Time-Domain Waveform Studies for ARIANNA

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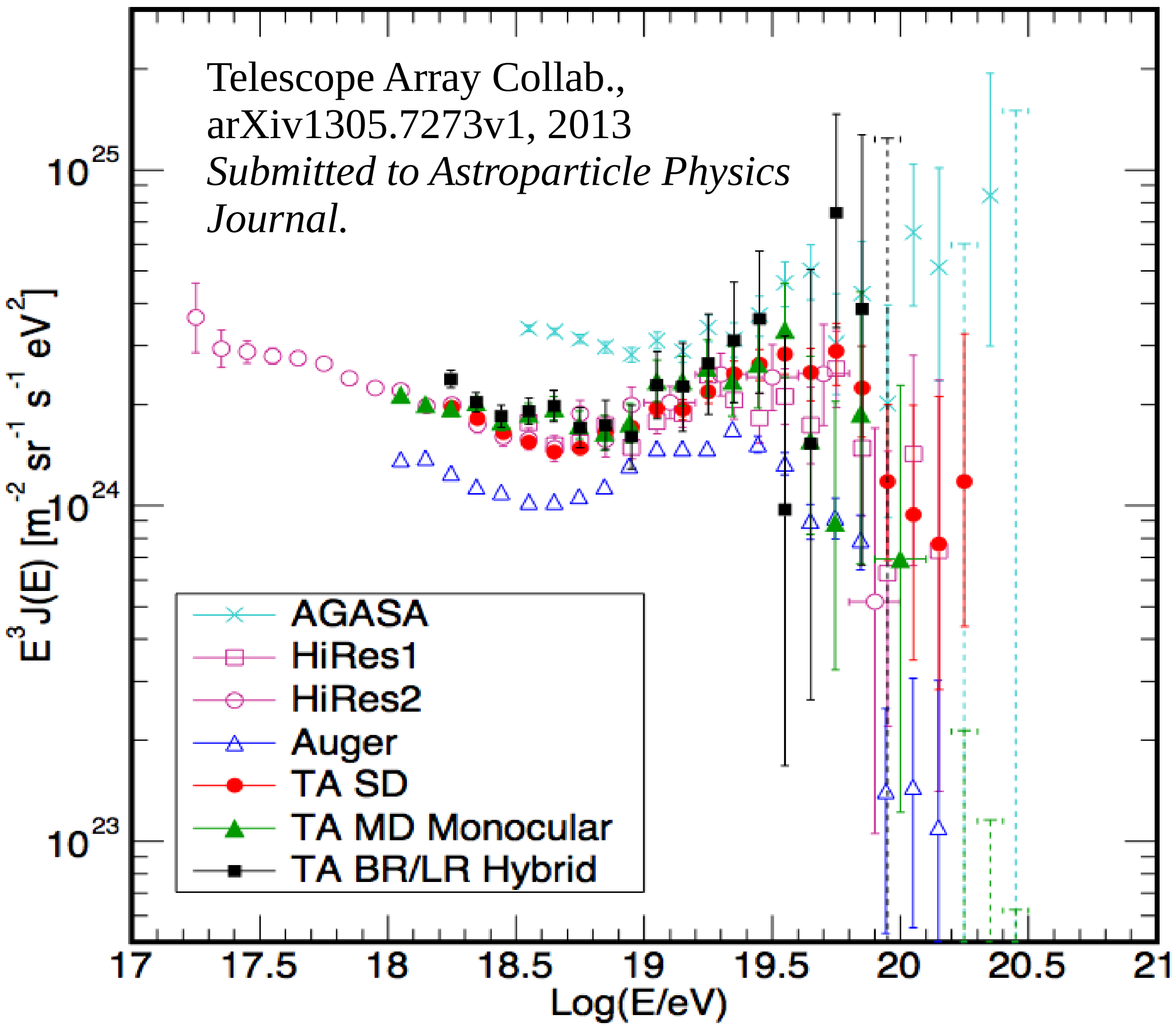
Ultra-High Energy Neutrino Parallel Session, TeVPA (2013)

August 26th, 2013

Outline

- **How we plan to detect *high-energy neutrinos* via the Askaryan effect**
- **Conversion of analytical electric fields to voltage waveforms in ARIANNA DAQ (LTI systems)**
- **Anechoic Chamber measurements performed at the University of Kansas**
  - ***Experimental Setups (4)***
  - ***Types of data taken (scalar versus frequency, time-domain waveforms)***
- **Calculation of *effective height* operator of the signal antenna**
  - ***The best-fit effective height operator***
  - ***Including the AC-coupled low-noise amplifier (LNA)***
  - ***Checking off-axis***
- **Deriving *template waveform induced by neutrino interaction* in ice**
- **Future work**

High Energy Cosmic Ray Spectral Cutoff (GZK effect)



Nucleon-photon* threshold effect which produces secondary particles, including *neutrinos

What is the precise origin of these particles?

