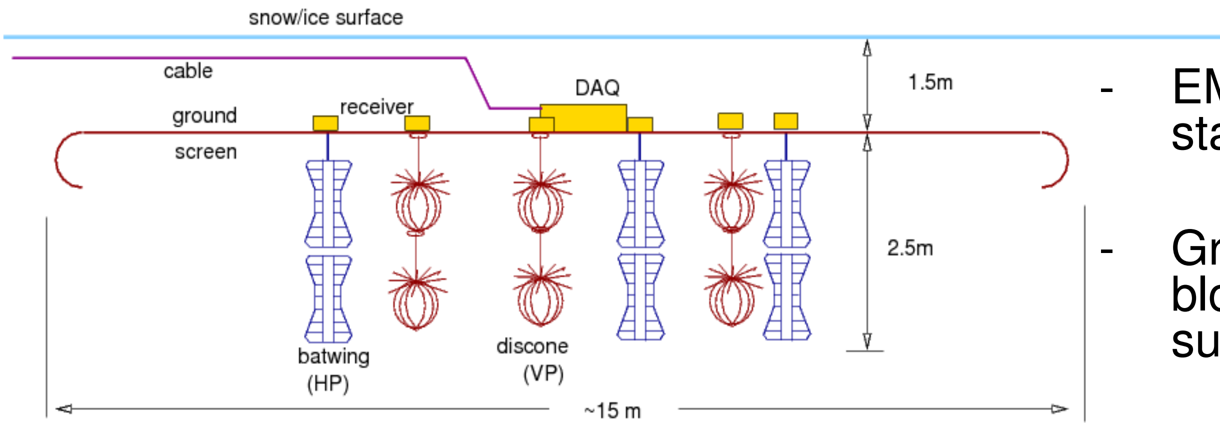
➔ Hybrid CR compositon

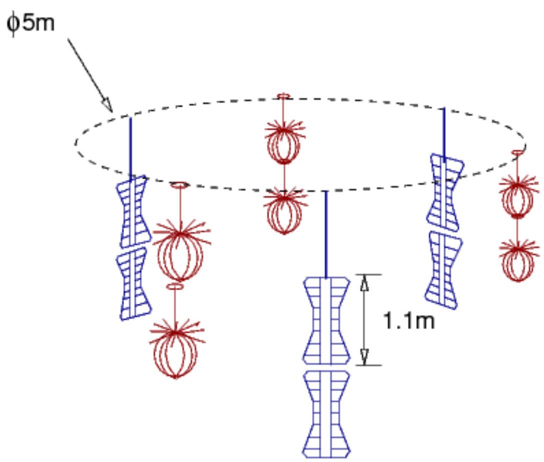
Three-prong hybrid air shower studies

(1) IceTop, (2) Muons in deep ice, (3) Radio

Proposal submitted to European funding agencies

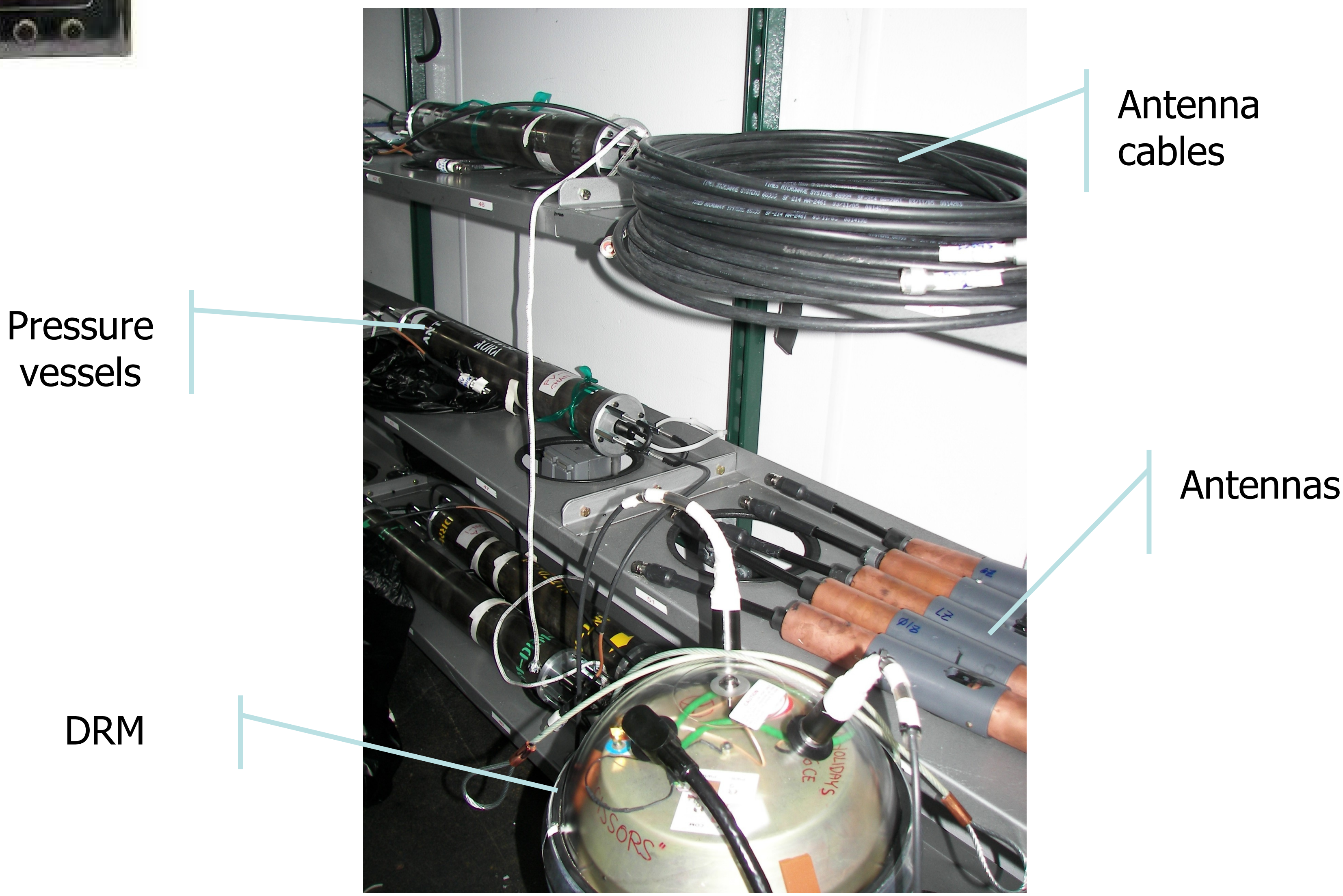
EMI test bed



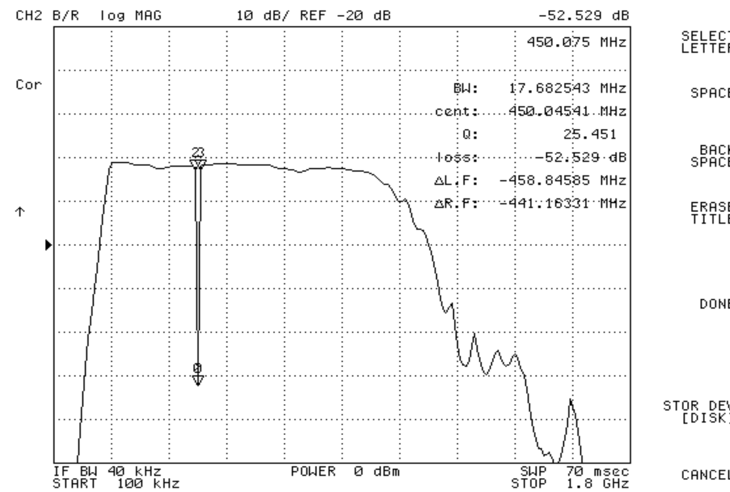


- EMI monitoring ~2km out of the station.
- Ground screen above array to block galactic, solar , aircraft and surface RF noise
- 115-1200 MHz
- Hardware exist
- Independent proposal submitted
- Also: checking option to use firn holes near and away station to study firn and EMI emission (not a part of IceRay).

Waiting to be deployed



RF signal



Antennas:

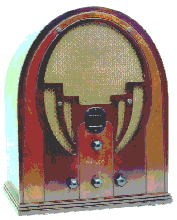
- Broad band dipole antennas
- Centered at 400 MHz

Front end electronics contains:

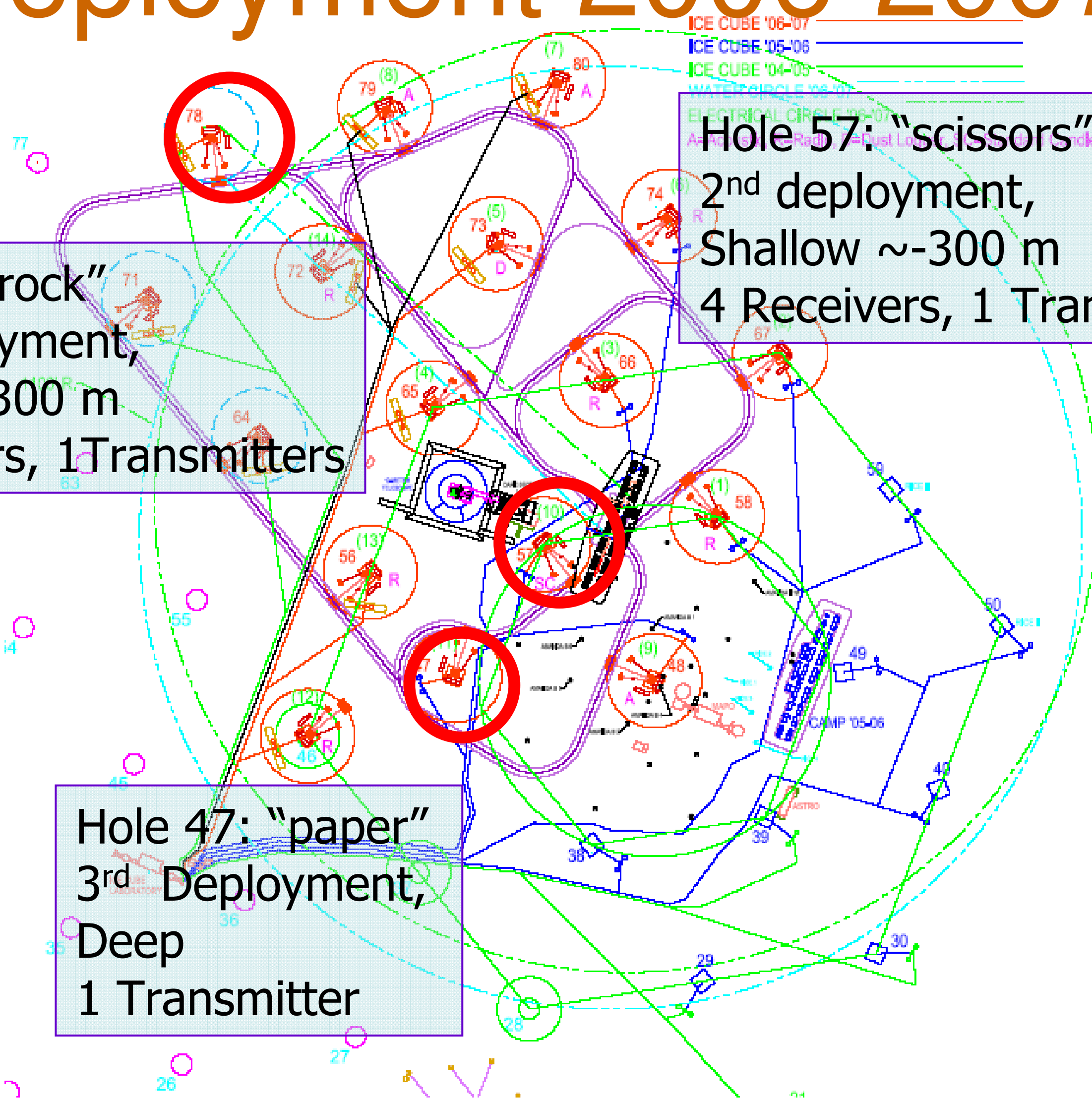
- 450 MHz Notch filter
- 200 MHz High pass filter
- ~50dB amplifiers (+20 dB in DRM)

LABRADOR digitizer:

Each antenna is sampled using two 1GHz channels to a total of 512 samples per 256 ns (2 GSPS).



