Askaryan Radio Array

Chiba University

In-situ calibration and anechoic chamber measurement for radio antenna development

Myoungchul Kim

Outline

- Brief introduction of ARA antenna

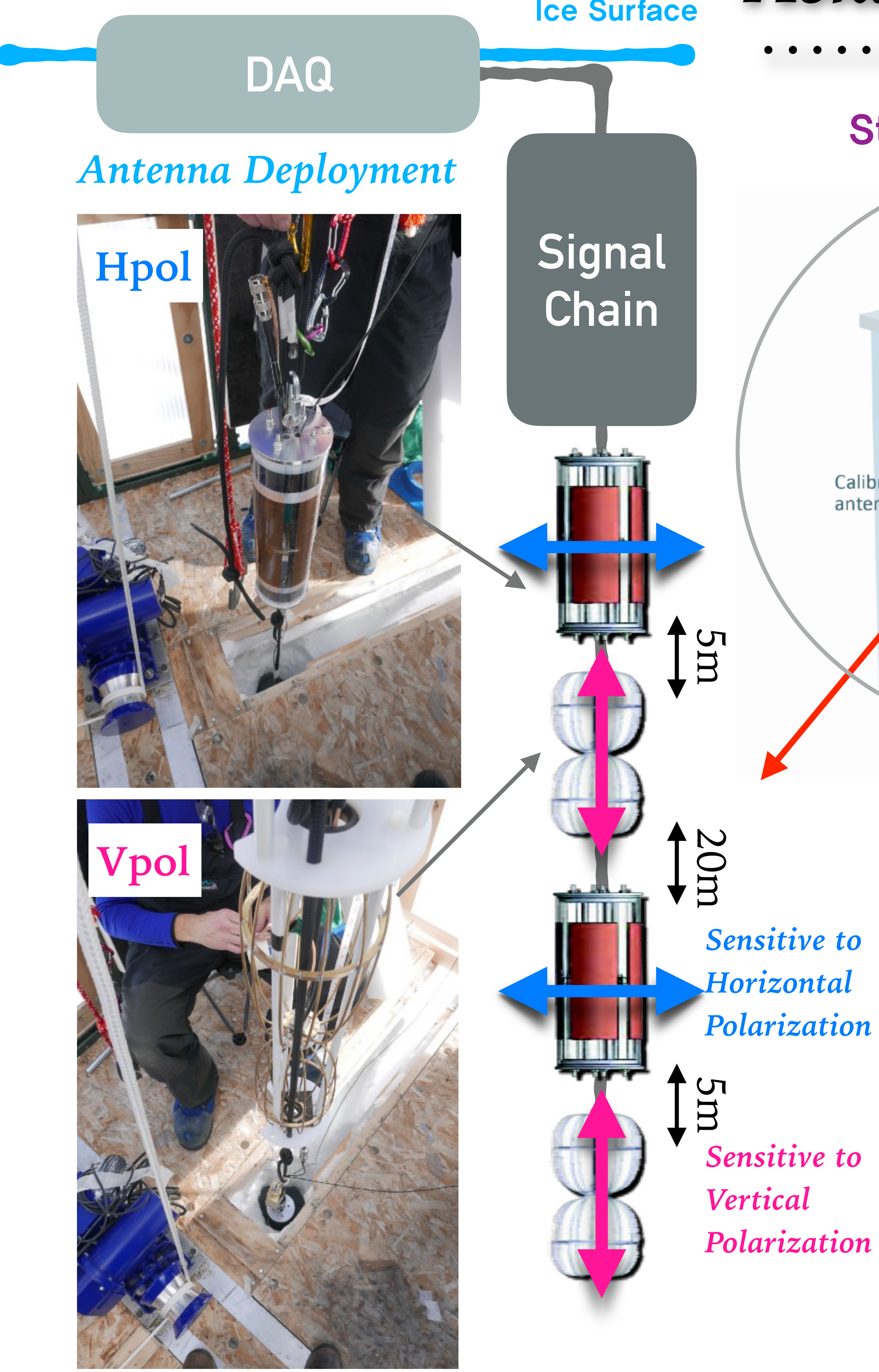
- Strategy for developing antenna model (lesson learned)
  - In-air to in-ice transition strategy
  - Calibration in-air (Anechoic chamber) and in-ice (in-situ calibration)
  - Transition by simulation (XFDTD)
  - Empirical antenna model based on in-situ

- Slim antenna study
  - Development and optimization
  - Measurement at the South pole and Anechoic chamber

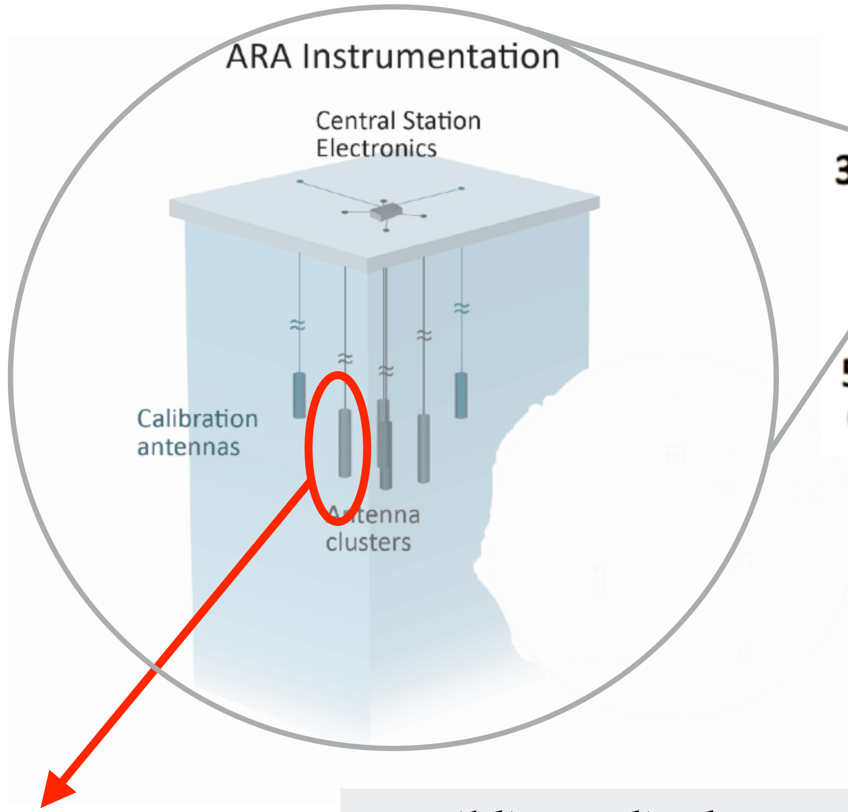
- Summary / Discussion

Askaryan Radio Array (ARA)

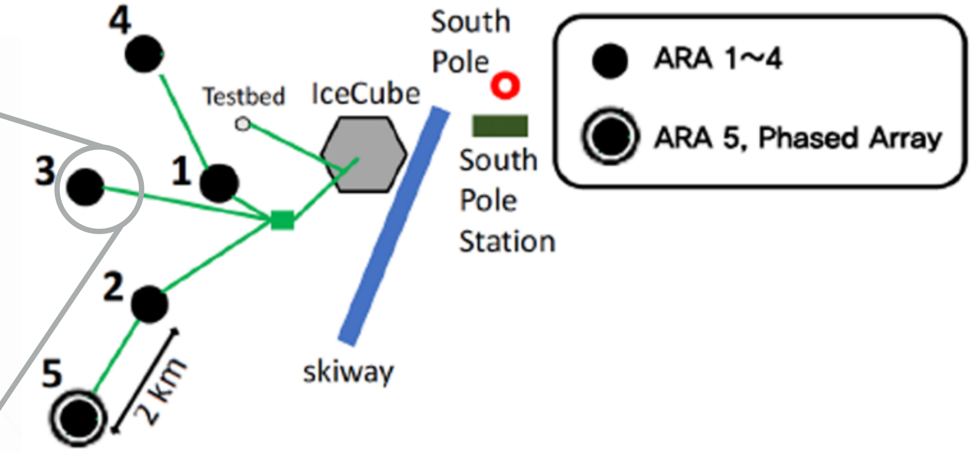
Detector Schematic



Station Schematic



ARA Five–Station

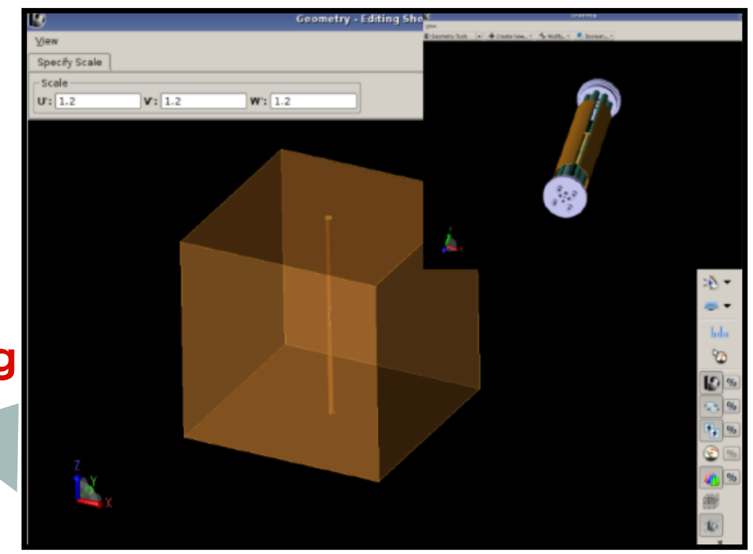


- Building radio detector in the Antarctic ice, a large volume of radio transparent medium with a long radio-wave attenuation length of ~1 km, would be cost-effective and the best option to observe UHE neutrinos.
- **Five independent ARA stations** are constructed 200 m below the ice surface with 2 km spacing.
- In each station, **16 RF antennas** + 4 calibration pulsers equipped with 6 downhole strings.
- **Vertically polarized** (Vpol, Z-axis) and **horizontally polarized** (Hpol, XY-plane) antennas are deployed to measure the polarization of the electric field.
- Signal chain corresponds to LNA, RFoF, and Amplifier

Strategy for developing antenna model

- The goal is to have an accurate antenna model for Gen2-Radio simulation.
- Developing an antenna model based on in-situ calibration is the optimal approach.
  - It can reflect the real environment, but difficult to scan the full angular gain pattern when detector is placed in the ice.
- Constructing in-air to in-ice transition strategy for covering the gap.
  1. Measurement in anechoic chamber (in-air) -> easily perform detail scan.
  2. Antenna simulation (XFDTD) -> bridge for in-air to in-ice transition (It was challenging).
  3. Verifying results with In-situ calibration (in-ice).
- Eventually, an **empirical antenna model** was developed based on **in-situ data.**

