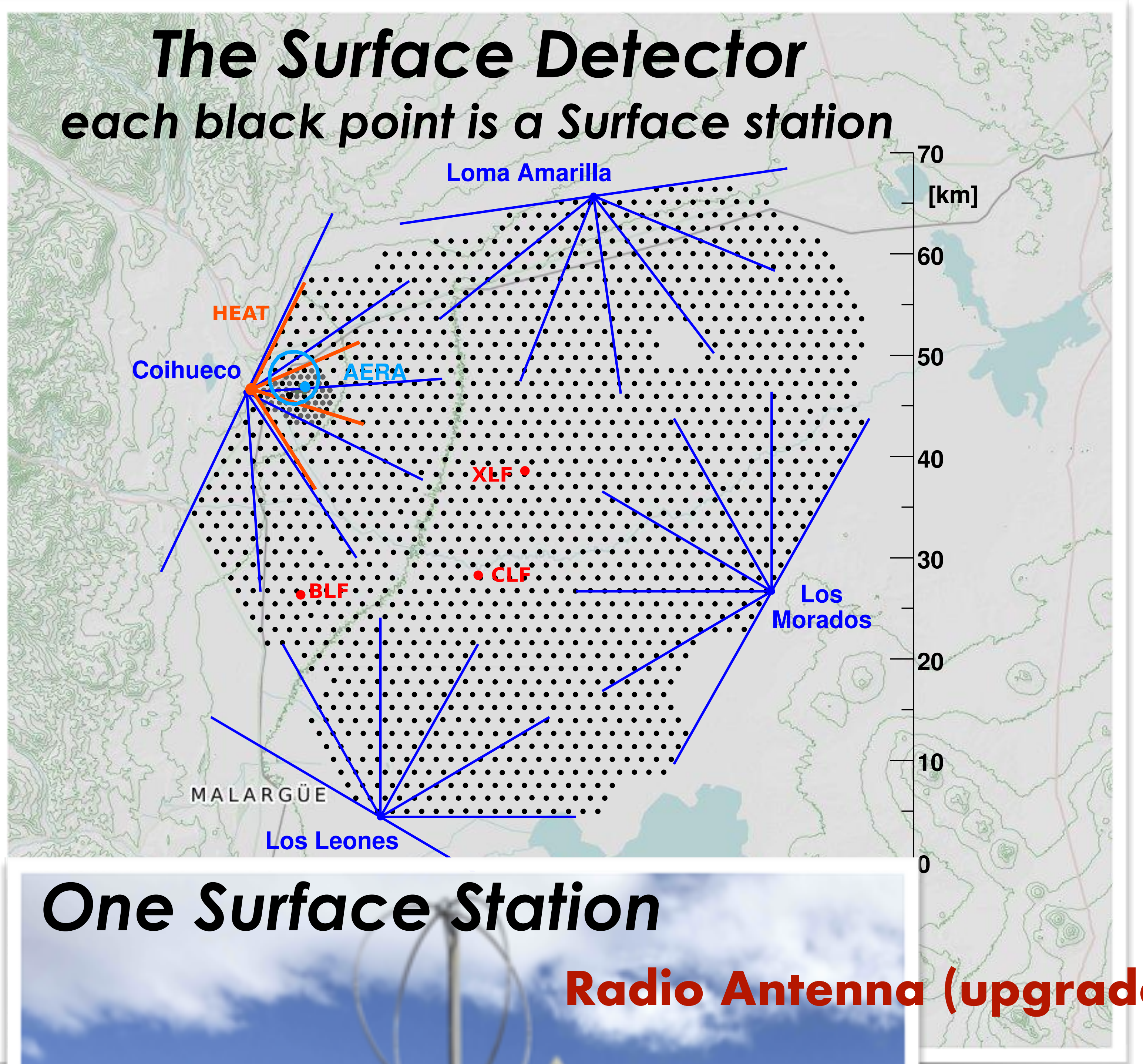
# Simulations of antenna response for the Radio Detector of the Pierre Auger Observatory

Ugo Giaccari, on behalf the Pierre Auger Collaboration

IMAPP, Radboud University Nijmegen, Nijmegen, The Netherlands

# The Radio Detector of the Pierre Auger Observatory





## AUGER UPGRADE PROGRAM

***"AugerPrime"***

*arXiv:1604.03637*

see Julian Rautenberg's talk

### Planned Upgrades

- Surface Scintillators (Surface Scintillator Detector) and **Radio Antennas (Radio Detector) above the existing Water-Cherenkov-Detectors (WCD)**
- New electronics for faster sampling of both WCD and SSD signals (better timing accuracy, increased dynamic range)
- Underground Muon Detectors n the SD area of 25 km$^2$ ("infill area")
- Extend Fluorescence Detector duty cycle from ≈ 15% to ≈ 20%

### Motivations

- **Investigate nature of UHECRs (mass composition) in the suppression region**
- Reach the sensitivity to detect a small contribution (~10%) of protons in the suppression region (CR astronomy)
- Study hadronic interactions at center-of-mass energies above 100 TeV

### Radio Detector

- Short aperiodic loaded loop antenna (SALLA) sensitive in two polarisation directions
- Bandwidth 30-80 MHz
- atop each of the 1661 WCD over the full area of 3,000 km2

***World's largest radio array for the detection of cosmic particles***

# The Vector Effective Length of an antenna

Vector Effective Length (VEL) H(ω): ratio of the voltage V(ω) developed at the terminal to the value of an incoming field E(ω)

$$V(\omega) = \overrightarrow{H}(\omega) * \overrightarrow{E}(\omega)$$

Far field conditions (use spherical coordinates) → VEL depends on frequency (ω), theta (ϑ) and azimuth ($\varphi$)

$$\overrightarrow{H} = \overrightarrow{H}(\omega, \theta, \phi) = \hat{e}_\theta\ H_\theta(\omega, \theta, \phi) + \hat{e}_\phi\ H_\phi(\omega, \theta, \phi)$$

**VEL measurements**


**VEL simulations with antenna modelling software**

**In this contribution description of the method used to simulate the antenna response with 4NEC2 program**

**NEC (Numerical Electromagnetics Code) is a popular antenna modelling system for wire and surface antennas and simulates the electromagnetic response of antennas and metal structures.**

A few NEC softwares (all cost-free resources)

- **4nec2** A NEC2/NEC4 implementation available for Windows. This tool has many options
- **cocoaNEC** Available for MACOSX, includes NEC2 and supports NEC4. This tool has limited options
- **nec2++** an extensive rewrite of NEC-2 in C++

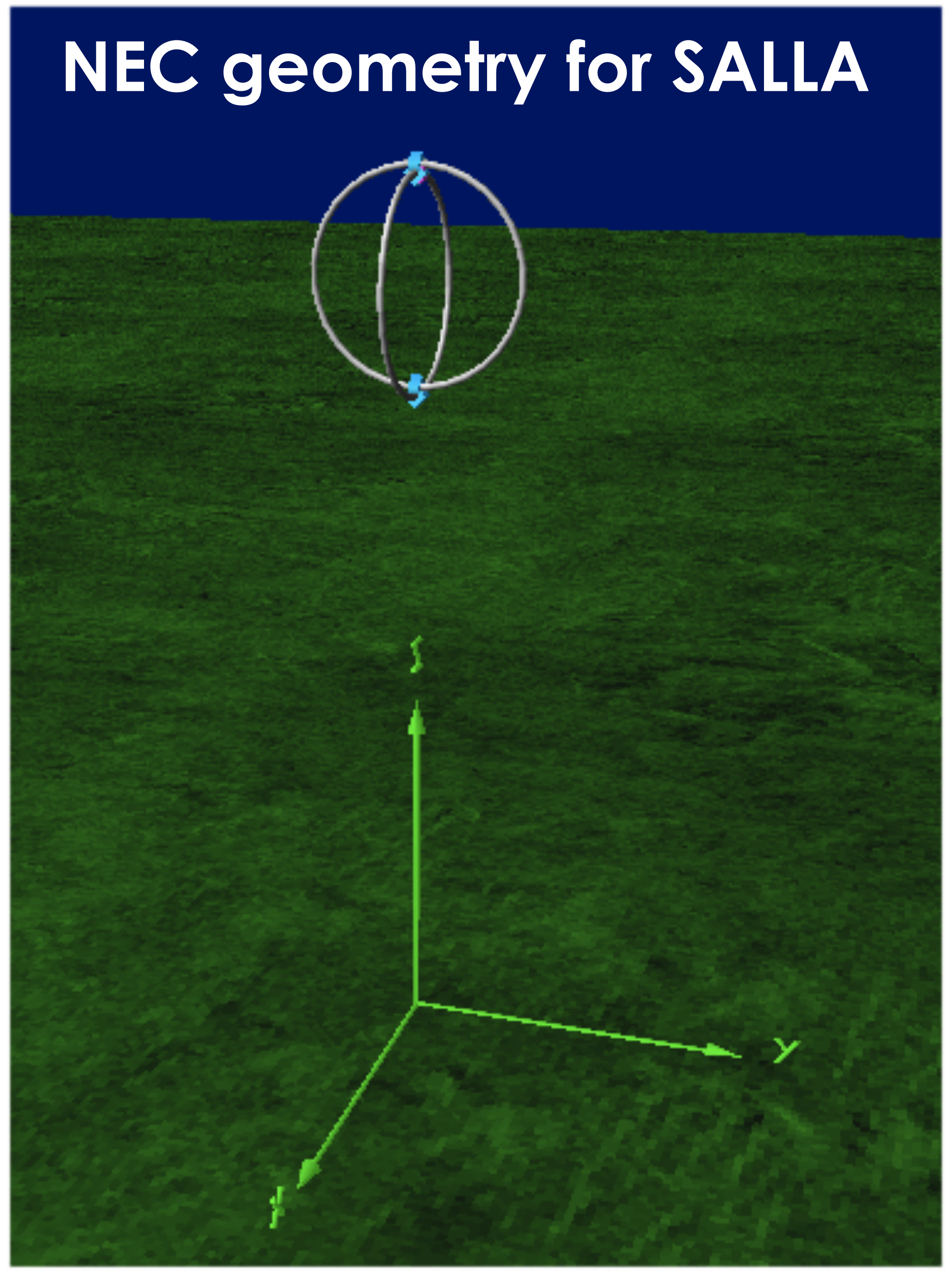
# Short Aperiodic Loaded Loop Antenna (SALLA)


**Resistive terminated loop to get directivity as in a Beverage antenna**

- Two polarisation planes: EW, NS. Bandwidth 30-80 MHz
- Dipole loop of 1.2 m diameter with a tube radius = 1 cm
- On each loop bottom termination resistor 390 Ω in series with 240 nH inductor

**Reduce antenna sensitivities towards the ground**

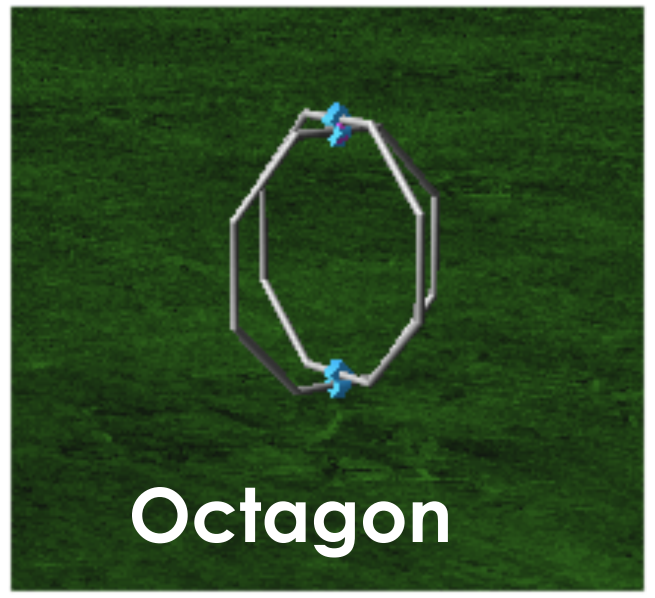
- At the top Low Noise Amplifier (LNA) 450 Ω in series with 200 nH inductor

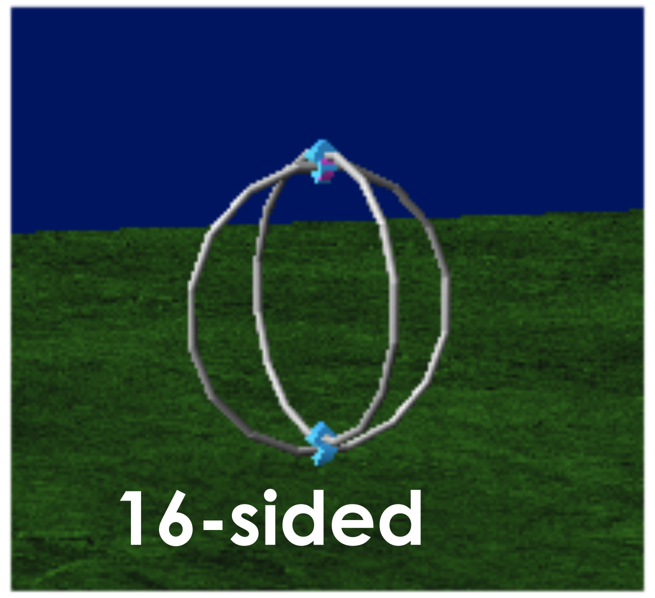


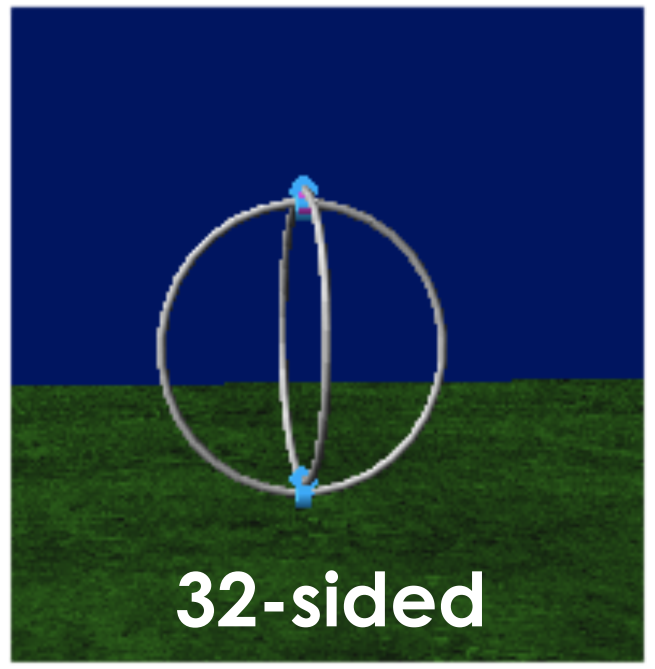

**NEC model for the SALLA**

- **32-sided polygon** each segment ≈ 40 cm to fulfil NEC requirements (segment length ~ 0.1 $\lambda$)
- Use EK option for dealing with small segments
- Top of antenna at 5m above ground
- Voltage source at the terminal of SALLA and input impedance LNA on the other loop (swap voltage source and load for the second loop)
- Ground parameters same as in AERA: $\epsilon = 5.5 \quad \sigma = 0.0014 \ S/m$
- **Real ground (aka Sommerfeld-Norton)** → **highest accuracy**

# SALLA geometry in NEC



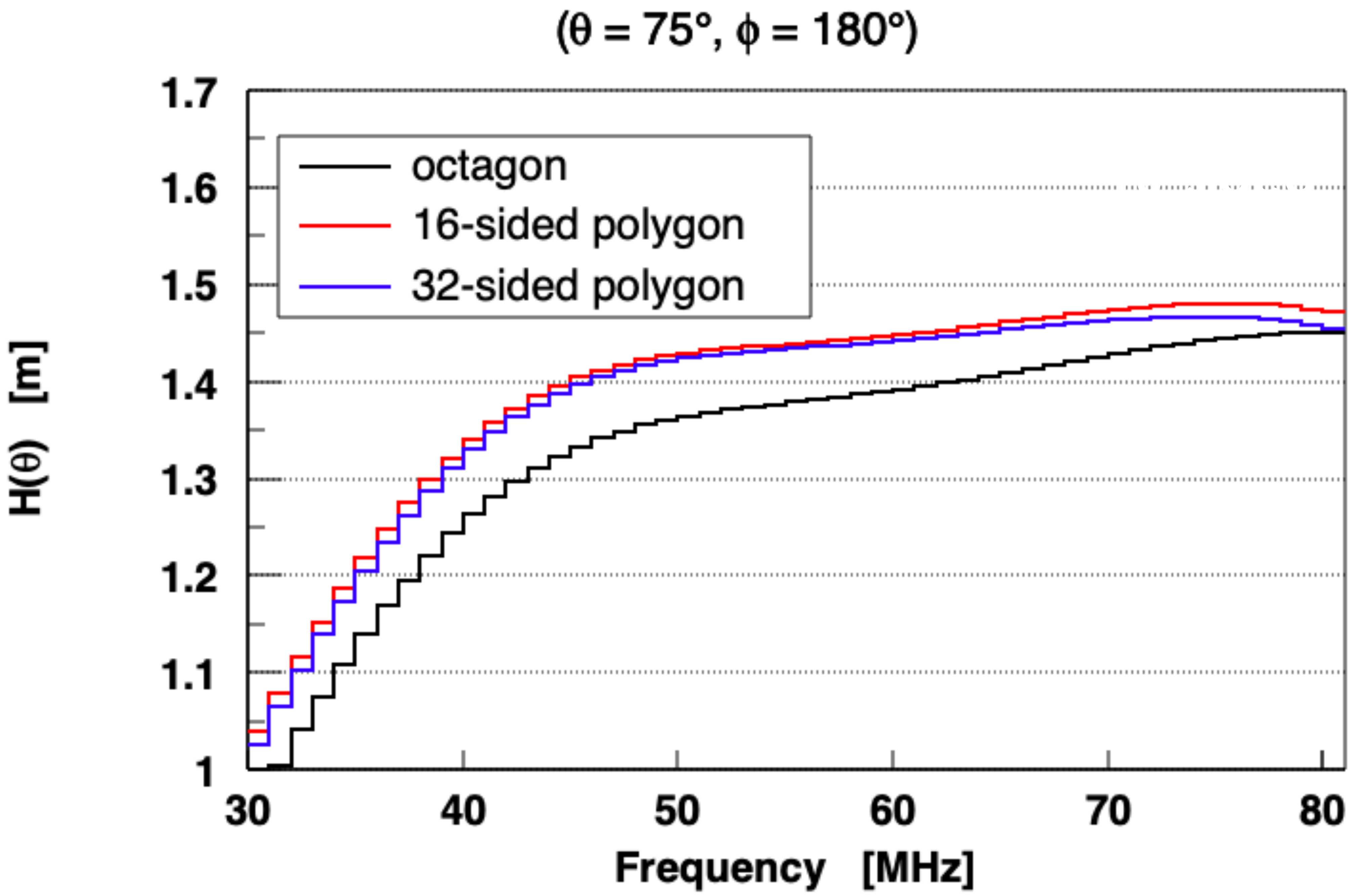



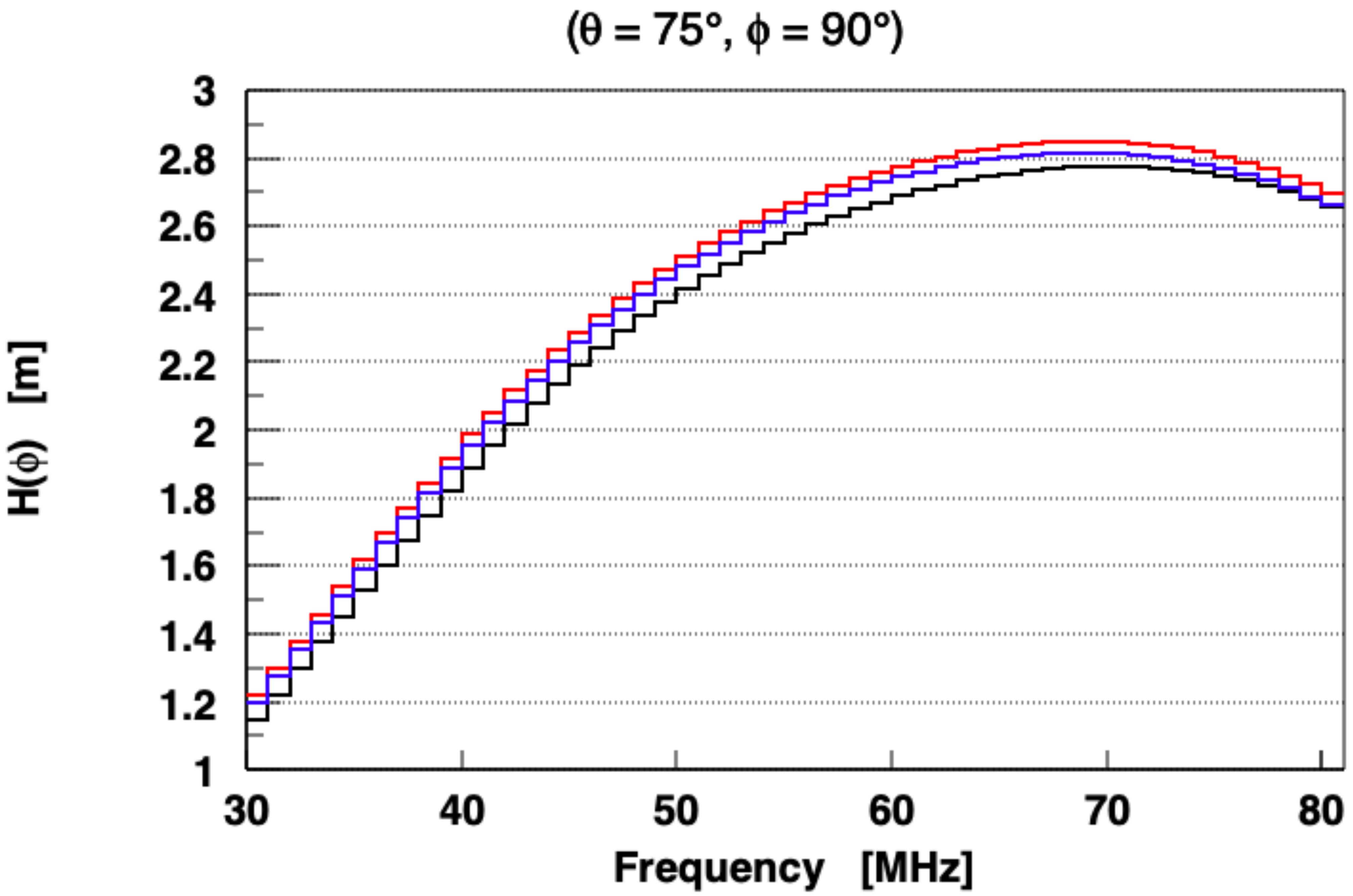




Vector Effective Length (VEL)

$$\vec{H} = \vec{H}(\omega, \theta, \phi) = \hat{e}_\theta H_\theta + \hat{e}_\phi H_\phi$$

**EW loop**



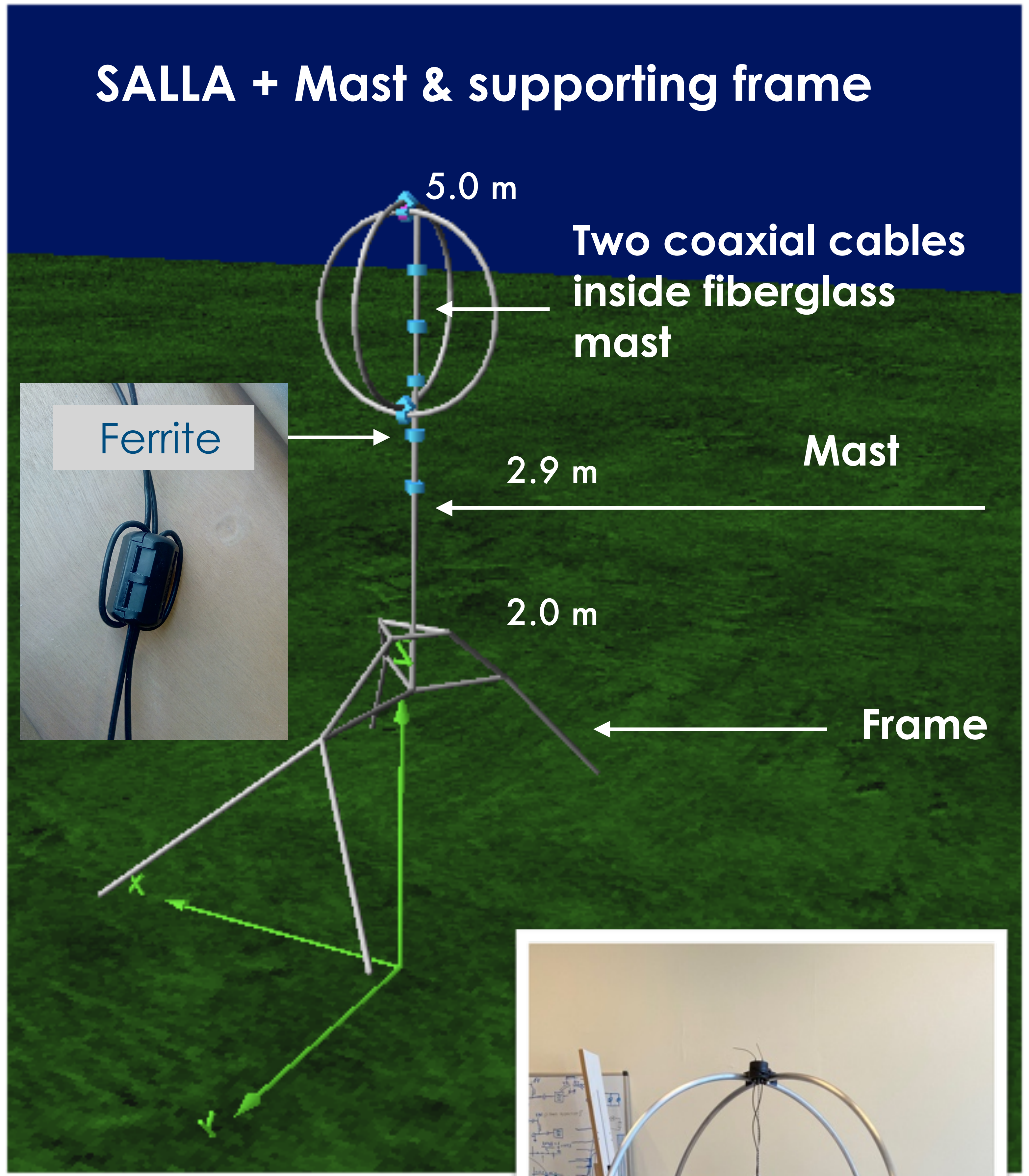

average difference over all directions

**Octagon vs. 32-sided: <5 %**

**16-sided vs. 32 sided: < 1.5%**

→ **32-sided model**

# Mast and supporting frame

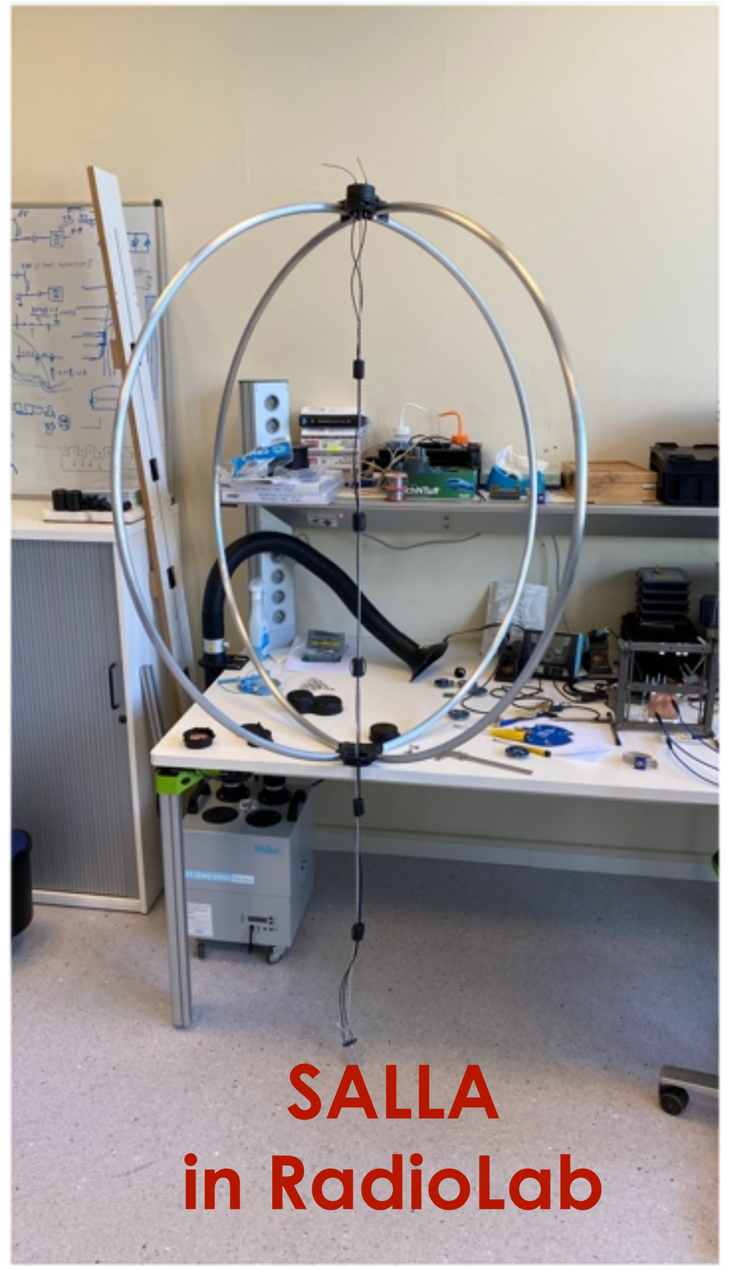



From the LNA signal through **two coaxial cables inside fiberglass mast** to the digitiser. Each cable diameter 0.2 cm (metal shielding part).
**In NEC geometry one conductor with twice the circumference, one cable (wire) with radius 0.2 cm**

**Mast** with radius 1.5 cm (also in NEC geometry model)

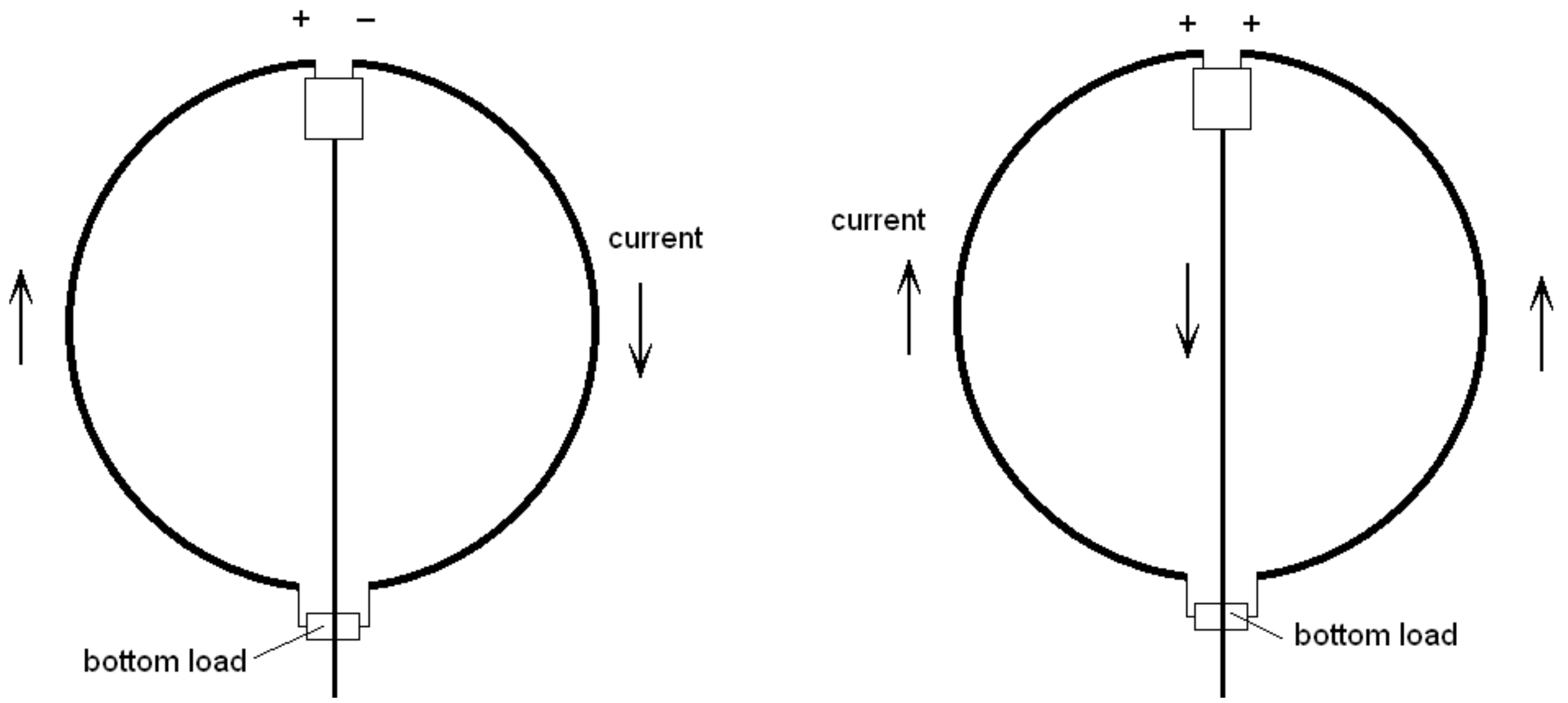
## Mast and cables have to be decoupled from SALLA!

**Without decoupling effect of mast/cables significative**



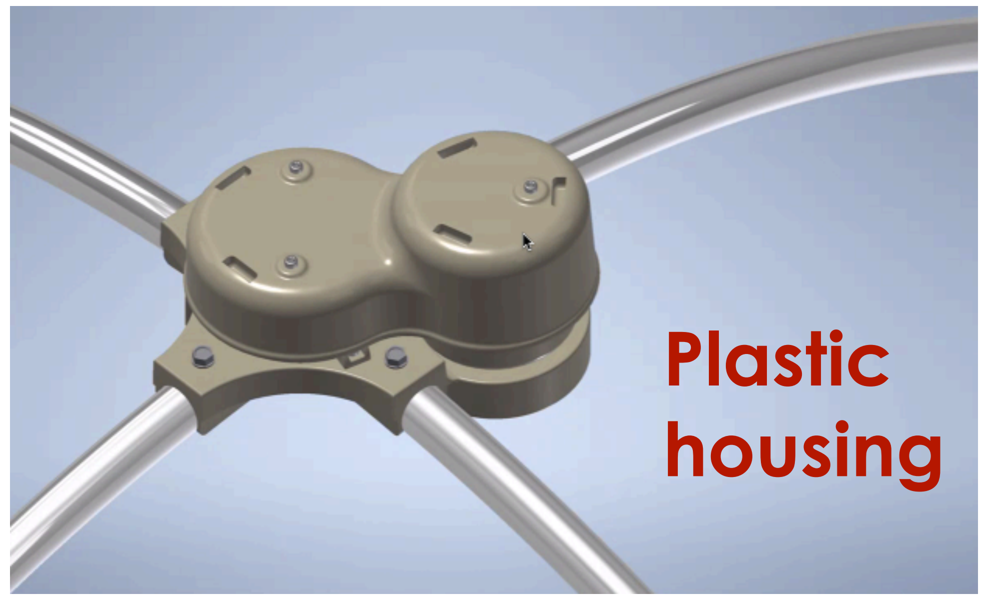

Effect of ferrite cores positions investigated with simulations!

**Coupling of the loops by the cable**




Ferrite cores are in the same positions as in reality!