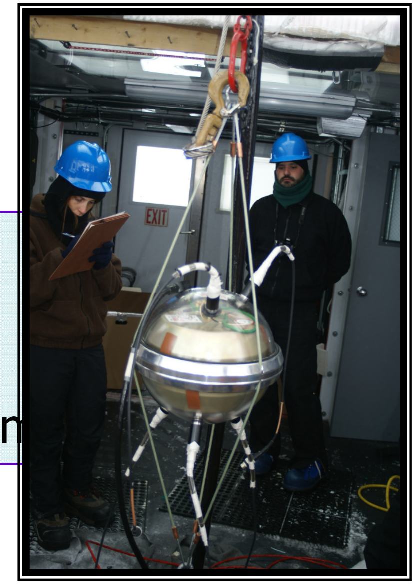
Deployment 2006-2007

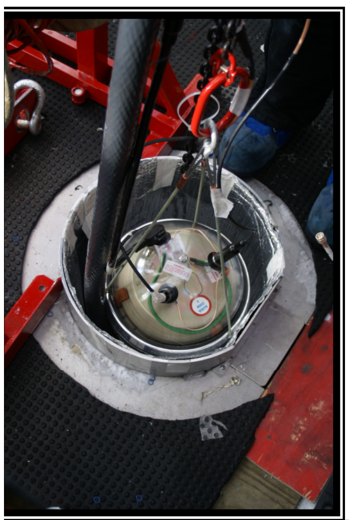


Hole 78 :"rock"
1st deployment,
Deep ~-1300 m
4 Receivers, 1Transmitters

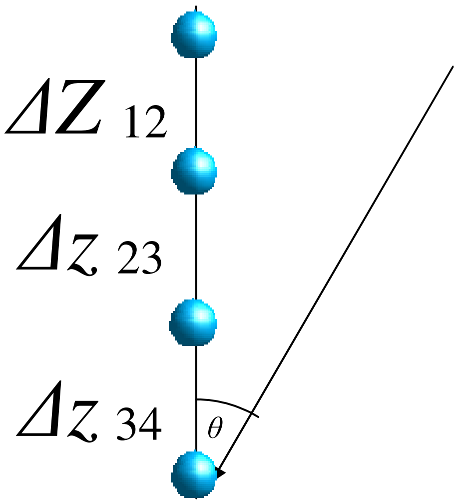
Hole 57: "scissors"
2nd deployment,
Shallow ~-300 m
4 Receivers, 1 Transm

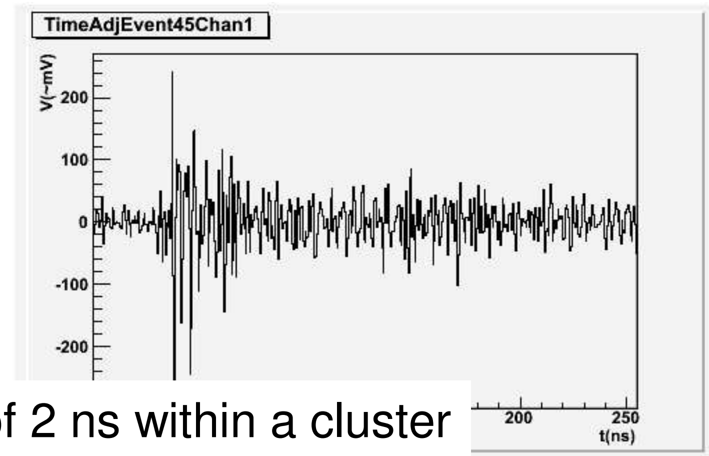
Hole 47: "paper"
3rd Deployment,
Deep
1 Transmitter



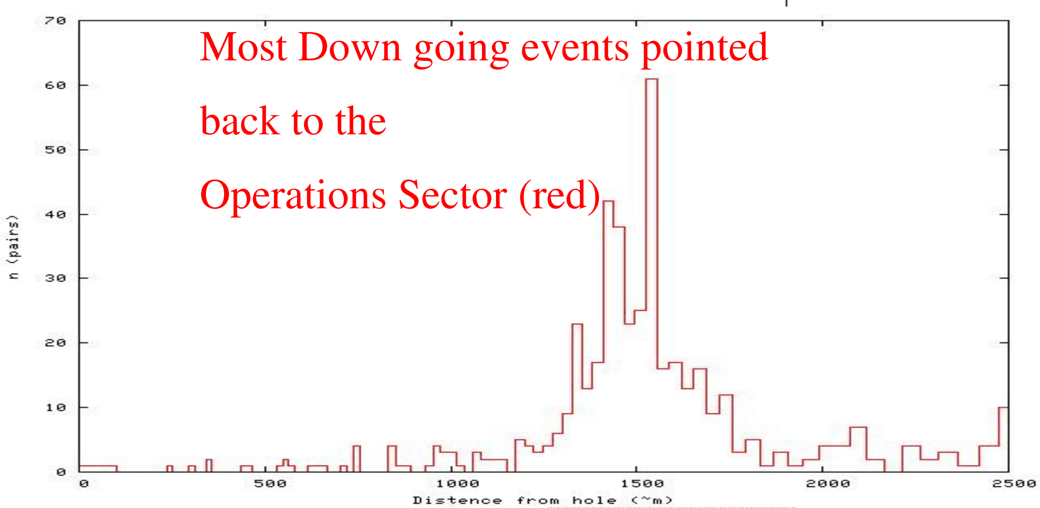


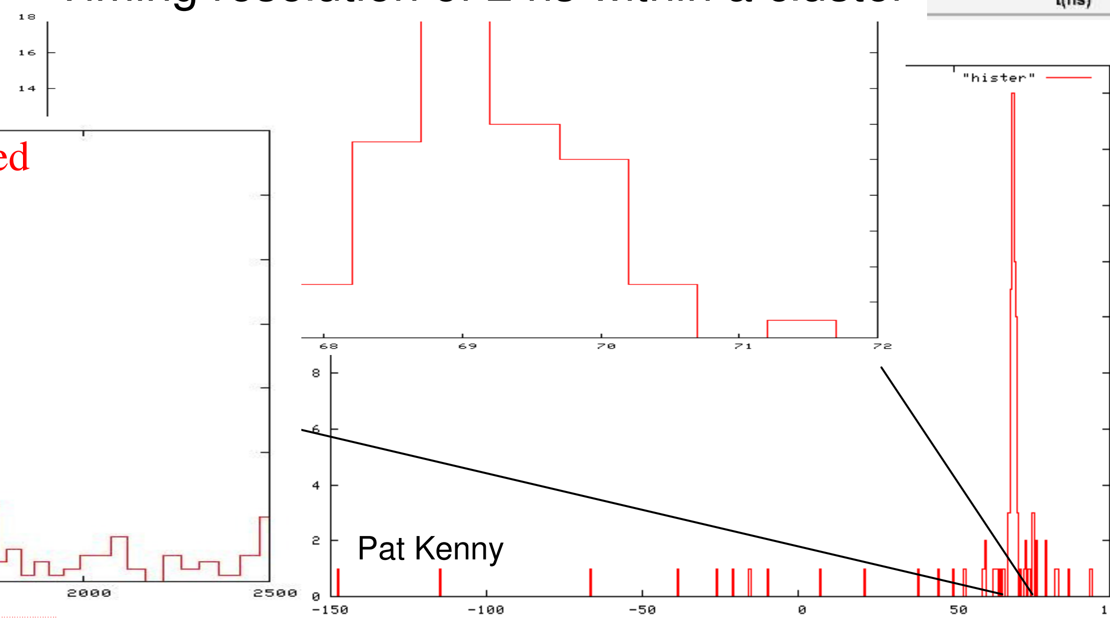
Inter-cluster timing





Timing resolution of 2 ns within a cluster





Time difference in 0.5 ns bins

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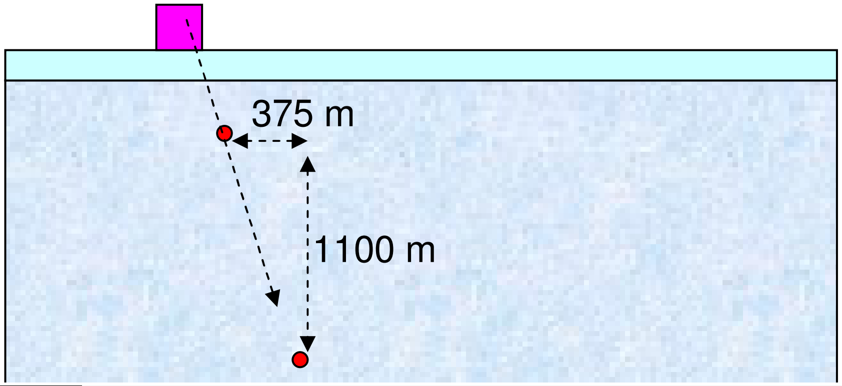
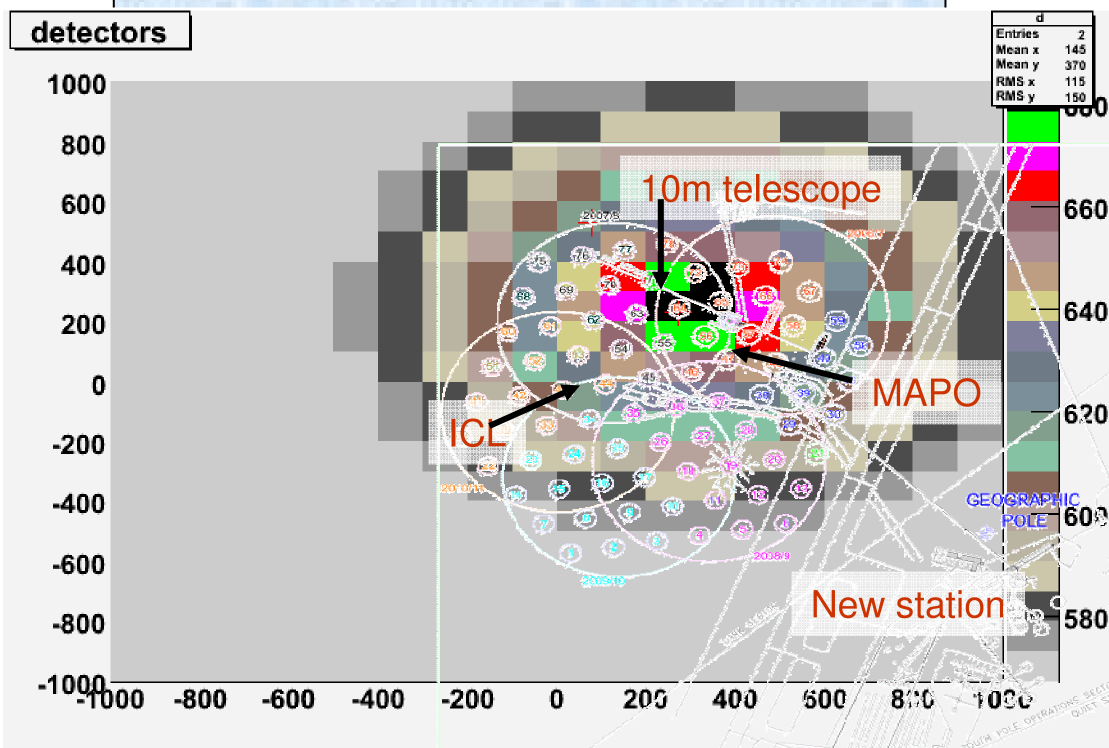
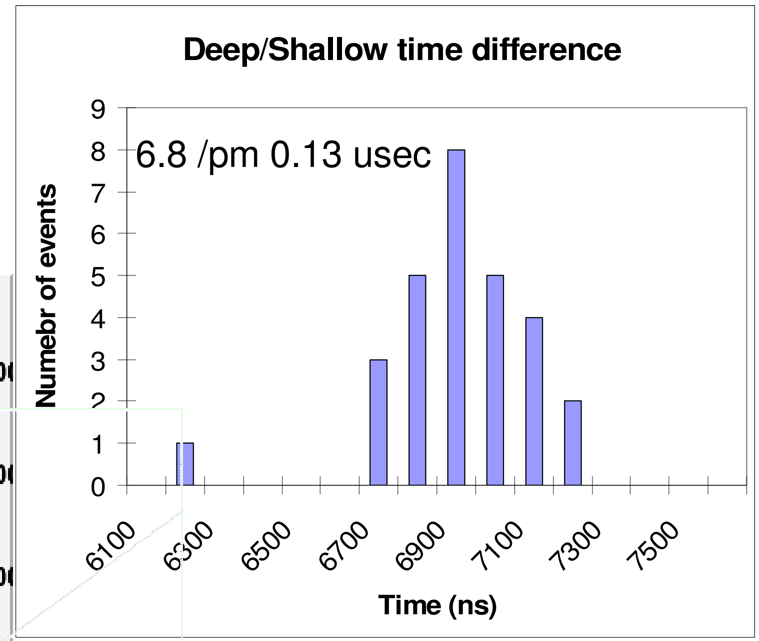
IceCube Science Advisory Committee,May 13 09;