Antenna simulation
(In–air to In–ice transition)



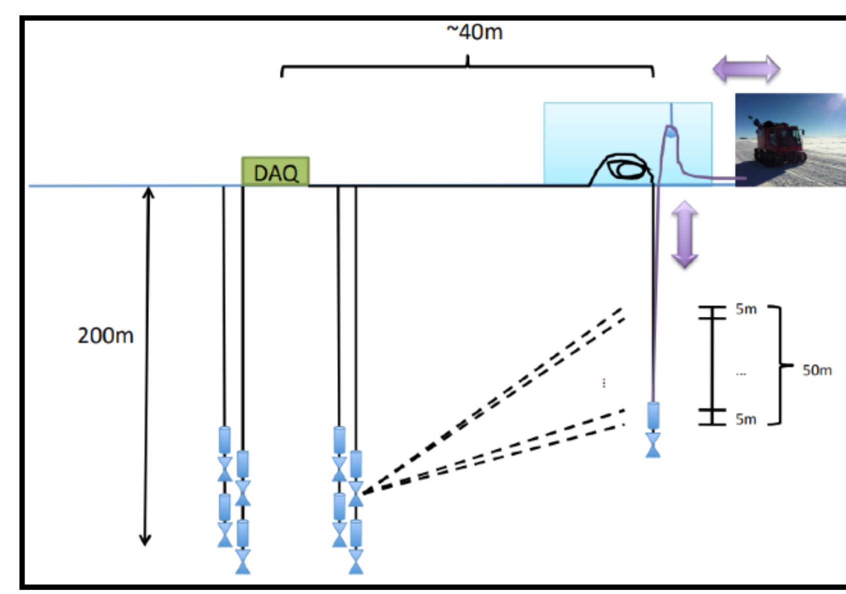
modeling

Verification

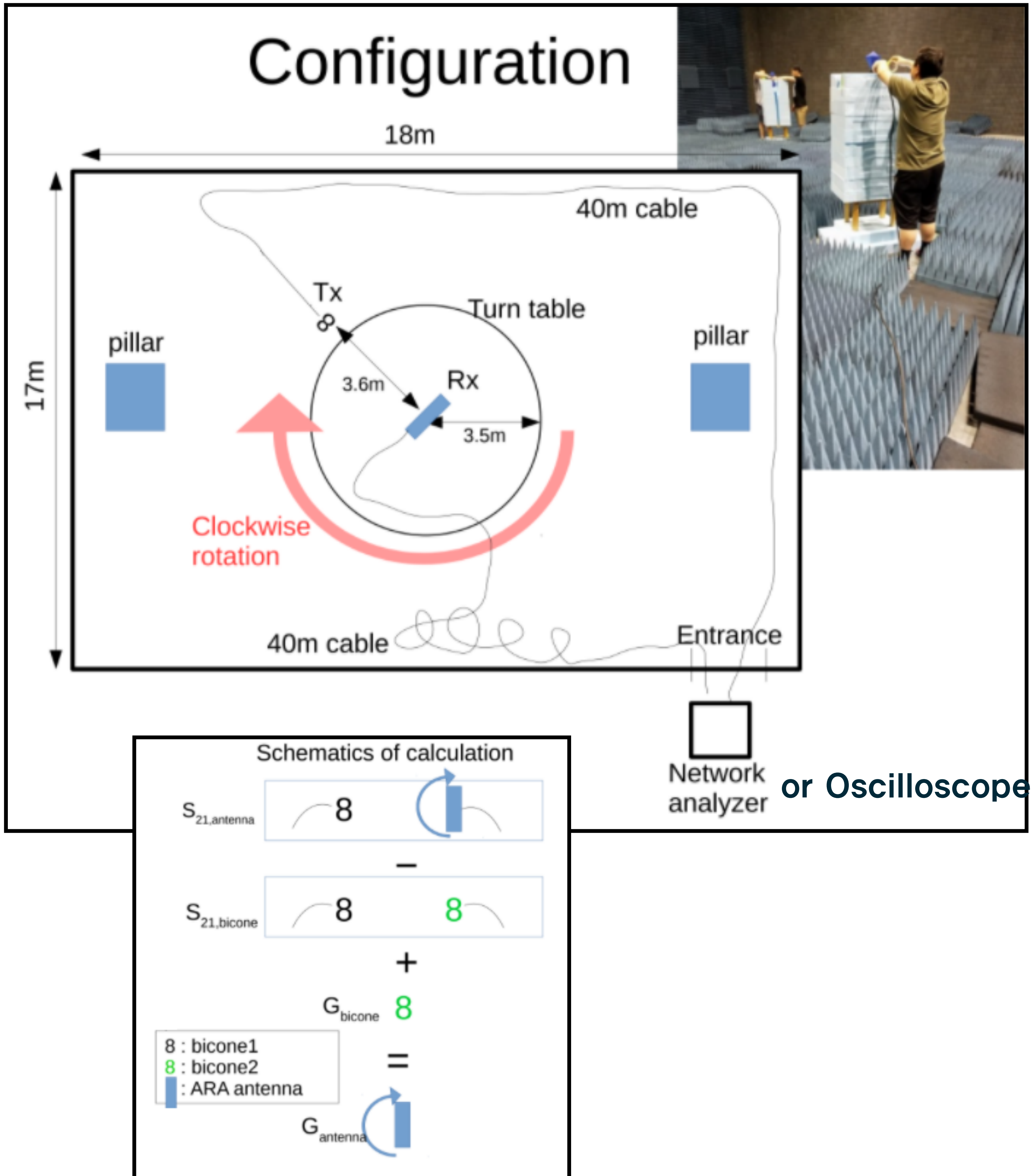
Antenna gain in–air
(Anechoic chamber measurement)

comparison

Antenna gain in–ice
(In–situ calibration)

