Status of Acoustic R&D in IceCube

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bmb+f - Förderschwerpunkt
Astroteilchenphysik
Großgeräte der physikalischen Grundlagenforschung

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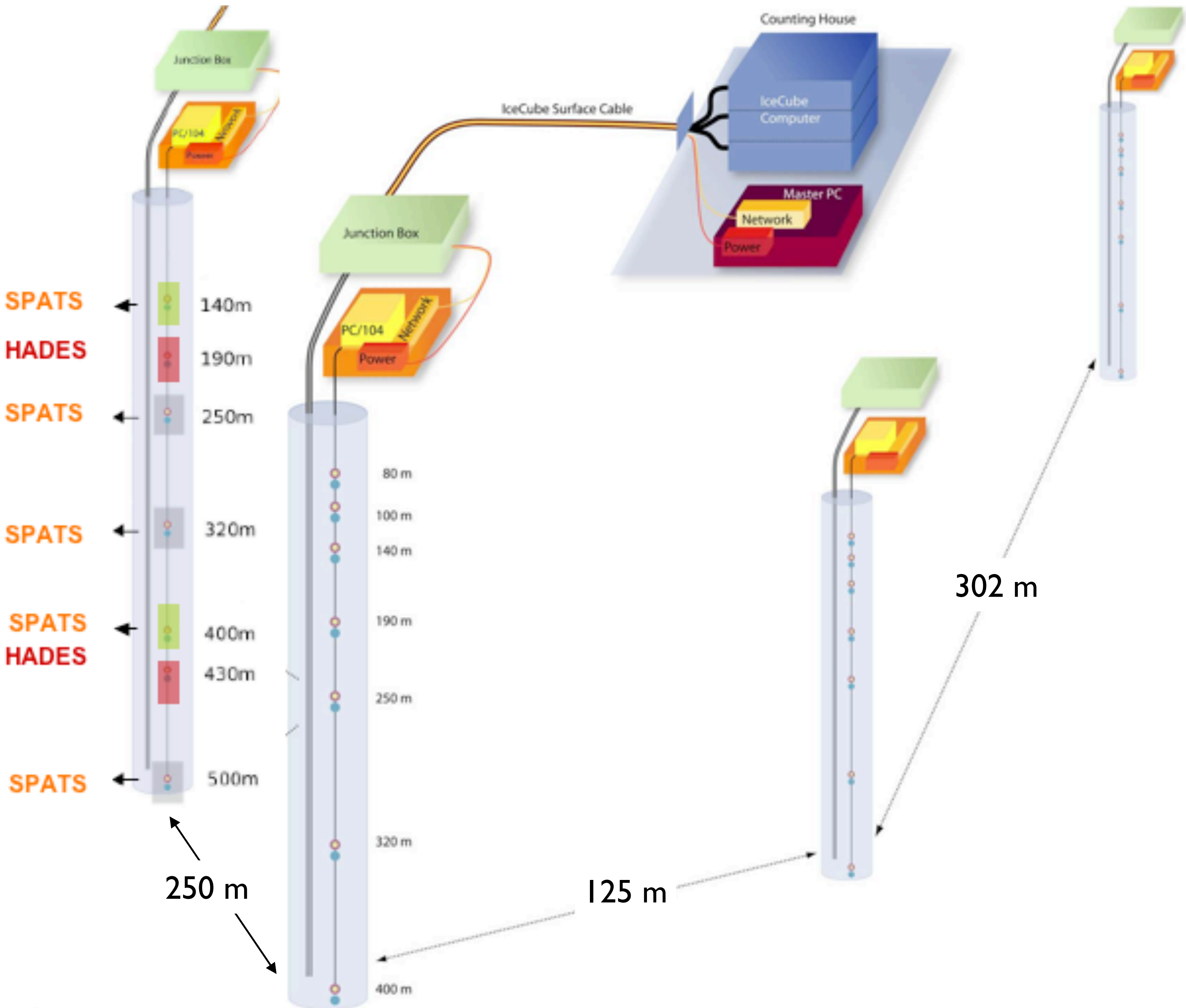
Aim of SPATS: Ice properties (10 − 100 kHz)

➡ Get realistic sensitivity estimate for an acoustic neutrino telescope

- Speed of sound and its variation with depth
  - significant refraction would make vertex reconstruction difficult
- Attenuation length
  - determines sensor spacing / effective volume of neutrino detector
  - frequency dependence allows to determine attenuation mechanism
- Noise floor
  - determines energy threshold
- Transient noise sources
  - impulsive noise must be separated from neutrino signal

Hardware overview

South Pole Acoustic Test Setup (SPATS)



- 4 strings in IceCube drill holes
- instrumented depth: 80 m − 500 m
- per string:
  - 7 sensors
  - 7 transmitters
- String-PC
  - digitization
  - time stamping
  - monitoring (p, T)
- Master-PC
  - data storage
  - GPS clock
  - data transfer via satellite

Strings A, B, C installed in 2006/07
String D installed in 2007/08

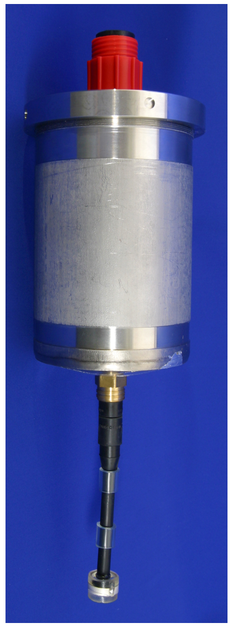
SPATS stage design

Transmitter:

- ring shaped piezo ceramic coated in resin
- HV generator

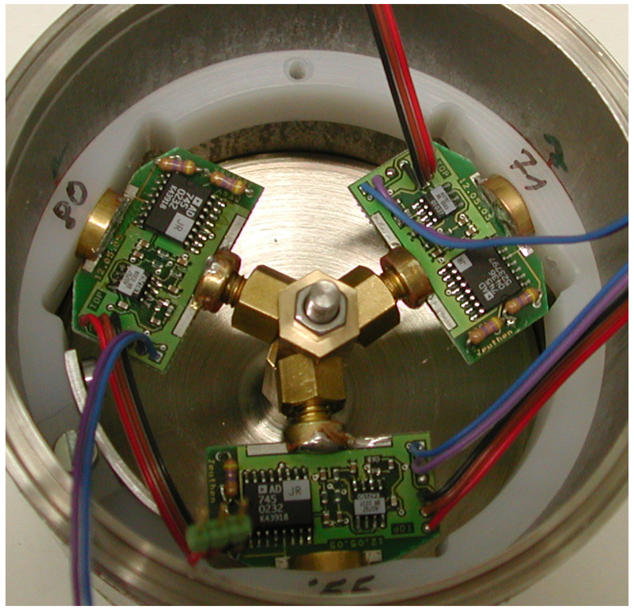
Sensor:

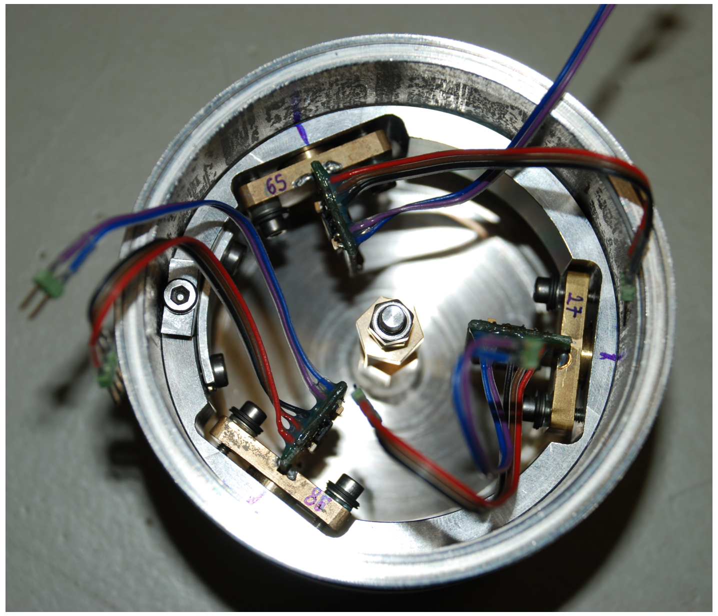
- 3 channels / sensor
- pre-amplifier
- analogue signal transmission
- steel pressure housing



String-D:

- improved sensors: mechanical decoupling of sensor channels
- improved transmitters: higher power
- HADES: alternative sensor design with piezo ceramics outside the steel housing



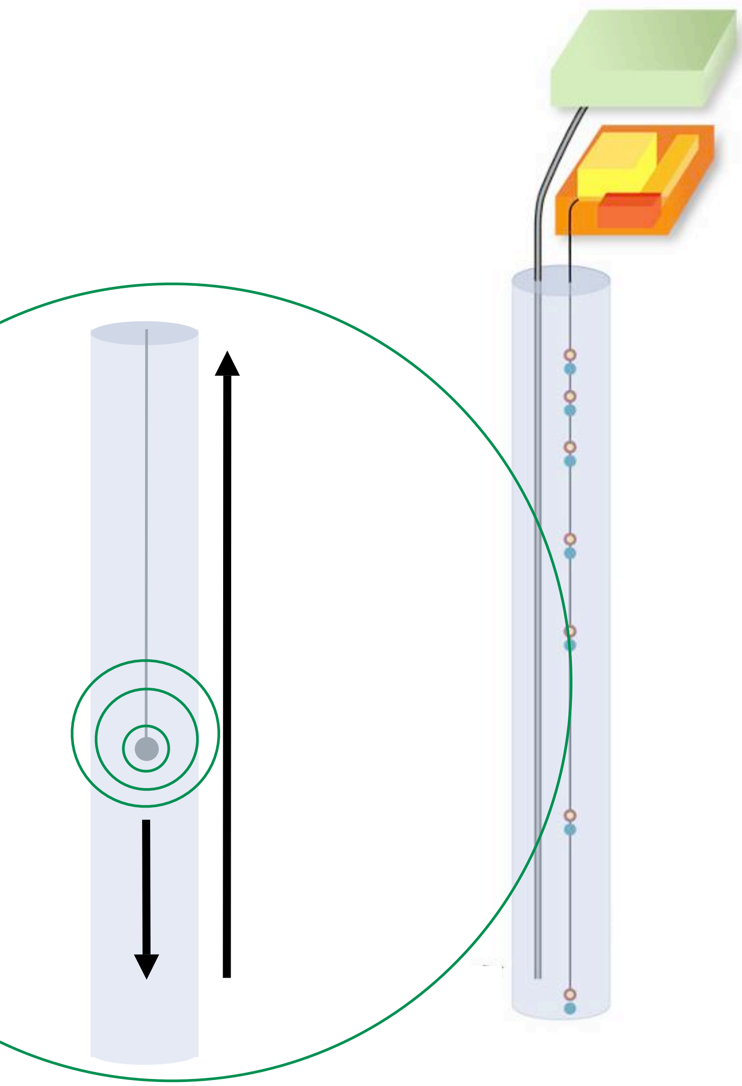


Data taking modes

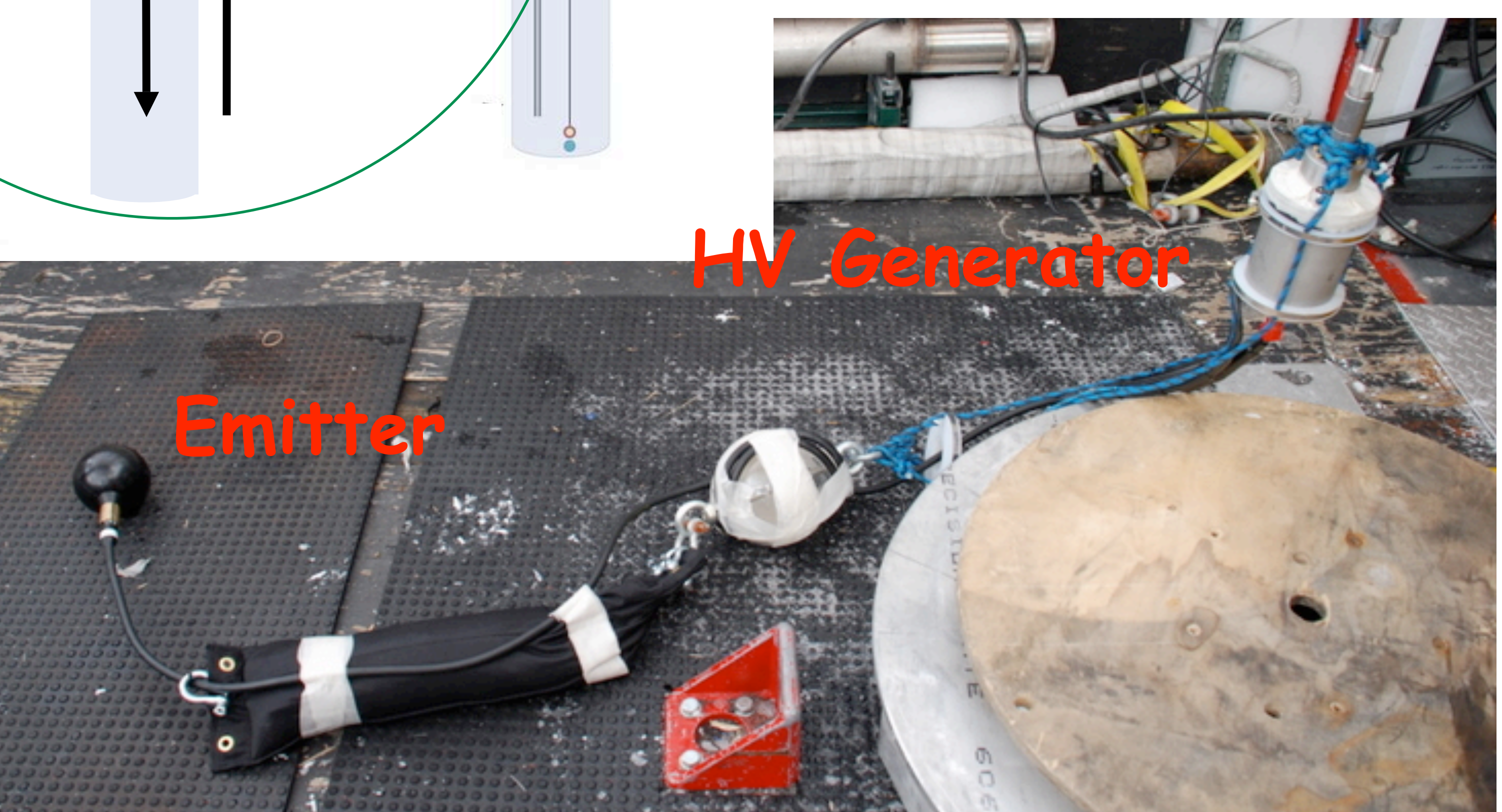
- Triggered mode: 45 minutes of every hour
  - Threshold trigger on 3 sensor channels / string
  - Threshold 5.2 σ_{noise}
  - Offline coincidence building
- Noise monitoring: 0.1 seconds of every hour
  - Untriggered read-out @ 200 kHz
  - All 3 channels / sensor simultaneously
  - Loop over all sensors
- System health monitoring: once every hour