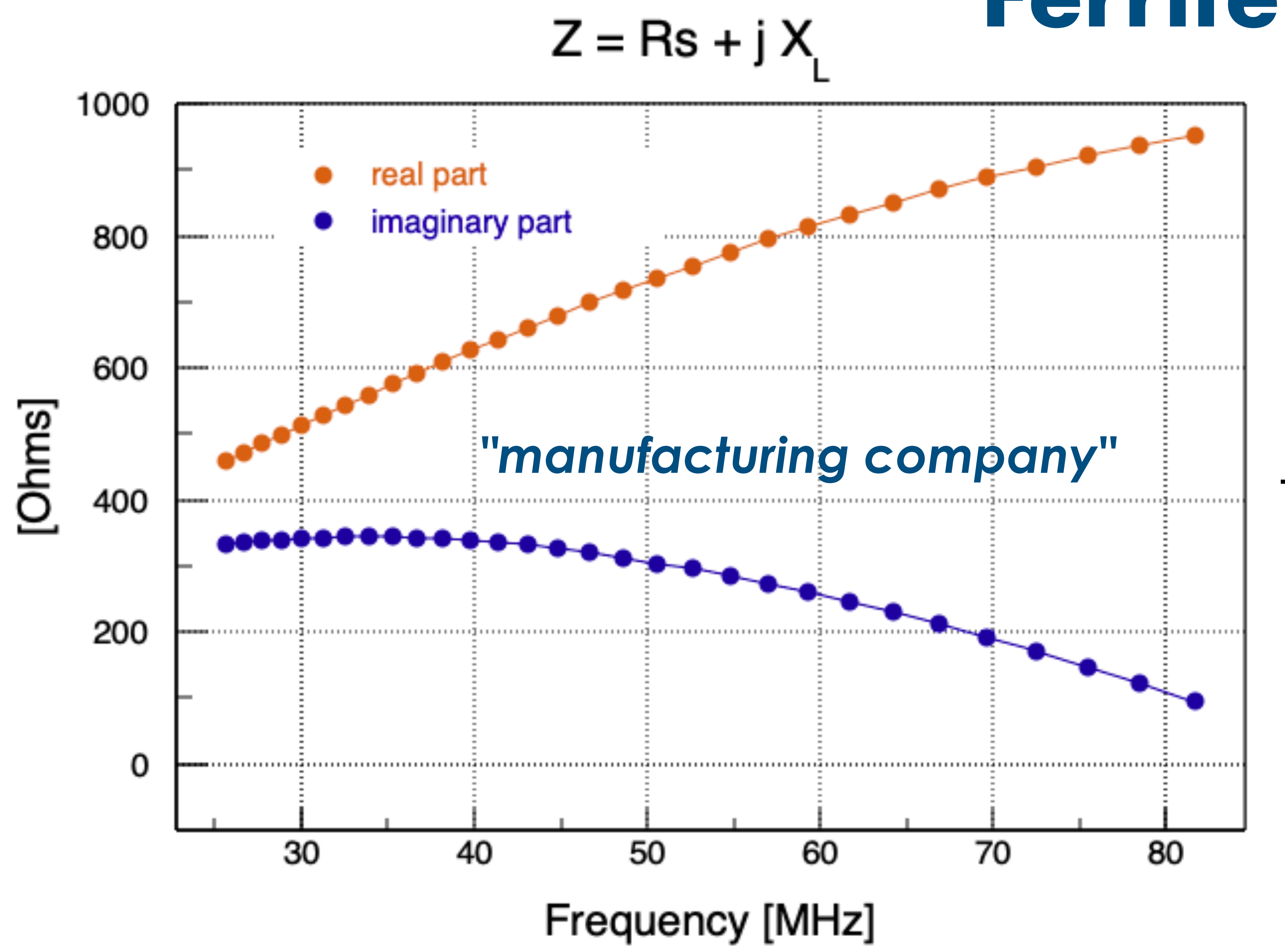
**Cables inside fiberglass mast not in the center**

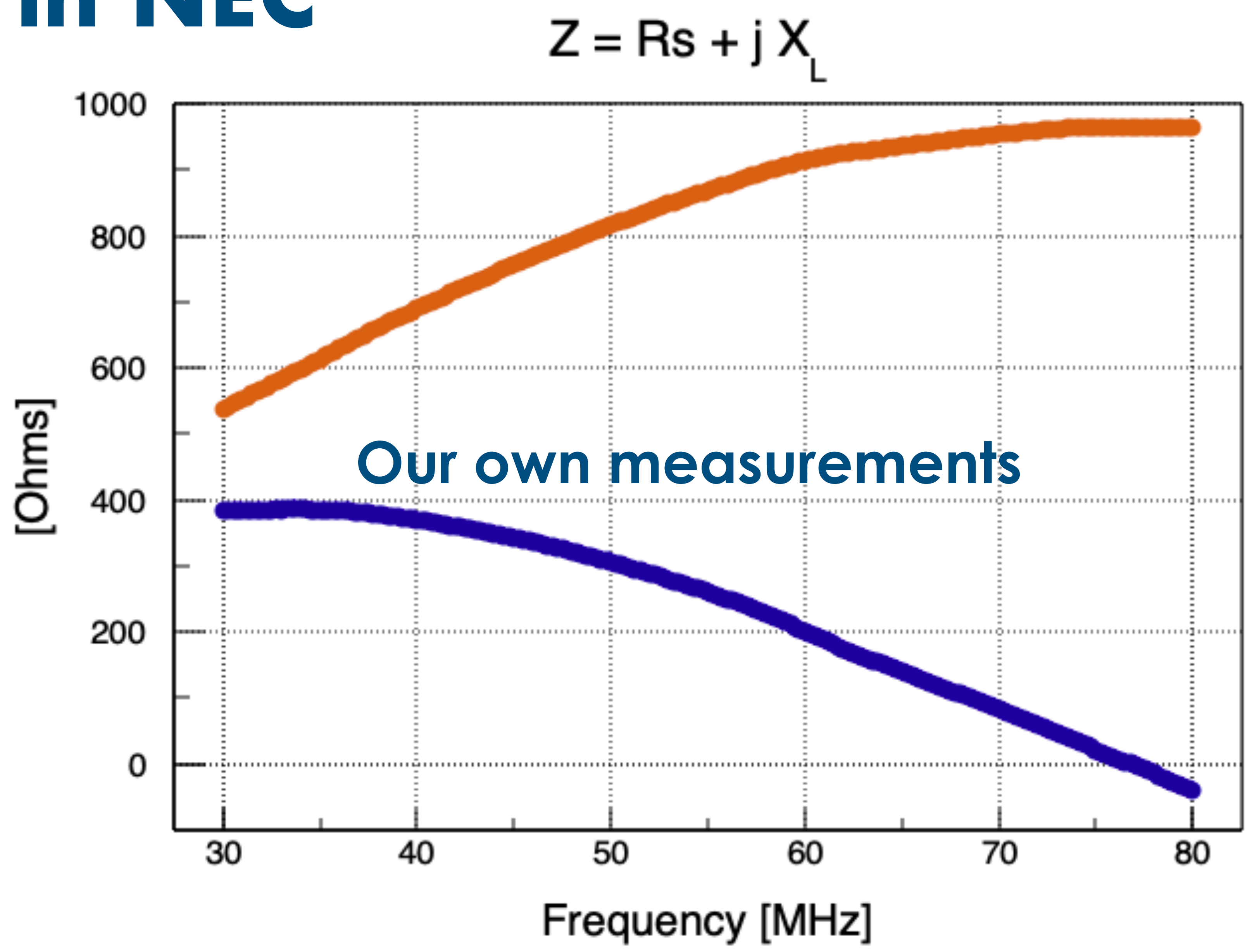



**Decoupling with 5 ferrite cores**

https://www.fair-rite.com/product/round-cable-snap-its-431167281/

# Ferrite cores model in NEC

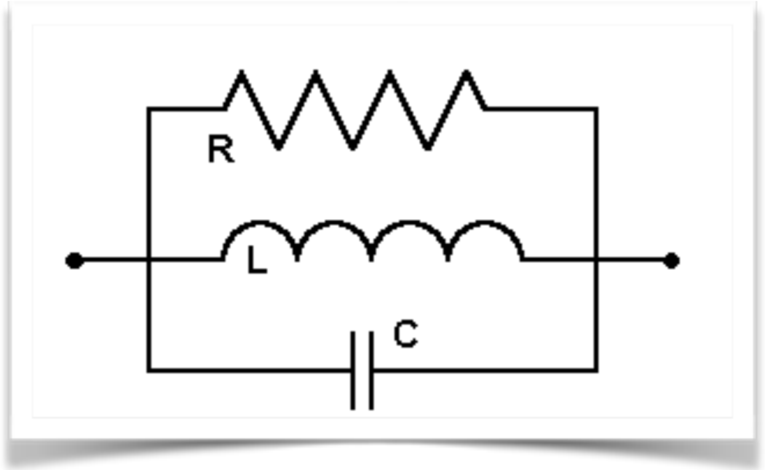



*N(winding) =2*

## *Modelling ferrite cores in NEC*

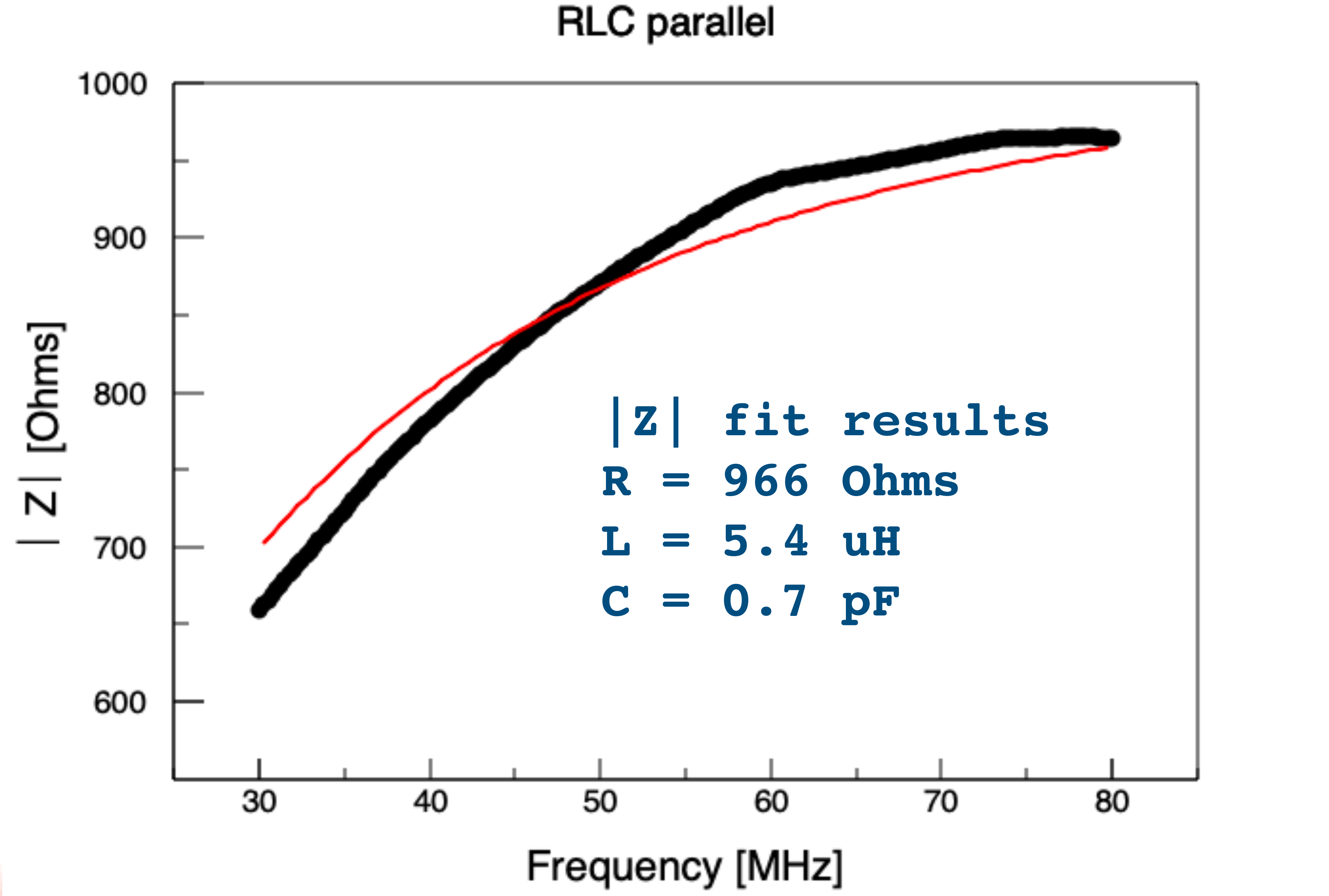
*RLC parallel circuit*




Difficult fit Z with RLC parallel circuit

fit separately |Z| and phase

fit |Z| only

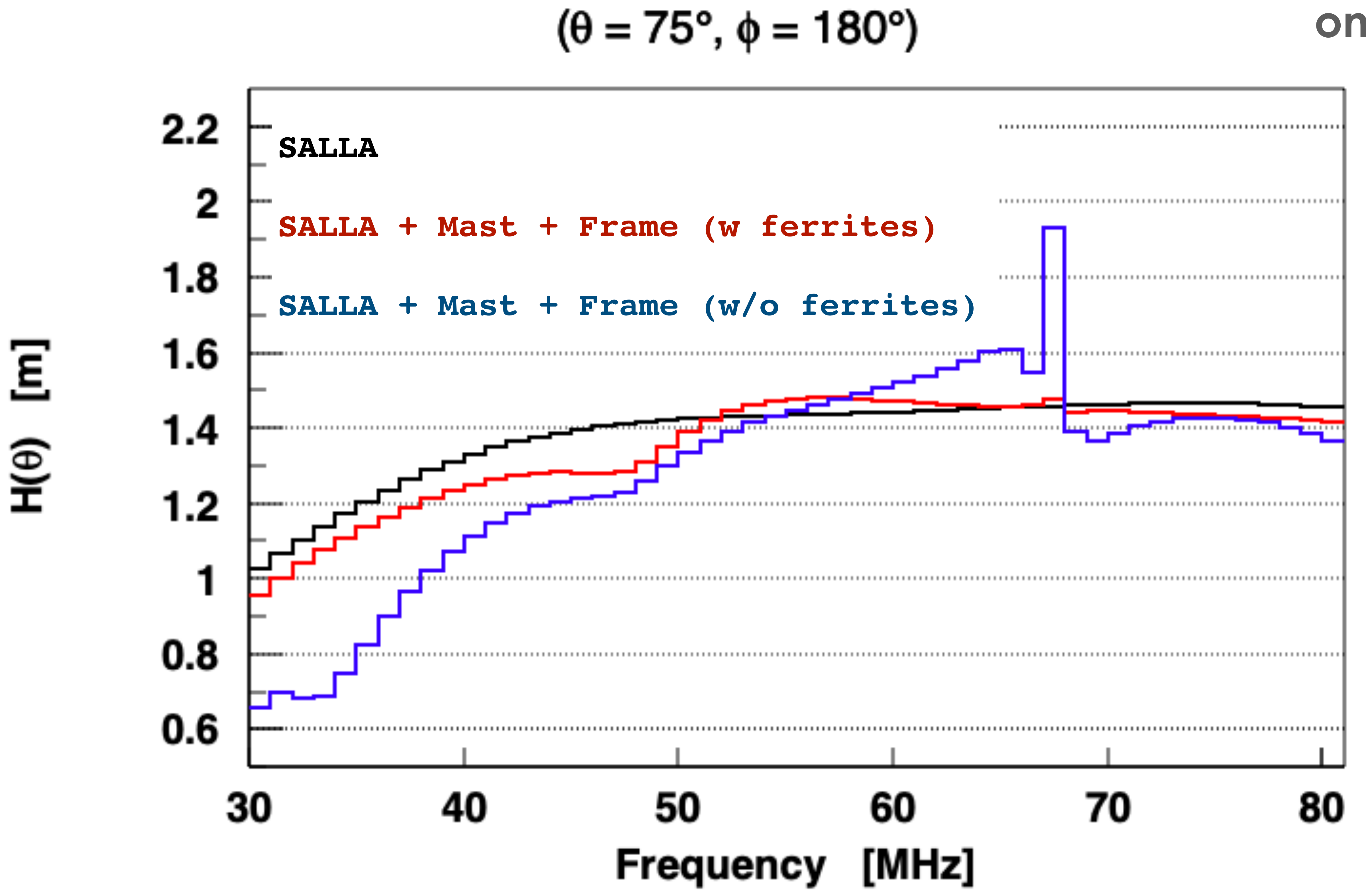


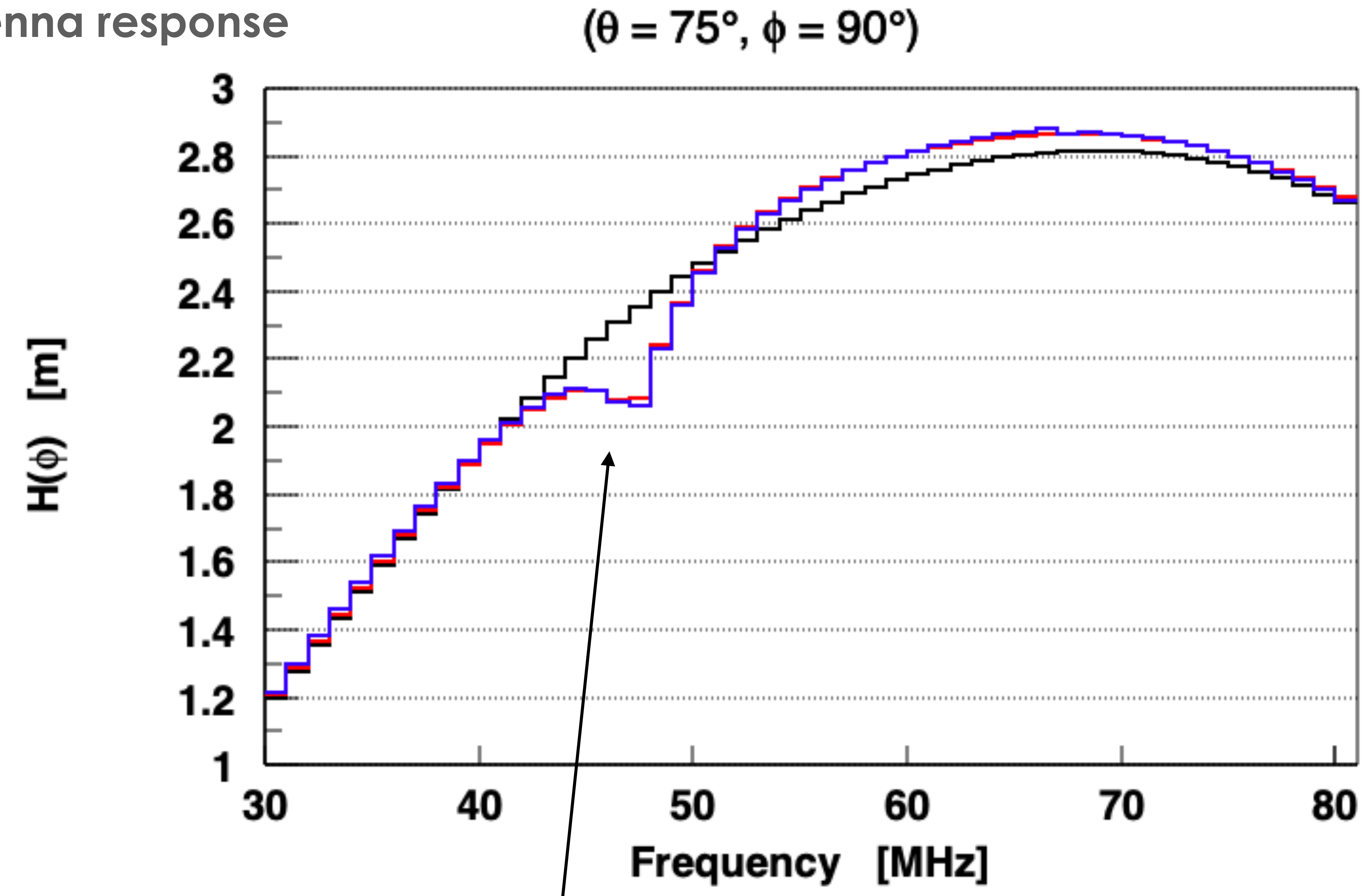
# Mast and supporting frame

EW loop

Effect

on antenna response



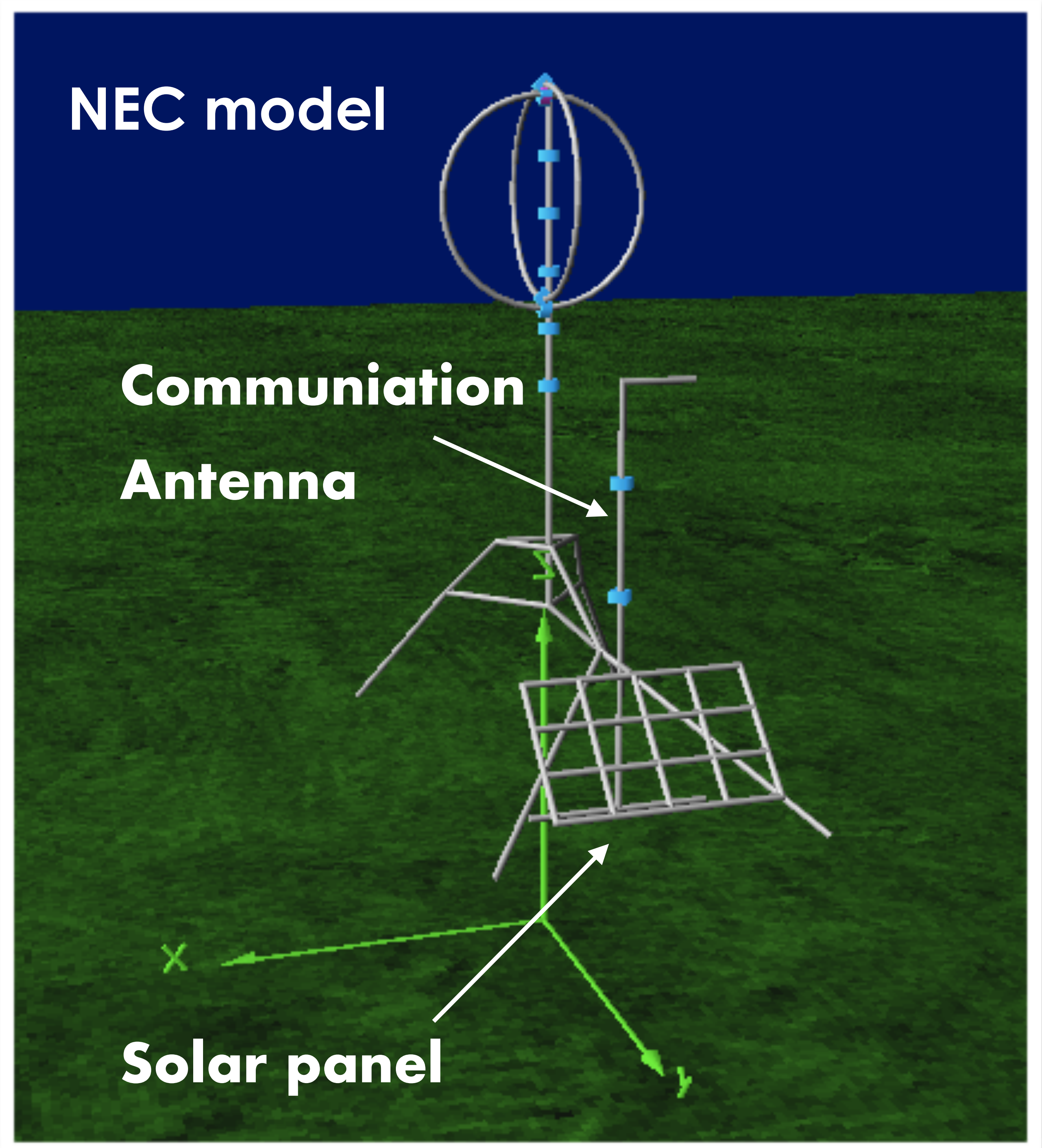




**w/o decoupling the effect on the pattern are in average 60%**
(over all directions)

**with decoupling the effect in within 6%**
(most important effect < 50 MHz)

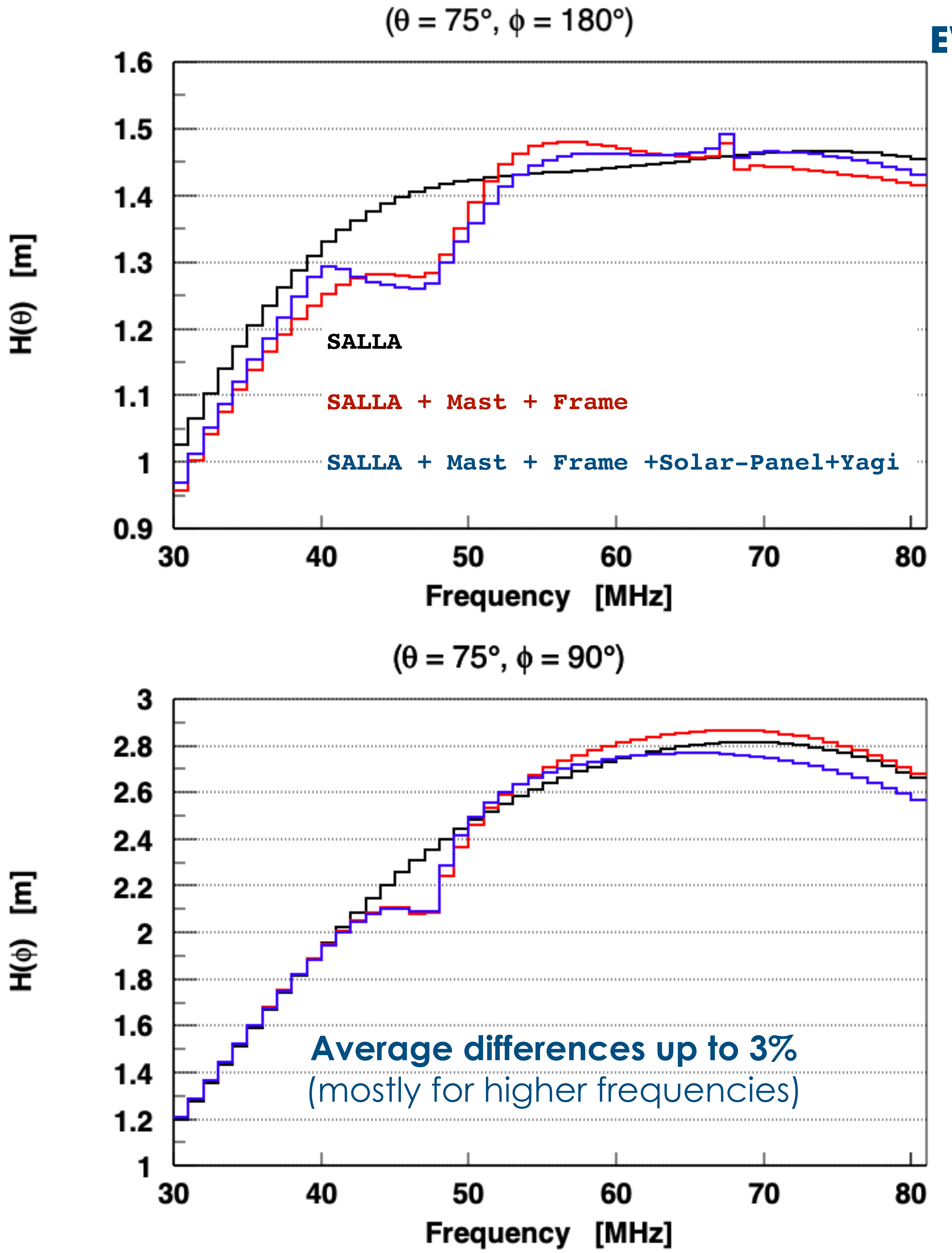
**Mast + frame influence pattern around 47 MHz**
(4-5% in average)

# Solar Panel & Communications antenna



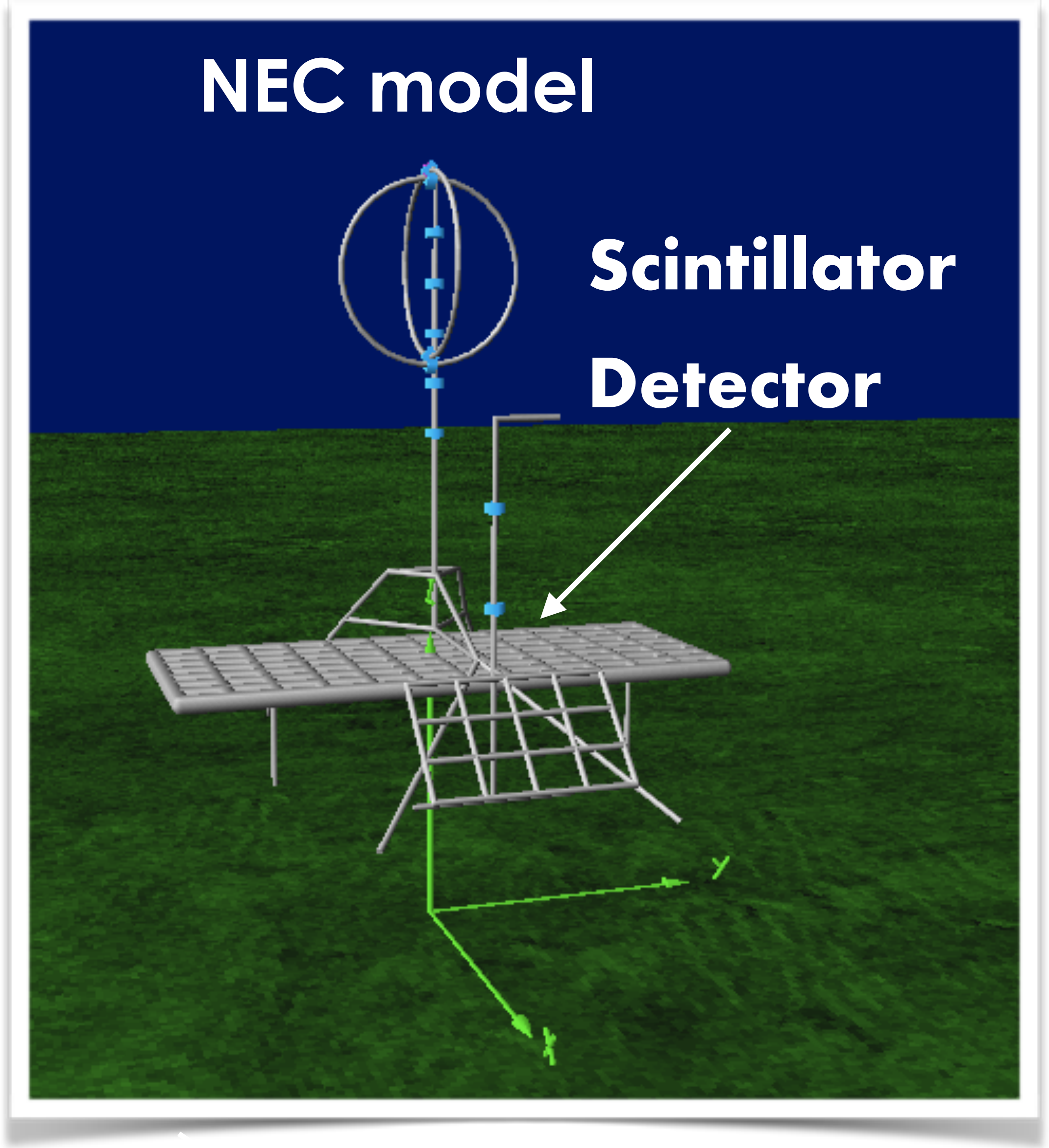

- Solar Panel modelled as a grid with 0.25*0.3 m2 grid size with radius = 15 mm conductors for the grid wire
- Communication antenna - radius = 5 mm
- Communication mast - radius = 15 mm

EW loop




Average differences up to 3%
(mostly for higher frequencies)