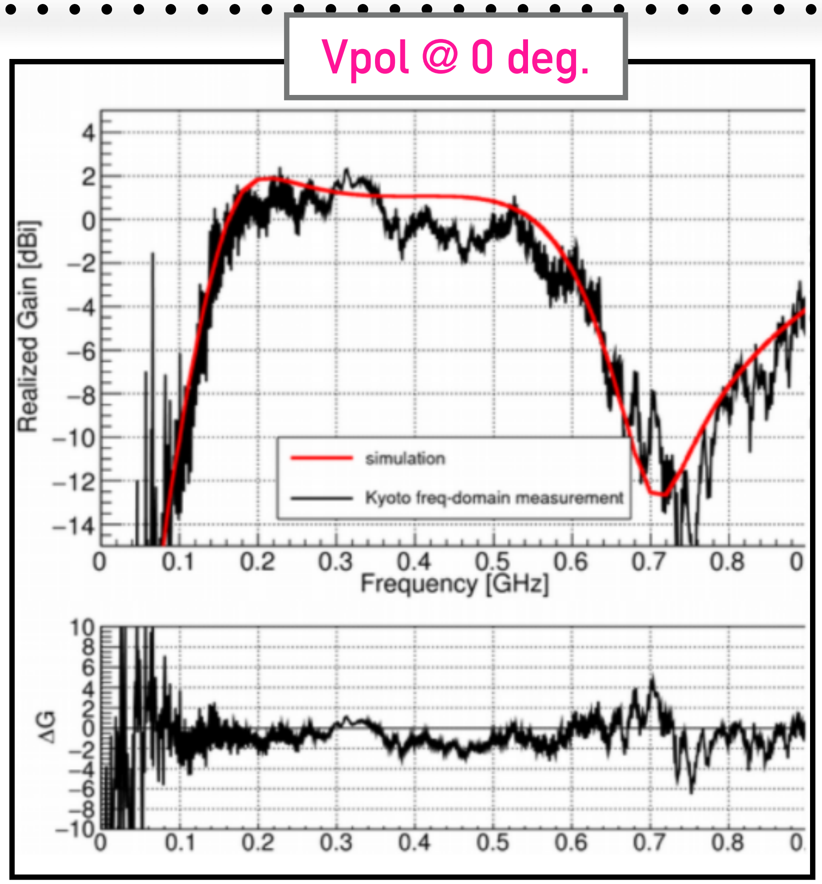


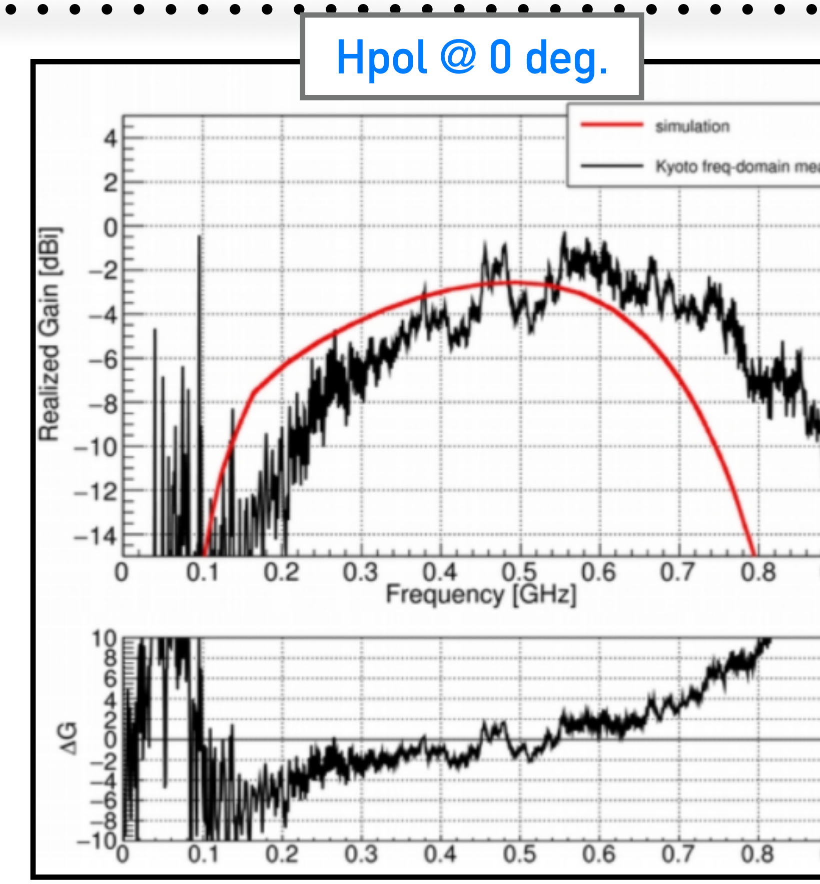
Anechoic chamber measurement



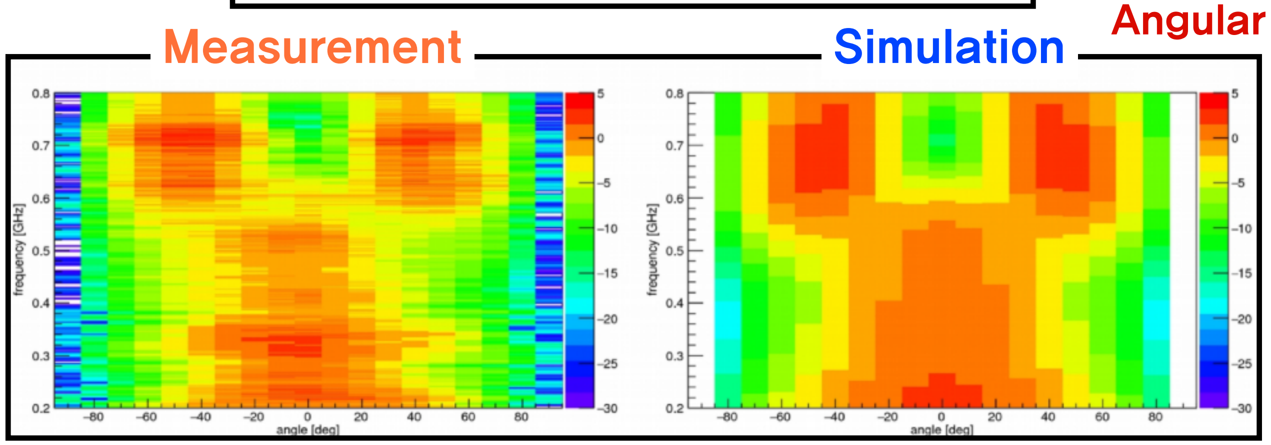
- The goal is measuring ARA antenna gain in air and verifying the simulation results.
- The measurement was performed in a large anechoic chamber at Kyoto (18 m x 17 m x 7.3 m) which is big enough to confirm the far-field effect.
- We measured,
  1. Vpol and Hpol antenna
  2. Original and slim antenna(later slide)
  3. 10 deg interval (for original antenna)
  4. Network analyzer : F-domain
  5. Oscilloscope : T-domain
- Bicone antenna was used for transmitting the signal and later it was removed from gain calculation.

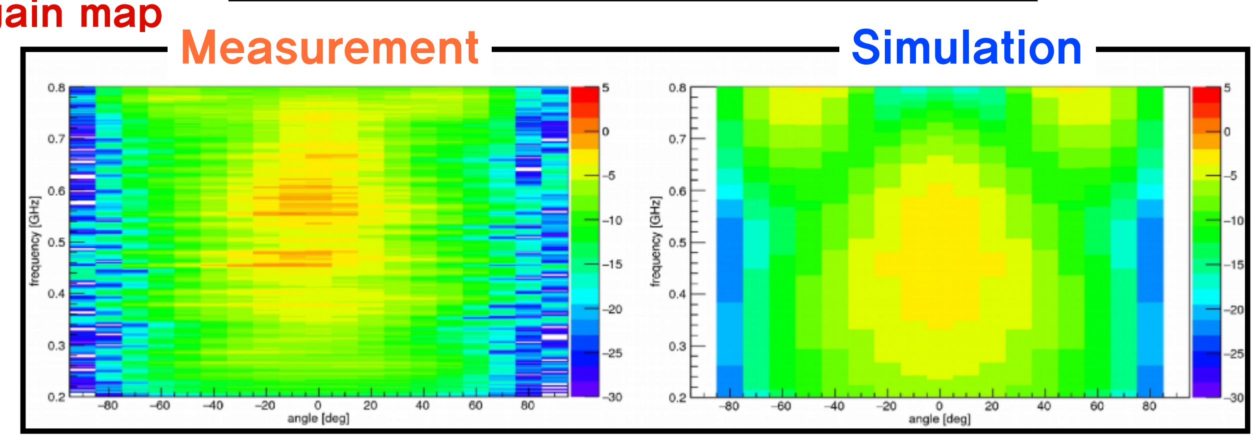
Anechoic chamber measurement





Angular gain map



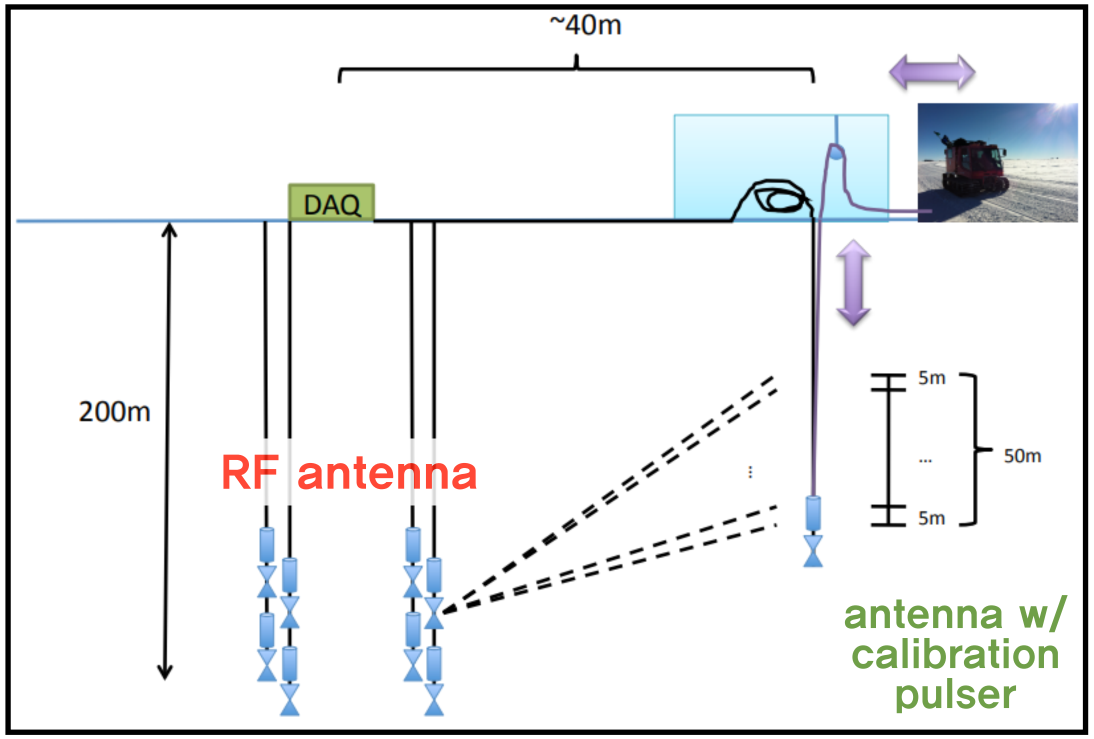


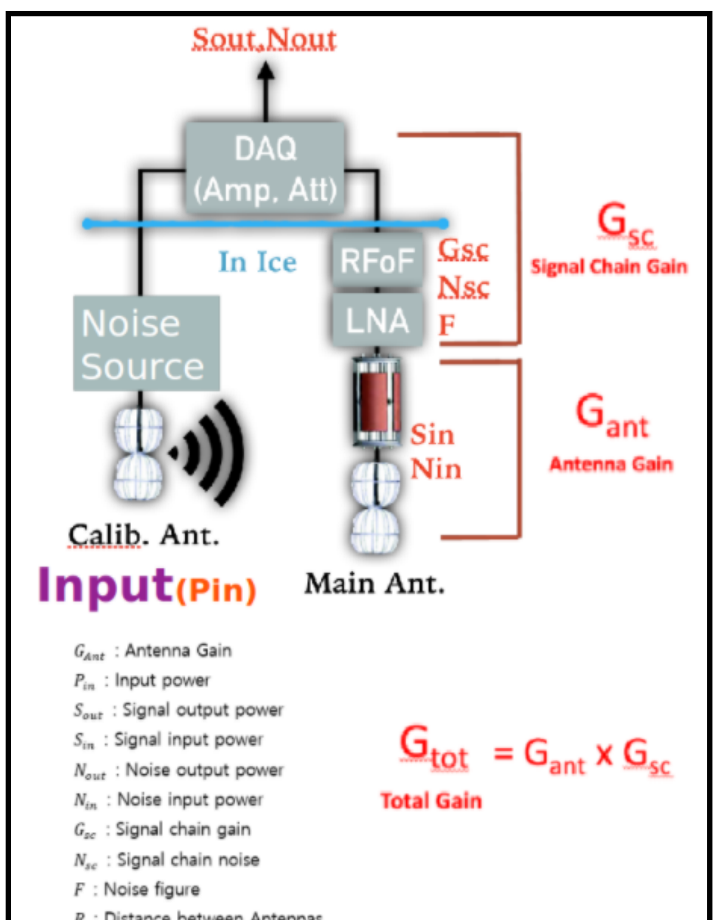
- **Vpol**: The gain frequency tendency is roughly the same as simulation. ΔG(measurement – simulation): -0.79 ± 1.85 dB
- **Hpol**: Unknown ferrite property caused mismatch with simulation (frequency shift). The simulation cannot describe the data well. ΔG: -0.48 ± 3.65 dB

$$\sigma_{\Delta G}=\sqrt{\frac{\sum_{angle,freq}\left(\Delta G(\theta,f)-\mu_{\Delta G}\right)^2}{n}}$$

In-situ calibration

Pulser lift measurement





Antenna Eq. (Friis Eq.)

$$G_{Ant} = \sqrt{\frac{1}{P_{in}}\left(\frac{4\pi R}{\lambda}\right)^2 \frac{S_{out}}{N_{out}}(N_{in} + N_{sc})}$$

Signal Chain Eq.

