A04 : ARA Detector Development and Calibration

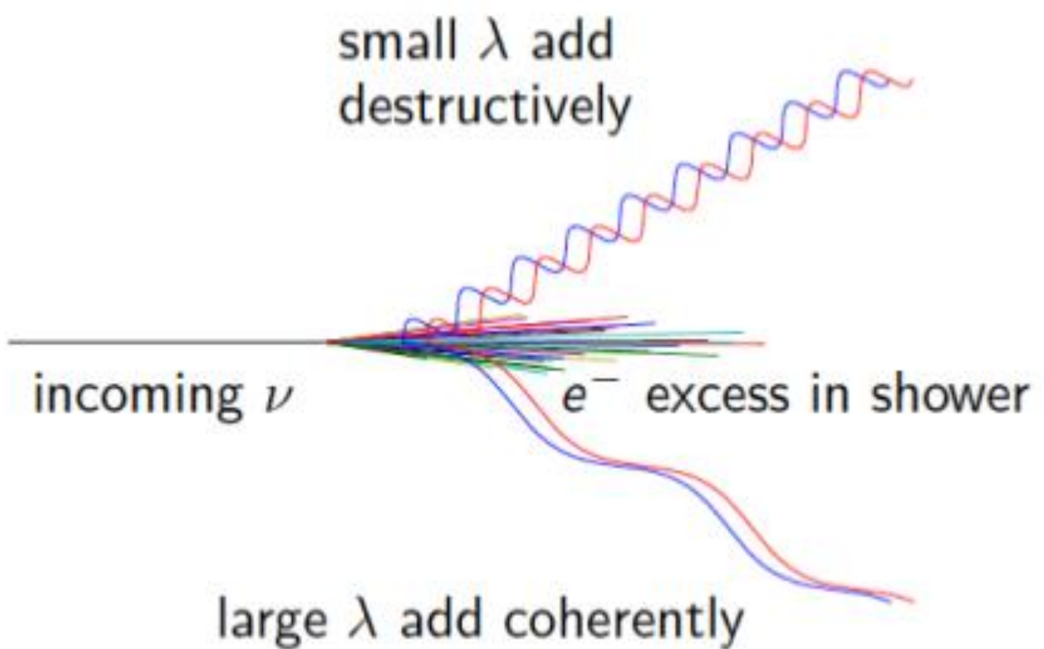
Chiba University
Hikaru Isobe

Outline

- What is the **Askaryan Radio Array (ARA) experiment ?**
  - Askaryan effect
  - Configuration of the ARA
- What **Chiba group did** for so far.
  - Calibration of the original **antenna**.
  - Development and calibration of **RFoF modules** for the signal transmission for 2017 plan.
- For next ensuing term : Development of slim antennas for optional plan
  - To **finish construction** of the detector ASAP
- Summary

Askaryan effect

- 1962, Askaryan predicted coherent radio emission from excess negative charge in an EM shower (~20% due to mainly Compton scattering and positron annihilation).



"Shower size ≪ λ " to be coherent

- Askaryan effect
  - **power $\propto \Delta q^2$,**
    - Thus, prominent at EHE($\geq \sim 10[PeV]$)

Cherenkov emission (Frank – Tumm result)

$$\frac{d^2W}{d\nu dl} = \frac{4\pi^2\hbar}{c}\alpha z^2\nu\left(1-\frac{1}{\beta^2 n^2}\right)$$

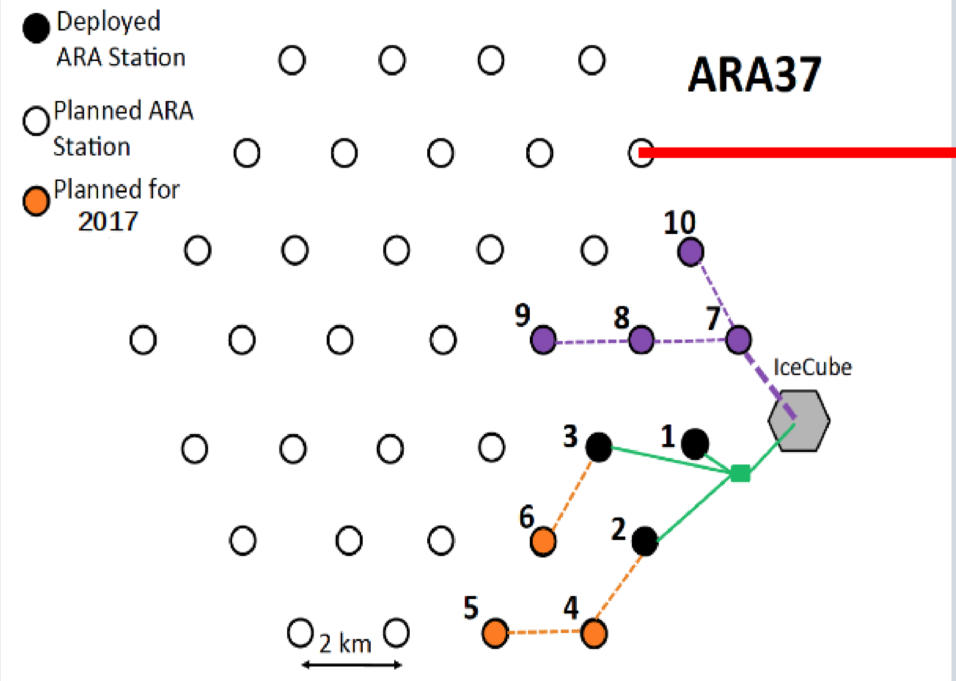
In case N electrons,

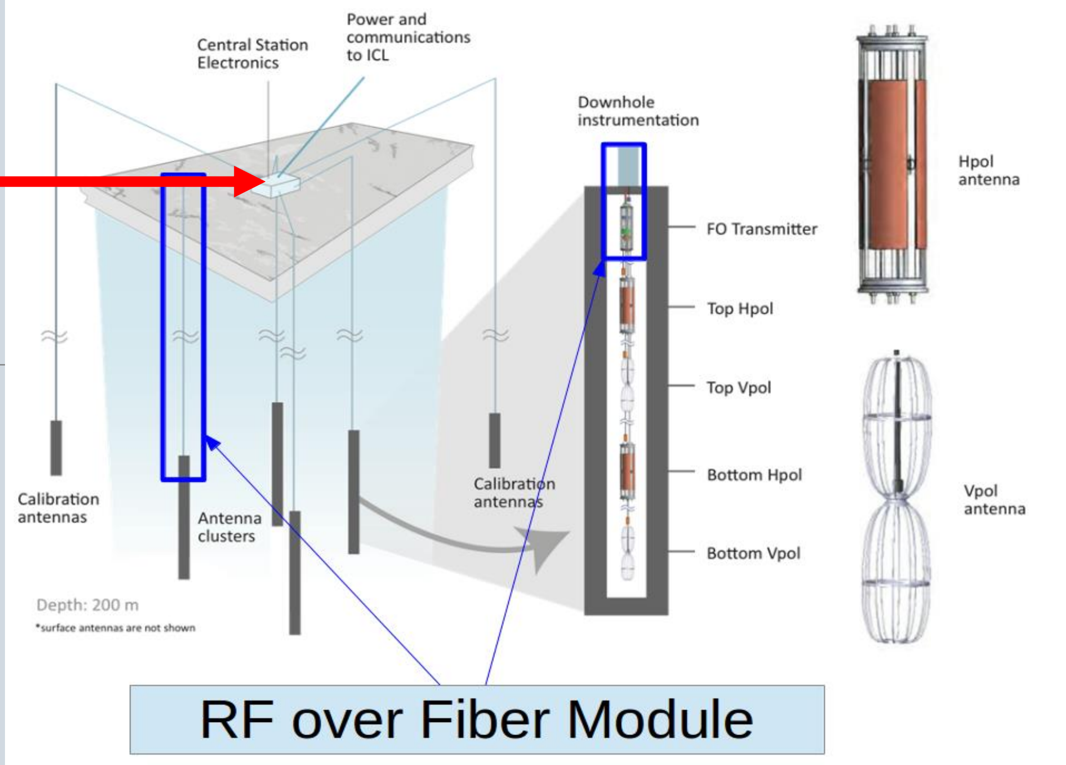
$z = 1\ (not\ coherent) \rightarrow W \propto N$

$z = N\ (coherent) \rightarrow W \propto N^2$

Askaryan Radio Array

for ultra-high energy cosmic neutrino



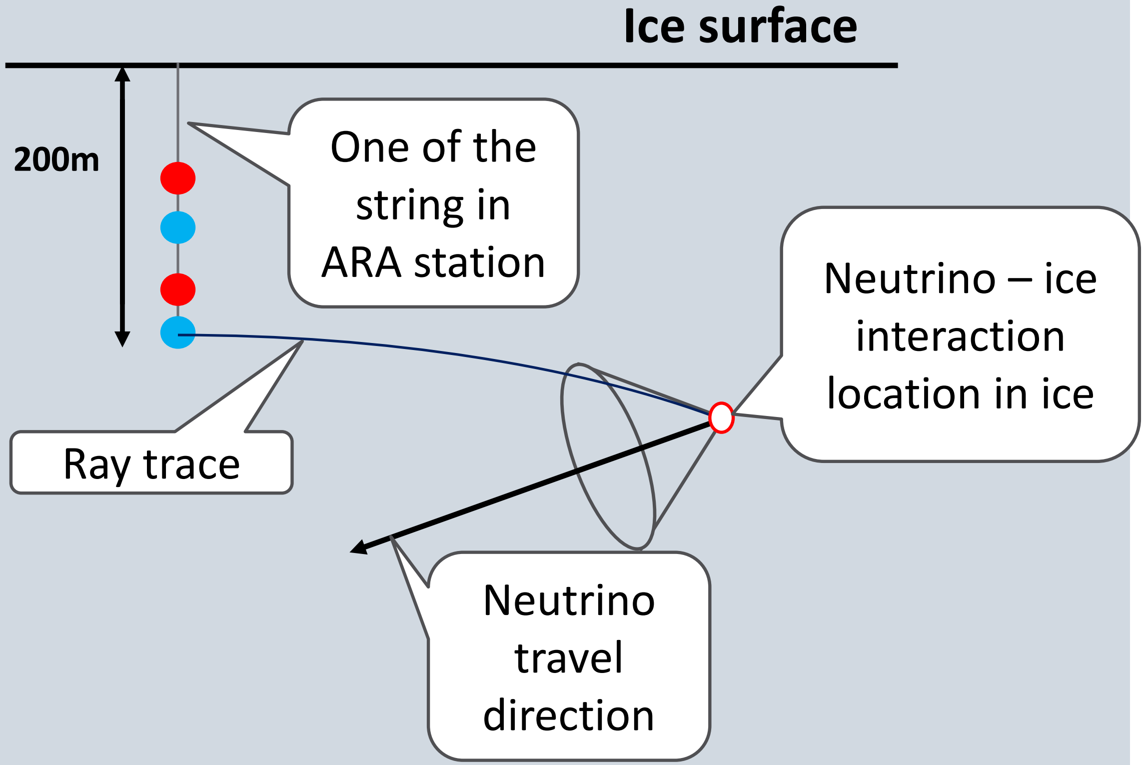


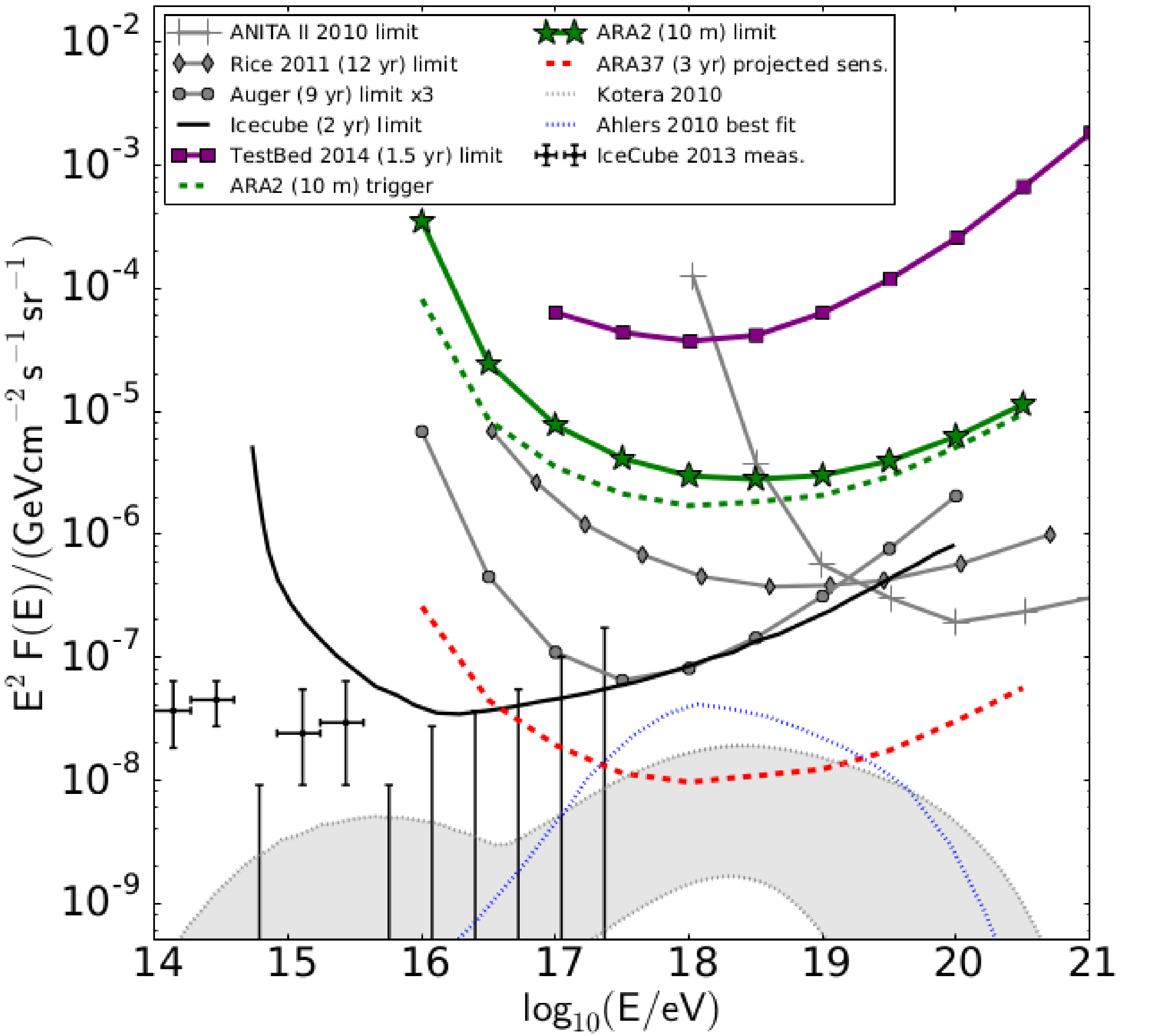
- Attenuation length of the south pole ice
  - Optical : $\sim 100m$
  - **Radio : $\sim 1km$**
- Easier to make a bigger detector in an economical way

- Aiming to detect GZK neutrinos
  - $10[PeV]$ Askaryan signal
- **37 stations**
  - Each station has **4 strings** of 200m depth
  - Each string has **2 Vpol + 2 Hpol** broadband antennas (sensitivity : 200MHz ~ 800MHz) and **1 RF over Fiver**
  - Total surface area : $\sim 100\ km^2$

The ARA sensitivity

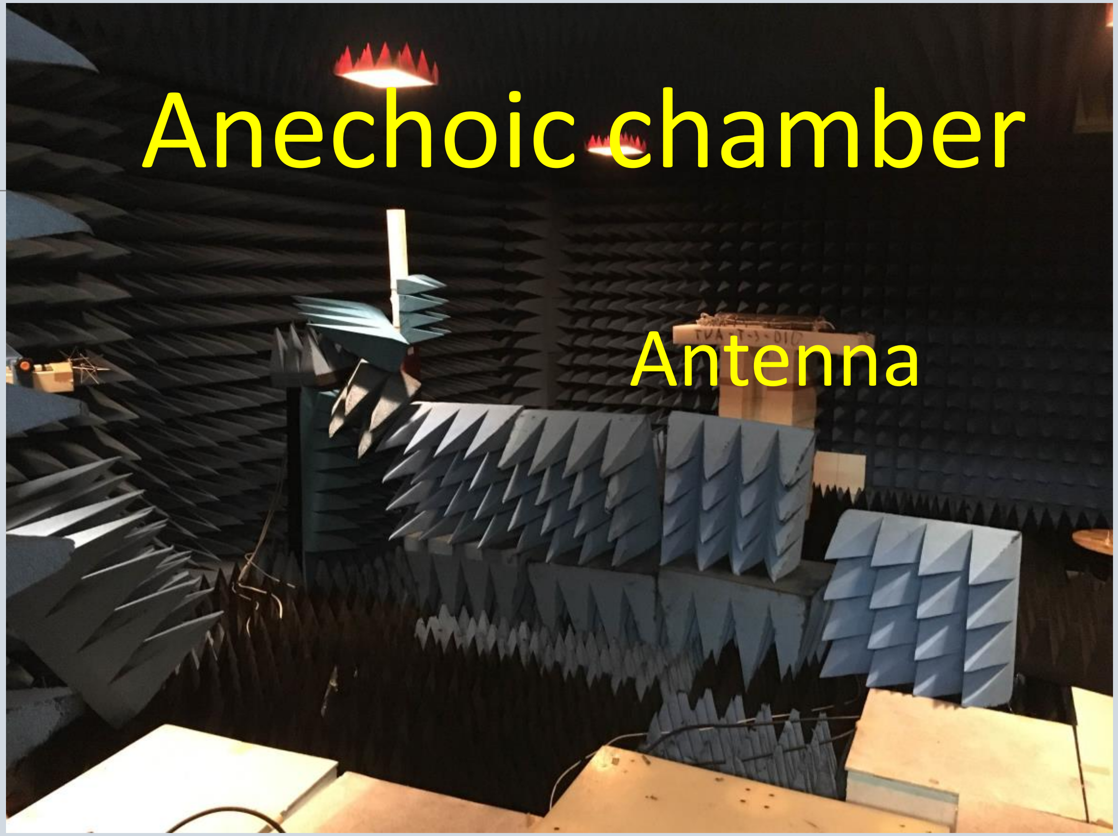
Sensitivity ~ 10 times higher than IceCube.





