The Askar'yan Radio Array

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Université Libre de Bruxelles
VLVnT11 – Erlangen, Germany
14 October 2011

The ARA Collaboration

Taiwan National University

University of Kansas at Lawrence

UNIVERSITY OF DELAWARE

千葉大学 Chiba University

THE UNIVERSITY of WISCONSIN MADISON

UNIVERSITY OF MARYLAND

UNIVERSITY OF HAWAI'I

THE OHIO STATE UNIVERSITY

UCL

University College London

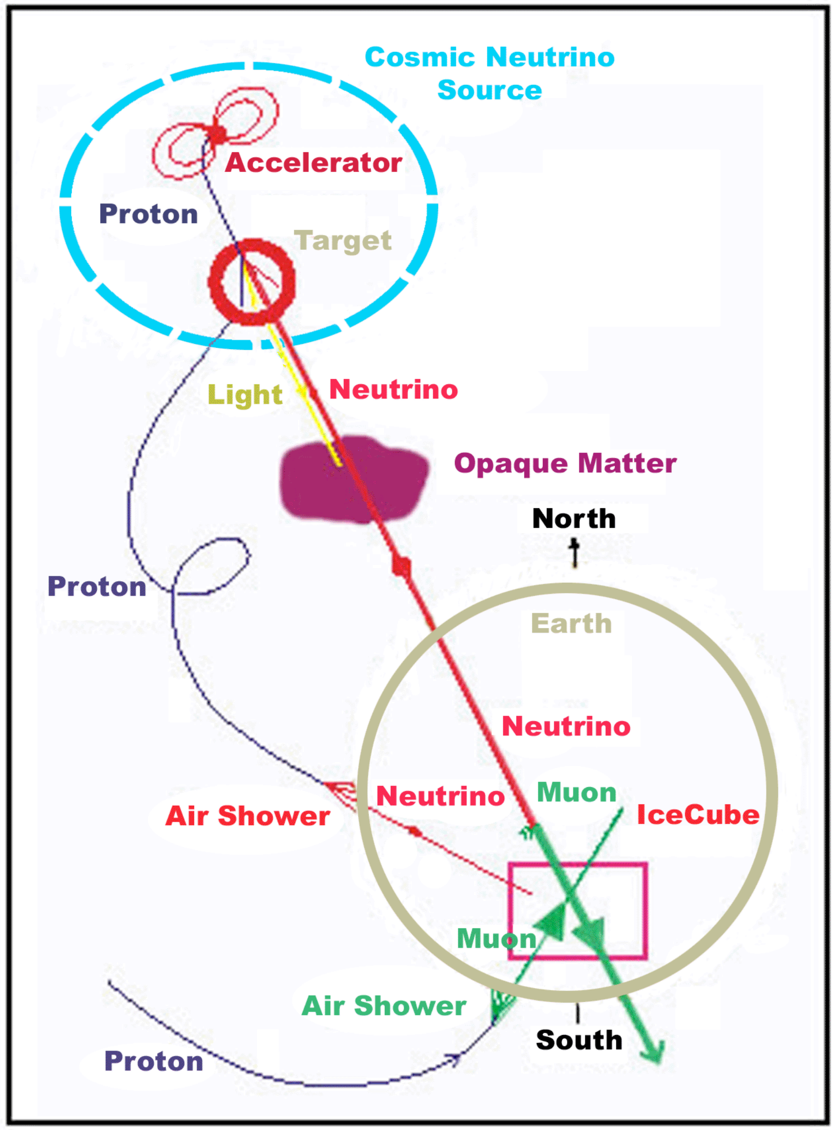
ULB UNIVERSITÉ LIBRE DE BRUXELLES

ARA Project Science Goals

- Detection of UHE neutrinos, principally those produced in scatter of UHECR on CMBR (GZK) but also neutrinos from source
- You can find the details in arXiV:1105.2854 (submitted to Astropart. Phys.)
- Often billed as radio extension to IceCube:
  - While "hybrid" optical / radio event would be fantastic golden event validating radio detection technique …
  - and while there exists considerable overlap in Venn diagrams describing ARA / IceCube collaborations …
- ARA was built to stand on its own. In fact design optimized such that each station is sufficient detector of UHE neutrinos. This optimizes efficiency at "low" energies below 10^{18} eV.

Neutrinos: the (almost) ideal messengers

- Neutrinos being neutral and weakly interacting are good choice for astrophysical messenger particle - they travel direct from production point even if obscured by material.
- Of couse the weak cross section is a curse while it is a blessing
  - horribly weak fluxes of TeV neutrinos need km^2-scale (or bigger) detectors such as IceCube
  - ridiculously weak fluxes of EeV-scale scale neutrinos want 100's of km^2 to achieve events. Optical detectors in ice cannot scale that big - need RF.



A standard IceCube diagram which depicts production, transit, and detection of cosmic neutrinos. This almost works for ARA but that the Earth is opaque to neutrinos of E > 100's of TeV.

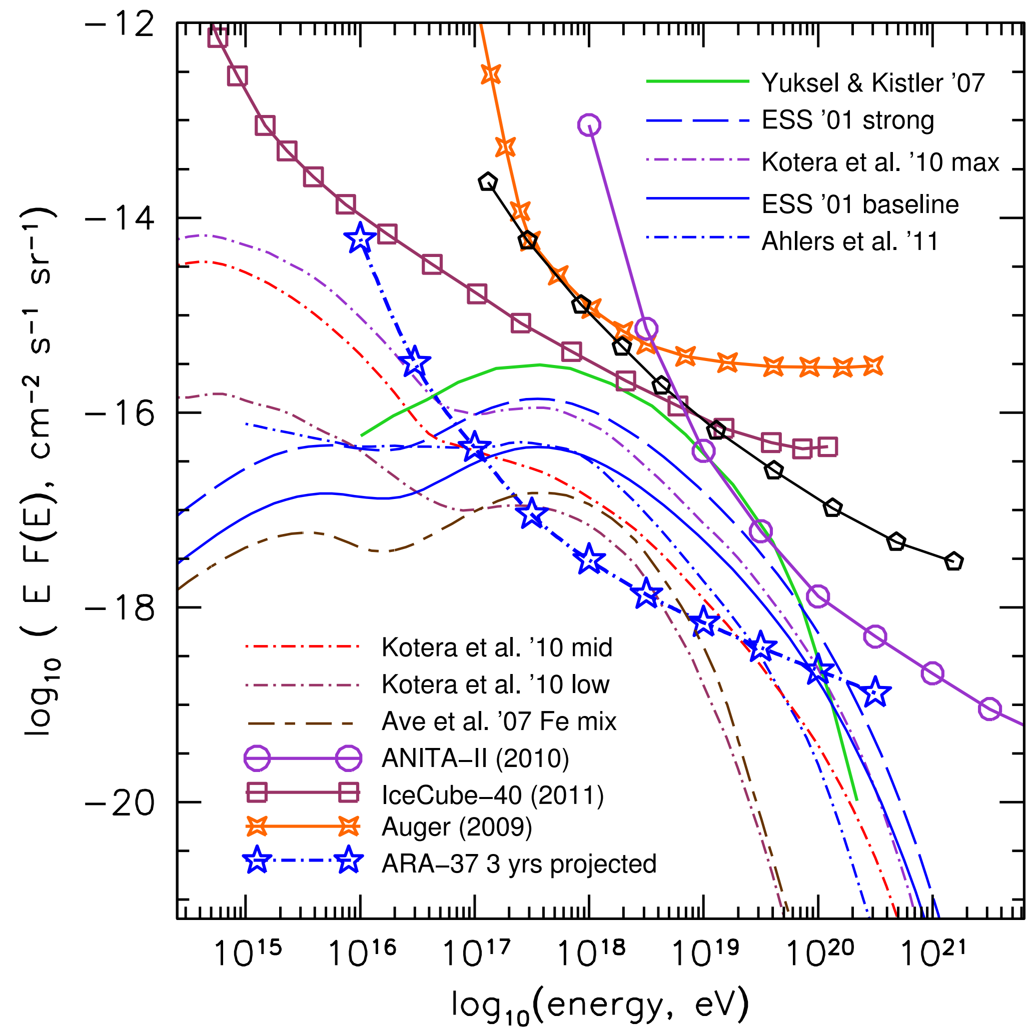
The State of the Art in GZK Neutrinos

At 30 EeV CMS energy sufficient in proton scatters off of CMB to produce pions through delta resonance. This resonant enhancement of cross section becomes principal absorption process for UHE CR protons limiting the mean free path to 10's of Mpc.

$$p + \gamma_{\mathrm{CMB}} \rightarrow \Delta^{+} \rightarrow p + \pi^{0}$$
$$\rightarrow n + \pi^{+}$$

This same interaction produces UHE neutrinos through mesonic decay which *can* propagate over cosmological distances even if their parent protons are absorbed nearby source. The neutrino arrival directions should be strongly correlated with source location due to parents' rigidity.

PAO data suggests cutoff in UHECR spectrum consistent with GZK phenomenon, however mass composition at these high energies is debated. Proton dominance would imply strong flux of GZK neutrinos while heavier compositions lead to significantly reduced fluxes.



Sensitivities of UHE neutrino observatories to GZK neutrino flux models. Original plot by P. Gorham.

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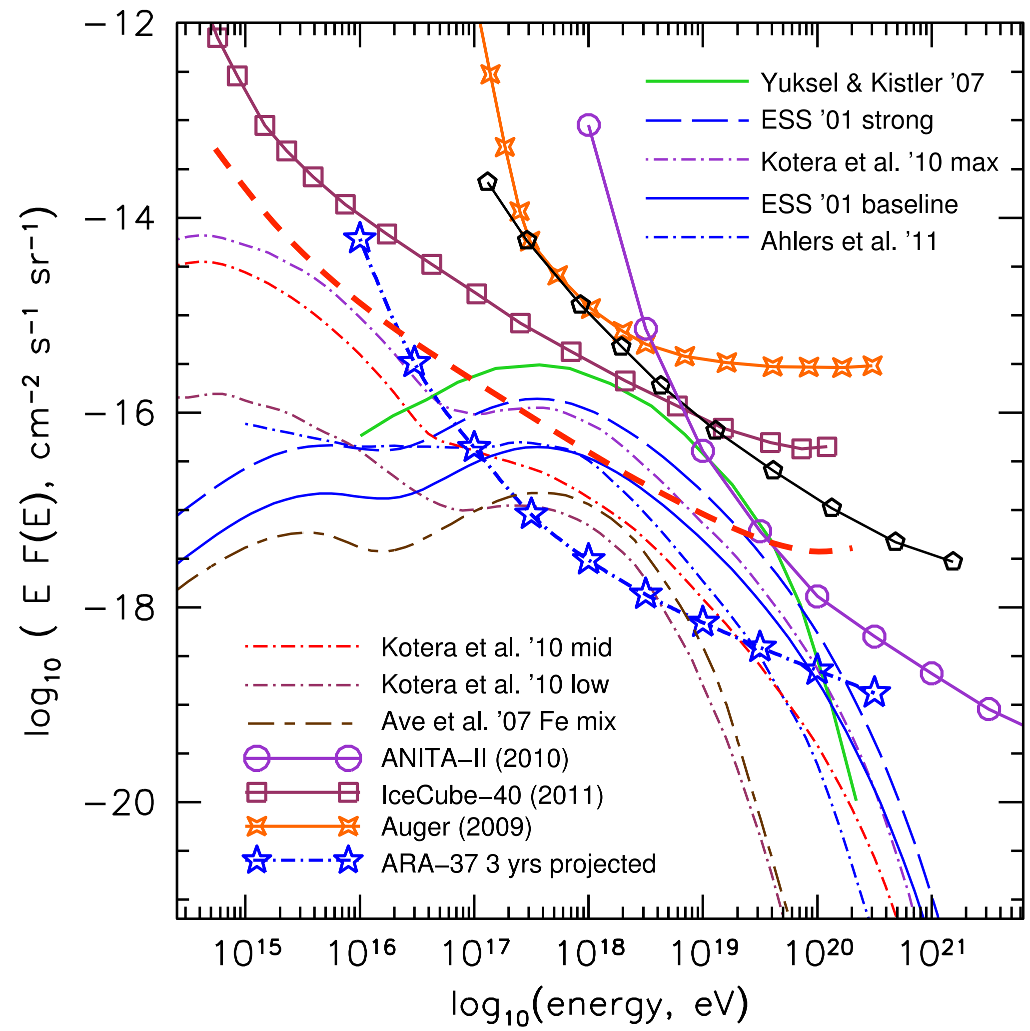
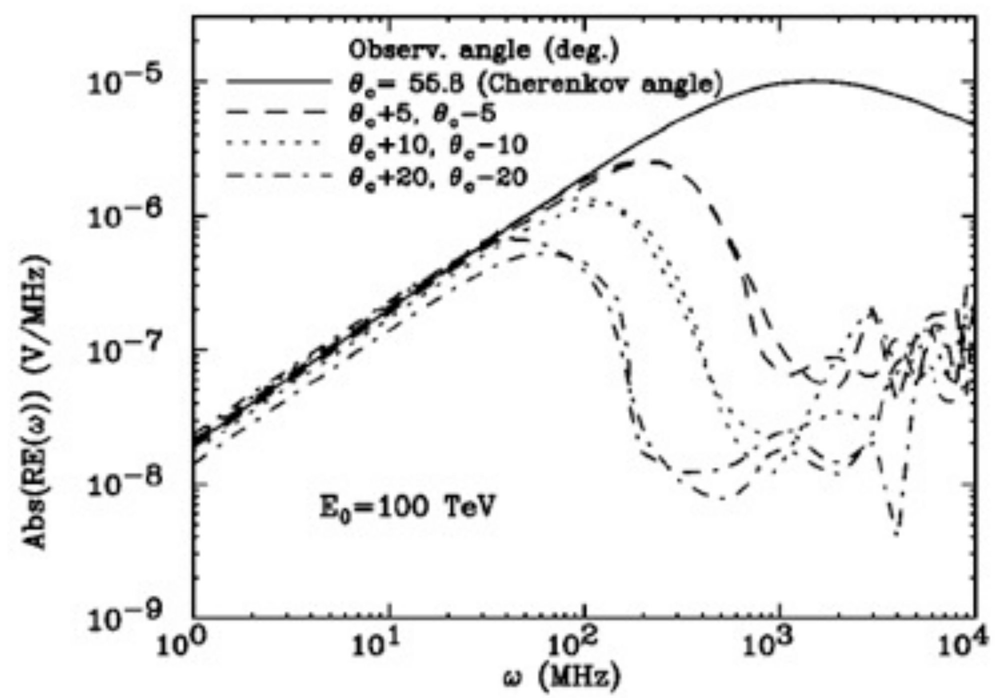


Sensitivities of UHE neutrino observatories to GZK neutrino flux models. Original plot by P. Gorham.