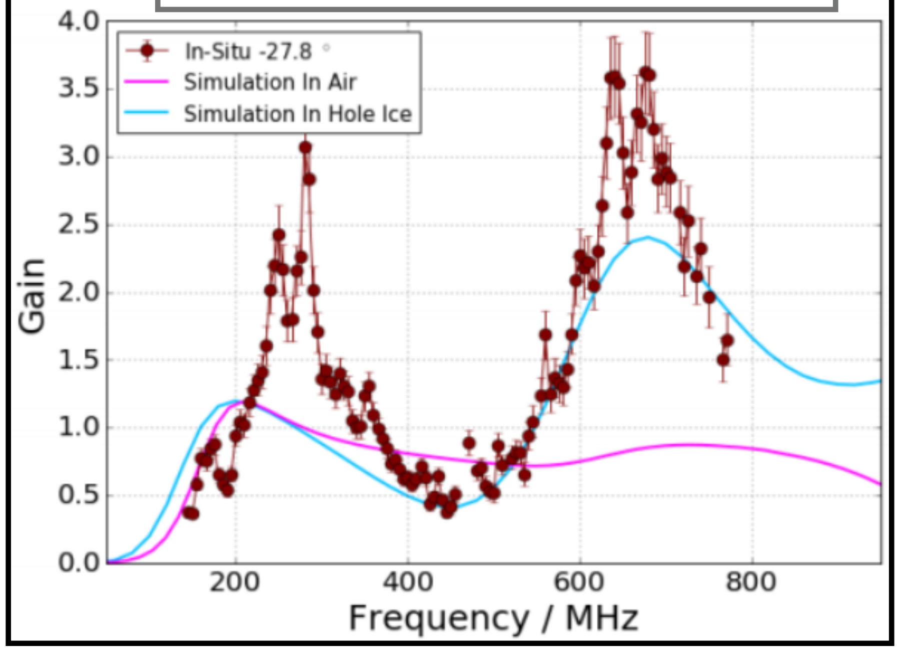
$$G_{sc} = \frac{N_{out}}{(N_{in} + N_{sc})}$$

- The crucial data for developing/verifying the antenna model. But it has limitations for measurement.
- Pulser lifting measurement (by Ming-Yuan Lu, Madison): lifting calibration string that contains transmitter antennas and pulser module.
- It was performed for measuring the zenith-dependent antenna pattern in ice.
- By gradually lifting pulser up to 50 m, **~60 degree** amount of zenith angle data was obtained.
- Antenna gain and signal chain gain were calculated based on the Friis equation method (by Thomas Meures, Madison) by reflecting the real ice-hole/temperature environments.