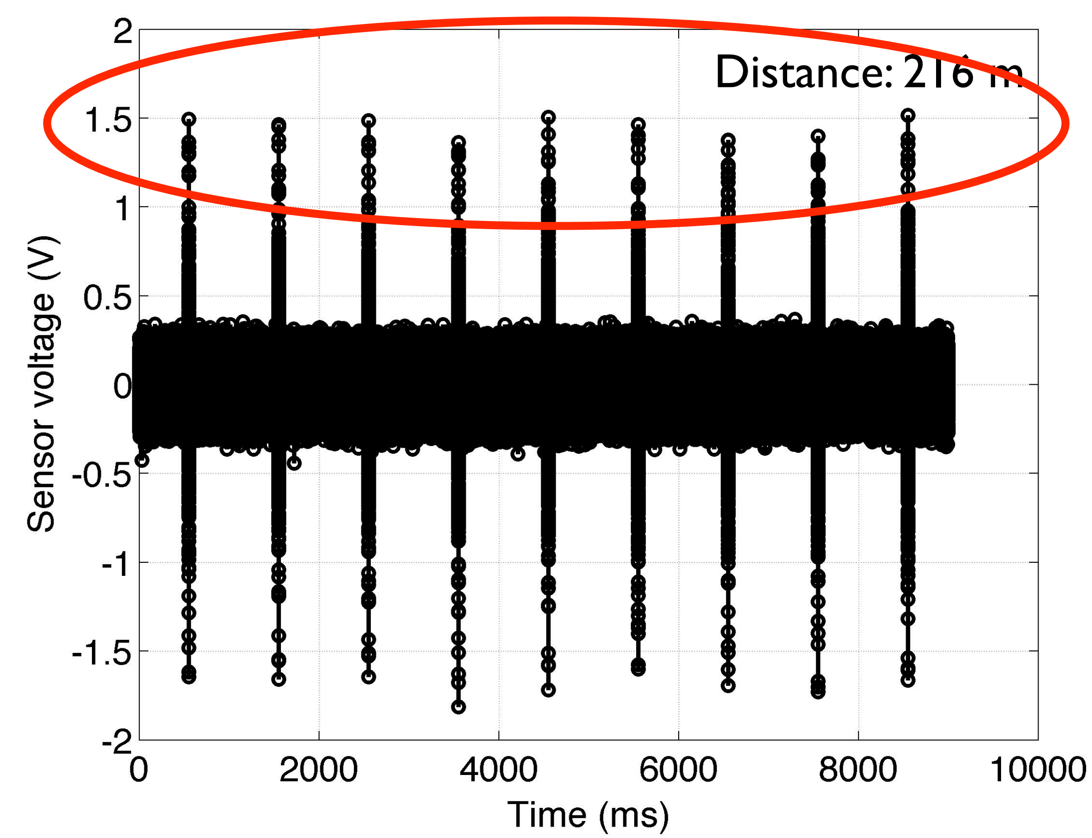
➡150 MB / day transmitted via satellite

Extended range: The retrievable pinger 2007/08

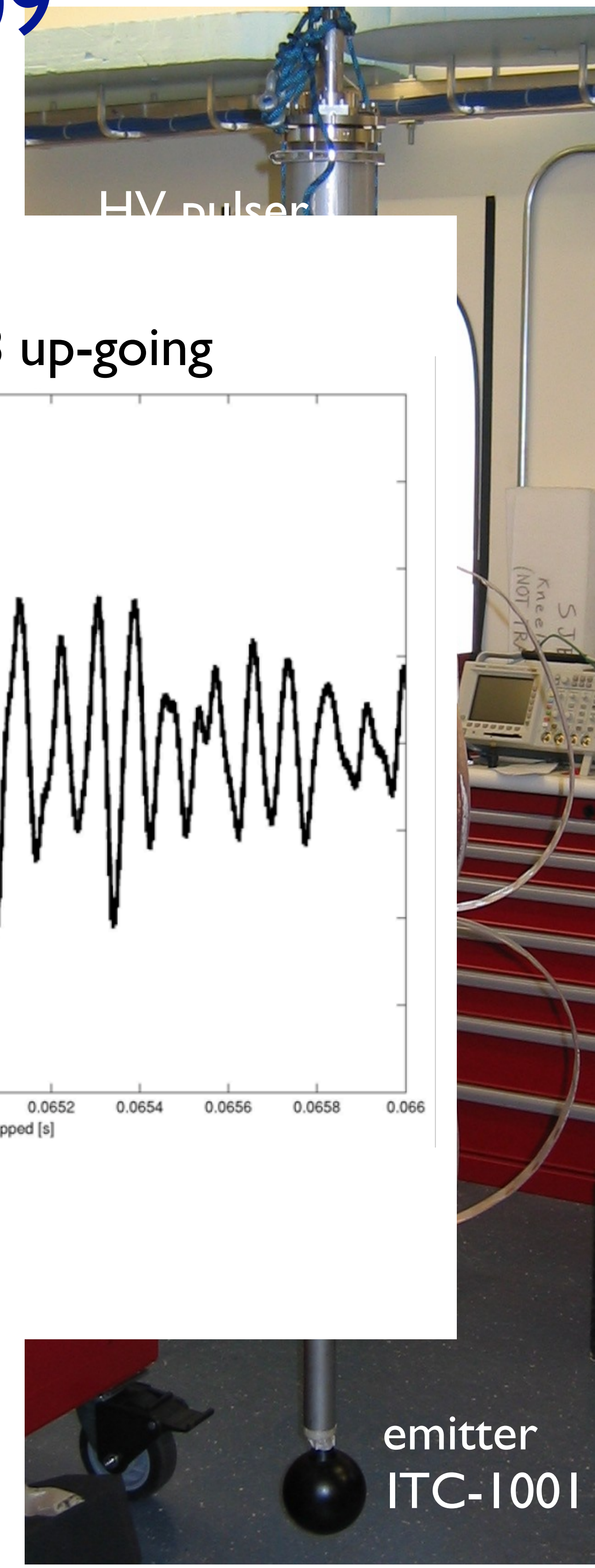


- Use newly drilled IceCube holes to lower retrievable transmitter
  - increased distance range for attenuation length measurements
  - sound speed depth profile
  - relative sensor calibration

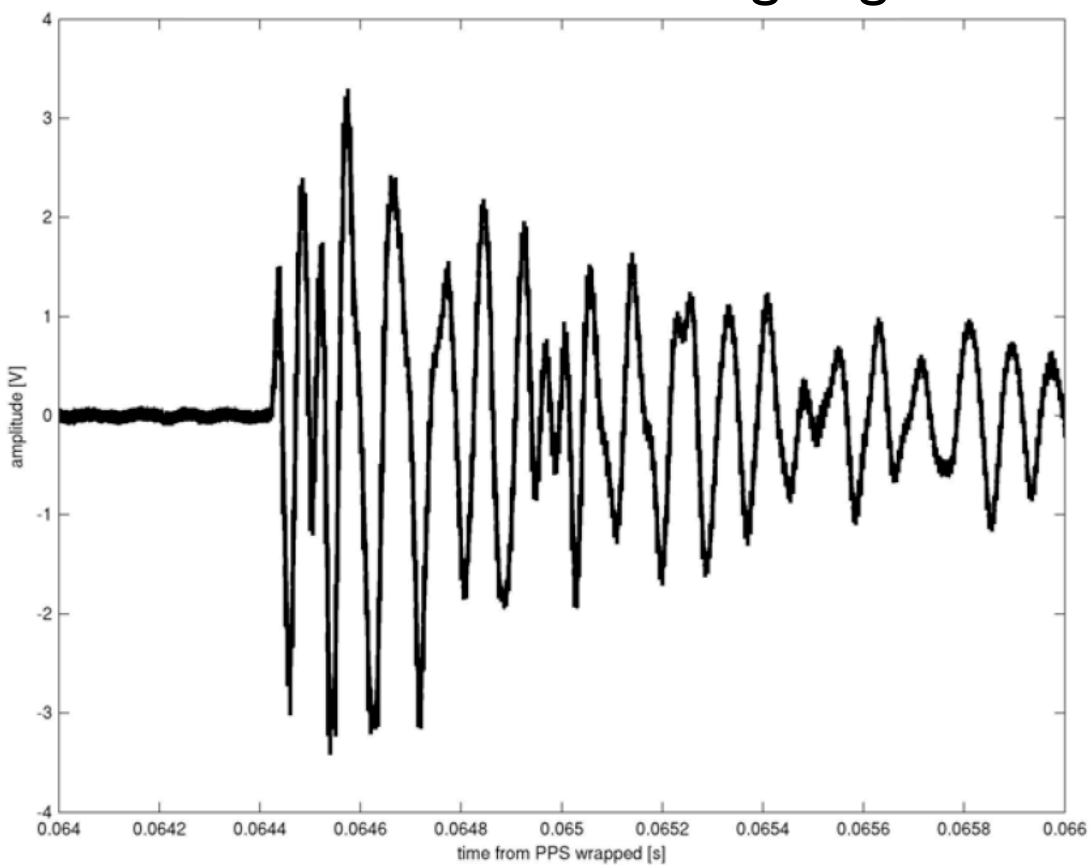




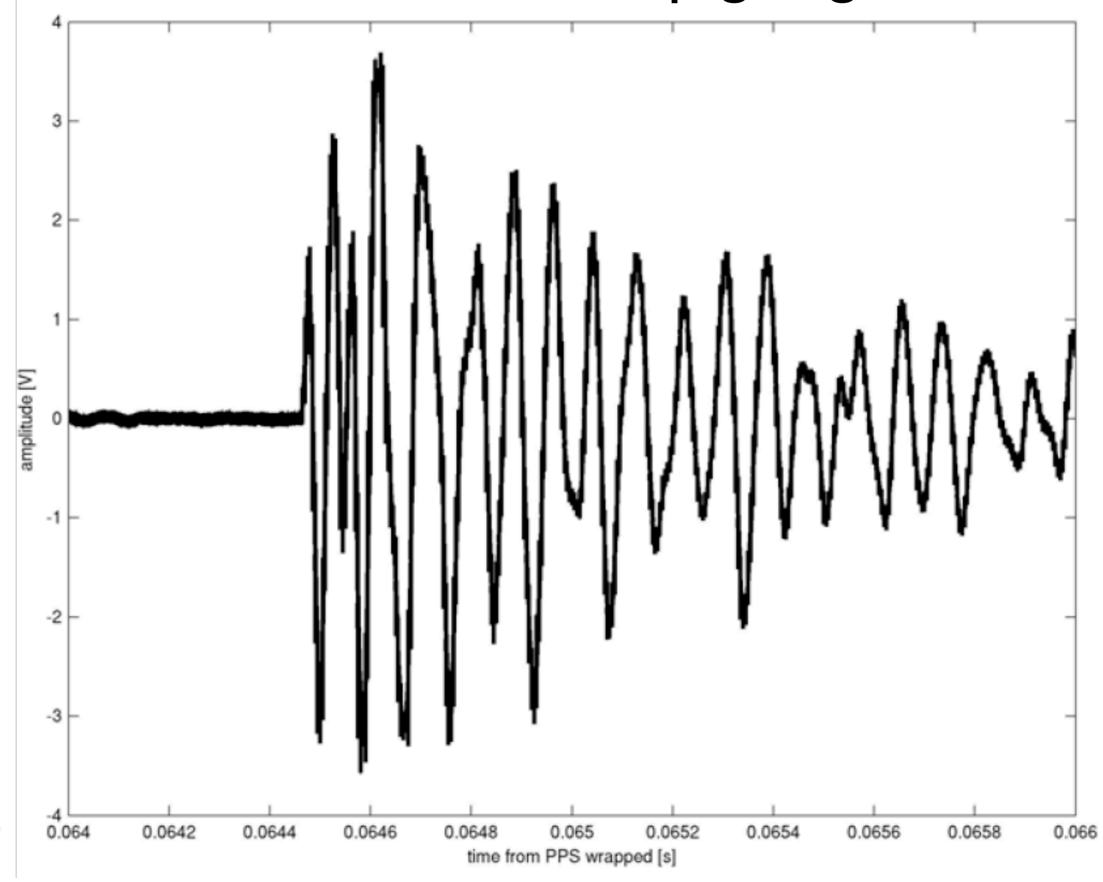
The “stabilized” pinger 2008/09



CS6-0 hole 28 down-going

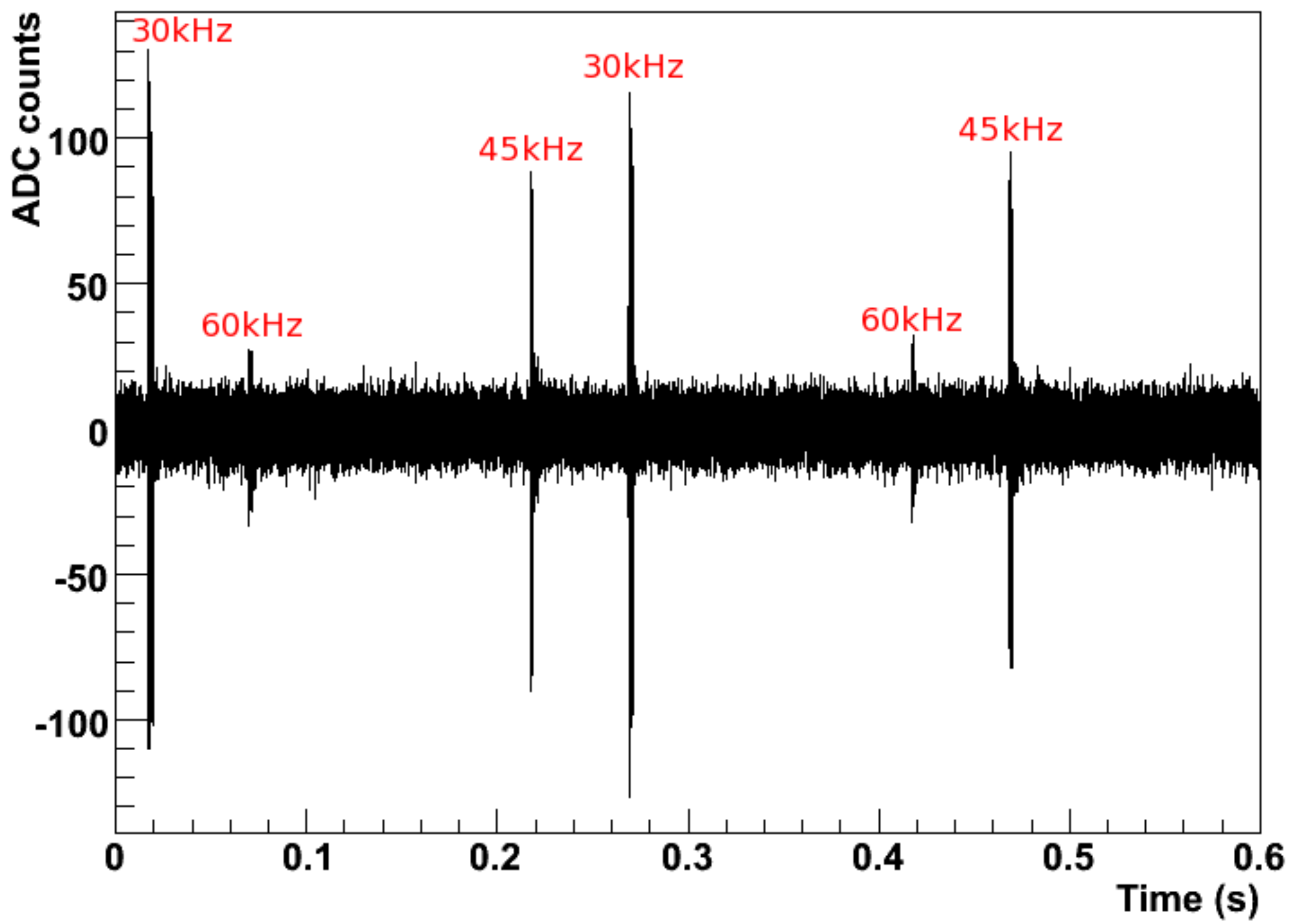


CS6-0 hole 28 up-going



High quality data!

The "multi-frequency" pinger 2009/10

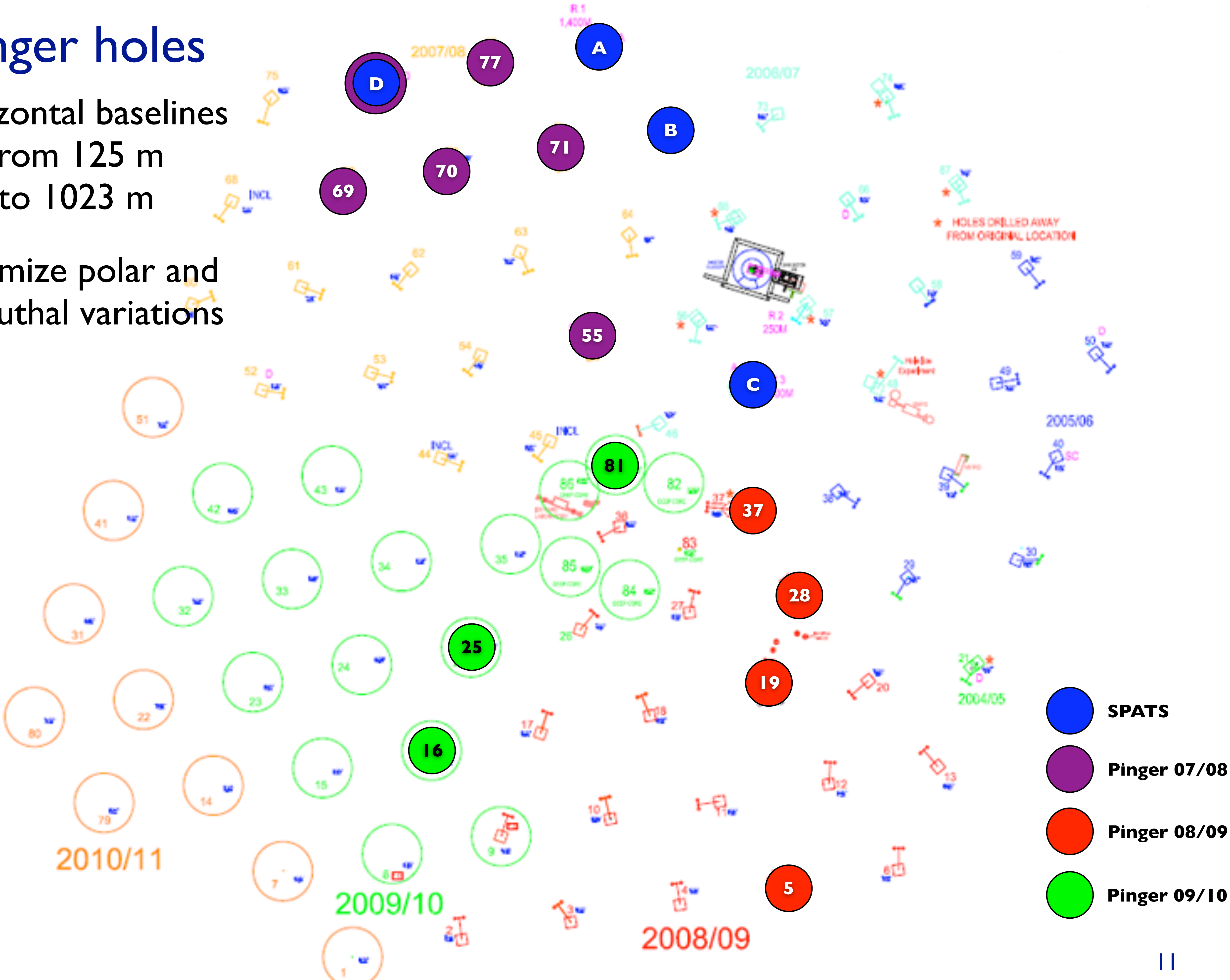


- Frequency dependence of attenuation length ⇒ attenuation mechanism
  - Absorption: frequency independent; Scattering: $\alpha_{att} \propto f^4$
- Deep stops (up to 1000 m) to measure sound speed and attenuation in deep ice and on inclined paths
  - Also interesting for Glaciology (ice crystal orientation)
- Data under study