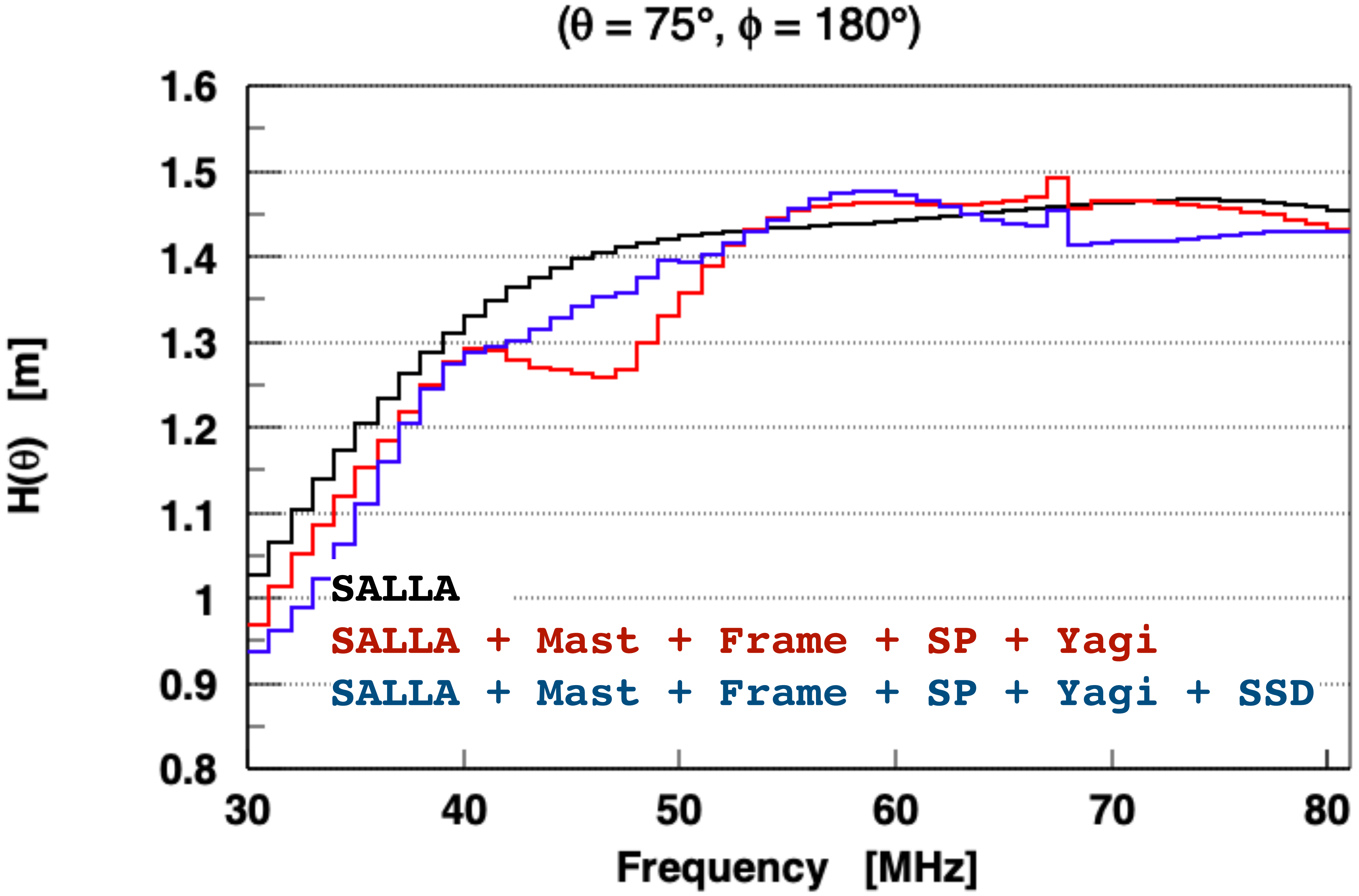
# Scintillator Detector



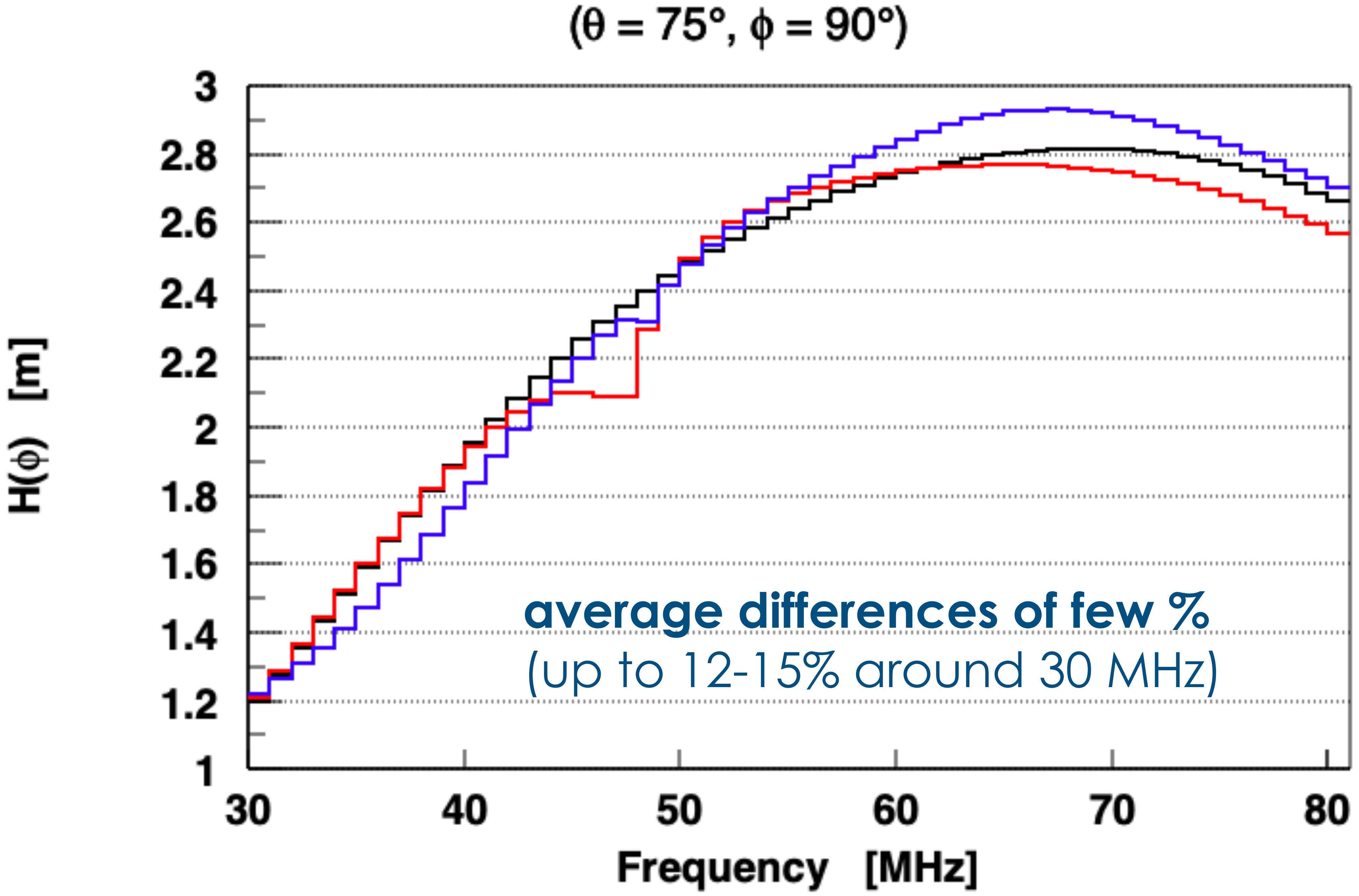

modelled as a grid with 0.2*0.3 m2 grid size

with radius = 60 mm conductors for the grid wires

Thicker diameter used to account for reflections from scintillator detector



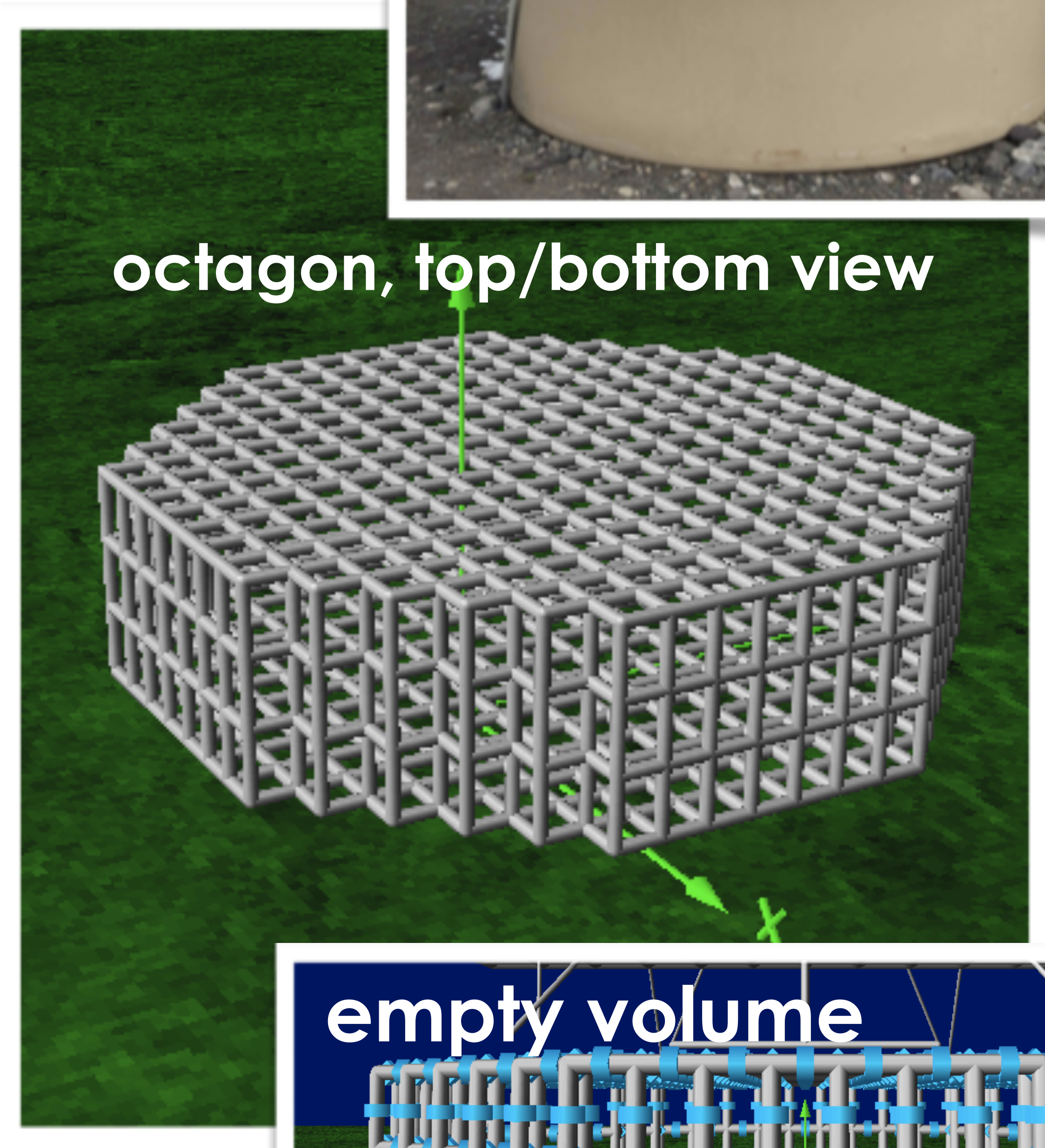

EW loop




average differences of few %

(up to 12-15% around 30 MHz)

# **Water Cherenkov Detector** Surface model




**Nec cannot simulate dielectric volumetric objects**

**Nec model: WCD modelled as an octagon, top/bottom mesh (0.2*0.2 m2) and on the side (0.2*0.3 m2) . Loads constant in the full 30-80 MHz range.**

**Characteristic impedance of pure water** (at 50 MHz) **≈ 42 Ω**

**Reflection coefficient** (for vertical radiation)

$$\Gamma = \frac{Z_0 - Z_L}{Z_0 + Z_L} = \frac{42 - 377}{42 + 377} \approx -0.8$$

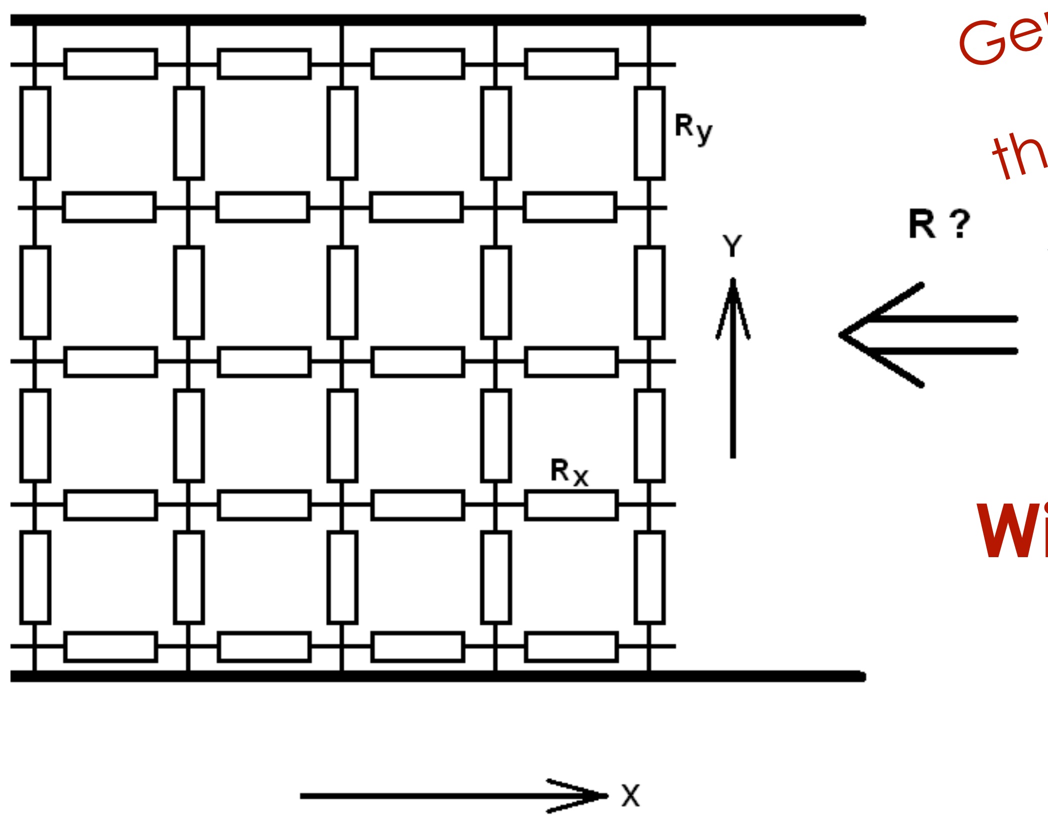
One interface (real situation): air - water.

Two interfaces in the model: air - water, water - air

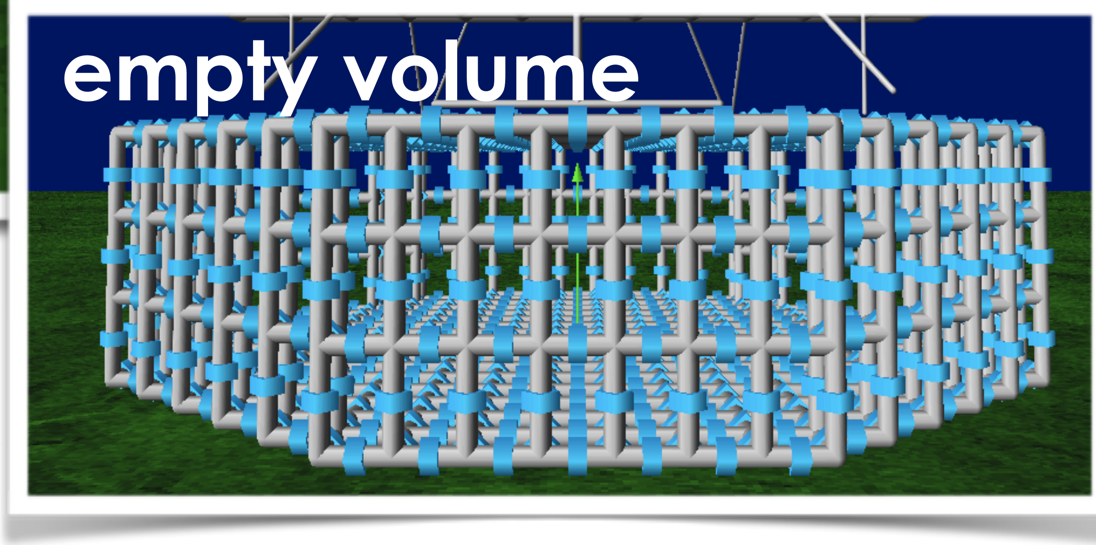
47 Ω in parallel with 377 Ω gives us 42 Ω

**Empty volume with $R_{sq}$ = 47 Ω (square resistance) same reflection coefficient**

Square resistance $R_{sq}$ of a mesh

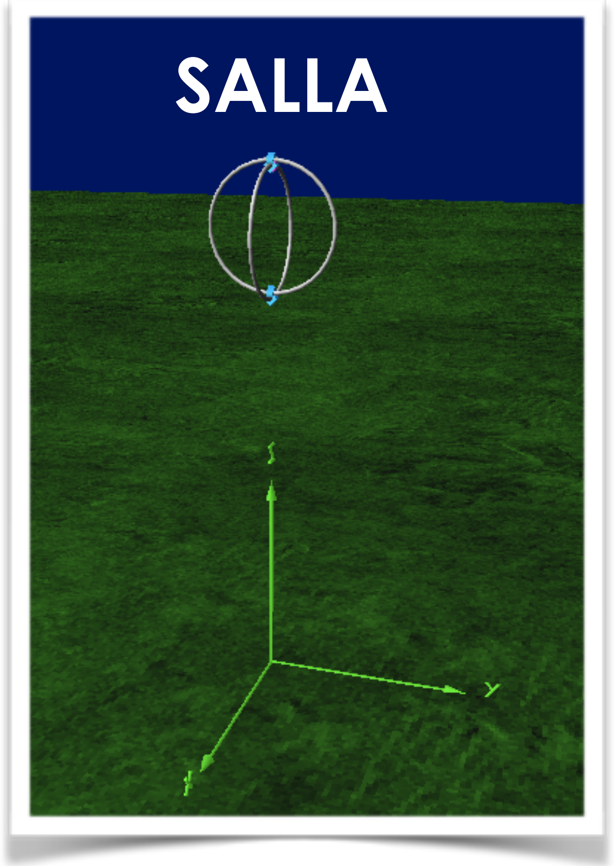


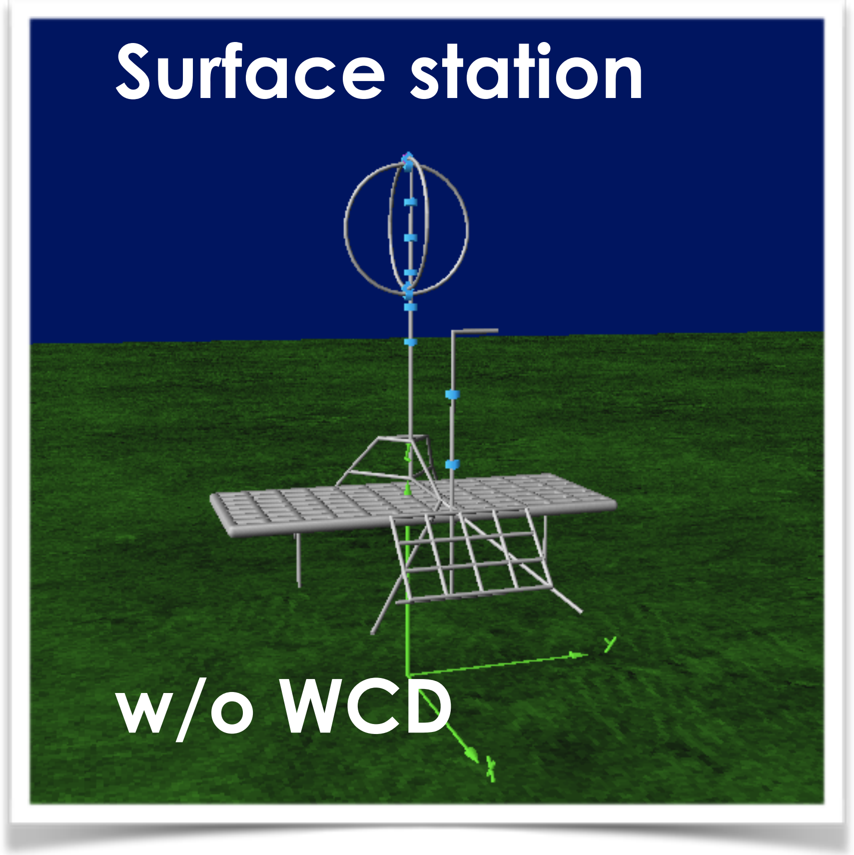

Generalisation for the octagonal model

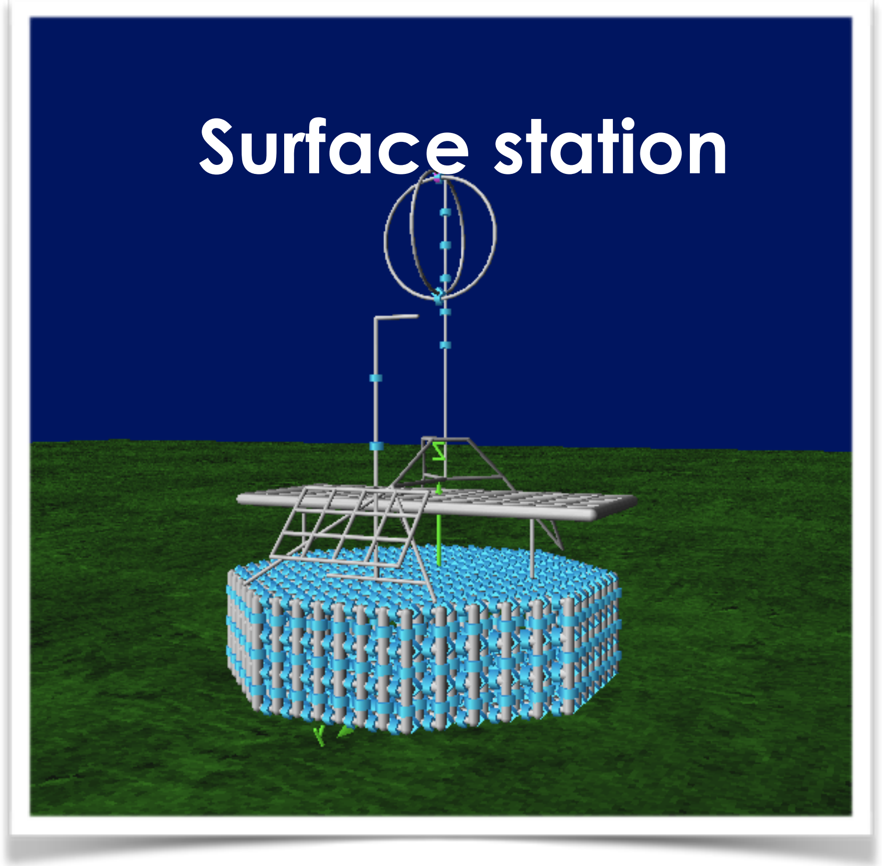


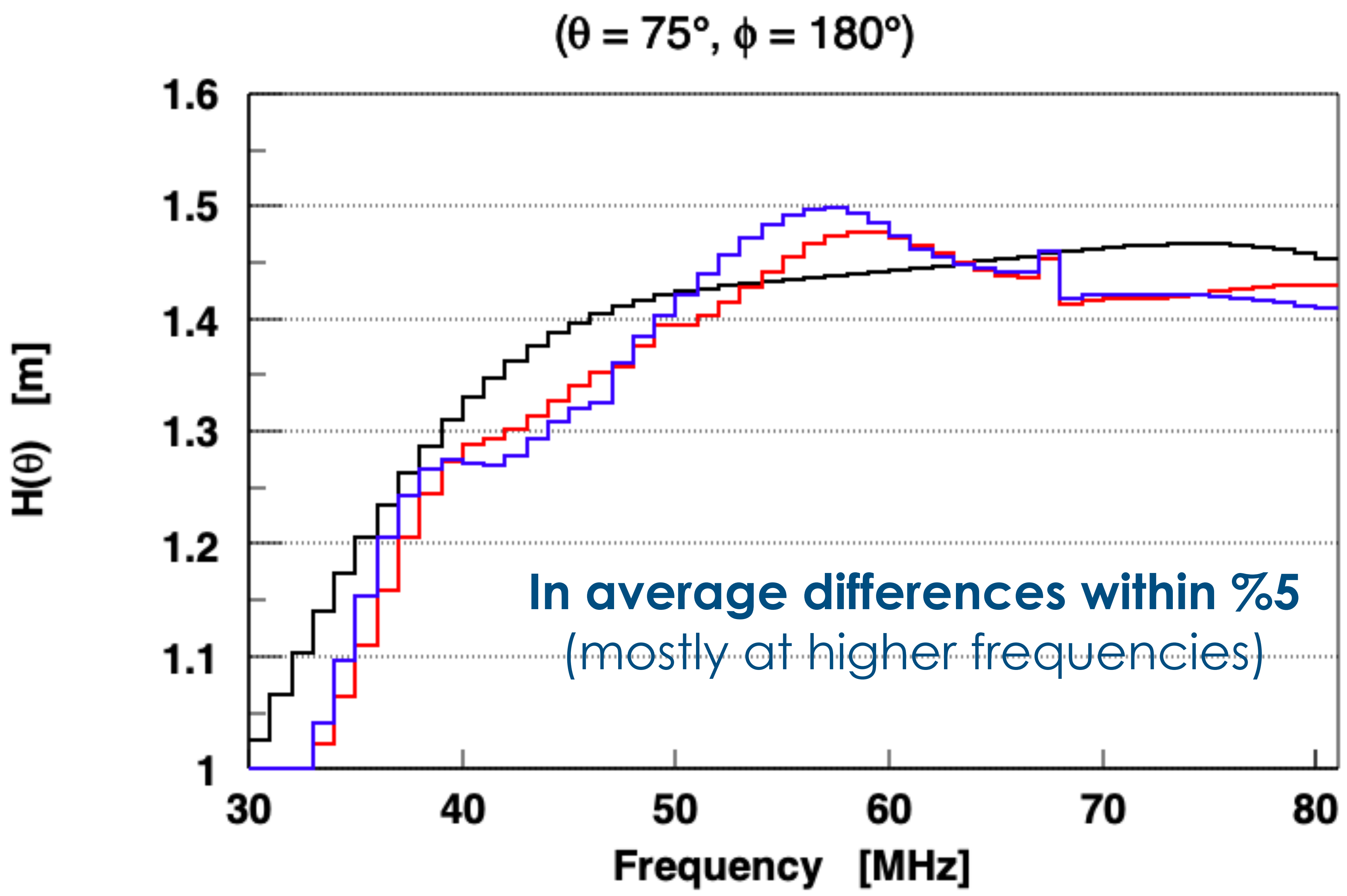

**With the model reflecting of the water properties we run into 4nec2 limitations**
(number of segments and loads)

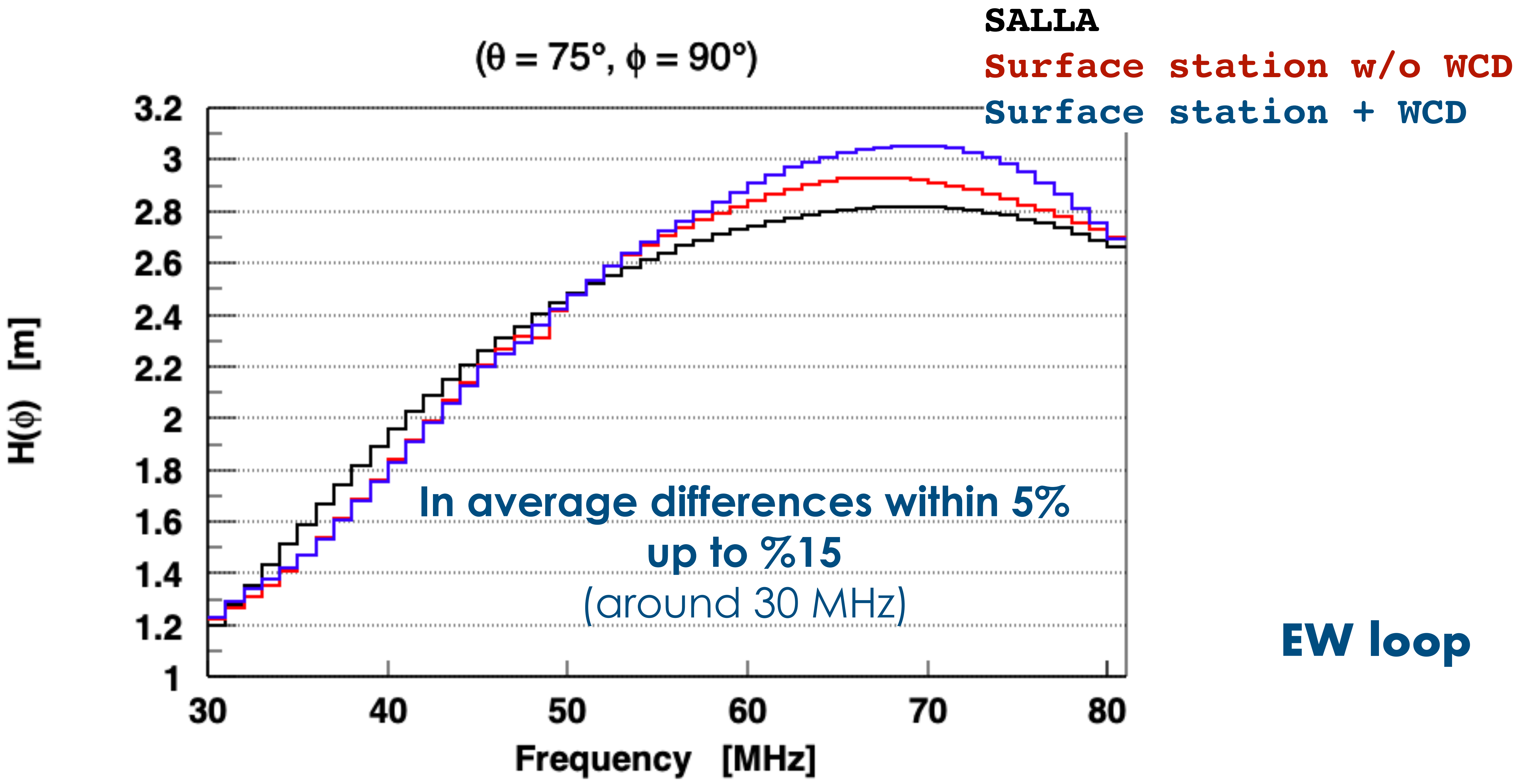
# Water Cherenkov Detector



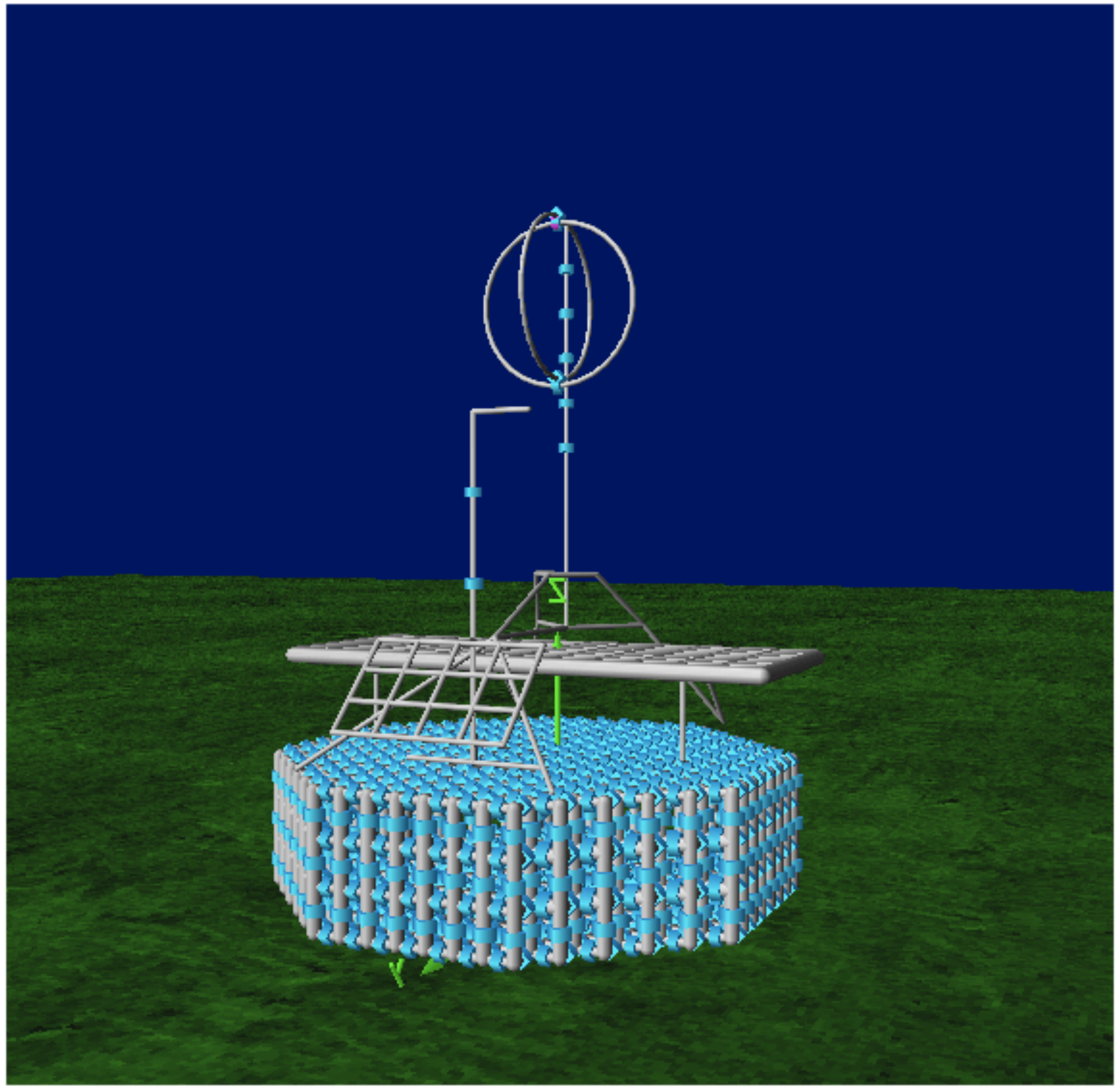




**EW loop**

# 3D Nec model of the Surface Station



**SALLA** modelled as an 32-sided polygon, tube dimeter = 20mm

Decoupling of the mast  and cables well described in the model

**Scintillator Detector** modelled as a grid grid with 0.2*0.3 m2 grid size with diameter = 60 mm conductors for the grid wires.

Thicker diameter to account for reflections

**Yagi antenna** and **solar panel**

Yagi orientation does not affect antenna response

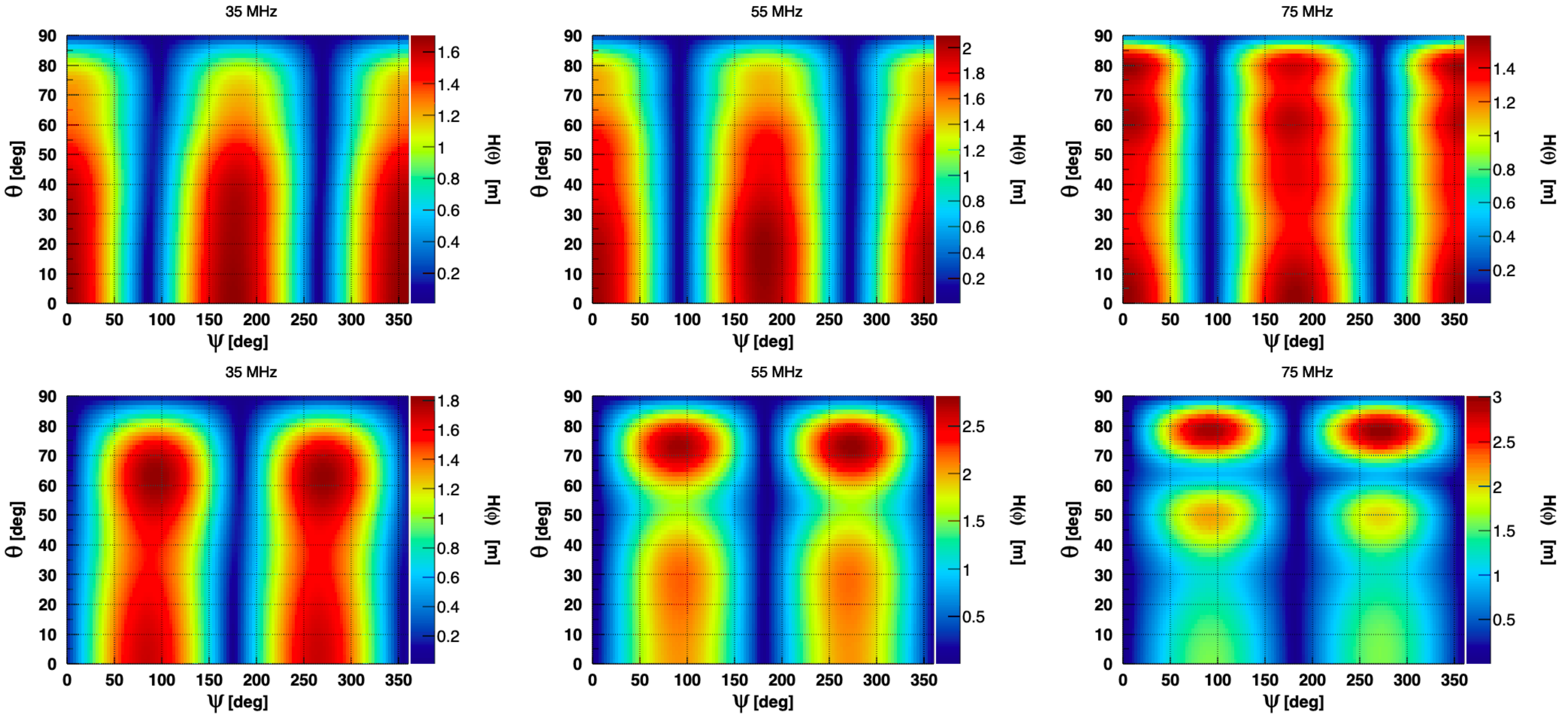
**WCD** modelled as an octagon (approximately 1.4m each side).  Top/bottom square ($20*20$ cm²) and vertical square ($20*30$ cm²) . **WCD** does not touch the ground (not possible with real ground )

WCD take into account reflection properties of pure water
(shape with this model doesn' t influence antenna response)

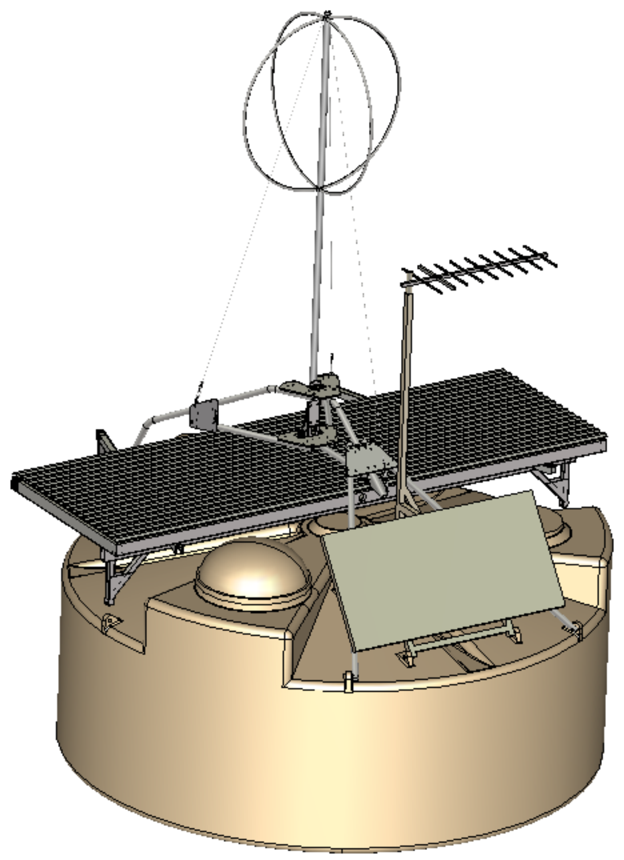
**AGT test is under +/- 0.3 dB for all frequencies** (integrity test for the model)