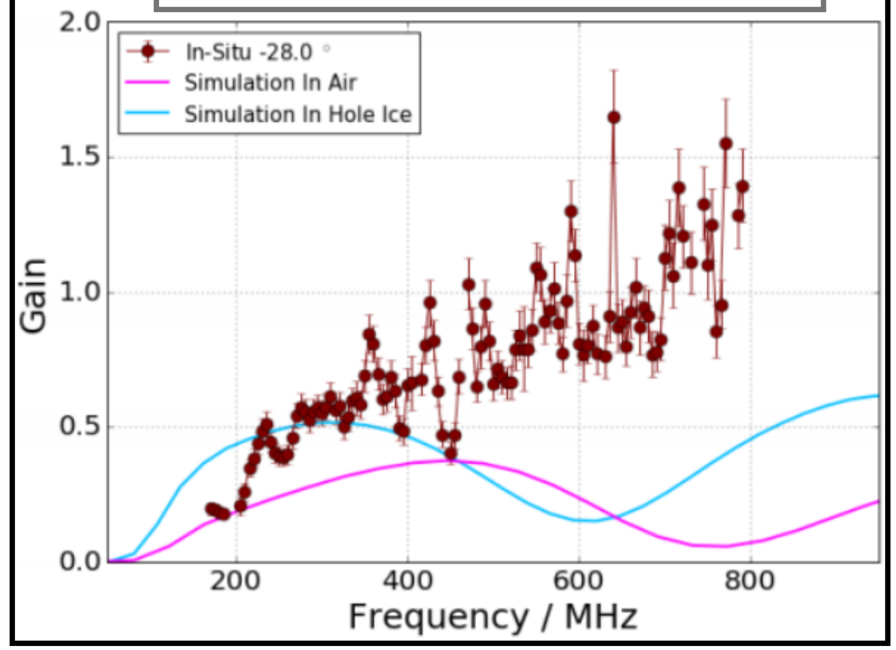
In-situ calibration

Linear scale

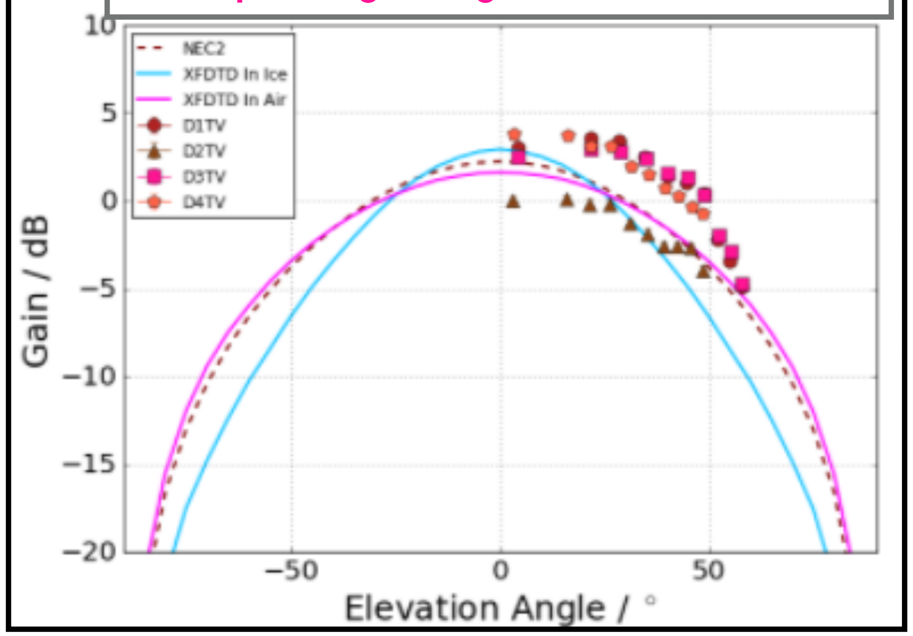
Vpol



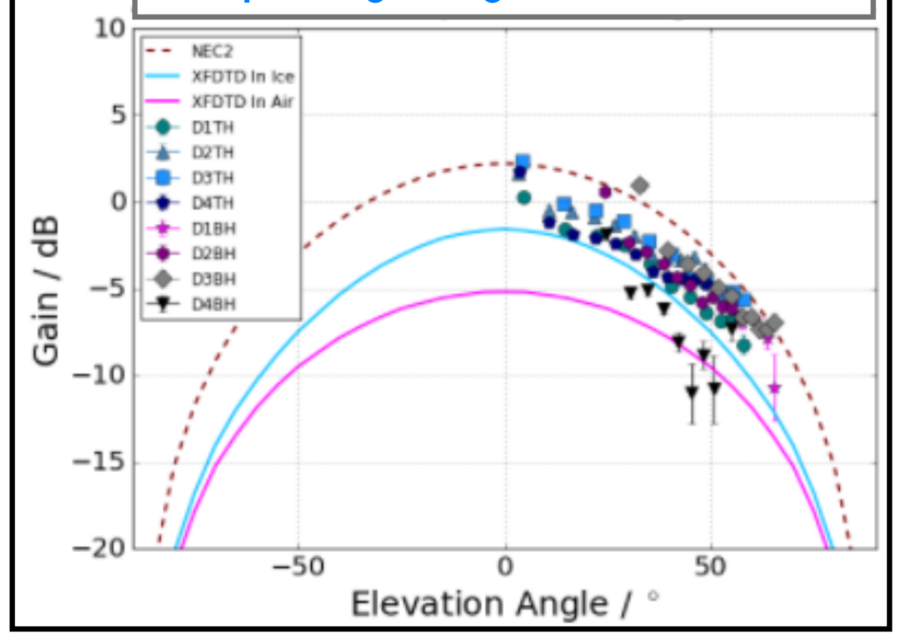
Hpol



Vpol angular gain @ 250 MHz

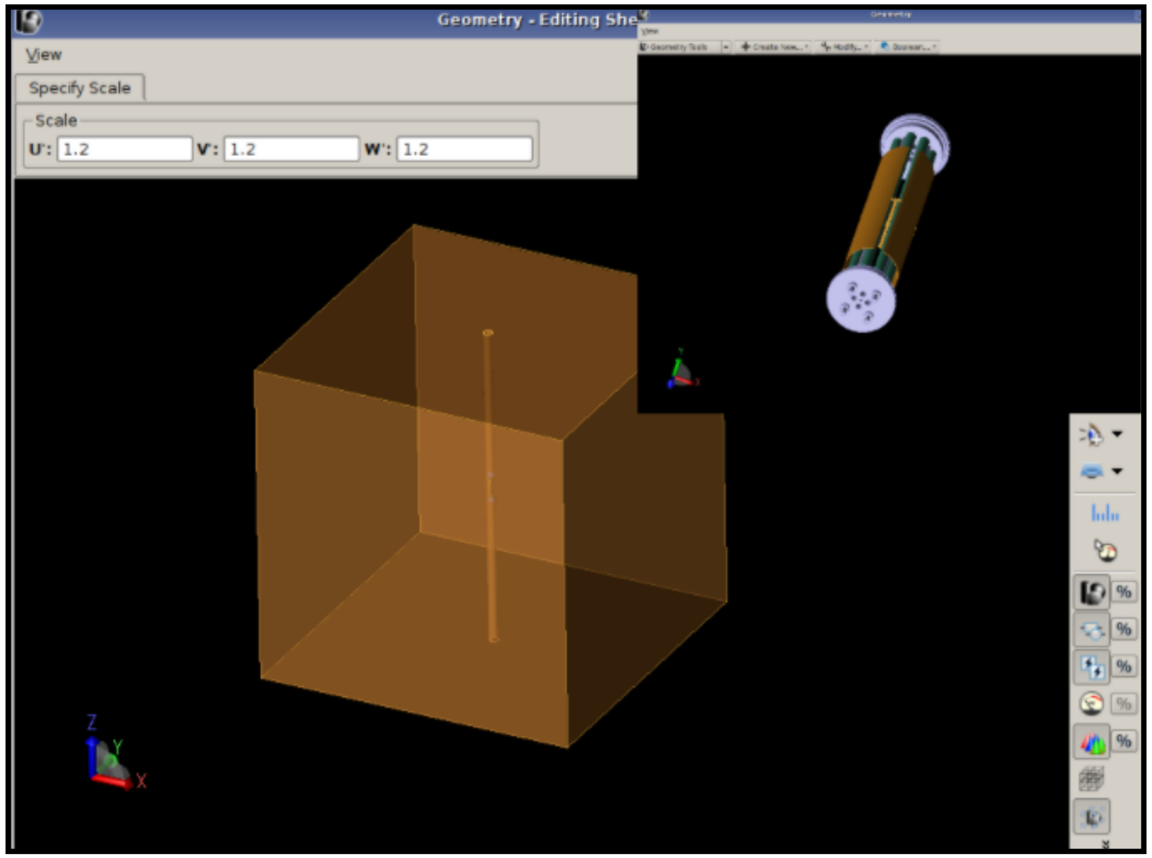


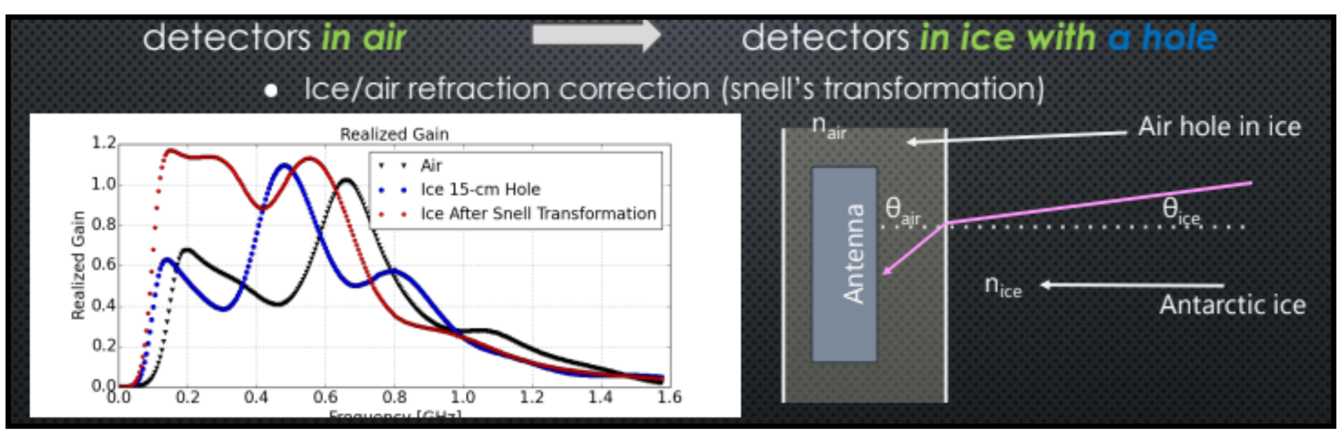
Hpol angular gain @ 250 MHz



- **Vpol**: The results show acceptable agreement to the in-ice XFDTD simulation prediction.
  - The in-ice XFDTD simulation: simulating antenna inside of cube of ice block with dry hole.
- **Hpol**: The results generally disagree with simulation in high frequency region.
  - The simulation cannot describe the data well.

Transition by simulation (XFDTD)

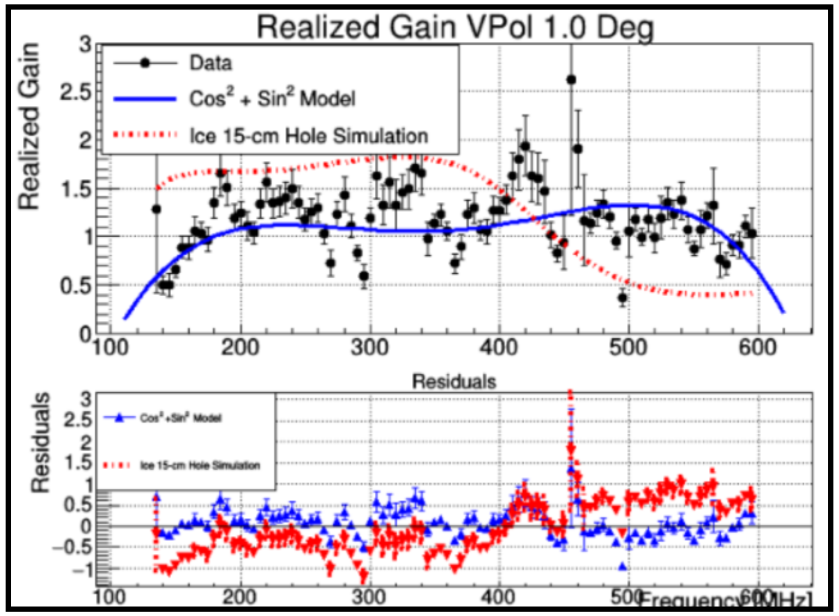


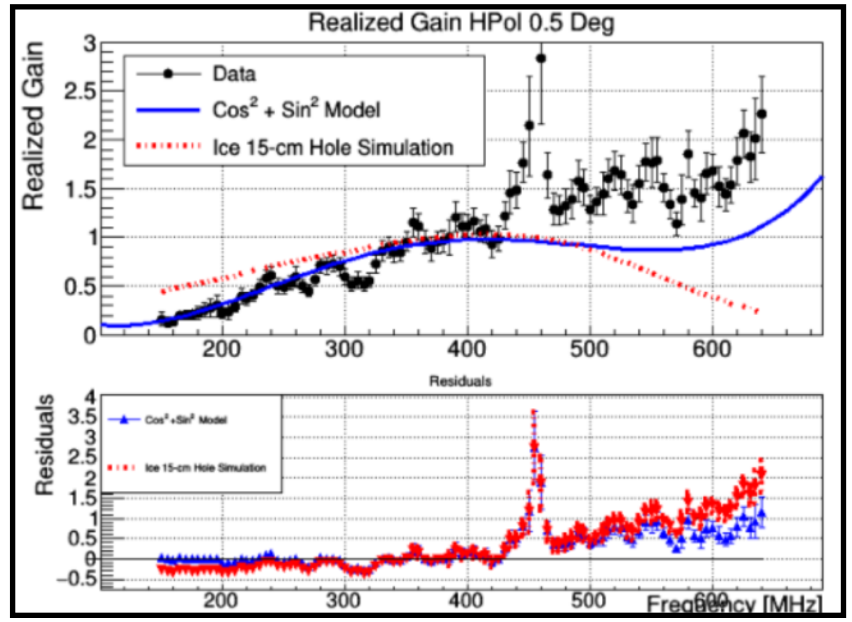


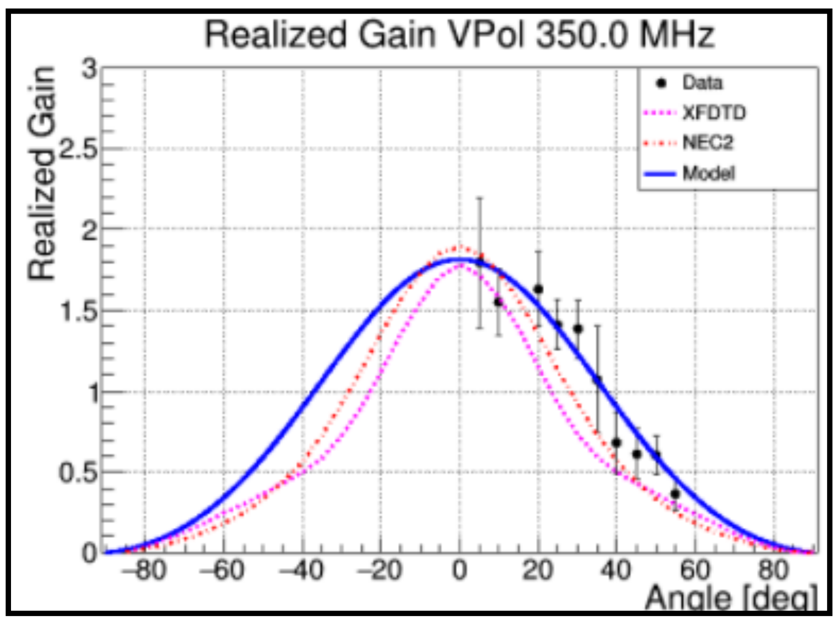
Both hole and snell's method were failed to reproduce the in-situ data

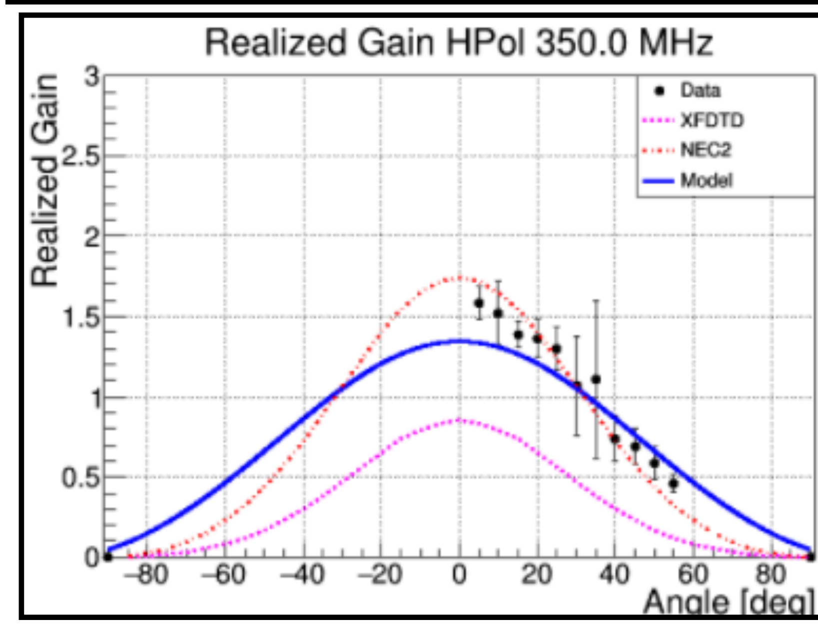
- XFDTD simulation was used for in-air to in-ice transition.
- The in-ice simulation was made by placing an antenna inside a cube of ice including a simulated dry hole.
- **The transition was challenging!**
  1. Vpol: It agrees better in the air but difficult to reproduce in ice measurements.
  2. Hpol: Lack of ferrite information cause a general mismatch in both air and ice results.
- Couldn't establish transition by XFDTD simulation.
- Need to make an **empirical antenna model** based on in-situ data.

Empirical antenna model









- Need to develop a model that describes both polarization and estimates different angles in ice.
- In-situ calibration data was used.
  - pros: reflects the real ice-hole/ temperature environments.
  - cons: only limited angular coverage.
- The model-based from Legendre polynomials which should describe any angular patterns.
  - A(f)*Cos^2(B(f)θ) +C(f)*Sin^2(D(f)θ)
- Fit n-order polynomials to parameters to describe their behavior with frequency.
- Error is calculated by taking the difference between model and data error values (statistical uncertainty + 20% systematics).