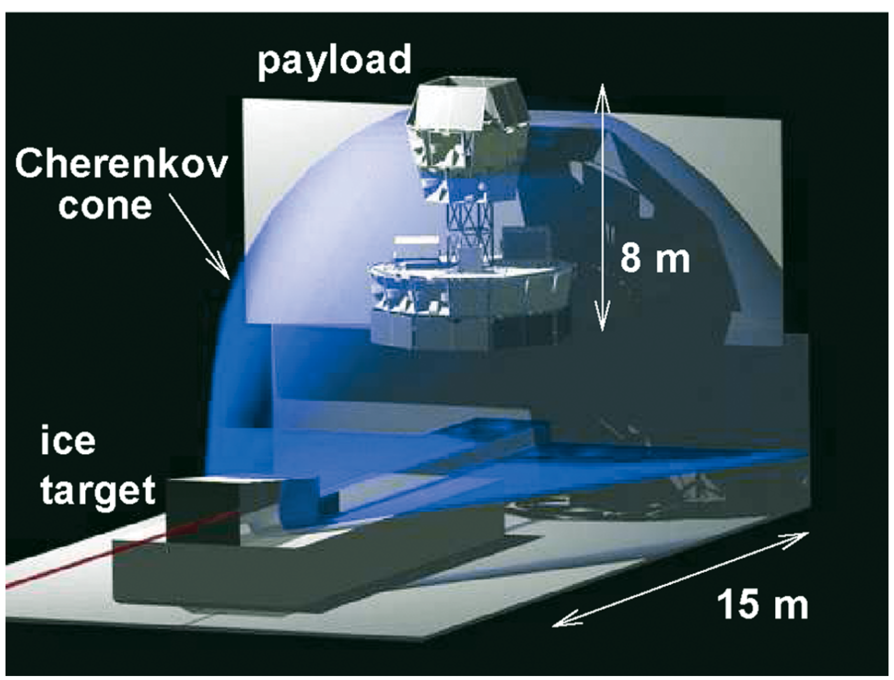
Detection of UHE neutrinos in ice: the Askar'yan Effect

From Alvarez et. al. Phys. Rev. D **61** 023001



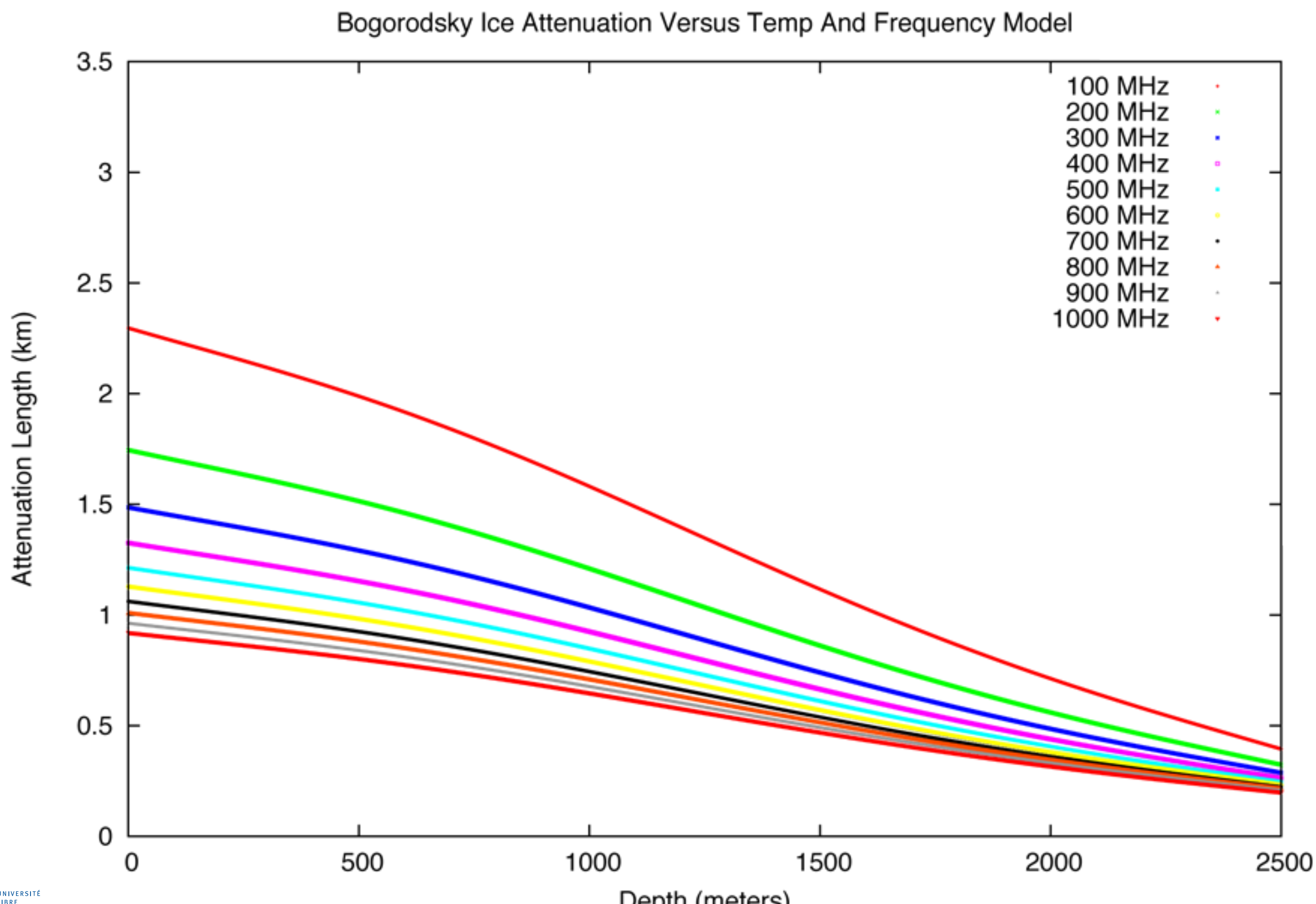
First proposed by G. Askaryan in 1960's the Askaryan effect occurs in energetic cascades due to slight excess of negative charge over positive charge; this leads to a coherent EM pulse, parameterized by ZHS (PRD 45 (1992) 362), AVZ (PRD 61 (1999), and others. General features of radiation include:

- Approx. linear scaling of impulse with cascade energy
- Peak power at 1 GHz when detector at Cherenkov angle
- Width of cone extremely narrow at GHz (degree) widening to tens of degrees at 100 MHz

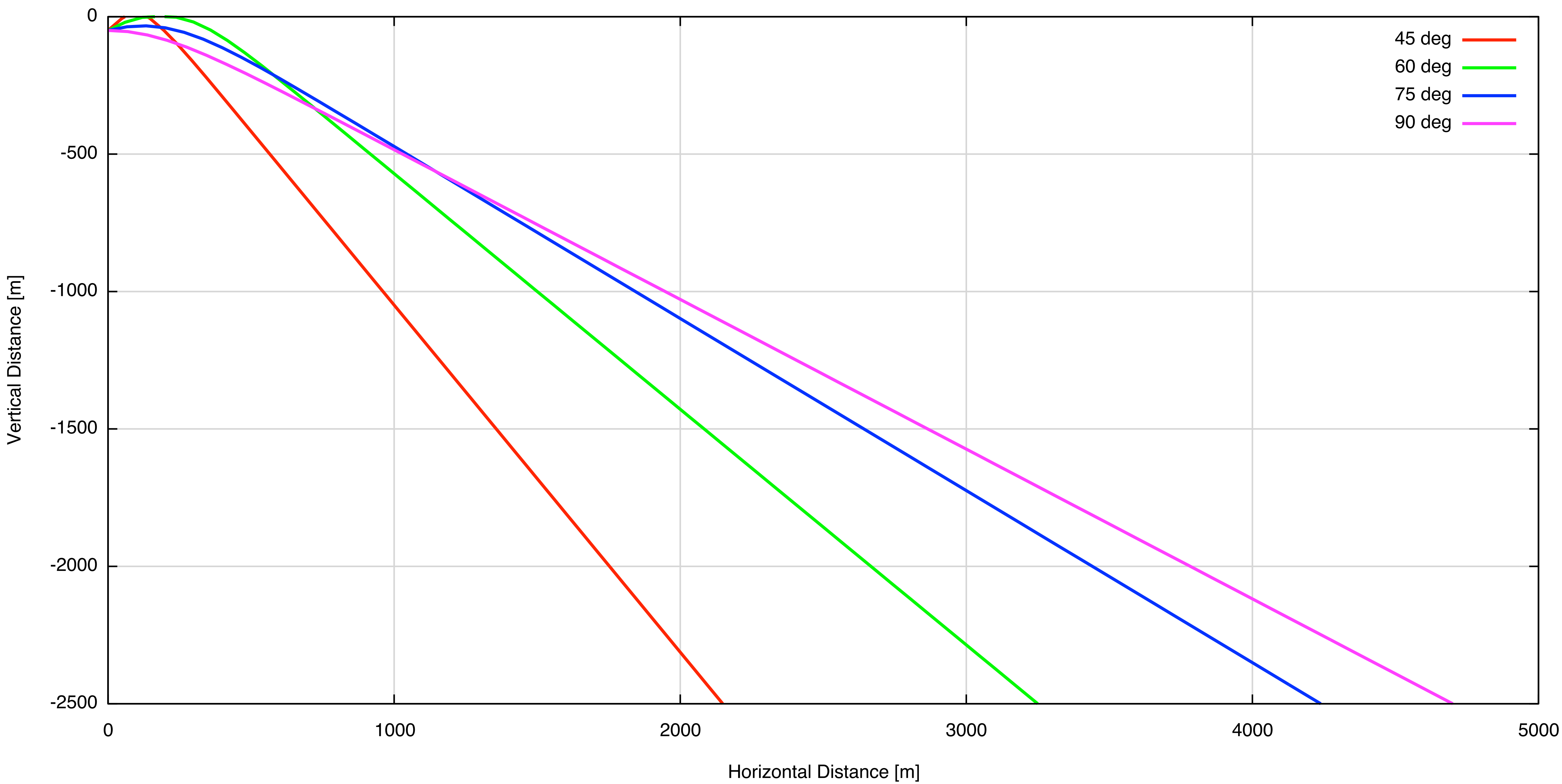


- The Askaryan effect and the parametrization of the EM field by ZHS and later AVZ has been experimentally verified at SLAC T460 test beam (Gorham et al PRL 99 (2007) 171101)
- **Why South Pole ice?** The colder the better - top cold part of glacier at -40° C to -50° C with RF attenuation lengths of over 1 km for f = 100's of MHz and 100's of m for f ~ 1 GHz
- Antennas should be buried in bulk ice below firn layer in order to avoid ray bending in index of refraction gradient in firn.