Pinger holes

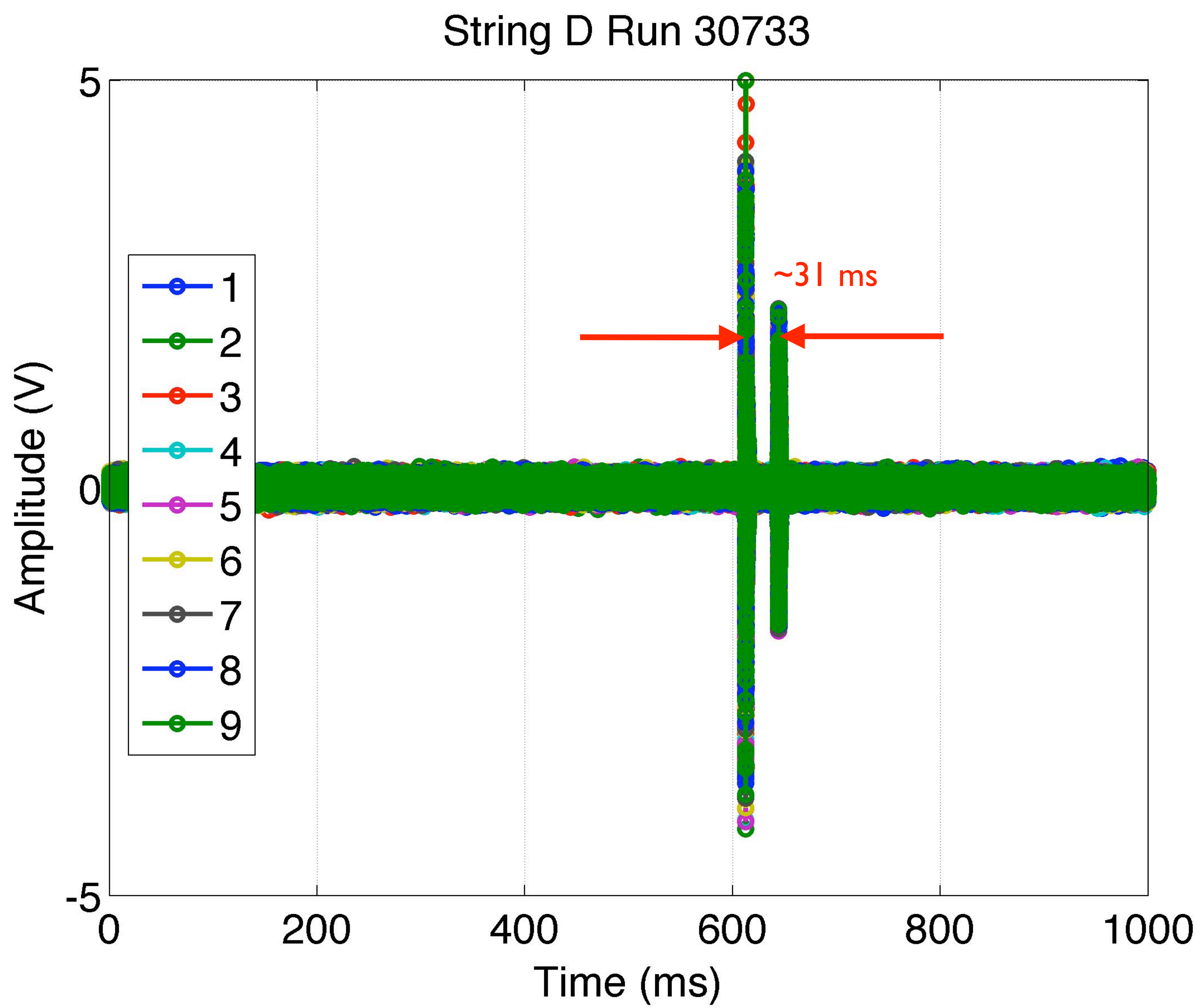
Horizontal baselines
from 125 m
to 1023 m

Minimize polar and azimuthal variations



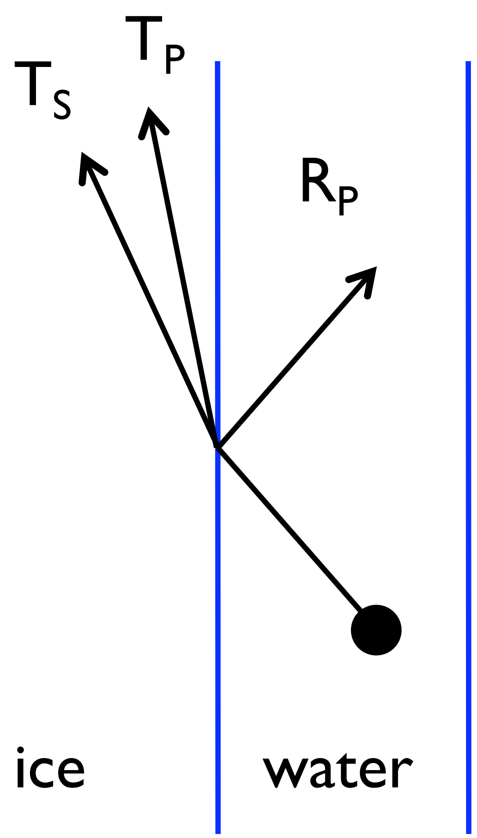
Speed of sound

After-pulses observed in some pinger runs

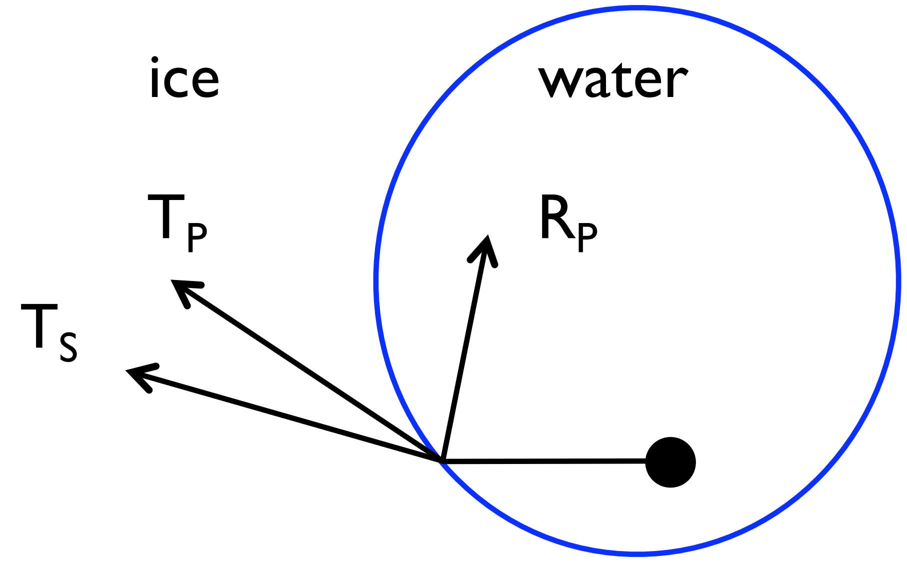


- After pulses observed for near-distance pinger sensor combinations
  - Arrival time compatible with expected shear wave velocity,
  - BUT transmitter in water (no direct production of shear waves possible)

Complicated water → ice transmission



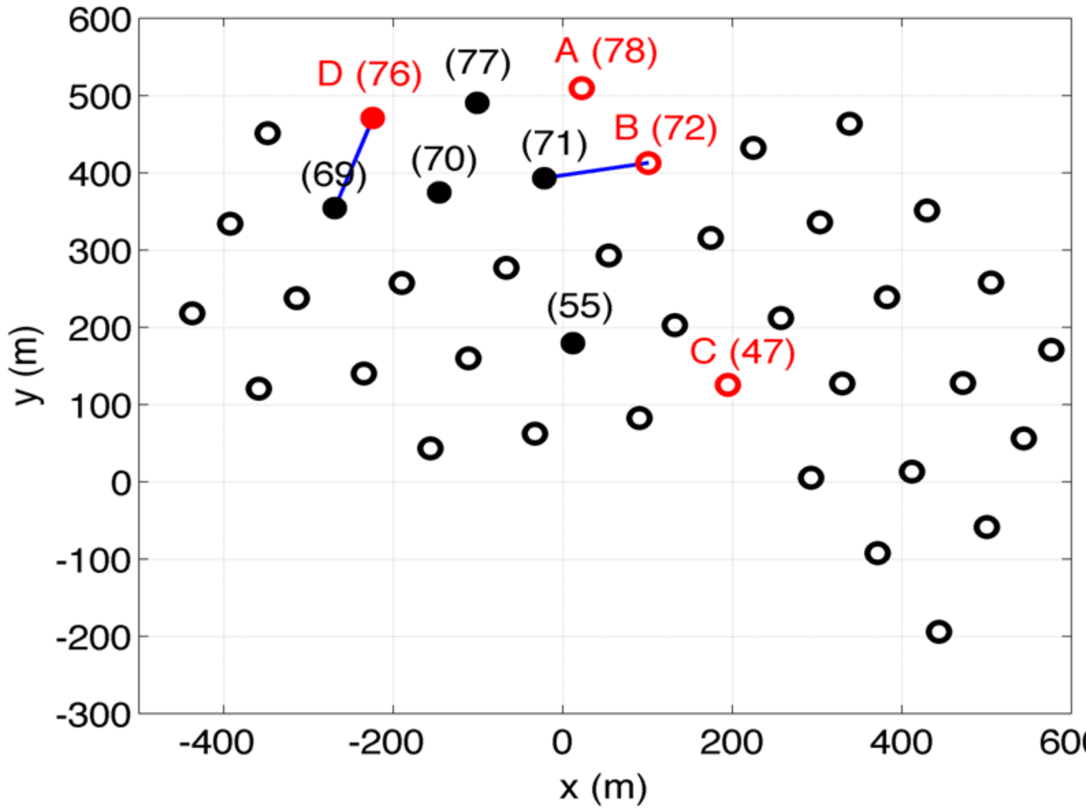
side view

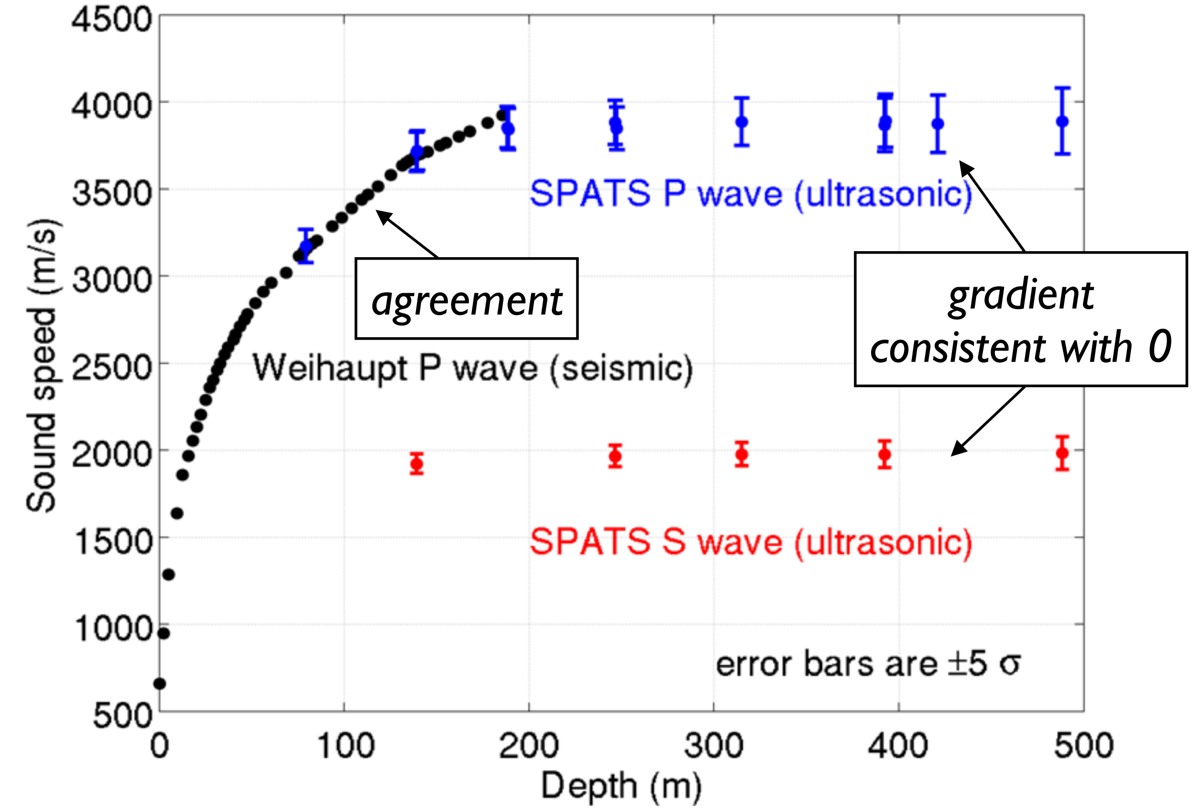


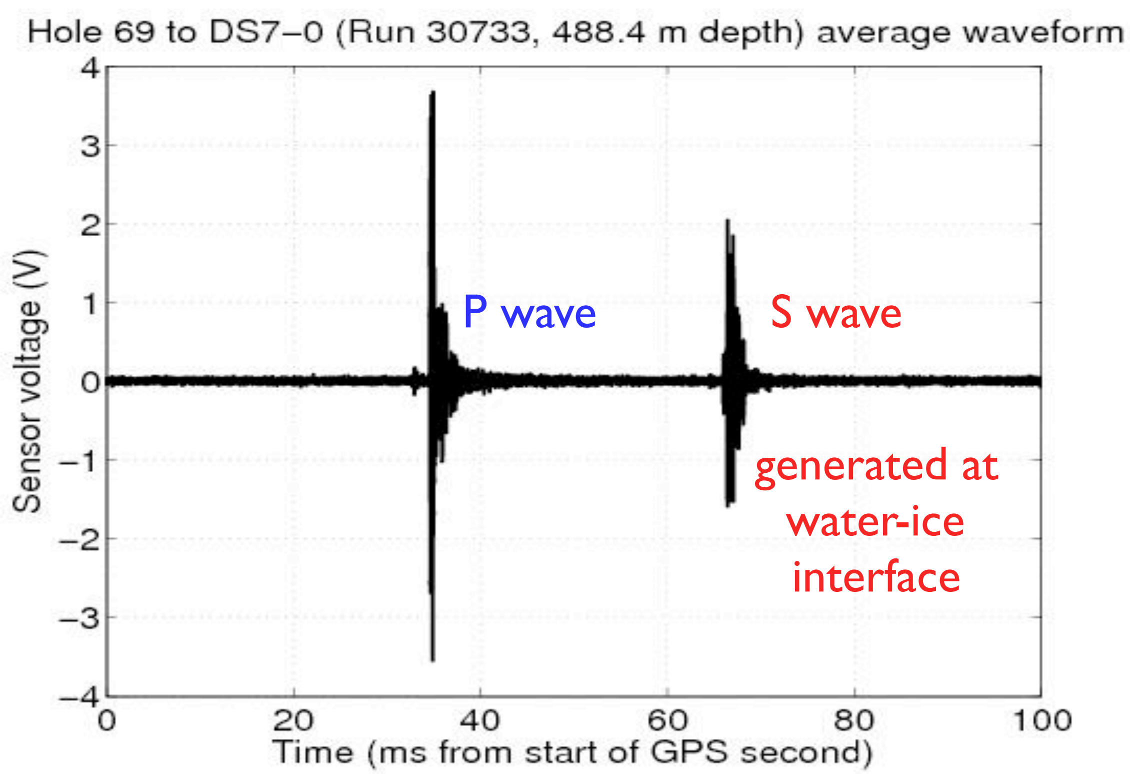
top view

- Mode conversion at interfaces
  - at larger incident angle, shear waves have increased amplitude (and P waves have decreased amplitude!)
- For large incident angles need 3D calculation of
  - $\theta_{incident}$
  - then $RP(\theta_{incident})$, $TP(\theta_{incident})$, $TS(\theta_{incident})$

Sound speed depth profile







- 2 combinations, 125 m distance from pinger data season 2007-2008
- Better than 1% accuracy
- First measurement in situ for P and S waves

$$v_P(375m) = 3878 \pm 12 \;\; m/s$$

$$v_S(375m) = 1975.8 \pm 8.0 \;\; m/s$$

accepted for publication in Astropart. Phys., arXiv:0909.2629 [astro-ph.IM]

Attenuation length

Attenuation length

Expectation: several kilometers ↔ Measurement: 300 m

Analysis	α_{att} (km^{-1})
Pinger data (time domain)	3.20 ± 0.57
Pinger data (frequency domain)	3.75 ± 0.61
Inter-string data (same level)	3.16 ± 1.05
Inter-string data (3-level ratios)	4.77 ± 0.67
Transient events	3.64 ± 0.29