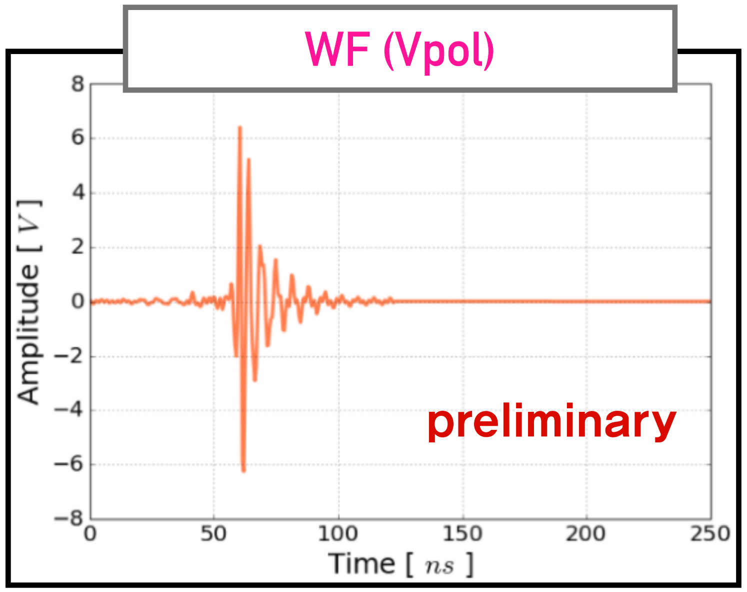
	VPol	HPol
Data (Average)	1.010 +/- 0.008	1.006 +/- 0.008
Model (rel Average / Systematics / reduced χ^2)	-16% / 38% / 1.8	-13% / 32% / 3.9
XFDTD (rel Average / Systematics / reduce χ^2)	-30% / 43% / 4.9	-57% / 64% / 17

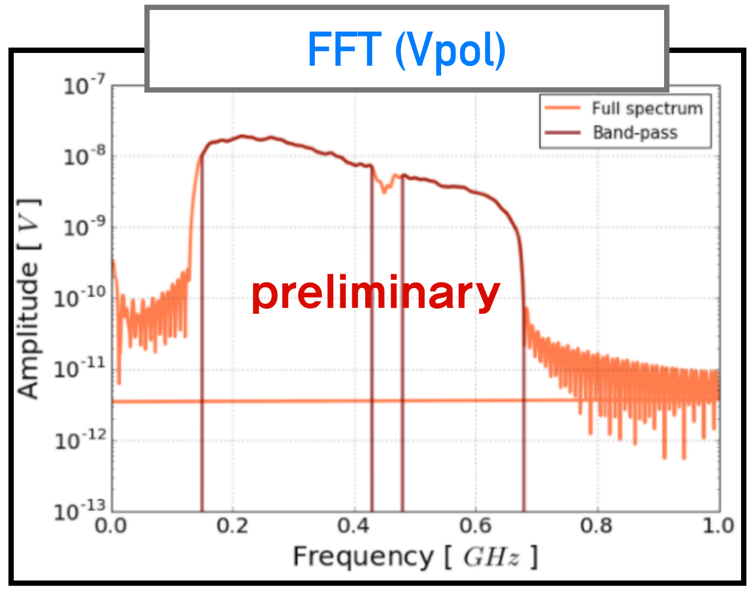
- **Lesson learned:**

1. **Thorough in-situ calibration is crucial for detector modeling/development.**
2. **The future detector should be able to perform full in-situ calibration including wide angular gain scan and signal chain gain.**

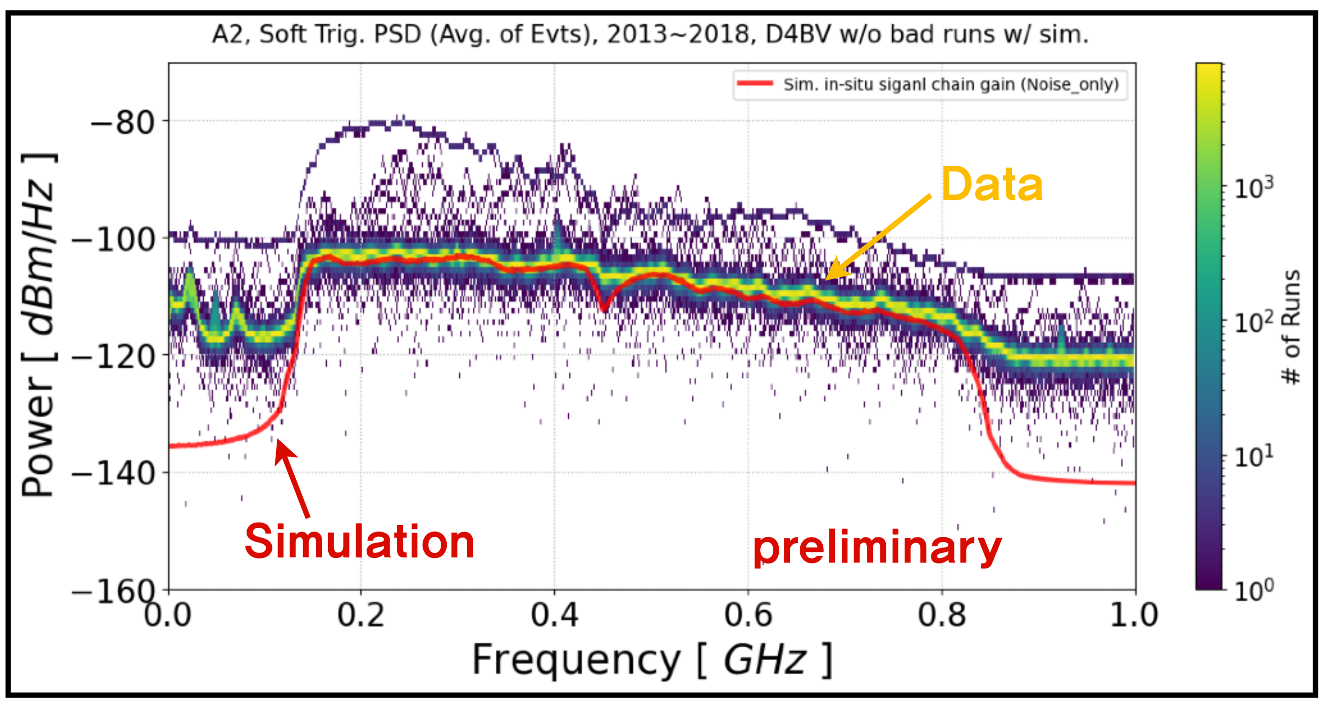
Analysis based on empirical antenna model (on progress)

Simulated Neutrino signal based on empirical antenna model





In−situ signal chain gain model w/ data



- Empirical antenna and signal chain model is currently used in the template-based analysis (matched filtering method inspired by LIGO)
- The template is designed to including detector response and Nu. model.
  - Need to input accurate detector model.
  - Simulating an accurate frequency spectrum is crucial.
- Analysis is on progress.

Matched filtering Eq.

$$z(t) = 4\int_0^{\infty} \frac{h\ (f)s^*(f)}{S_n(f)} e^{2\pi i f t} df$$

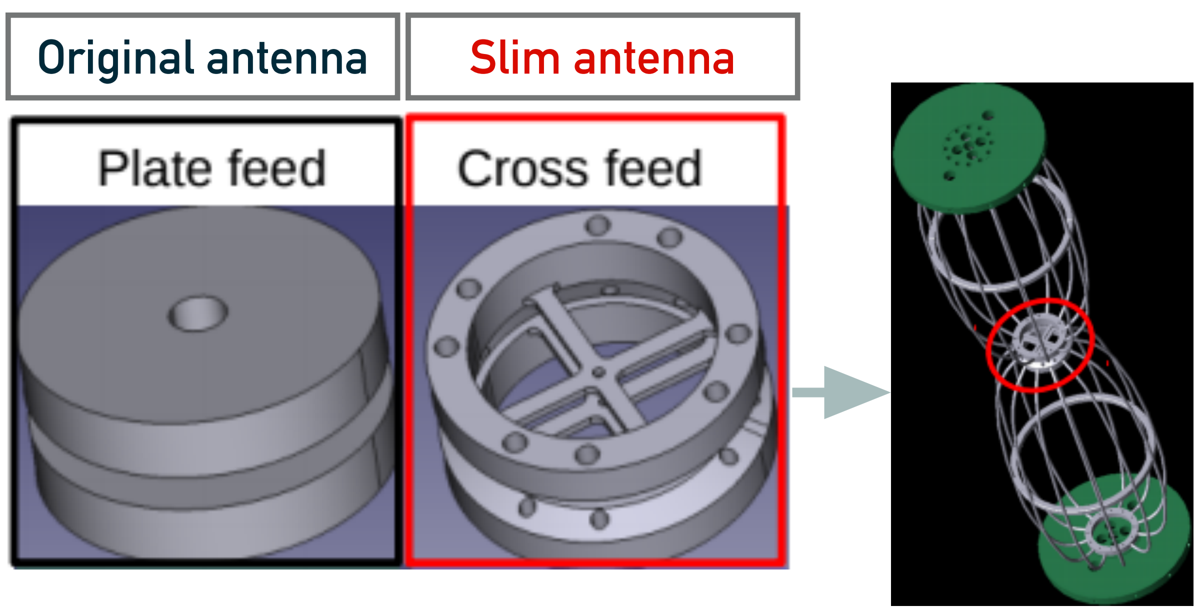
$$\sigma^2 = 4\int_0^{\infty} \frac{|h\ (f)|^2}{S_n(f)} df$$