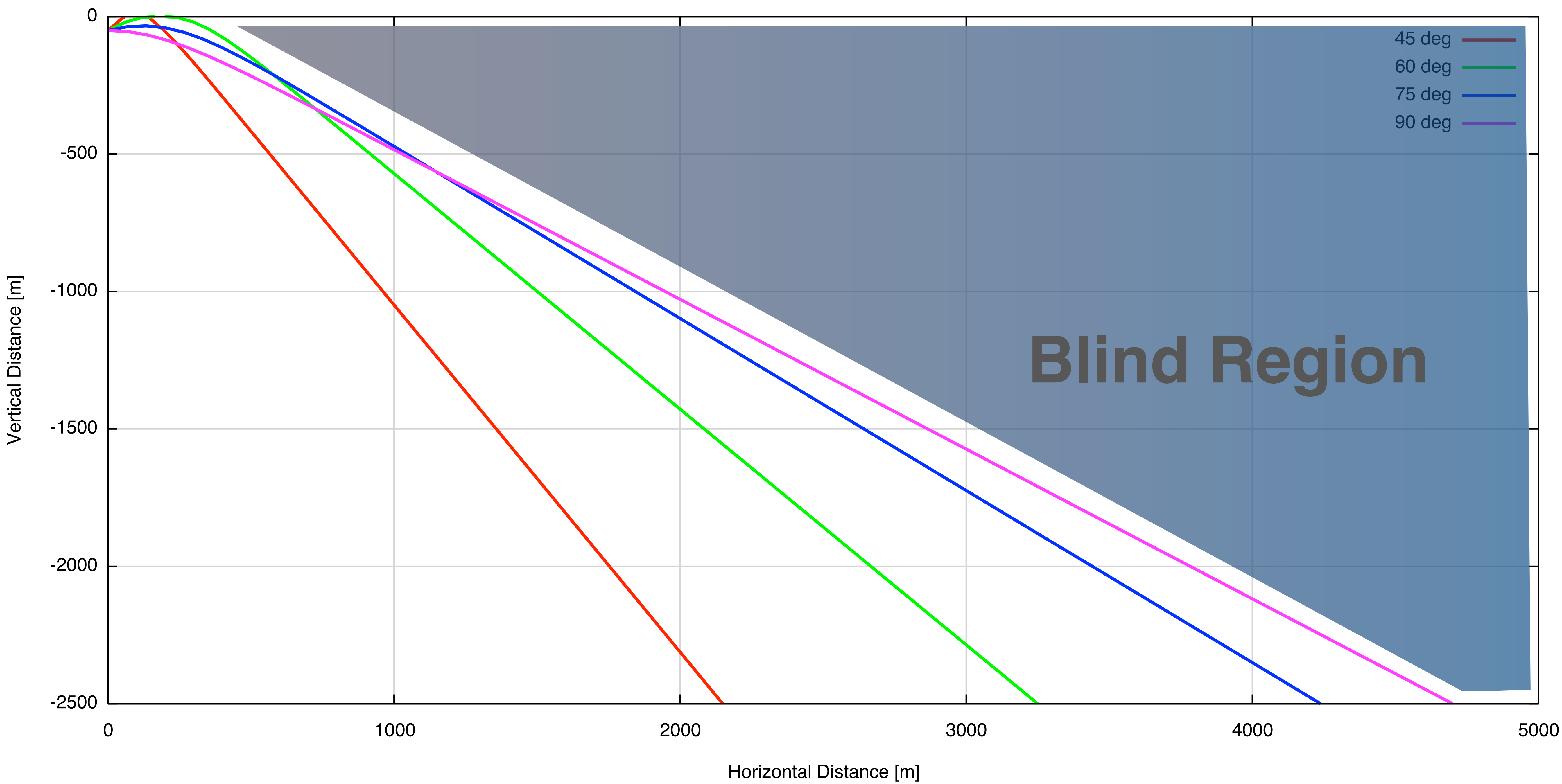
Ice Attenuation vs Depth



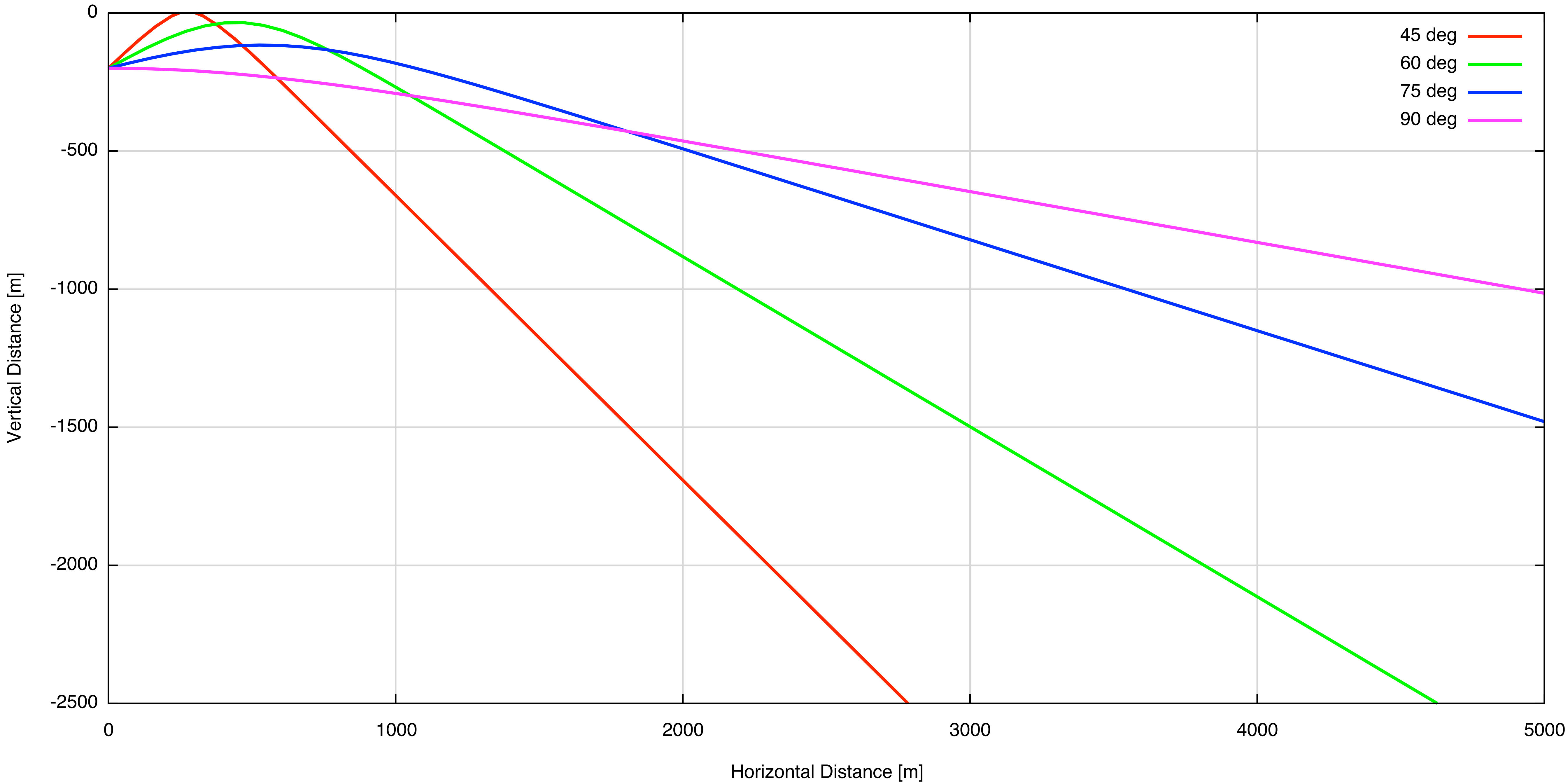
Raytracing : Shallow Detector



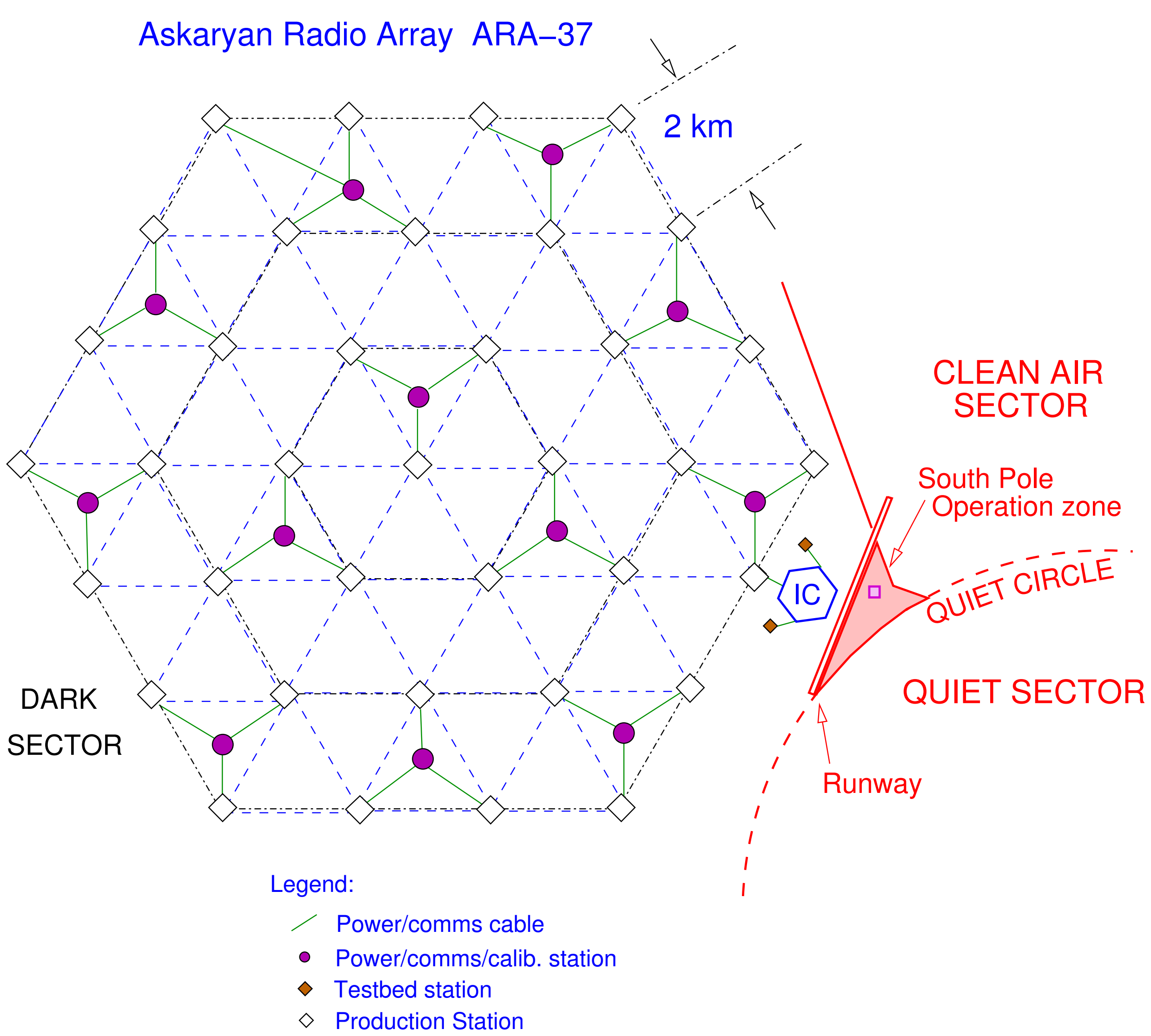
Raytracing : Shallow Detector

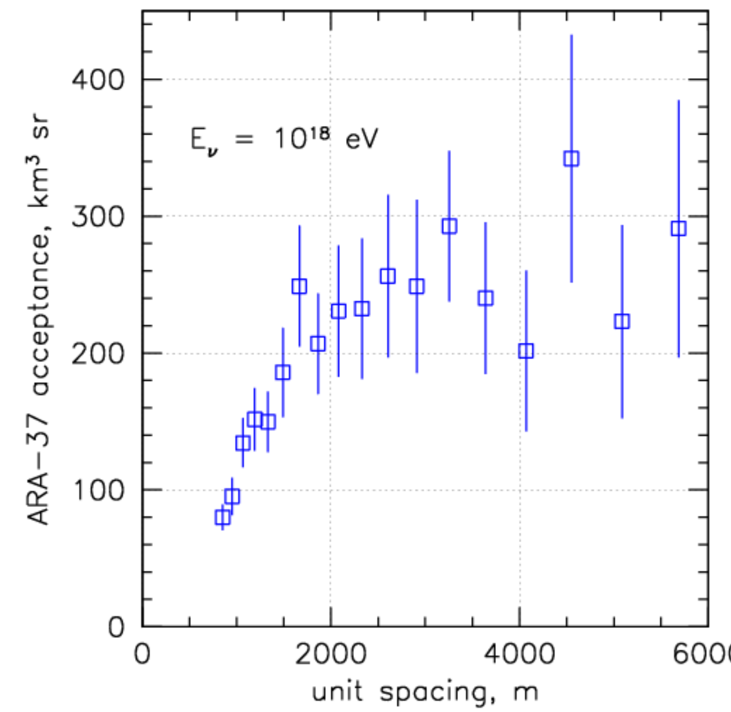


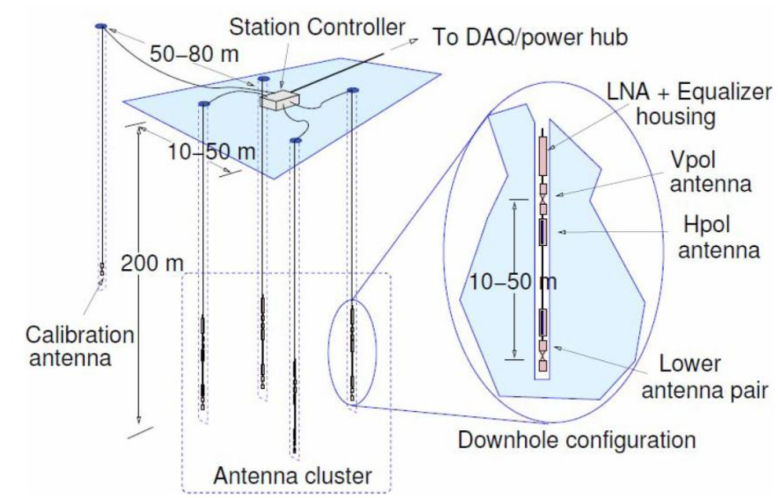
Raytracing : Deep Detector



Array Geometry

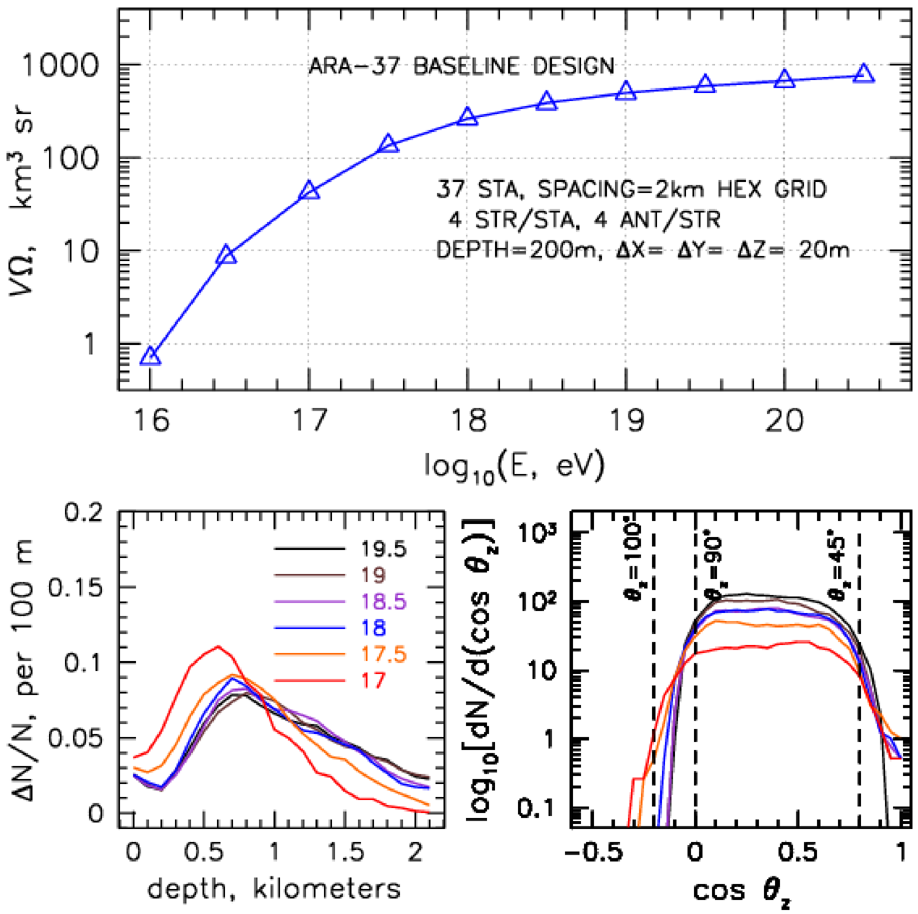




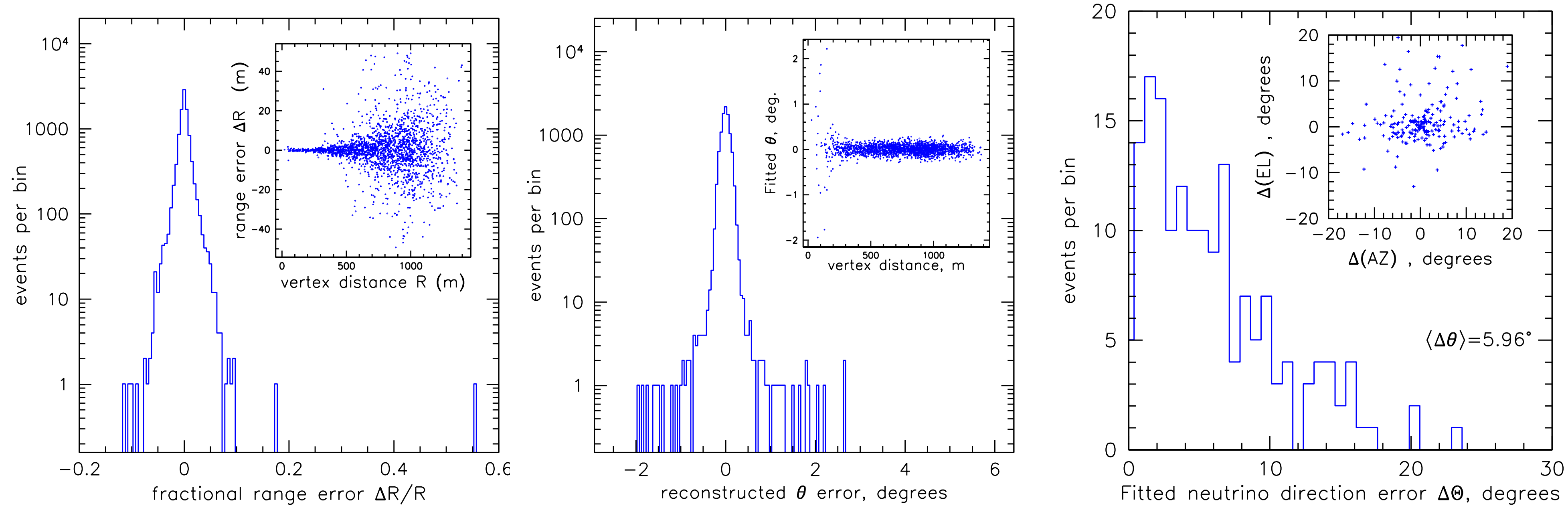


Effective Volume and Event Rates

Model & references N_ν:	ANITA-II, (2008 flight)	ARA, 3 years
Baseline cosmogenic models:		
Protheroe & Johnson 1996 [36]	0.6	59
Engel, Seckel, Stanev 2001 [23]	0.33	47
Kotera,Allard, & Olinto 2010 [48]	0.5	59
Strong source evolution models:		
Engel, Seckel, Stanev 2001 [23]	1.0	148