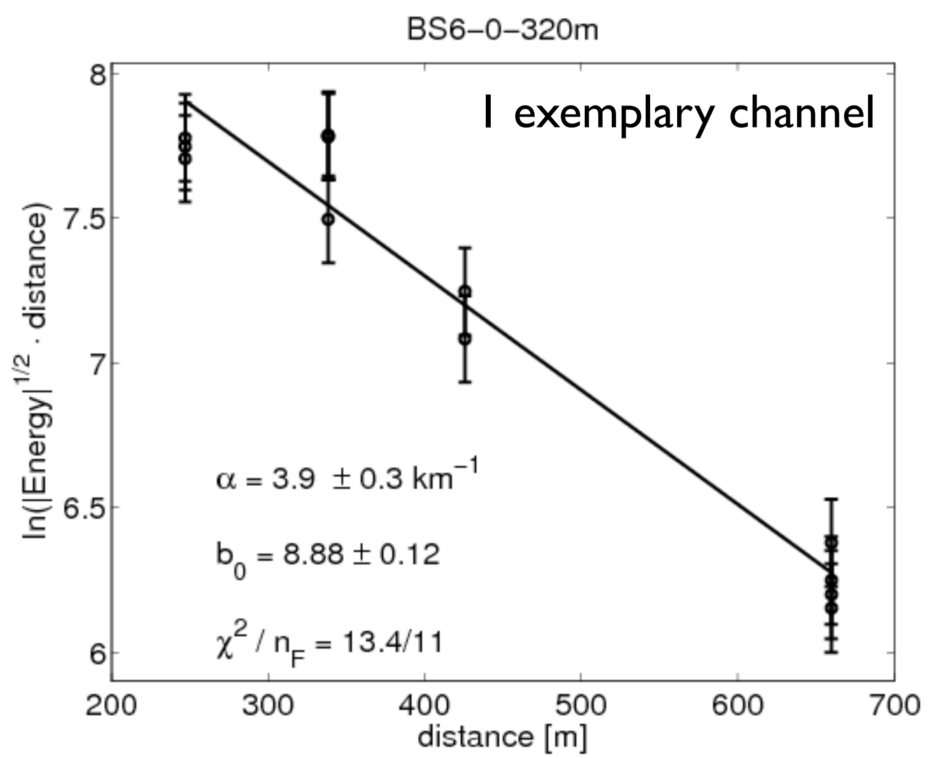
- No significant evidence for depth dependence, but not excluded
- Unclear frequency dependence: absorption or scattering?
  (analysis with new pinger data in progress)

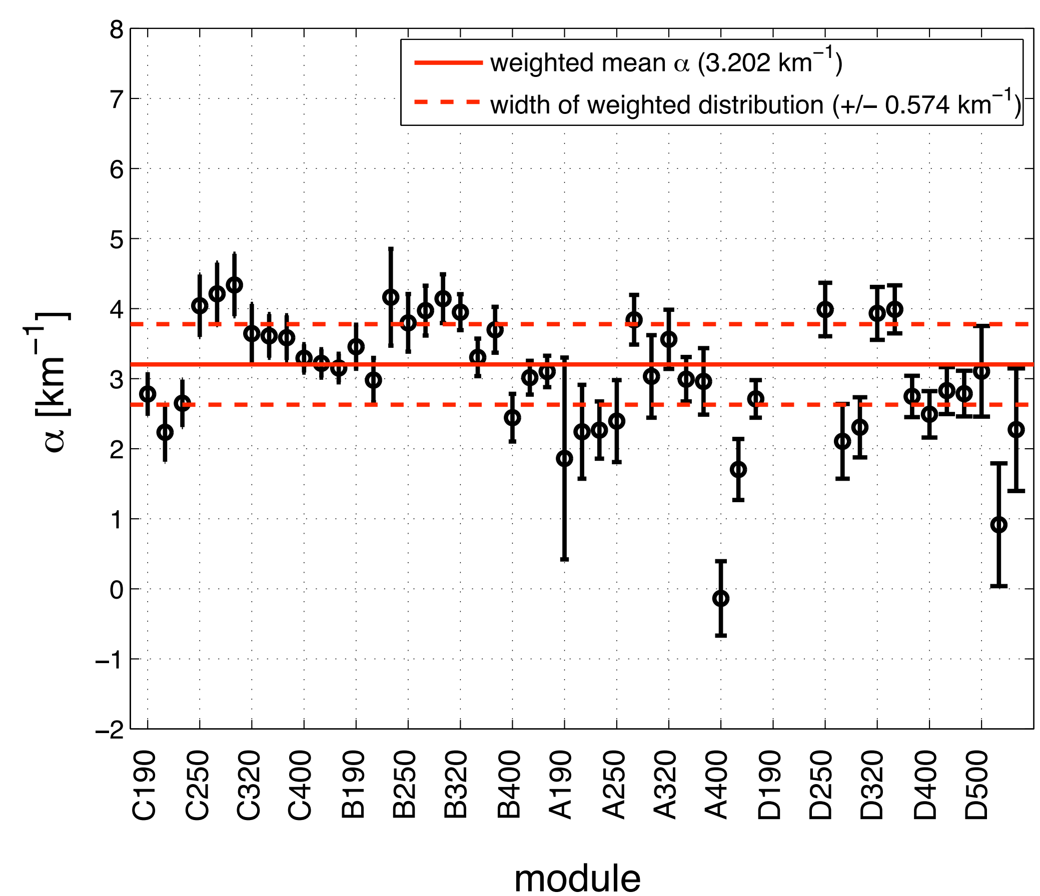
submitted to Astropart. Phys., arXiv:1004.1694 [astro-ph.IM]

Pinger attenuation analysis

- Signal energy E calculated for each channel and over all pinger holes, noise subtracted from pinger-off runs
- Linear fit of y = ln (distance × √energy) yields attenuation coefficient α
- 47 independent measurements; 45 after quality cut $|\alpha| \geq 3\,\sigma_\alpha$
- Weighted mean value and width of distribution: $\alpha = 3.20 \pm 0.57\ \mathrm{km}^{-1} \leftrightarrow$

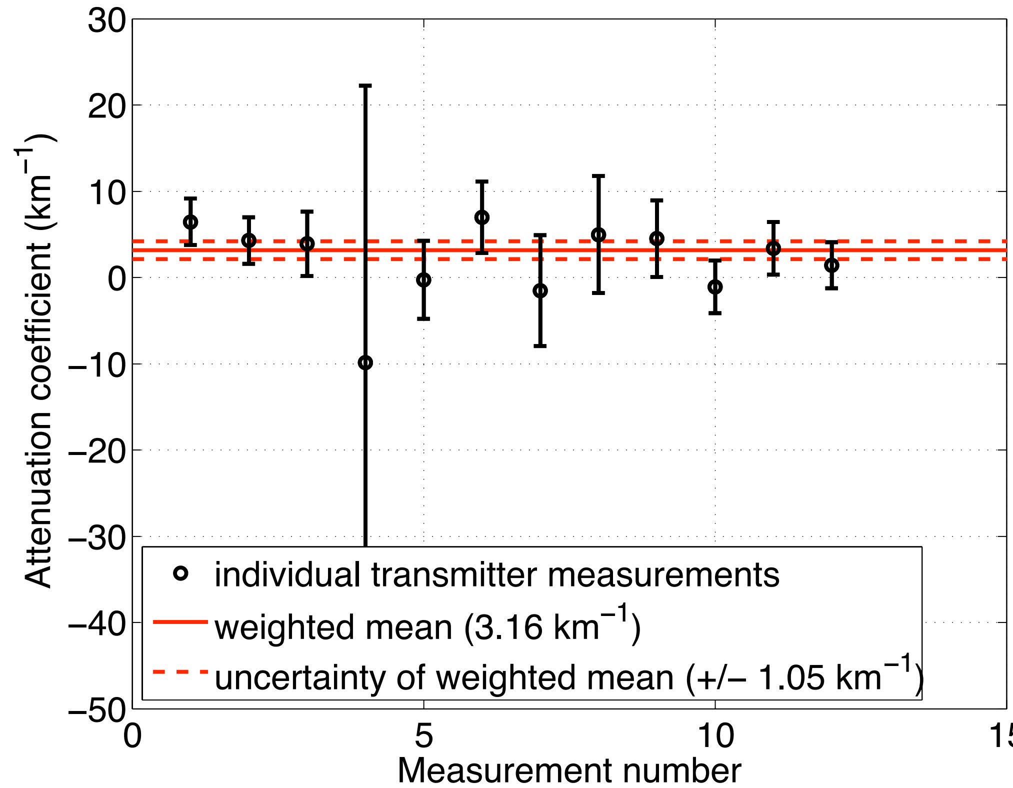
  $\lambda = 313 \pm 57$ m

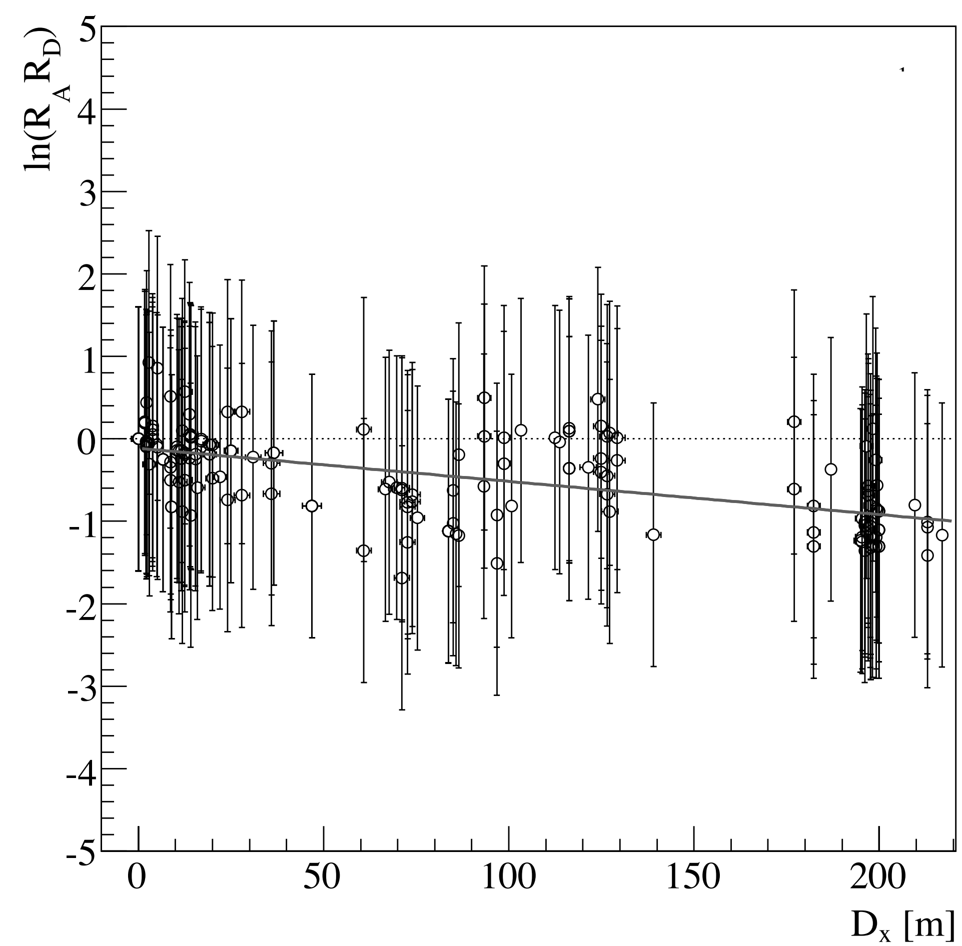




Inter-string attenuation analysis

- Inter-string data:
  - pulse with a frozen-in transmitter
  - listen with all the other sensors
- Same-level method:
  combine a single transmitter
  with all sensors at the same depth
  - Systematic uncertainty:
    combines unknown azimuthal
    response of sensors and transmitters
  - $\alpha = 3.16 \pm 1.05\ \mathrm{km}^{-1}$
- Ratio method:
  ratios of all the combinations
  - Higher statistics
  - Systematic uncertainty:
    combines unknown azimuthal and polar
    response of sensors and transmitters
  - $\alpha = 4.77 \pm 0.67\ \mathrm{km}^{-1}$

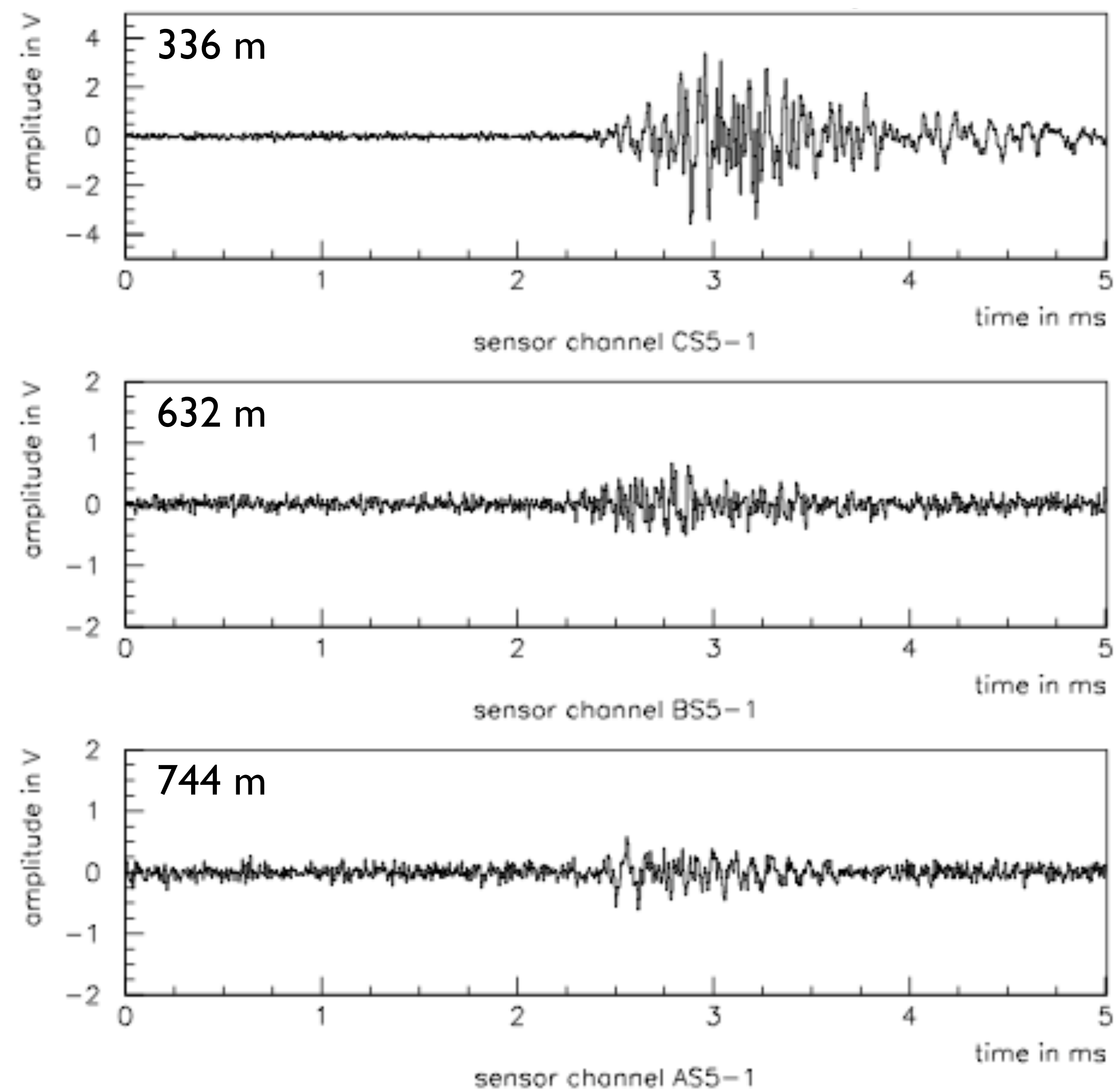




Transients attenuation analysis

- "Cracking" in refreezing IceCube holes
  - single pulses observed with SPATS sensors at different distances
  - pulses have frequency contributions up to 80 kHz
- Attenuation coefficient derived from 13 events (statistical errors only)
  $\alpha = 3.64 \pm 0.29\ \mathrm{km}^{-1}$