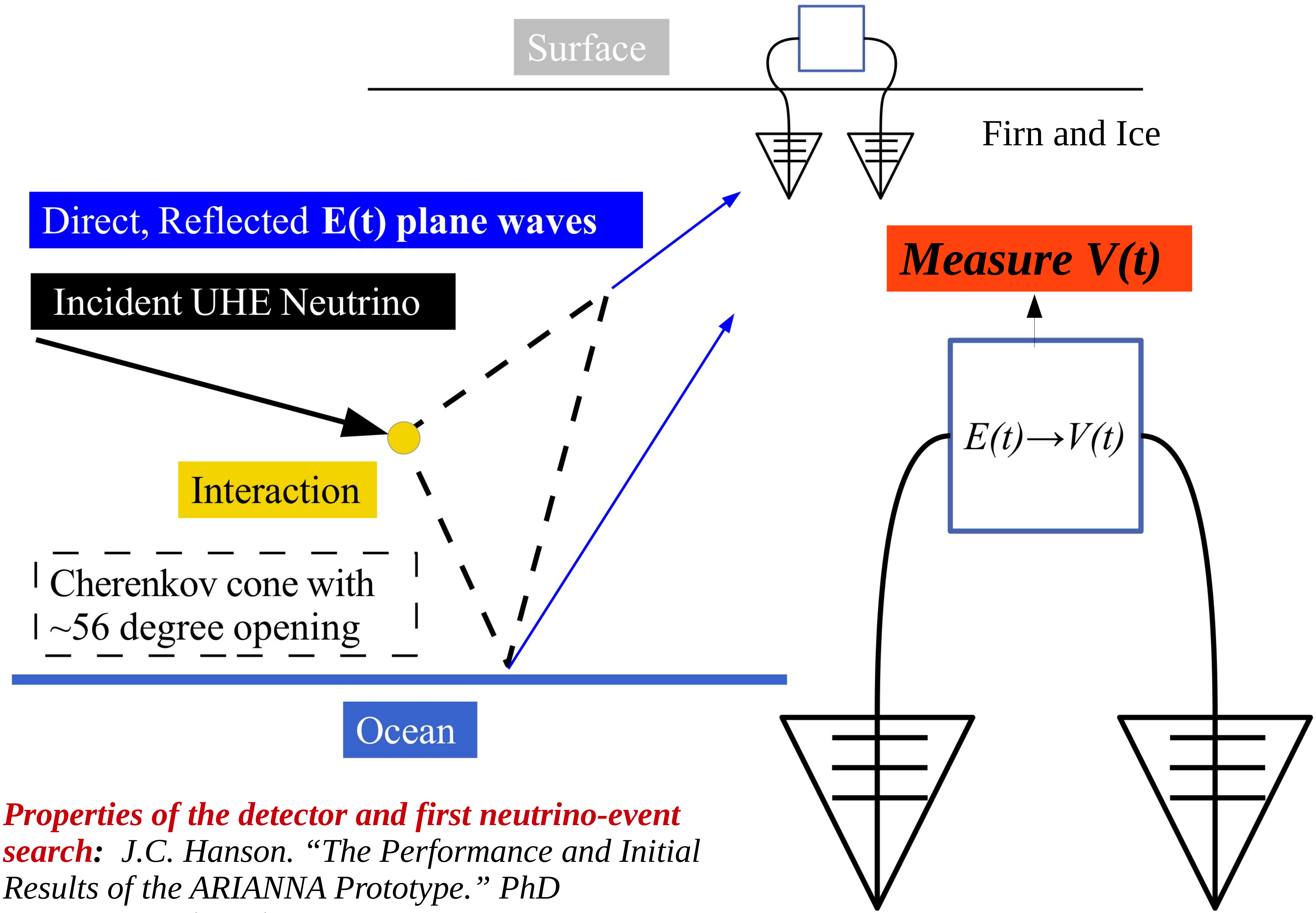
How heavy are they (are they mostly protons, or heavier)?