Calibration of the original antenna

- ARA group have deployed antennas made in Taiwan into ARA station 1 to 3.
- Chiba group **reproduced antennas same as Taiwan one**.
  - To understand antennas responses well.
  - **To improve antenna simulation model** is used in current analysis.
- Simulation : done with **XFDTD** (time domain simulation software)
- We measured characteristic of the antenna in anechoic chamber
  - Compare with measured data to simulation



Antenna characteristics

Circuit

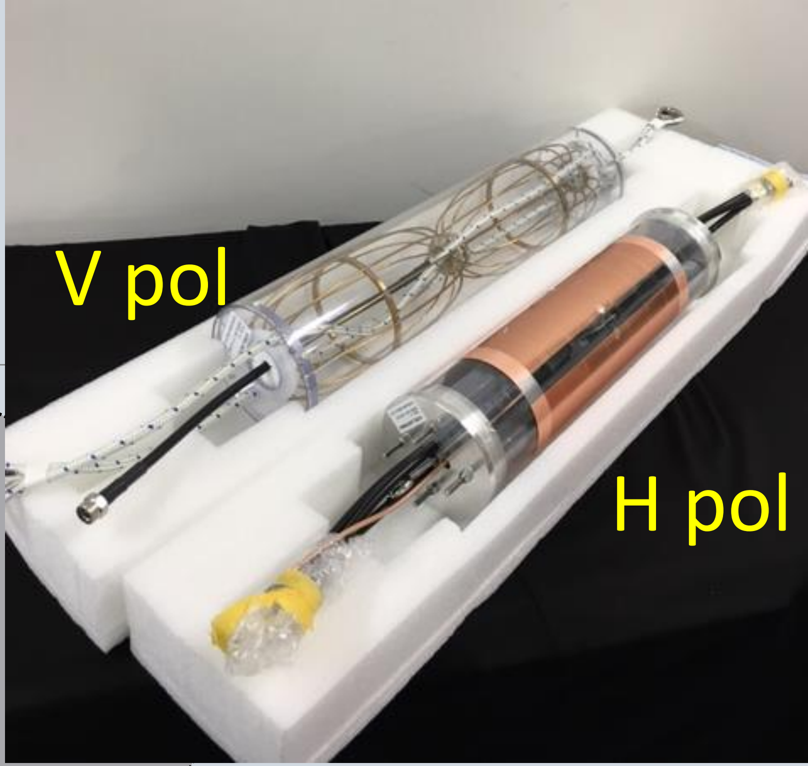
Input impedance
radiation resistance
VSWR
Return loss
Reflection coefficient
Radiation efficiency
bandwidth

Antenna

Current distribution
Antenna coefficient

EM field

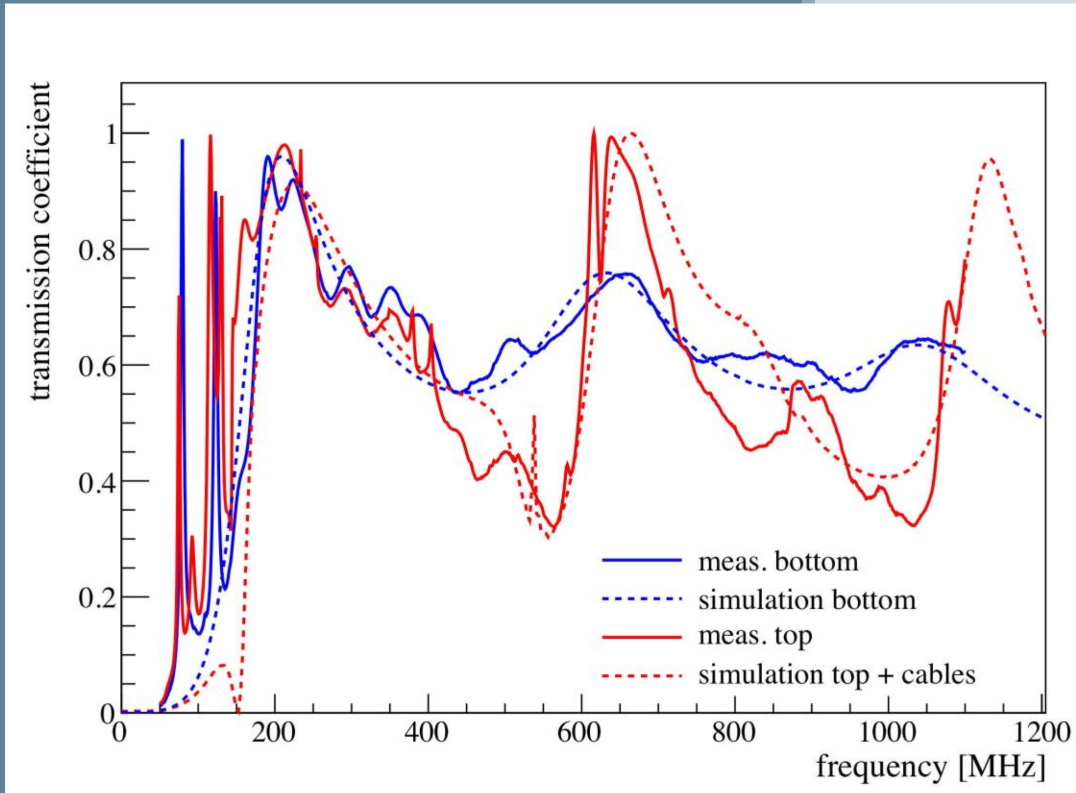
Radiation pattern
Directional gain
Gain
Beam width
Polarization
Effective area
RCS
Radiation efficiency
bandwidth

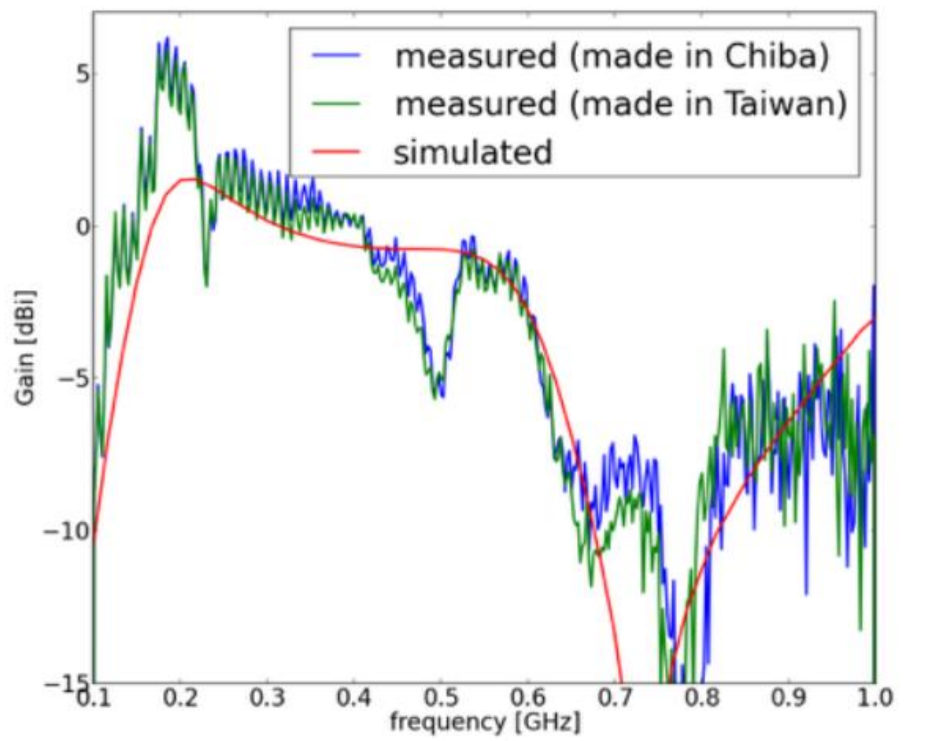


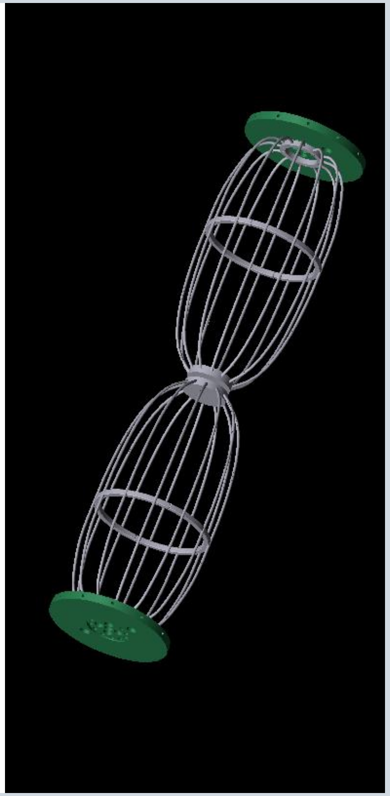
- Antenna measurement requires two different types of measurements; one is **circuit characteristic**, another is **radiation characteristic**.
- We measured particularly important values of VSWR and Gain.
- VSWR and Gain directly impact on sensitivity of the detection of cosmogenic neutrinos.

Gain and Transmission coefficient

Vpol bottom







$$T = \frac{2}{VSWR + 1}$$

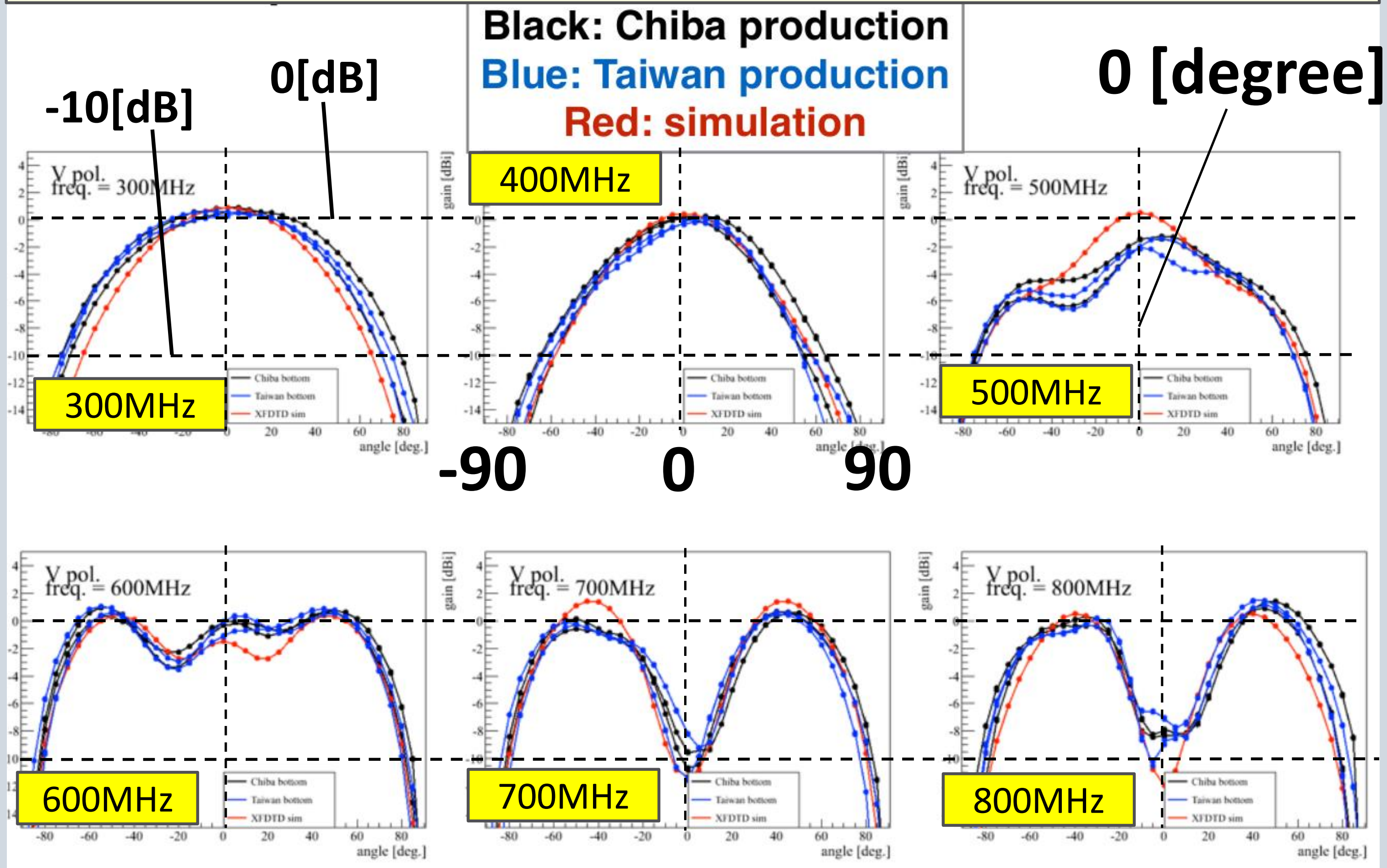
$T \text{ is Transmission coefficient}$

- There are **nice agreement** between measured data and simulation both VSWR and Gain
- Antenna response is very stable Chiba antenna to Taiwan one.
- These more exact antenna characteristics **will be added to ARA simulation (AraSim).**

Gain results of V pol bottom antenna : Frequency domain

- Simulation data are well reproducibility each angle and each frequency.
- Coincidence between Chiba antenna to Taiwan one.

Antenna gain : **Frequency** with angular dependence

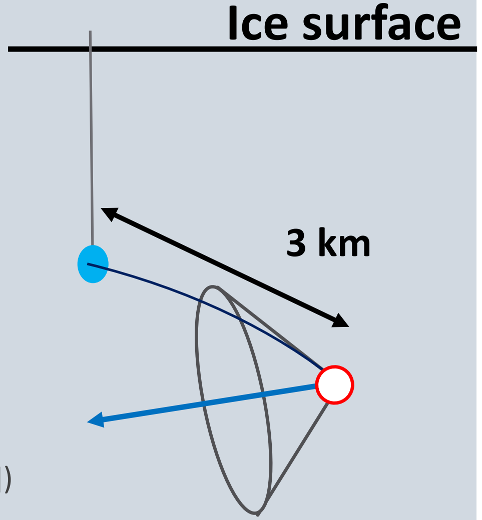


x-axis → angle[degree], **y-axis** → Gain$[dBi]$

RF over Fiber (RFoF) modules

for signal transmission

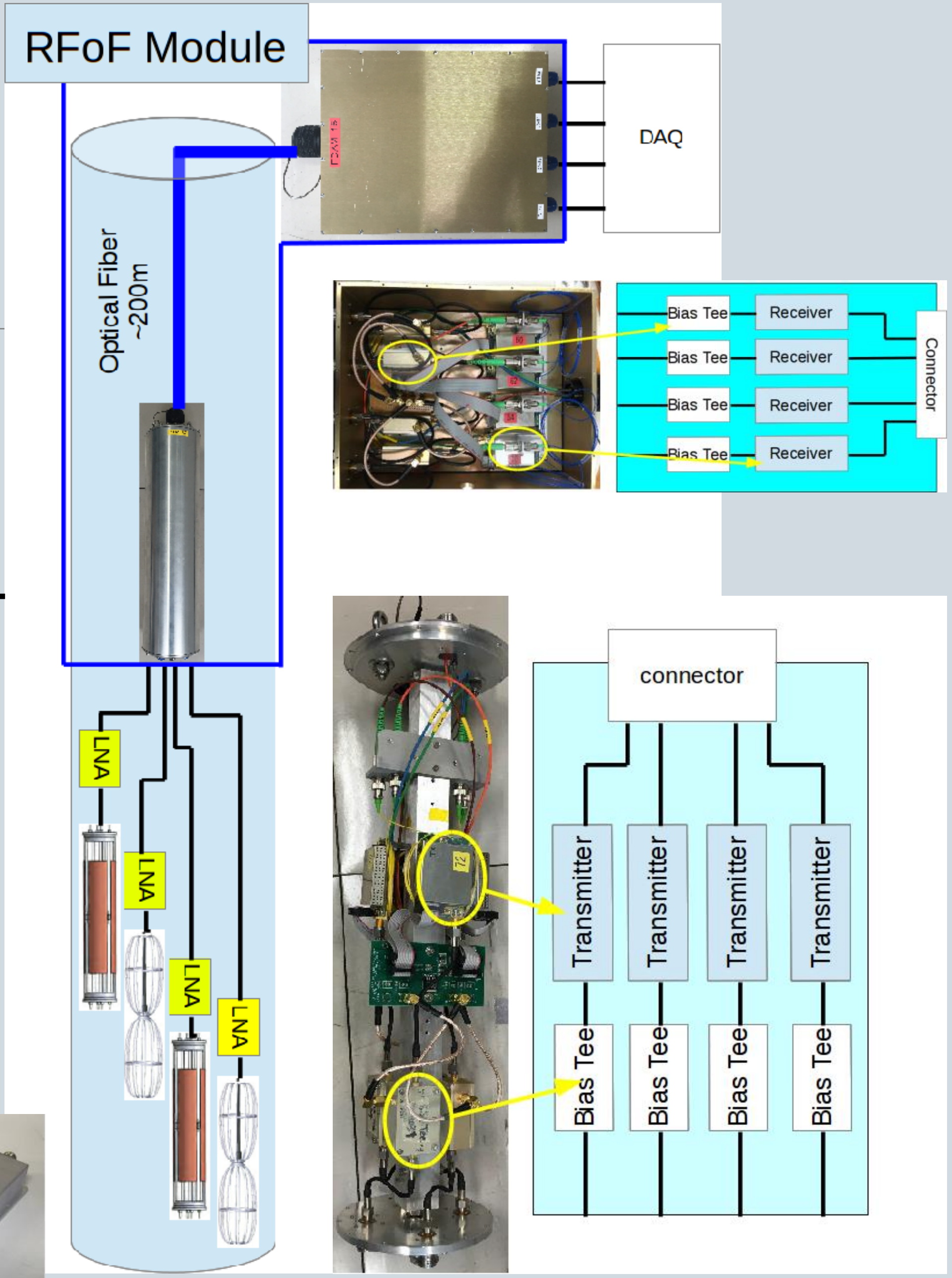
- **Convert radio signal to optical**
  - For low loss transmission over distances involved (200m)
- Low noise module
- **Gain**($\sim 20[dB]$) the signal for dynamic range
  - Reduce the each Channel(CH) dispersion within $32[dB]$
- Aiming at $10[PeV]$ Askaryan signal
  - Requirement of the DAQ dynamic range
  - **Signal : $7[{}^{V}/_{m}]\ for\ 1\ \times\ 10^{18}\ [eV]$**
    - $\sim 3km$ between signal and detector : → $\mathbf{0.02[mV]}$
  - Attenuation : $\sim {}^{1}/_{100} \rightarrow \sim 2\ \times\ 10^{-4}\ [mV]$
  - Total gain needed over the dynamic range : $\sim \mathbf{80[dB]}$
    - **LNA :** $\sim 35[dB]$, **DAQ :** $\sim 32[dB]$ (adjustment range in steps of 0.25[dB])