Kalashev *et al.* 2002 [37]	5.8	146
Barger, Huber, & Marfatia 2006 [41]	3.5	154
Yuksel & Kistler 2007 [44]	1.7	221
Mixed-Iron-Composition:		
Ave *et al.* 2005 [40]	0.01	6.6
Stanev 2008 [45]	0.0002	1.5
Kotera, Allard, & Olinto 2010 [48] upper	0.08	11.3
Kotera, Allard, & Olinto 2010 [48] lower	0.005	4.1
Models constrained by Fermi cascade bound:		
Ahlers *et al.* 2010 [49]	0.09	20.7
Waxman-Bahcall (WB) fluxes:		
WB 1999, evolved sources [47]	1.5	76
WB 1999, standard [47]	0.5	27



Reconstruction Performance

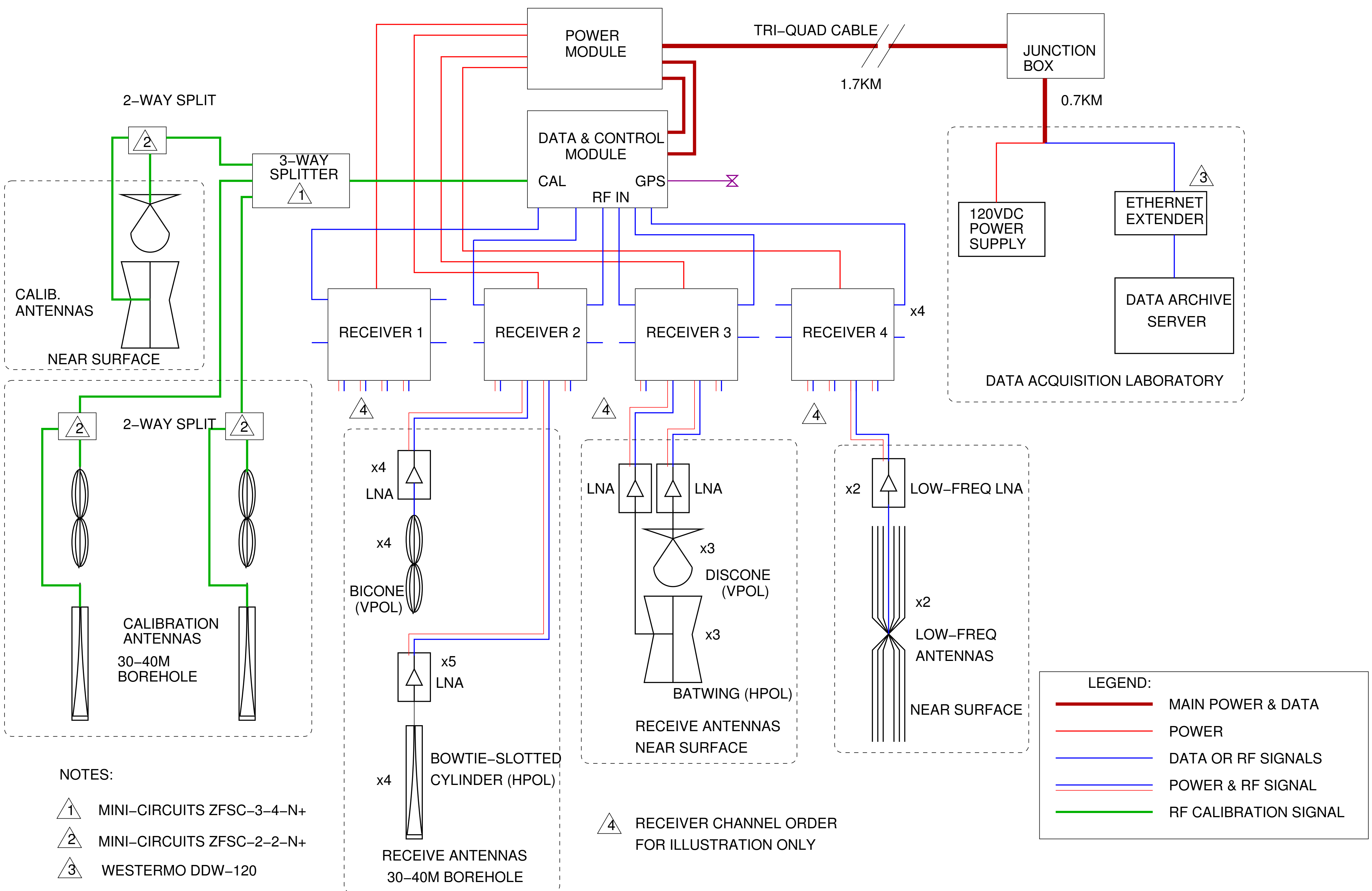


- Vertex resolution:
  - Easy to obtain angles to source of radio emission
  - Range from curvature determination requires hyperfine (10’s of ps) resolution on arriving pulses.
- Neutrino:
  - Direction: about 6°
  - Energy: TBD