How does a neutrino interact with matter at COM energy of 100 TeV?

$$p^+_{CR} + \gamma_{CMB} \rightarrow \Delta^+ \rightarrow p^+ + \pi^0 \rightarrow p^+ + 2\gamma$$

$$p^+_{CR} + \gamma_{2.7K} \rightarrow \Delta^+ \rightarrow n^0 + \pi^+ \rightarrow n^0 + \mu^+ + \nu_\mu \rightarrow n^0 + e^+ + \nu_e + \nu_\mu + \bar{\nu}_\mu$$

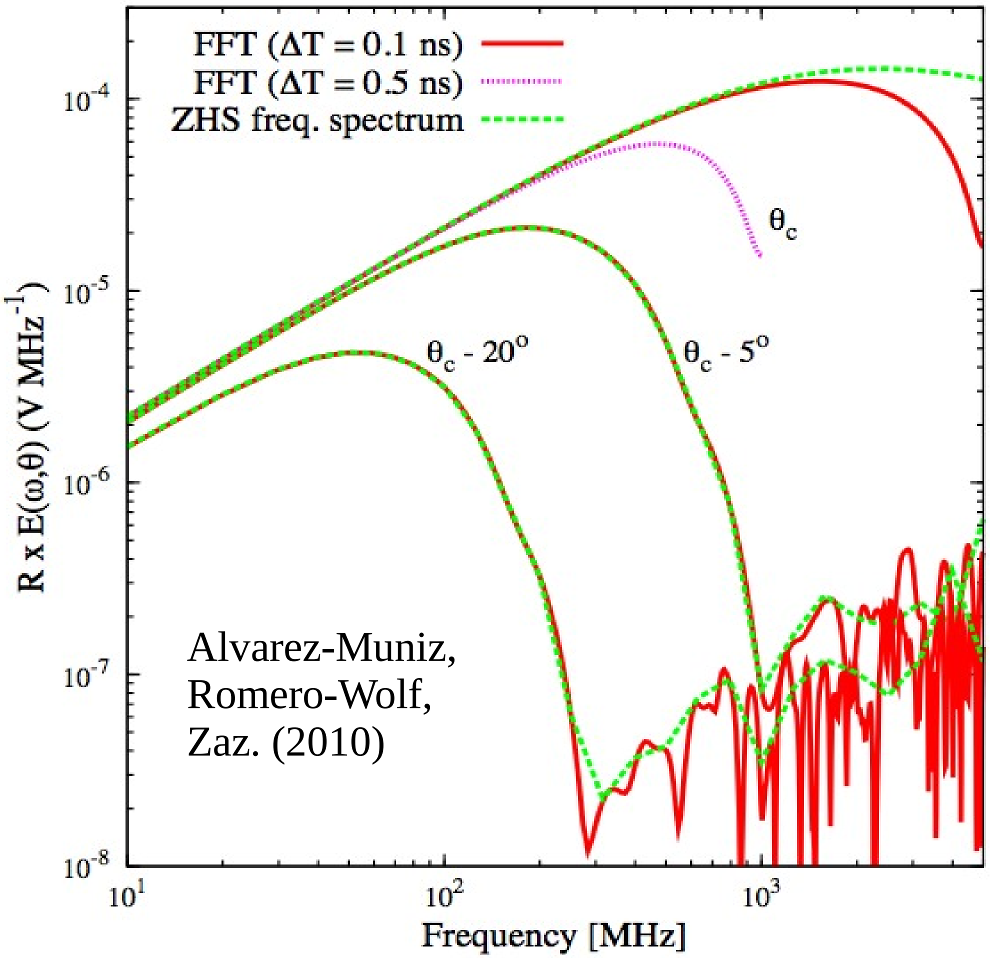
Statement of the Problem