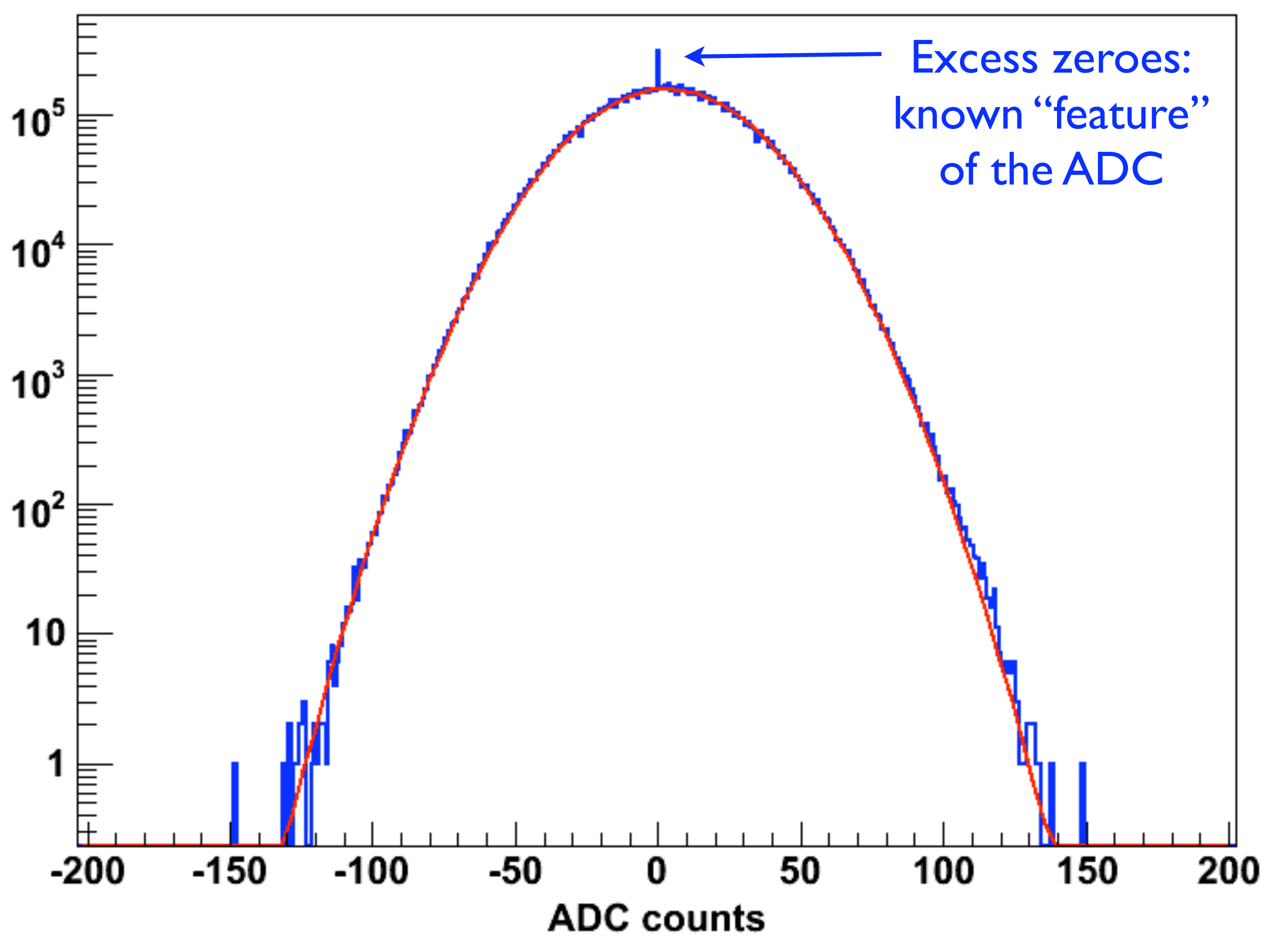
Transient event from hole 19 refreezing

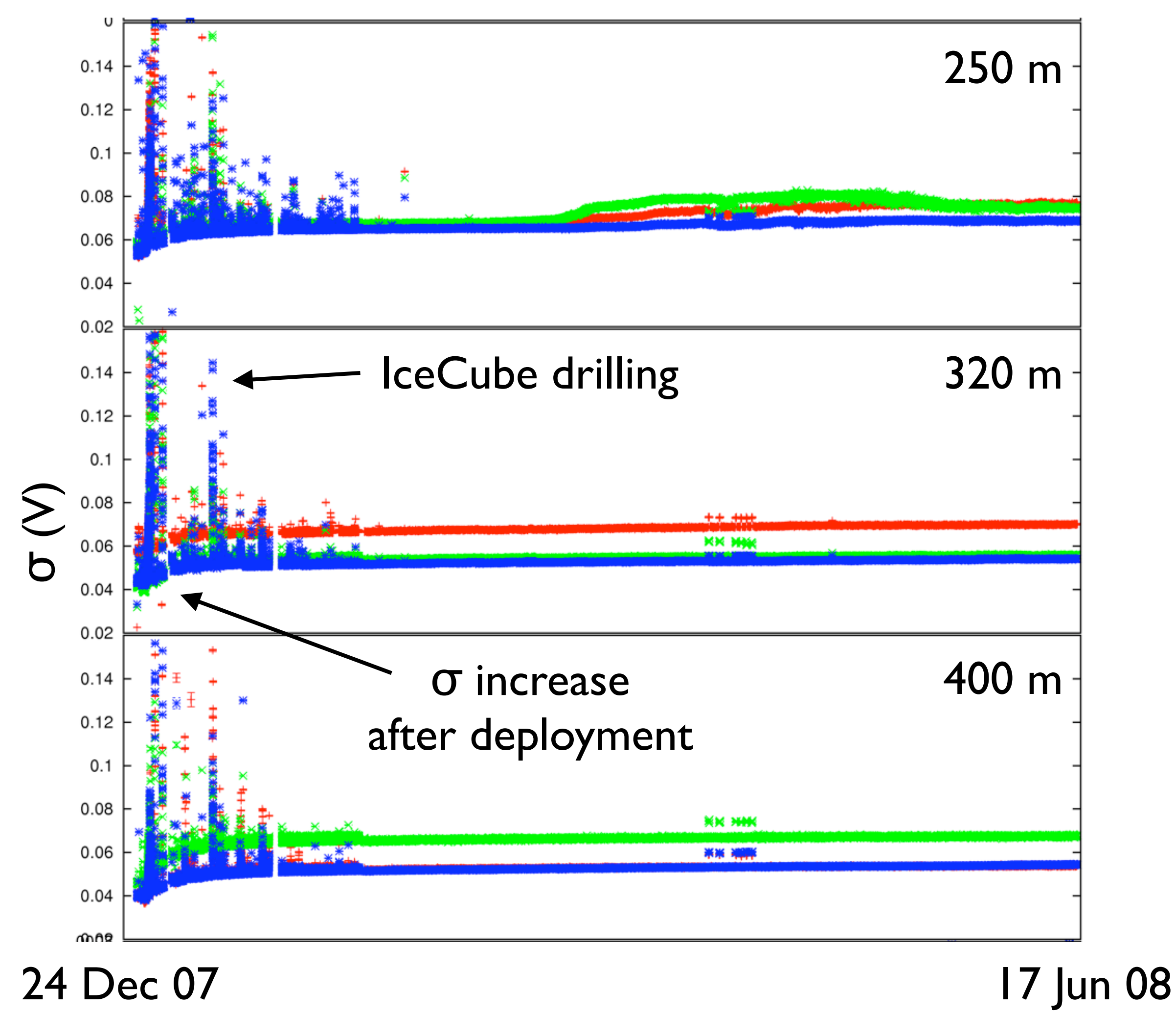


Absolute noise level
&
Sensor calibration

Noise: properties and temporal evolution

- Gaussian and stable over long time
- Peaks correlated with IceCube drilling, inter-string data taking
- Hypothesis: freeze-in improves coupling to ice causing noise level to increase and then stabilize in the first couple months





Absolute noise level

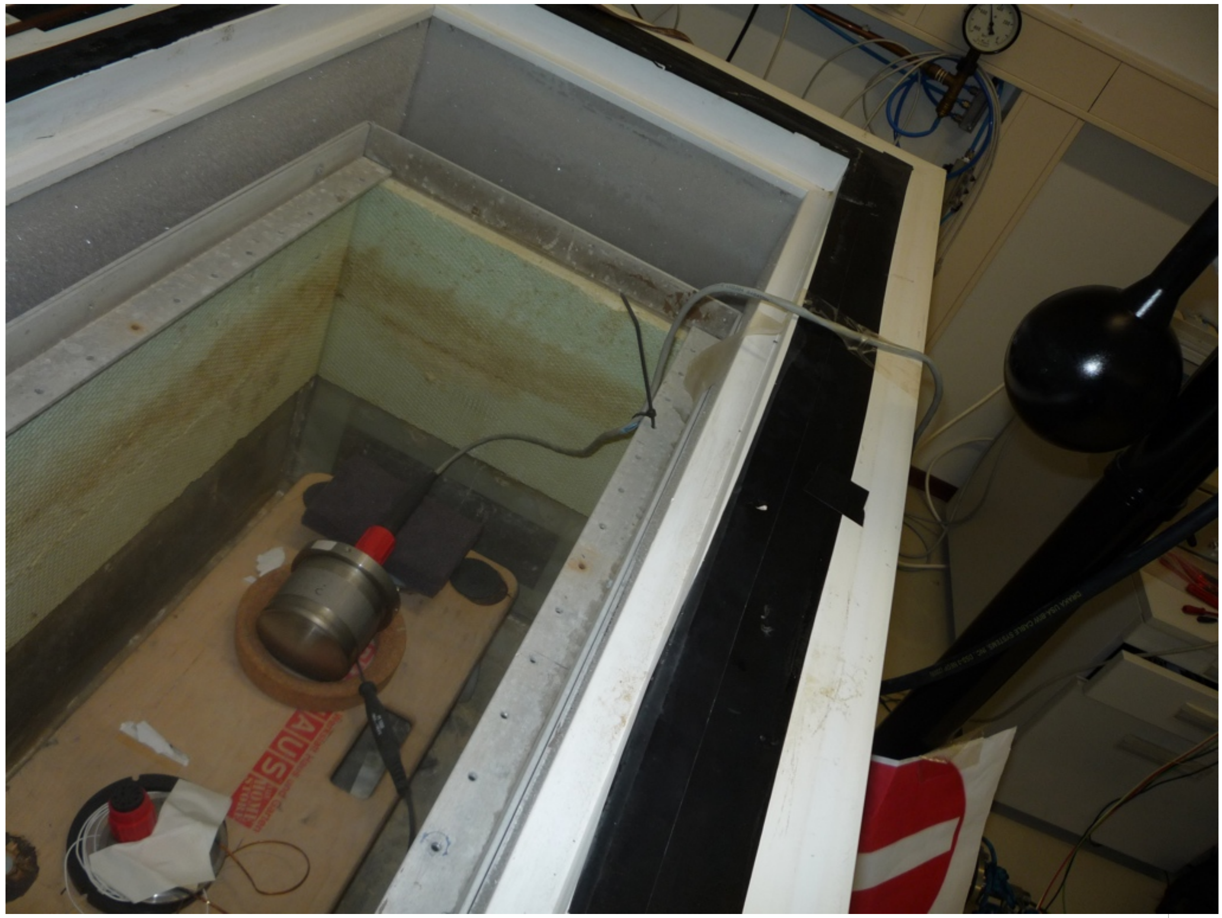
- SPATS sensors have been calibrated in water at 0℃ prior to deployment (relative to a reference hydrophone SensorTech SQ-03)
- But, can we use this calibration for in-situ measurements at South Pole?
  - Temperature −50℃
  - Increased static ambient pressure
  - Different coupling from medium to sensor (acoustic impedance)
- In-situ calibration is challenging, but
  - ‣ Can study different effects separately in the lab

Wuppertal Water Tank
11 m^3 water

Aachen Ice Tank
3 m^3 bubble free ice

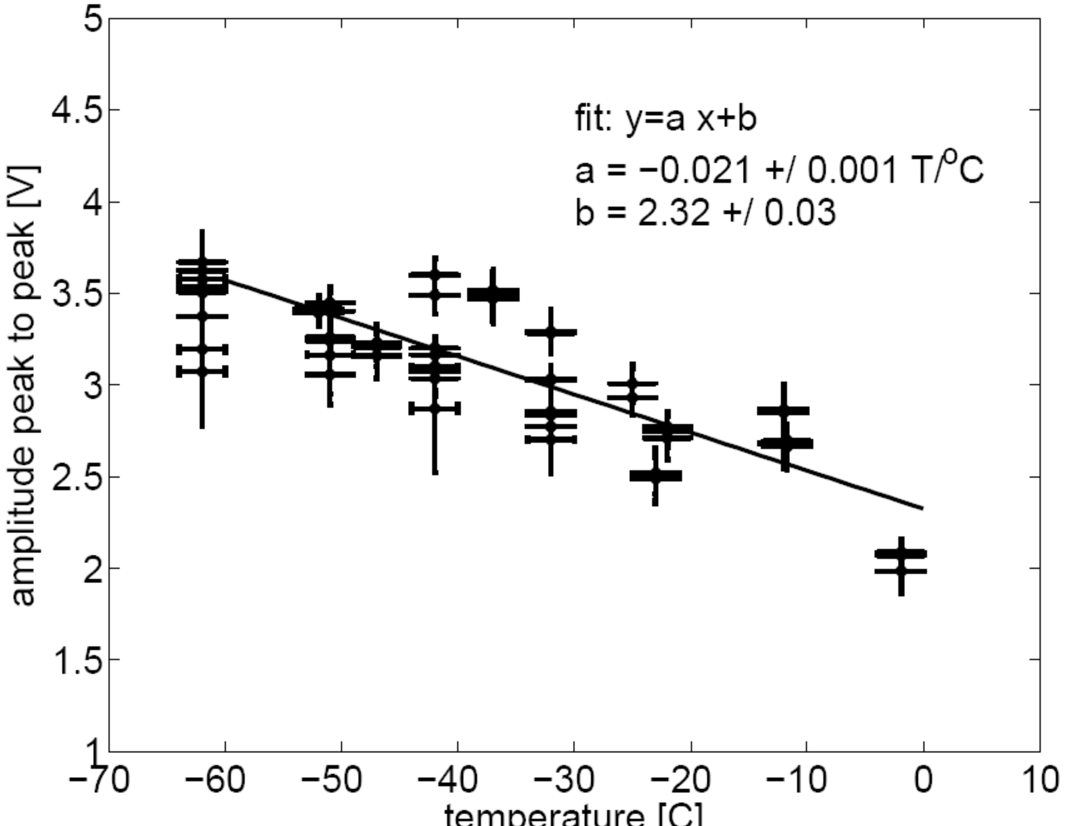
Uppsala Pressure Vessel
liquid filled,
cable feeds,
up to 1000 bar

Sensitivity dependence on temperature



- SPATS sensor cooled down in air
- Transmitter ITC-1001 at room temperature; pulse repeated at 5 Hz
- Peak-to-peak amplitude is a measure for sensitivity

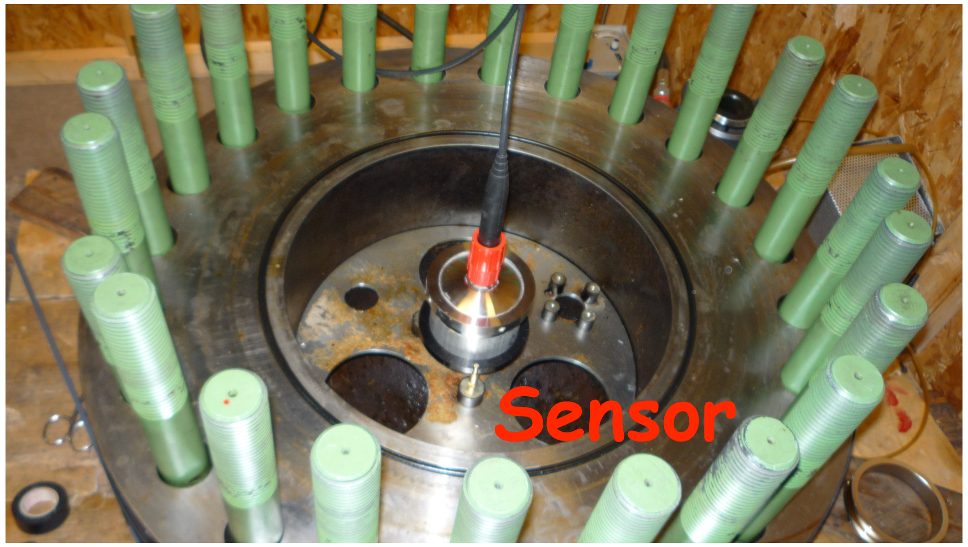
➡From all channels and cycles:
Sensitivity increases by factor 1.5 ± 0.2 from 0 to −50℃

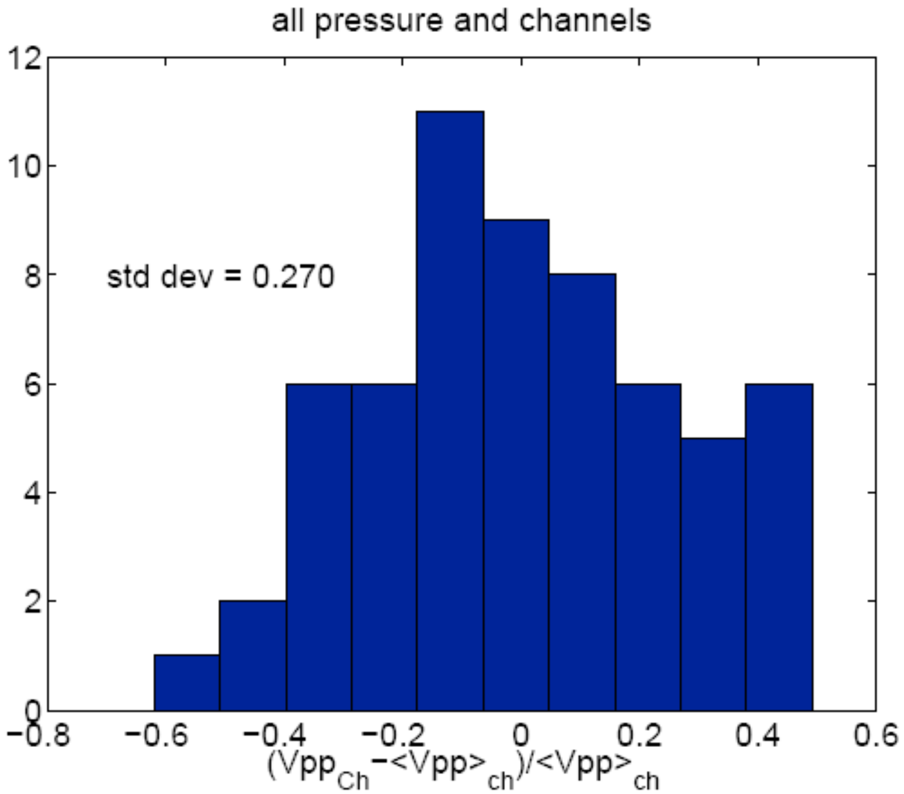


Sensitivity dependence on pressure

- Sensor in liquid inside pressure vessel
- Transmitter coupled from outside to steel vessel (pressure free)
- Peak-to-peak is a measure for sensitivity
- No systematic sensitivity variation with pressure observed