Inter string Results

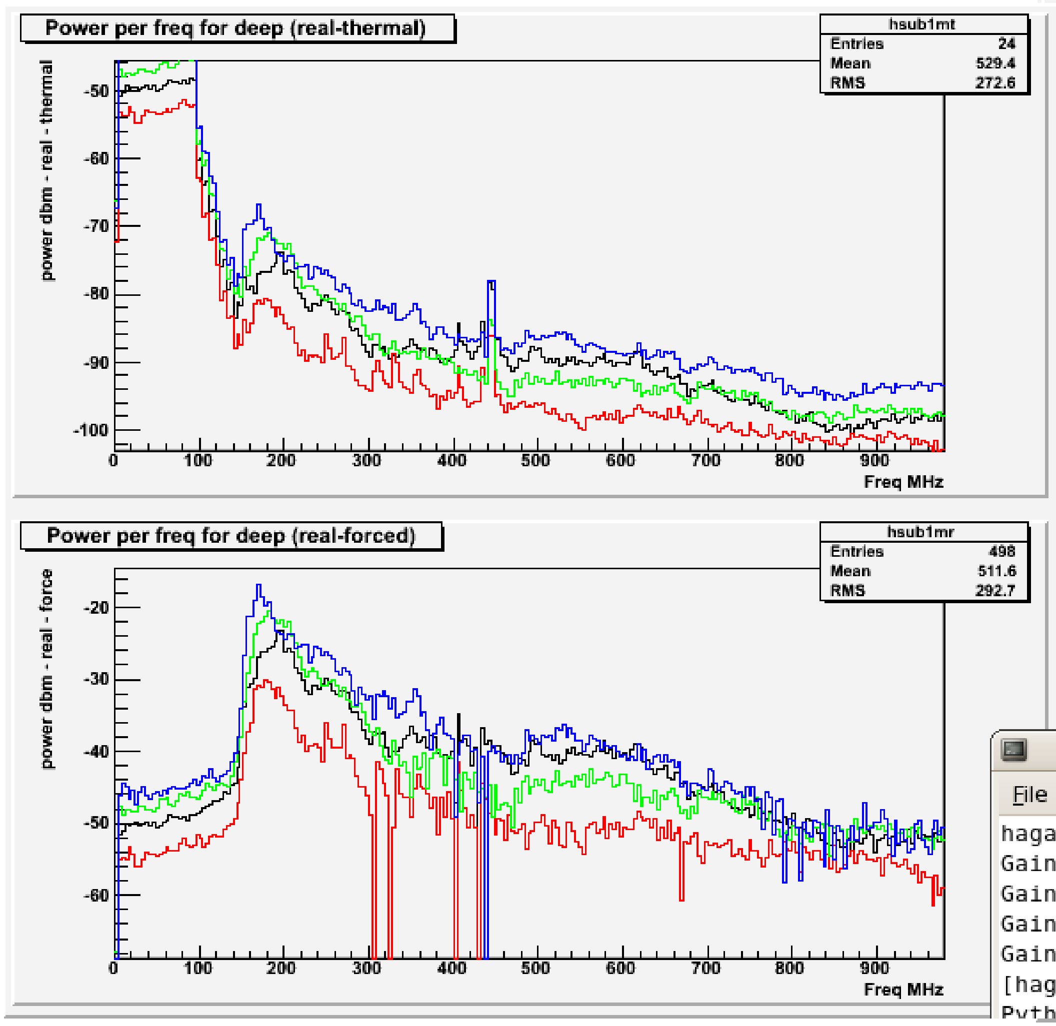


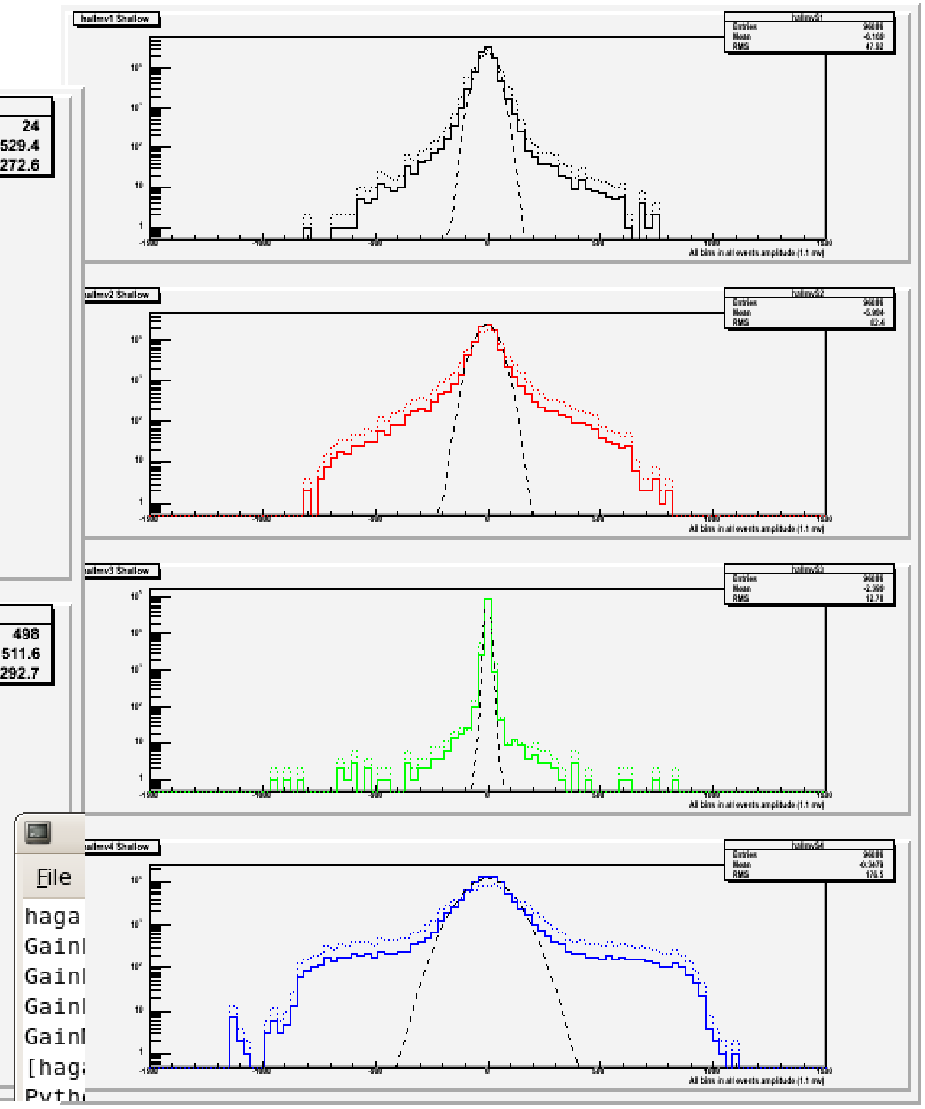




Also looking for coincidences with Ice Top

Background and signal levels





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RF Signal

- Nyquist: $V_{rms} = (4K_b TR\Delta F)^{1/2}$
  - V=3 mVolts= RMS of 3-5 bins
- Environment background:

  Average In Ice background up to 1 GHz:

  -86 dbm = 2.5 E-9 mW

  After ~70 db amplification:
  - 16 dbm → 35mV RMS → 30 DAC counts rms (for 2007)
  - 16 dbm → 35mV RMS → 60 DAC counts rms (for 2009)
- Maximum signal:

  Dynamic Range=1200 counts
  - → 1320 mV RMS → 15 dbm → -55dbm = 3E-6 mW before amps (07)
  - → 720 mV RMS → 10 dbm → -60 dbm= 1E-6 mW before amps (09)

2007 cluster mV/DAC is ~1.1

2009 cluster mV/DAC is ~0.6

Suitability of IceCube environment

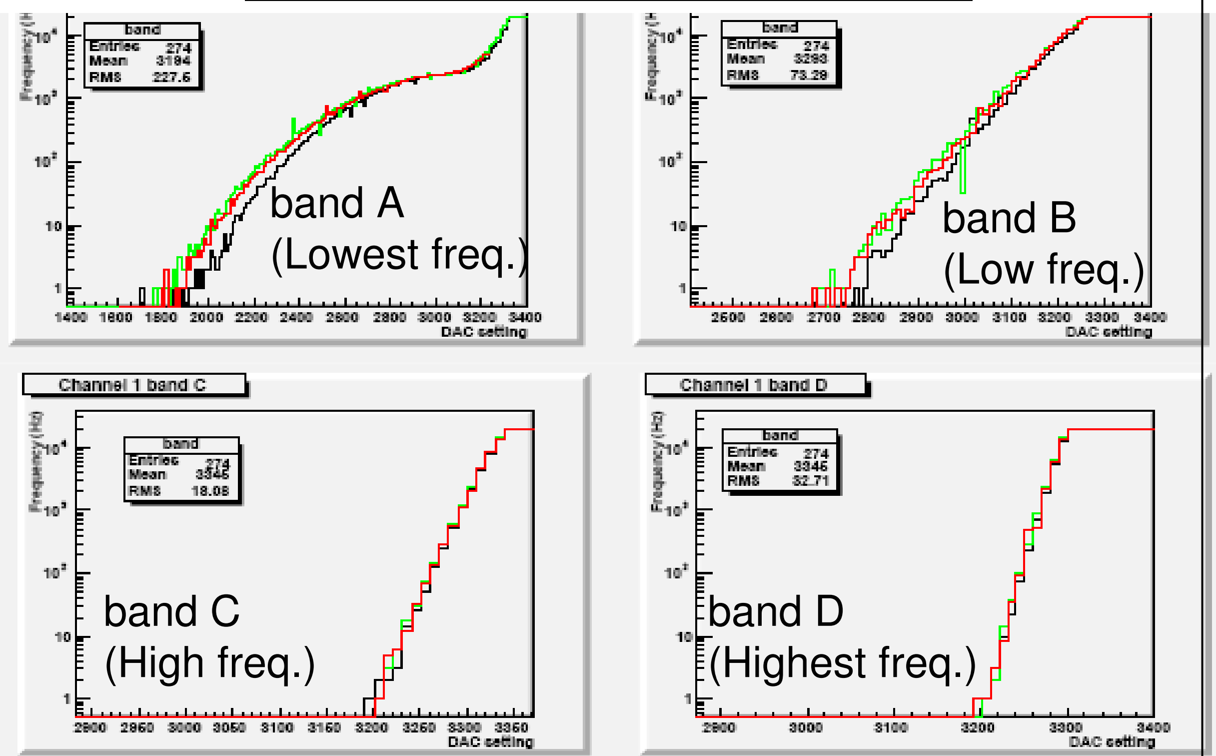
- Channel and cluster trigger rates were compared when IceCube/AMANDA were idle and taking data

IC + AMANDA on
AMANDA off
IC + AMANDA off

- Noise from IC/AMANDA is enhanced in lower frequency on a given channel/band.
- Combined trigger reject most of this noise.
- Measurement only down to ~200 MHz

Channel 1

Scaler rate vs. Discriminator value



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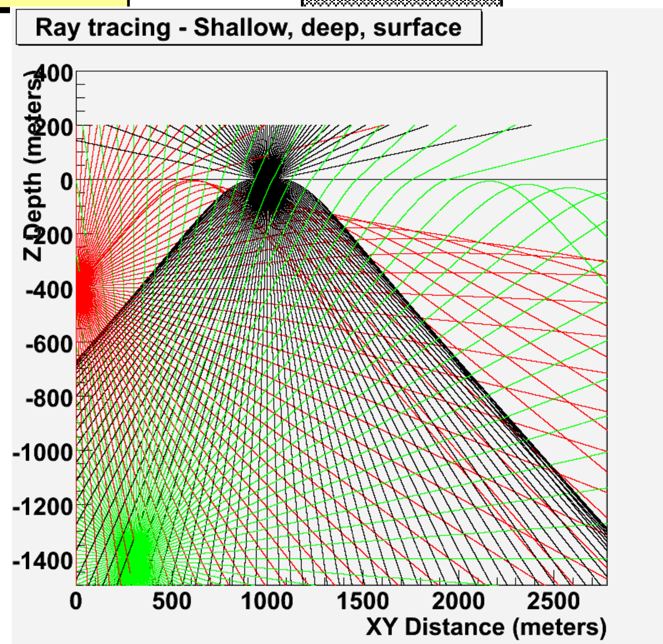
Existing external sources

- RICE
  - CW – observed and measured by shallow cluster
  - Pulse – not observed, too weak.

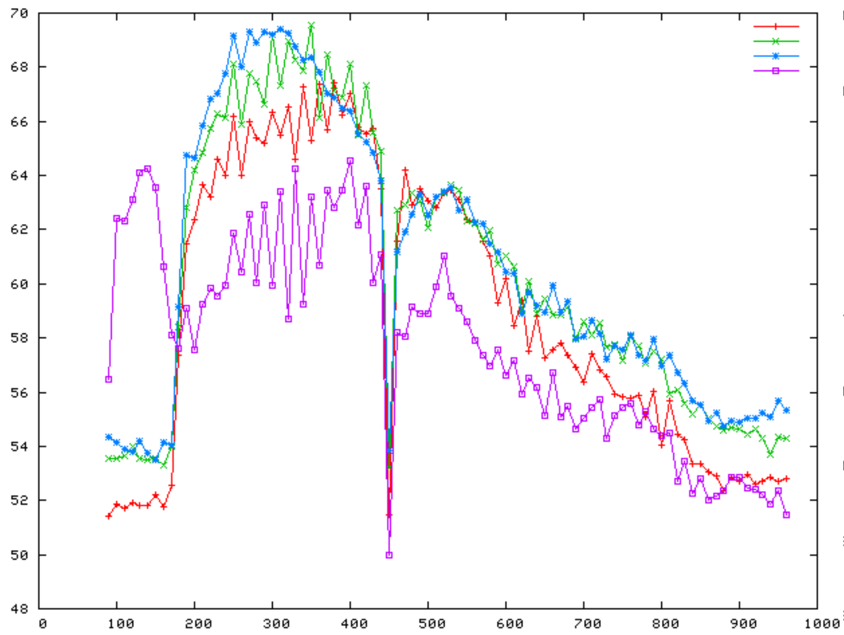
  Another RICE test is scheduled.
- Other cluster's ACU
  - ACU too weak – Development of stronger ACU
- Same ACU
  - Shows signal elongation (we'll get back to this point)

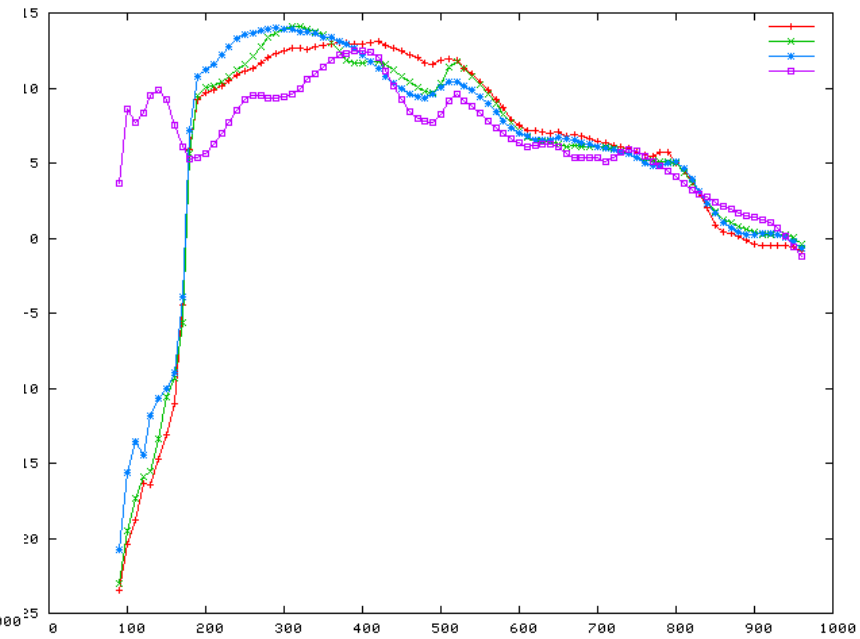
xy Seperation	Shallow -300m	Deep -1400m	Pinger -1400 m	RICE -10-200m
shallow		375 m	125 m	150 m
Deep	375 m		400 m	500 m