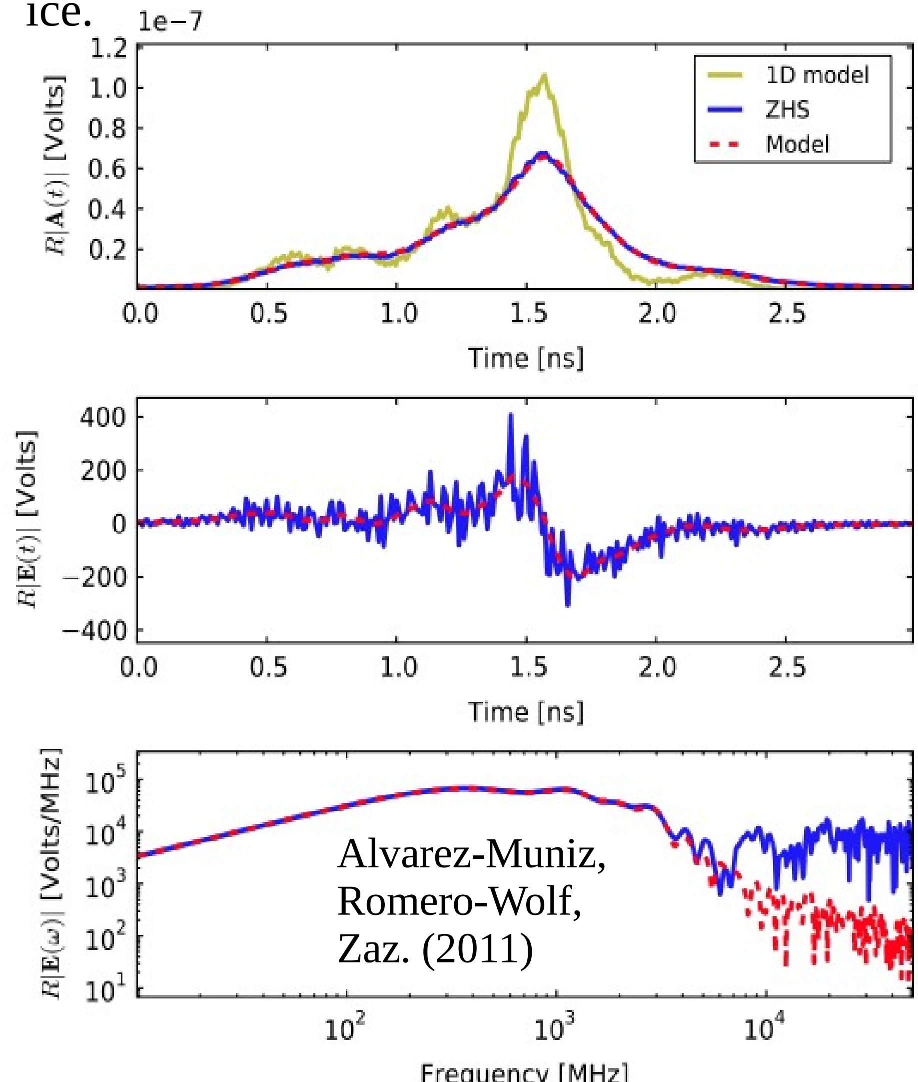
Properties of the detector and first neutrino-event search: *J.C. Hanson. "The Performance and Initial Results of the ARIANNA Prototype." PhD Dissertation. (2013)*

Statement of the Problem, II: the signal to detect

Spectrum of electric field from 1 PeV shower in ice

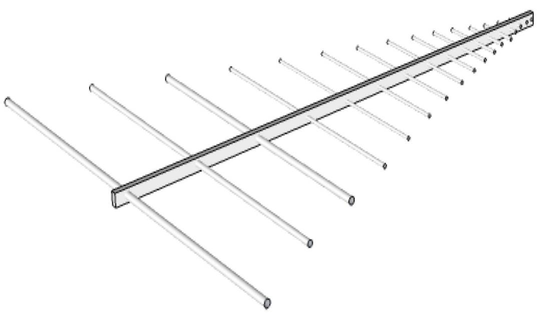


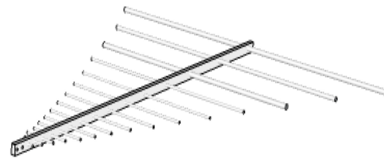
Spectrum+time-domain of 3 EeV shower in ice.