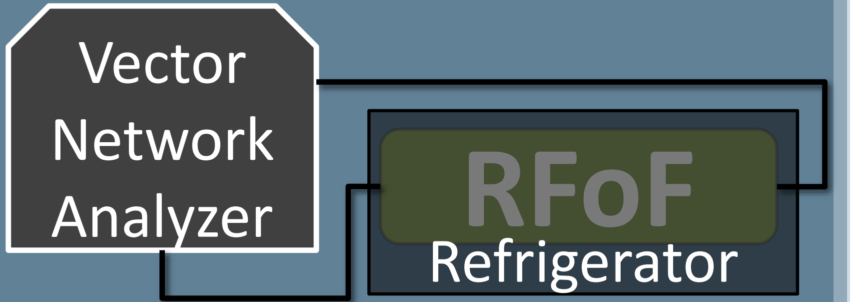
→**RFoF modules are required $\sim 20[dB]$ gain.**

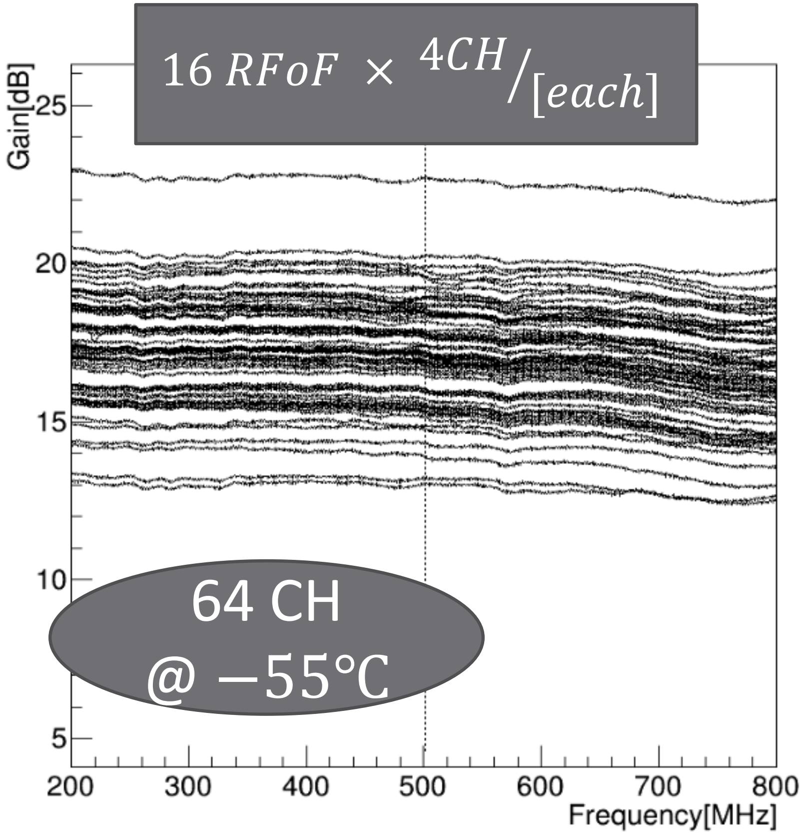
→We've developed **16 RFoF for 3 stations and 1 set of backup**

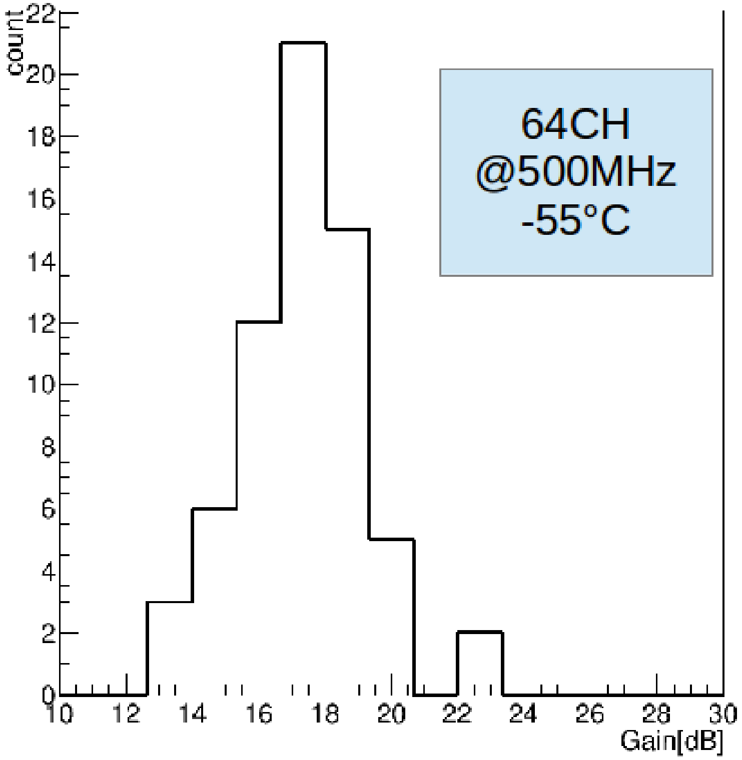
→**each RFoF module has 4 channel**



RFoF Calibration Gain Results







- We took calibration of the RFoF gain using **Vector Network Analyzer**.
- The gain values of all the 64 CH (16 RFoF : each has 4 CH) are in the range of <u>**$\sim 13[dB]$ to $\sim 23[dB]$**</u> and flat against frequency as desired.
- Even if 13dB, total gain is $78[dB]$ (LNA:33[dB], RFoF:13[dB], DAQ:32[dB]).
  - This means 8000 times amplification in power ([Watt]).
  - Signal will be $\sim 1.6[mV]$: **acceptable level for dynamic range**.

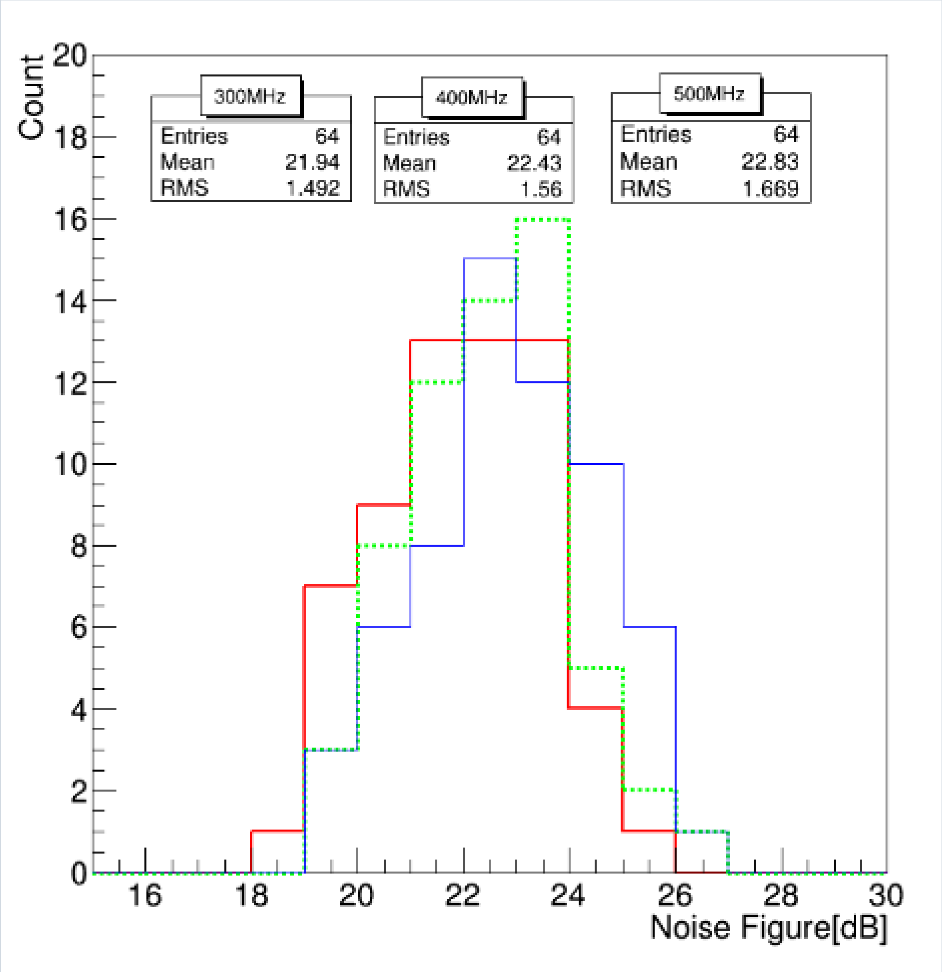
RFoF Calibration Noise Figure Results

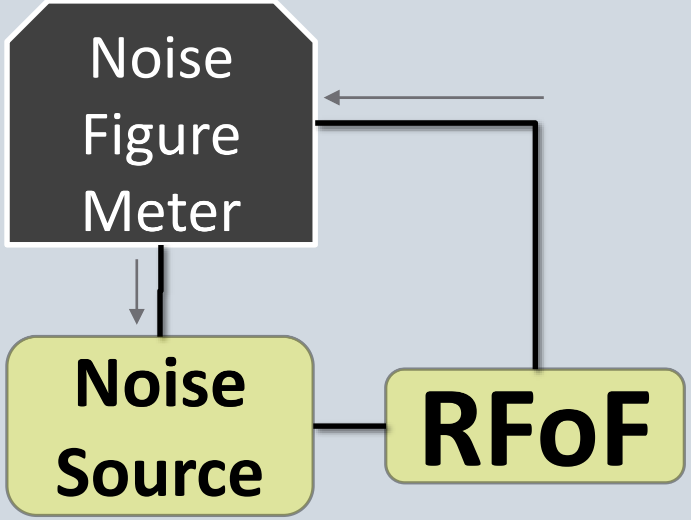
- Noise Figure (NF) is a measure of **additional thermal noise** is added to the system when the signal passes through each device.

$$NF = 10\log_{10} F,$$

$$F = \frac{S_{input}/N_{input}}{S_{output}/N_{output}}$$ F is Noise Factor.

$$F_{totl} = F_1 + \frac{F_2 - 1}{G_1} + \cdots$$
(1)





- This plot is the distribution of RFoF(64CH) NF at 300MHz,400MHz and 500MHz. Its value looks quite large but this RFoF NF value is not so important because the largest contribution to the decision of Noise Factor comes from first stage of amplifier (1).
- In our case, first device is **LNA (Low Noise Amplifier : NF = 0.9[dB], F = 1.23, Gain = 33[dB]).**

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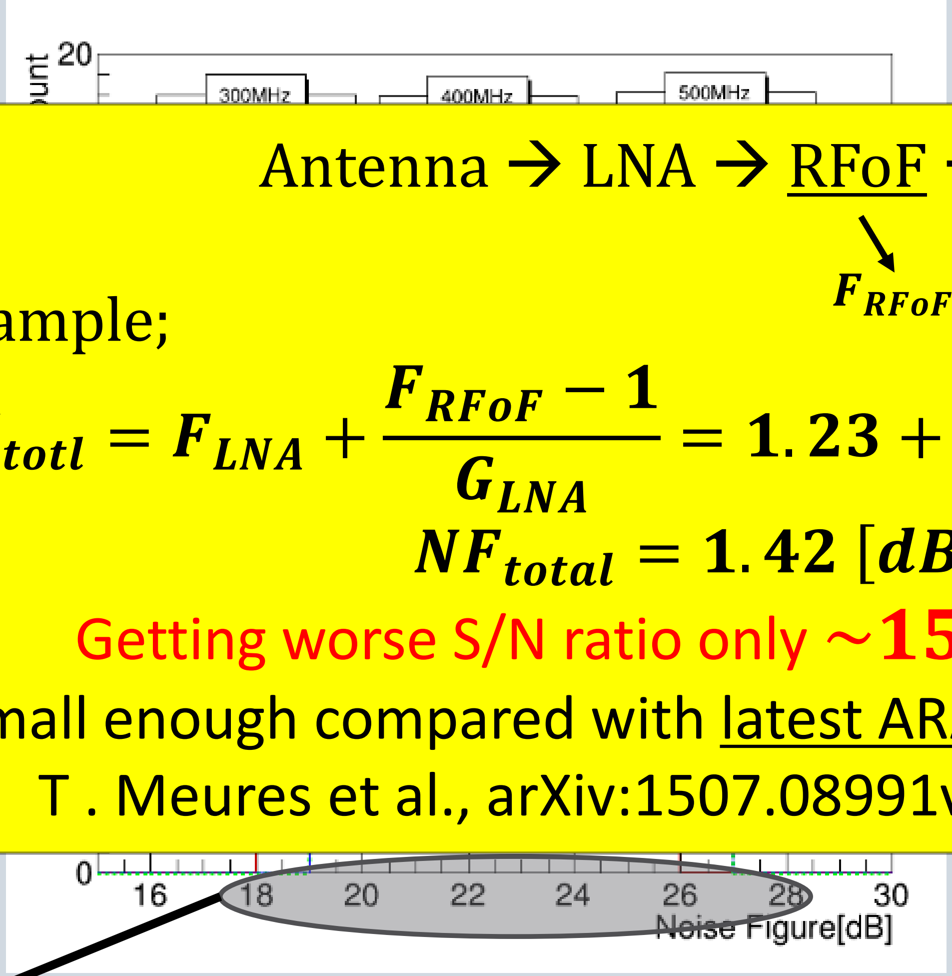
Noise



Antenna → LNA → RFoF → DAQ

$$F_{RFoF} = 10^{\frac{NF_{RFoF}}{10}} \cong 316$$

Example;

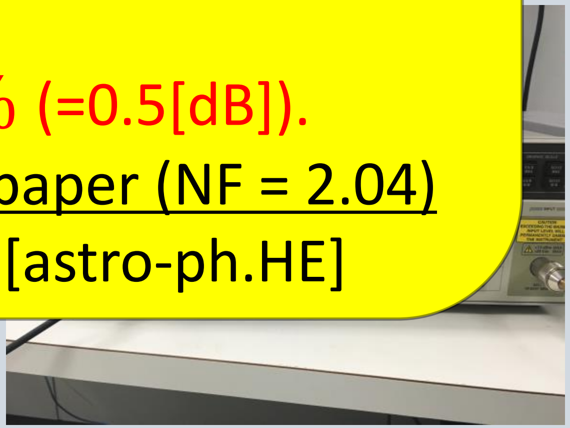
$$F_{totl} = F_{LNA} + \frac{F_{RFoF} - 1}{G_{LNA}} = 1.23 + \frac{316 - 1}{1995} = 1.39$$

$$NF_{total} = 1.42\ [dB]$$

Getting worse S/N ratio only ~15% (=0.5[dB]).