Gain Calibration

- DRM 1:
- <u>Full Cluster</u> <u>DRM only</u>

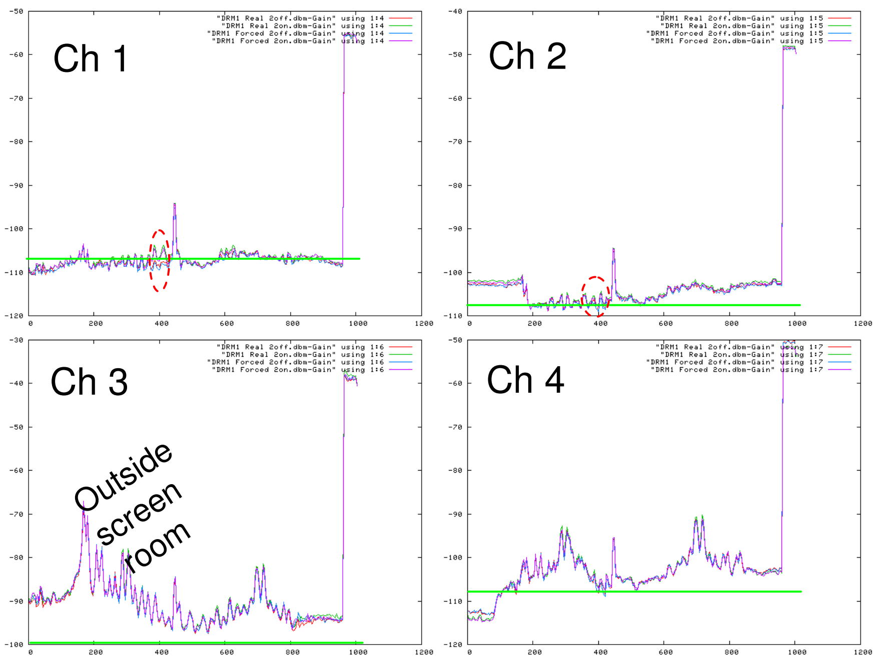




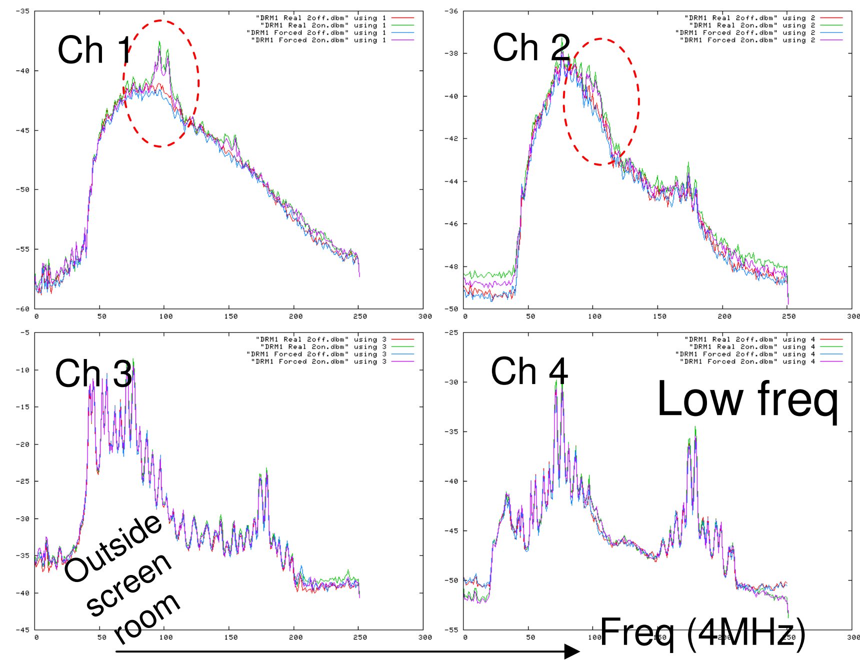
Is the DRM quiet

- Screen chamber was built inside the old dfl
- -174 dbm/Hz thermal floor translates into -108 dbm/4Mhz.
- DRM1 is watching DRM2:

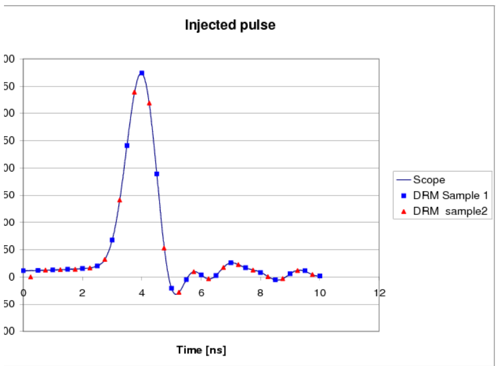
Gain corrected Average FFT Spectrum:



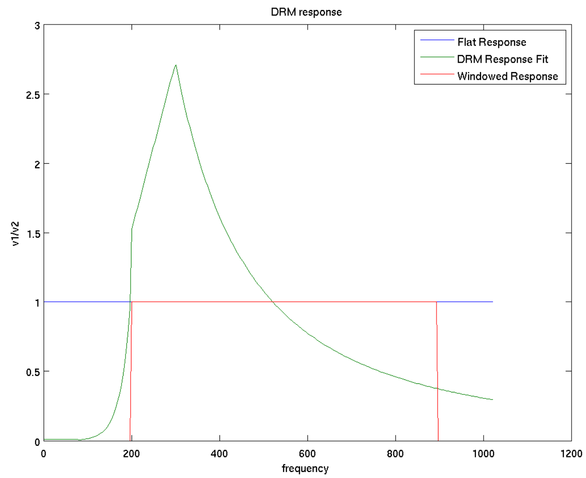
Average FFT Spectrum:



Confirmed Response to a sharp pulse



⊗



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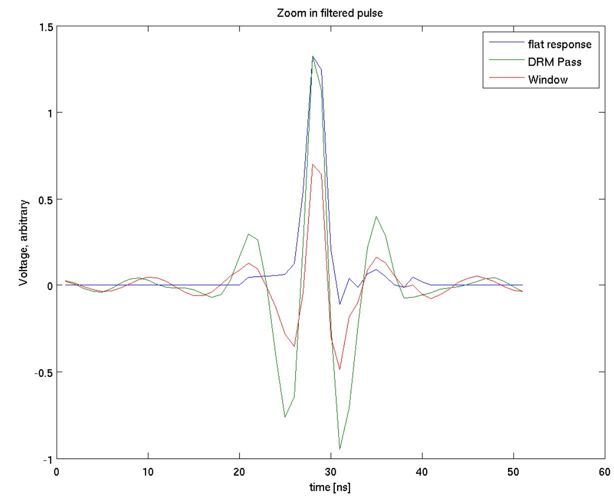
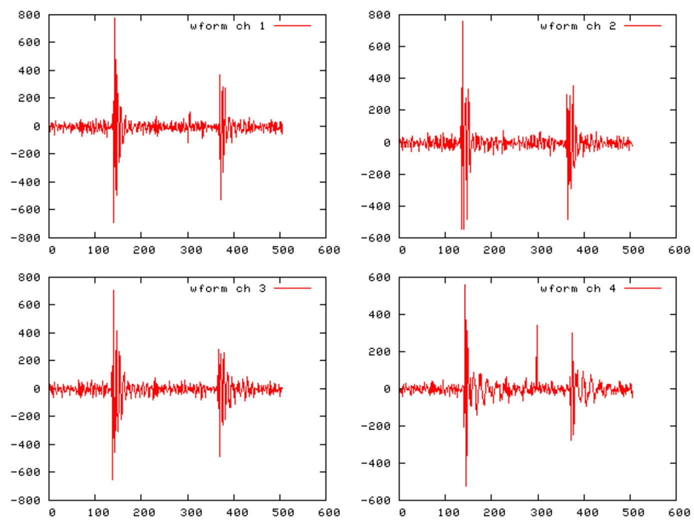
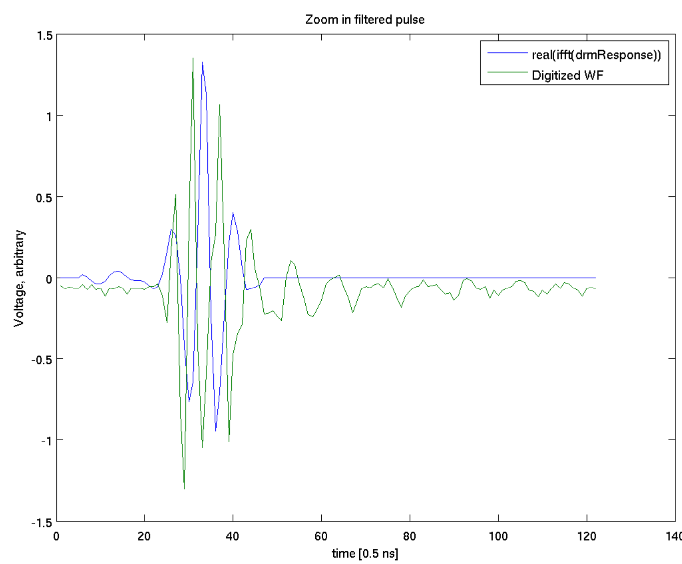


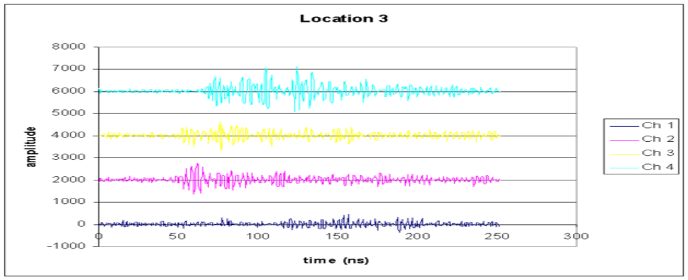


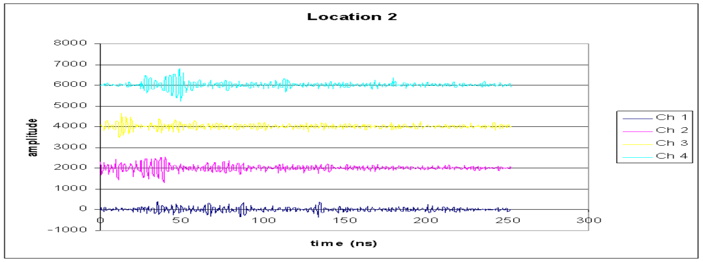


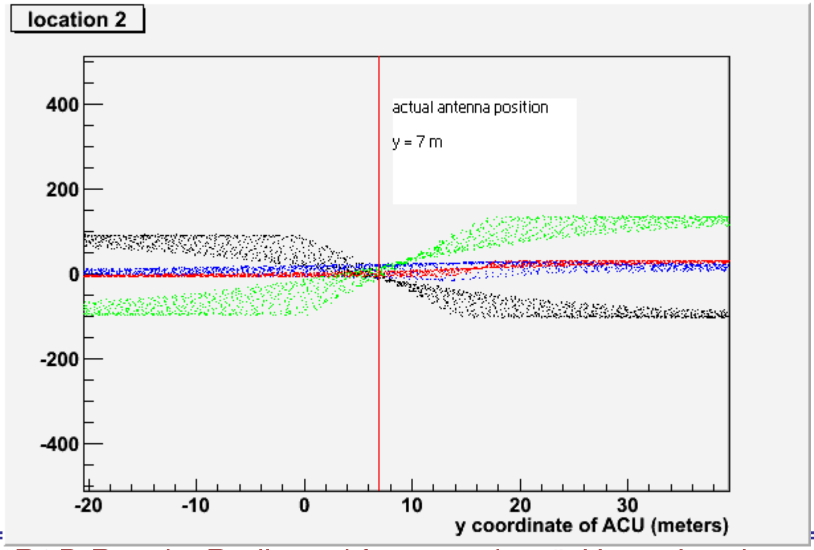
"R&D Results Radio and future options", Hagar Landsman; IceCube Science Advisory Committee,May 13 09;

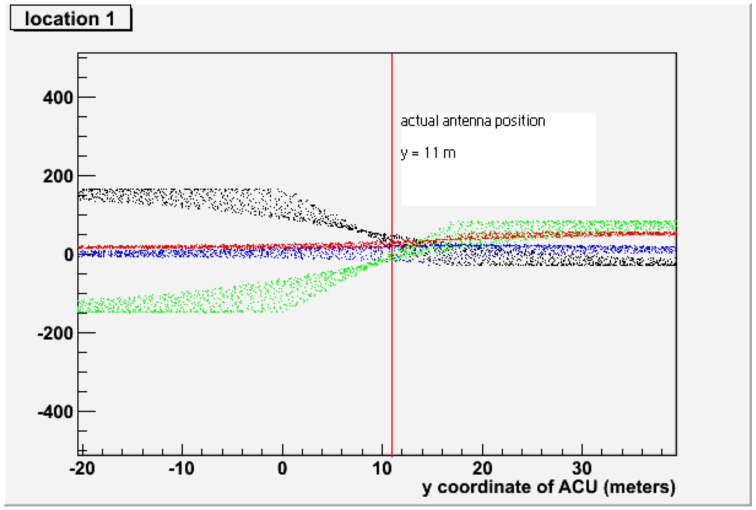
Confirmed vertexing ability

- Cluster was spaced in the PSL production hall. Antennas ~3 m high.