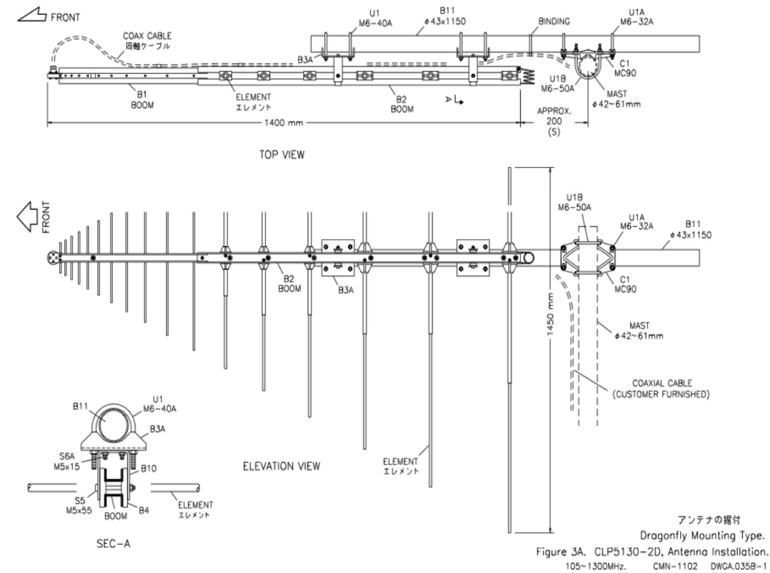


Search: ***1 GHz*** ***bandwidth,*** ***several hundred V/m*** ***electric field pulse traveling ~ 1 km through*** ***ice***

The signal antenna: Log-Periodic Dipole Array







Example of a ***frequency-independent*** antenna (bandwidth of 100-1300 MHz)

Radiation pattern is maximal in direction of ***bore-sight*. ** The *bore-sight* configuration (shown above) optimizes reception.

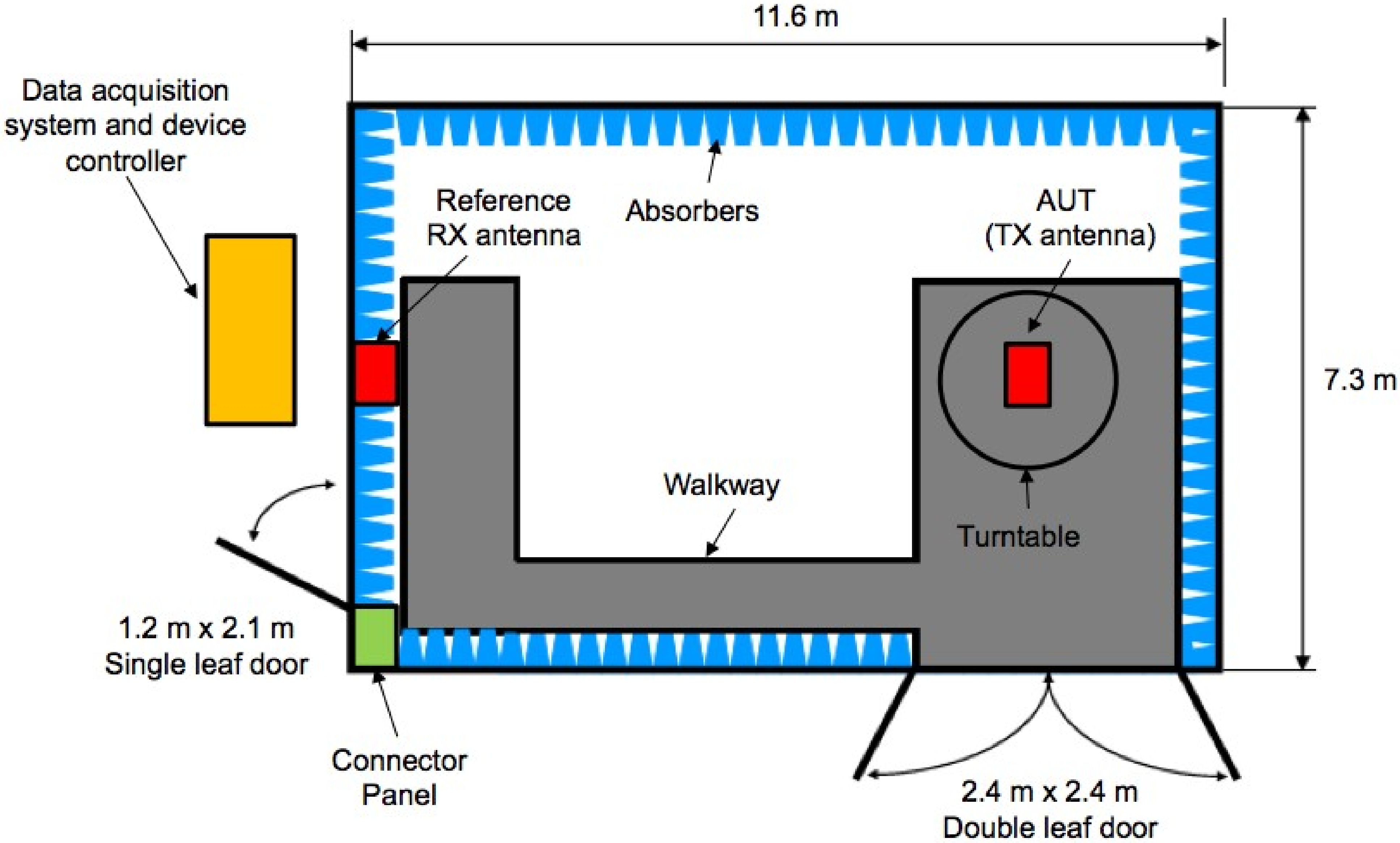
Linearly polarized*.** The E-plane is the plane containing the dipole elements, the H-plane is perpendicular to E-plane, containing only the ***spine of the antenna