Small enough compared with latest ARA paper (NF = 2.04)

T . Meures et al., arXiv:1507.08991v2 [astro-ph.HE]



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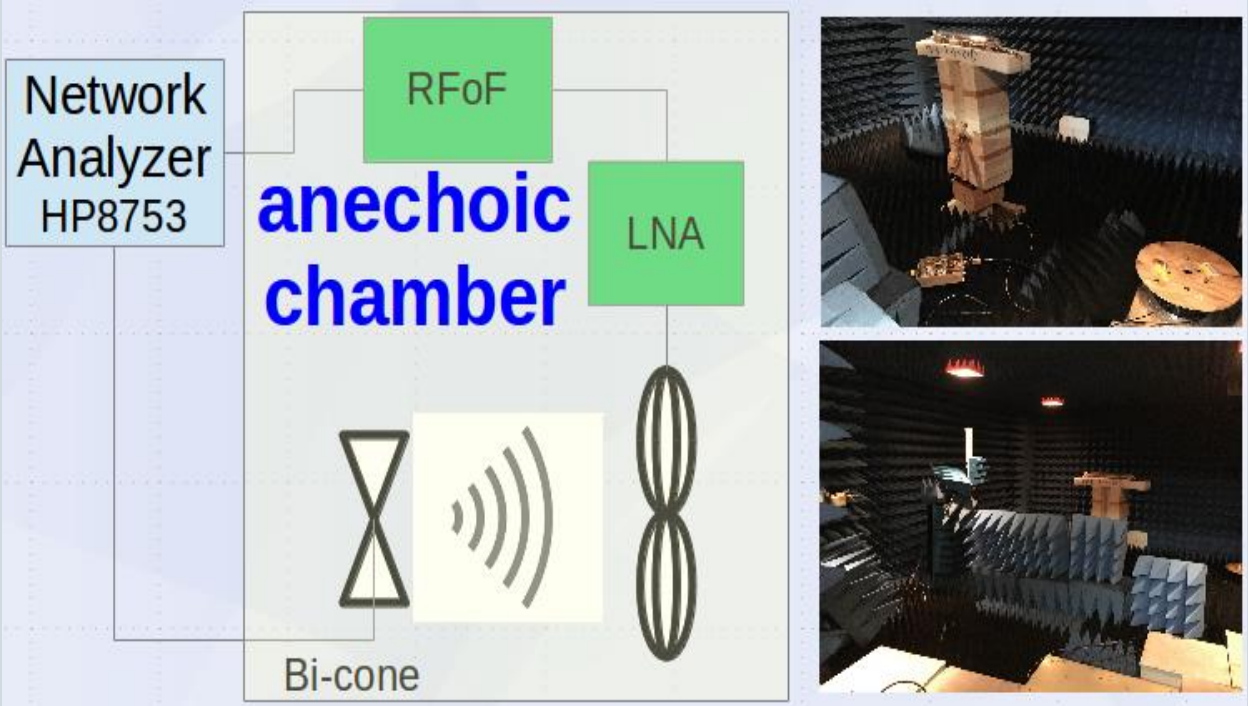
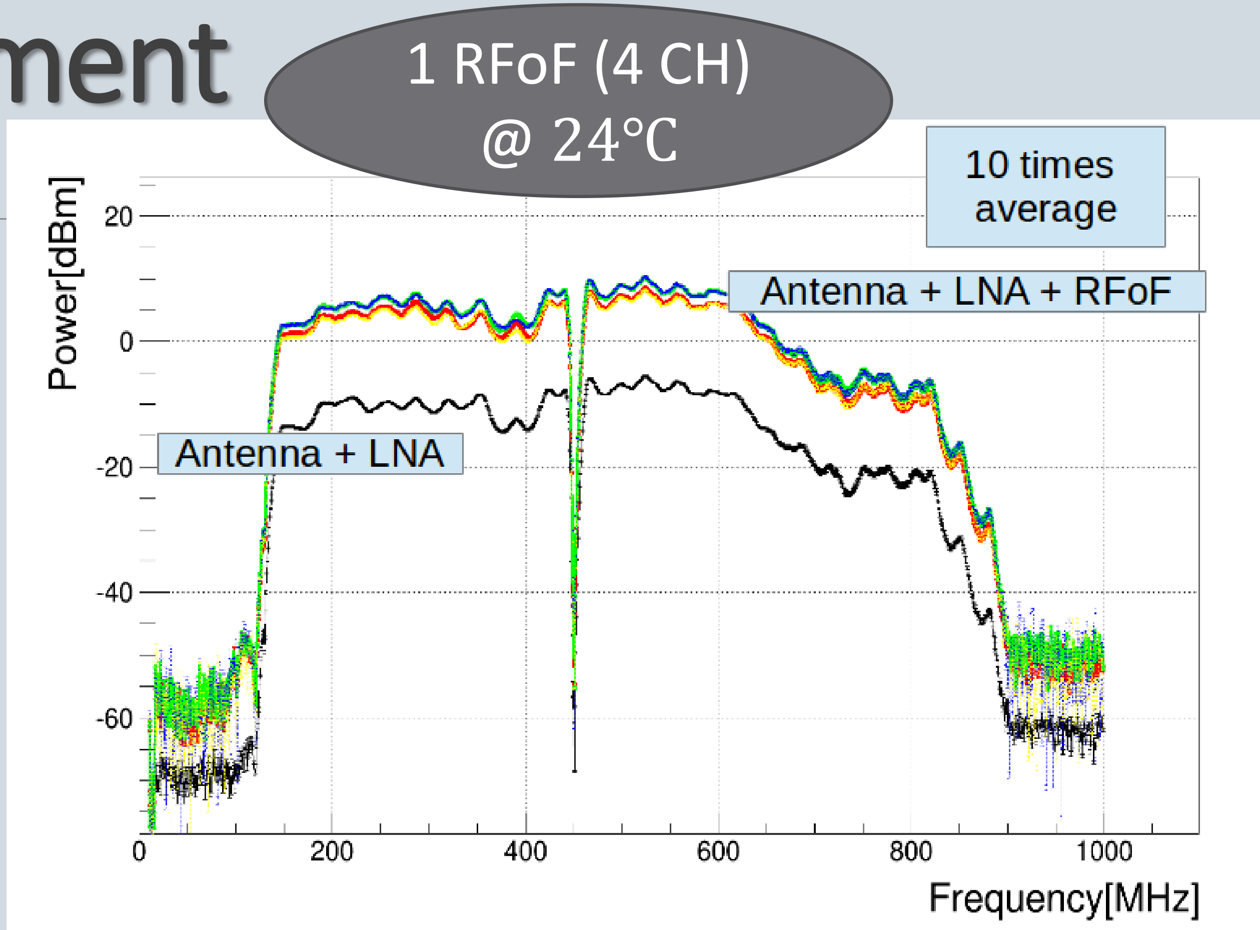
End-to-End Measurement

Antenna + LNA + RFoF module



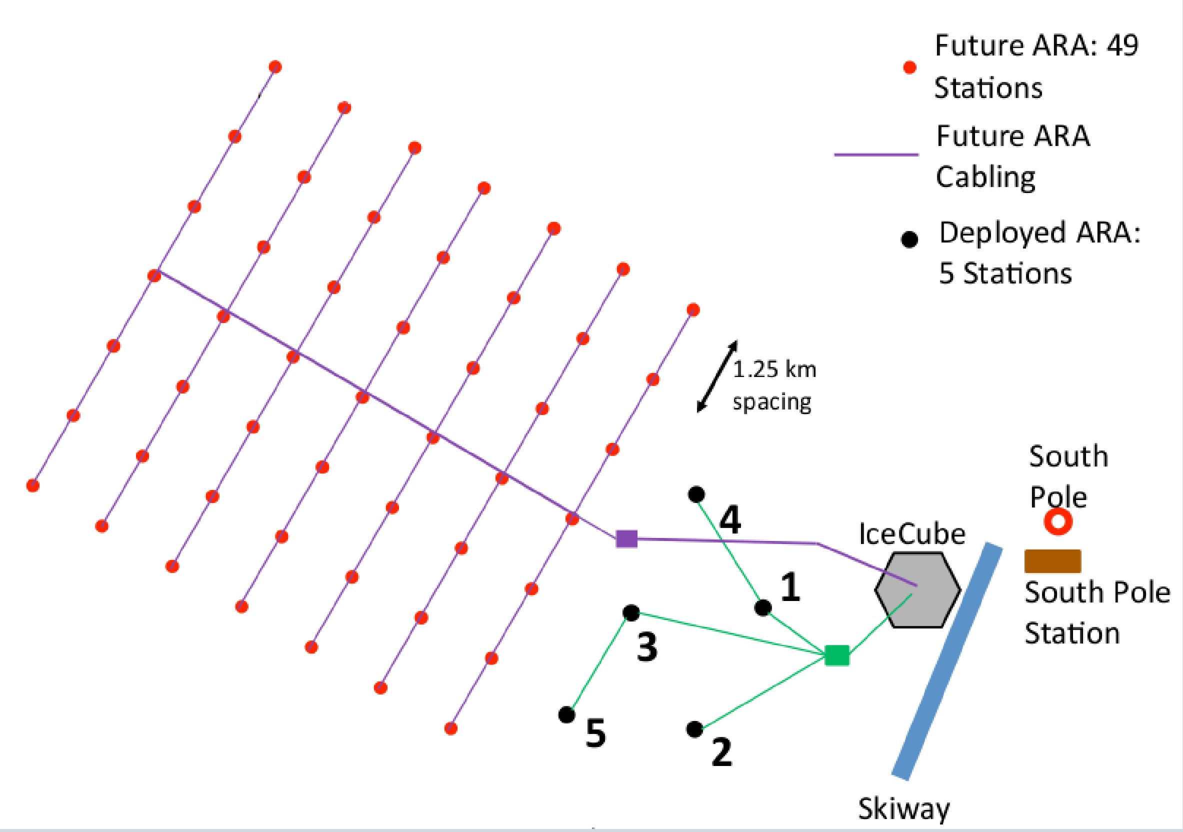


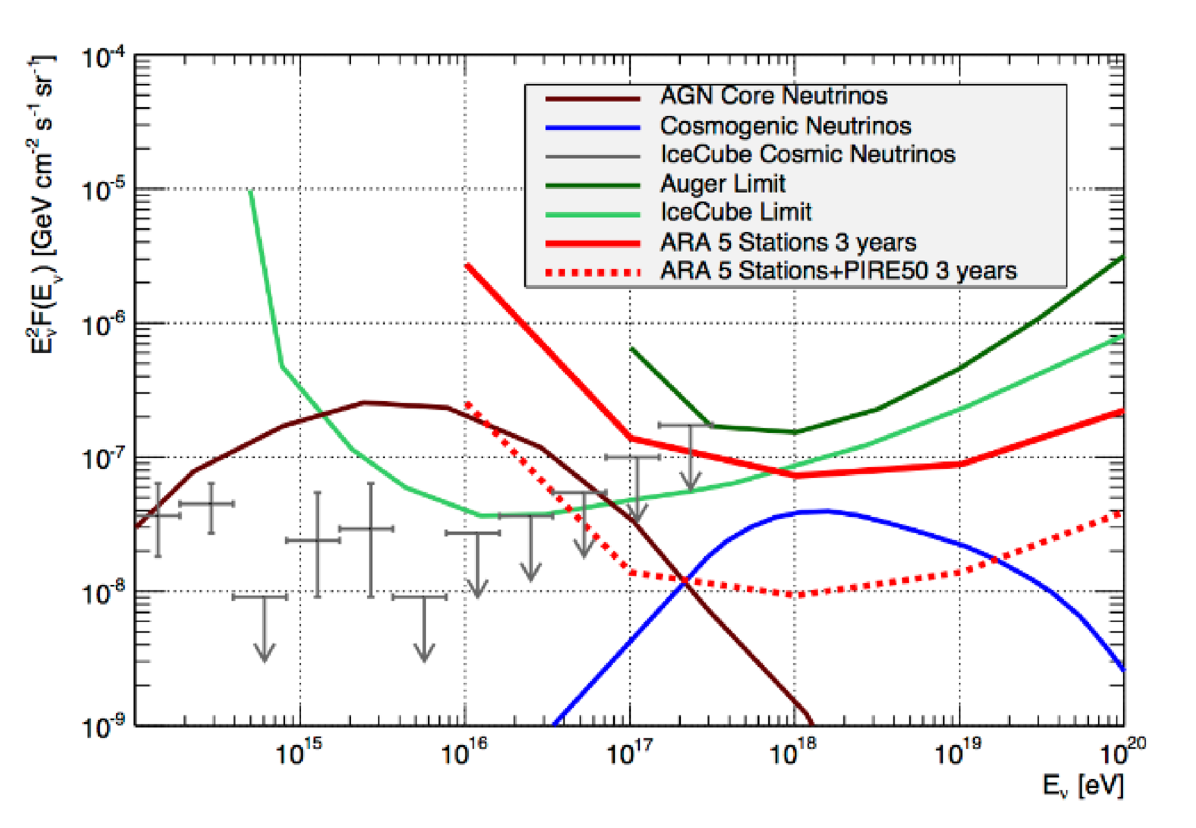
- We also measured **End-to-End calibration**, connecting an **antenna** similar to be one use at South Pole, a **LNA** and a **RFoF module** in an anechoic chamber.
- Results for **one RFoF (4 CH)** with an **antenna** and a **LNA**.
- Gain values are almost match as we expected.

Further plan : R & D for Slim Antennas

- ARA : aiming to discover ultra-high energy cosmic neutrinos ($\sim \geq 100\ [PeV]$)
  - should be first around the world
- Want to **construct detectors ASAP**
- Bottom neck : **delay of drilling ice**.
  - Option : Rapid Air Movement (RAM) drill
  - **$\sim$10 times faster** than current drill. (Also reduce the cost)
  - 10 cm diameter (presently : cm)
- Needed to **develop slim antenna** to fit in with new hole.
  - Decided structure of the antenna
- **Simulated** the response
- **Produced and measured** slim antenna response.
  - In anechoic chamber
  - Compared with…
    - Simulation to measured value
    - Original to slim one

Layout plan and expected sensitivity





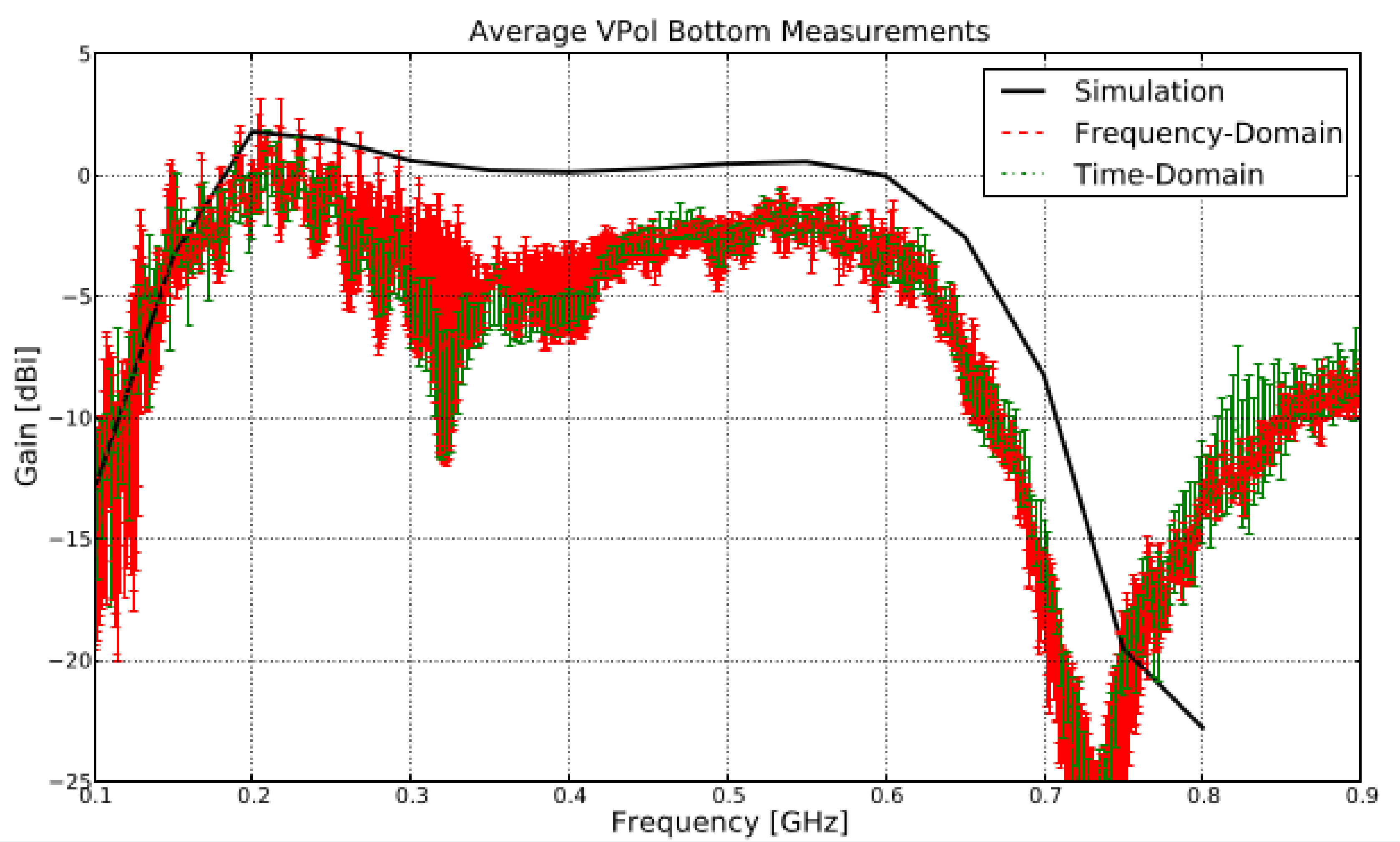
Results of Slim Antennas measurement

- This is **V pol bottom original antenna result**

- Details are explained by **S . Archambault** in poster session.