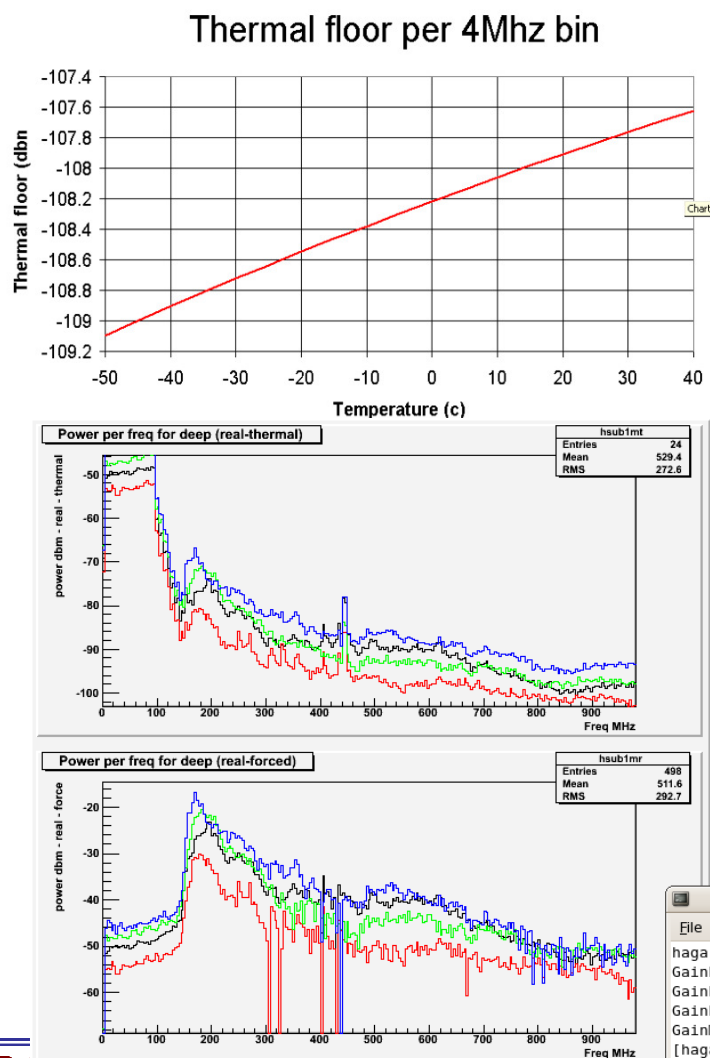


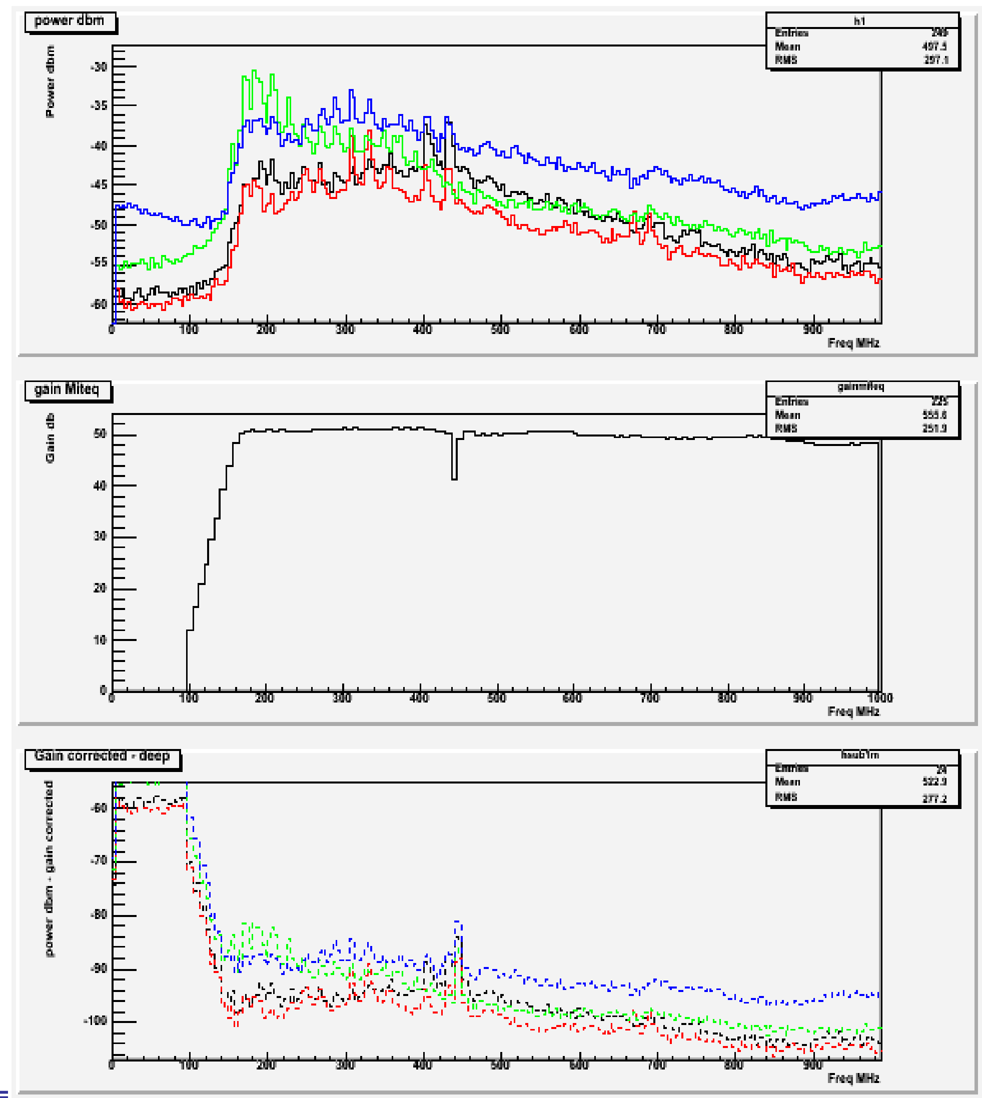




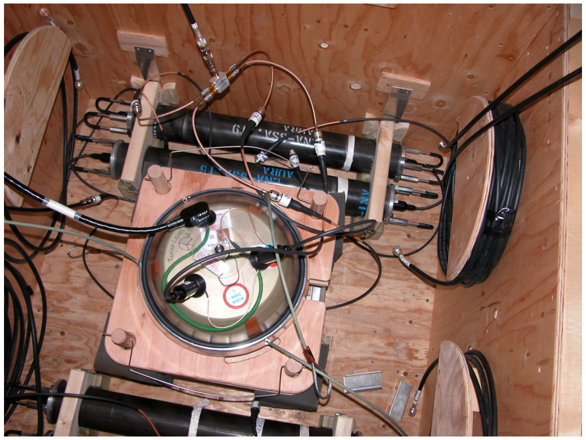
"R&D Results Radio and future options", Hagar Landsman; IceCube Science Advisory Committee,May 13 09;

Noise levels – per freq bin

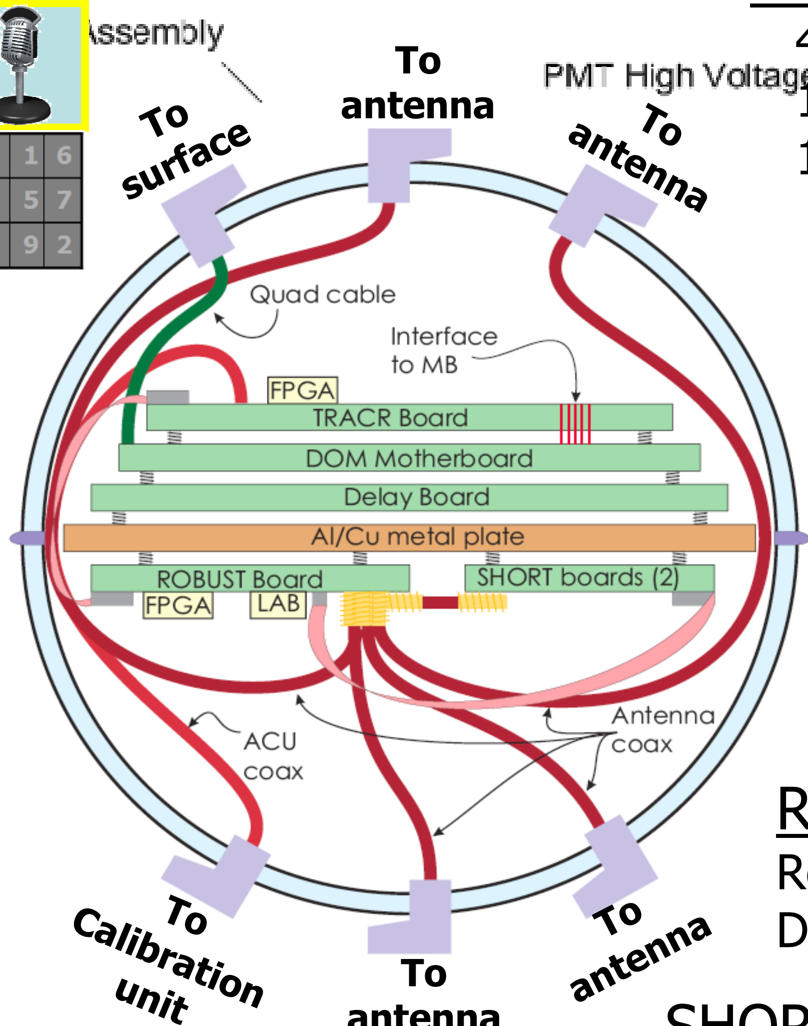




“R&D Results Radio and future options”, Hagai Landsman;
IceCube Science Advisory Committee,May 13 09;



Digital Radio Module (DRM)



<u>6 Penetrators</u>:

- 4 Antennas
- 1 Surface cable
- 1 Calibration unit

<u>TRACR Board</u>

Trigger Reduction and Comm for Radio

Data processing, reduction, interface to MB

<u>MB (Mainboard)</u>

Communication, timing, connection to IC DAQ infrastructure,

<u>Shielding</u> separates noisy components

<u>ROBUST Board</u>

ReadOut Board UHF Sampling and Triggering Digitizer card

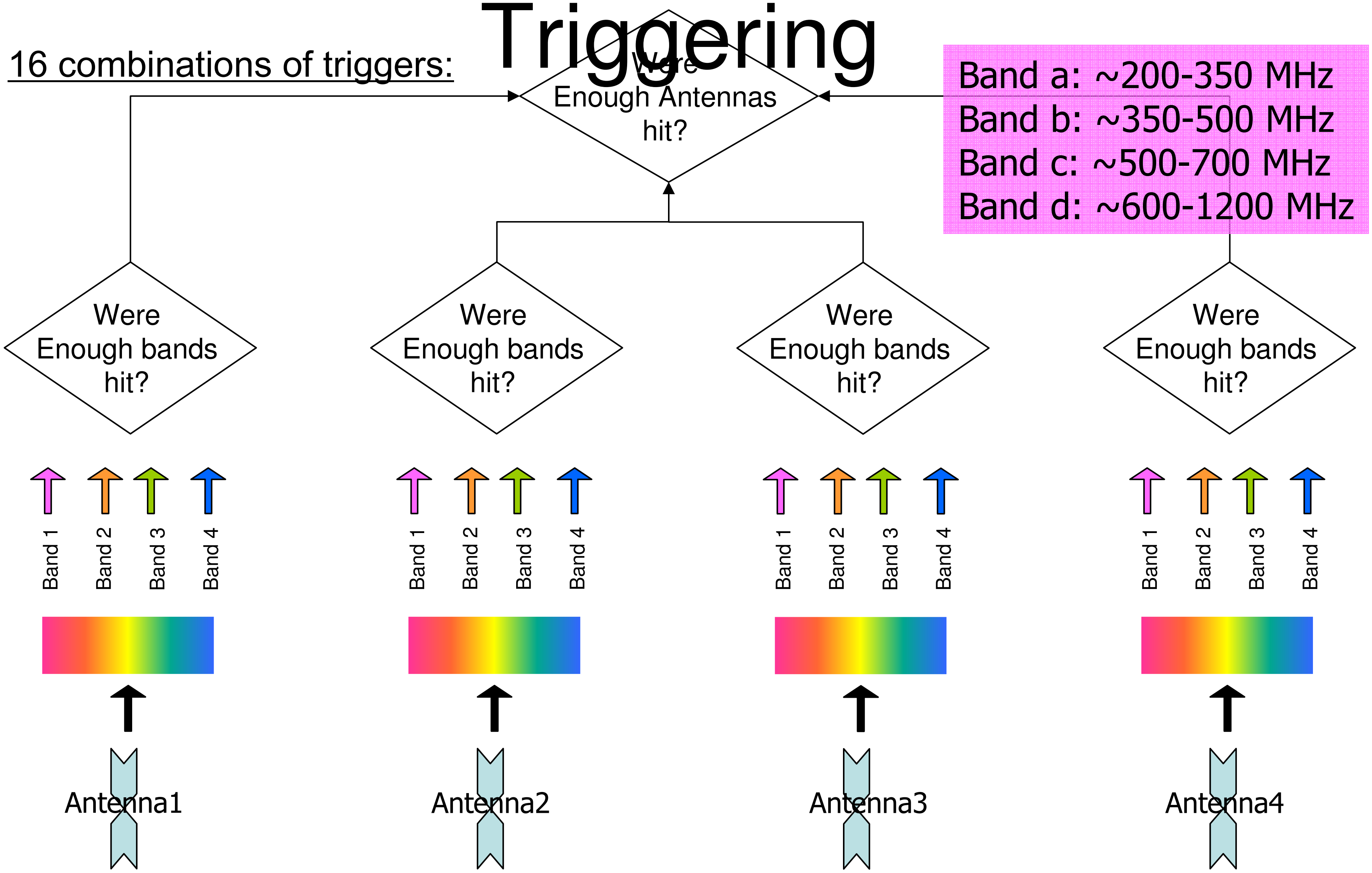
<u>SHORT Boards</u>

Surf High Occupancy RF Trigger Trigger banding

Triggering

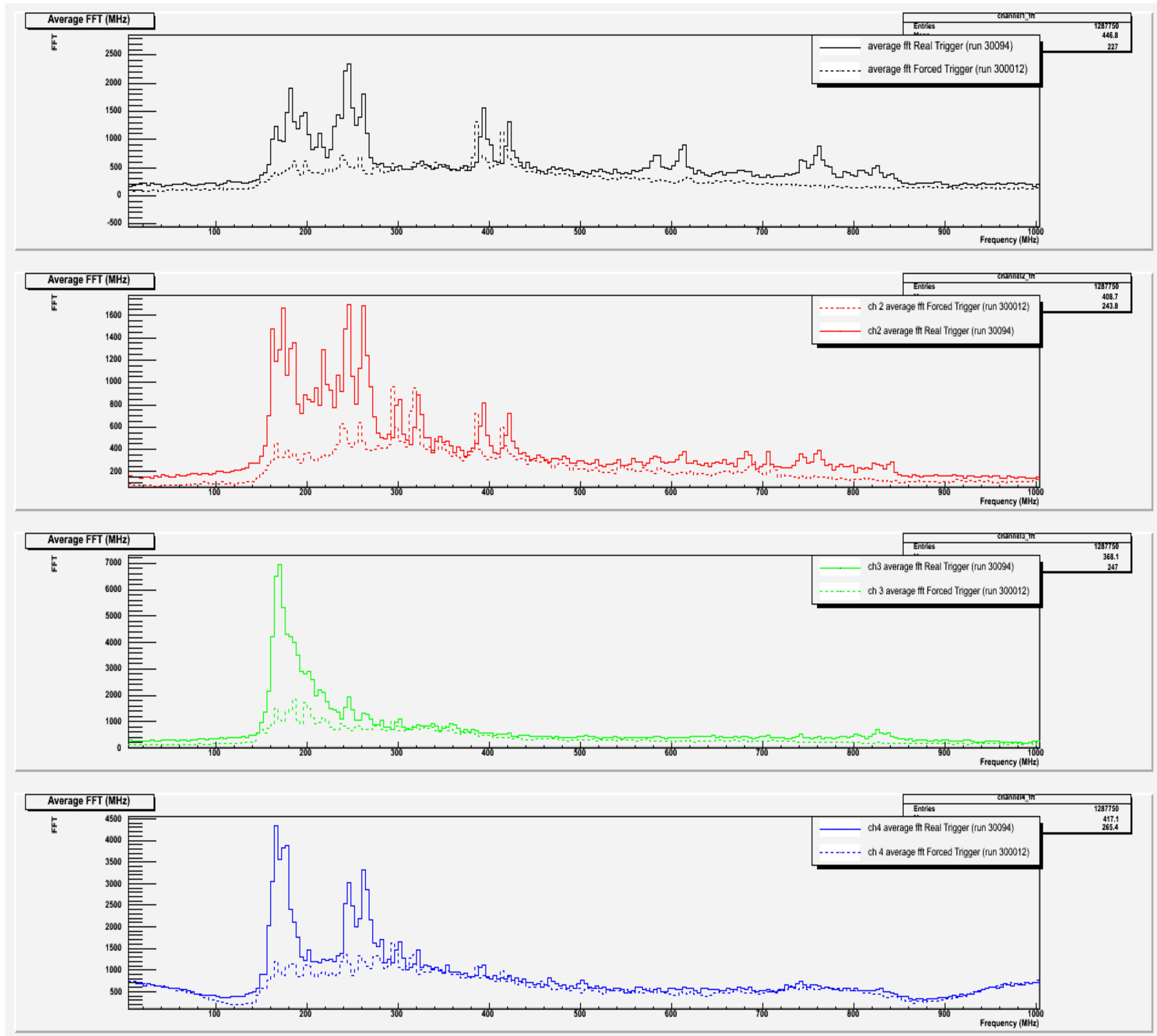
16 combinations of triggers:

Band a: ~200-350 MHz
Band b: ~350-500 MHz
Band c: ~500-700 MHz
Band d: ~600-1200 MHz

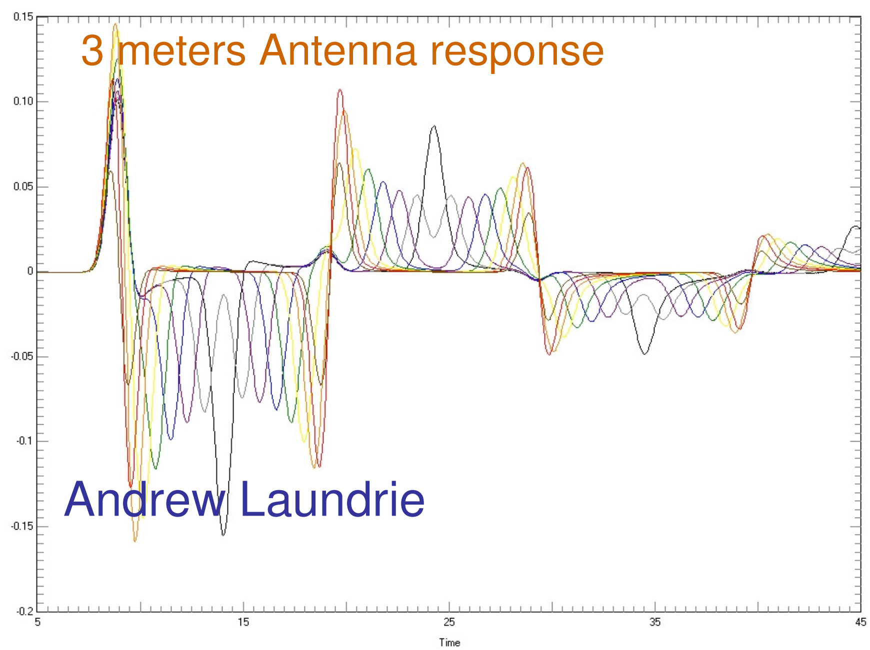


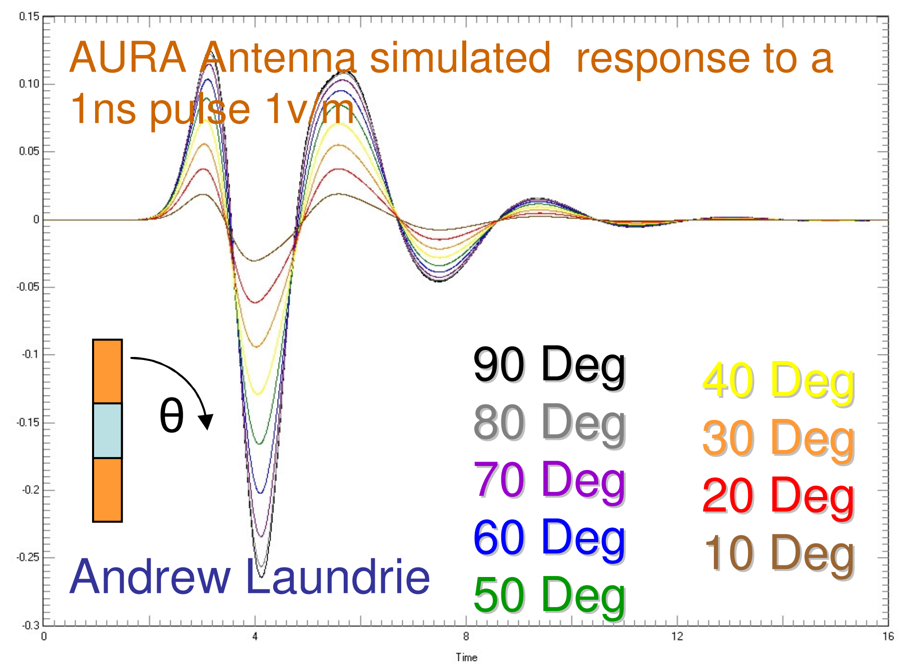
Solid- “Real Trigger”

Dashed -“Forced trigger”



Antennas simulation using Finite-Difference Time-Domain Analysis



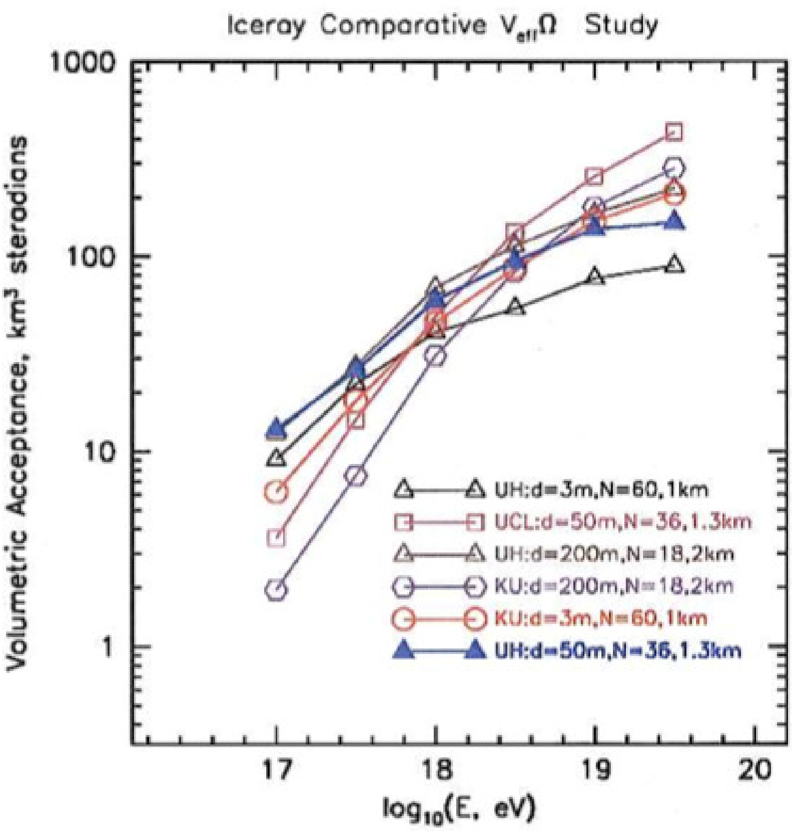


As the source pulse becomes shorter relative to the electrical length of the antenna, the resulting waveform has more information about the angle of arrival

Longer antenna may

- Also working on: Simulated Cherenkov radiation
- Antenna for transmitting Cherenkov-like radiation (useful for testing hardware)

Acceptance and Event Rates



Cosmogenic neutrino model	36sta/50m events/yr	18sta/200m events/yr
Fe UHECR, std. evolution	0.50	0.60
Fe UHECR strong src. evol.	1.6	1.8
ESS 2001, $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$	3.5	4.4
Waxman-Bahcall-based GZK-ν flux	4.2	4.8
Protheroe and other standard models	4.2-7.8	5.5-9.1
Strong-source evolution (ESS,others)	12-21	13.8-28
Maximal, saturate all bounds	24-40	32-47

Initial phase achieves 3-9 ev/year for “standard” fluxes

Final phase: ~100 ev/year

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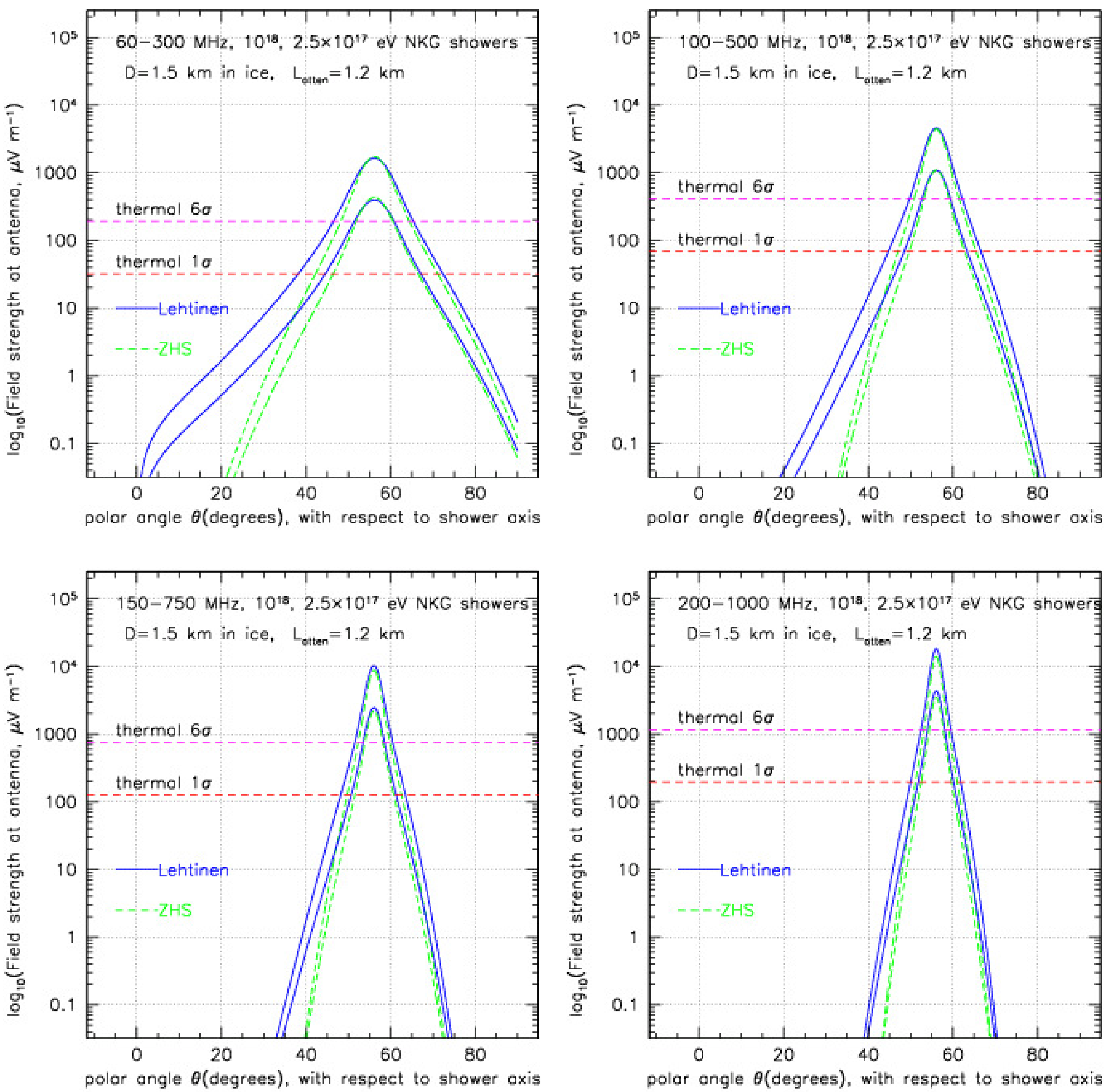
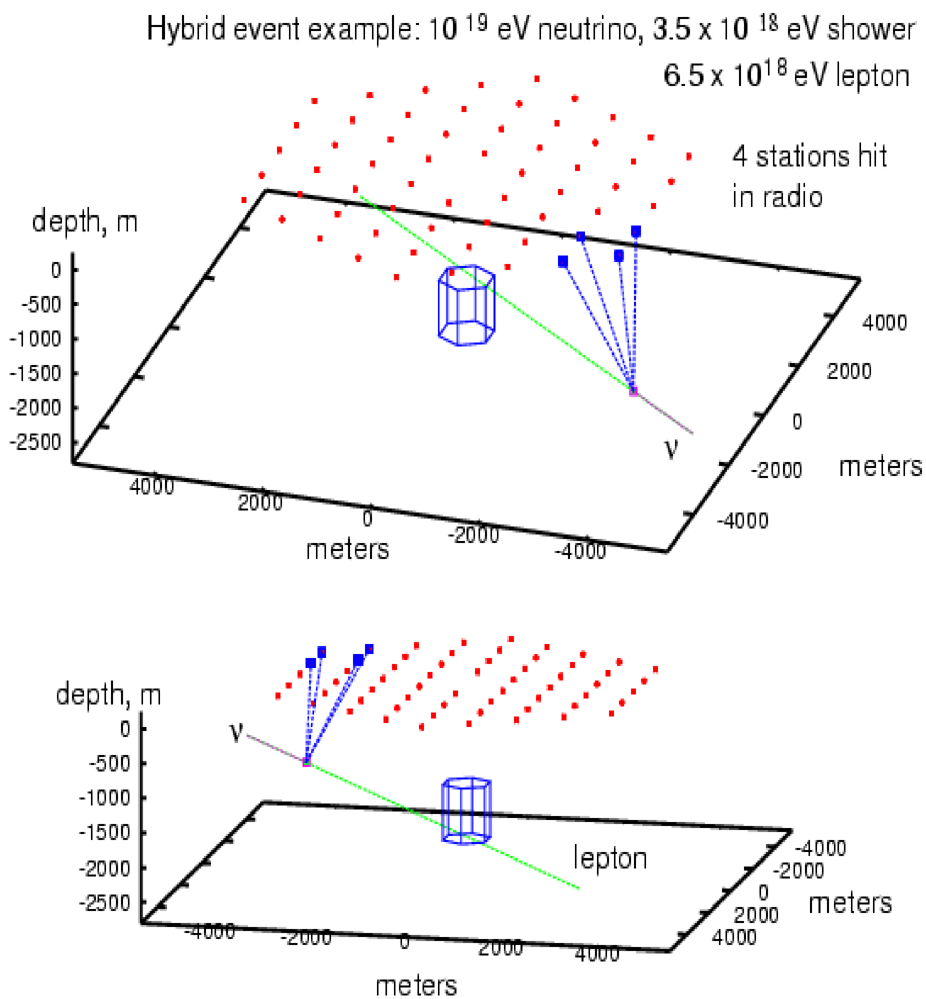
IceCube Science Advisory Committee,May 13 09;