- Sensitivity variation due to pressure < 30% from 0 to 100 bar

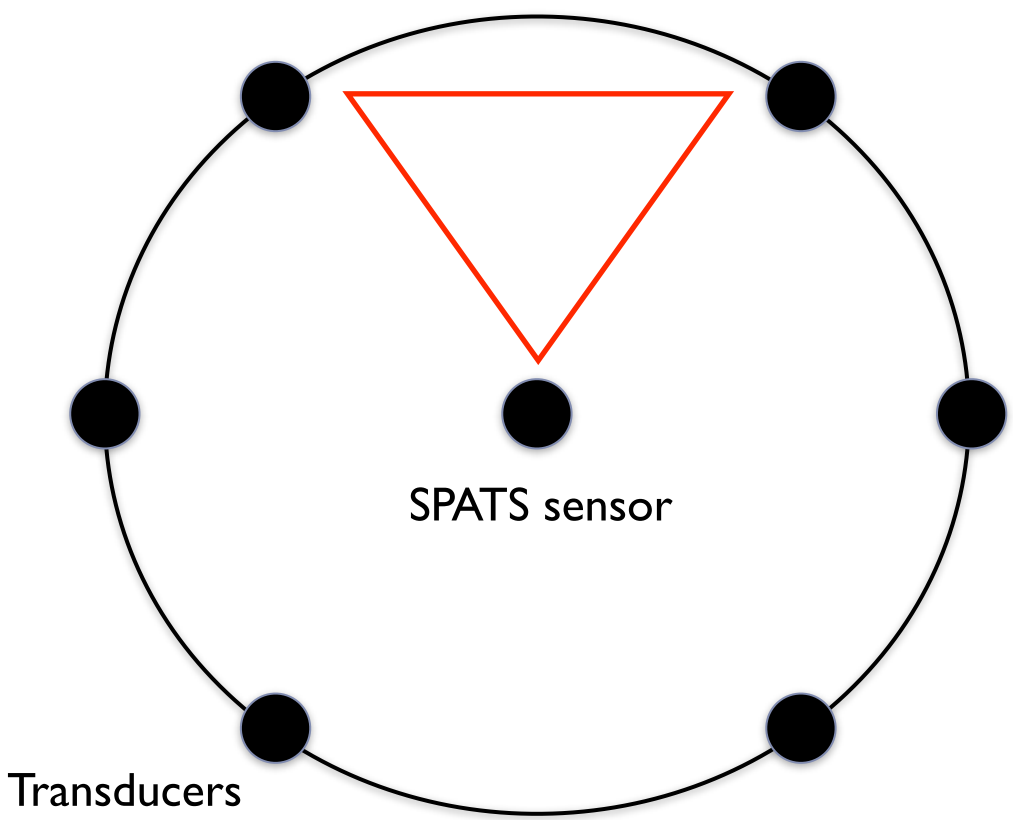


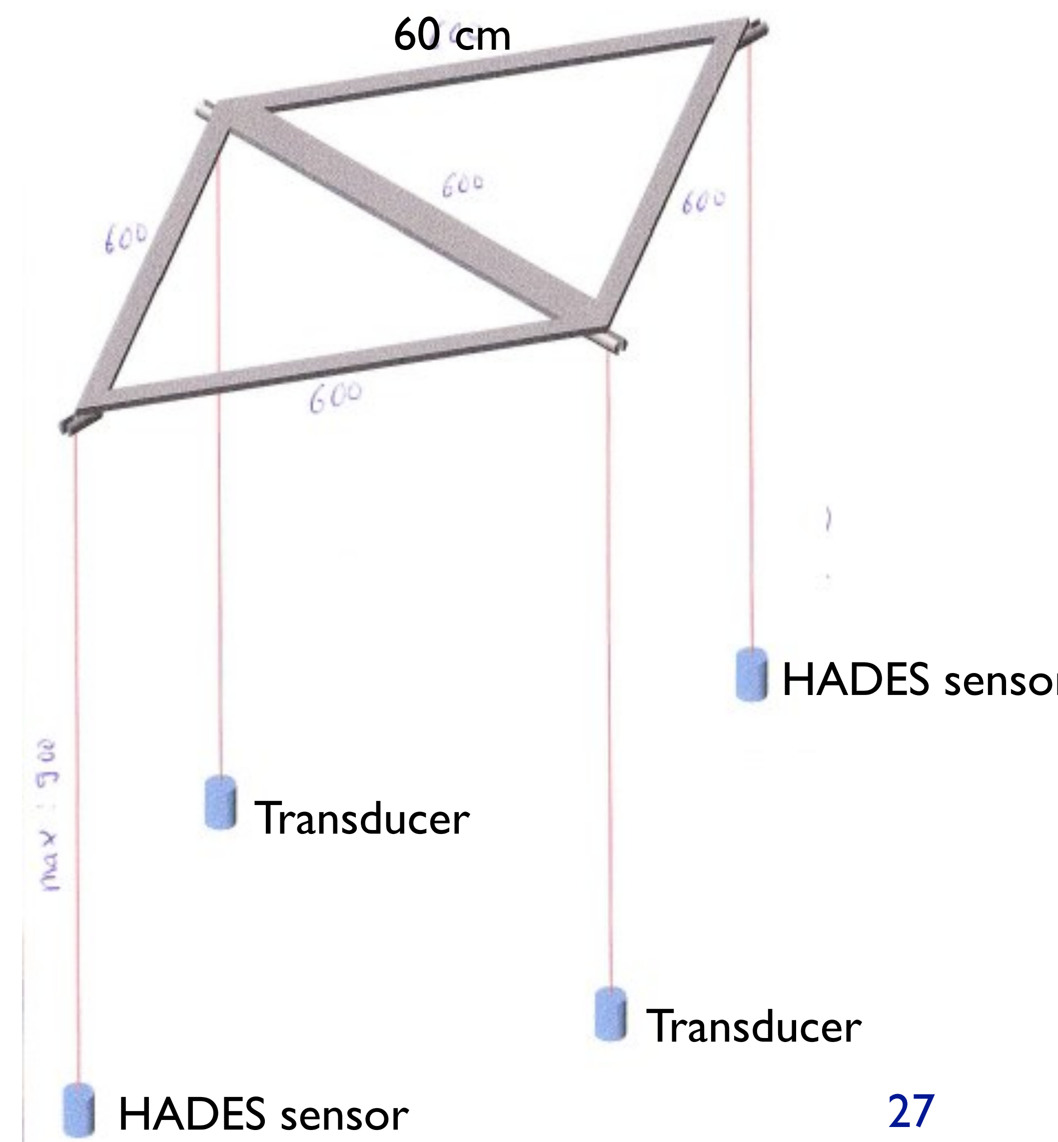


How to calibrate in ice? - Reciprocity method

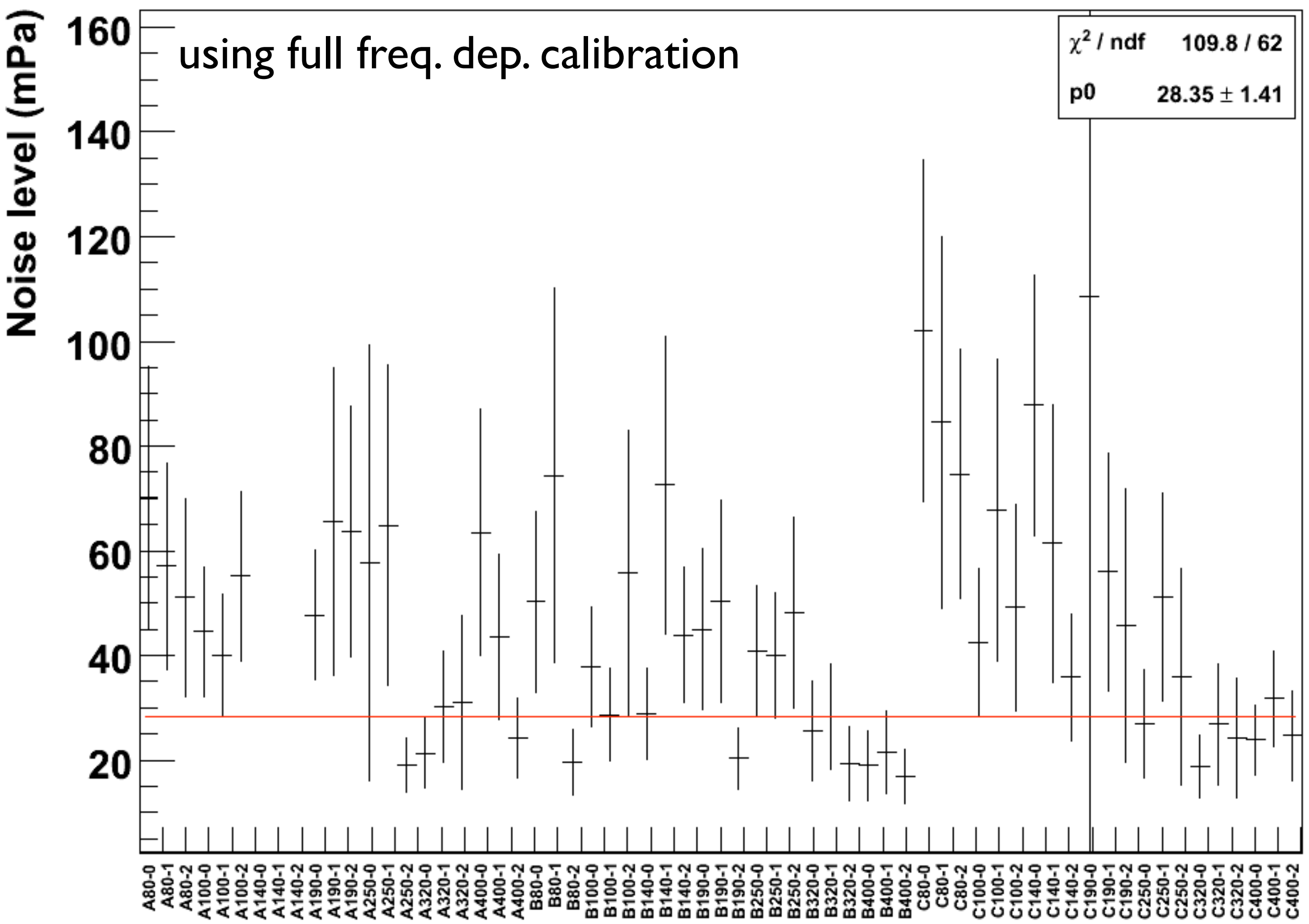
- Allows calibration without an absolutely calibrated reference
- Method tested in water: results highly reproducible
- Freeze as many equilateral triangles as possible

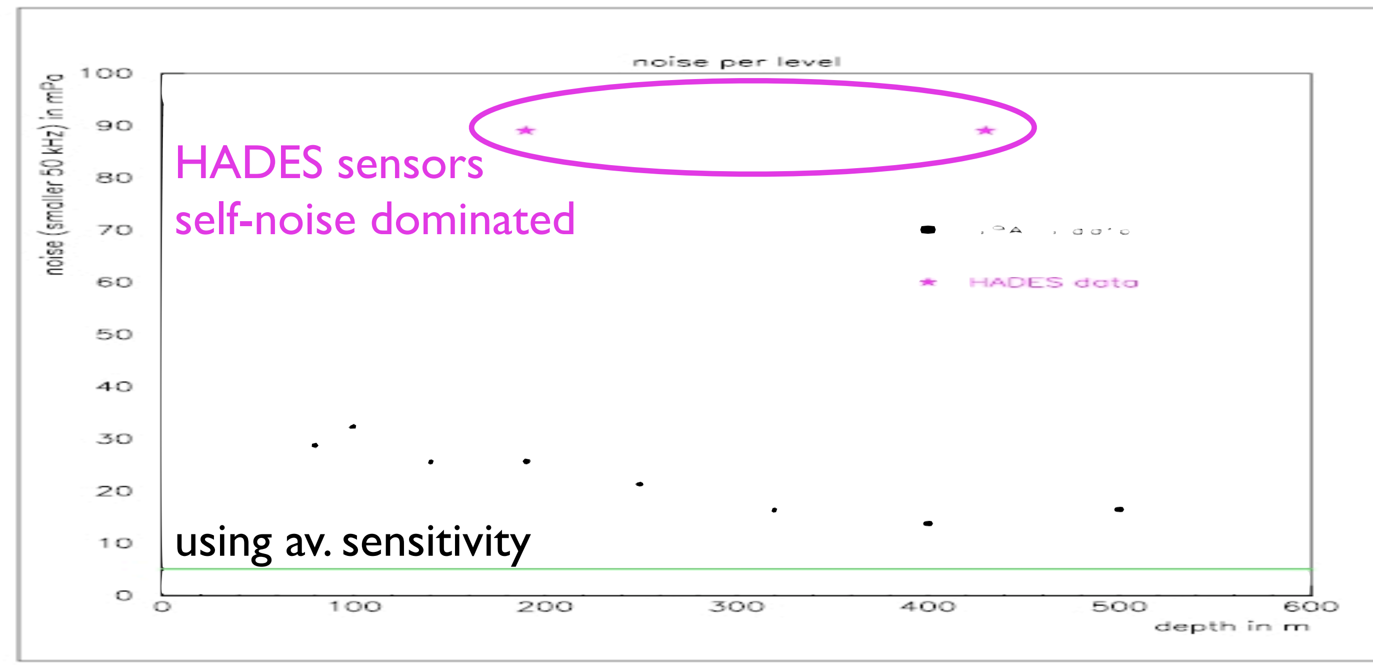
$$M_{\mathrm{Rx}} = \sqrt{\frac{2a}{\rho f}\frac{U_1 U_1'}{U_2 I'}}$$





Estimation of noise level (10 – 50 kHz)