- Those antennas are in transit to South Pole.

- We (K.Mase) will go there and take some measurement to confirm the feasibility of the slim antenna.



- Gain is systematically below expected value from simulations; this could affect experiment's overall sensitivity.
- Gain is optimal in range from $\sim 200\ MHz$ to $\sim 600\ MHz$ to match expected Askaryan signal.

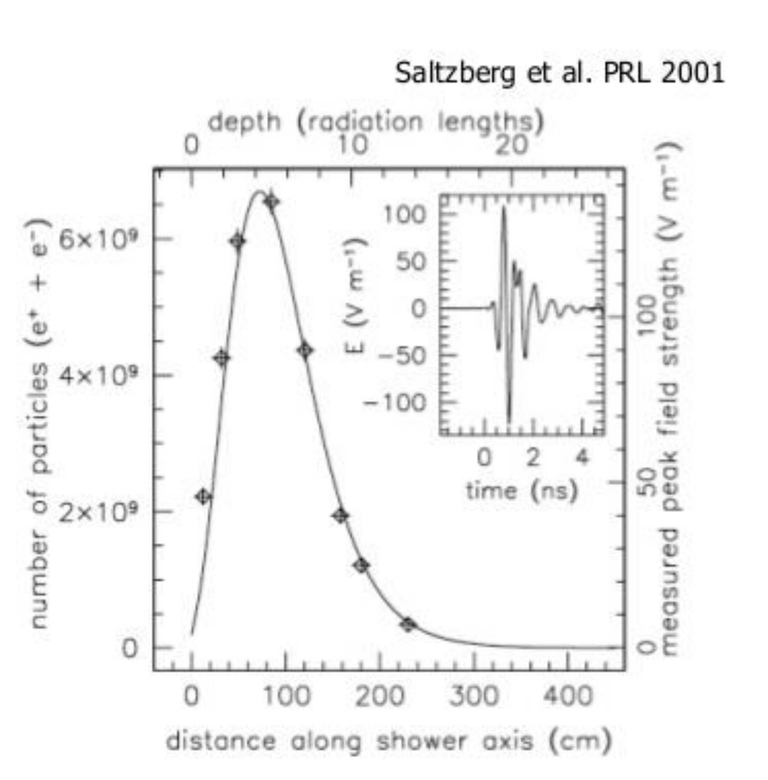
Summary and Future

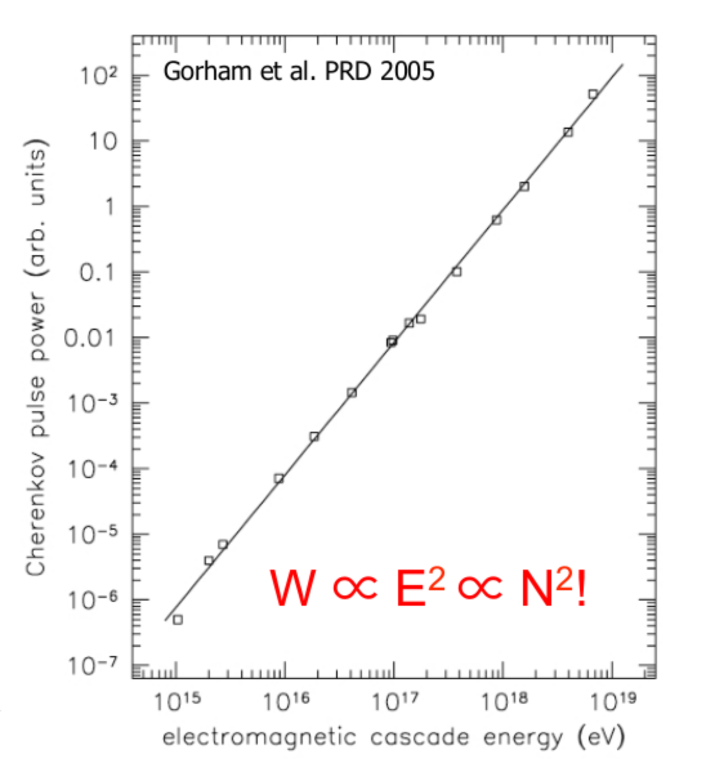
- We have **produced original antennas** same as first deployment
  - Built **simulation** and took **measurement** in anechoic chamber
  - Current : Trying to improve the simulation by using other simulation software
- Developed signal transfer system called **RFoF modules for 3 stations and one set of backup**.
  - Calibrated RFoF **Gain** and **Noise Figure**
  - **Total thermal noise is small enough** : There is no problem about noise.
  - Operation confirmation as **full chain (antenna + LNA + RFoF module)**
  - RFoF will be shipped to Madison to take more realistic measurement
    - Longer time, antenna + LNA + RFoF + DAQ
    - Then, **will be deployed south pole next summer**
- R & D for new **slim antenna** to early completion of the detector construction
  - Simulation
  - Produce and measure the characteristic, **will take measurement at South Pole this winter !!**

Backups

Confirmation of Askaryan effect

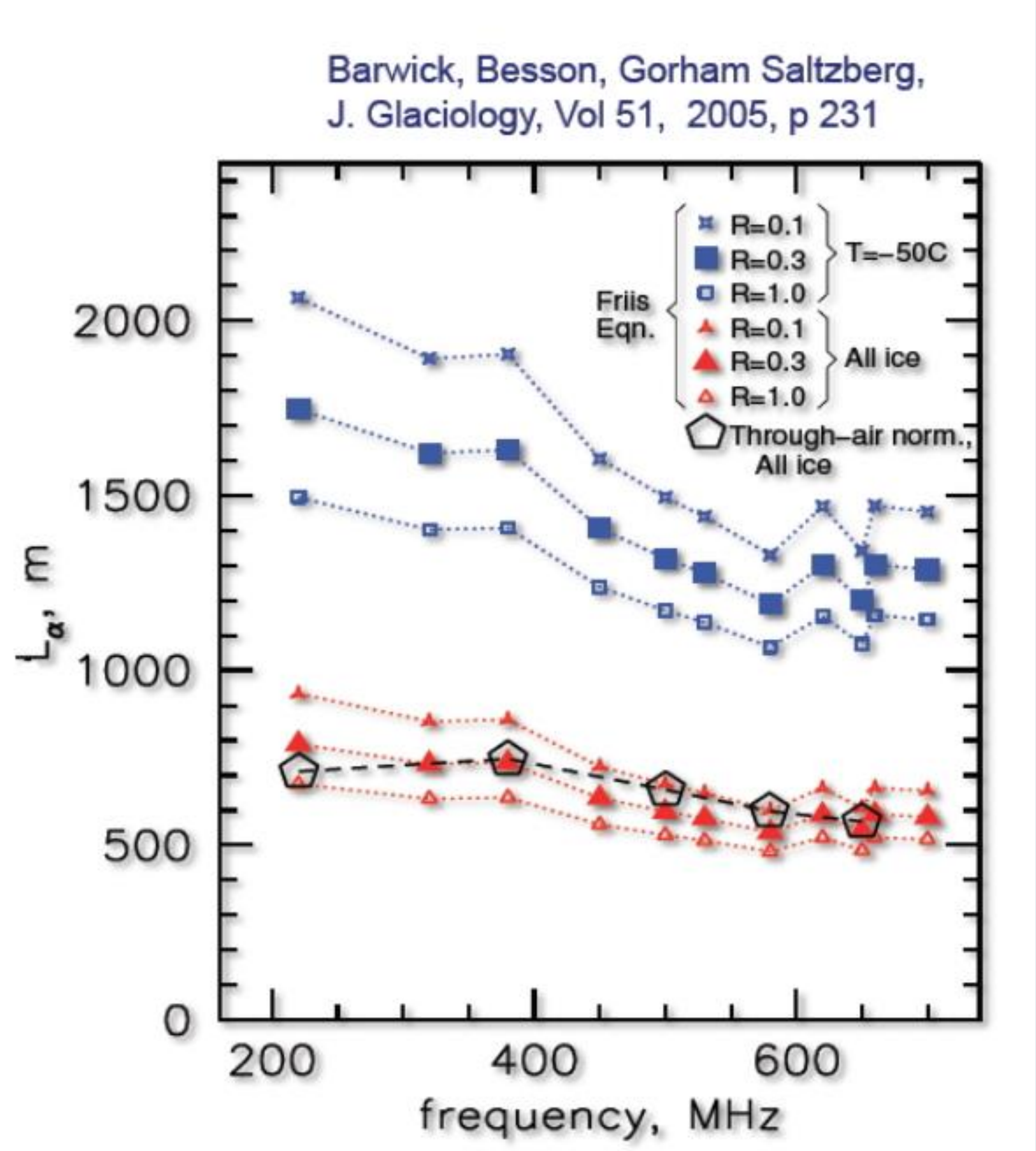
- ✓ 2001 : firstly confirmed at SLAC with Silica sand (D.Saltzberg et al.)
- ✓ 2005 : confirmed with salt (P.Gorham et al.)
- ✓ 2007 : confirmed with ice (P.Gorham et al.)
- ✓ The effect started to be well understood.





Why radio wave ?

- Attenuation length of the south pole ice
  - **Optical : $\sim 100\ m$**
  - **Radio : $\sim 1\ km$**
- Easier to make a bigger detector in an economical way

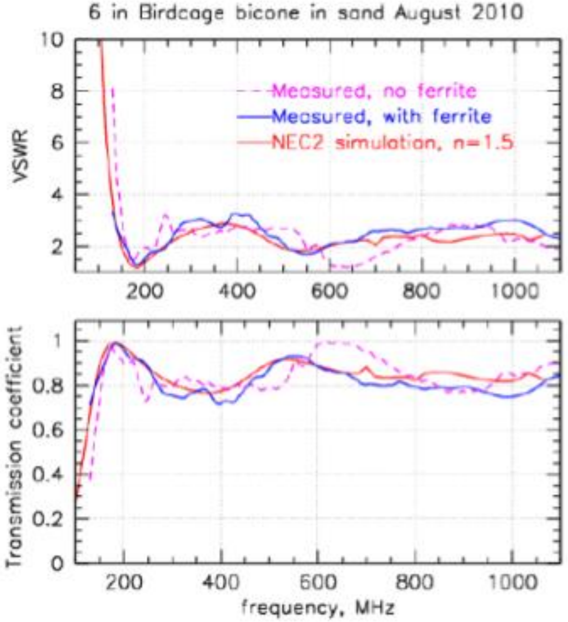


Antennas

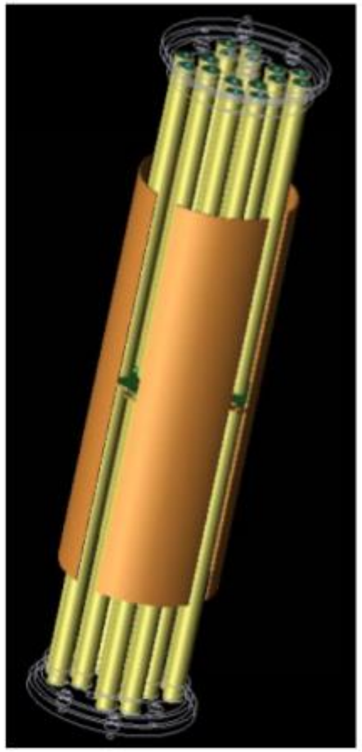
V-pol antenna

Bicone

150-850 MHz



K. Mase

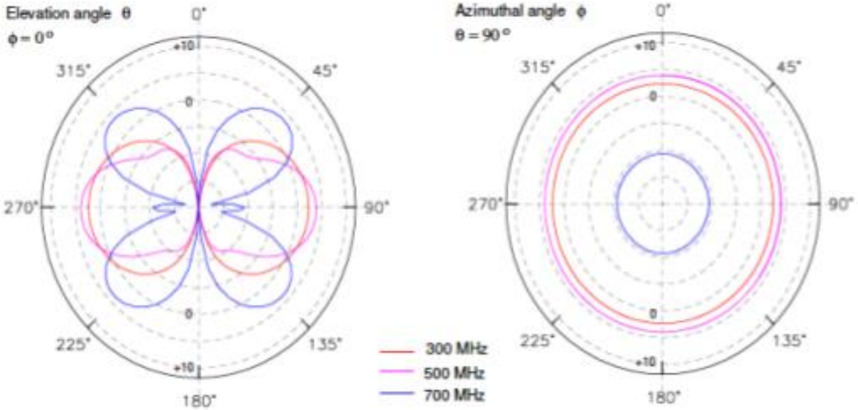


H-pol antenna

Quad-slot cylinder

200-850 MHz

Gain similar to dipole (+2 dBi)



$\Gamma = \frac{Z_L - Z_O}{Z_L + Z_O}$ *where* Z_O (= 50[Ω], *usually*) *is transmissiion impedance*, Z_L *is load impedance.*

Γ *is Reflection coefficient.*

$VSWR = \frac{1+|\Gamma|}{1-|\Gamma|}$: *Voltage Standing Wave Ratio.*

$T = 1 - \Gamma = \frac{2}{Z_L + Z_O} = \frac{2}{VSWR + 1}$

T *is Transmission coefficient.*

if $Z_L = 75[\Omega]$,

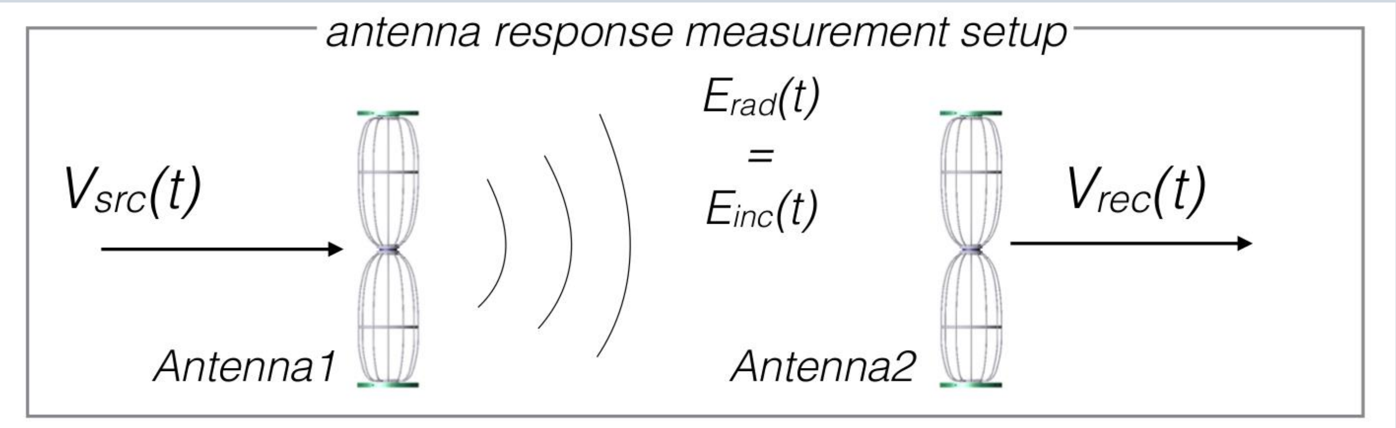
$$\Gamma = {}^{25}/_{125} = 0.2 : 20\%\ reflection.$$

$$T = 0.8 : 80\%\ transmission.$$

$$VSWR = 1.5$$

Idea of the antennas measurement in time domain

- Antenna has an input but the output is a field
- Put two antennas face to face
- Simulation was done with time domain simulation software (XFDTD)
  - Input a Gaussian pulse : V_{src}
  - Save output voltage : V_{rec}
  - Compute the antenna response according these equation.



$$\frac{E_{rad}(t)}{\sqrt{377\ \Omega}} = \frac{1}{2\pi c r}\, h_N(t) \circ \frac{dV_{src}(t')/dt}{\sqrt{50\ \Omega}} \qquad t' = t - r/c$$