Frequency Range



- Ice is better at low frequency (< 500 MHz)
- Solid angle also better at low freq.
- SNR goes as sqrt(bandwidth)
- Go low freq., high bandwidth: 60-300 MHz

"Golden" Hybrid Events



IceRay-36 / shallow

Cosmogenic neutrino model	IceCube 10 yrs	IceCube+ 10 yrs
ESS 2001 $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$	3.2	6.4
Waxman-Bahcall-based GZK-ν flux	3.8	7.6
Protheroe and other standard models	3.8-7.1	5.0-8.2
Strong-source evolution (ESS,others)	10-19	13-25
Maximal fluxes, saturate all bounds	22-36	30-44

- Triggering both IceRay and IceCube: rates are low, but extremely valuable for calibration
- High-energy extension (IceCube+ above) with 1.5km ring helps a lot
- Sub-threshold cross-triggering can also help

Askaryan effect

Neutrino interact in ice
→ showers
→ Many e^-,e^+, γ
→ Interact with matter
→ Excess of electrons
→ Cherenkov radiation
→ Coherent for wavelength larger than shower dimensions

$$dP_{CR} \propto \nu d\nu$$

Moliere Radius in Ice ~ 10 cm:
This is a characteristic transverse dimension of EM showers.
$\lambda \ll R_{Moliere}$ (optical), random phases $\Rightarrow P \propto N$
$\lambda \gg R_{Moliere}$ (RF), coherent $\Rightarrow P \propto N^2$

Hadronic (initiated by all ν flavors)
EM (initiated by an electron, from ν_e)

Vast majority of shower particles are in the low E regime dominates by EM interaction with matter

Less Positrons:
Positron in shower annihilate with electrons in matter $e^+ + e^- \rightarrow \gamma\gamma$
Positron in shower Bhabha scattered on electrons in matter $e^+e^- \rightarrow e^+e^-$

More electrons:
Gammas in shower Compton scattered on electron in matter $e^- + \gamma \rightarrow e^- + \gamma$

Charge asymmetry: 20%-30% more electrons than positrons.

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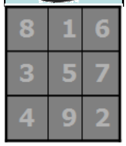
IceCube Science Advisory Committee,May 13 09;



LPM effect

Landau-Pomeranchuk-Migdal

☺ As the energy increases, the multiplicity of the shower increases and the charge asymmetry increases.

☹ As the energy increases, mean free path of electrons is larger then atomic spacing (~1 PeV) (LPM effect).
→ Cross section for pair production and bremsstrahlung decreases
→ longer, lower multiplicity showers

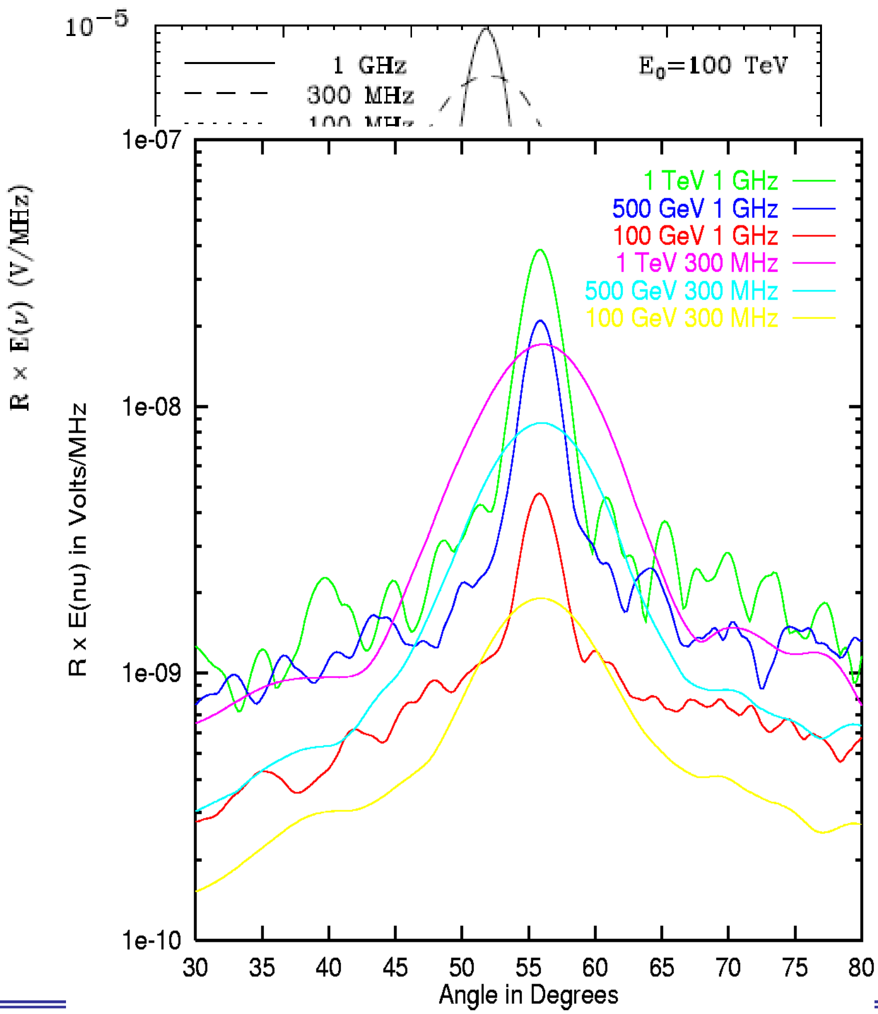
The Neutrino Energy threshold for LPM is different for Hadronic and for EM showers

→ Large multiplicity of hadronic showers. Showers from EeV hadrons have high multiplicity ~50-100 particles.
→ Photons from short lived hadrons
→ Very few E>100 EeV neutrinos that initiate Hadronic showers will have LPM

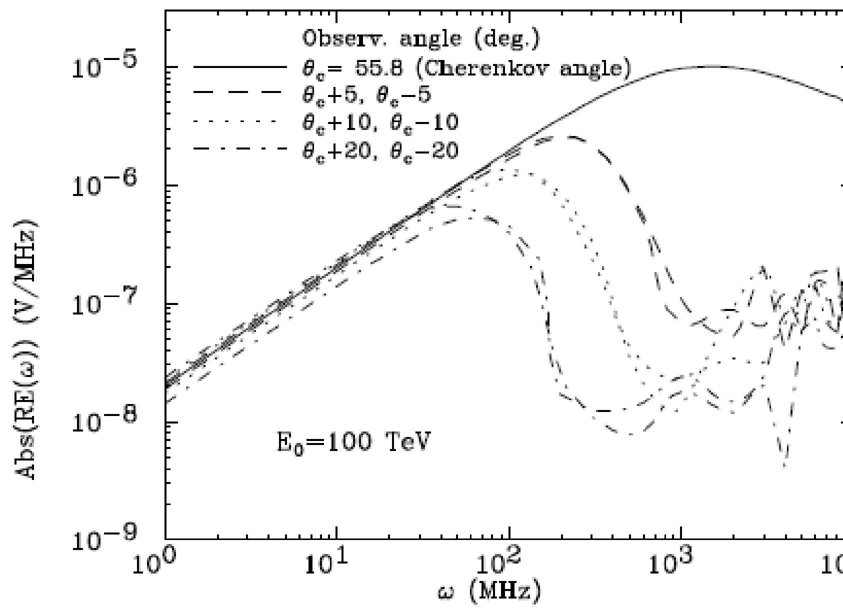
- **In high energy, Hadronic showers dominate**
- **Some flavor identification ability**

Askaryan Signal

Electric Field angular distribution



Electric Field frequency spectrum



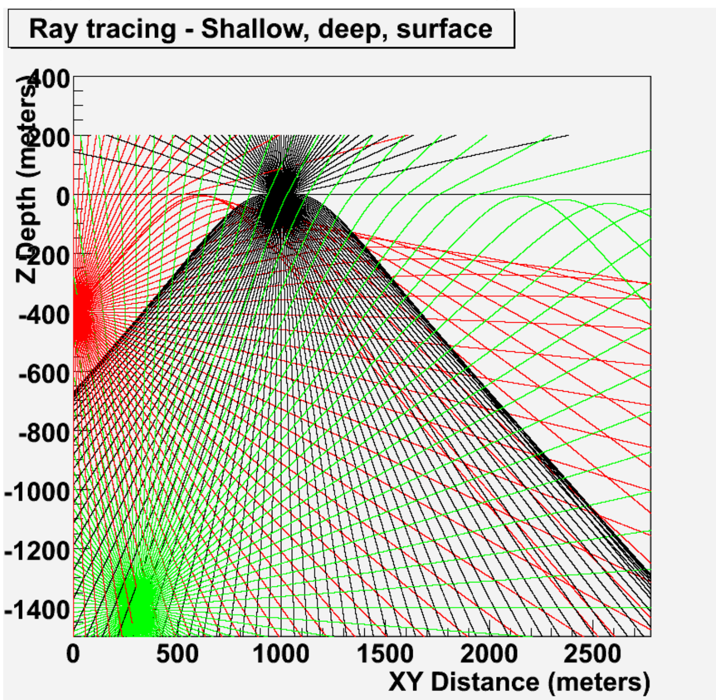
Astro-ph/9901278 Alvarez-Muniz, Vazquez, Zas 1999

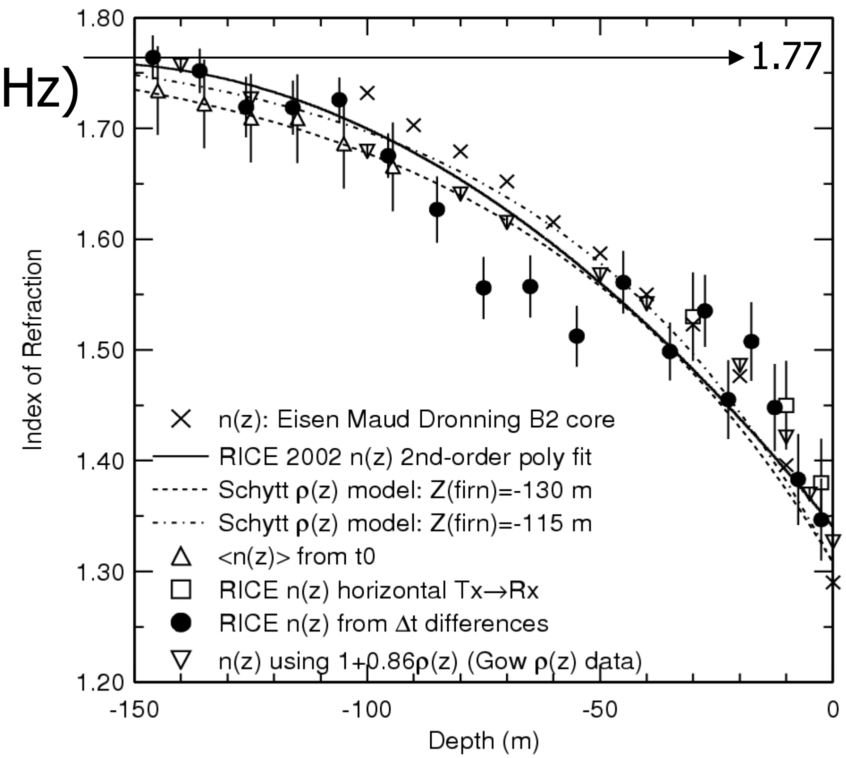
“R&D Results Radio and future options”, Hagar Landsman; IceCube Science Advisory Committee,May 13 09;