# Vector equivalent length

**EW loop**

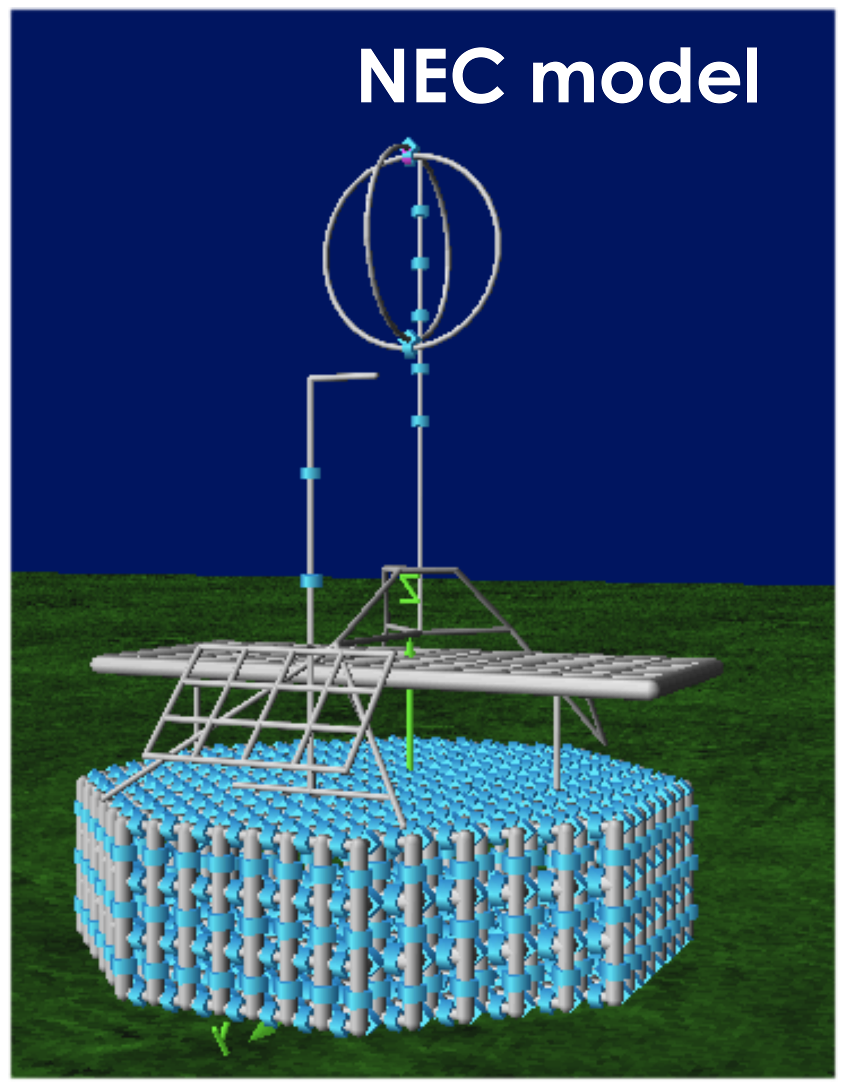


# Conclusions



**We have described a method to compute the vector equivalent length of the SALLA including all the components of the Surface Station of the Pierre Auger Observatory**

- All components of the Surface station have been included in the calculation and their effects studied
- Particular attention to the decoupling of the antenna (most important effect on antenna response)
- Some approximations have been used for some components




**All modelling systems have some limitations**

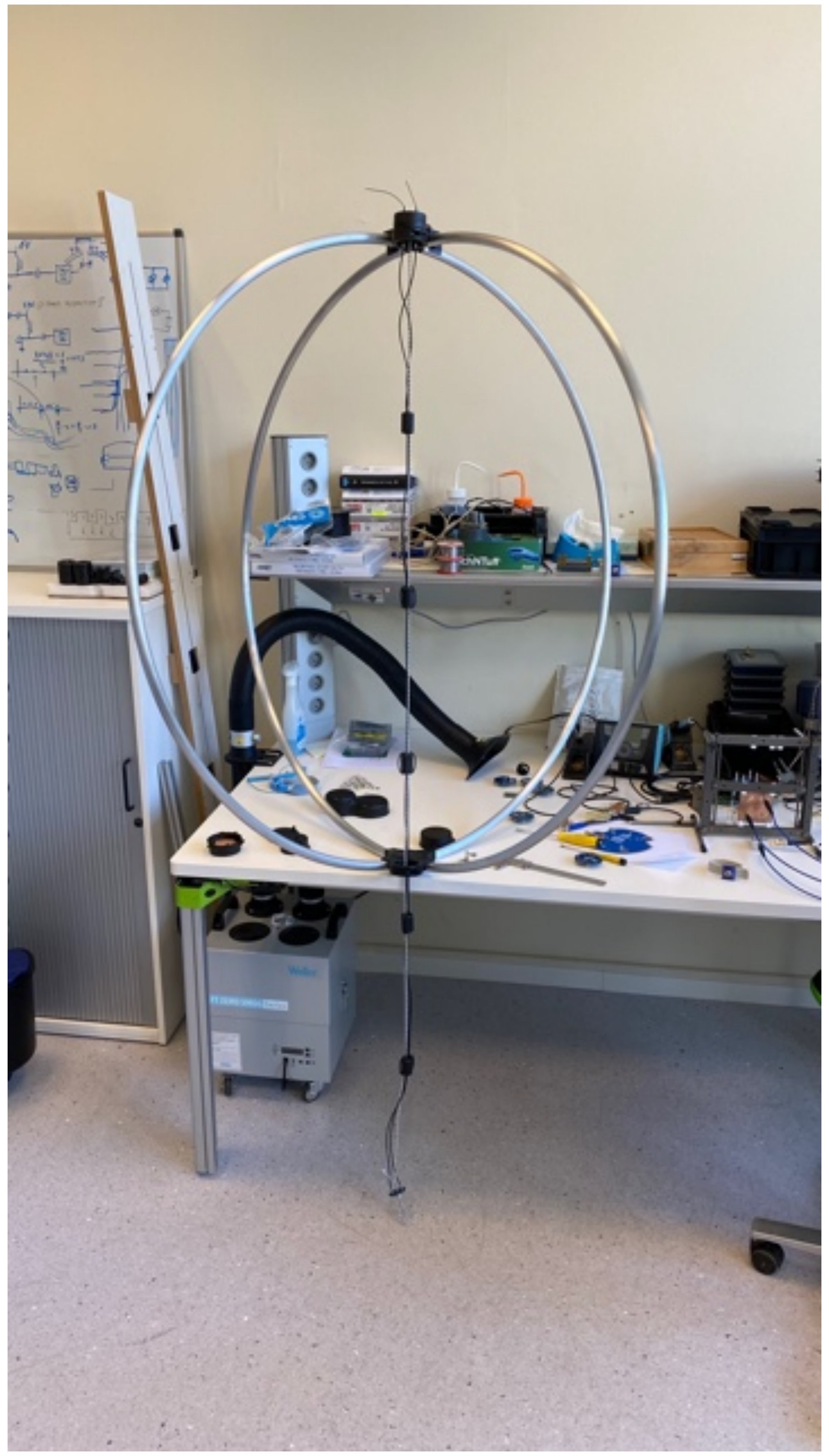
**Planned measurements in Malargüe next November**

**Cross-check of this calculation!**


# BackUp slides

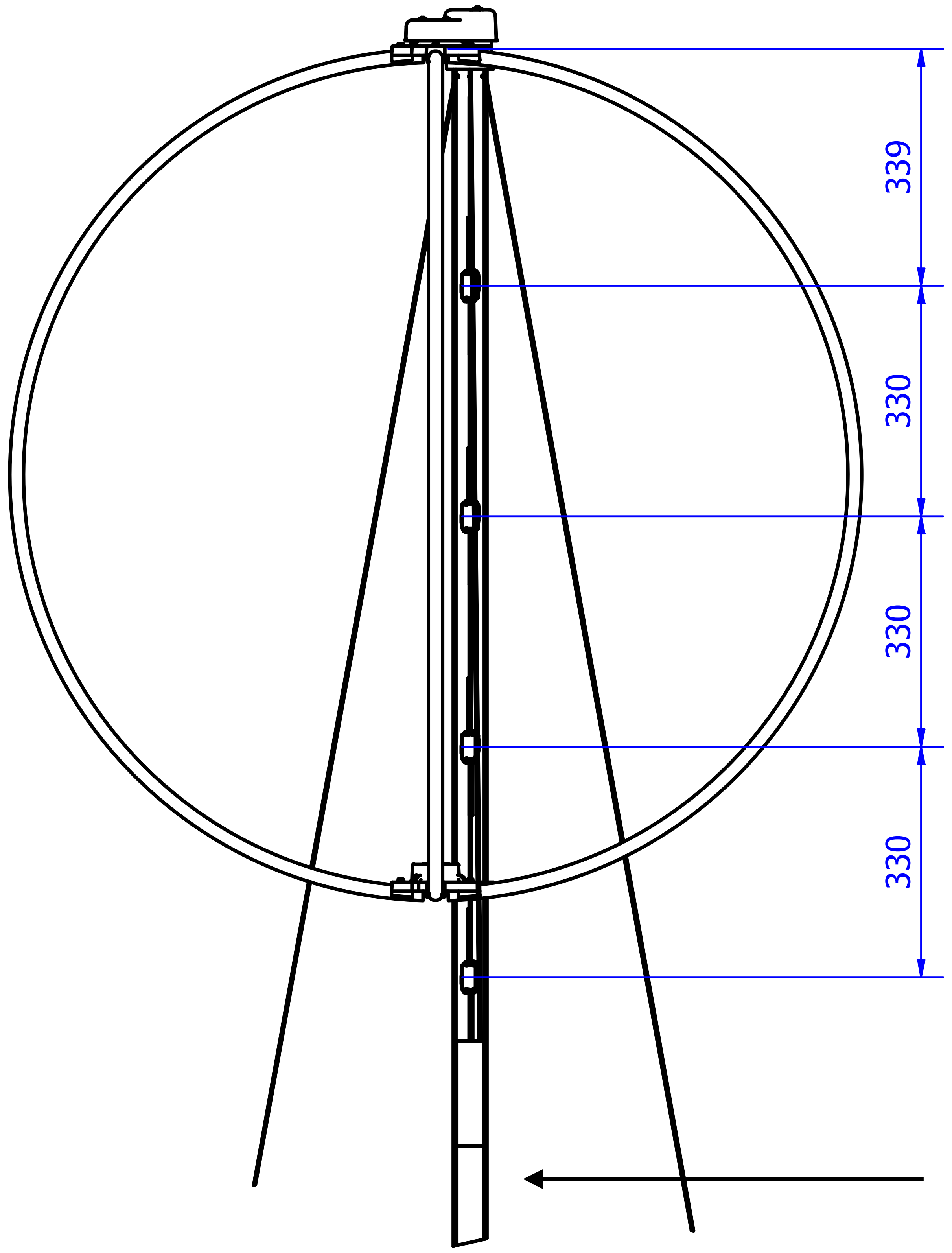
# Positioning ferrite cores in NEC

## SALLA in the lab



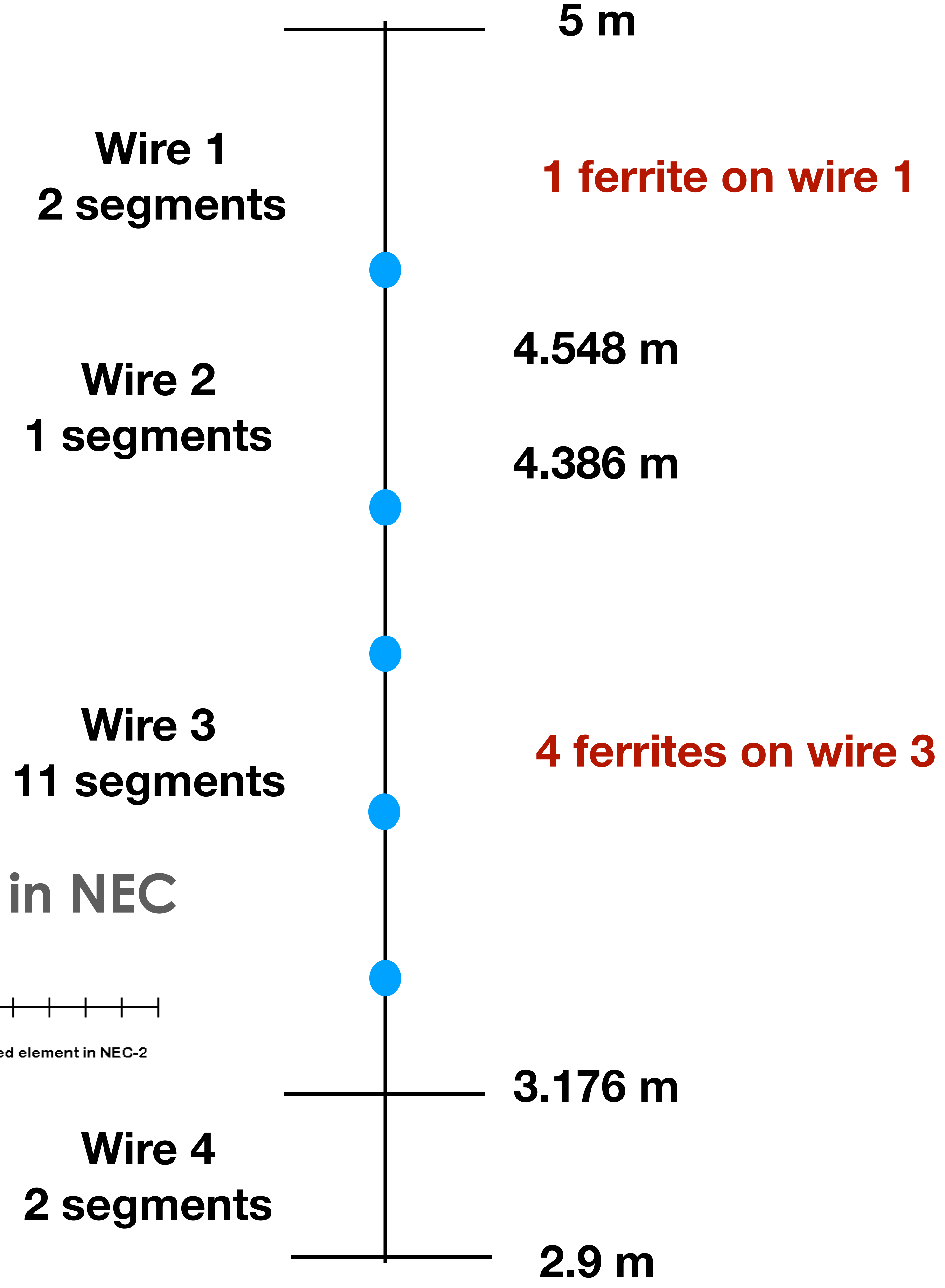
## Technical design

A ( 1:10 )




## Nec model

(very precise location of the ferrites)




## feedpoint in NEC

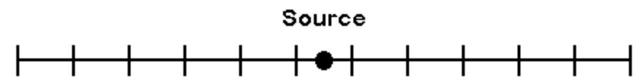



Fig. 1 Properly segmenting a fed element in NEC-2

**Effect of ferrite cores positions investigated with simulations!**

(see backup slides)

# RLC parallel model

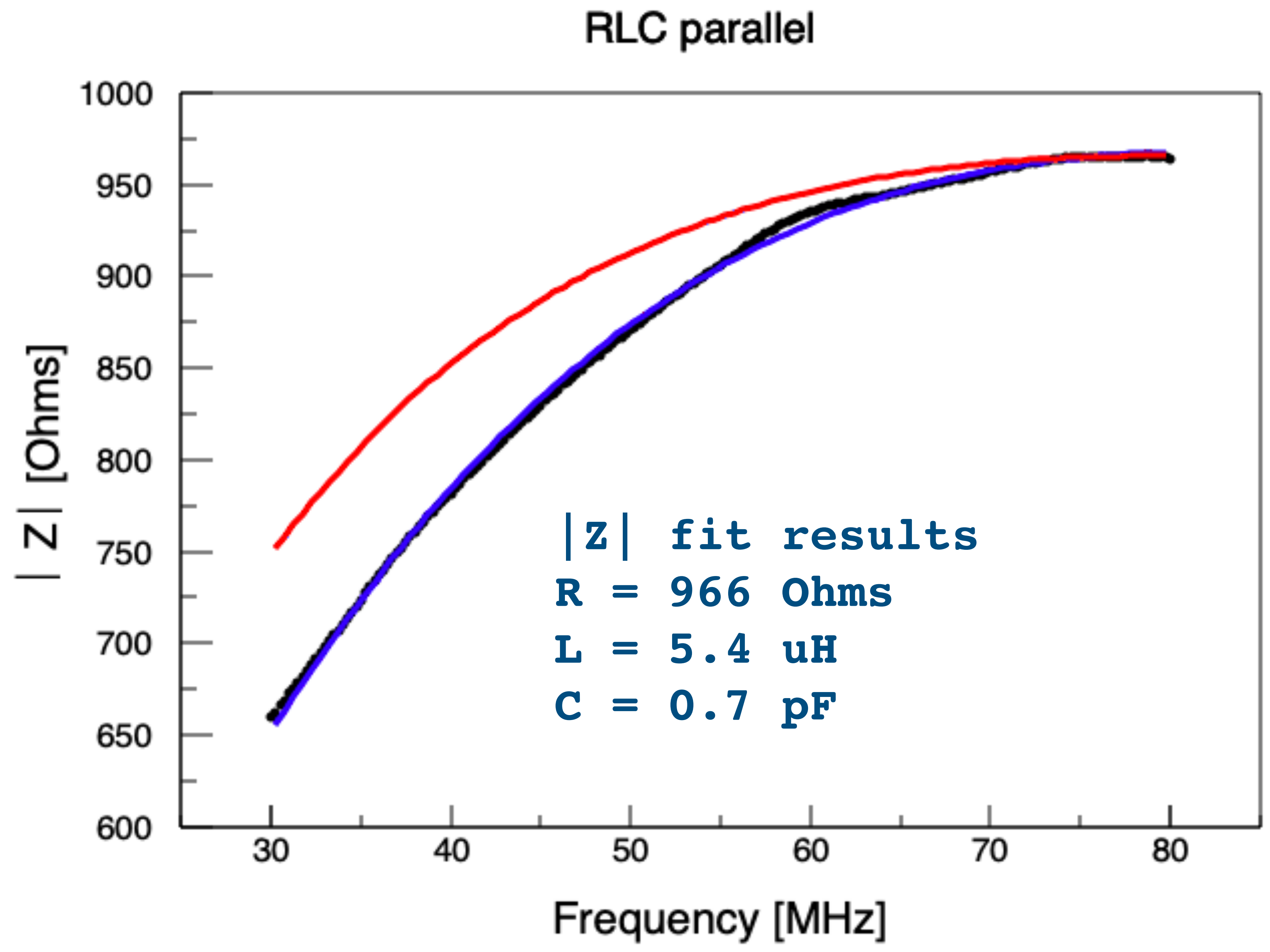
Difficult fit Z with RLC model

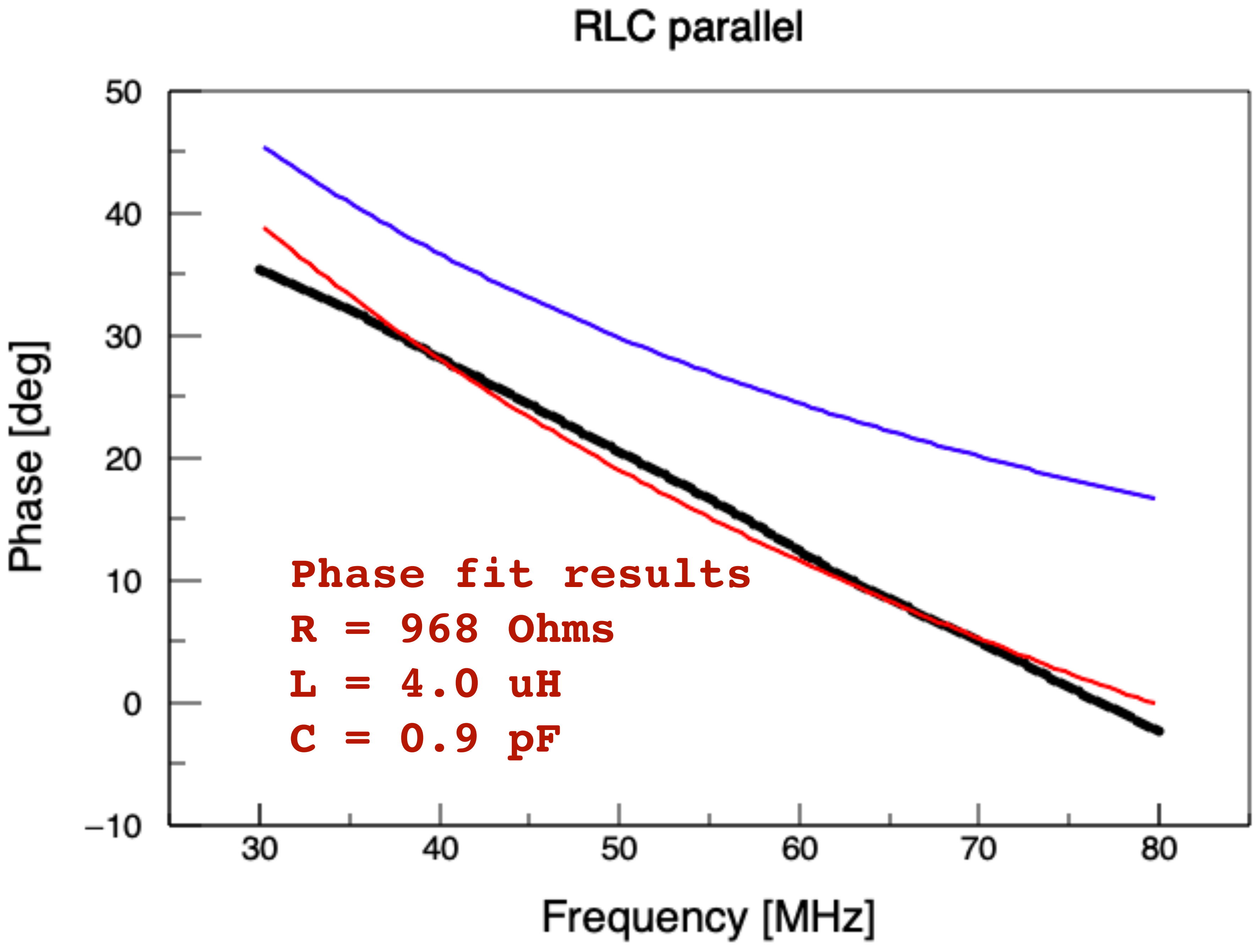
fit separately |Z| and phase

$$|Z| = \left(\frac{1}{R^2} + \left(\frac{1}{\omega L} - \omega C\right)^2\right)^{-1/2}$$

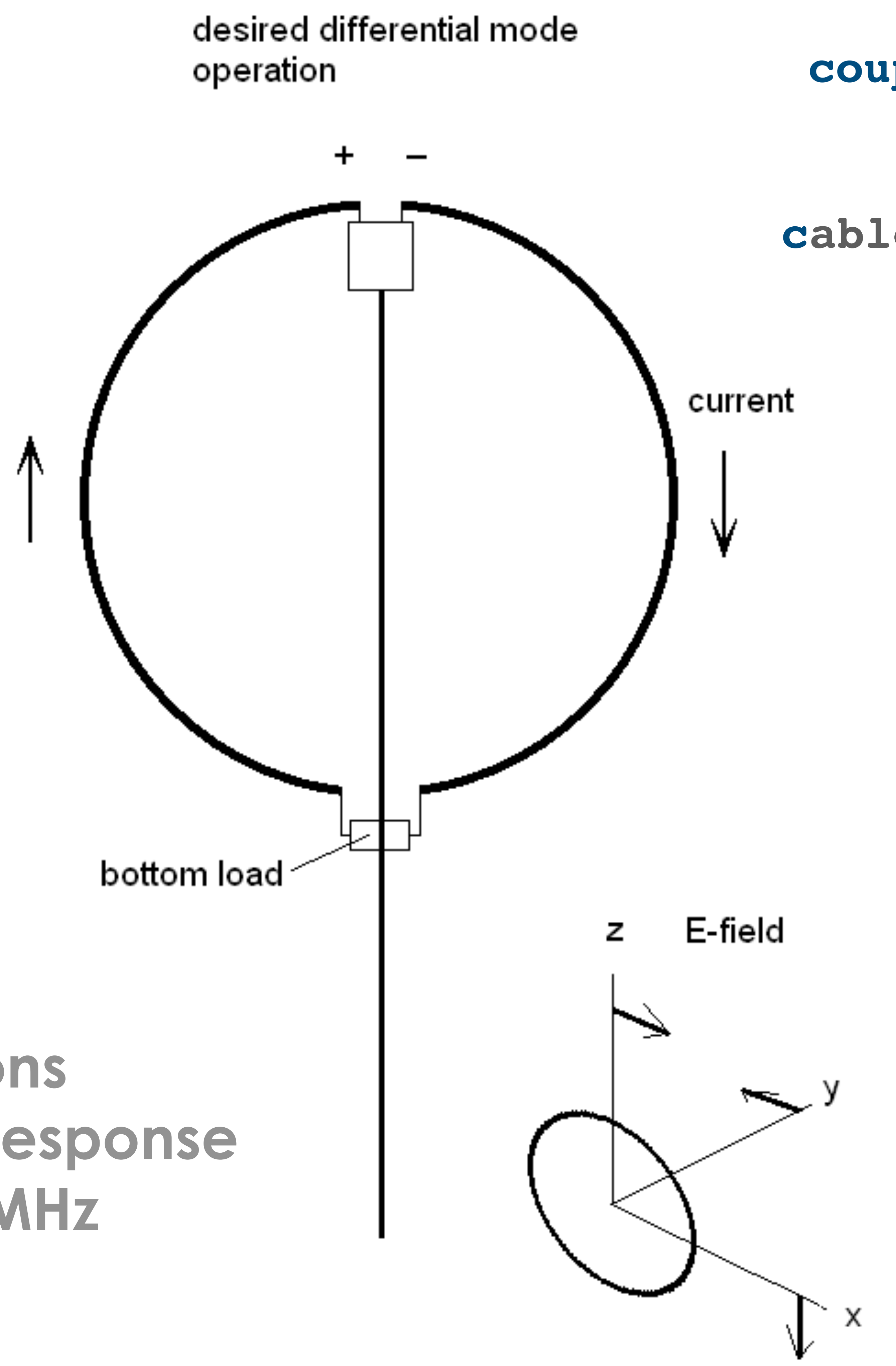
$$\Phi = \arctan\left(R\left(\frac{1}{\omega L} - \omega C\right)\right)$$

but use |Z| only results



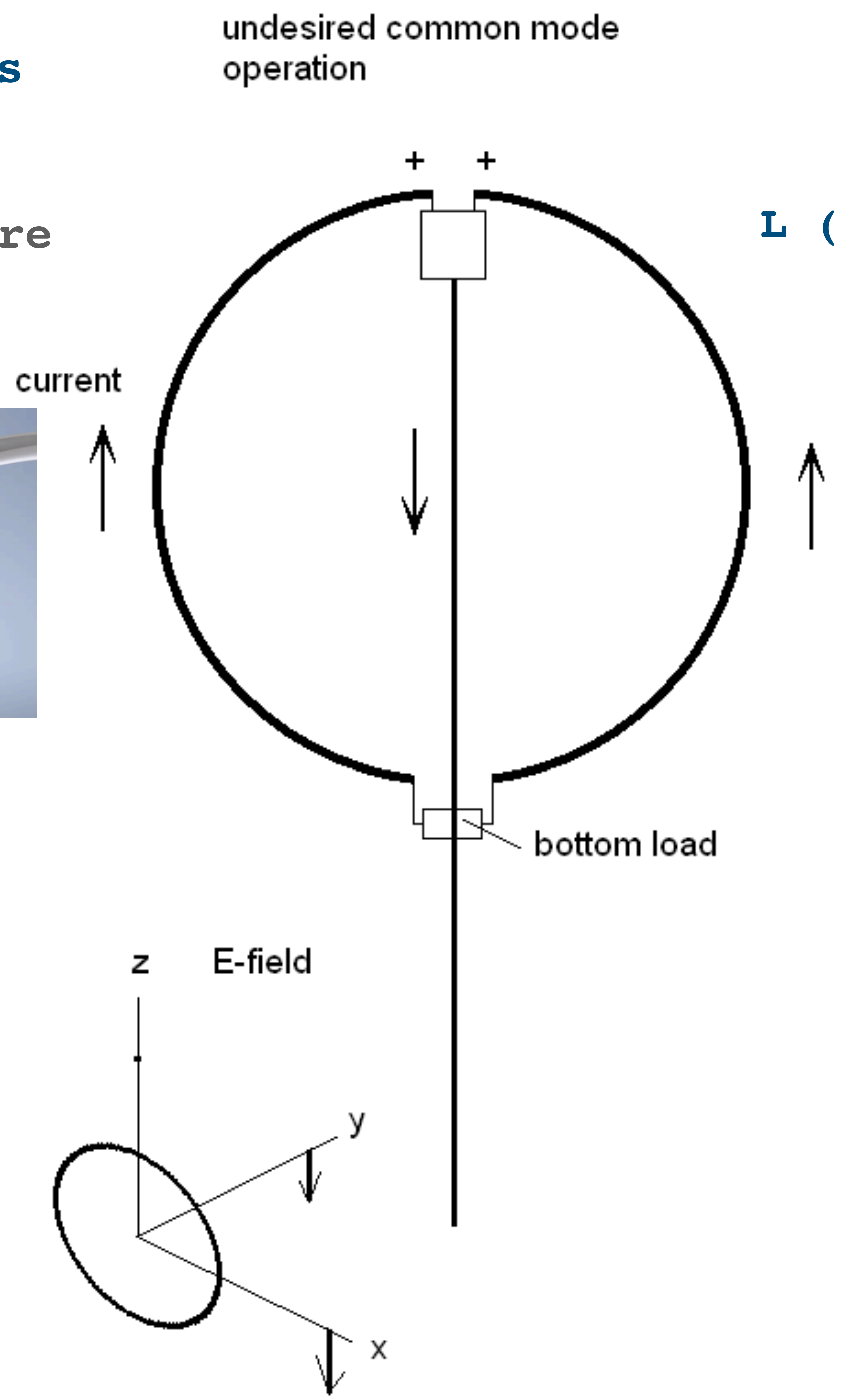



# Cables & Mast influence




coupling of the loops
by the cable

cable not in the centre
of the antenna



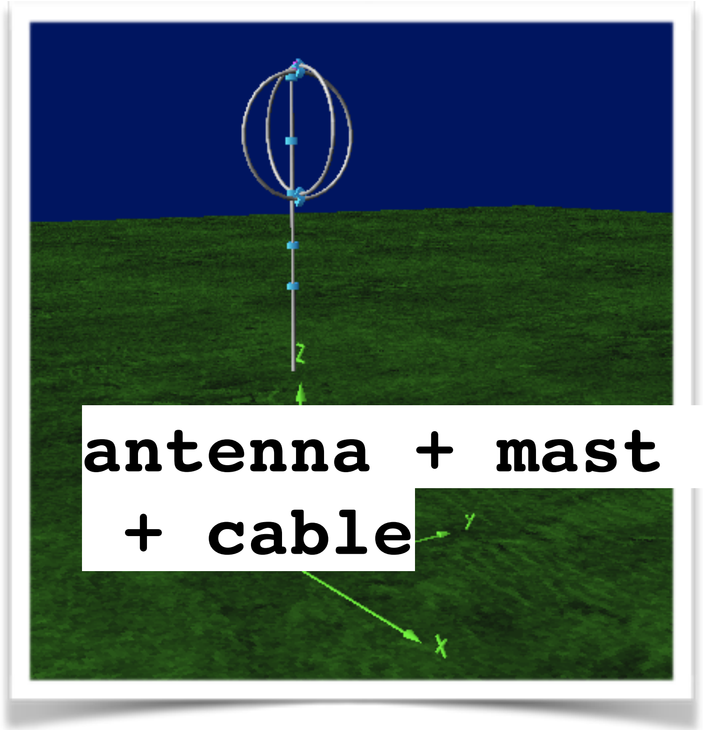

L (halve loop) = 1.8m

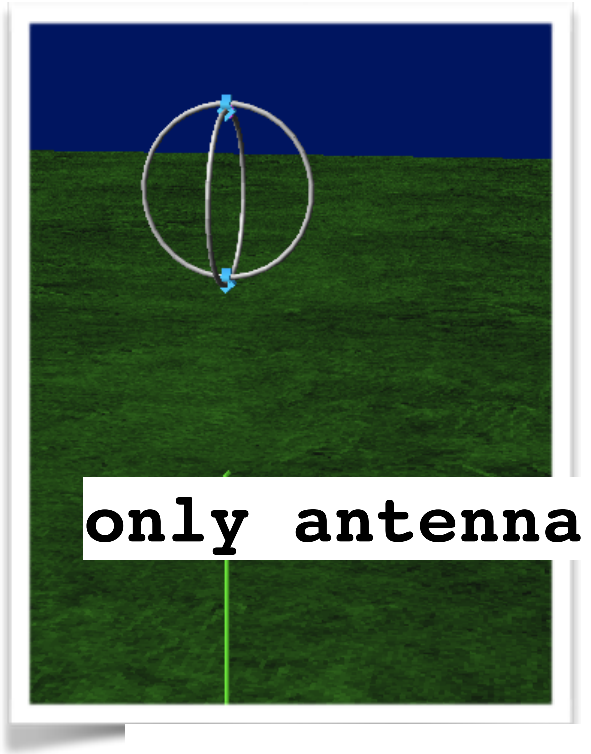
$$L \sim 0.5\ \lambda$$

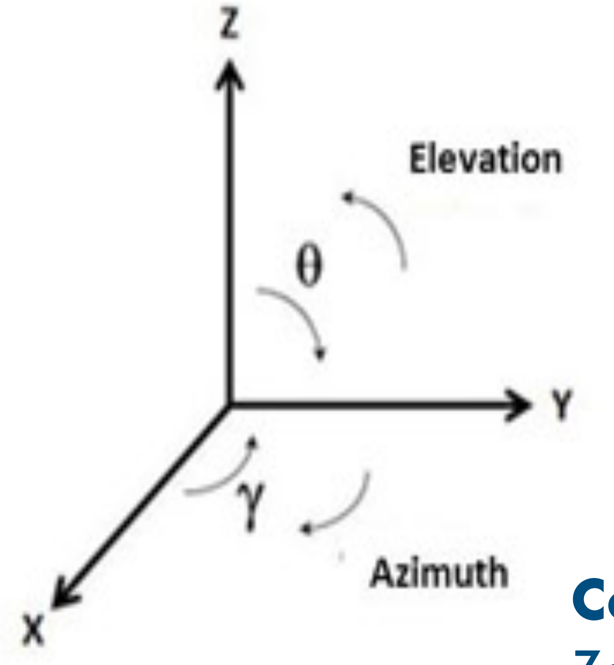
$$\lambda\ (75MHz) \sim 3.9\ m$$

With simulations
influence antenna response
above 62/63 MHz

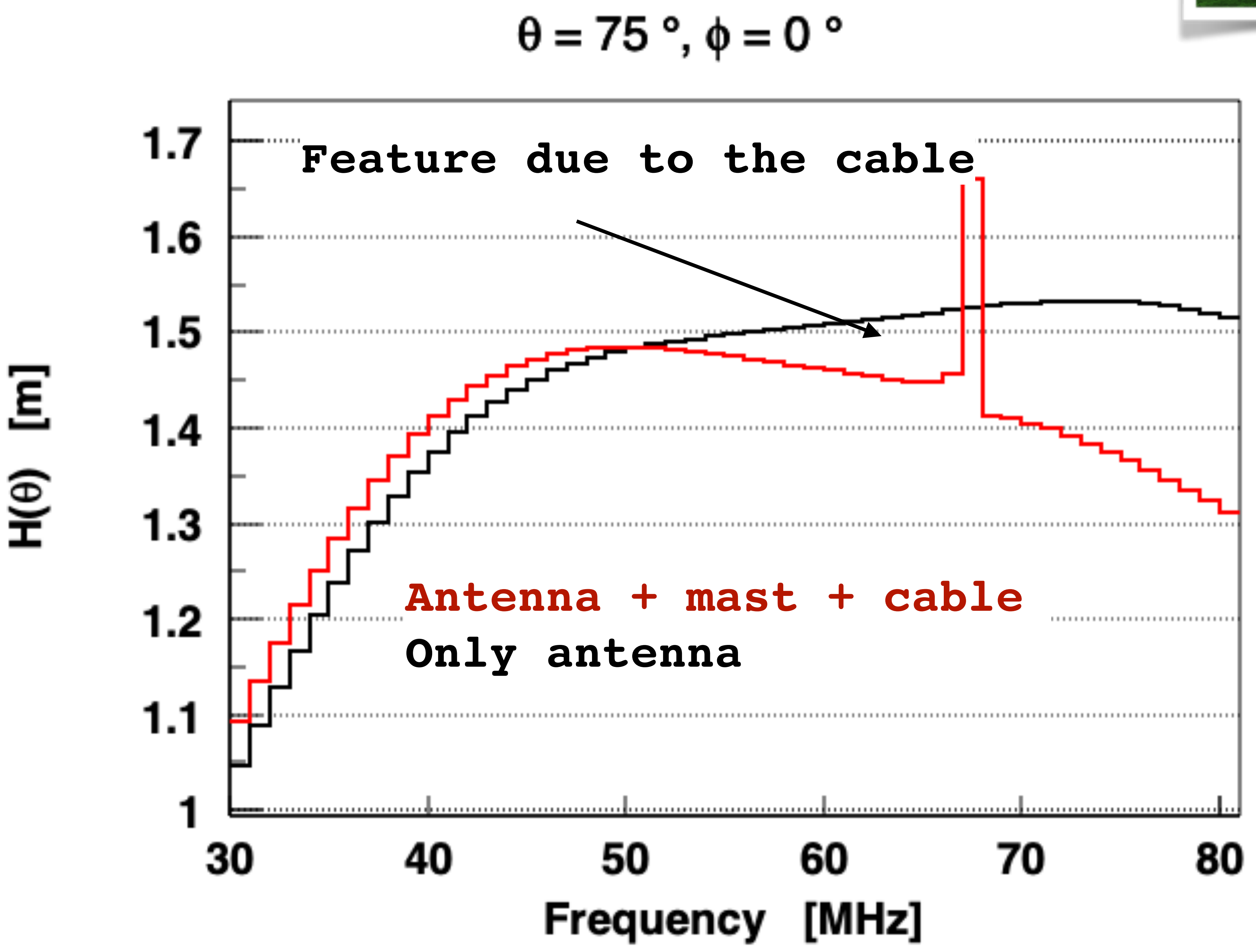
# Cables & Mast influence



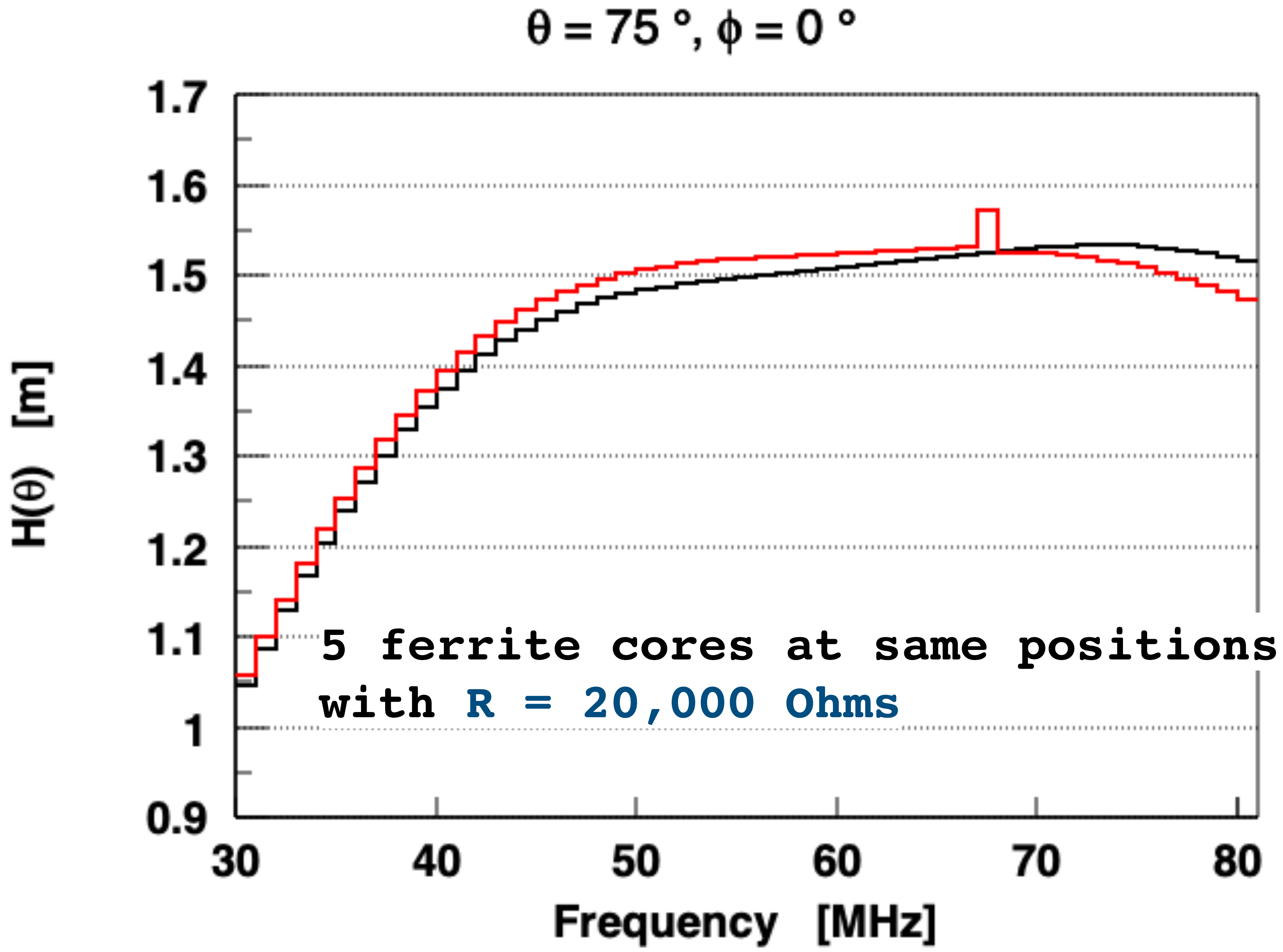




**Convention**
Zenith measured of the z-axis
Azimuth counterclockwise of the x-axis
XZ plane → EW direction
YZ plane → NS direction