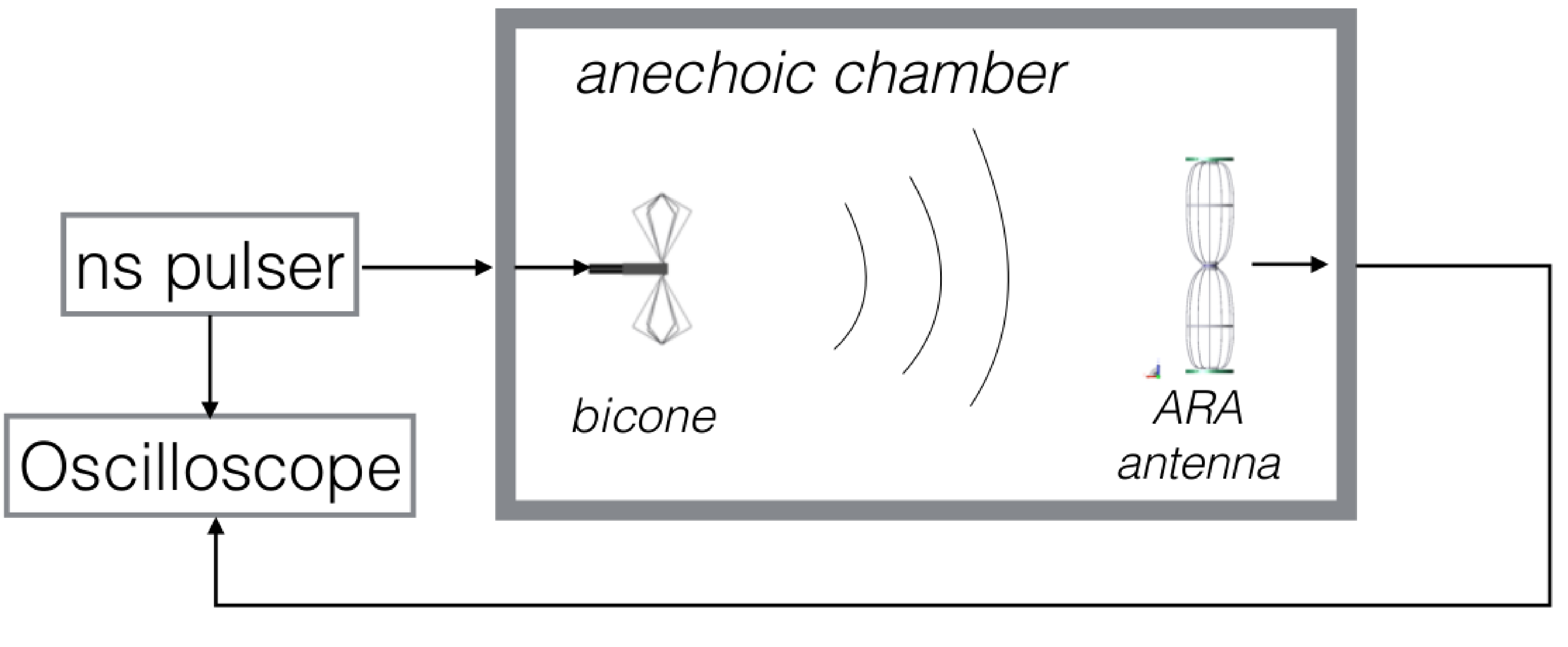
$$\frac{V_{rec}(t)}{\sqrt{50\ \Omega}} = h_N(t) \circ \frac{E_{inc}(t)}{\sqrt{377\ \Omega}}$$

convolution operator

antenna response equation

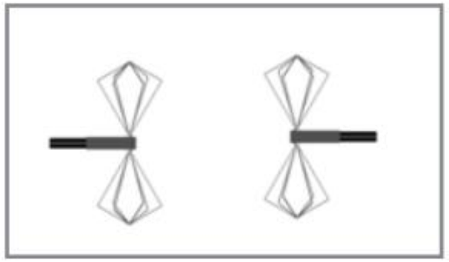
$$h(\omega) = \sqrt{\frac{2\pi c r}{j\omega \cdot exp(-jkr)} \cdot \frac{V_{rec}(\omega)}{V_{src}(\omega)\cdot}}$$

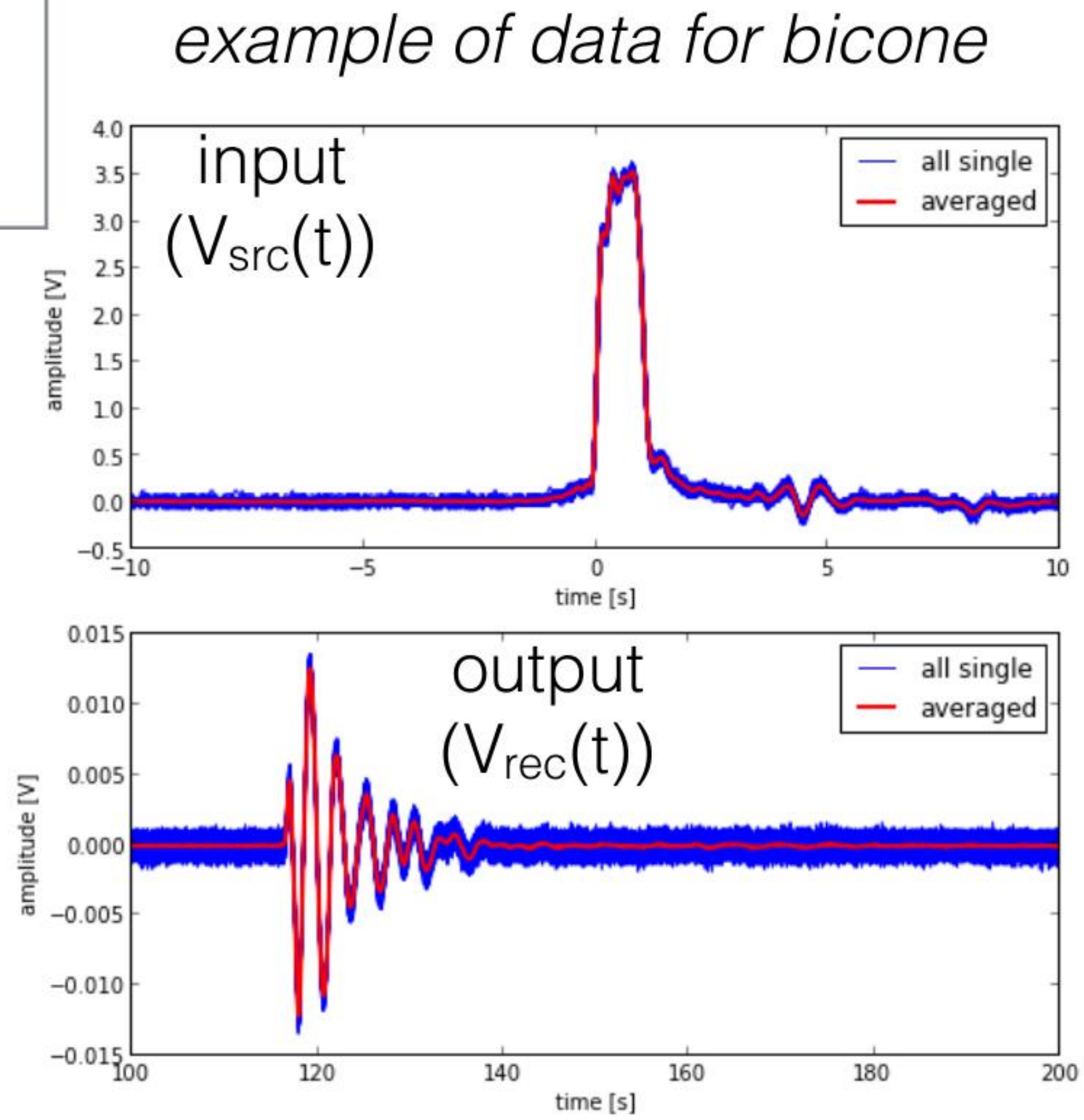
Set up for time domain



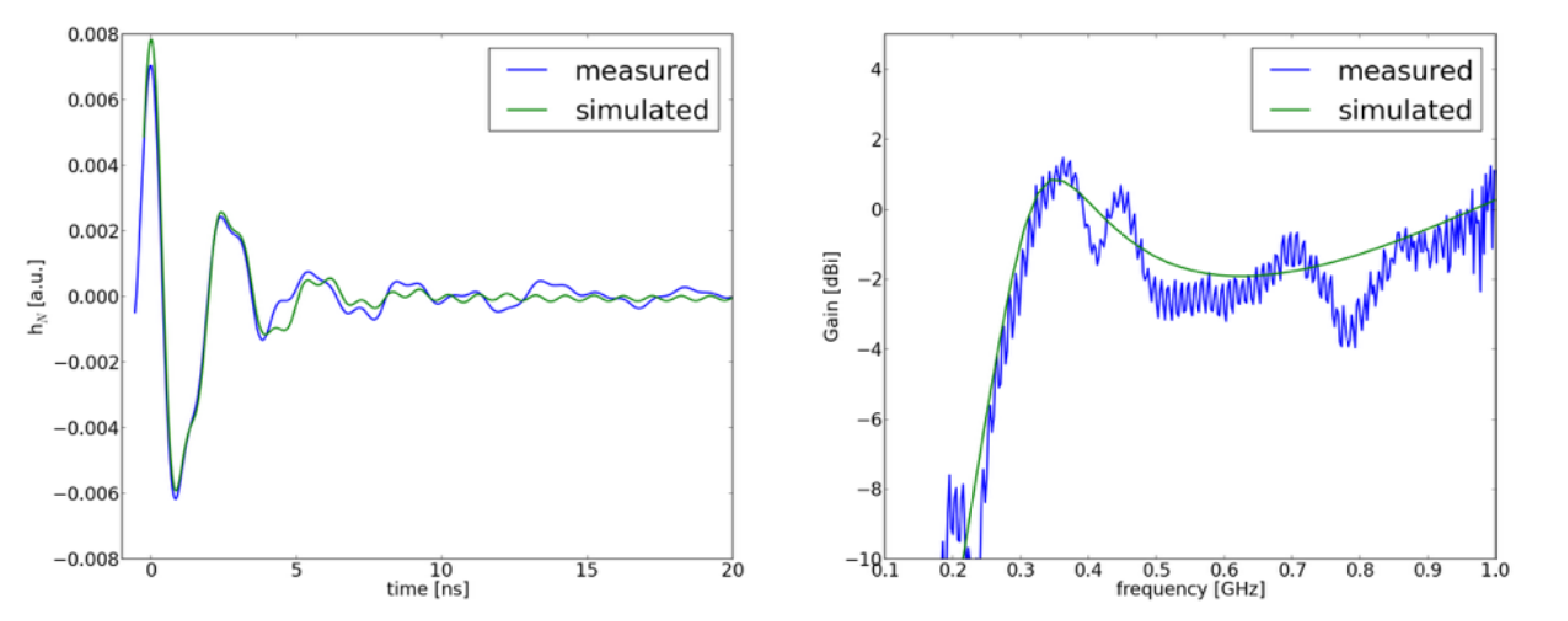
- Measurement's world harder than simulation's one
  - Two ARA antenna was impossible (size : $\sim 70\ cm$)
    - Calibrate 2 small bi-cones
    - Then calibrate ARA antenna knowing bi-cone response
  - Thermal noise on the antenna signal
    - Averaging is needed
  - Has to account for the cable delays
    - Measured the cable response separately

Bi-cone measurement



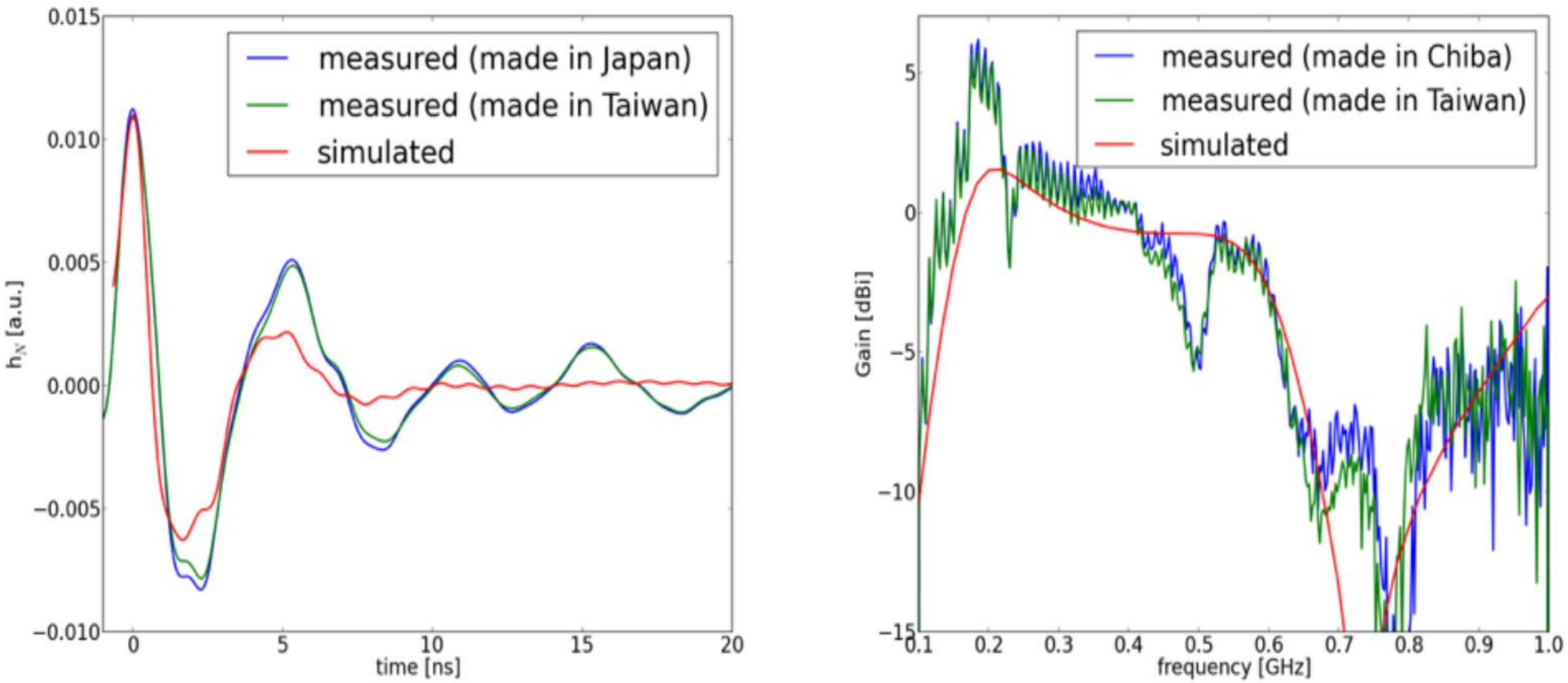


Results : bi-cone



- The time domain response is well reproduce.
- Some small structure of the gain are not reproduced by simulation.