Current

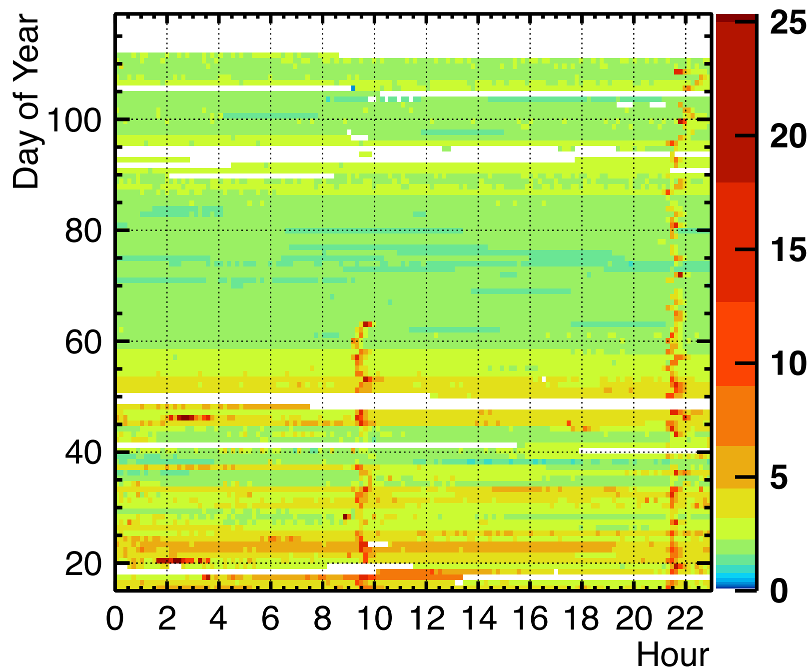
ARA TestBed and ARA Stations 1 and 2

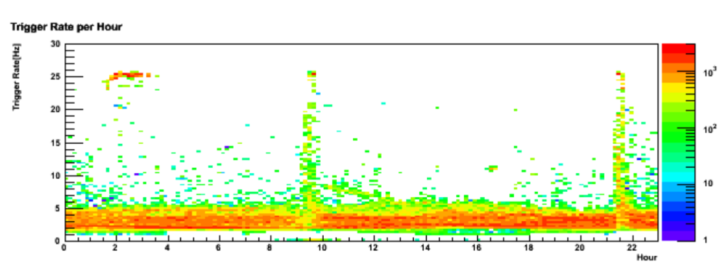
The ARA TestBed

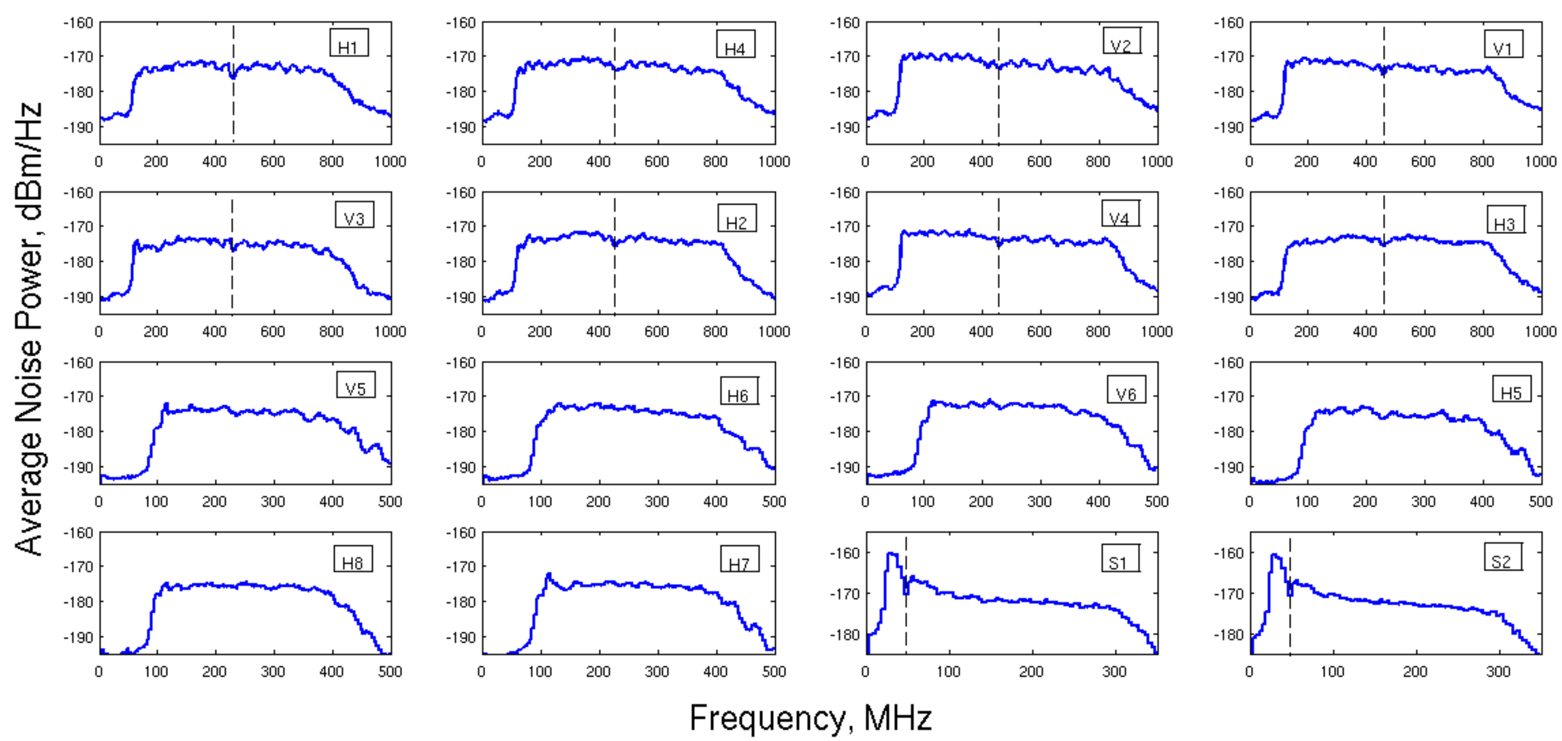


ARA TestBed Noise Performance

Principal goals of the TestBed were to demonstrate that the South Pole EMI environment was suitable for broadband radio detectors operating at or near thermal. This has been proven: the trigger rate as function of day of year and hour of day since Jan 2011 deployment is shown at left. As expected noise levels higher during summer season. Unexpected interference from telemetry on weather balloons 2x / day in summer which saturates TB trigger.





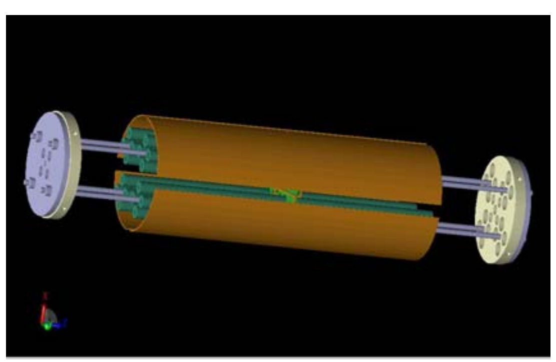


Antennas

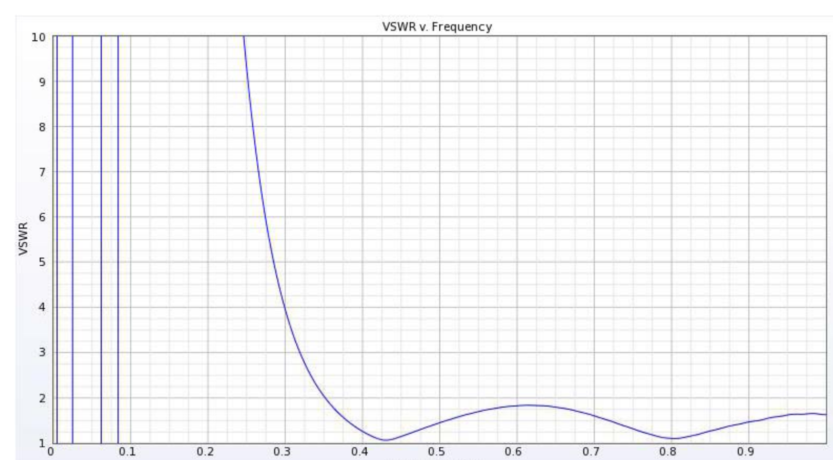
Antenna selection is severely constrained by need to fit inside 15 cm borehole. This limits low-freq performance of HPOL antennas especially.




Current HPOL design candidate is slotted, ferrite loaded cylinder.