$$\rho(t) = \frac{|z(t)|}{\sigma}$$

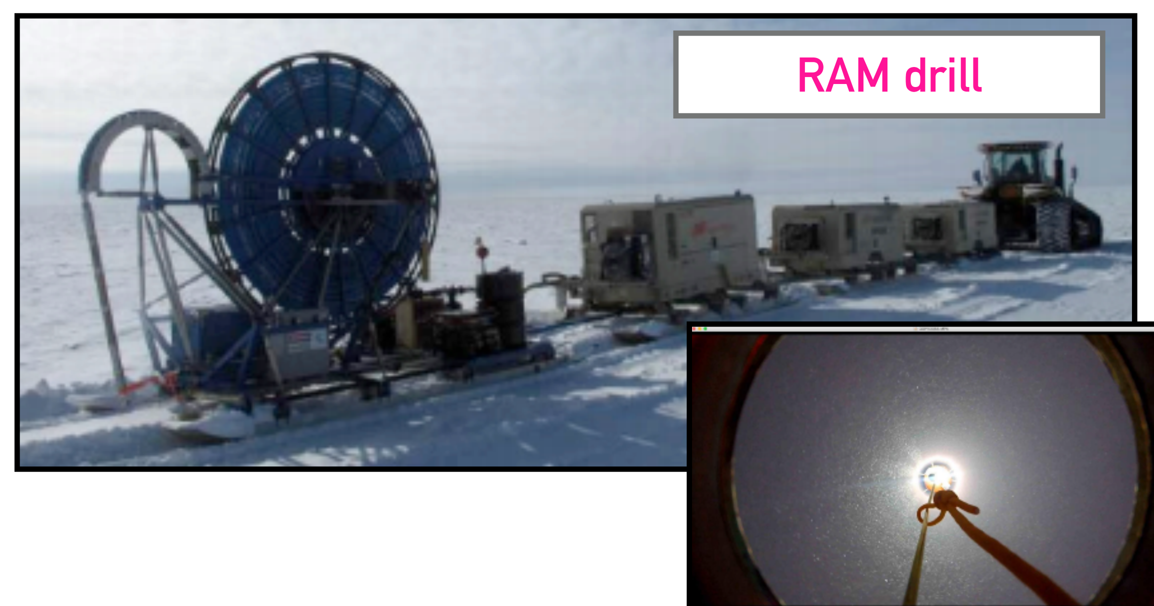
Eqs from LIGO paper Phys.Rev.D69:122001 ,2004

s(f) = ARA data spectrum
h(f) = Template spectrum
z(t) = Correlation (t-domain)
Sn(f) = clean noise power spectrum
σ = template normalization
ρ(t) = SNR vs lag plot [v/RMS]

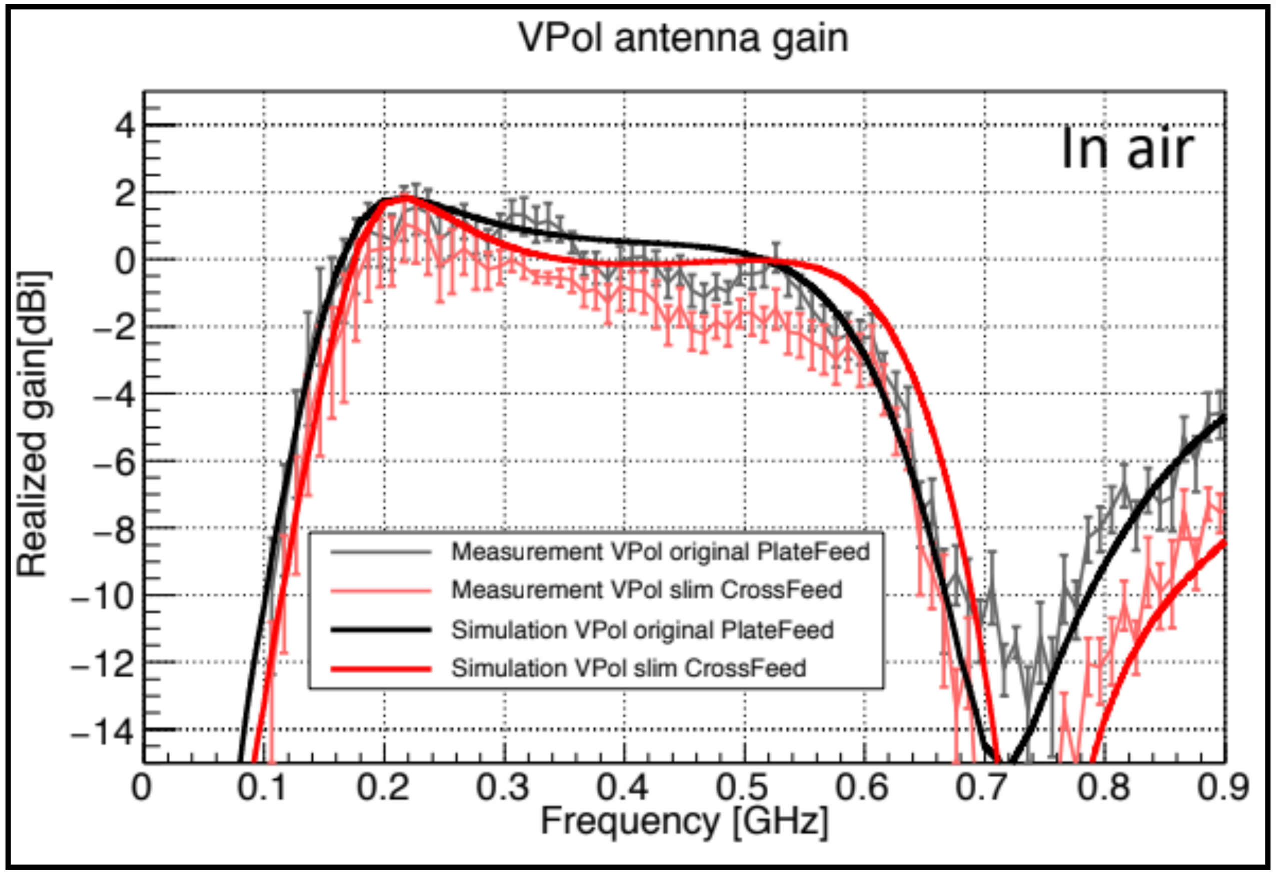
Slim antenna study

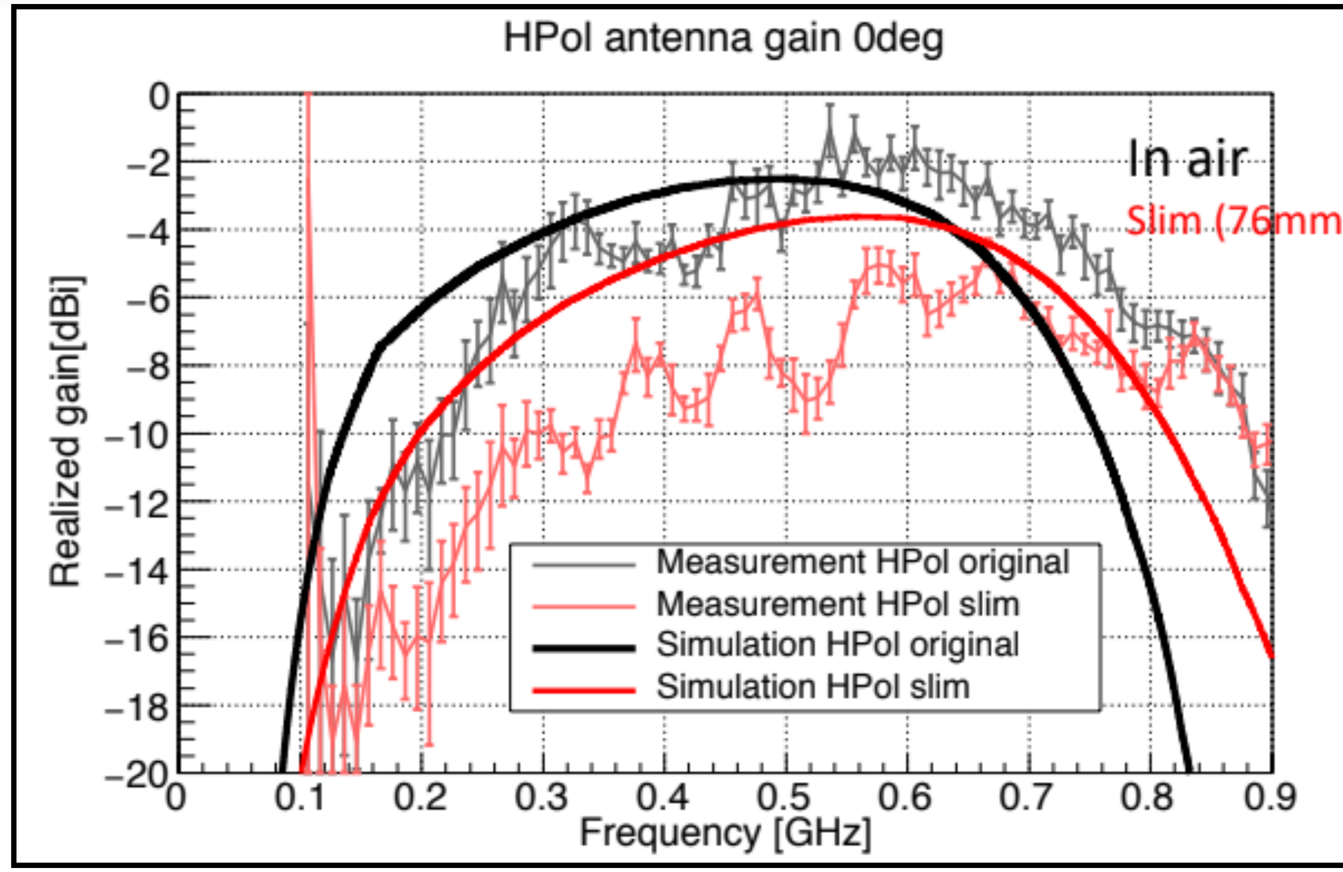


- The slim antenna was studied for next-generation detector design.
- The diameter of the antenna aimed to below 10 am for deploying it by RAM drill.
  - Very efficient (25 min. / hole. The current hot water drill 10 hours / hole of 200 m) ~10x faster.
  - The cost will be reduced by the speed of the drill (10 times less).
- The feed part is also optimized to reduce the impedance mismatch.