Linear Time-Invariant System

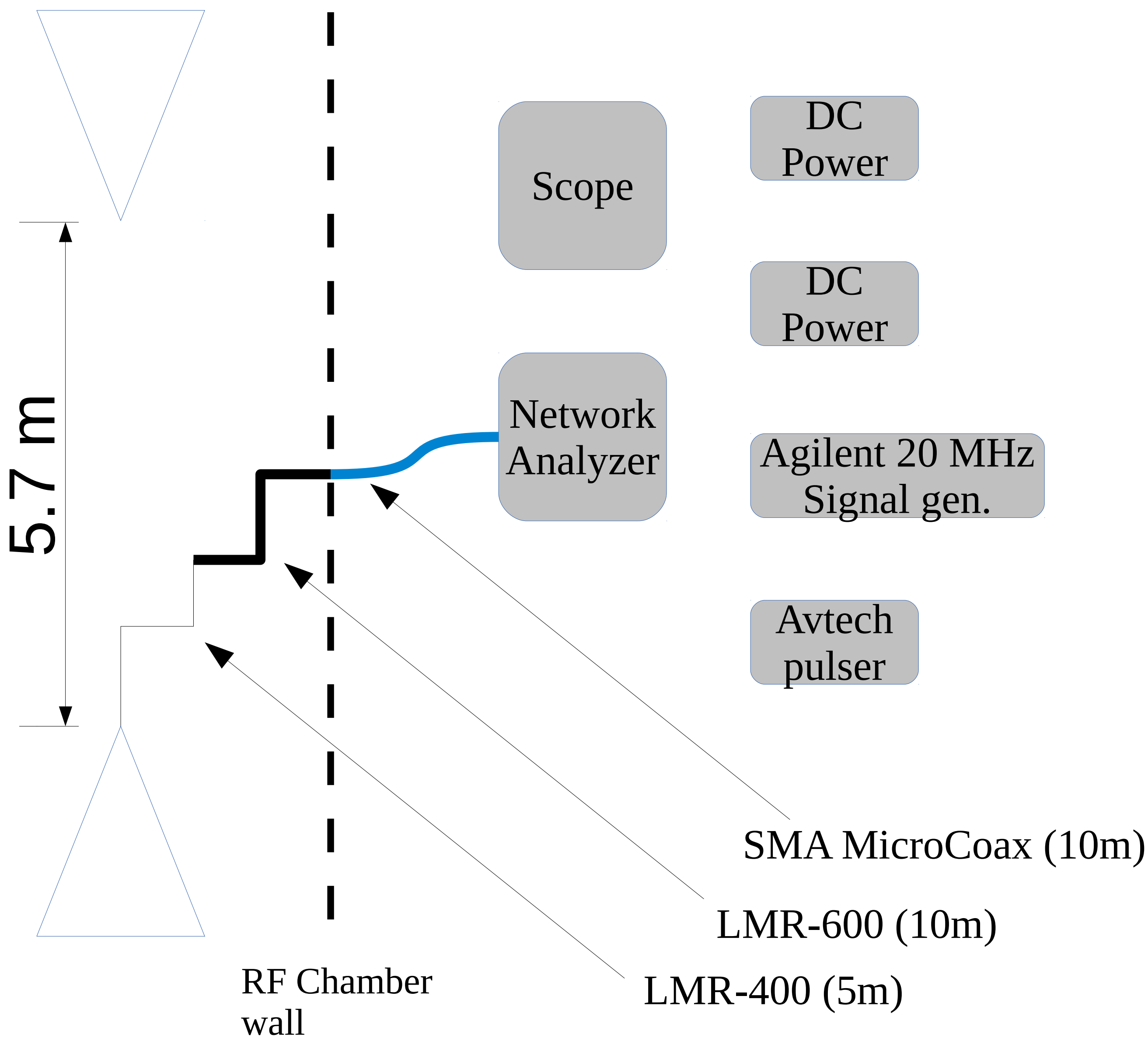
- ***Two property** system with single input x(t), single output y(t)*
  - ***Linearity:** $ax_1(t)+bx_2(t) = ay(t)+by(t)$*
  - ***Time-invariance:** $ax(t-T) = ay(t-T)$*
  - ***The convolution integral with kernel r satisfies these two criteria***
- ***Convolution:*** $$y(t)=\int_{-\infty}^{\infty} r(\tau)\, x(t-\tau)\, d\tau$$
- ***Specifically, for antennas, let y(t) = V(t), the time-dependent voltage. Taking r = h(t), the effective height, we have:***