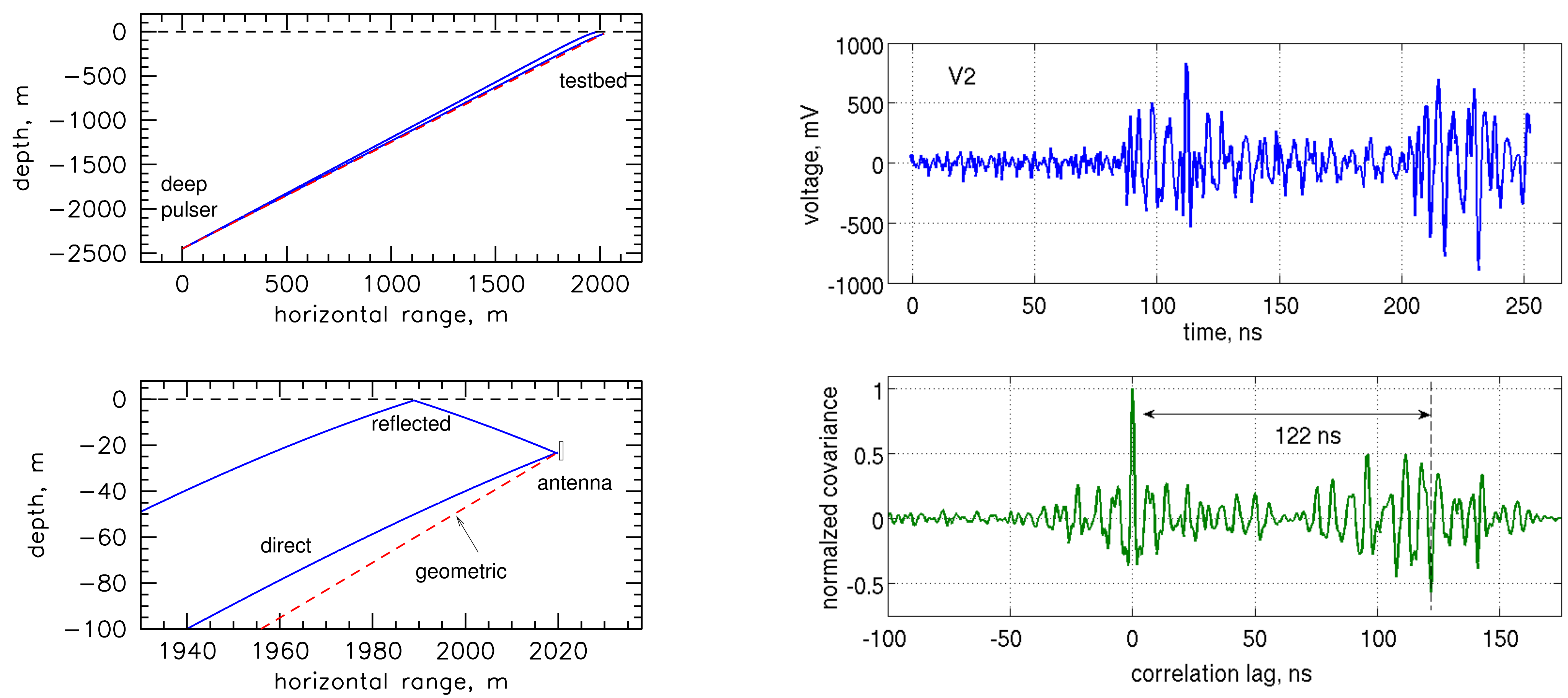


34 cm copper, 34 cm ferrites

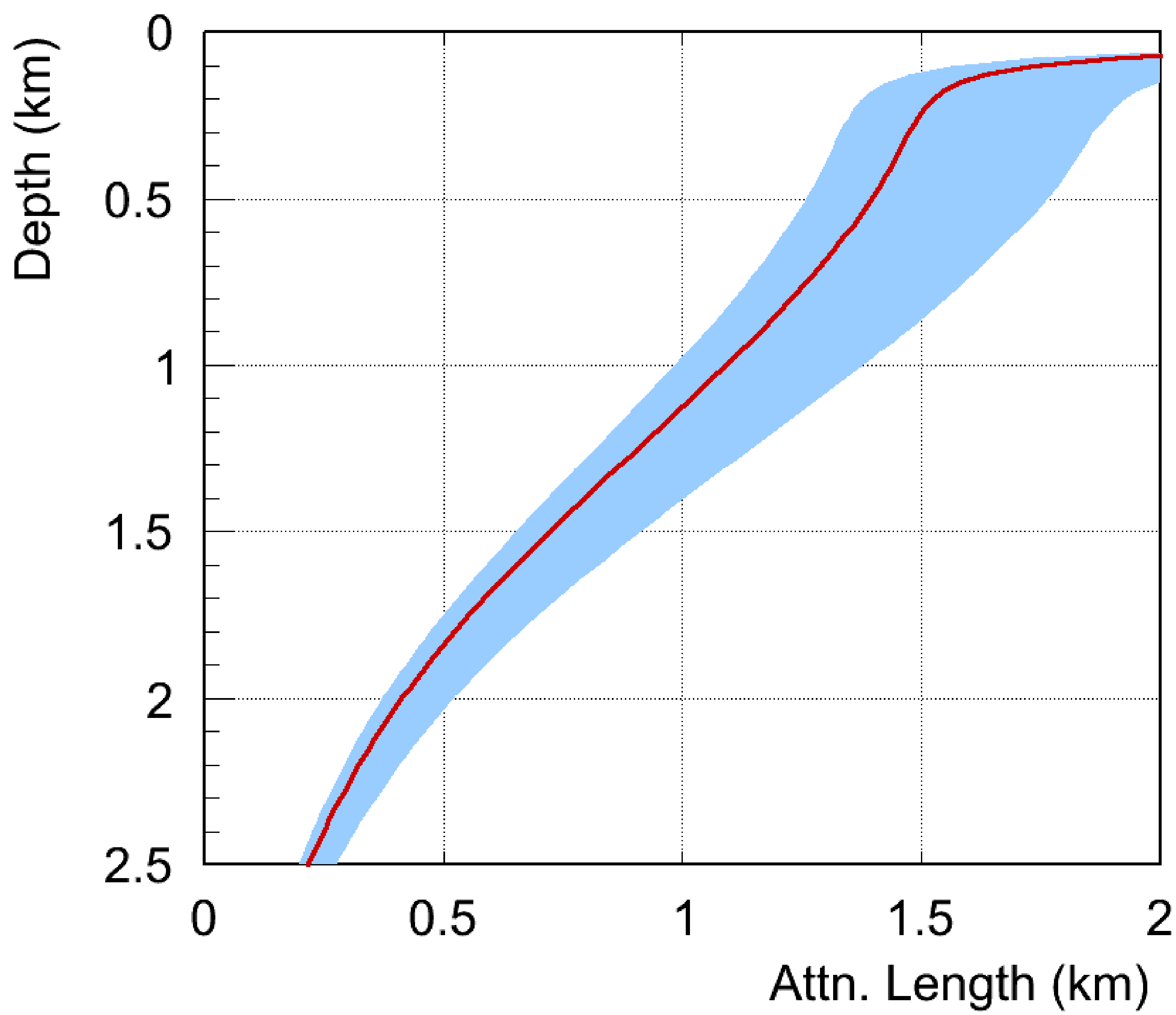


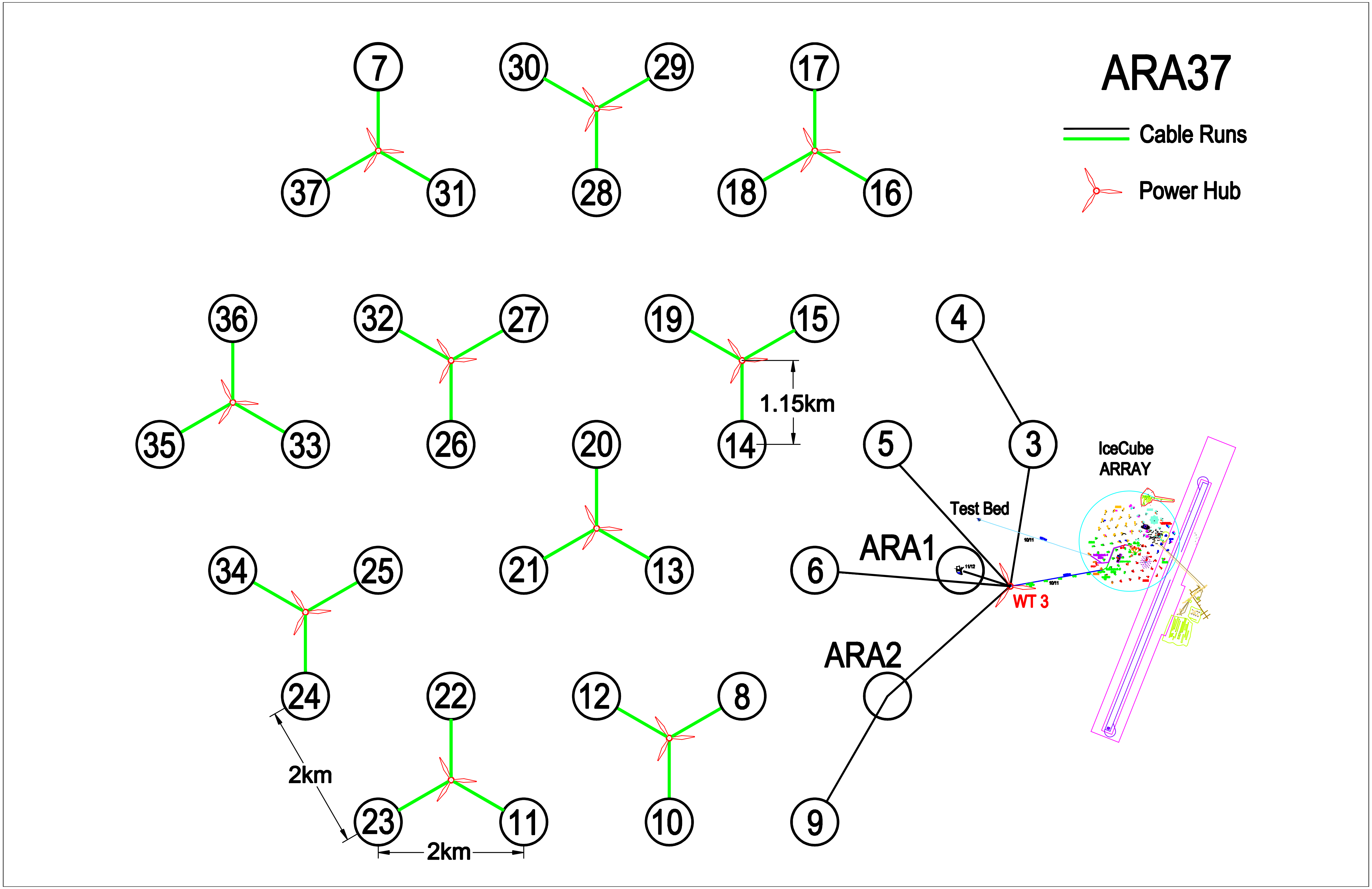
Deep Pulser Data

- Deep powerful 3.4 kV RF pulser deployed with last of IceCube strings - used as long distance calibration source.
- Preliminary results of analysis of this data indicate that attenuation length of pulses from this deep pulser ≈ 750 m (cf. previous est. ≈ 650 m - +15%)

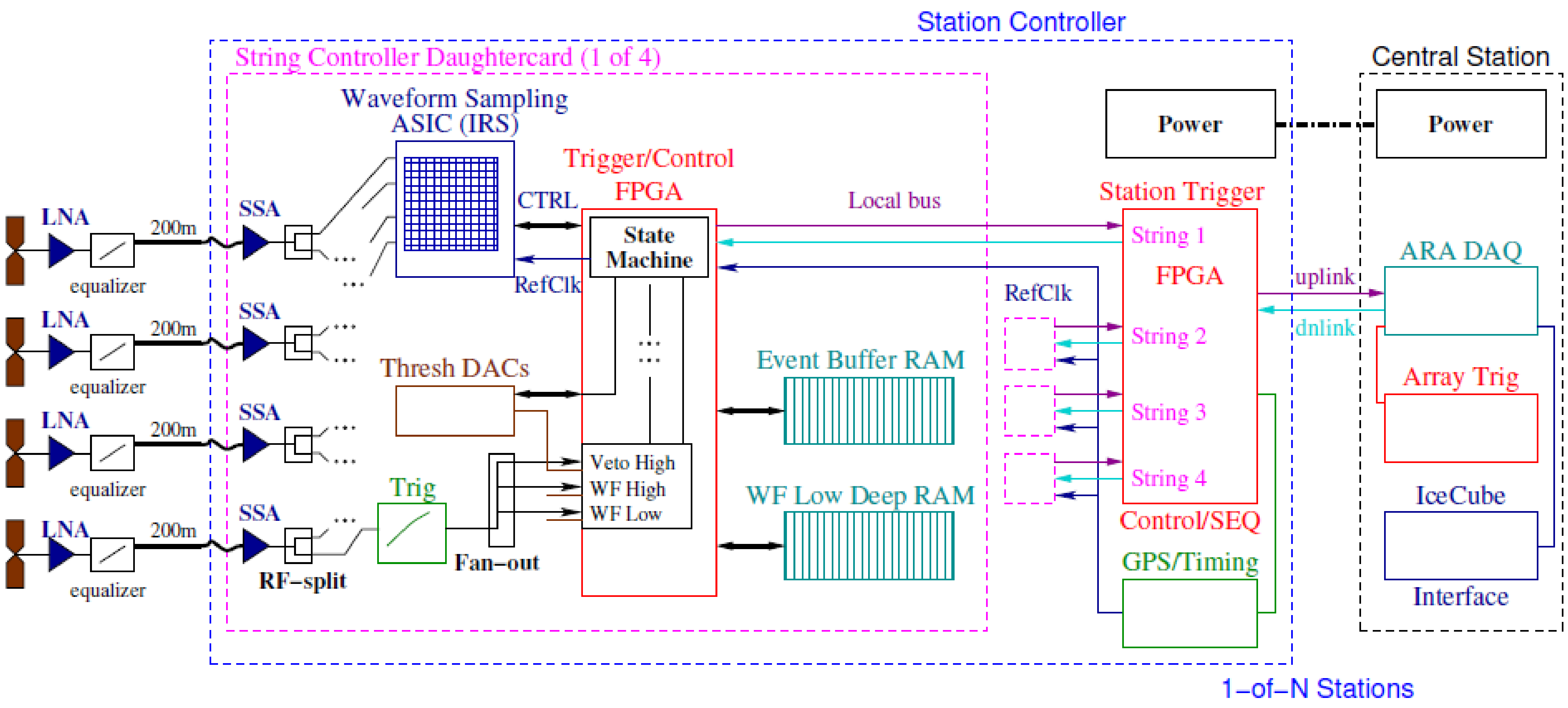


Attenuation Length from Pulser Data




ARA37
Cable Runs
Power Hub
7
30
29
17
37
31
28
18
16
36
32
27
19
15
4
1.15km
35
33
26
20
14
5
3
IceCube
ARRAY
Test Bed
ARA1
34
25
21
13
6
WT 3
ARA2
24
22
12
8
2km
23
11
10
9
2km

ARA General DAQ DataFlow



IRS2 ASIC

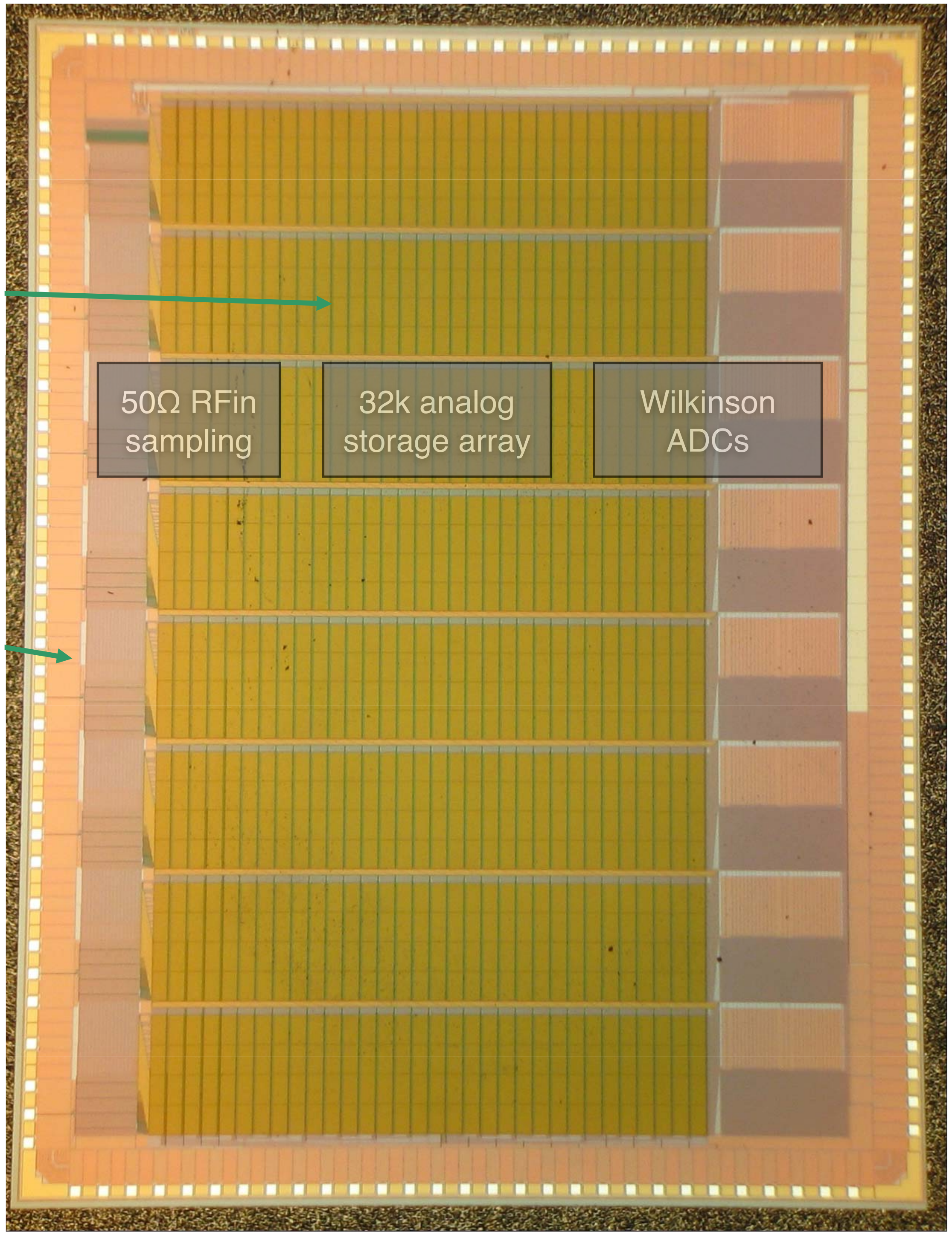


Image of 5.82 mm x 7.62 mm IRS2 die courtesy G Varner.

ARA design spec demands > 3 GHz sampling of RF transients from all antennas. This is achieved by the Ice Radio Sampler ASIC (IRS2) designed by G. Varner (U Hawai'i Manoa).

- 5.82 mm x 7.62 mm die
- TQFP128 package
- 1 GHz analog B/W at input
- Up to 4 GSPS
- 8 independent channels / chip
- 20 mW power dissipation per channel
- Each channel contains 32k analog storage addressed as 512 random r/w blocks of 64 samples each.
- On chip parallel Wilkinson converters
- ~ 15 μs/block conversion + readout time

ARA will use 1 IRS2 ASIC per string of 2 VPOL + 2 HPOL antennas: 4 such units per station.