Ice Properties: Index Of Refraction

- RICE Measurements (2004, Down to 150 m, 200MHz-1GHz)
- Ice Core Measurements (…-1983, down to 237 meters)

$$n(z) = 1.35 + 0.438(1.0 - e^{-0.0132Z})$$





Kravchenko et al. J.Glaciology, 50,171,2004

AURA-Askaryan Under-ice Radio Array

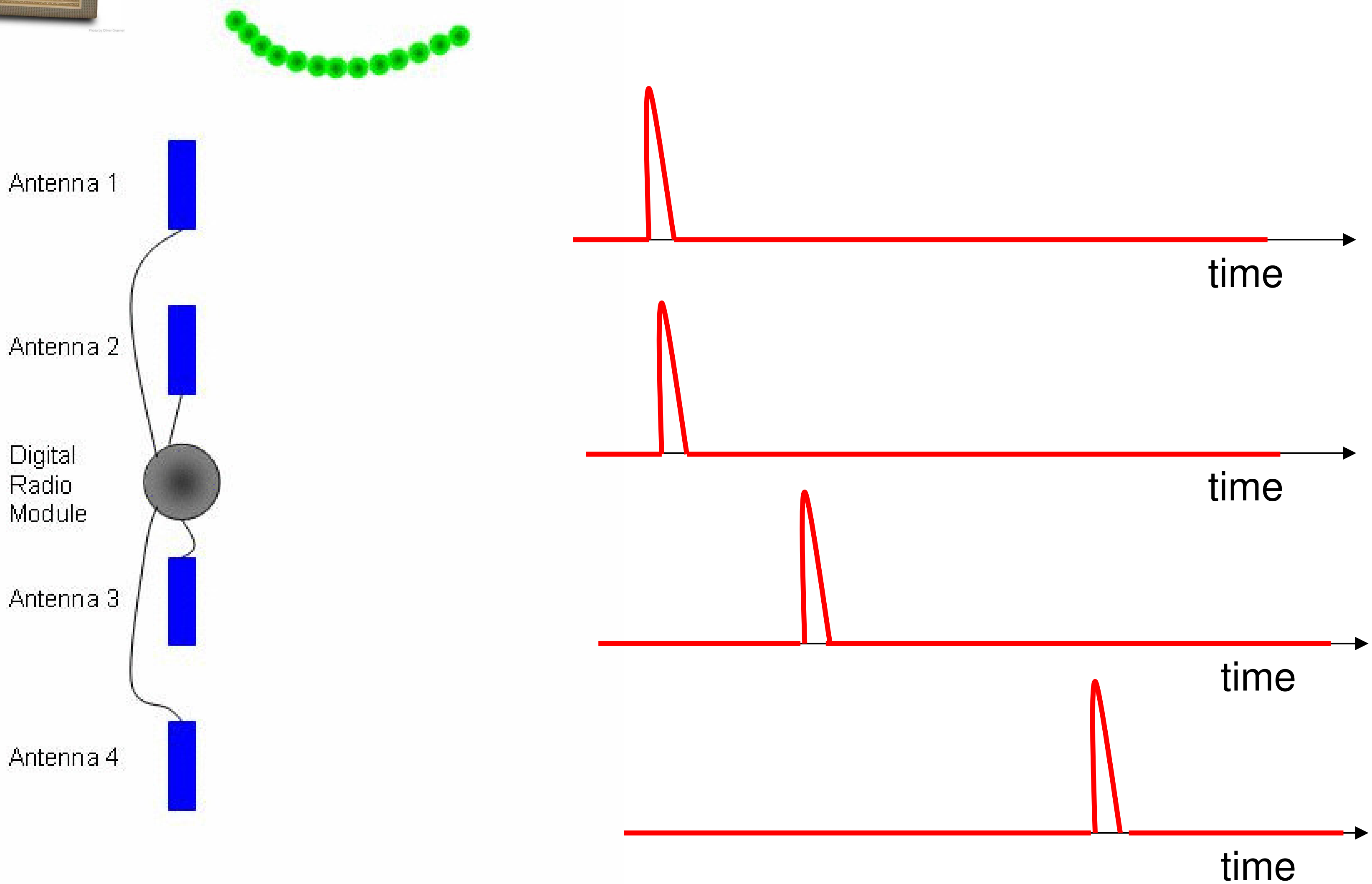
Prologue

Built upon "RICE" legacy,
"AURA" is an RF extension
to the IceCube array
as R&D towards a large scale
GZK detector in deep Antarctic ice.

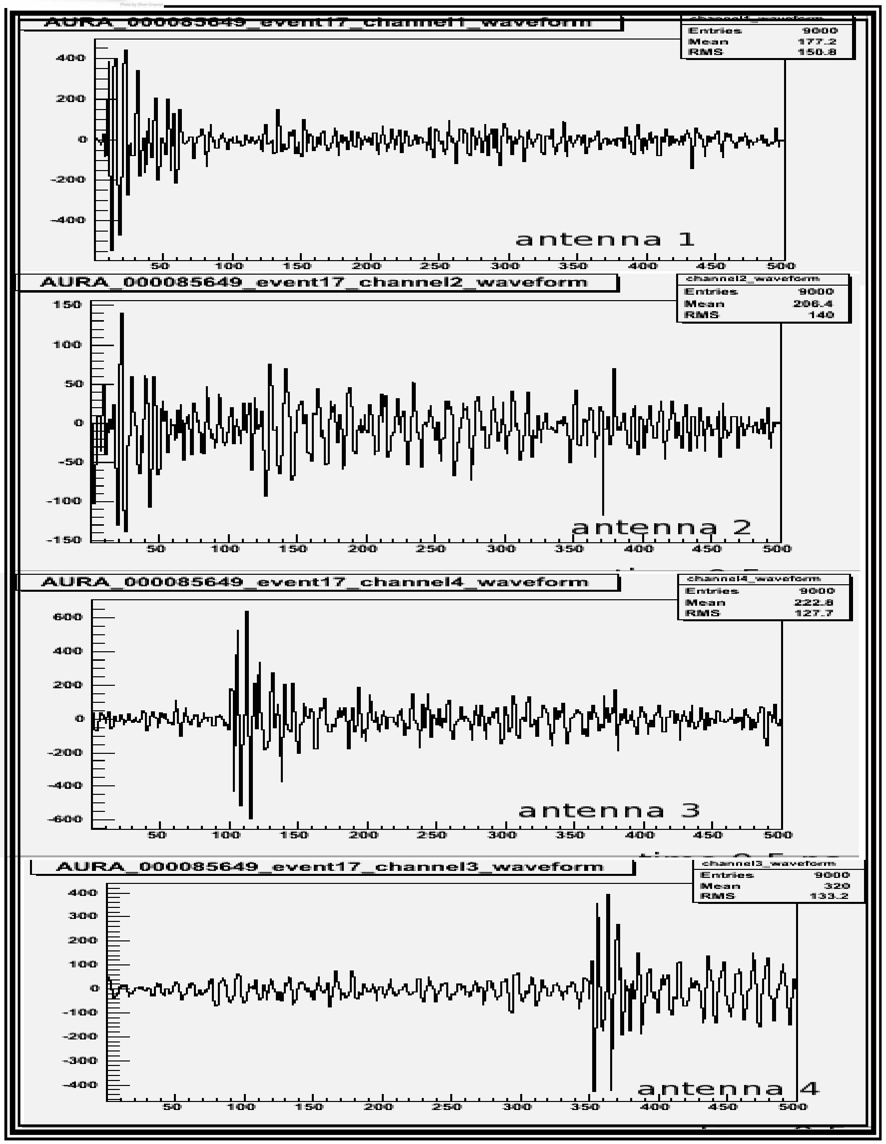
We have 5 Clusters deployed,
and hope to deploy 3 more
this winter

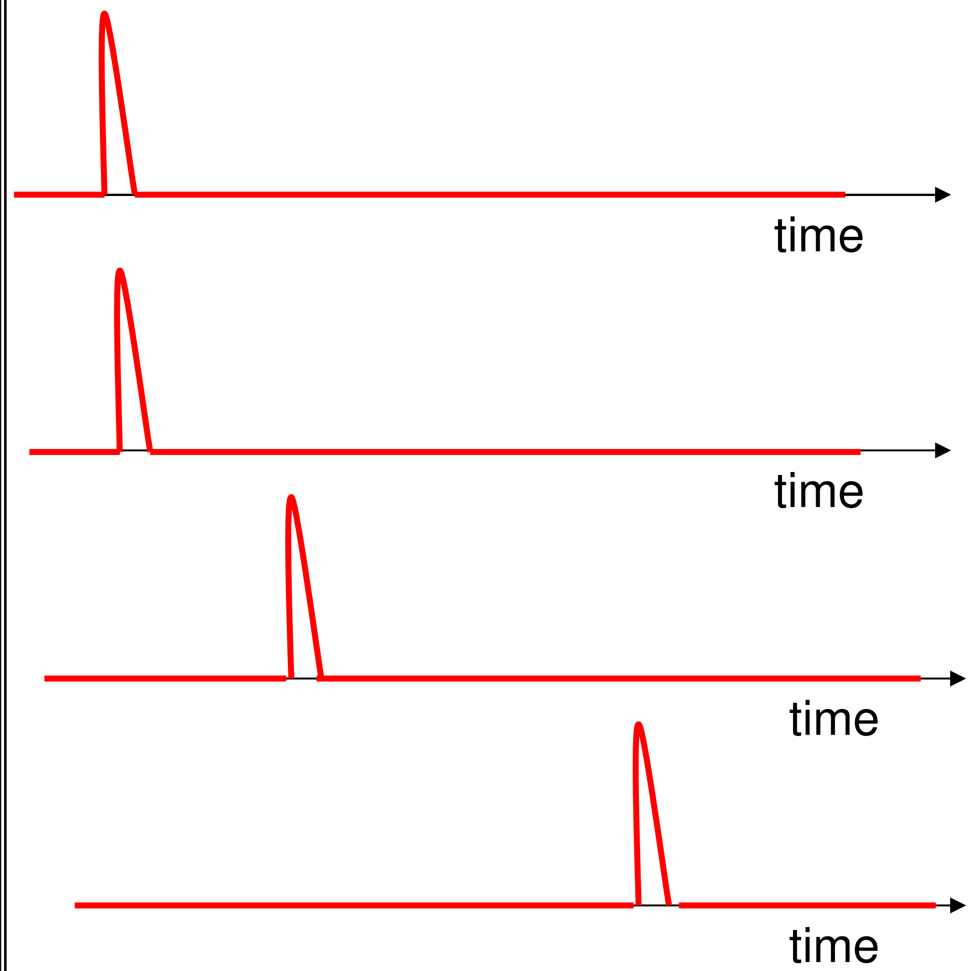
Photo by Jan auffenberg

Down going event signature



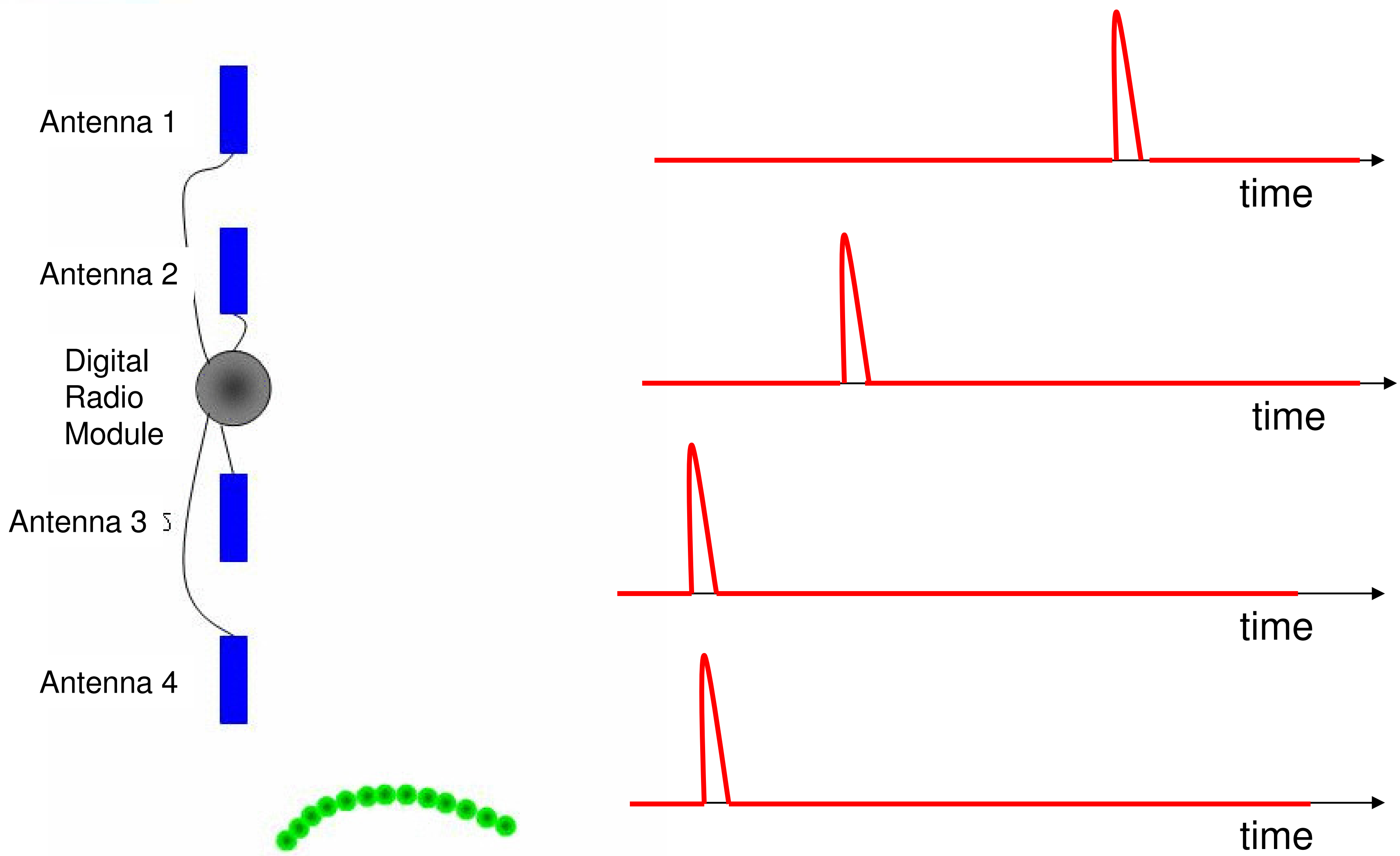
Down going event candidate





"R&D Results Radio and future options", Hagar Landsman;
IceCube Science Advisory Committee,May 13 09;

Up going event signature



"R&D Results Radio and future options", Hagar Landsman;
IceCube Science Advisory Committee,May 13 09;

Up going event signature