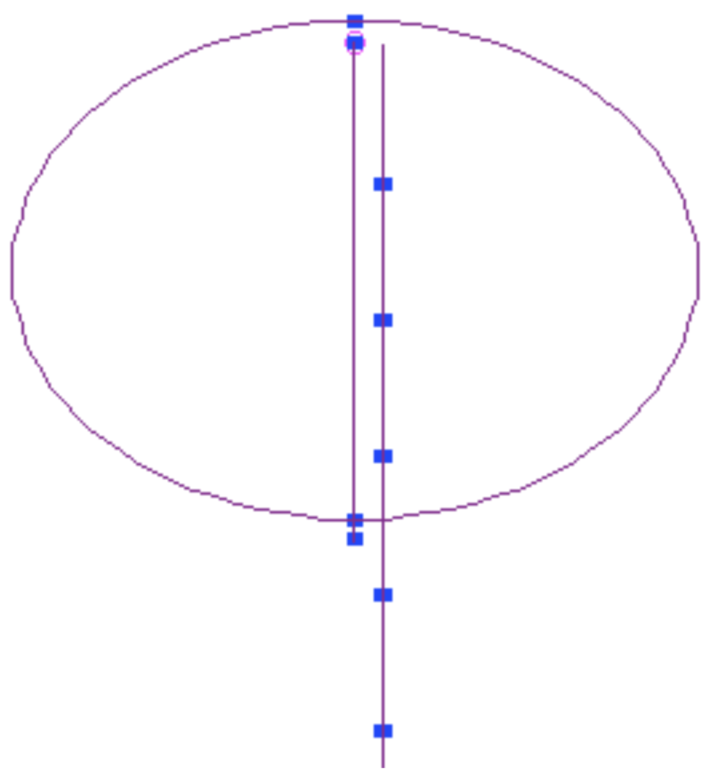



EW loop

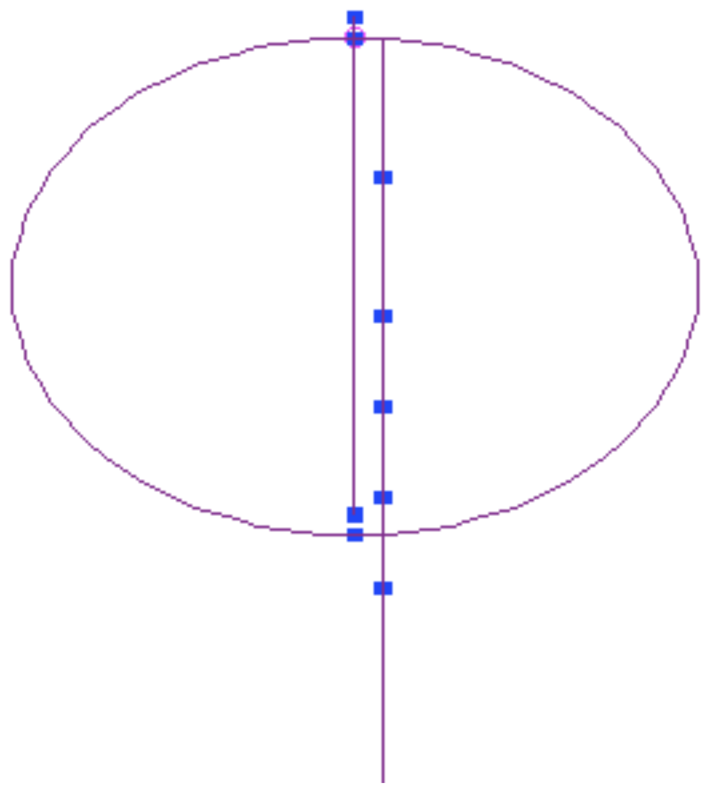


# Positioning ferrite cores in NEC

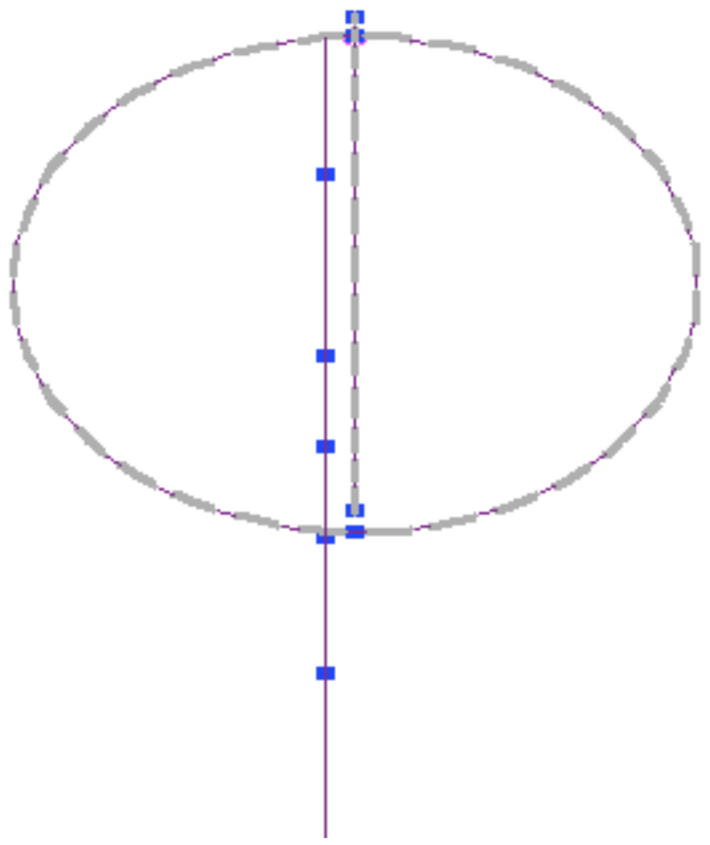
Default

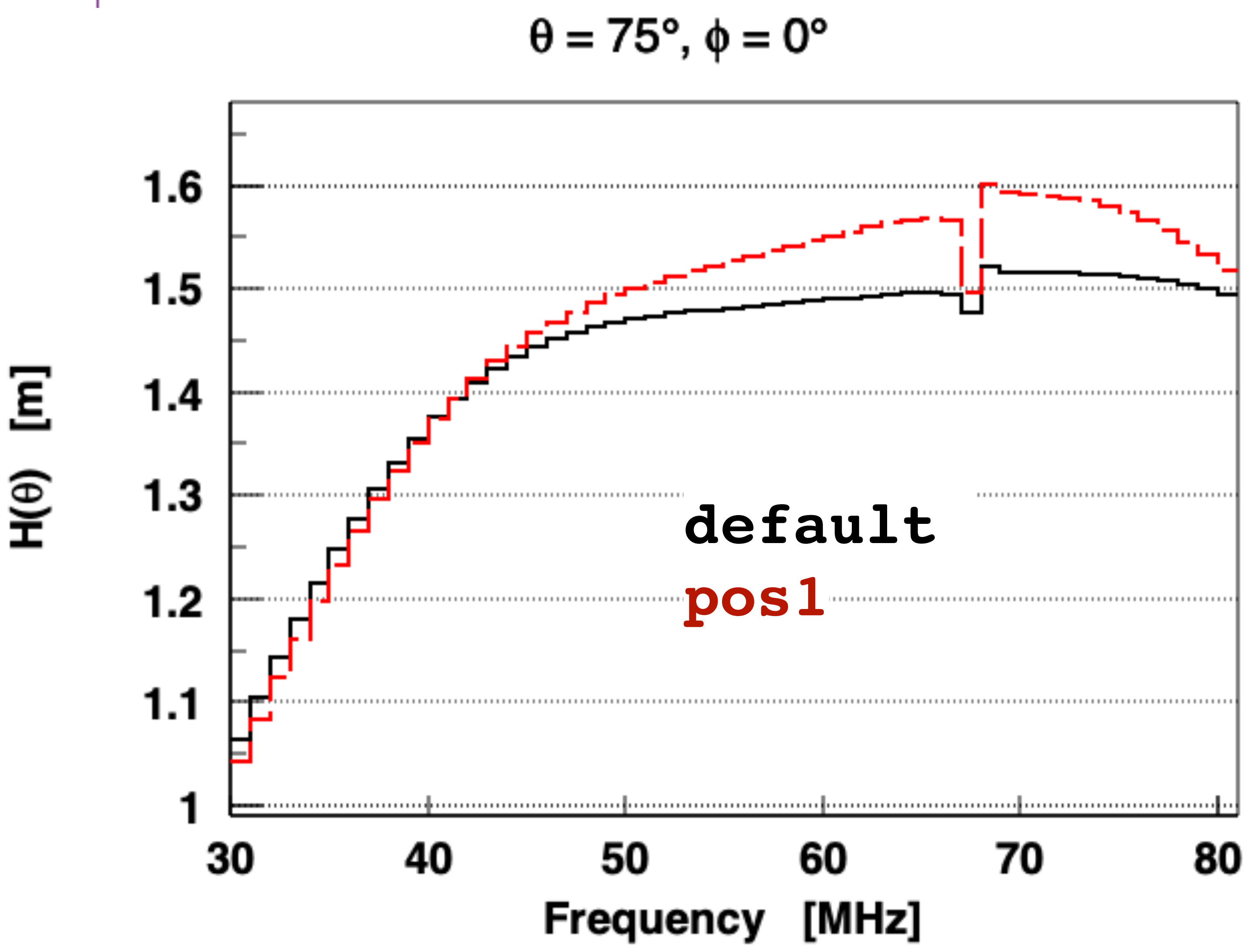


Pos1

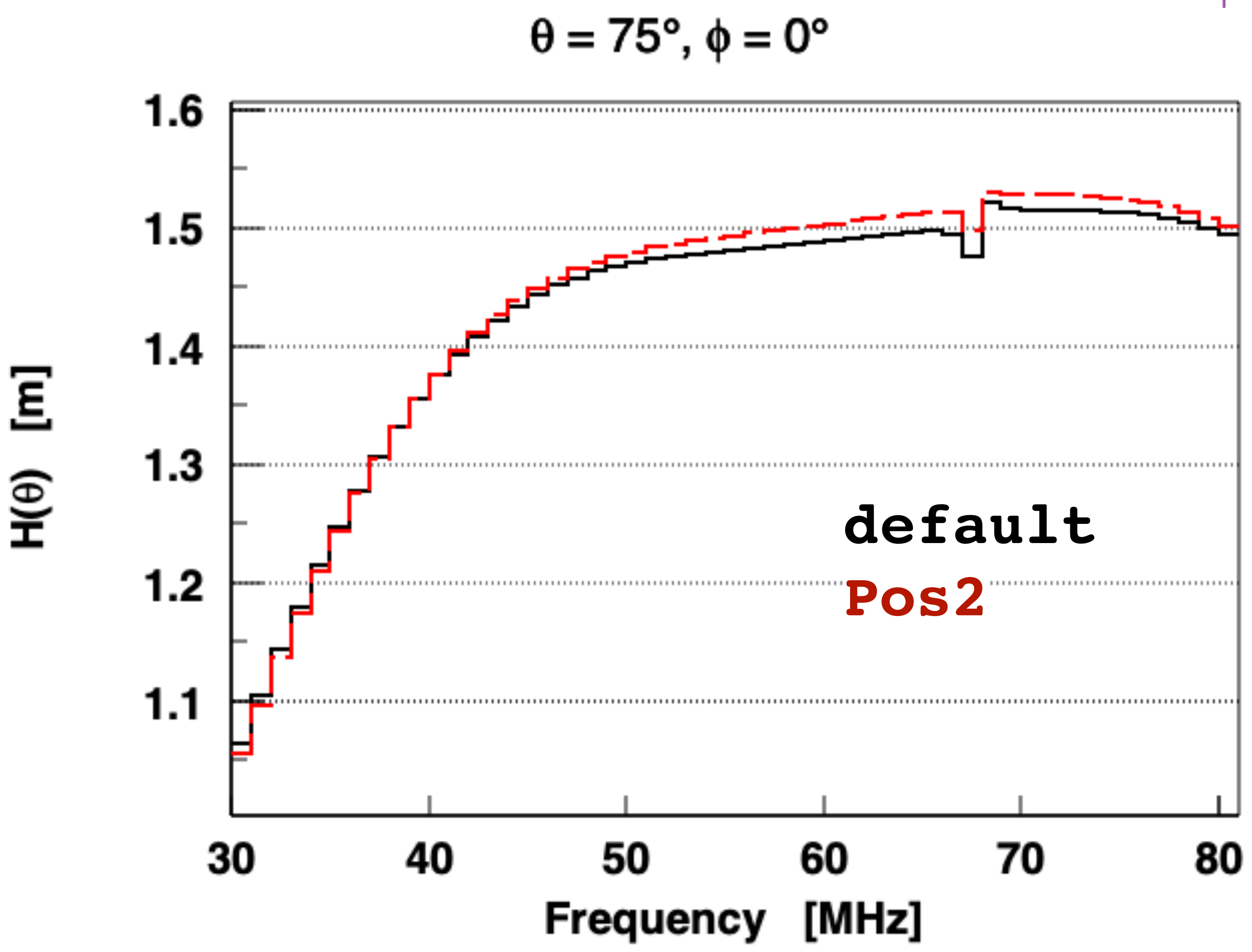


Pos2

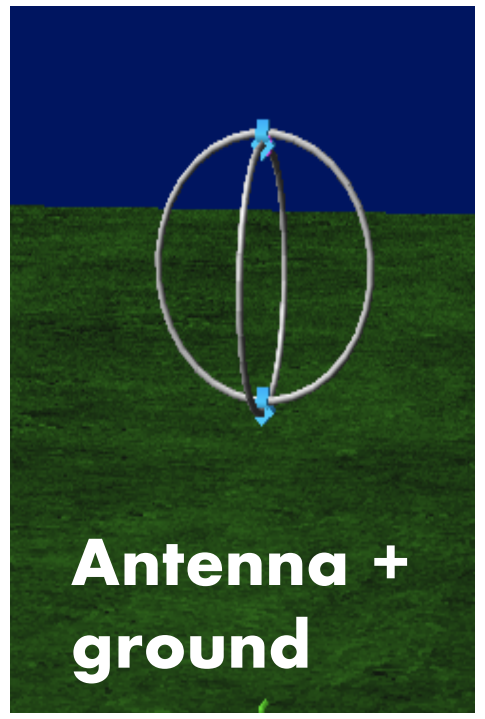


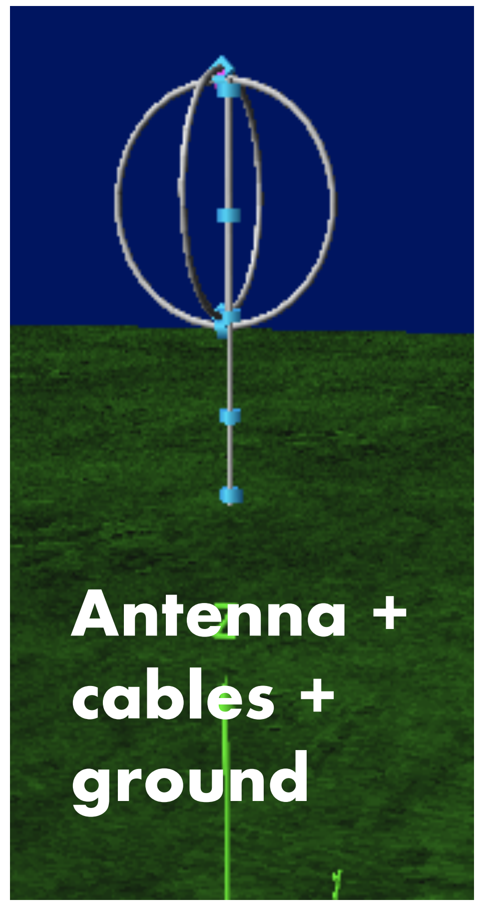


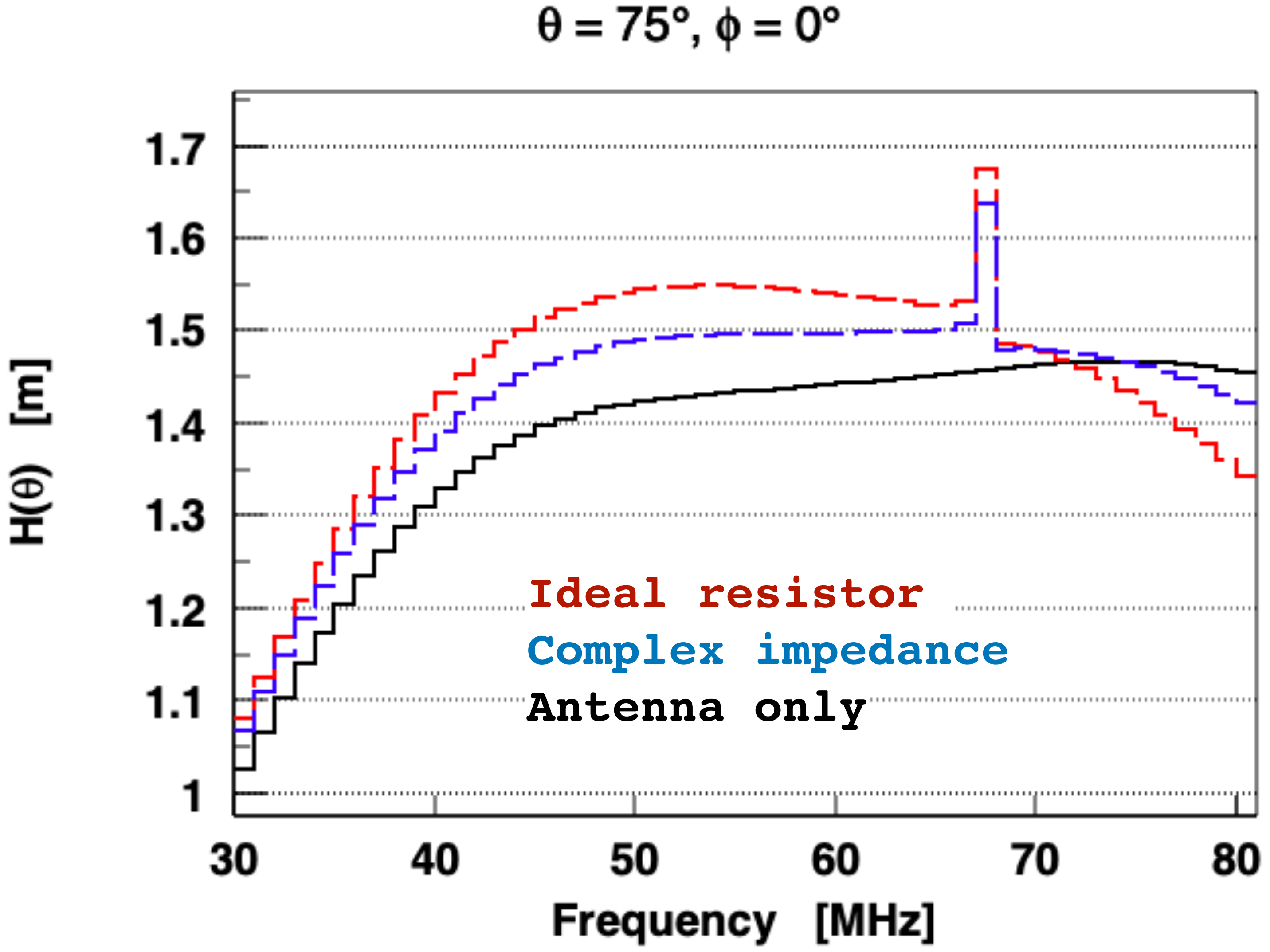

EW loop

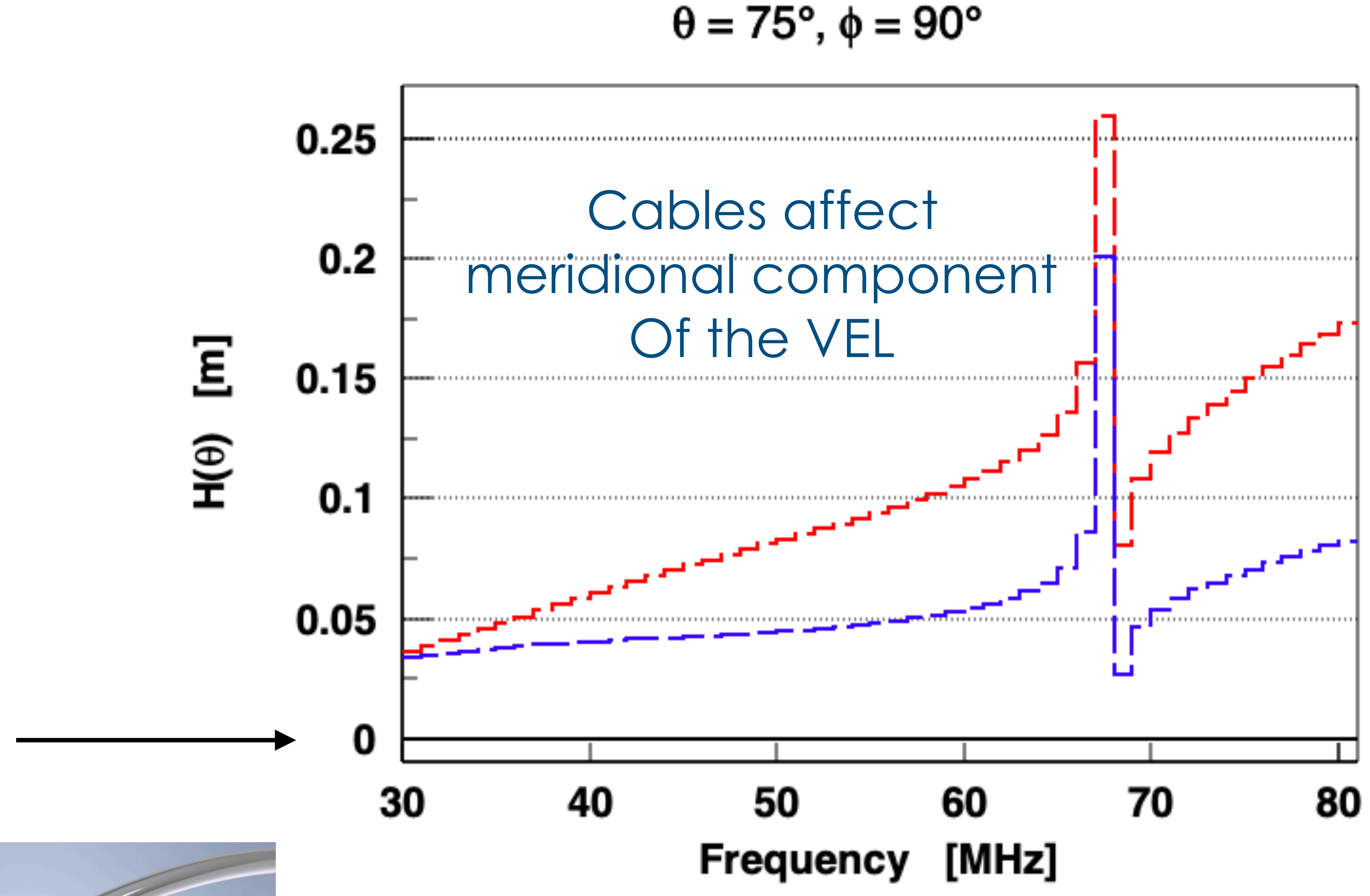


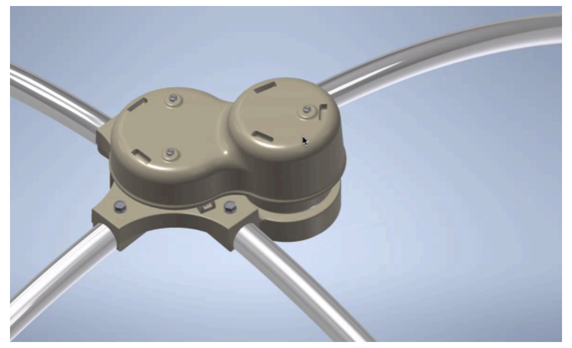
# 3D Nec model of the Surface Station

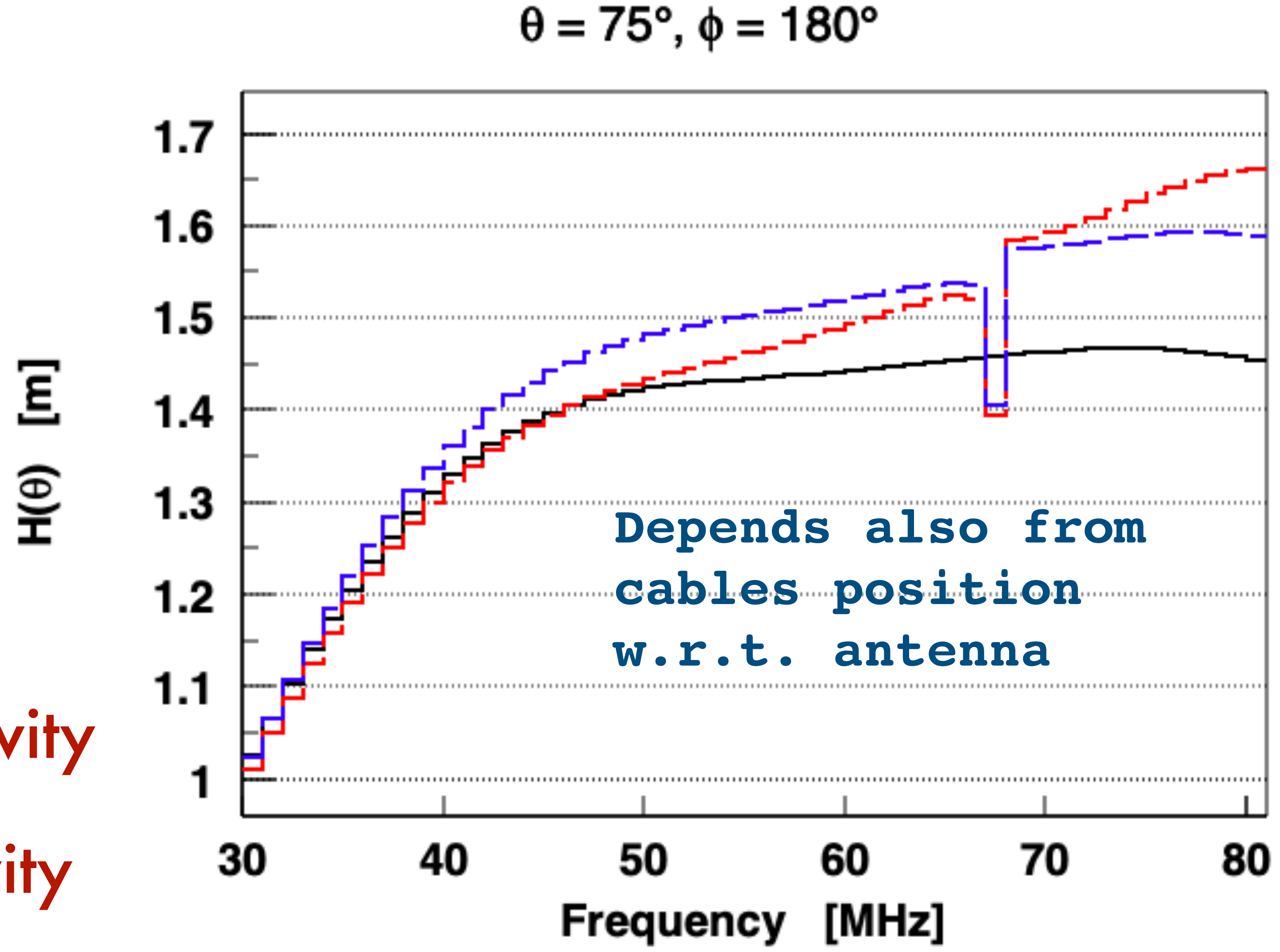


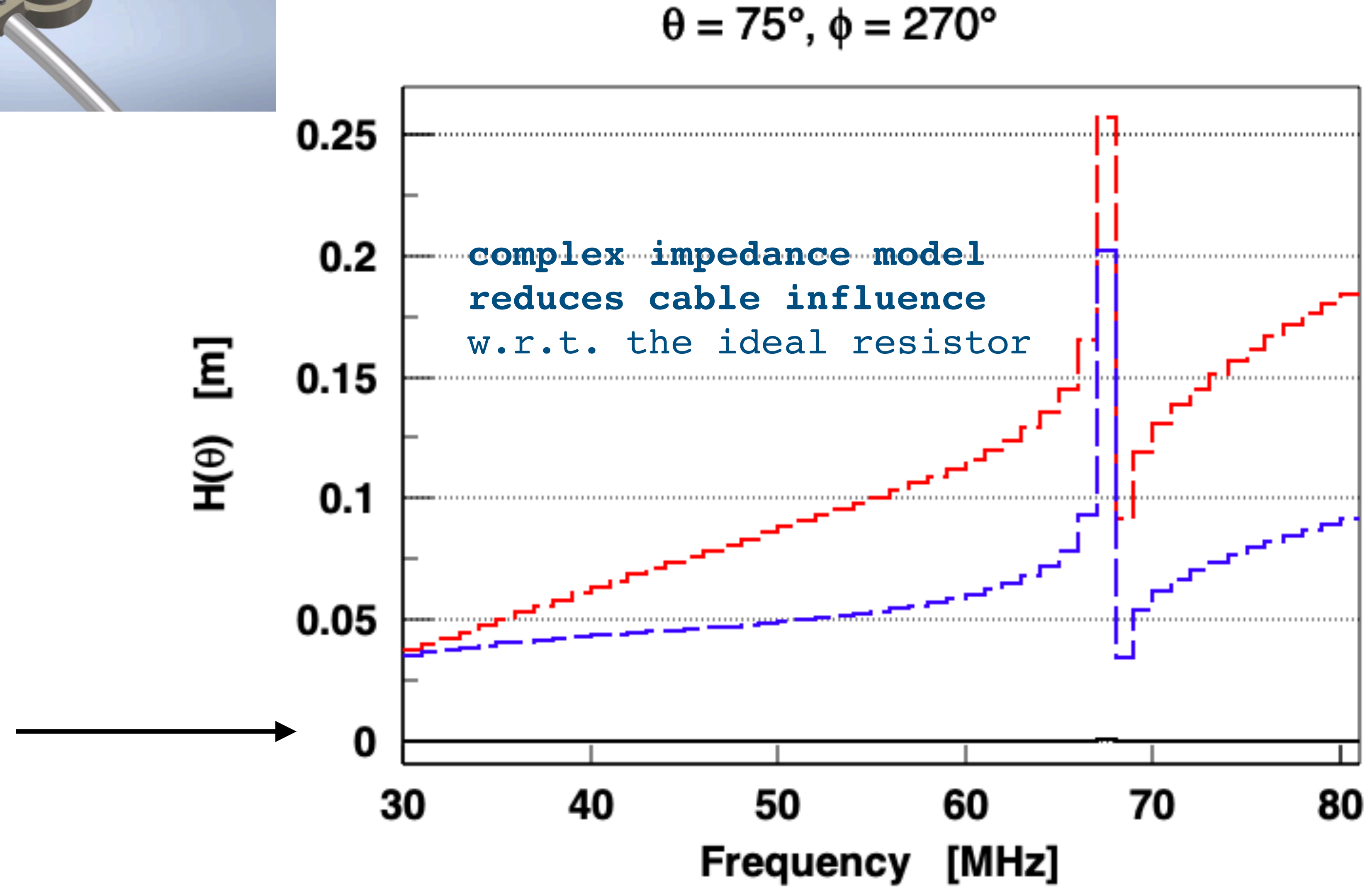





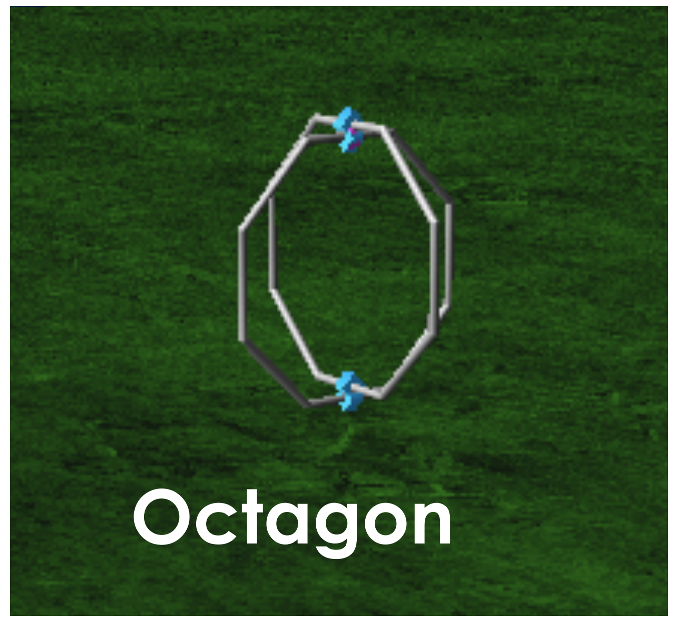



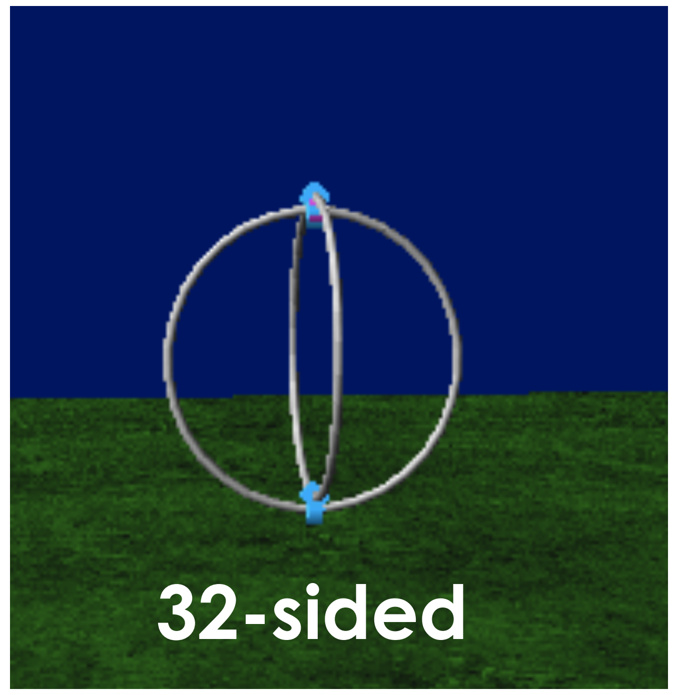

**EW loop**

$\phi = 0^\circ, 180^\circ$ Higher sensitivity

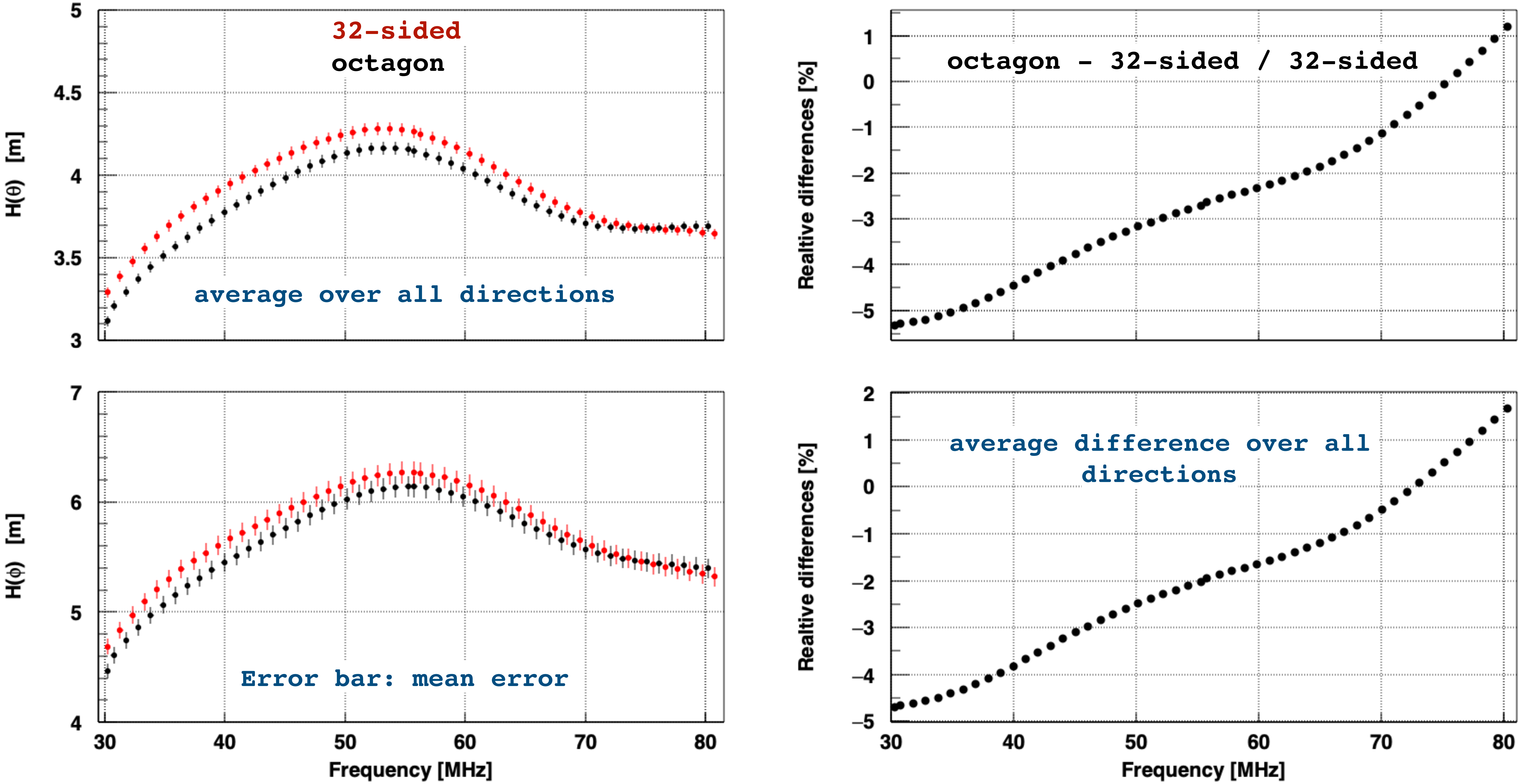
$\phi = 90^\circ, 270^\circ$ Lower sensitivity