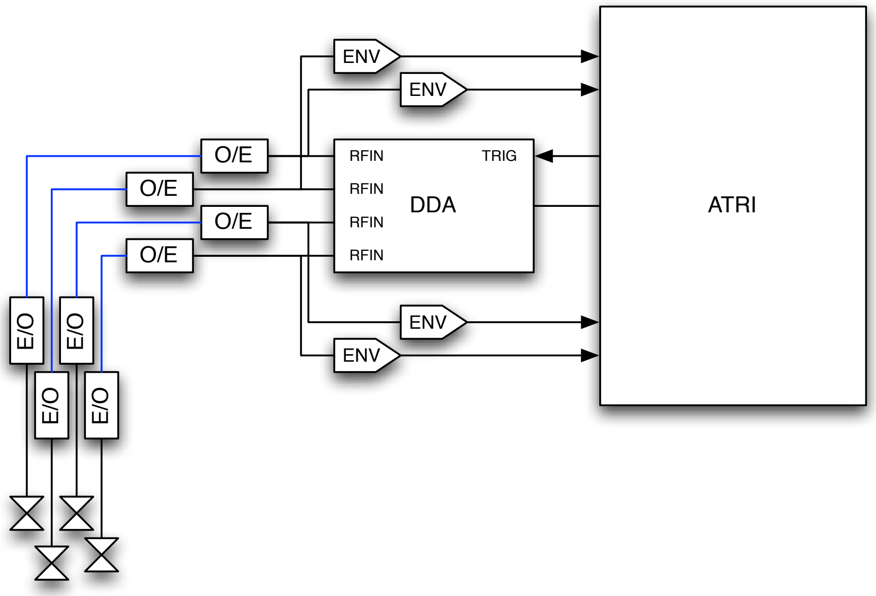
Triggering

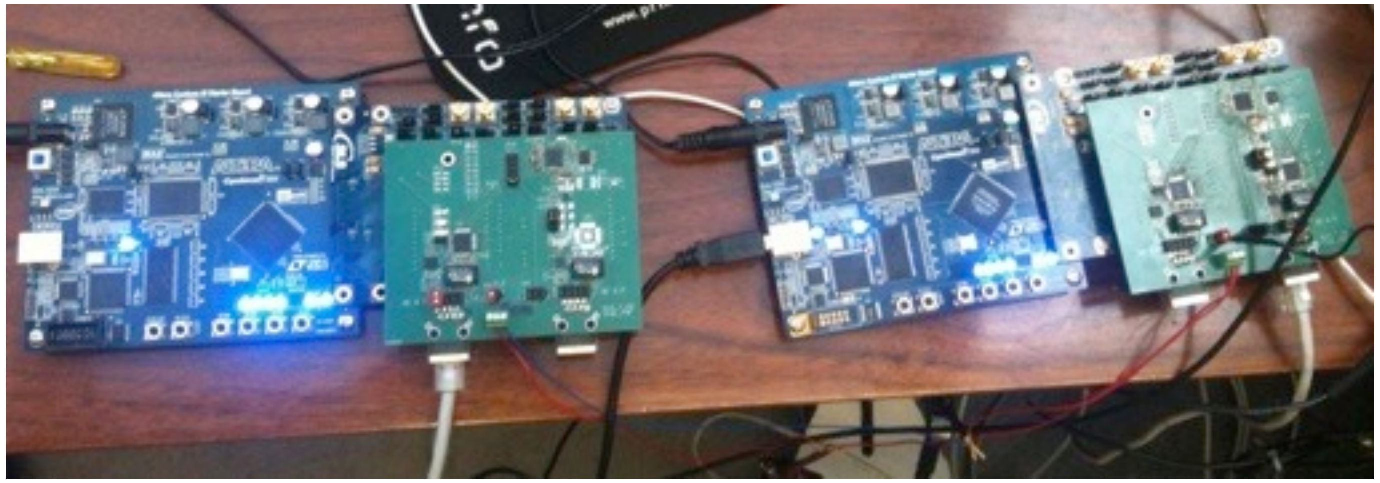
- During normal operation, the IRS2 is continuously acquiring samples to analog memory. At intended 3.2 GSPS operating point of ARA, this gives 10.24 μs analog memory depth.
- Using external logic and segmented structure of analog memory, the device allows *deadtime-free* acquisition of signals for suitably low trigger rates:
  - Each block of 64 samples represents 20 ns. Following a trigger, the ARA DAQ identifies the 10-20 most recently written blocks and queues them for digital conversion and readout.
  - These blocks are “frozen” (marked as non-writable) by the firmware.
  - Meanwhile other, non-frozen blocks continue to sample RF input.
- This flexible multi-buffer scheme allows kHz triggering of an ARA station - rate driven by conversion / readout speed and number of blocks readout per trigger.
- At lowest level, transient impulses sent to envelope detectors the outputs of which are discriminated. @ 2-3x kT noise gives ~ 1 MHz per antenna.
- 1-2 kHz trigger rate **long way** from ~ 10 MHz aggregate antenna L0 trigger rate
- Coincidence triggers not efficient at threshold. Investigations underway into firmware-based pattern triggers.

Future

ARA-37 Array

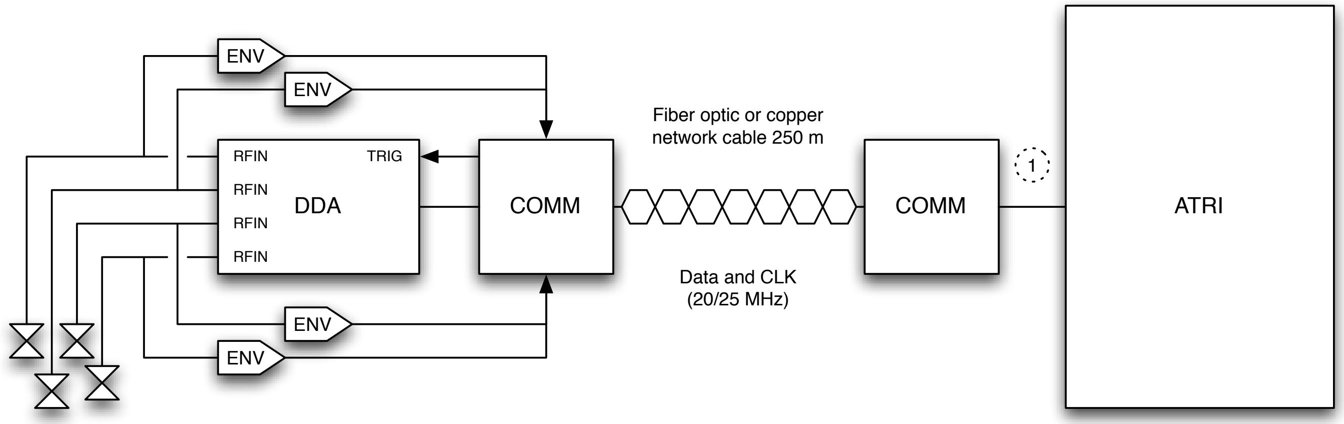
Down-hole digitization





RF signals from antennas 200 m deep can be either sent to surface or digitized locally. Shown here are the two competing schemes: analog RF-over-optical and digitization in the hole with digital transmission over Cu/FO.

We have been able to achieve clock synch reqt of **50 ps** skew jitter and data rate of **80 Mbit/sec** over 250m CAT5 using tweaked ethernet PHY. Tests with optical underway. Has advantage of 5x lower power than optical transmission of RF analog signals with disadvantages of limited comm rate (Cu) and additional complexity in the hole.

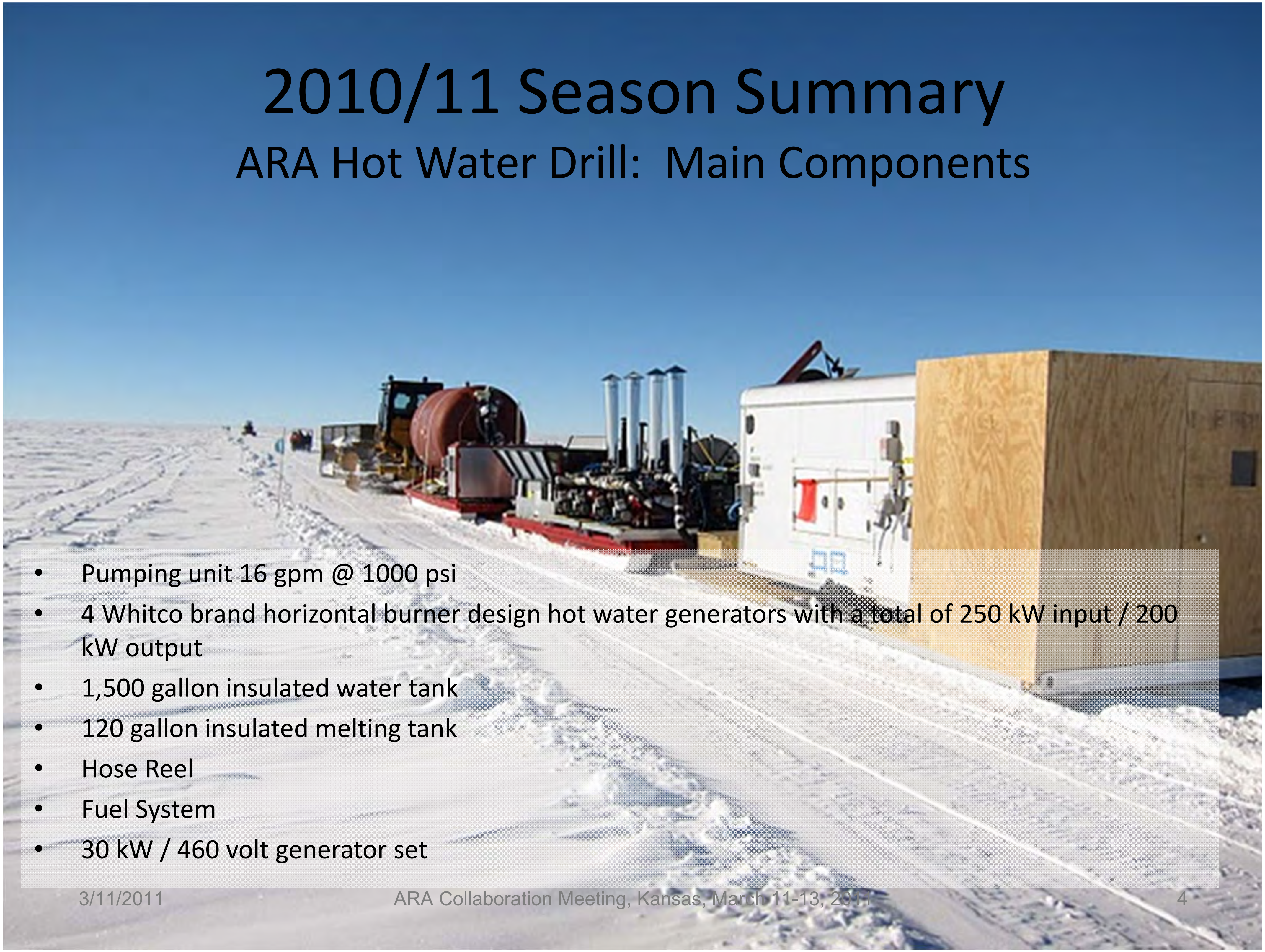


Autonomous Station Concept

- M12M (i-LOTUS) (successor of Motorola)
  - Time resolution: <10ns (<2ns with saw tooth correction)
  - -40 - +85 deg.
  - 2.85-3.15 Vdc, 185 mW

- **Windpower** 3 test wind turbines (Raum, Bergey, Hummer) deployed during 2010-2011 with mixed success
- **GPS timing** integrating OEM GPS boards in ARA-1 next year with laboratory time resolution of 2-3 ns
- **Wireless networking** tests of 802.11 commercial system in north during 2010-2011. First Pole test deployment this upcoming season.

Drilling


2010/11 Season Summary
ARA Hot Water Drill: Main Components
• Pumping unit 16 gpm @ 1000 psi
• 4 Whitco brand horizontal burner design hot water generators with a total of 250 kW input / 200 kW output
• 1,500 gallon insulated water tank
• 120 gallon insulated melting tank
• Hose Reel
• Fuel System
• 30 kW / 460 volt generator set
3/11/2011
ARA Collaboration Meeting, Kansas, March 11-13, 2011
4

Drilling

Actual Drilling results

Test Bed Holes

- 5 shallow holes, 6 inch diameter, average depth of 38 meters
- Drill time varied from 51 to 80 minutes (average = 67 minutes)
- Rate ~1 m/min
- Drill temperature varied from 79C to 90C (average = 83C)
- Average pressure of 252 PSI
- Approximate fuel use of 12 gal/hole

Deep Hole Test

- Drill speed up to 100 meters was similar to 50 meter holes (~1 m/min)
- From 100 to 180 meters slowed down incrementally and by hole bottom we were drilling close to 0.5 meters a minute
- Bringing the drill up, the hole narrowed down at 35 meters, requiring melting through narrow spot
- Approximately 6 hours (without ream)
- Approximate fuel use of 66 gal