Consistence between Taiwan to Chiba

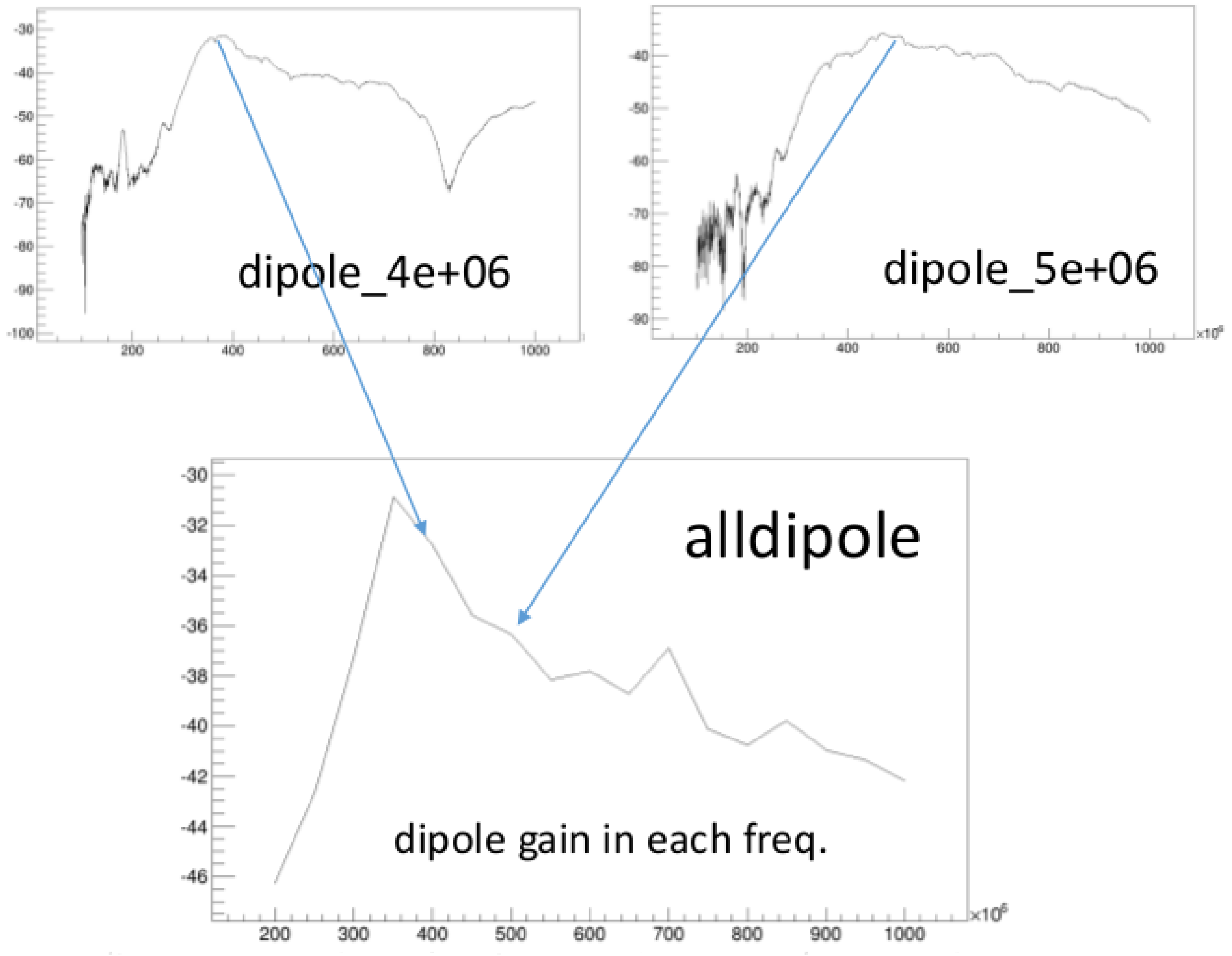


Frequency domain measurement

- Absolute calibration

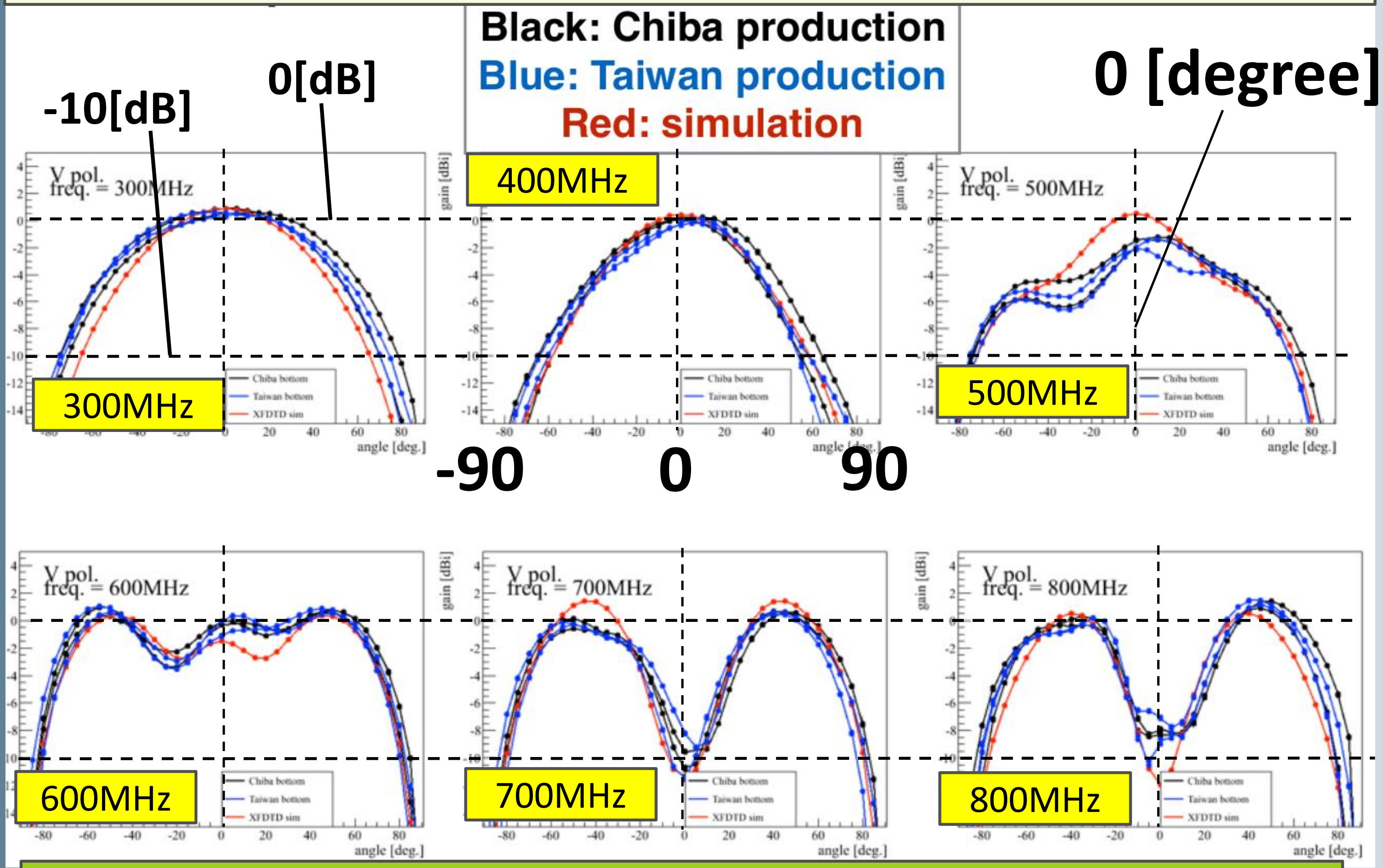
<u>Measurement method</u>
1. Measure the output power of dipole (200MHz to 1GHz)
2. Measure the pattern of antenna under test
3. Correct AUT meas. with dipole gain (2.15dB)→ **gain in dBi**

$$G_{abs,AUT}[dBi]$$
$$= G_{meas,AUT}[dB] - G_{meas,dipole}[dB] + 2.15[dB]$$

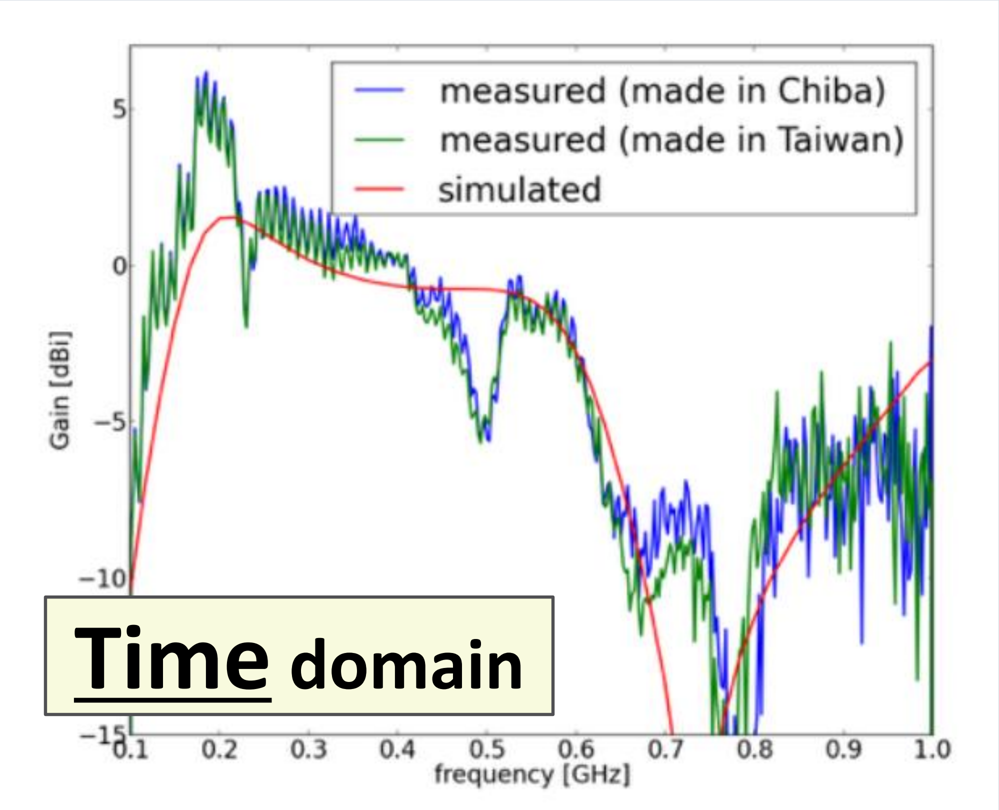


Gain results of V pol bottom antenna : Time and Frequency domain

Antenna gain : <u>Frequency</u> with angular dependence



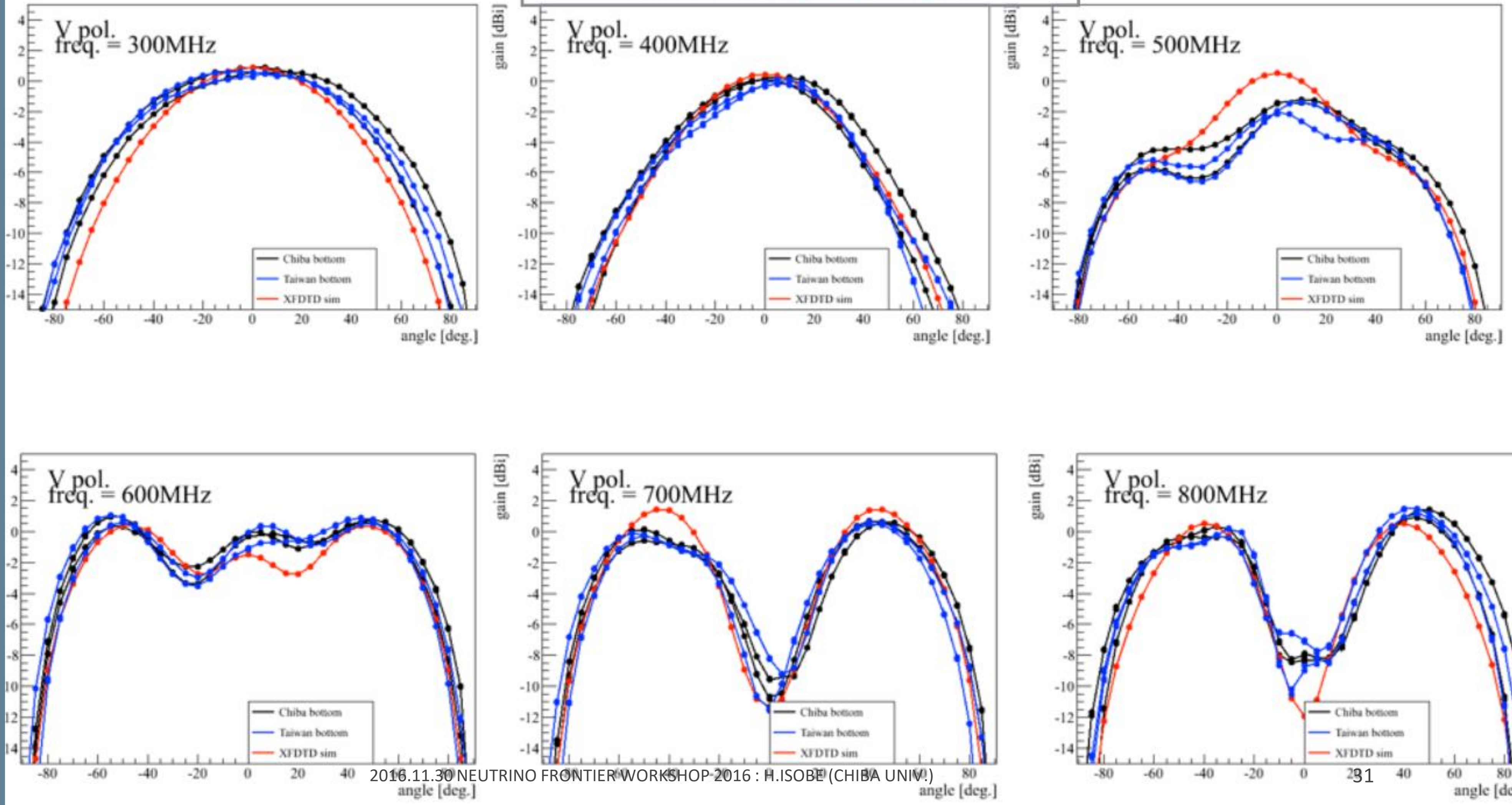
<u>x-axis</u> → angle[degree], <u>y-axis</u> → Gain$[dBi]$



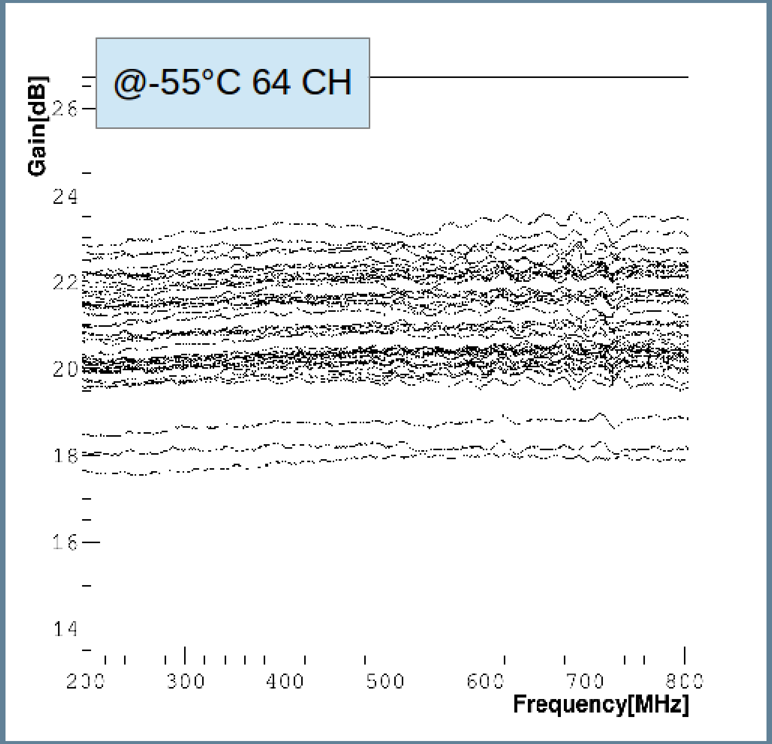
- Left : Frequency domain measurement.
- Right : Time domain measurement
- Coincidence of the simulation and measured data is good in both time and Frequency domain.

Vpol bottom:Data/sim

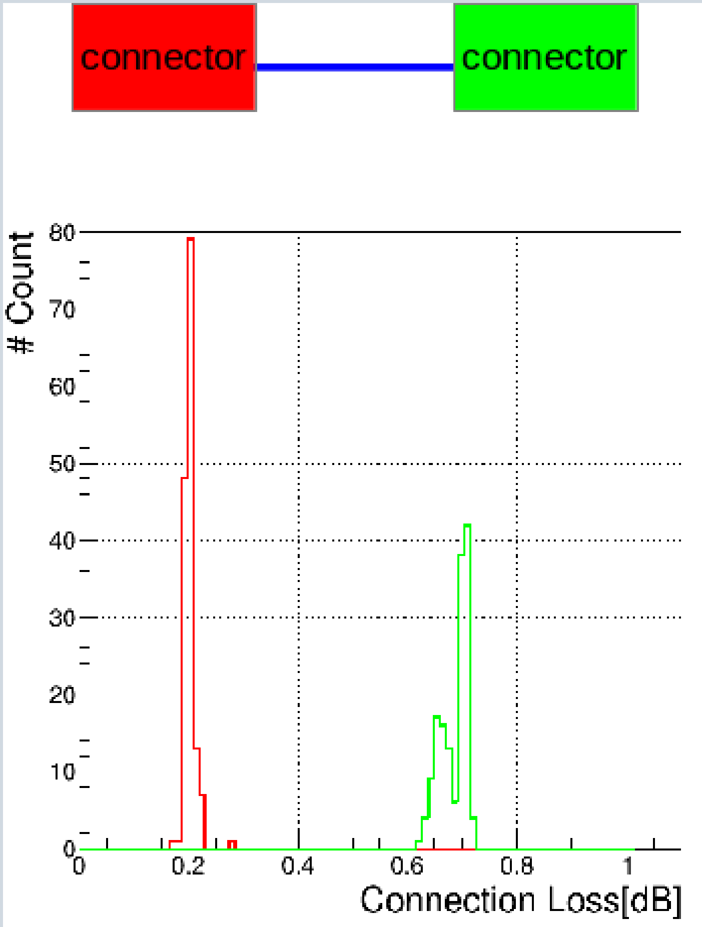
Black: Chiba production
Blue: Taiwan production
Red: simulation

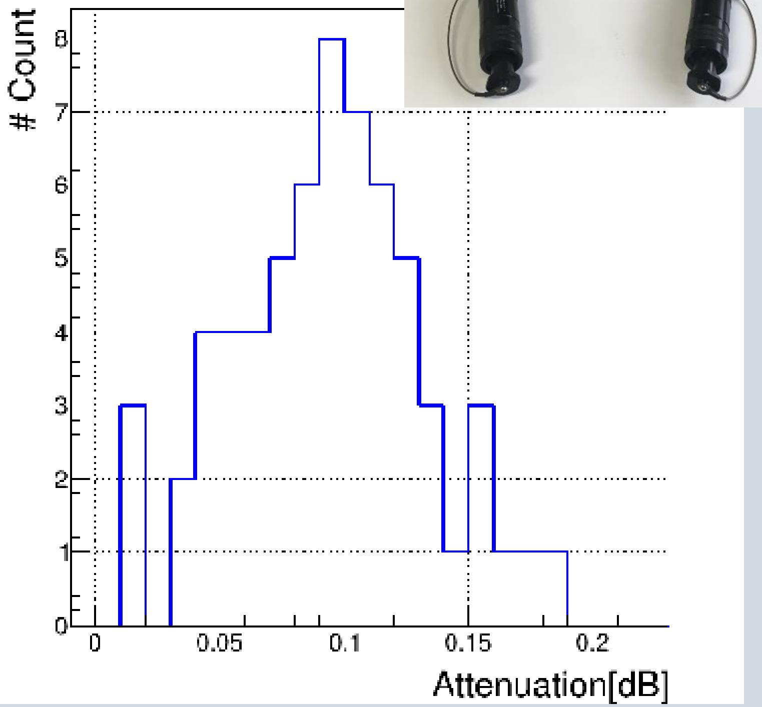


Device Calibration



- Gain of optimized combinations of the Transmitter and Receiver at – 55℃ .
- Flat against frequency.