# SALLA geometry in NEC

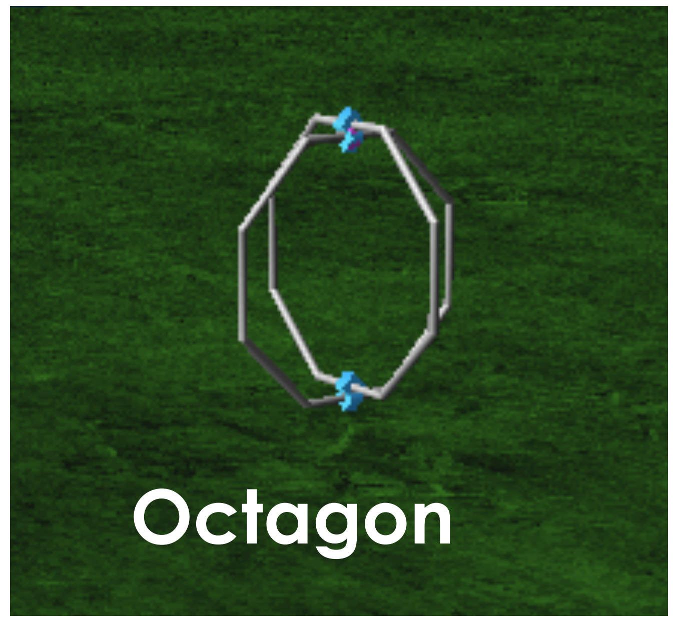


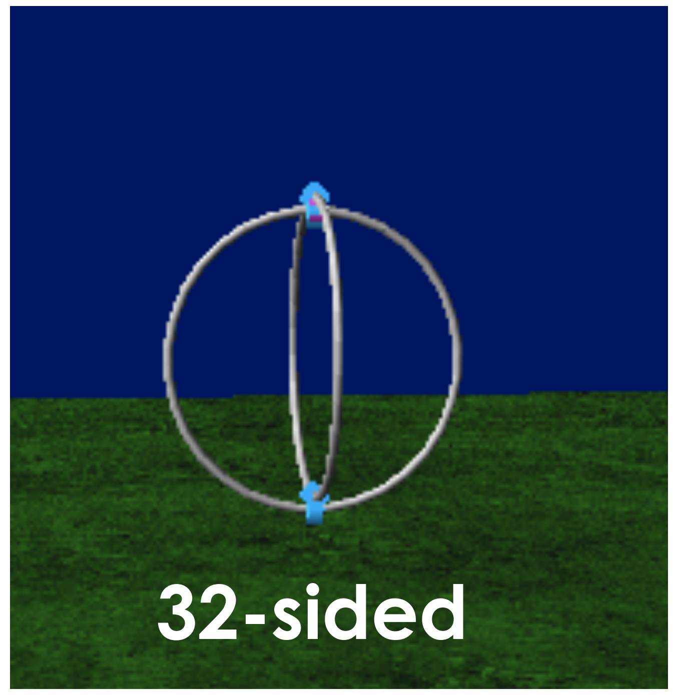




EW loop

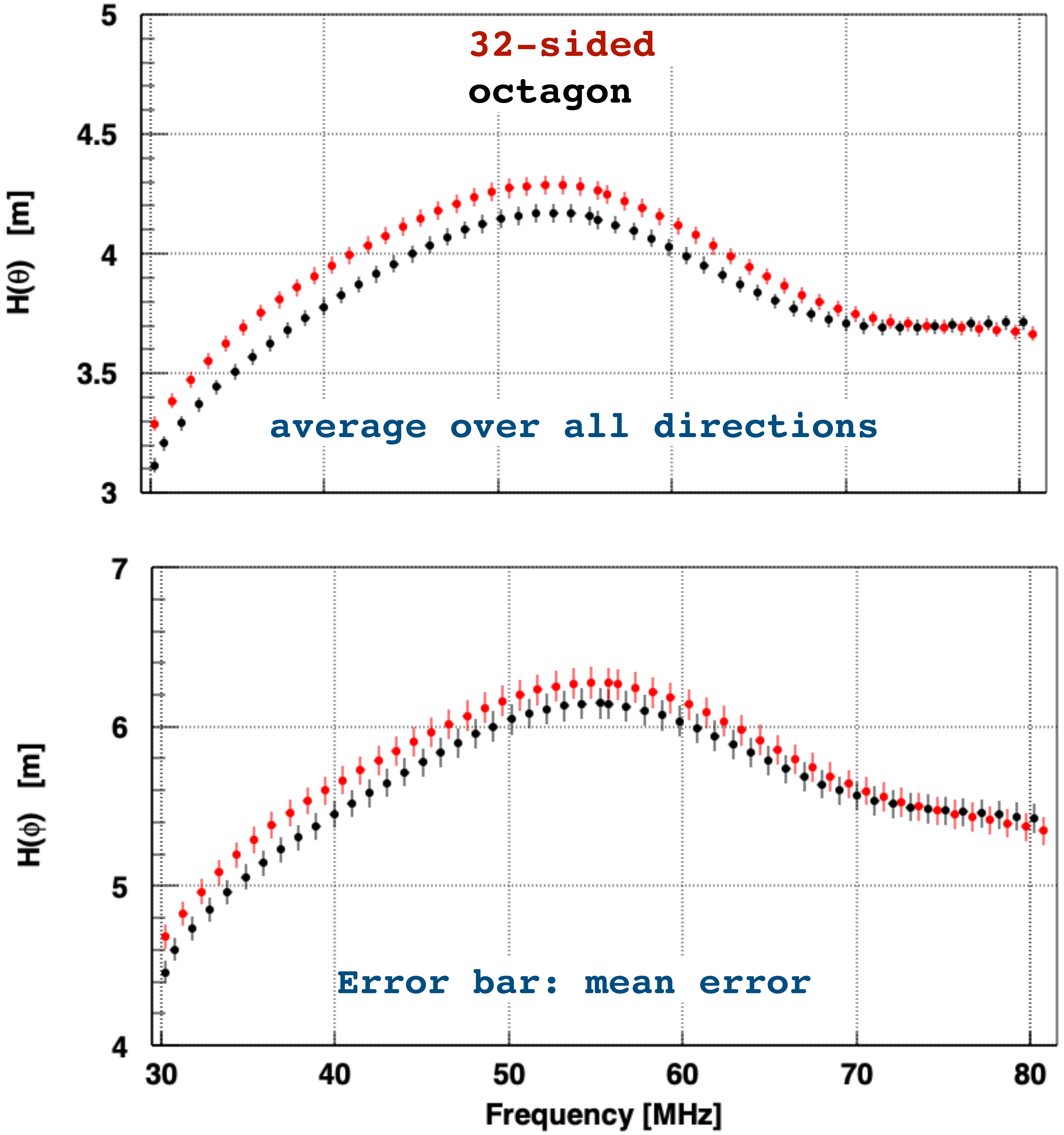


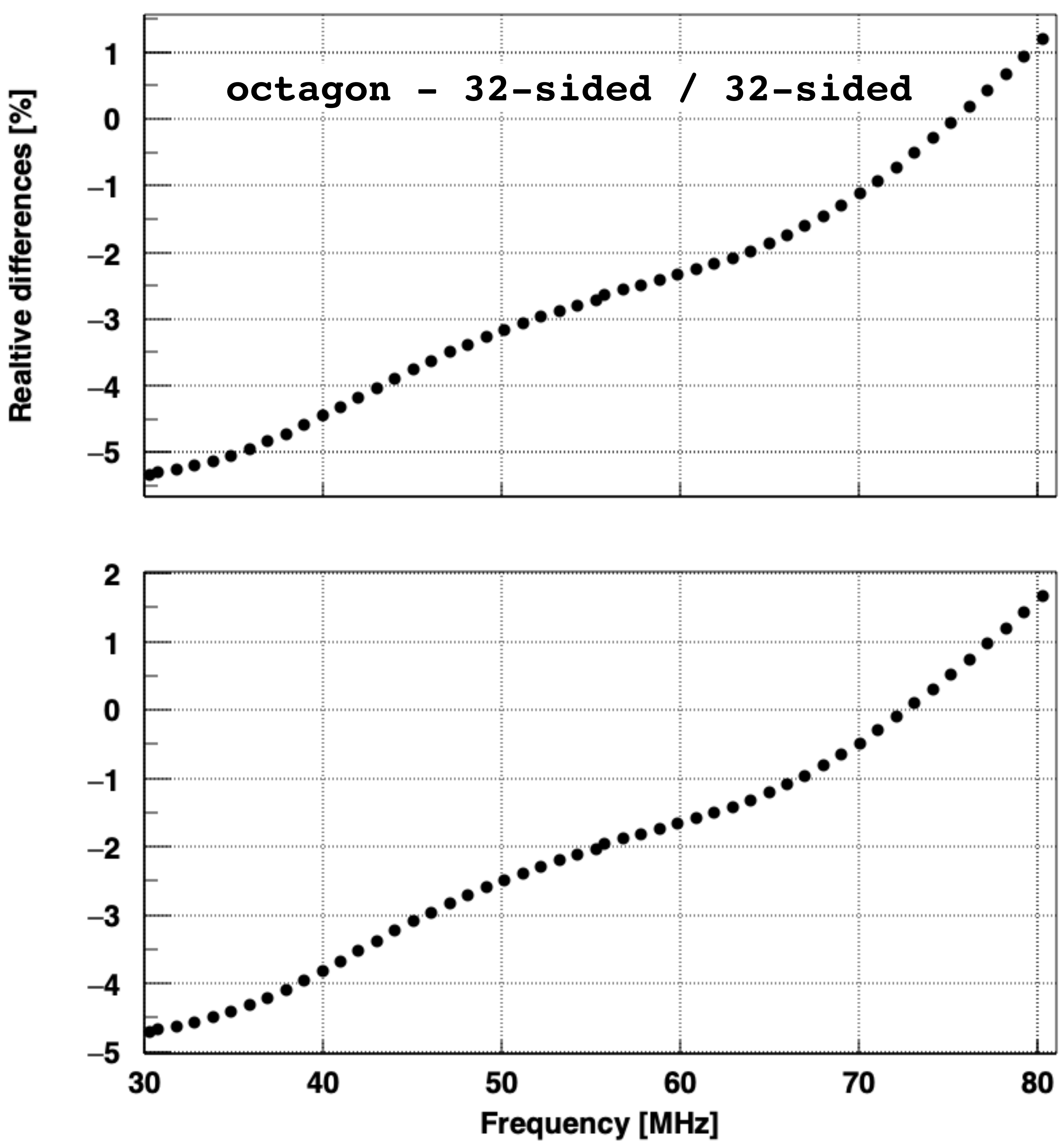
# SALLA geometry in NEC



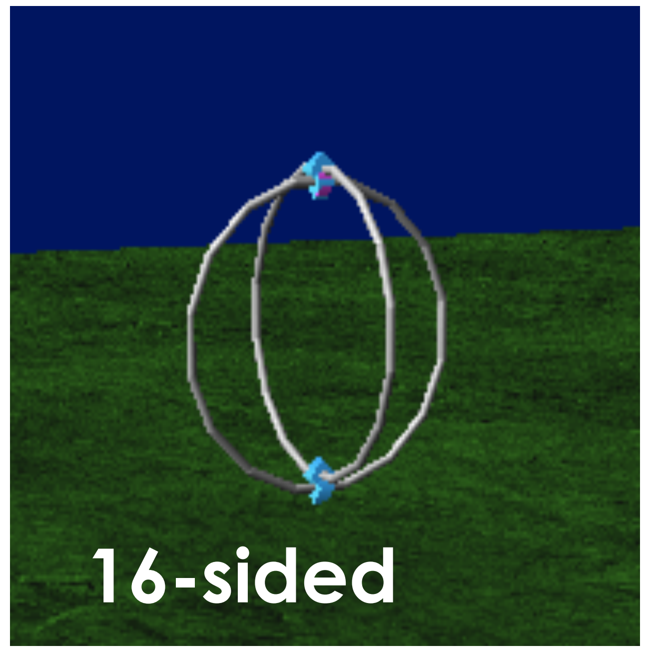



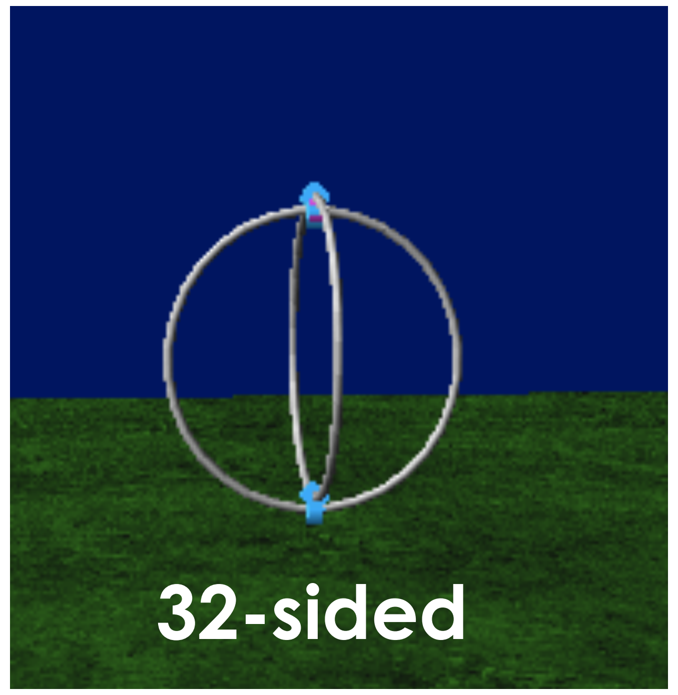

NS loop



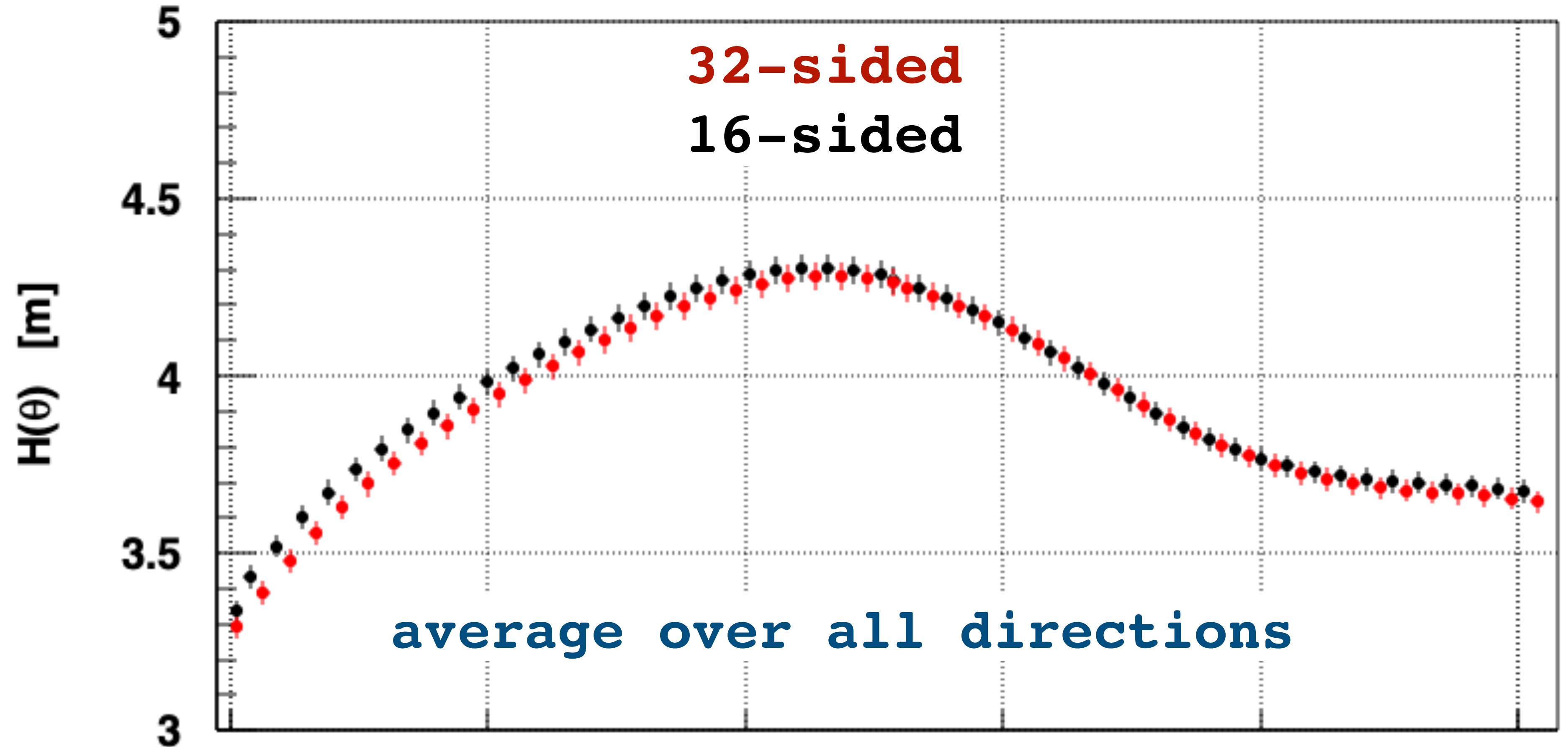



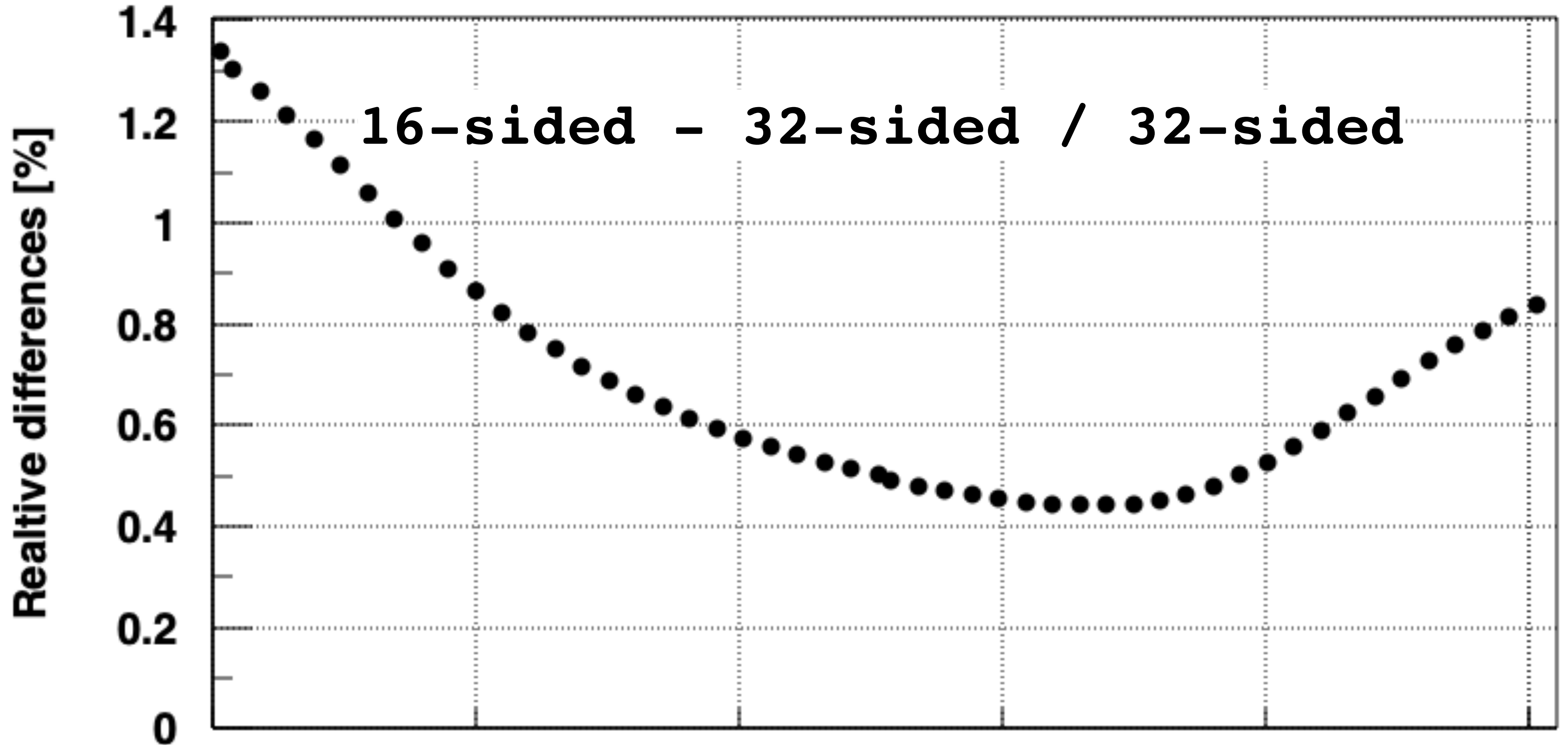
# SALLA geometry in NEC

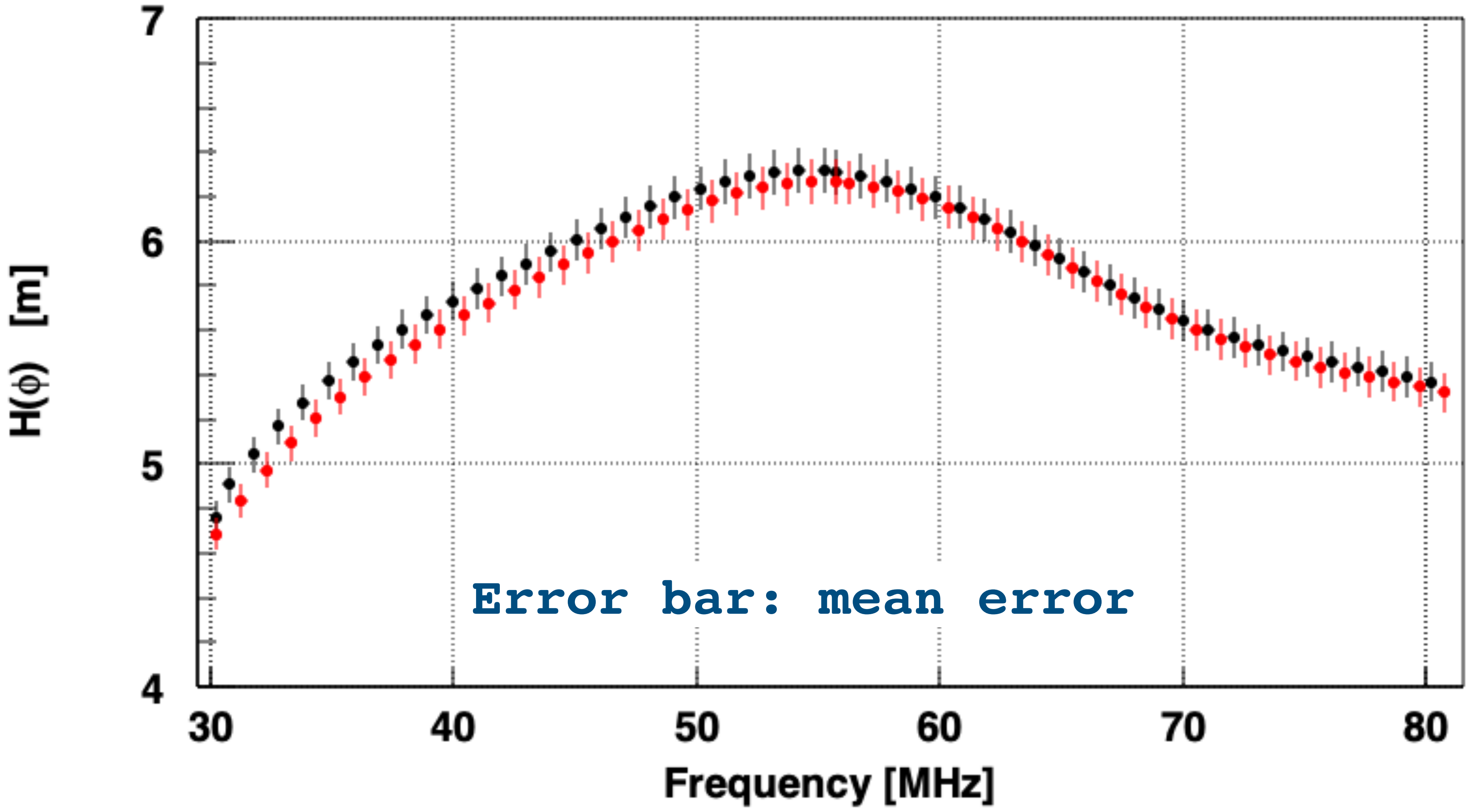


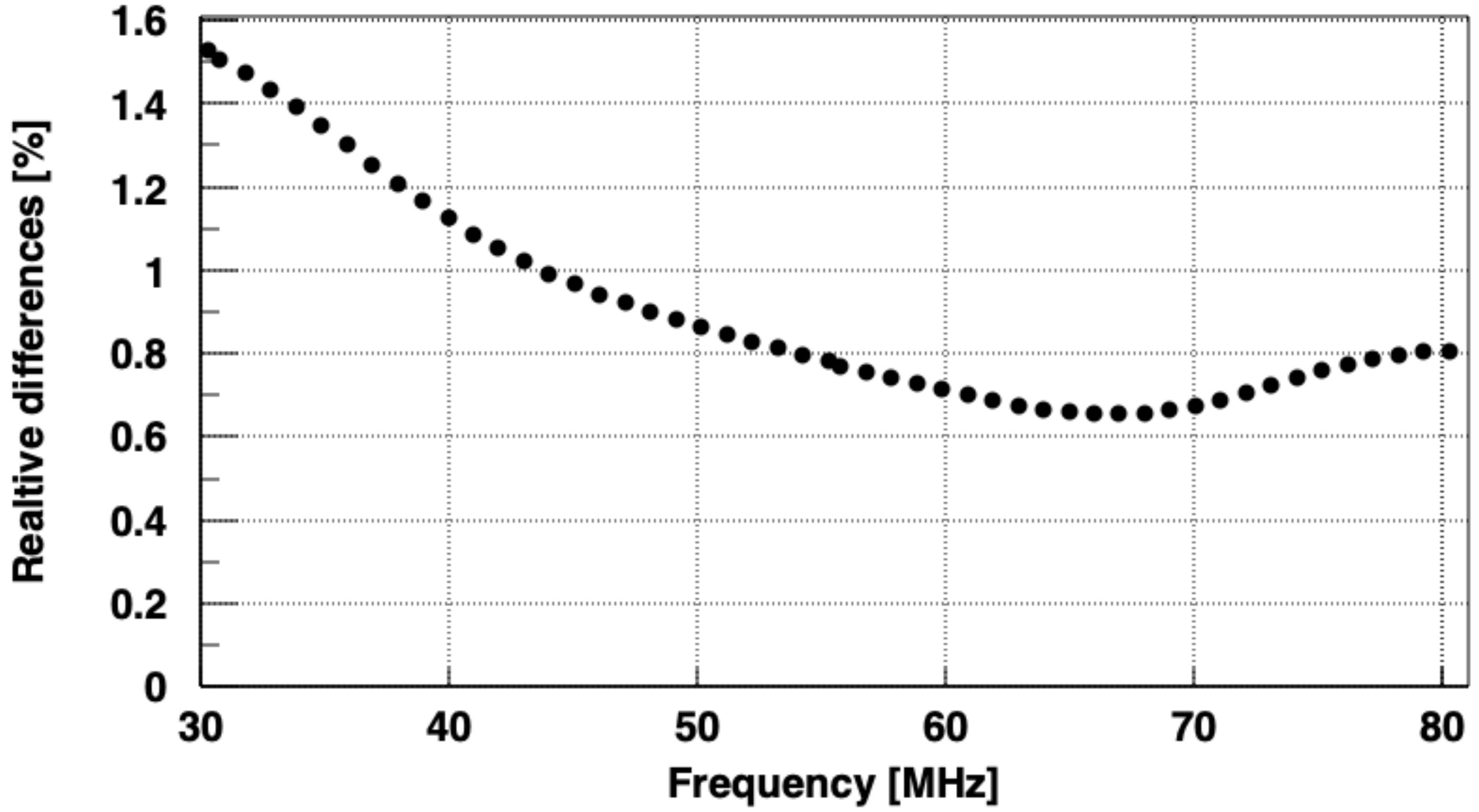




EW loop



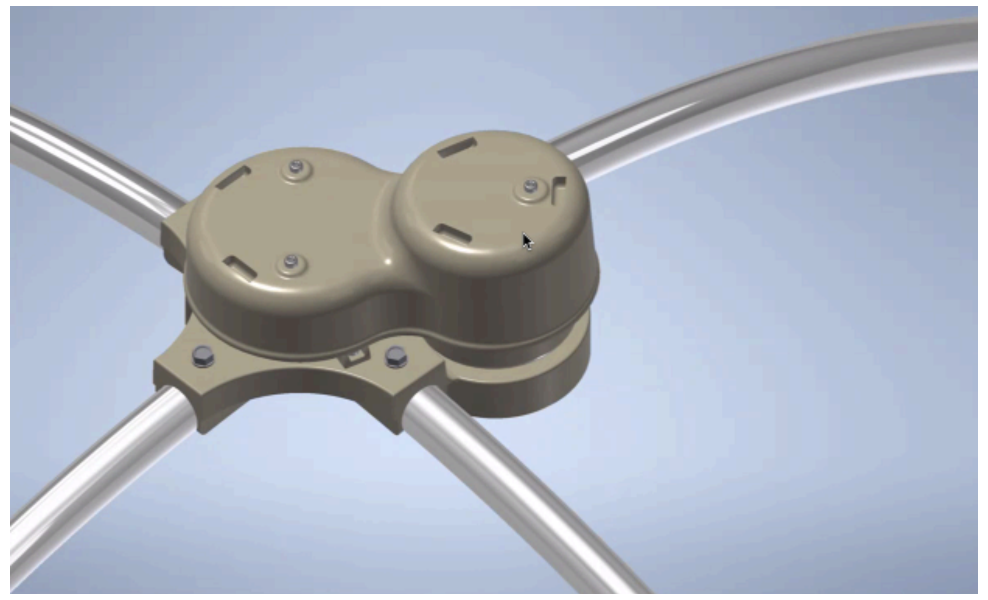



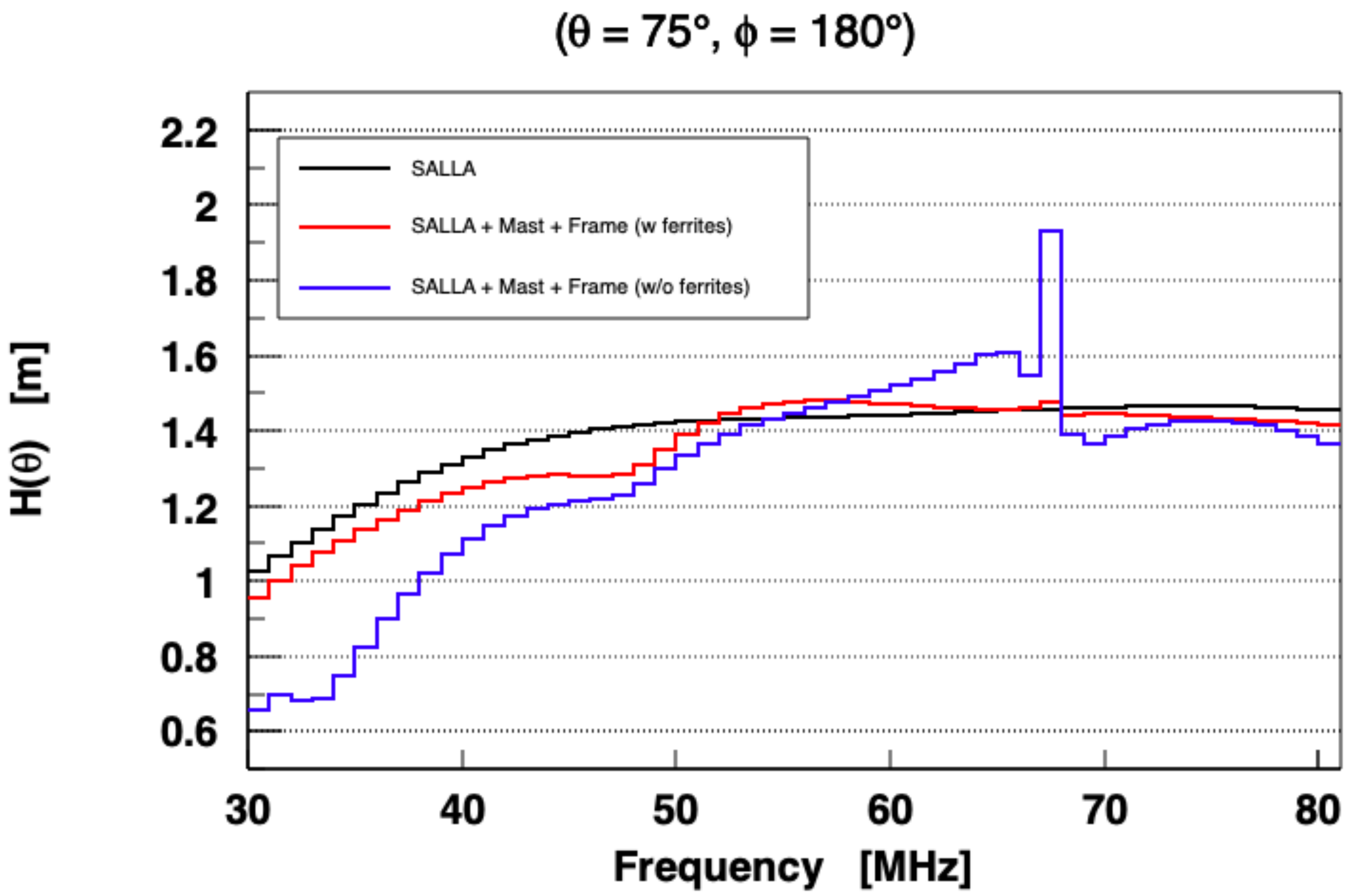



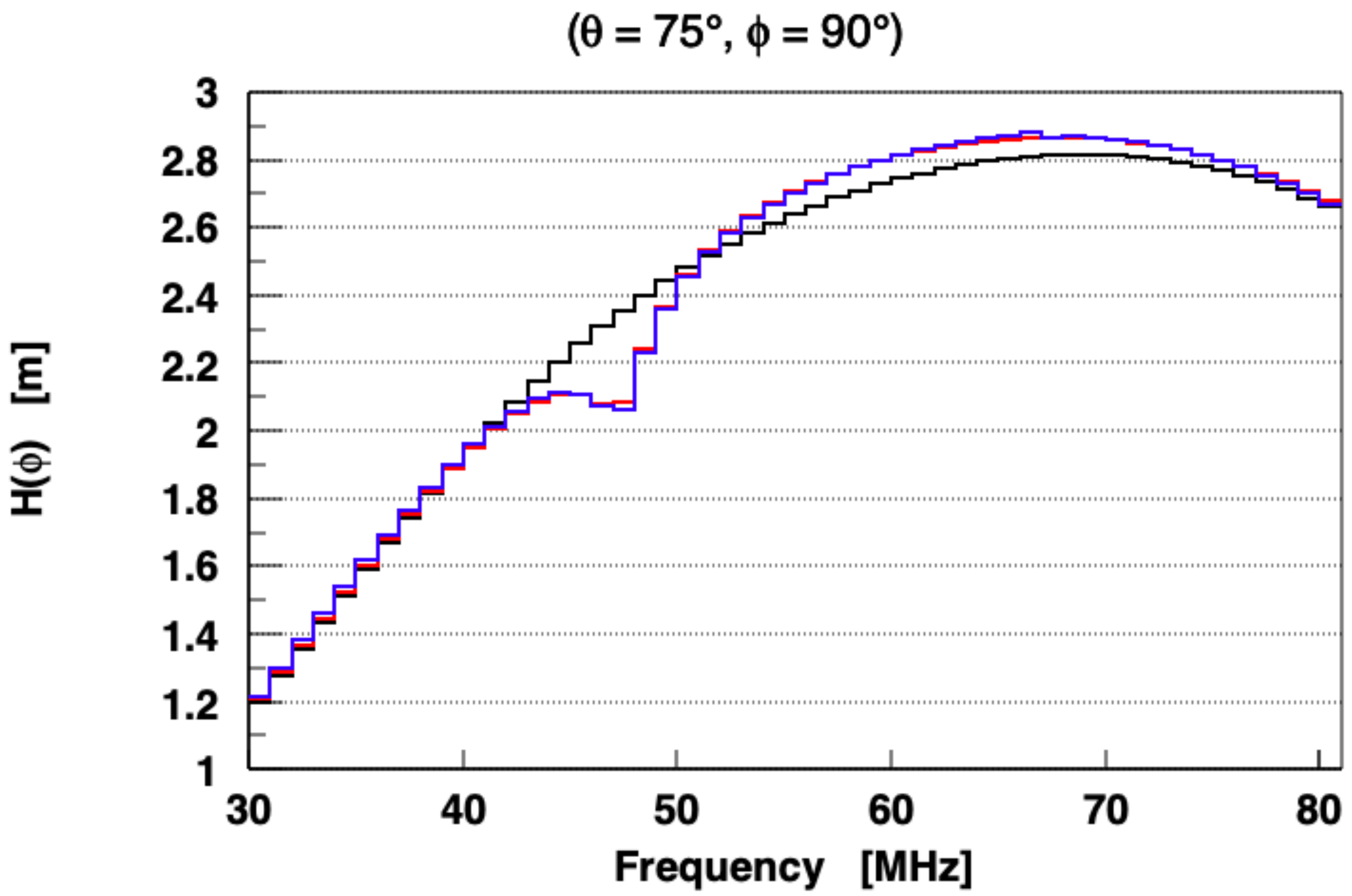



# Mast and supporting frame

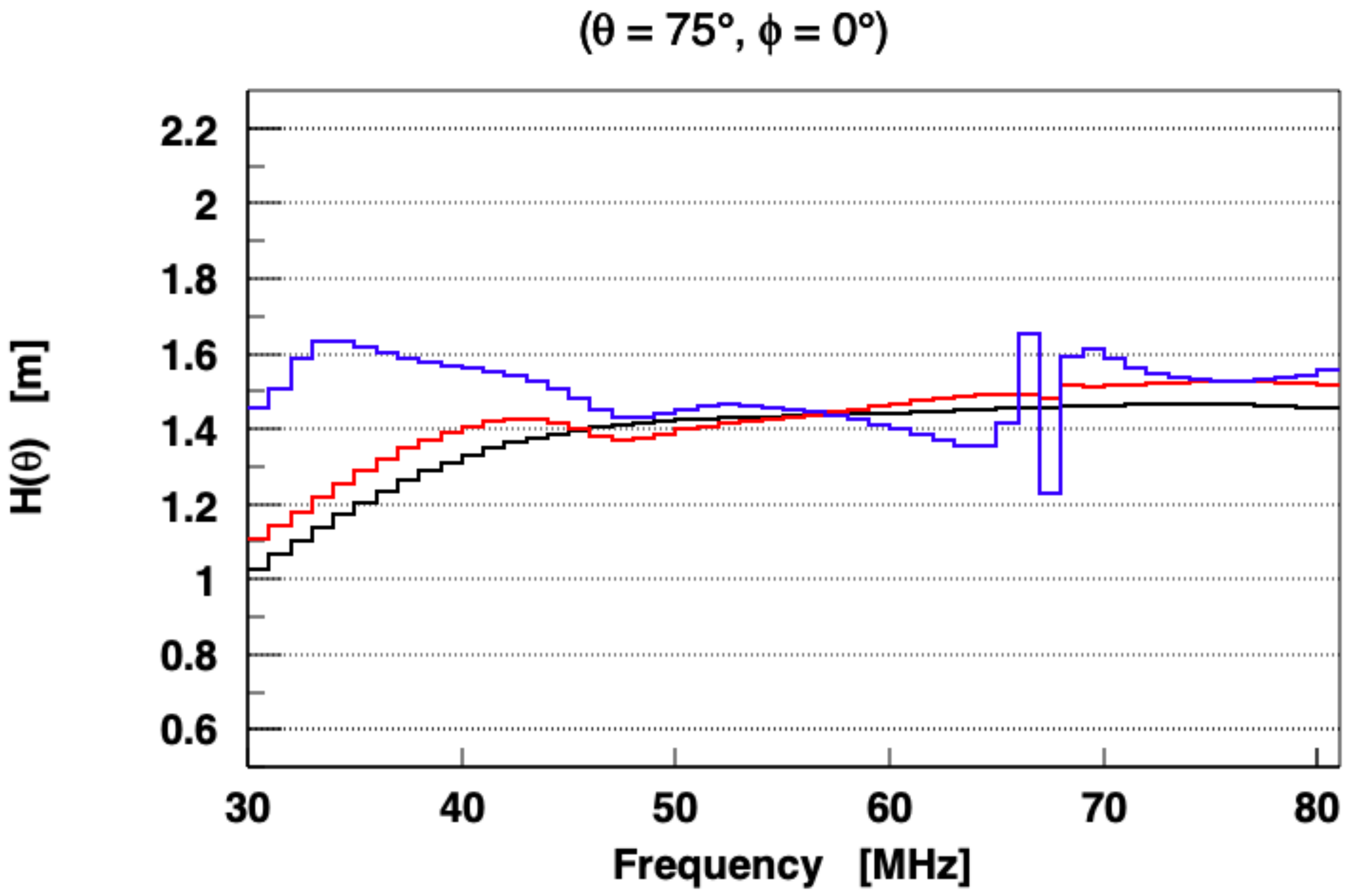
cable not in the centre
of the antenna

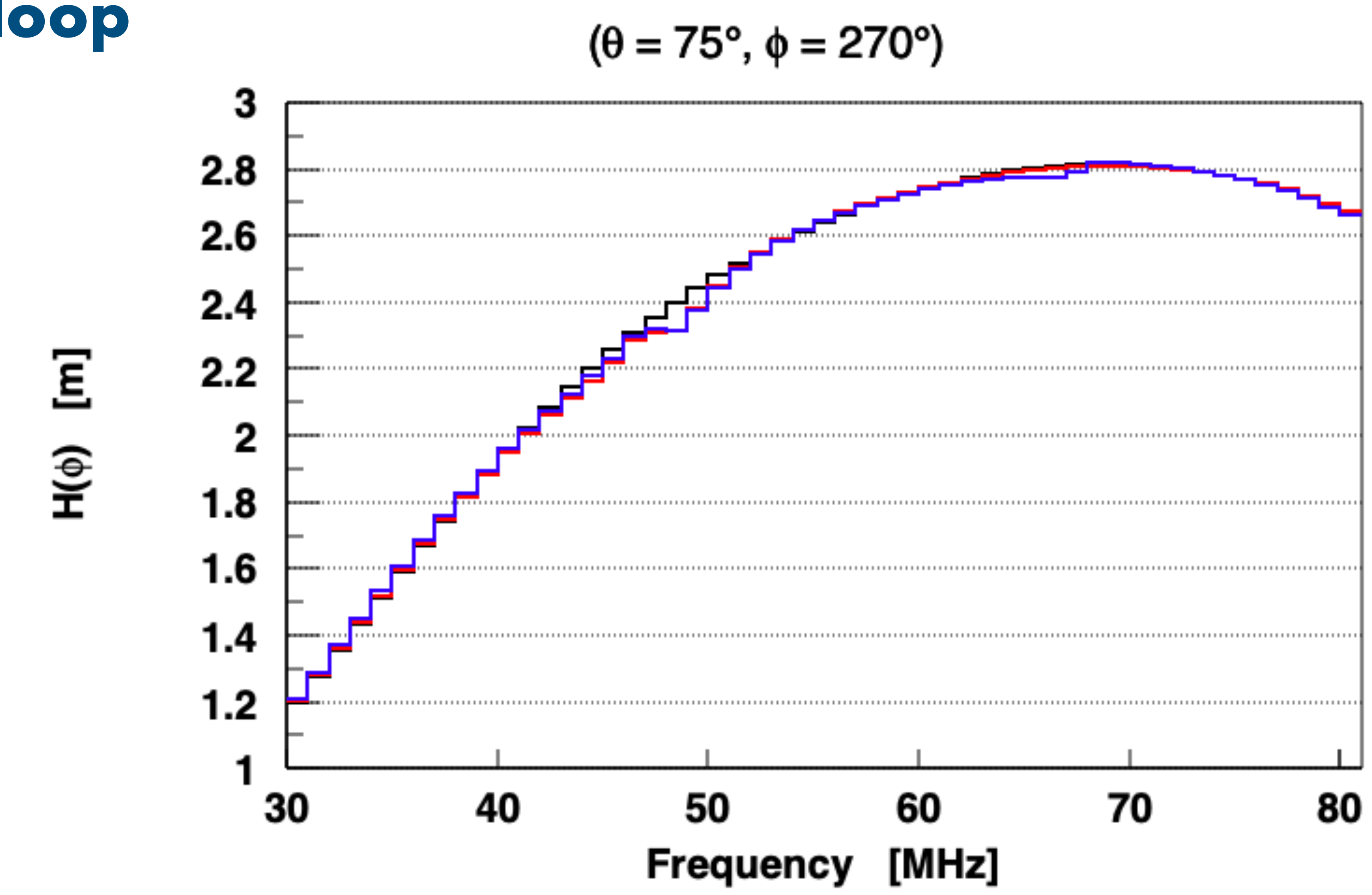




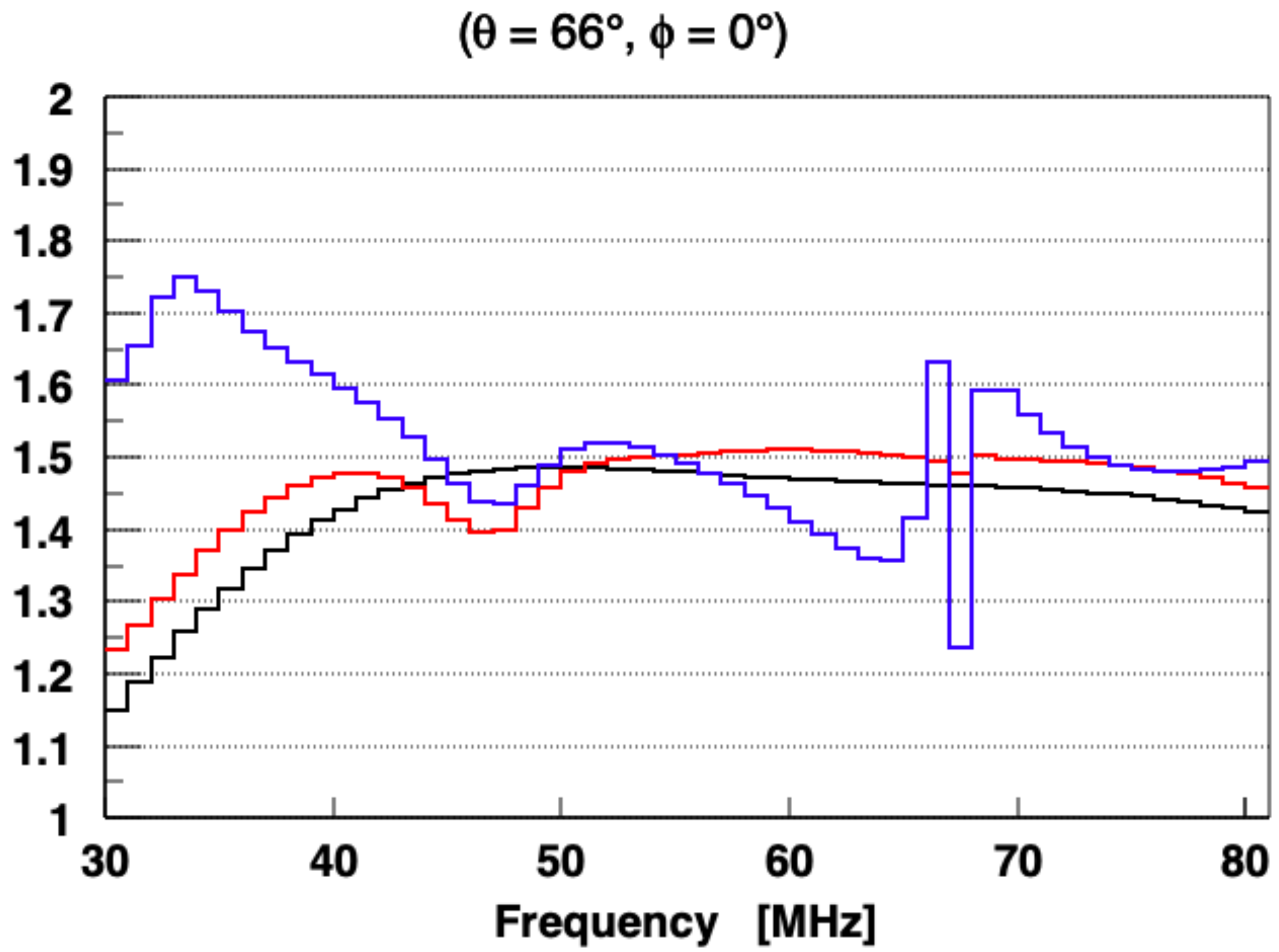

EW loop

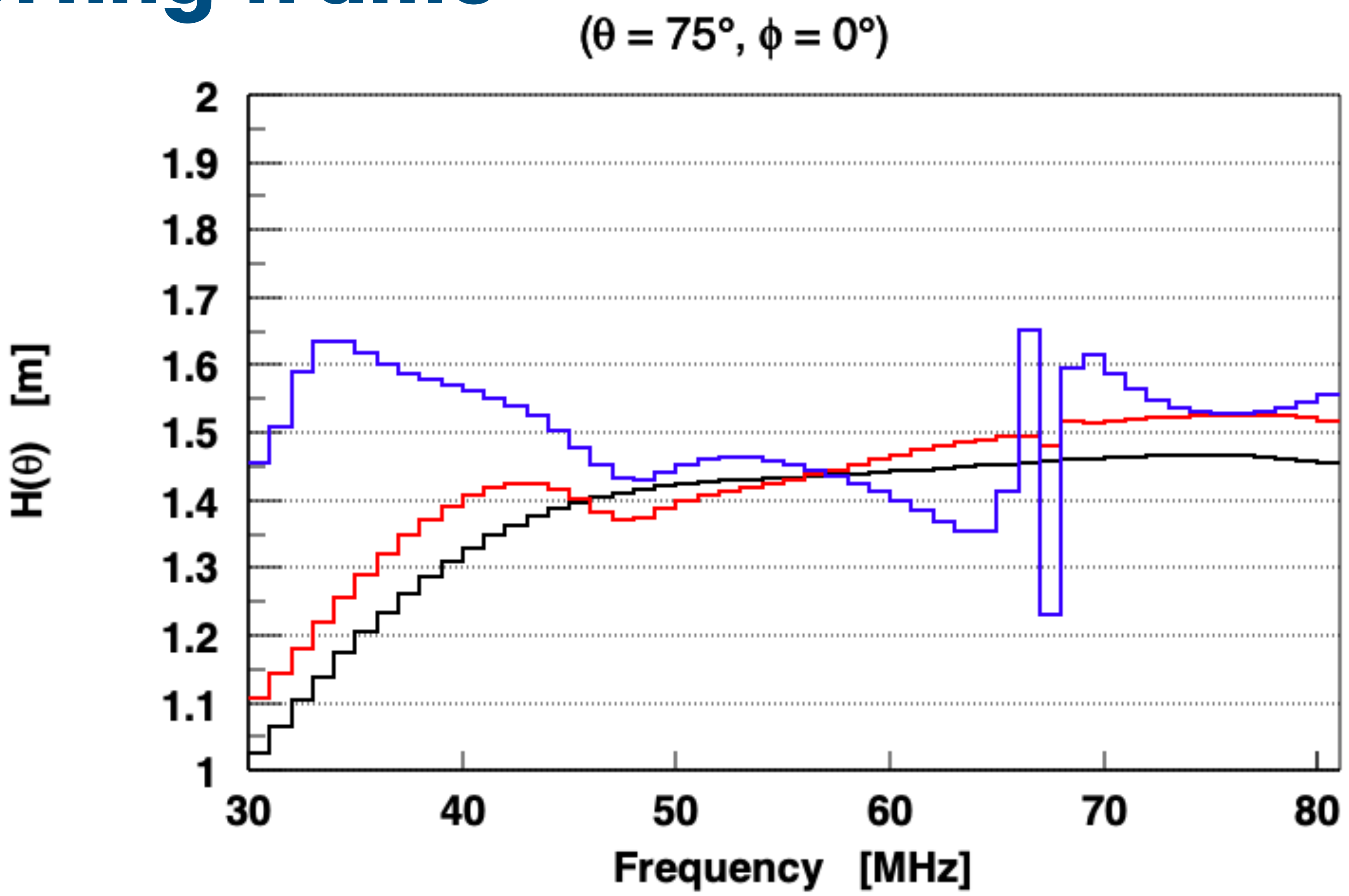


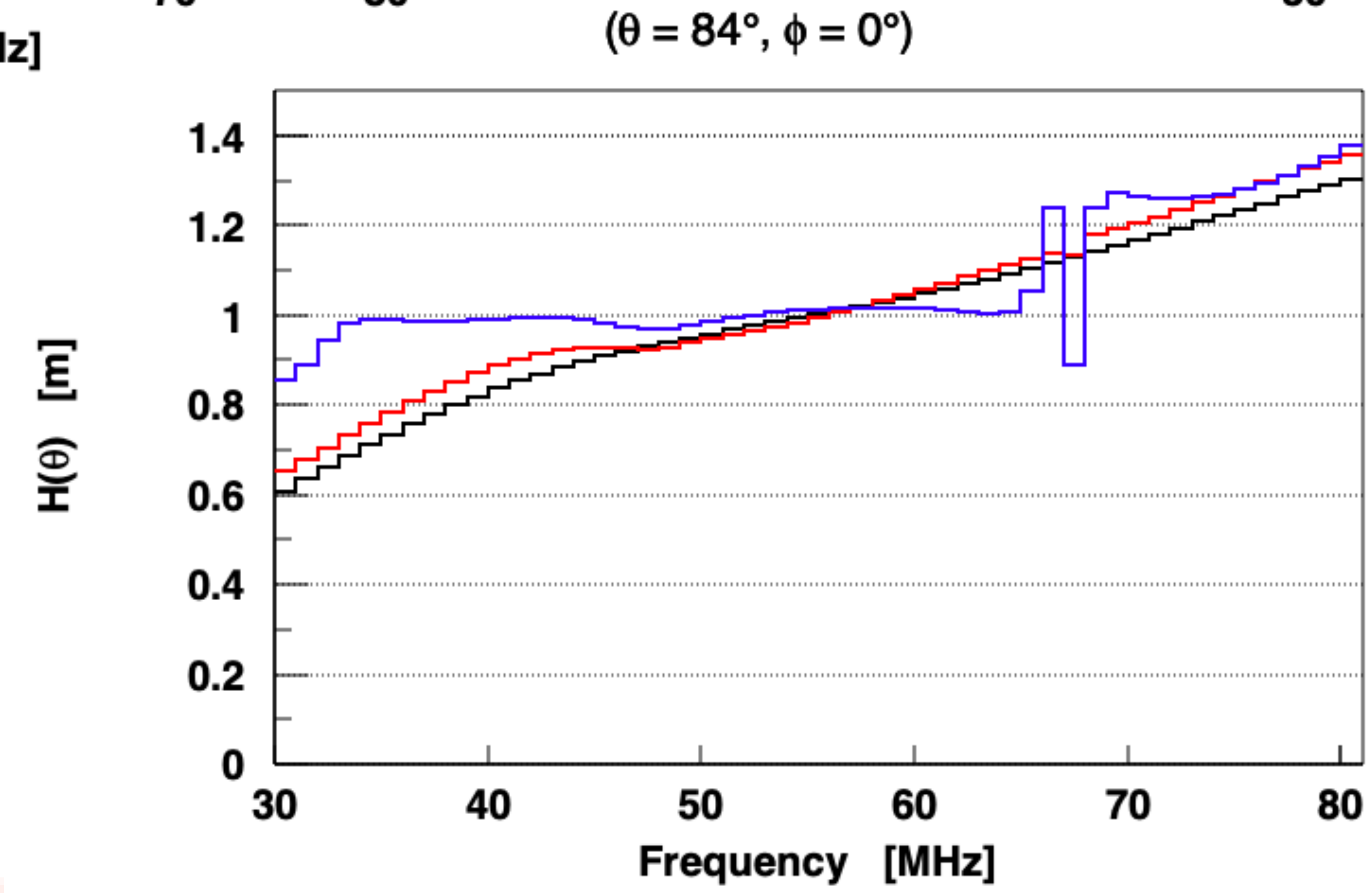




Effect
on antenna response

# Mast and supporting frame

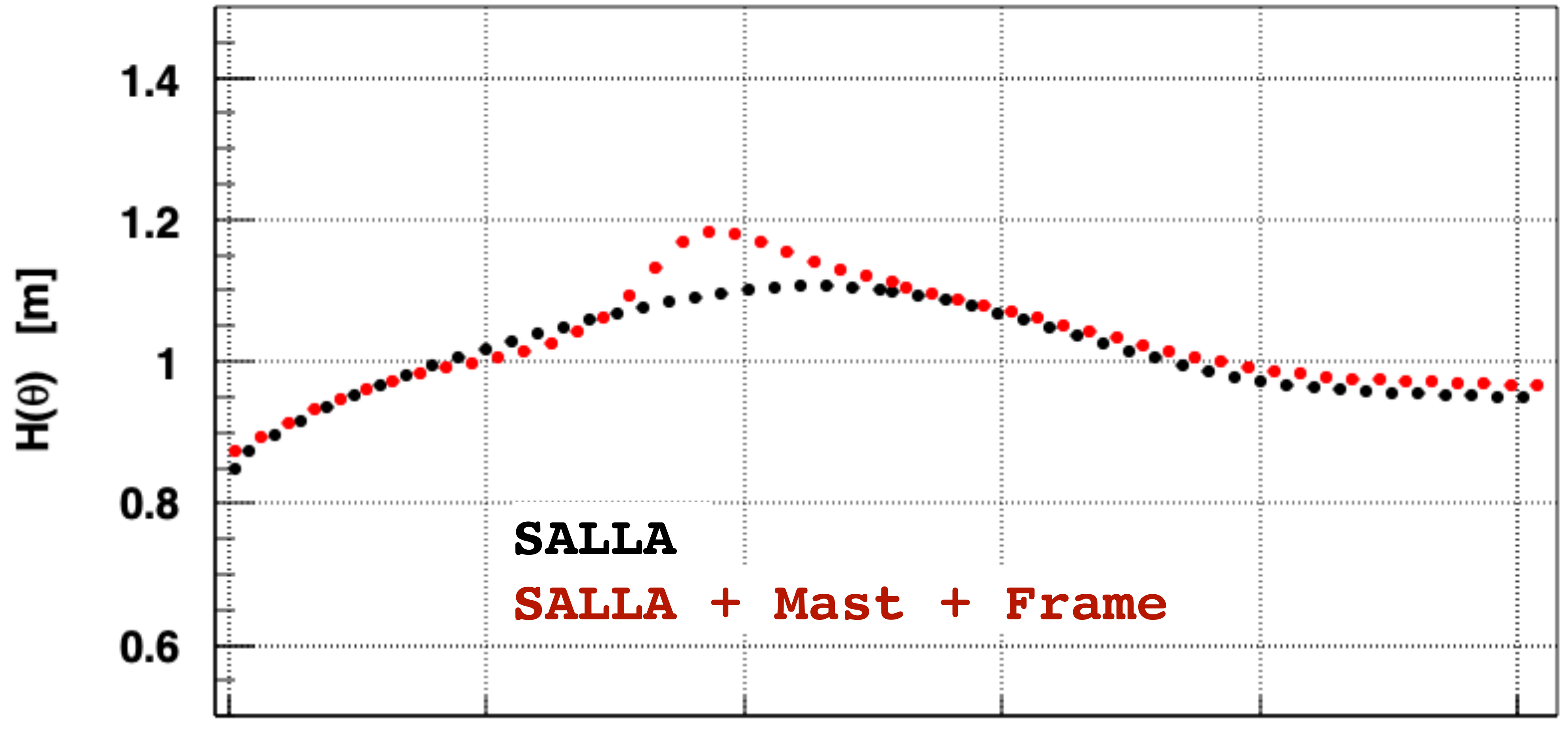


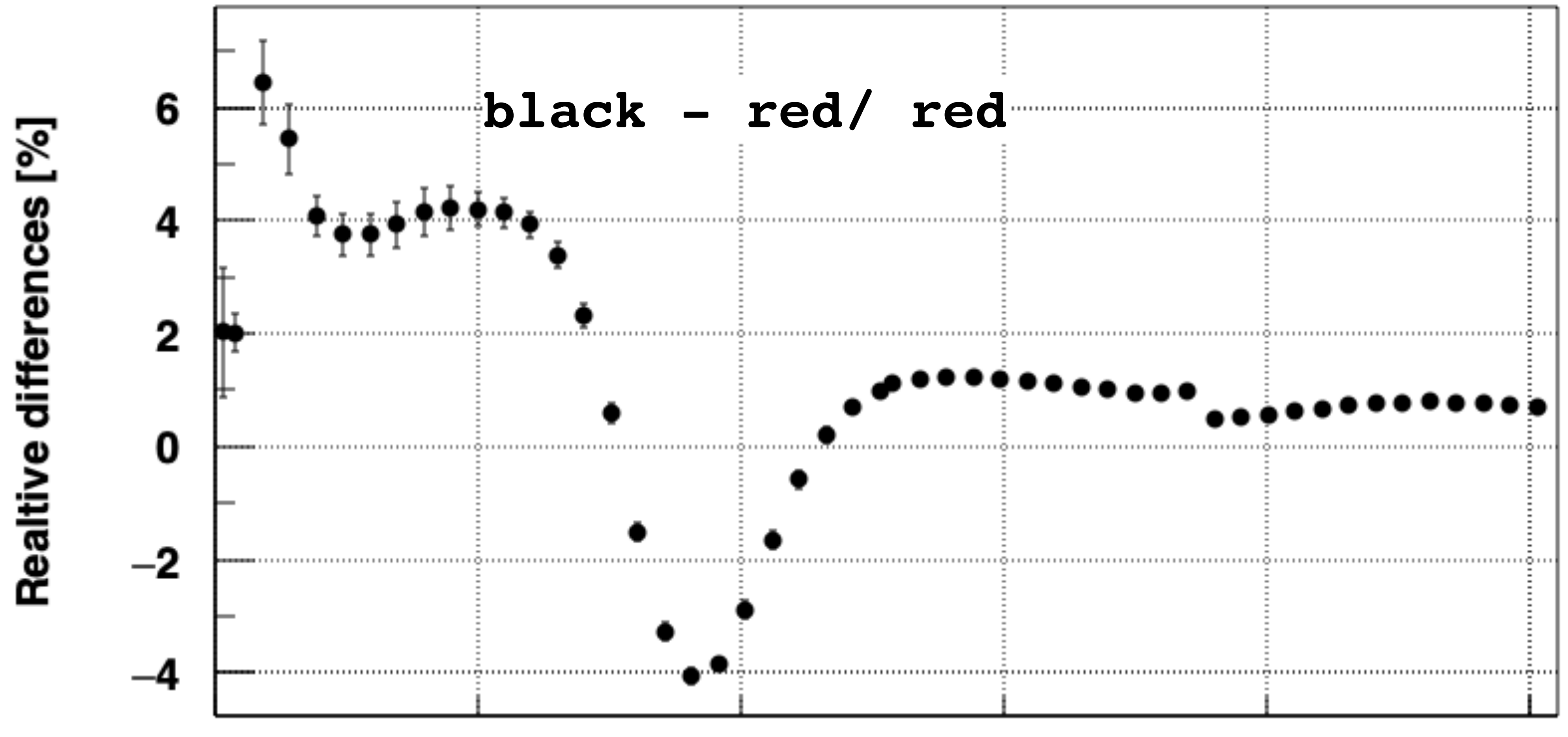



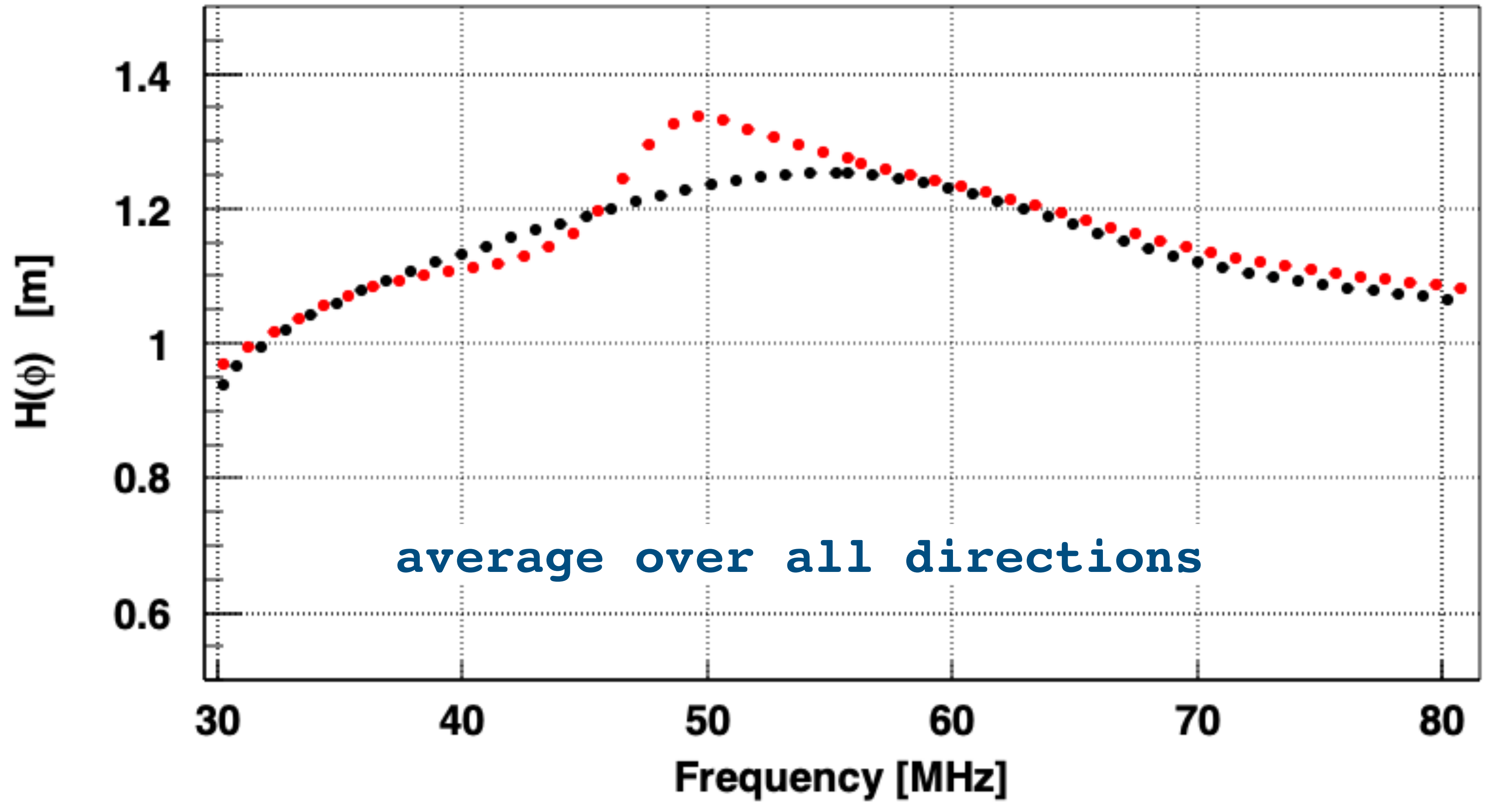



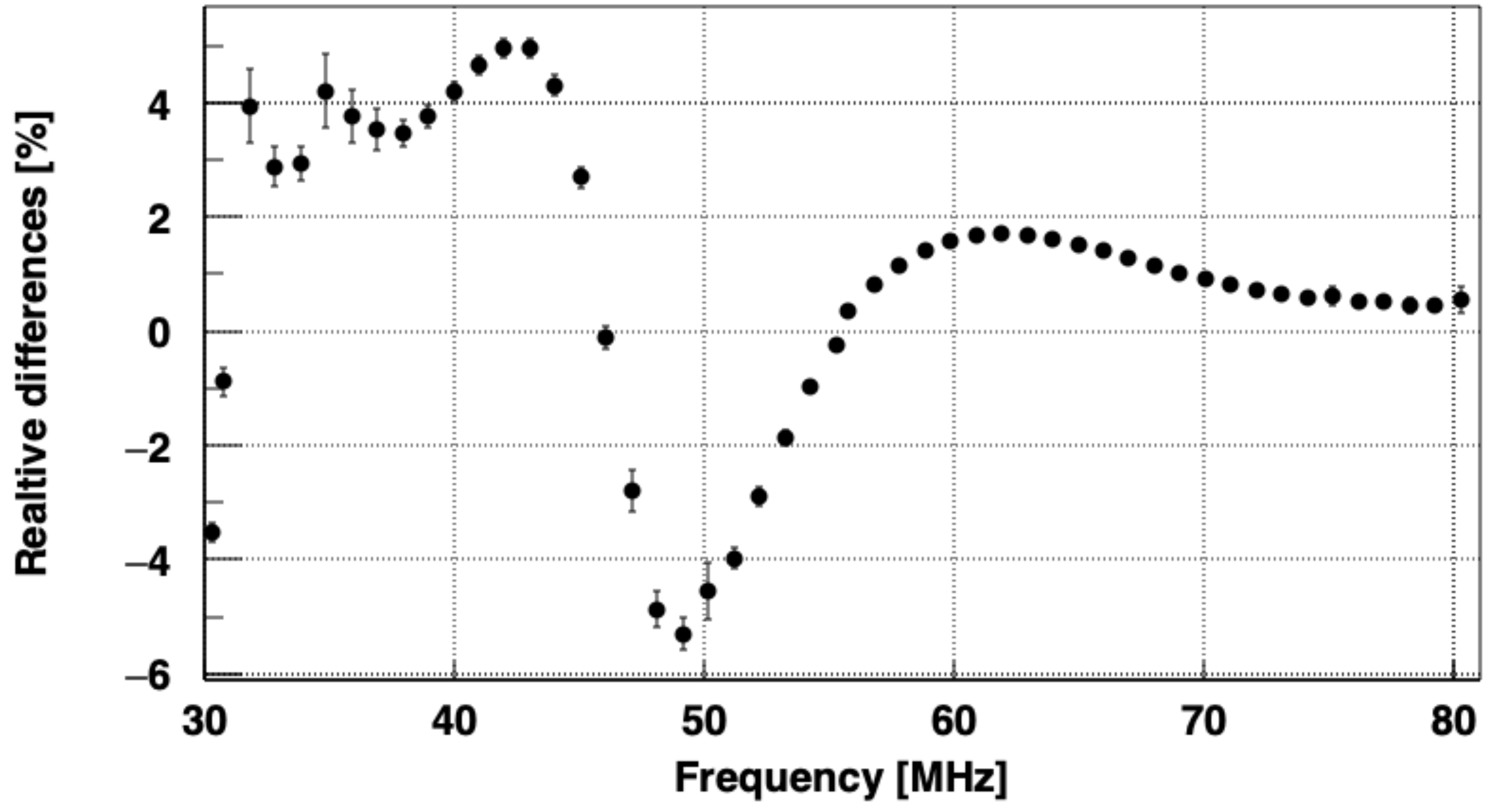
# Mast and supporting frame

EW loop



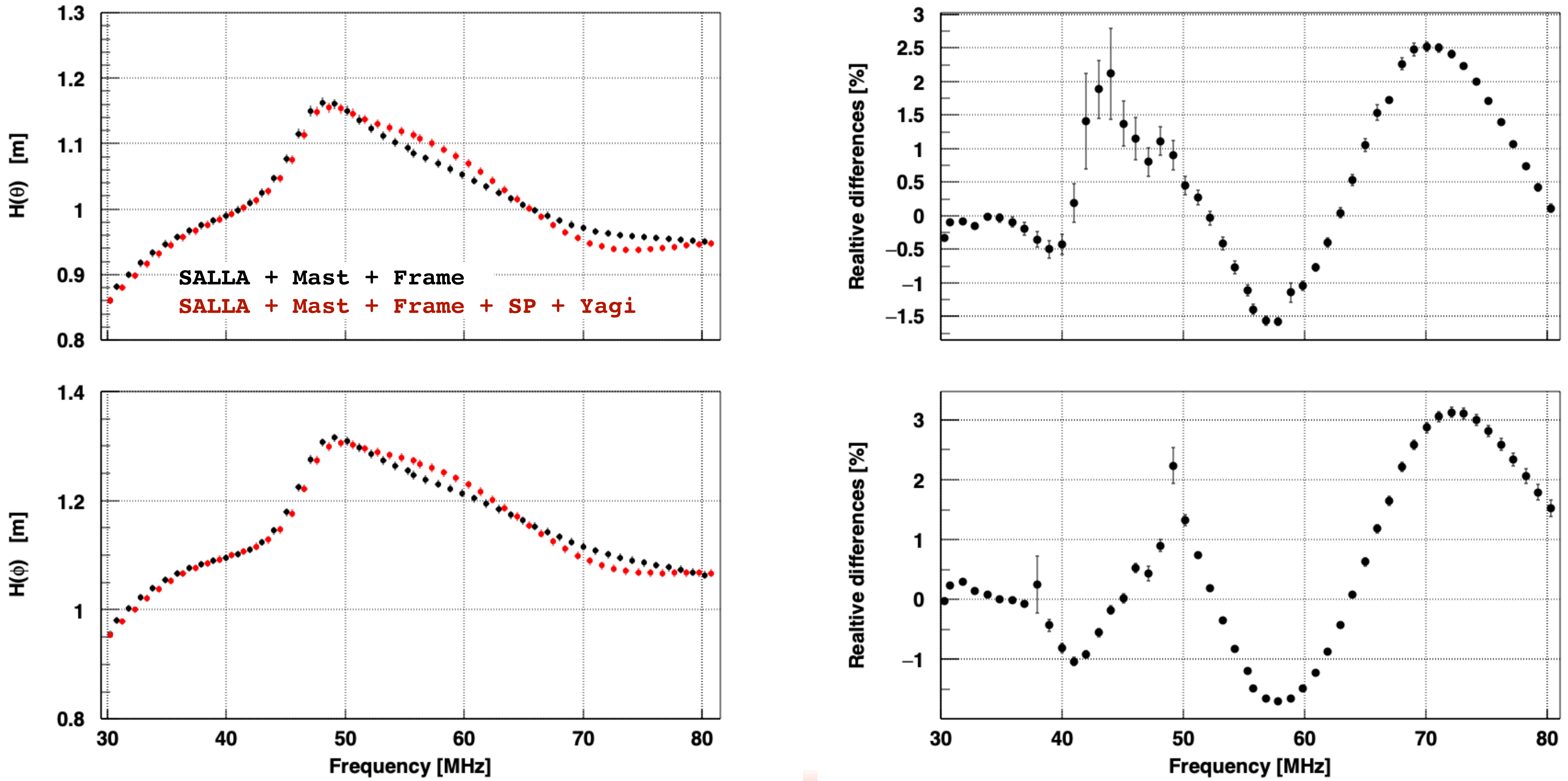