Far Future

Crystal ball WARNING! Caveat lector

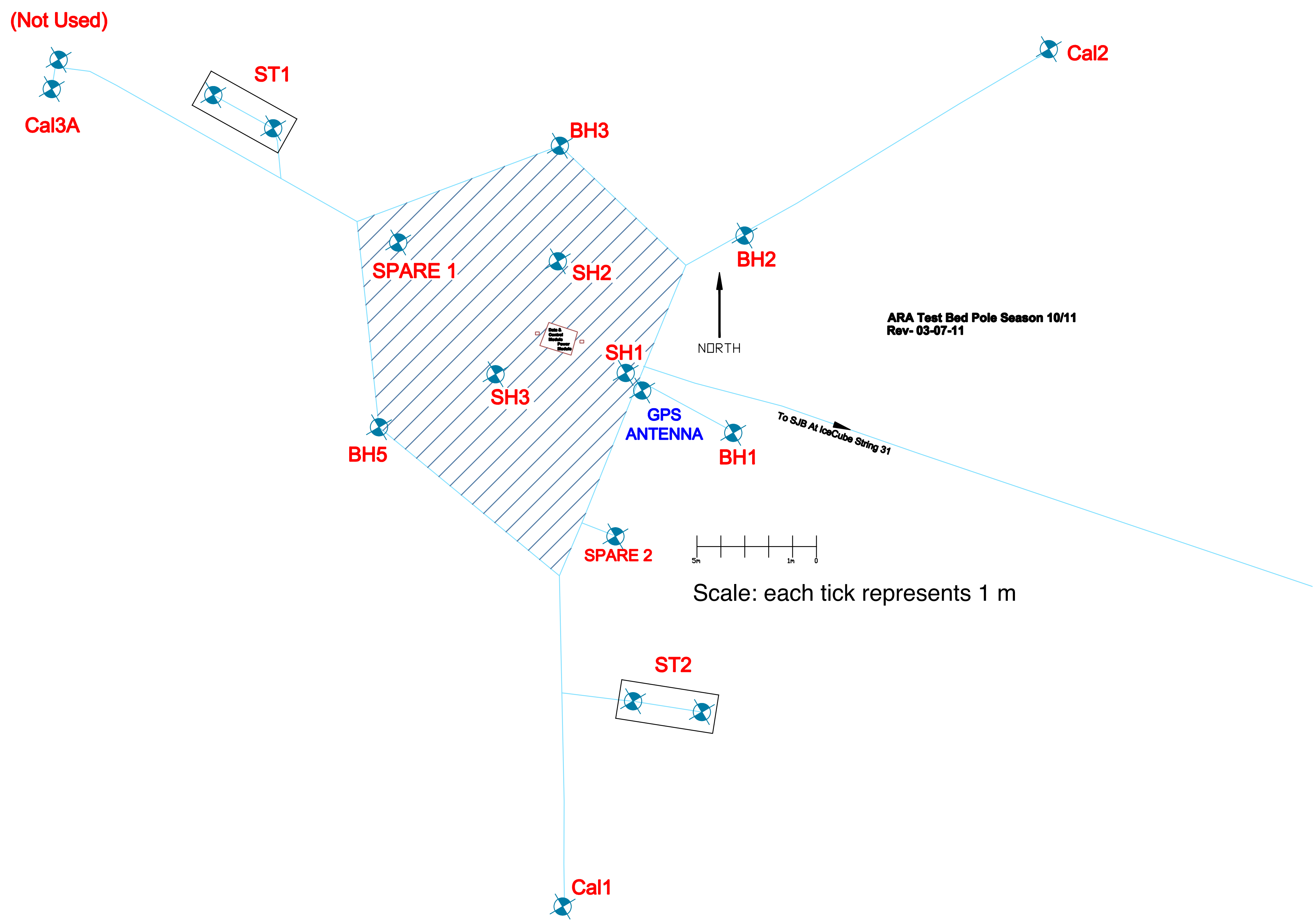
- ARA-37 is a discovery instrument. Even in the most optimistic models the array is expected to observe only dozens of events per an (but for this I would not complain, of course).
- To fully exploit the various physics topics (source physics, neutrino pheno at extreme CMS energies, cosmological propagation, …) we need LARGER DETECTORS - at least a factor of 10x
- In order to achieve this end we must invest in R&D now
  - Low power
  - Communications
  - Drilling technologies

Summary & Outlook

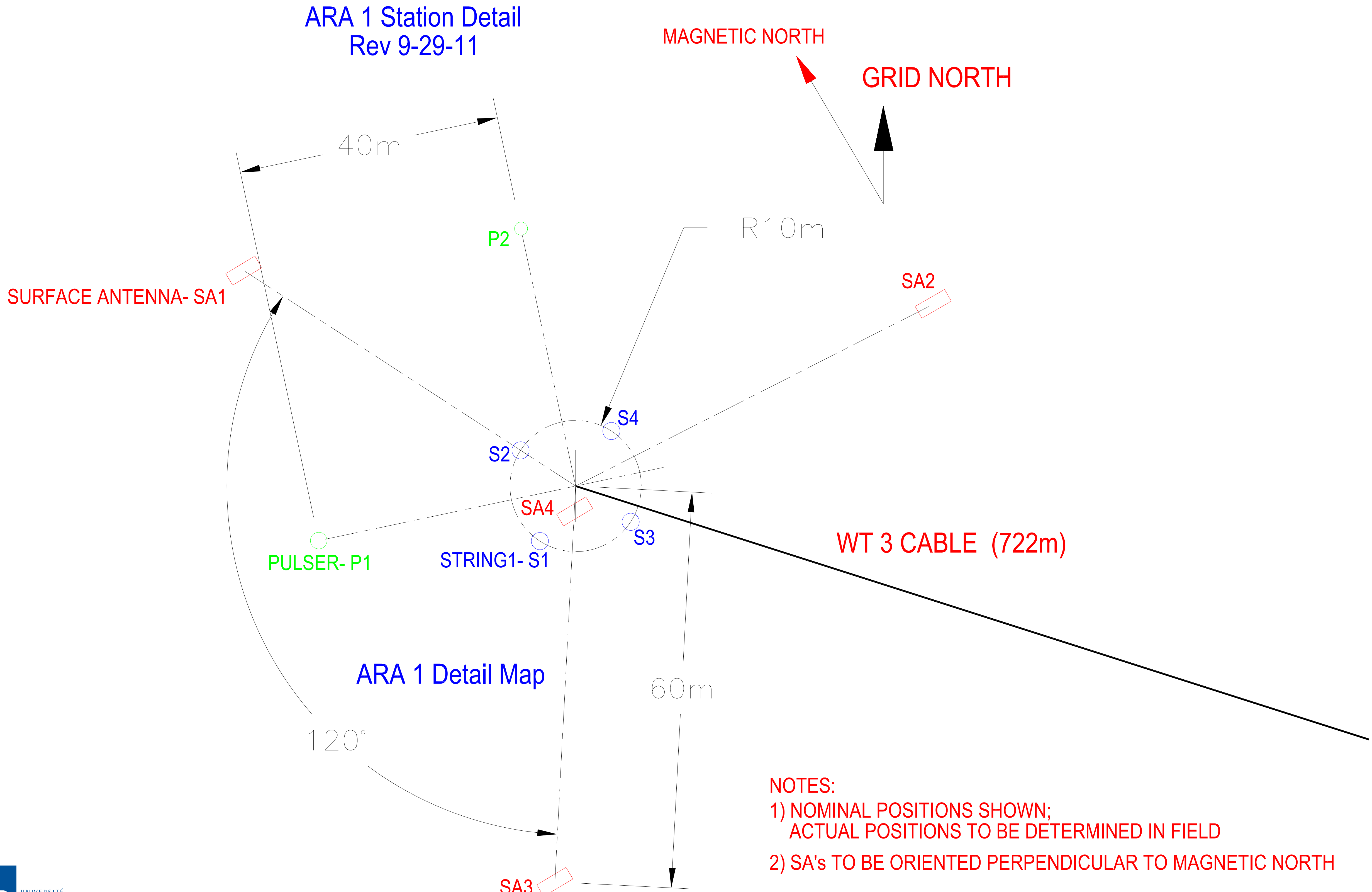
- **GZK** neutrino study demands new detector technologies to achieve target volumes sufficiently large to provide sizable event sample - 100's of km^3.
- The radio technique, exploiting the coherent RF emission theorized by Askar'yan 50 years ago, scales well to such large volumes.
- South Pole ice sheet is thick and cold - both good for RF attenuation.
- Measurements by ARA prototype test station deployment 2010-2011 show that South Pole is suitable from EMI background standpoint; initial measurements of RF attenuation length indicate better-than-expected.
- Initial phase of detector will deploy several stations in the ice over next two years.
- Full ARA-37 proposal to construct array that covers 100 km^2 area submitted.

Back-ups

ARA TestBed As-Built 2011



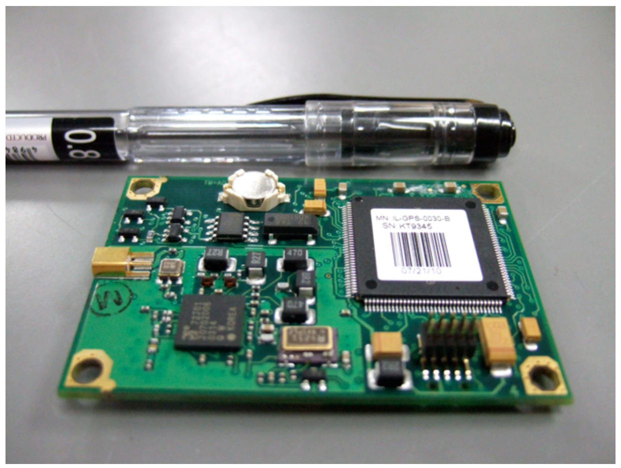
ARA Station 1 Plan



TestBed vs ARA-xx

Specified parameter	ARA 2012++ planned	ARA 2011 prototype
Number of Vpol antennas	8	6 (in ice)
Vpol antenna type	bicone	bicone
Vpol antenna bandwidth (MHz)	150-850	150-850
Number of Hpol antennas	8	8 (in ice)
Hpol antenna type	quad-slotted cylinder	bowtie-slotted-cylinder
Hpol antenna bandwidth (MHz)	200-850	250-850
Number of Surface antennas	4	2
Surface antenna type	fat dipole	fat dipole
Surface antenna bandwidth (MHz)	30-300	30-300
Number of signal boreholes	4	6
Borehole depth (m)	200	30
Vertical antenna configuration	H,V above H,V	V or H above H or V
Vertical antenna spacing (m)	20	5
Approximate geometry	trapezoidal	trapezoidal
Approximate radius (m)	10	10
Number of calibration antenna boreholes	3	3
Calibration borehole distance from center (m)	40 (2), 750 (1)	30
Calibration borehole geometry	isosceles triangle	equilateral triangle
Calibration signal types	noise and impulse	impulse only
LNA noise figure (K)	< 80	< 80
LNA/amplifier dynamic range	30:1	30:1
RF amplifier total gain (dB)	> 75	> 75

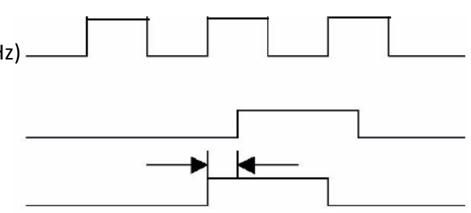
GPS (Chiba U - ULB)



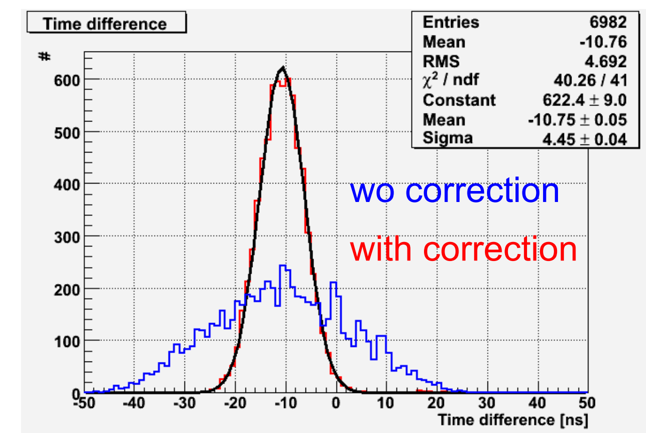
- M12M (i-LOTUS) (successor of Motorola)
  - Time resolution: <10ns (<2ns with saw tooth correction)
  - -40 - +85 deg.
  - 2.85-3.15 Vdc, 185 mW

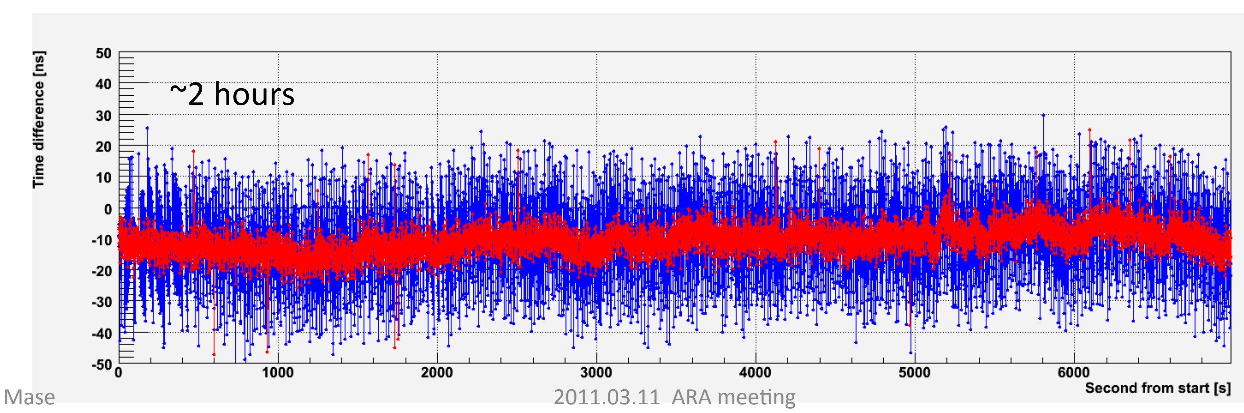
Saw tooth correction

- Resolution (wo correction): 9.2 ns
- Resolution (with correction): 3.1 ns



Can correct the time granularity by using the serial data information





K. Mase 2011.03.11 ARA meeting 5

Wireless Data Transmission (Chiba U - ULB)

Wireless hardware is 802.11n - could have 4x improvement in through put using channel bonding and other features of ‘n’.

Throughputs

Measured throughput
- TCP (iperf)
- Buffer 100k, window 1M