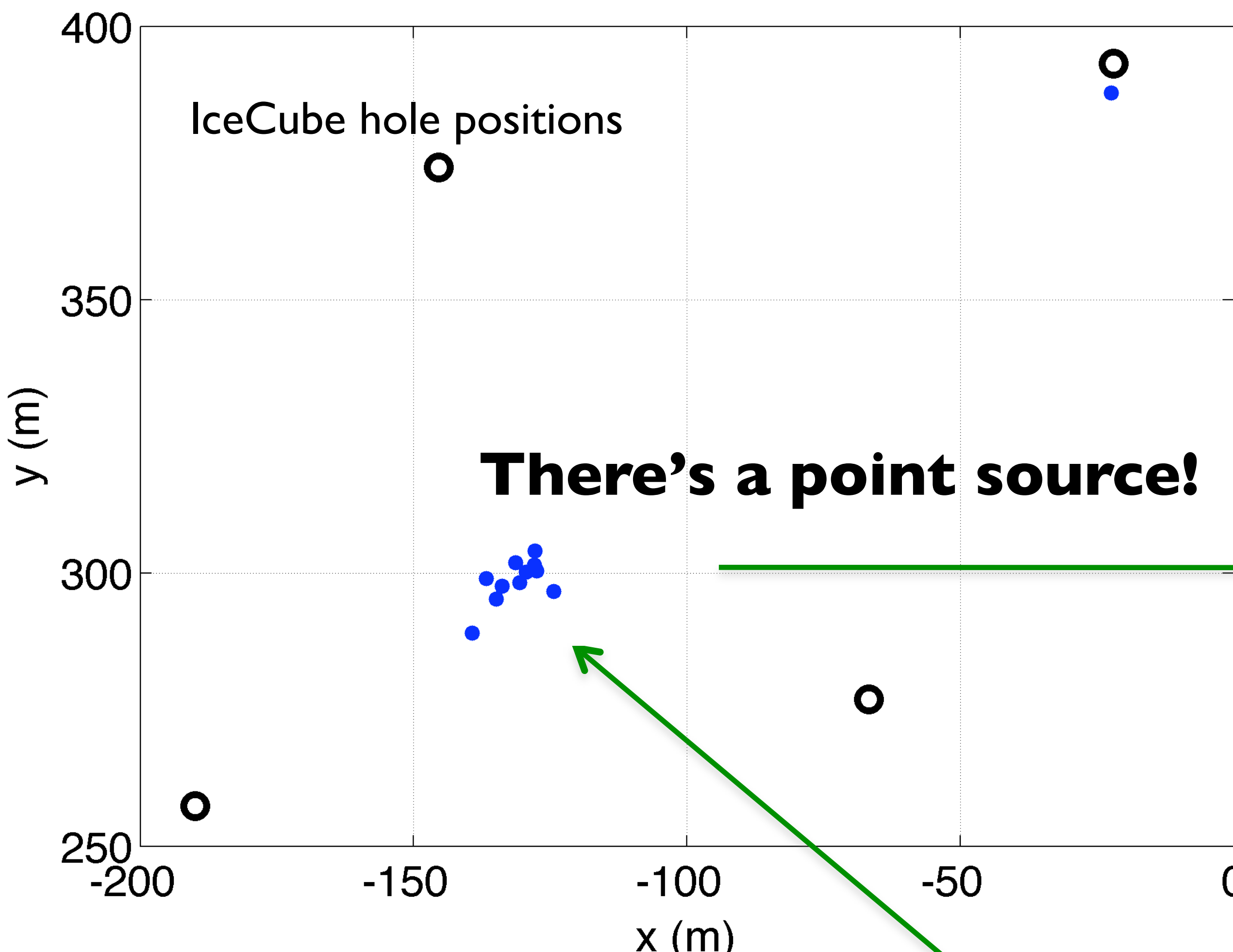


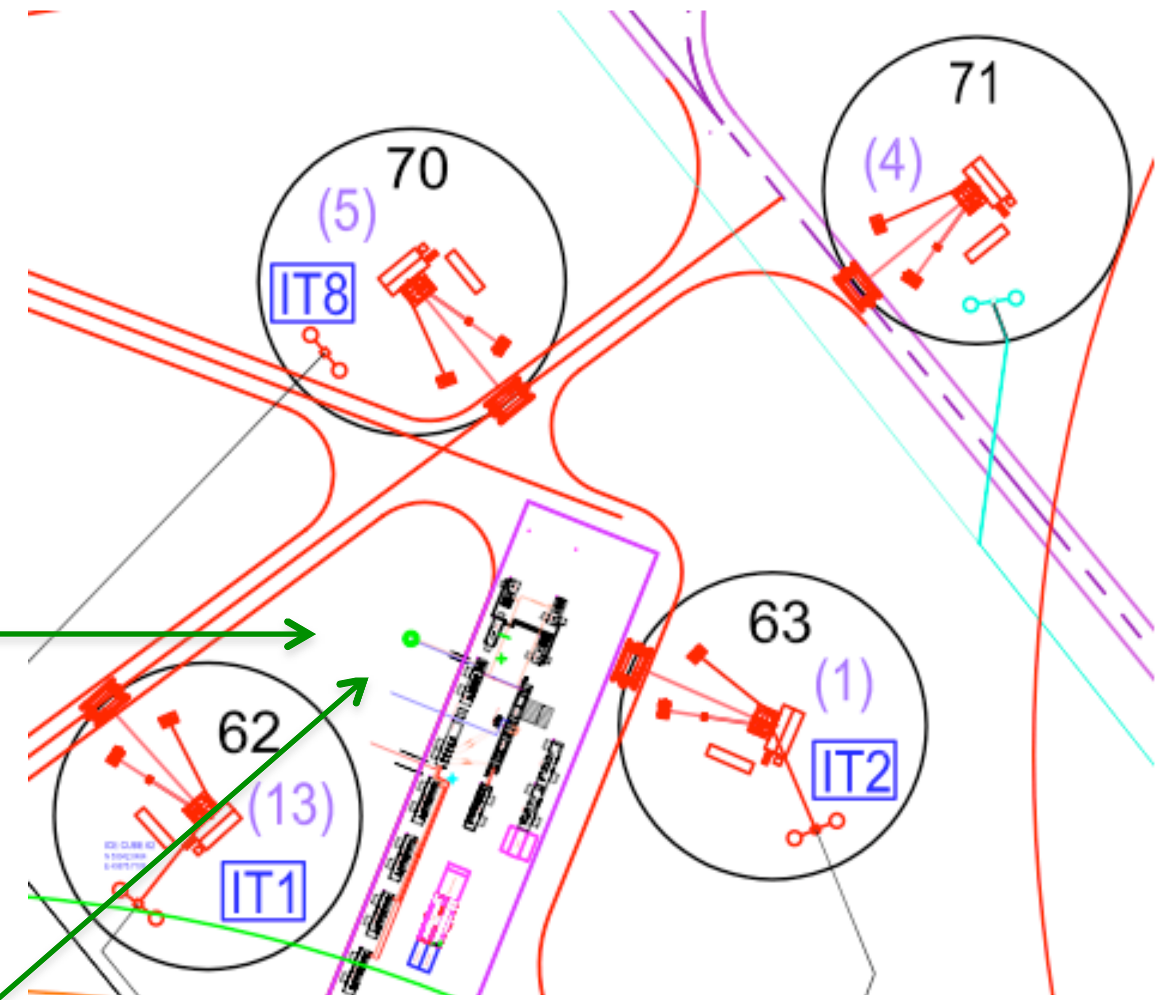


- Use sensitivity correction factor of 1.5 (from temperature)
- Sensitivity change due to freeze in under study
  - expect results in next three months
- Different approaches agree within a factor of 2
- In-situ measurement with different type of glaciophone desirable

Transient sources
&
Event reconstruction

The very first transient events in SPATS



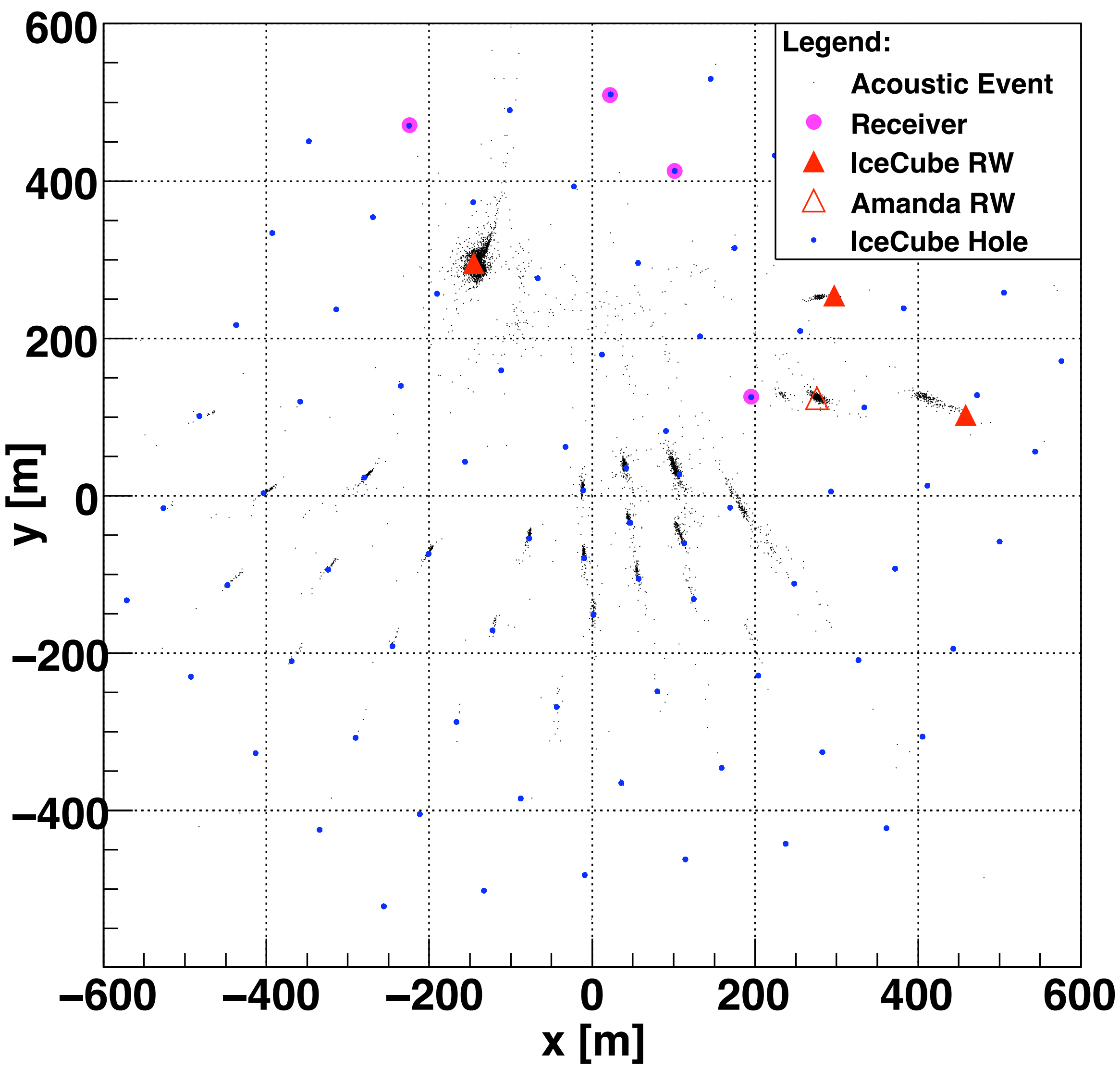


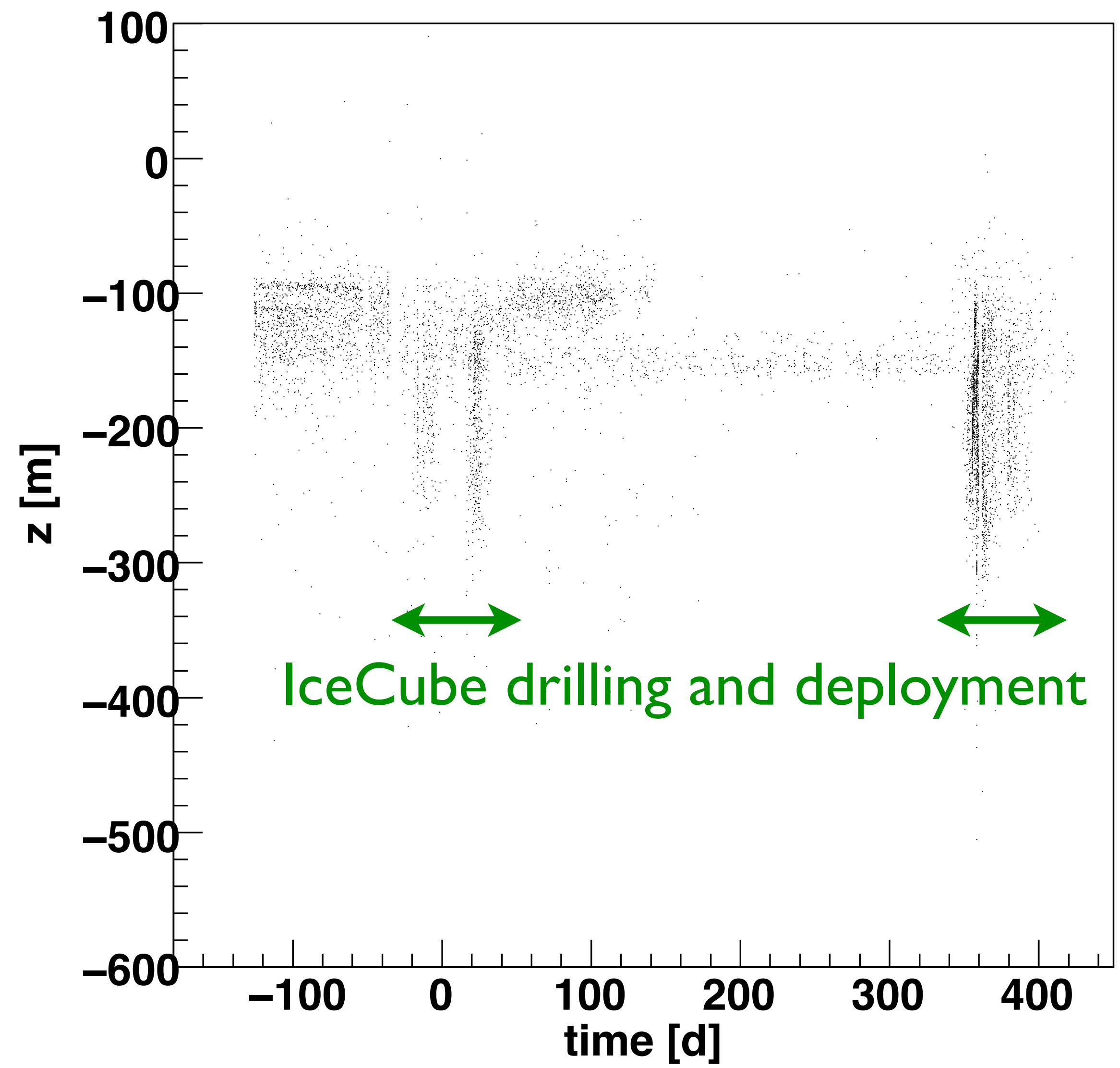
"Rod-well": sub-surface cavern used as water reservoir during drilling

Coincidence and localization

- Offline search for coincidences in time
- Coincidence window: 200 ms (= 700 m sound propagation)
- Apply channel and string multiplicity requirement
- Take only first hit per channel (ignore S waves and multiple triggering)
- Assume constant sound speed: 3850 m s^{-1}
- Reconstruct source location and emission time using analytical or numerical TDOA (time difference of arrival) technique

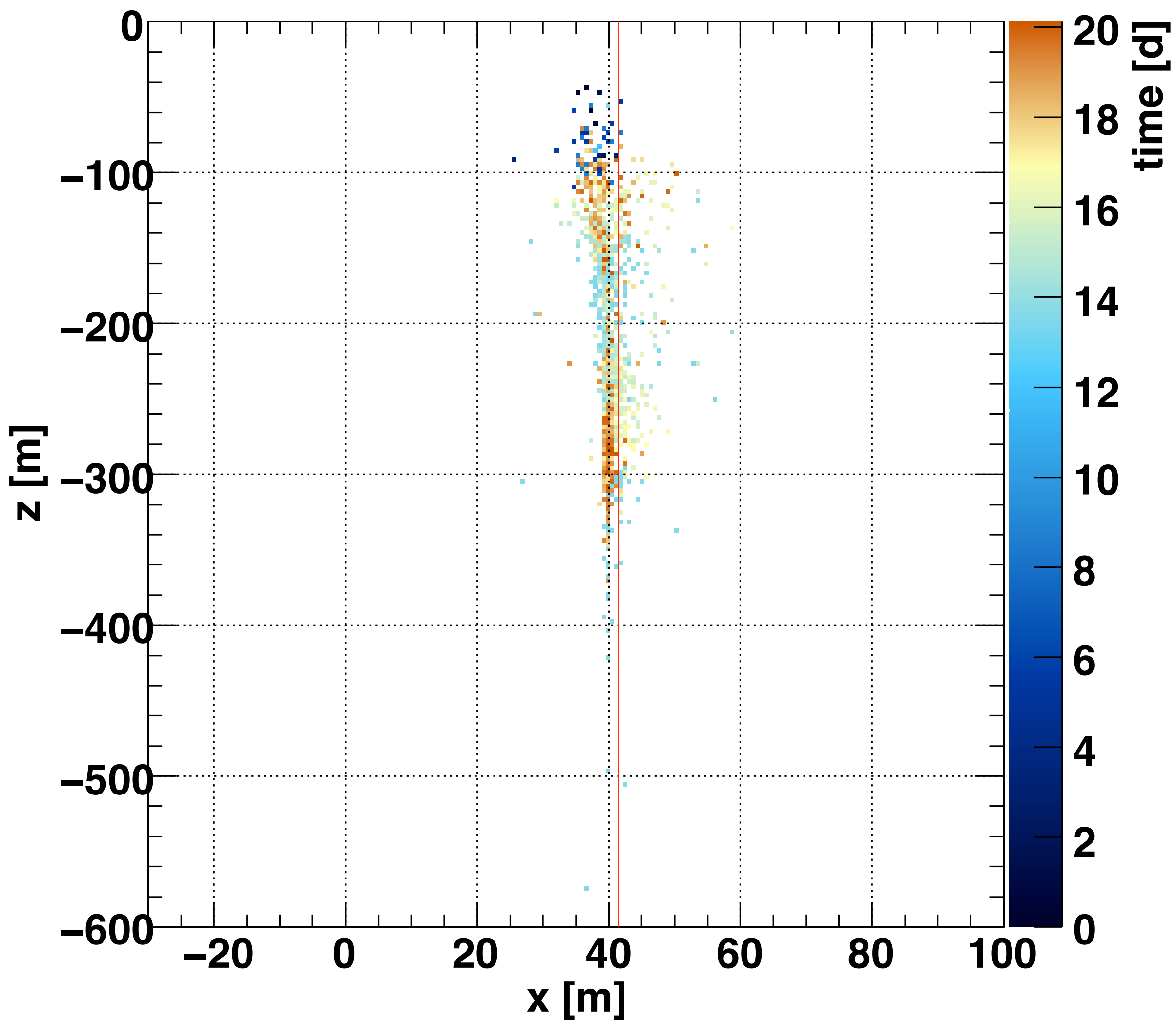
Spatial and temporal distribution of vertices

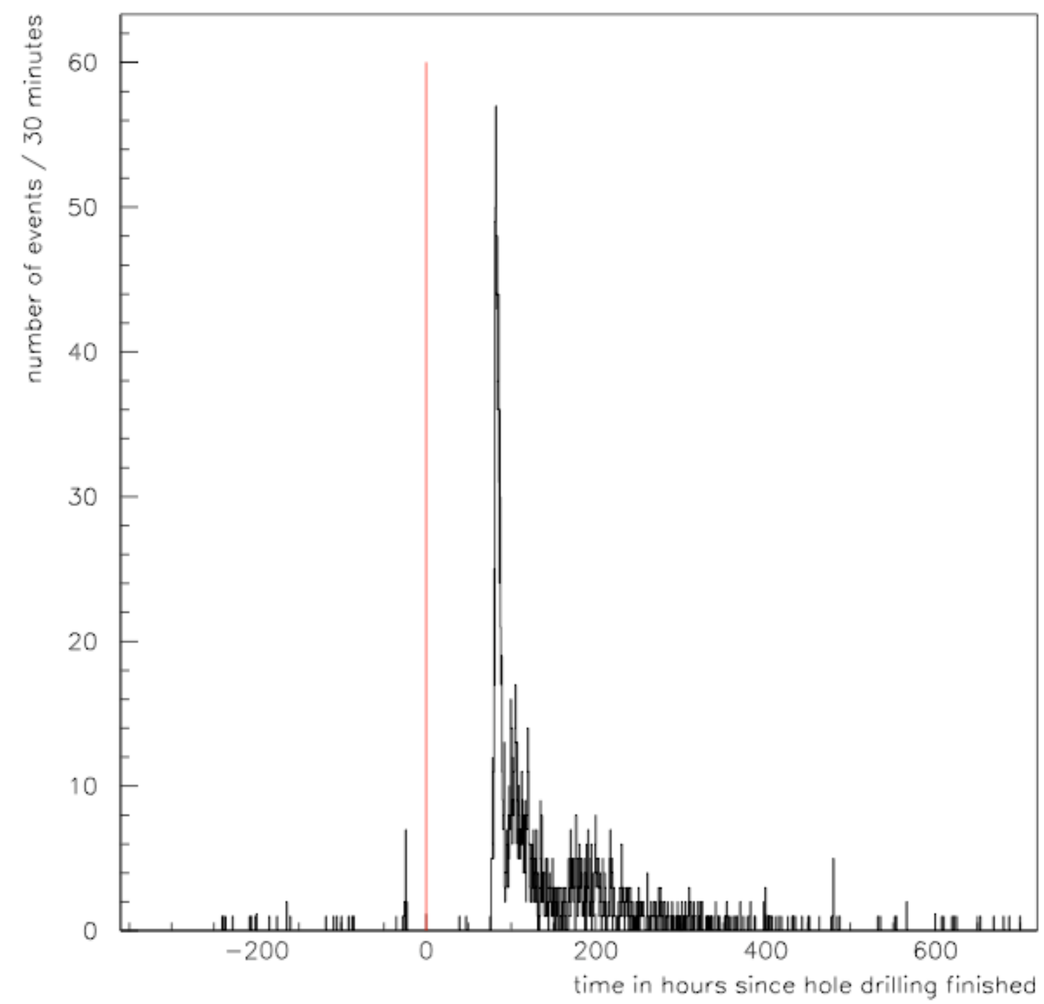




- Only shallow (top 200 m) transients observed outside IceCube drilling
- Refreezing of close IceCube holes and Rod-wells are main (only) sources
- "Smearing" understood artifact from reconstruction
  (constant sound speed assumed)