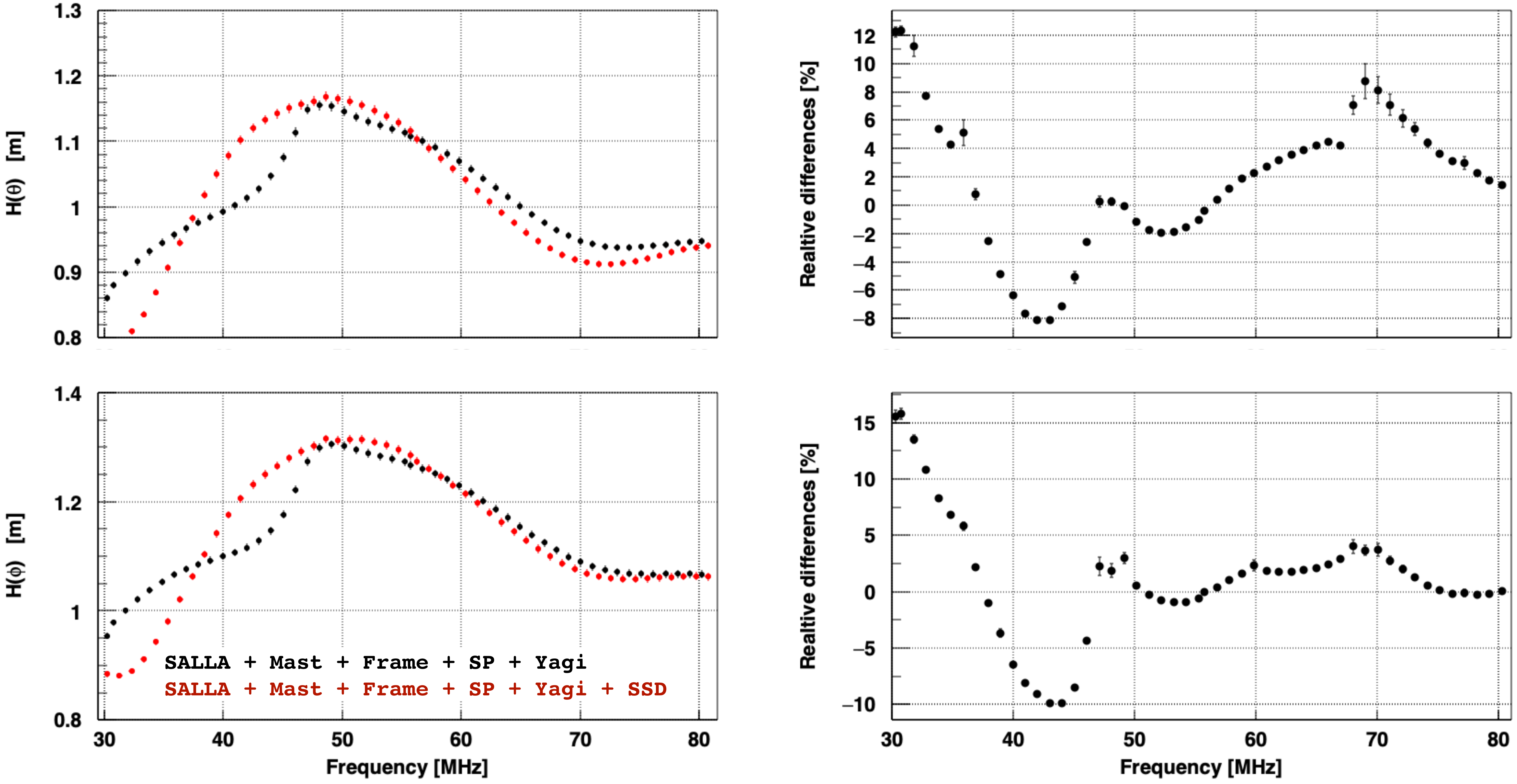
# Solar Panel & Communications antenna

EW loop



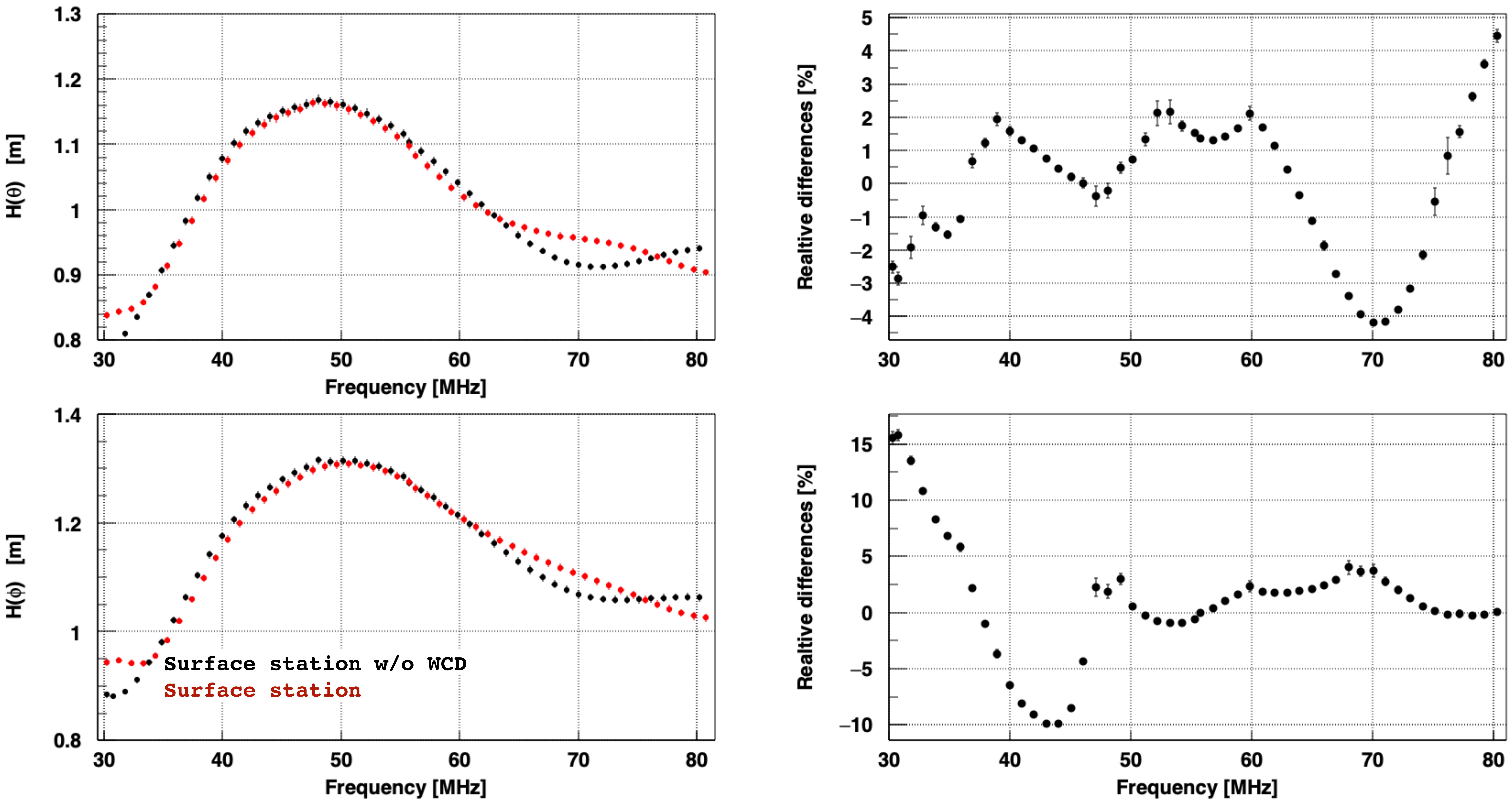
# Surface Scintillator Detector

EW loop



# Water Cherenkov Detector

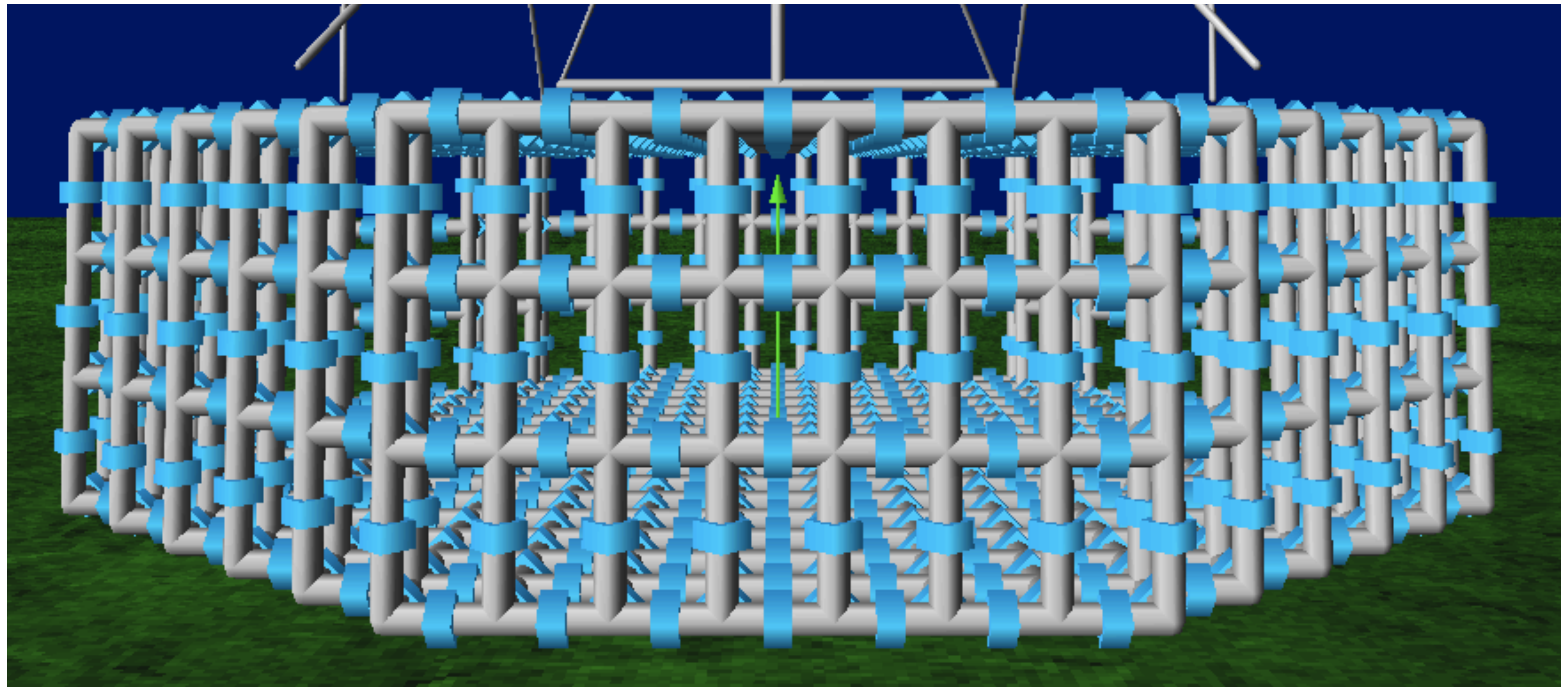
EW loop



# Modelling the WCD: Surface vs. Volume model

Can we improve the Nec model of the WCD? **No**

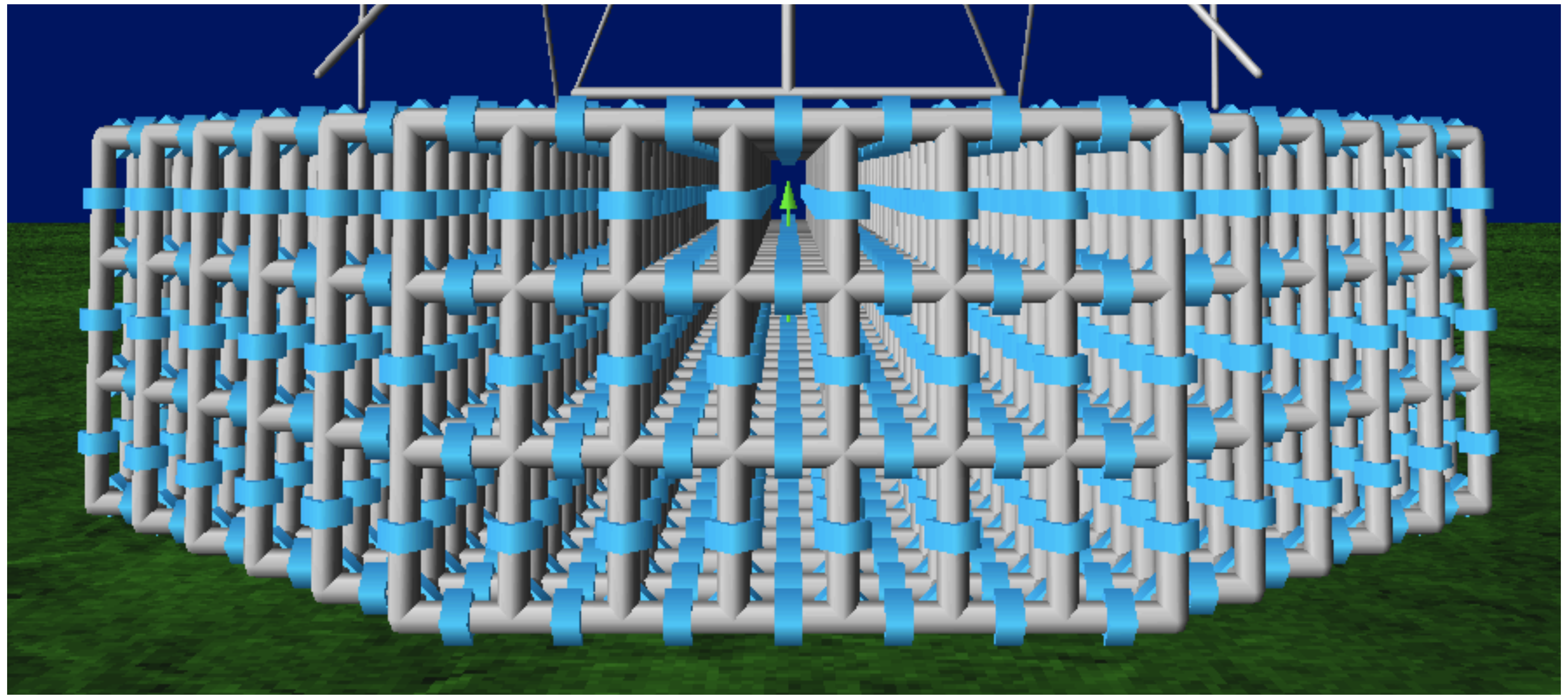
**Surface model** (previous slide)



**based on reflection proprieties of the water**

WCD shape with surface model
doesn't influence antenna response

**Volume model**



**based on the water properties**

better description of the refracted radiation
5% of the incident power re-radiated back in the air

With the volume model of the WCD we run into 4nec2 limitations (number of segments and loads)

# Water Cherenkov Detector: Surface model

Nec cannot simulate dielectric volumetric objects

Characteristic impedance of pure water (at 50 MHz)

$$\epsilon_r = 80 \qquad \mu_r = 0.999992 \approx 1$$

Reflection coefficient (for vertical radiation)

$$\Gamma = \frac{Z_0 - Z_L}{Z_0 + Z_L} = \frac{42 - 377}{42 + 377} \approx -0.8$$

with 47 ohms same reflection coefficient

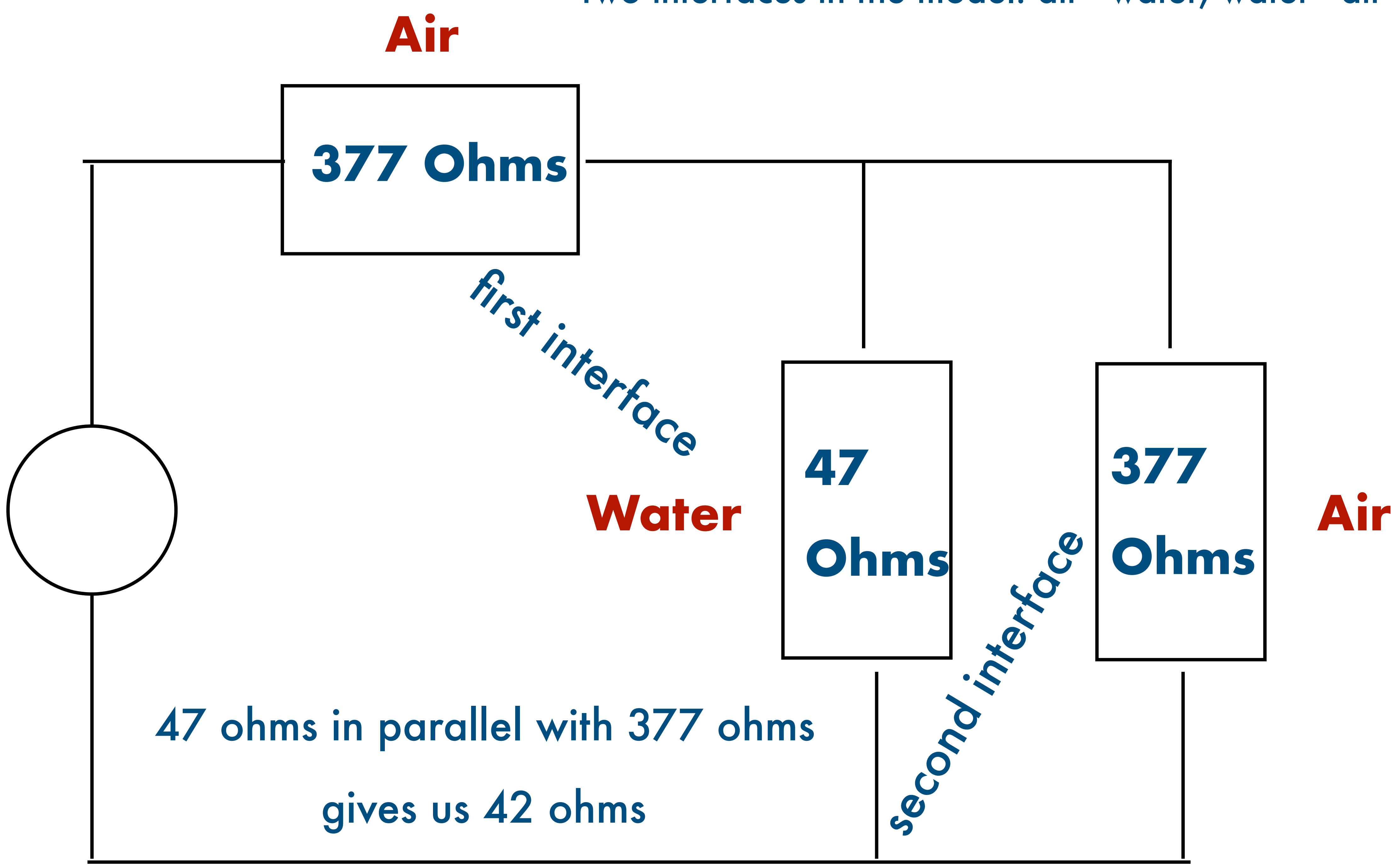