$$V(t)=\int_{-\infty}^{\infty} \vec{h}(\tau)\cdot\vec{E}(t-\tau)\, d\tau$$

Experimental Setup: The Anechoic Chamber



Experimental Setup: scalar LPDA properties (*e.g.* bandwidth)



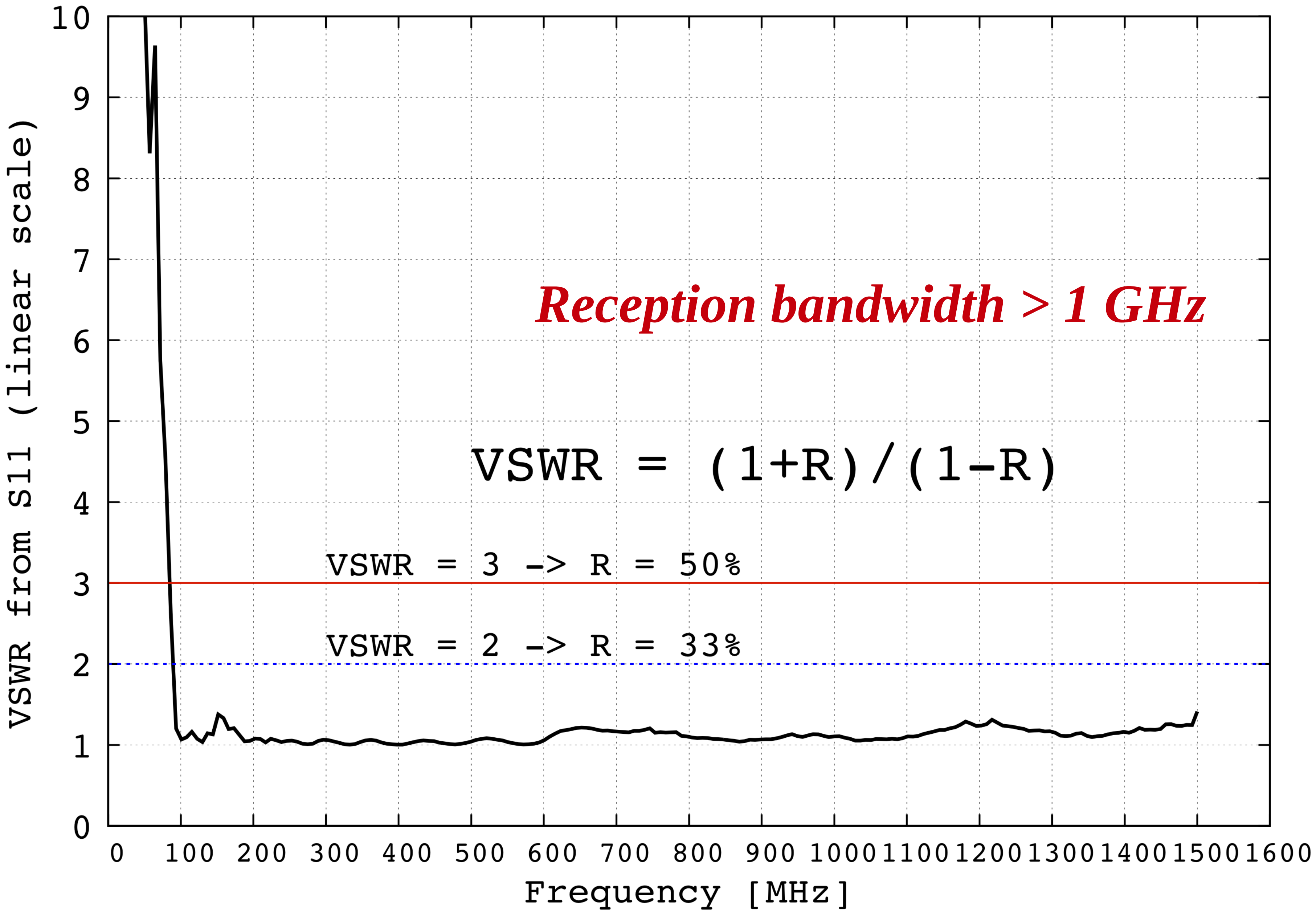
Attempting to be in the LPDA far-field