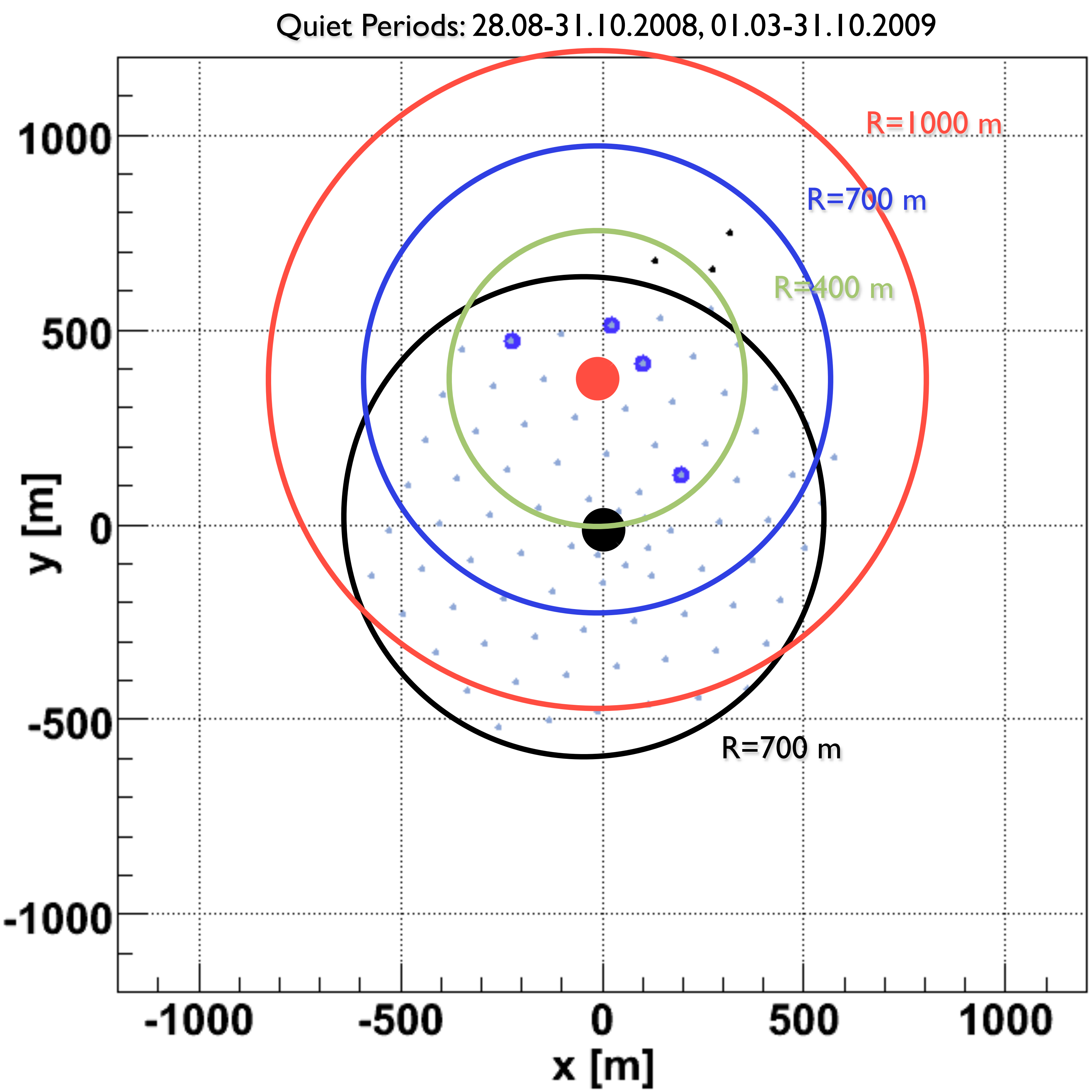
Refreezing of IceCube holes observed





- SPATS is able to monitor the refreezing of IceCube holes
  - quiet period after drilling
  - exponential decay of activity
  - development of water compartments in the hole

No "non-IceCube" transients observed below 100 m



Icecube Center
x=46 m; y=-34.5 m
Acoustic Center
x=23.5 m; y=379.7 m

R=1 km, 0<z<1 km
V=1.698 km^3 (4 Events)

R=0.7 km, 0<z<1 km
V=0.572 km^3 (3 Events)

R=0.4 km, 0<z<1 km
V=0.059 km^3 (2 Events)

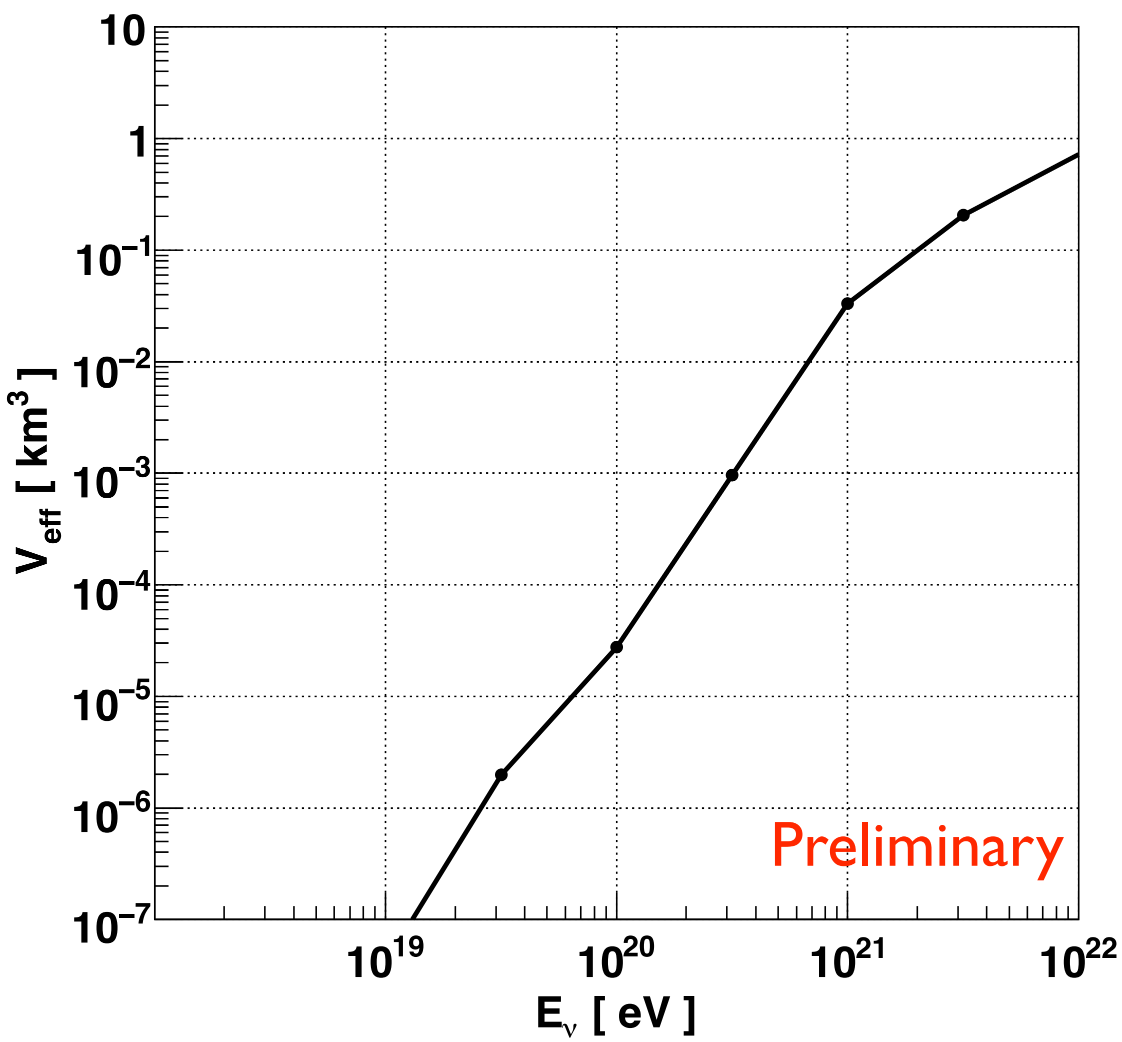
Event 1 05.09.2008
x=837.9, y=276.8, z=-77.1

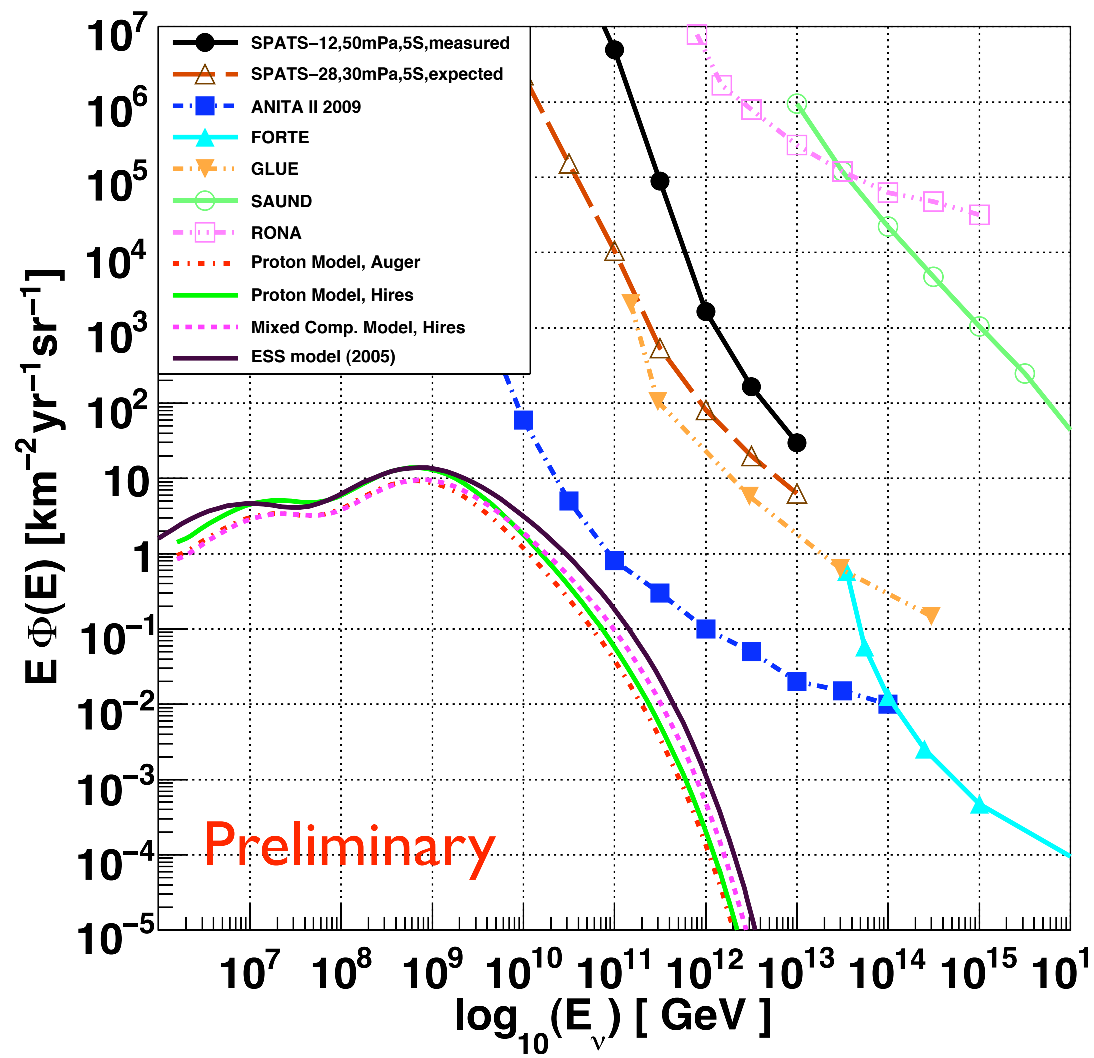
Event 2 20.09.2008
x=318.6, y=749.8, z=-95.7

Event 3 05.04.2009
x=274.3, y=651.8, z=-64.9

Event 4 11.10.2009
x=130.8, y=675.3, z=-68.6

SPATS sensitivity

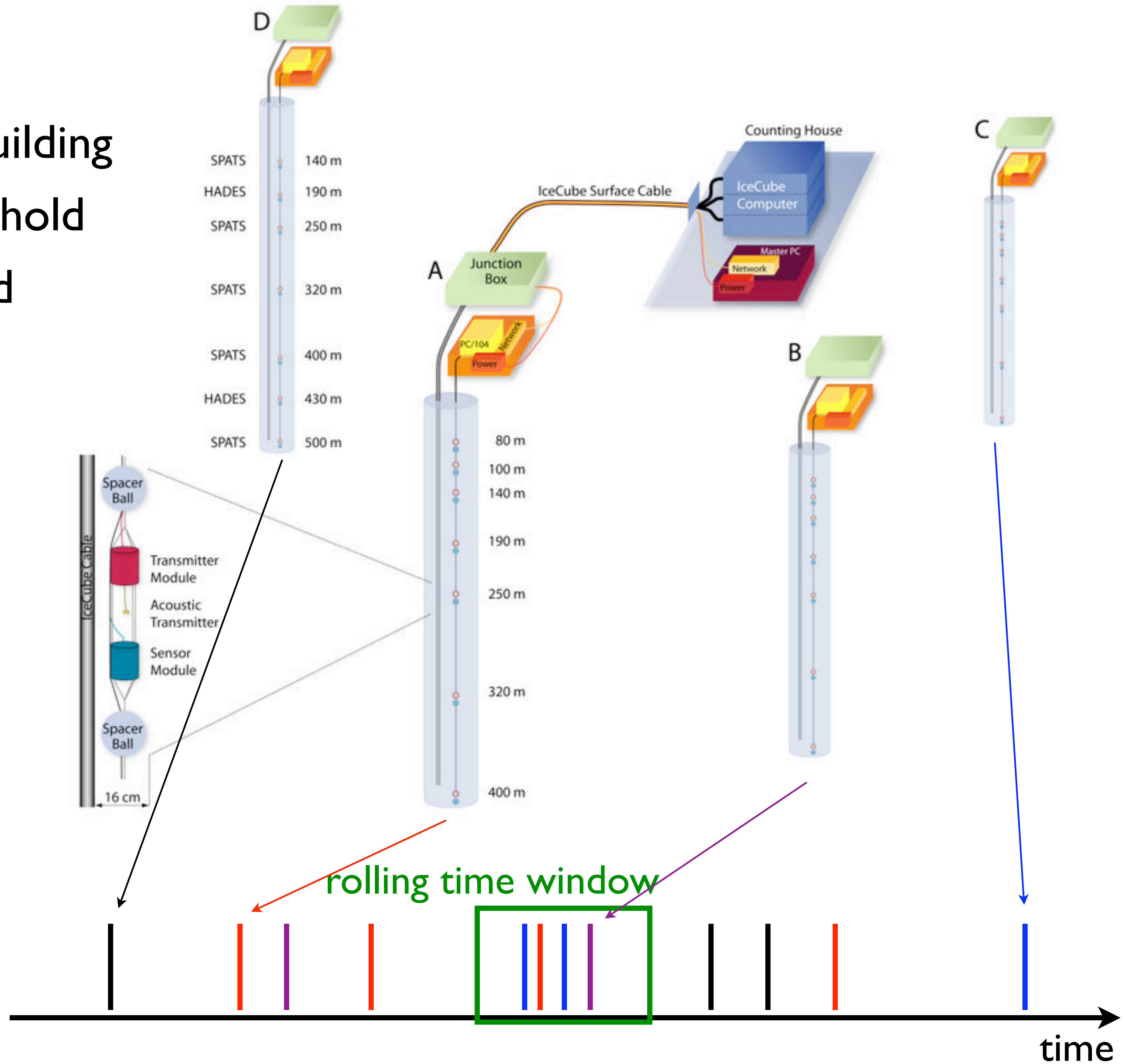




- Simulate ν interactions outside IceCube volume and below 200 m (no refraction)
- Trigger threshold 50 mPa (estimated)
- Very promising result for a test setup

New DAQ software

- Online coincidence building
  - lower trigger threshold
- Currently being tested at South Pole



Aim of SPATS: Mission nearly accomplished

- Speed of sound and and Refraction
  - speed of sound constant below 200 m
    no refraction
- Attenuation length
  - λ = 300 m (20% uncertainty), factor 30 smaller than expected
    larger influence of scattering and/or absorption?
  - frequency and depth dependence under investigation
- Noise floor
  - Gaussian and stable
  - Comparable to deep sea (with reasonable assumptions)
    better results soon to come
- Transient noise
  - Small rate and all deep events from identified sources

Open questions and Plans

- Absolute noise level
  - Deployment of low noise sensor pre-calibrated in ice planned for 2010/11
- Study mechanism of surprisingly short attenuation length
  - Interest from Glaciology community
  - Data available from "multi-frequency" pinger

➡ Have robust sensitivity estimate for acoustic technique at South Pole within next 12 months