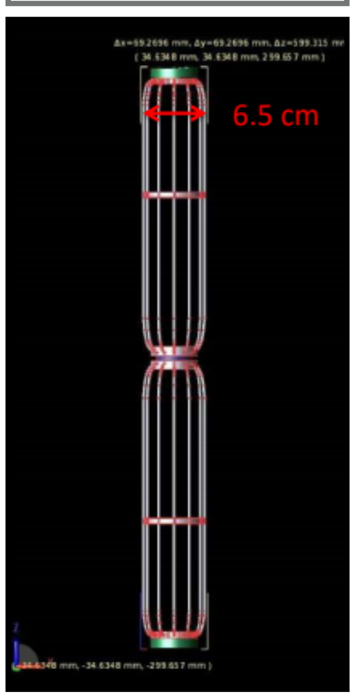


Anechoic chamber measurement

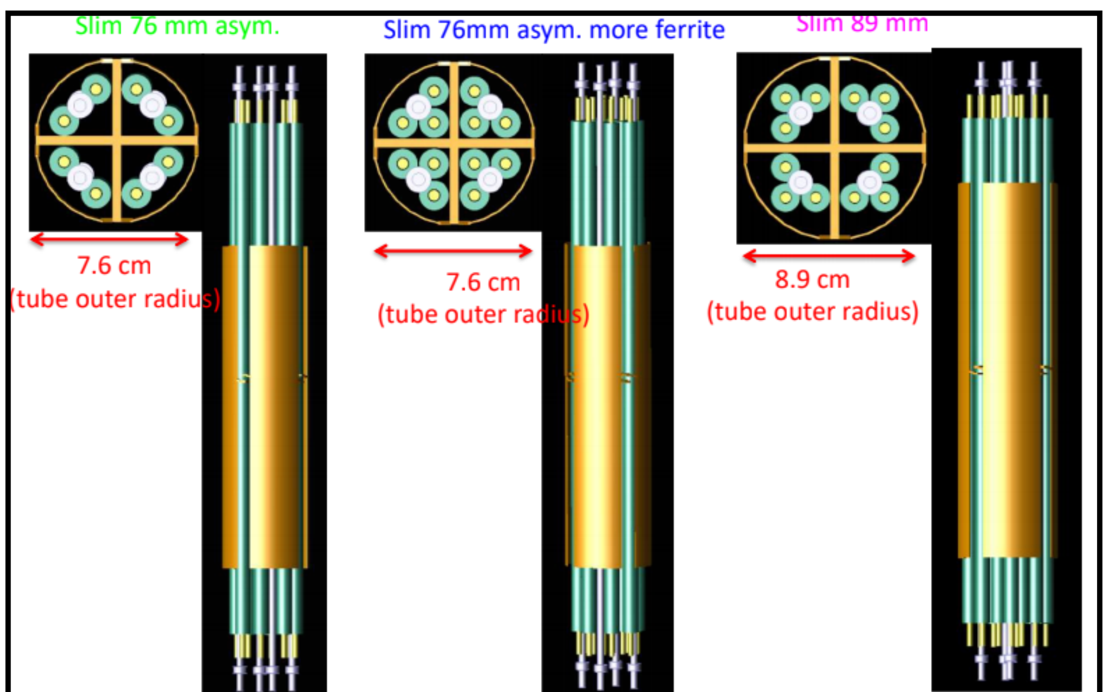




Vpol

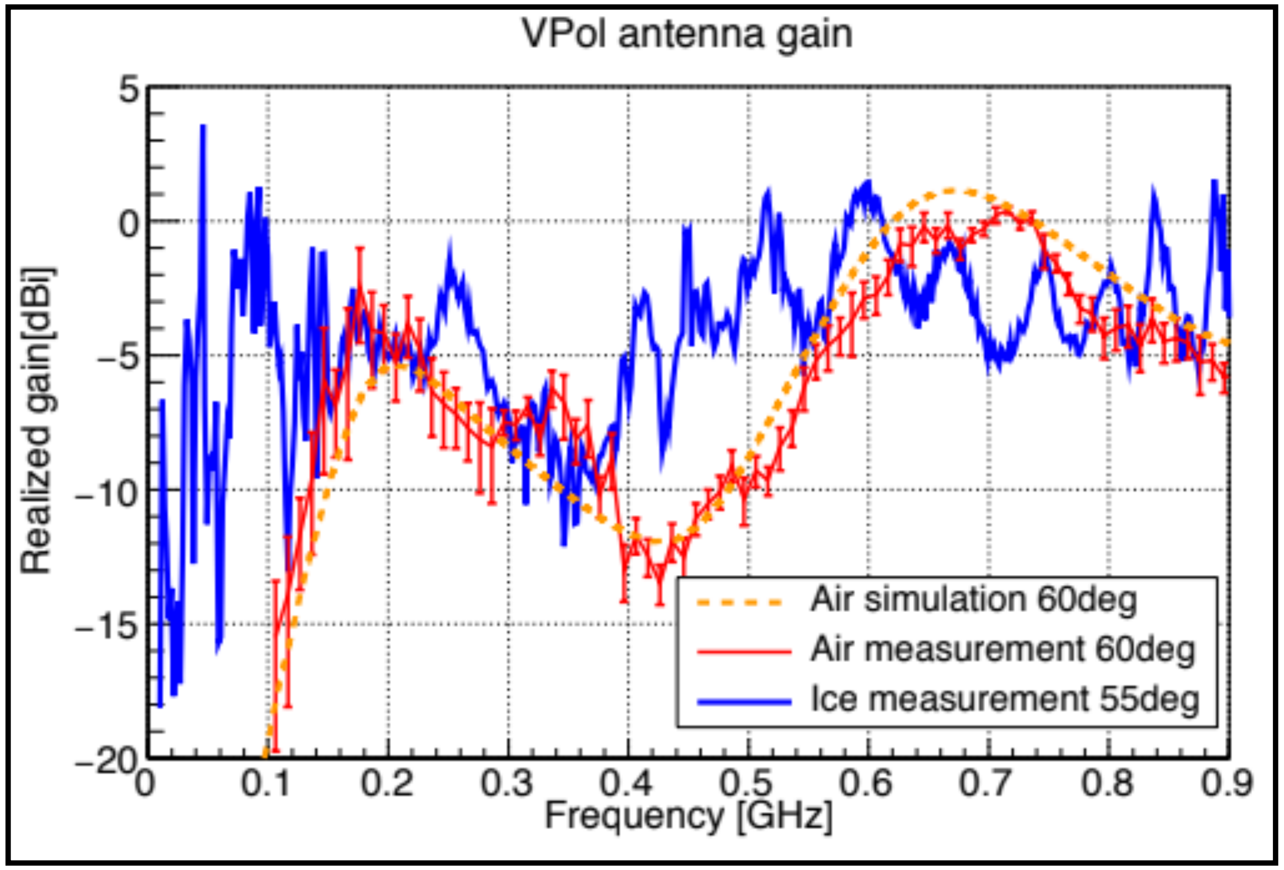


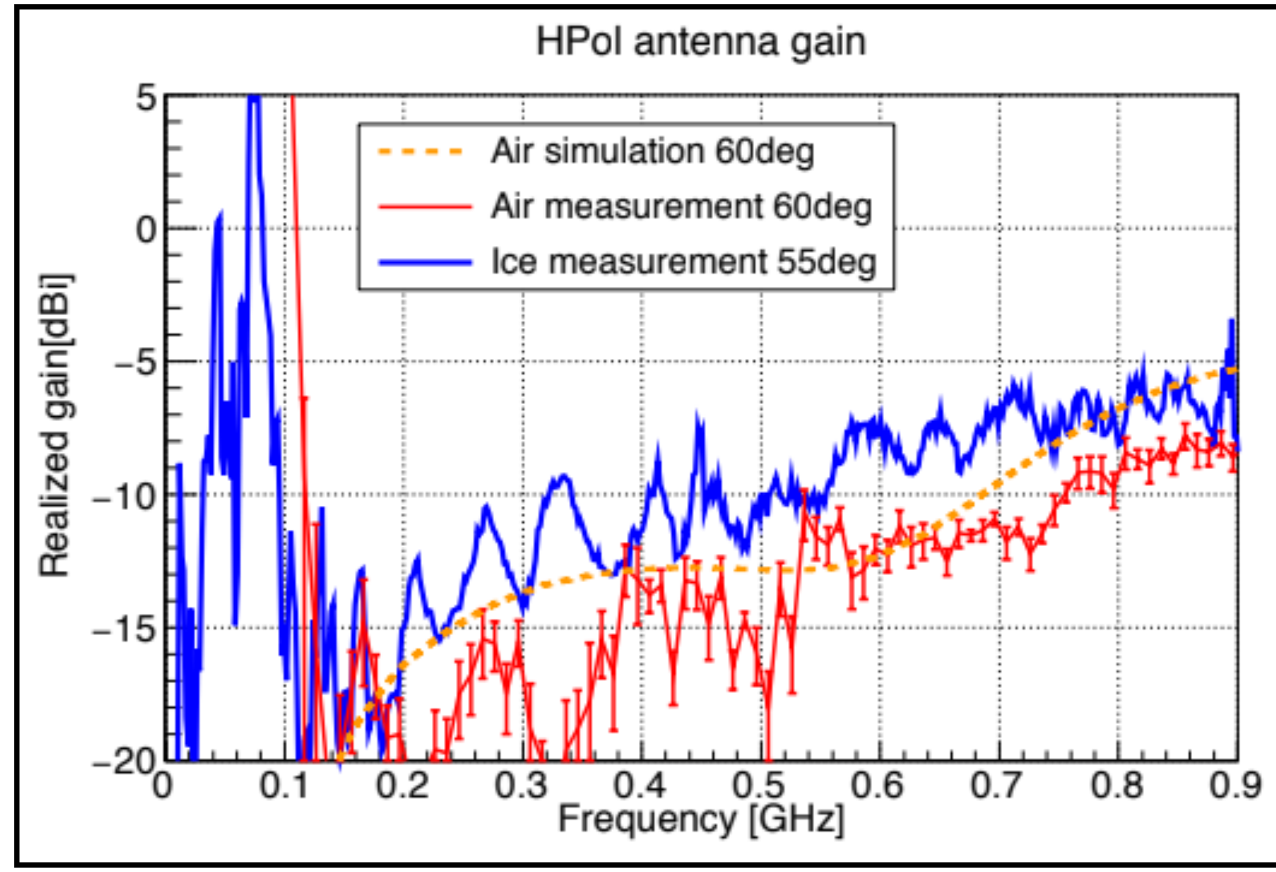
Hpol



- Measured slim Vpol antenna gain is about ~1 dB worse compared to the original size.
- Measured slim Hpol(76 mm asym.) gain is worse than the original by ~3 dB.
- Vpol slim antenna is a promising, slightly larger size for Hpol (89 mm) should be tried.

Measurement at the South pole





- Vpol: Relatively large fluctuations for the in-ice measurements. In-ice peak gain is not too different from in-air gain. Vpol slim antenna seems to be working properly.
- Hpol: Slim antenna also shows simulation/data mismatch for air (due to unknown ferrite characteristics). Larger gain in ice.
- Need more study for understanding in-ice behavior of the slim antenna.

Summary / Discussion

- Constructing an in-ice-with-hole detector model based on calibrations in anechoic chambers is challenging.
  - In-air measurement/simulation is not good enough for modeling in-situ behavior
- In-situ calibration is crucial for detector modeling/development.
  - Measuring more wider angular gain and signal chain gain in ice with good in-situ calibration plan would be crucial for future detector.
- The slim antenna is showing ~ 1dB (Vpol) and ~3dB (Hpol) worse than the original antenna but the quick deployment by RAM drill would reduce the cost.