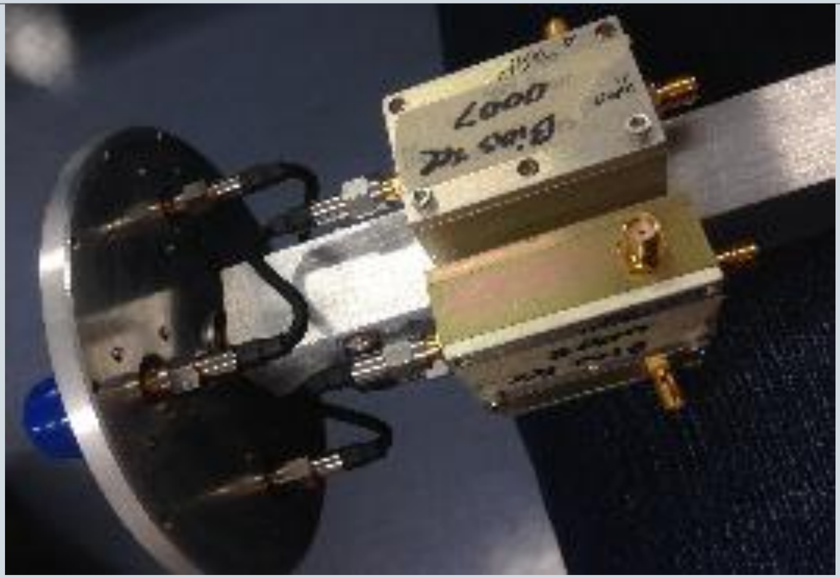
- Left : connector loss
- Right : 200 m optical fiber attenuation.

RFoF modules assembly

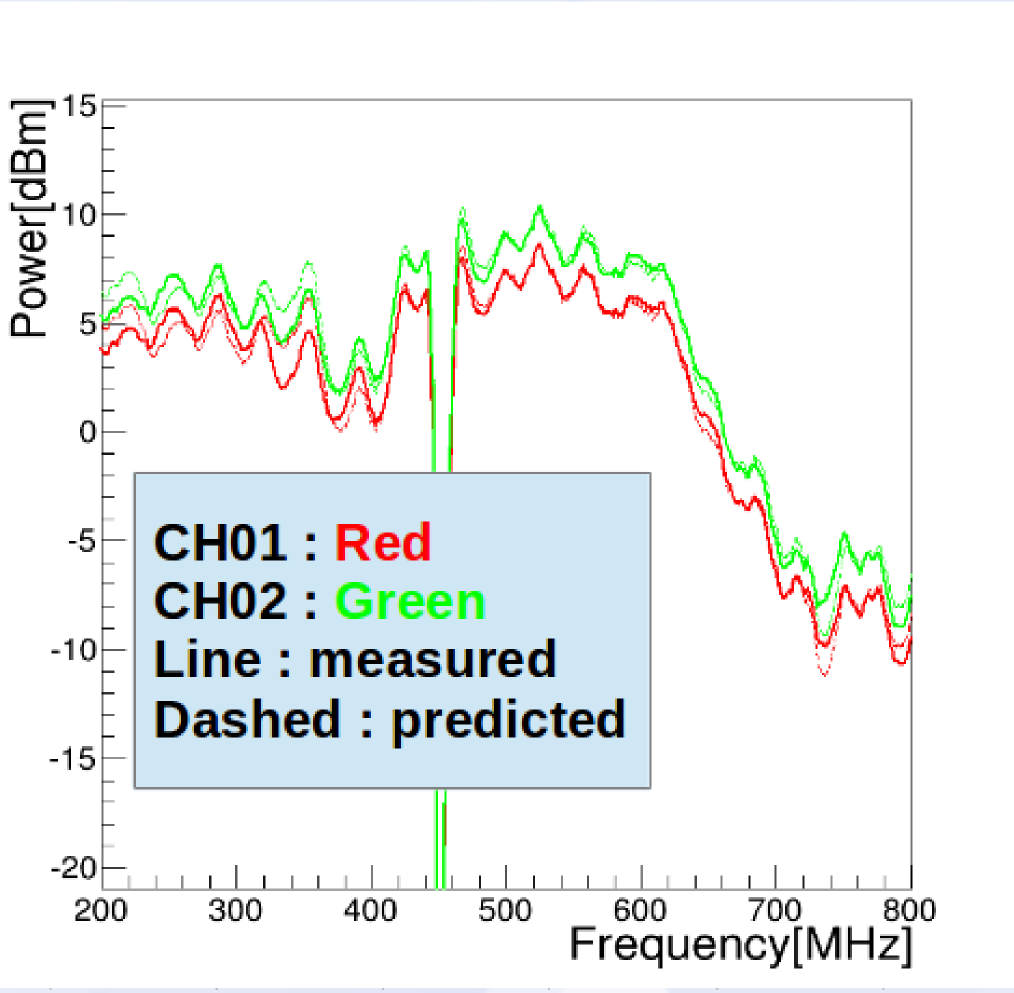
We have built 16 RFoF modules.

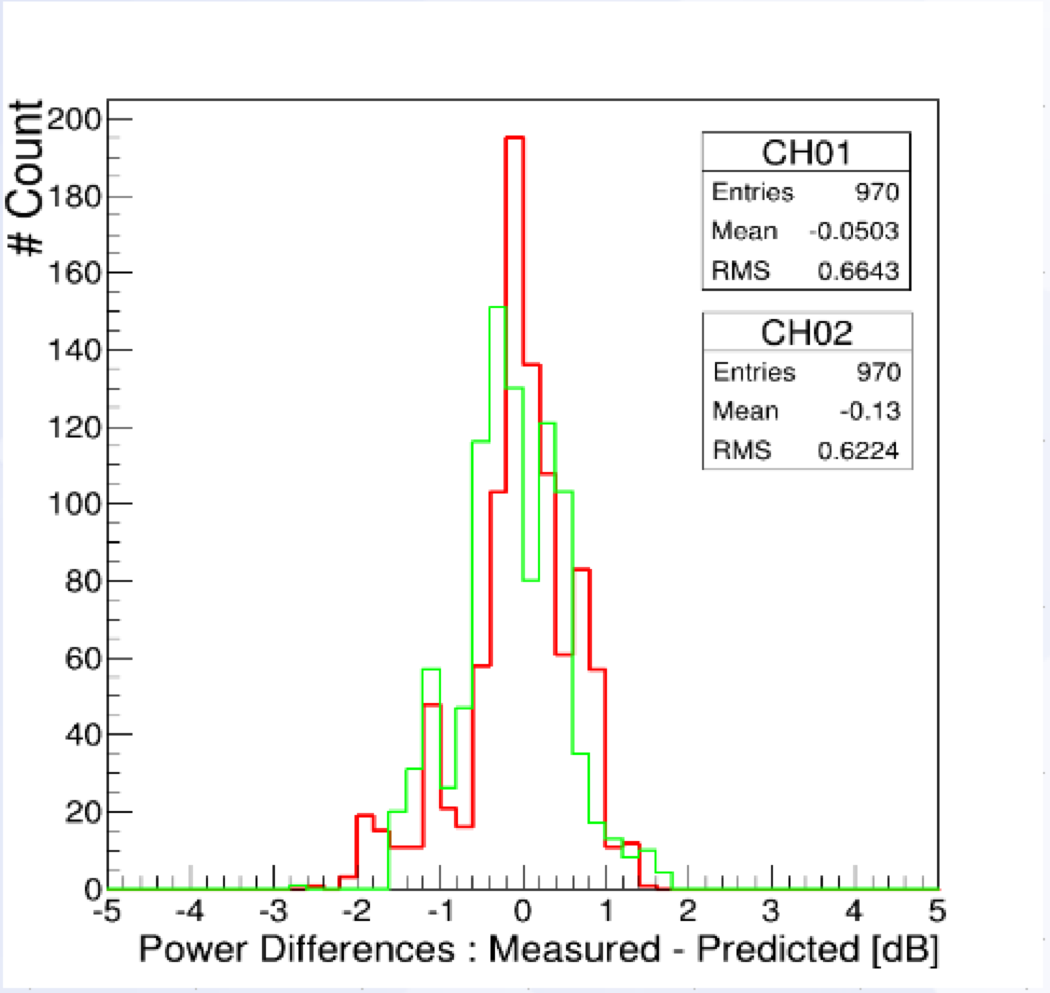
→ (16 DTM, 16 FOAM)

For 3 stations, 1 set is backup.

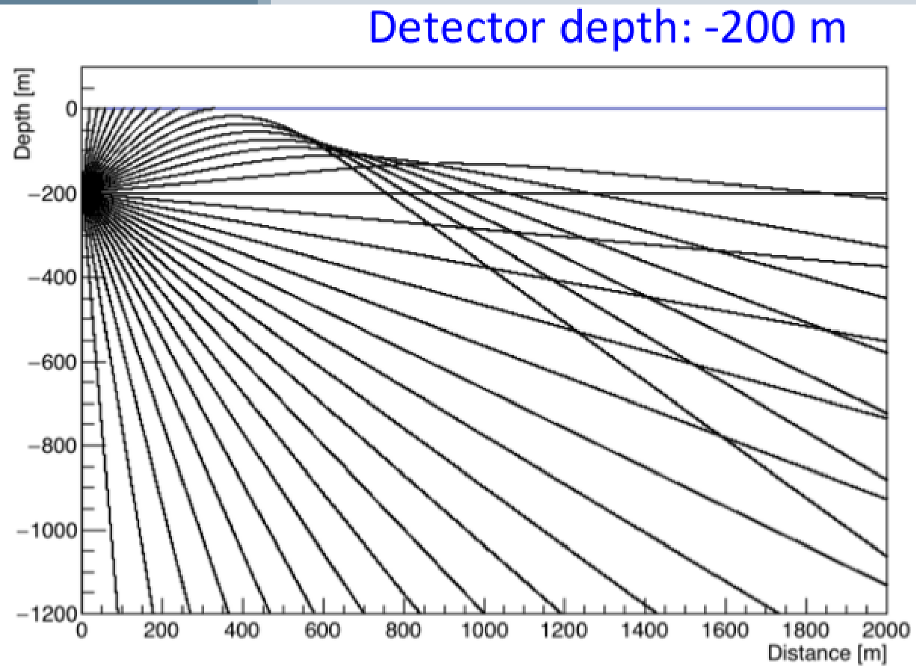


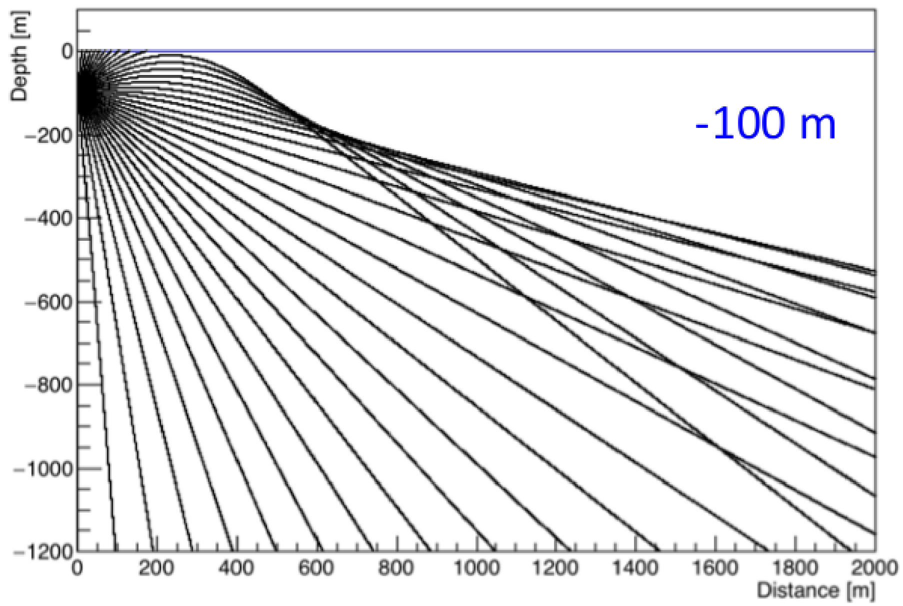
End-to-End measurement : Gain consistence

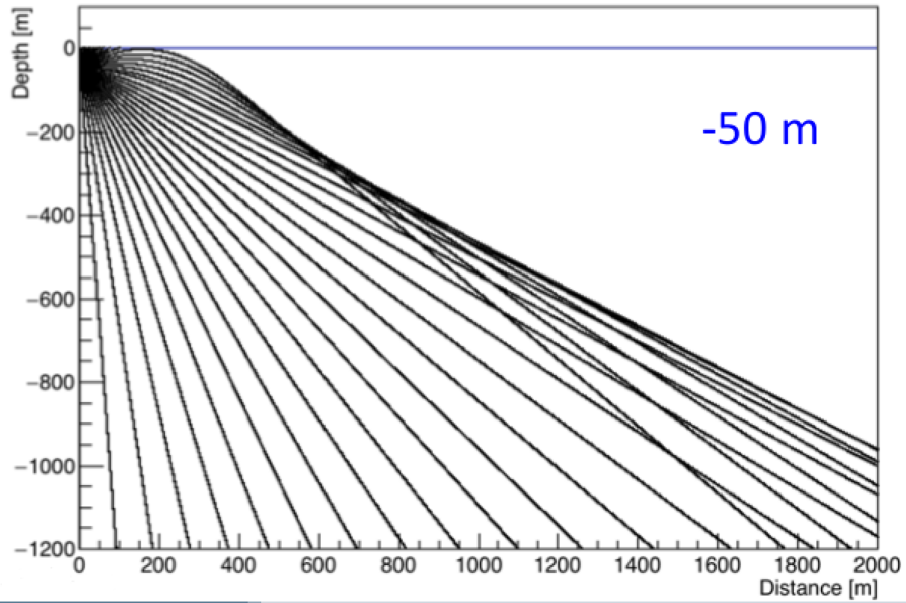




Ray trace



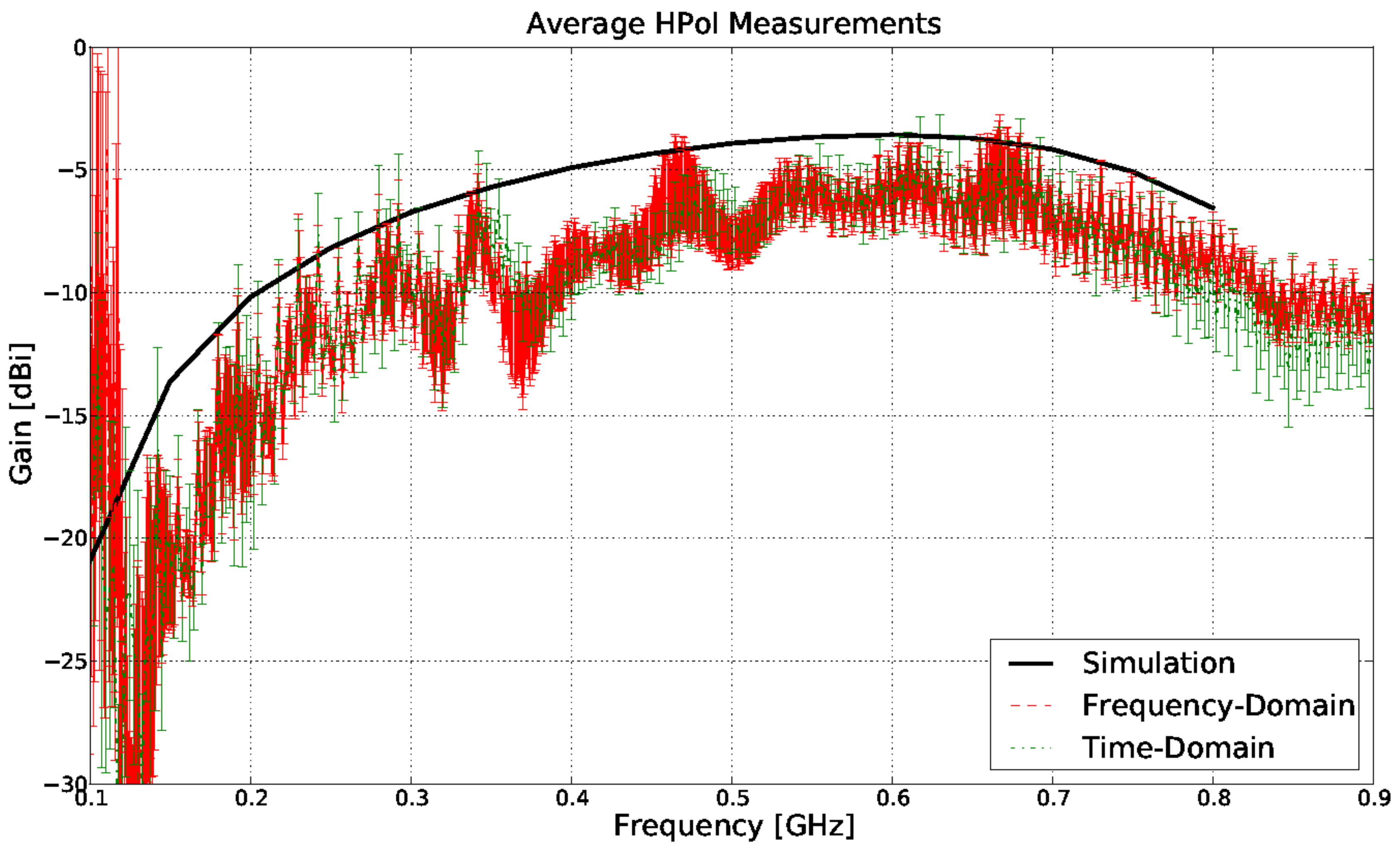




- ◆The area is factor 2 less compared to the current design
- ◆Almost recovered with 100 m depth

Results of Slim Antennas measurement (Hpol)

- Details are explained by **Simon** in poster session.
- Those antennas are in transit to South Pole.
- We (K.Mase) will go there and take some measurement to confirm the feasibility of the slim antenna.



- Gain is systematically below expected value from simulations; this could affect experiment's overall sensitivity.
- Gain is optimal in range from $\sim 200\ MHz$ to $\sim 600\ MHz$ to match expected Askaryan signal.