**Empty bow with $R_{sq}$ = 47 Ohms load (square resistance)**

based on reflection proprieties of pure water

$$Z = \sqrt{\frac{\mu}{\epsilon}} = \sqrt{\frac{\mu_0 \mu_r}{\epsilon_0 \epsilon_r}} = \sqrt{\frac{\mu_0}{\epsilon_0 \epsilon_r}} = \frac{Z_0}{\sqrt{\epsilon_r}} \approx \frac{377\ \Omega}{\sqrt{\epsilon_r}} \approx 42\ \Omega$$

One interface (real situation): air - water

Two interfaces in the model: air - water, water - air



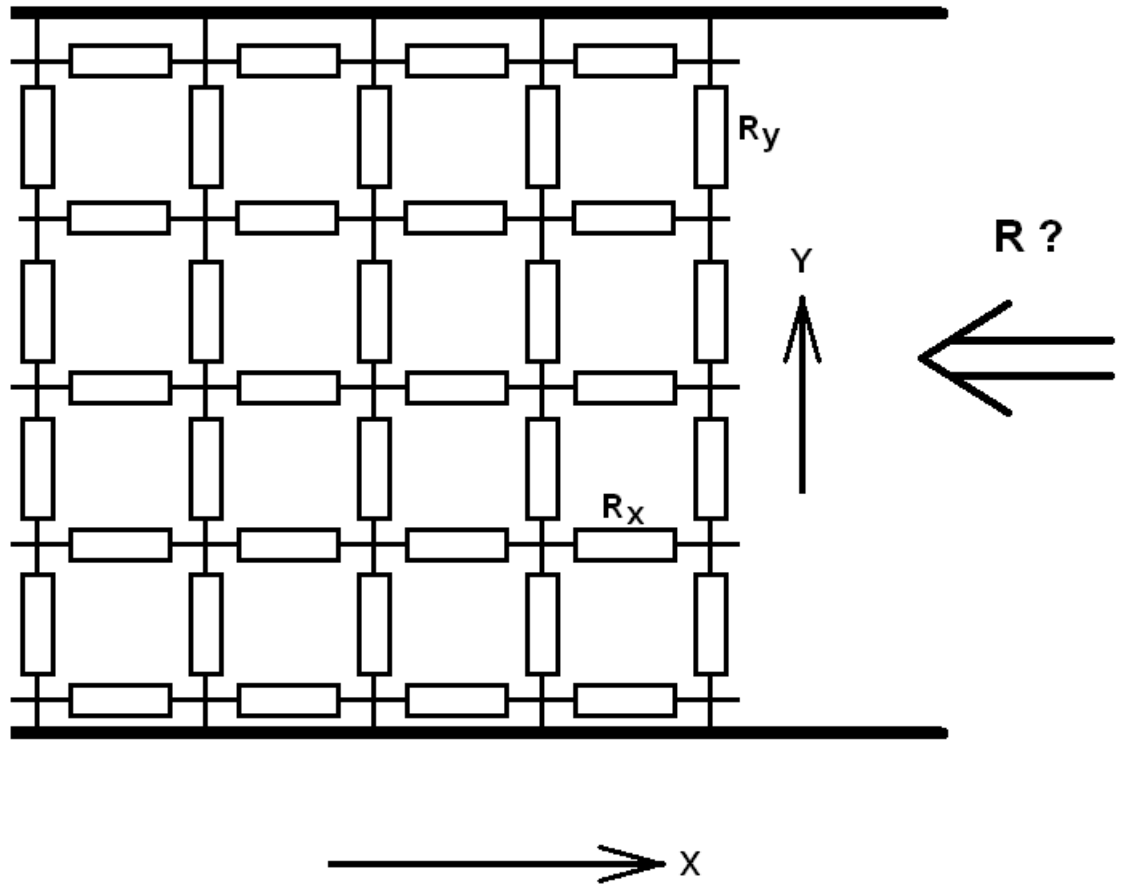
# Square resistance $R_{sq}$ of a mesh

Nec model: **WCD** modelled as an octagon, top/bottom mesh (0.2*0.2 m2) and on the side (0.2*0.3 m2) . **Loads** constant in the full 30-80 MHz range.

**$R_{sq}$ = 47 Ohms in our case**

resistor

for a square



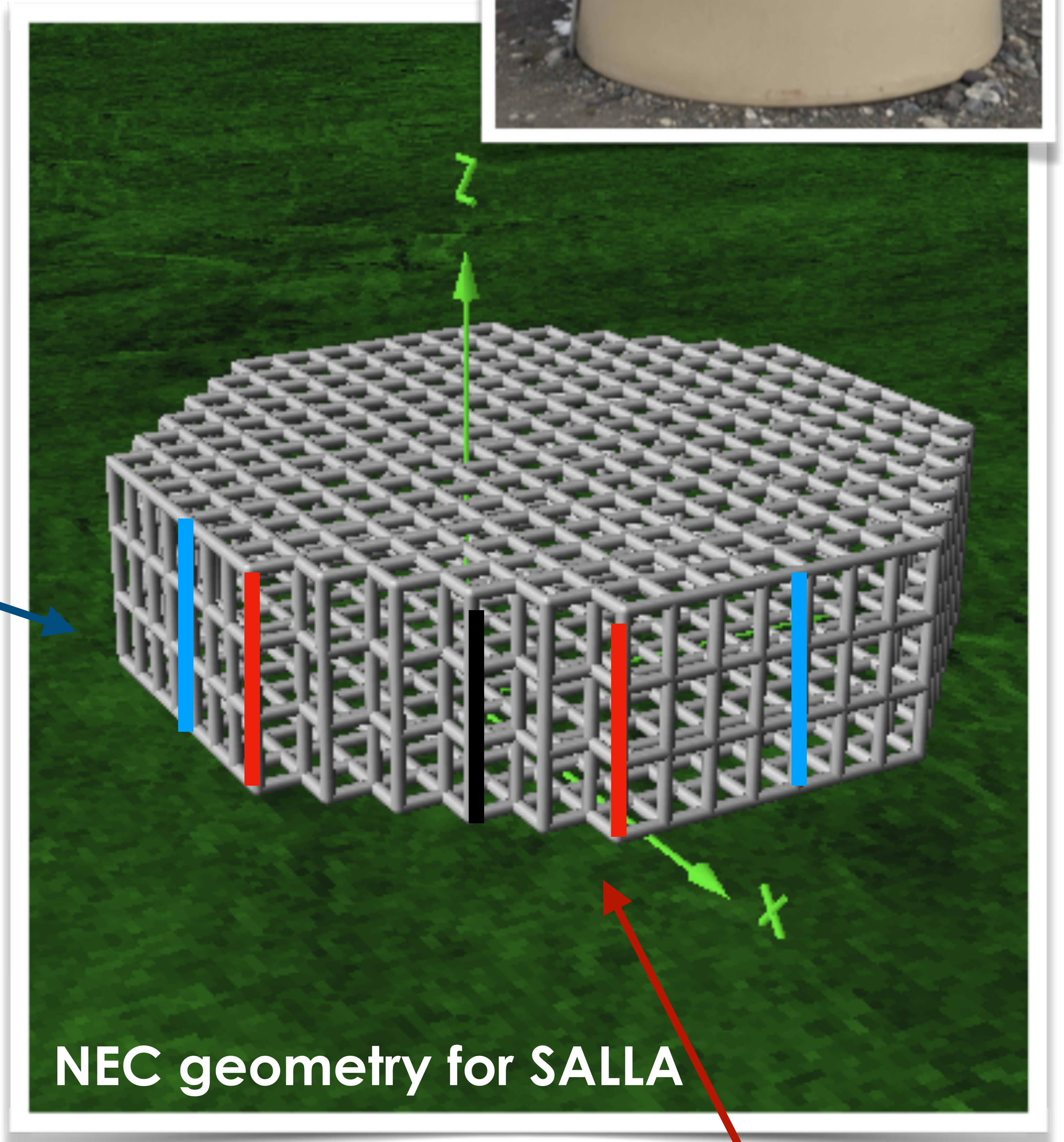

Regular side

Nx = 7, Nz = 3

Rx = 31.3 Ohms

Rz = 70.5 Ohms

for the octagonal model




$R_{sq,\,x} = R_y N_y / N_x = R_y L_x / L_y$

$R_{sq,\,y} = R_x N_x / N_y = R_x L_y / L_x$

**N = number of resistors**

**L = length of mesh in the relevant direction**

**With the model reflecting of the water properties we run into 4nec2 limitations**
(number of segments and loads)

Digitalised “zig-zag"side

Nx = 10, Ny = 3

Rx = 21.9 Ohms

Rz = 101 Ohms

At the border take

the arithmetic mean

Rz = 86 Ohms