Network analyzer measures reflection and scattering parameters vs. frequency

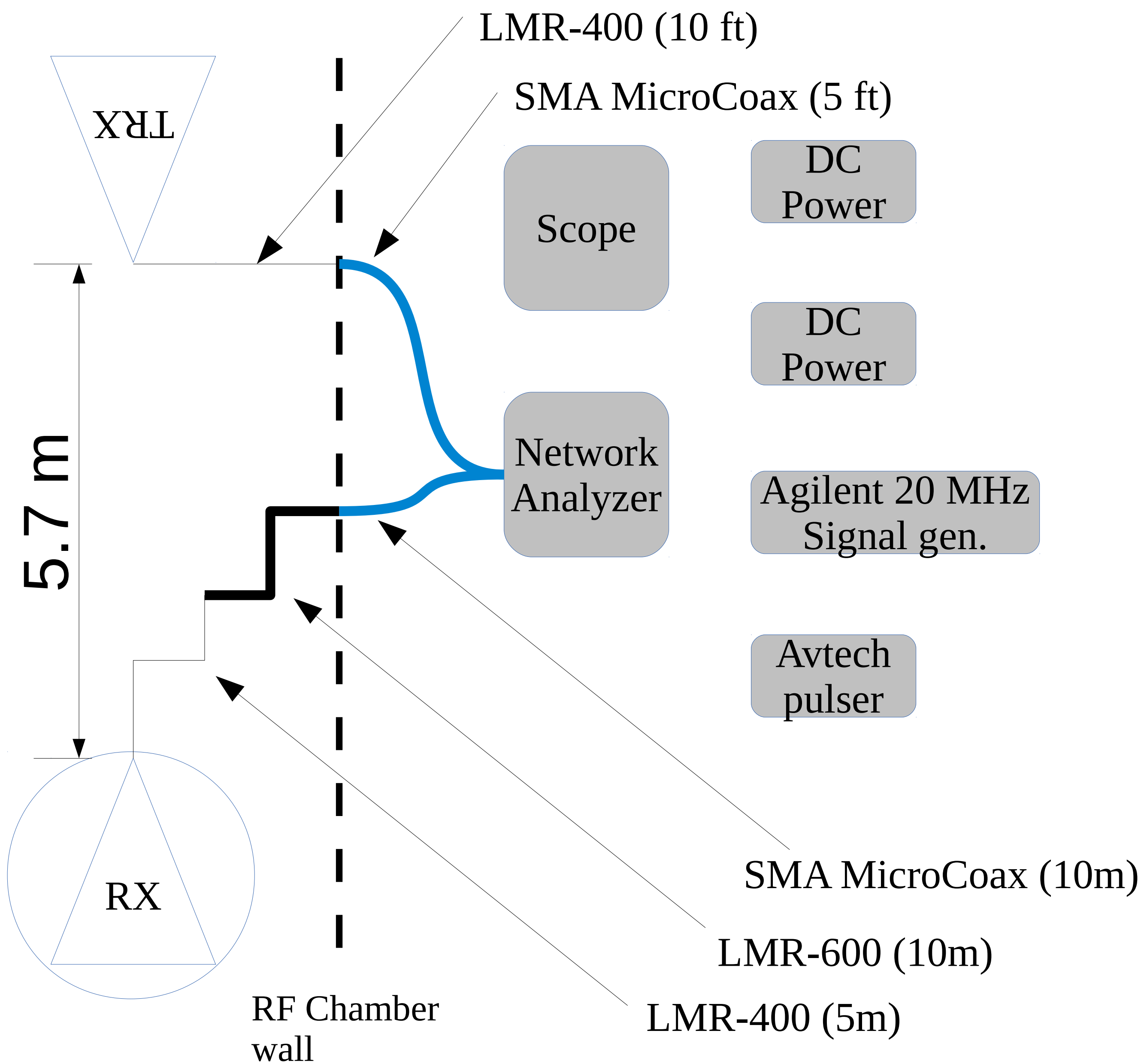
Cable attenuation is minimized (subsequent slides)

Other equipment used in subsequent measurements

Main Result #1: Checking the SWR



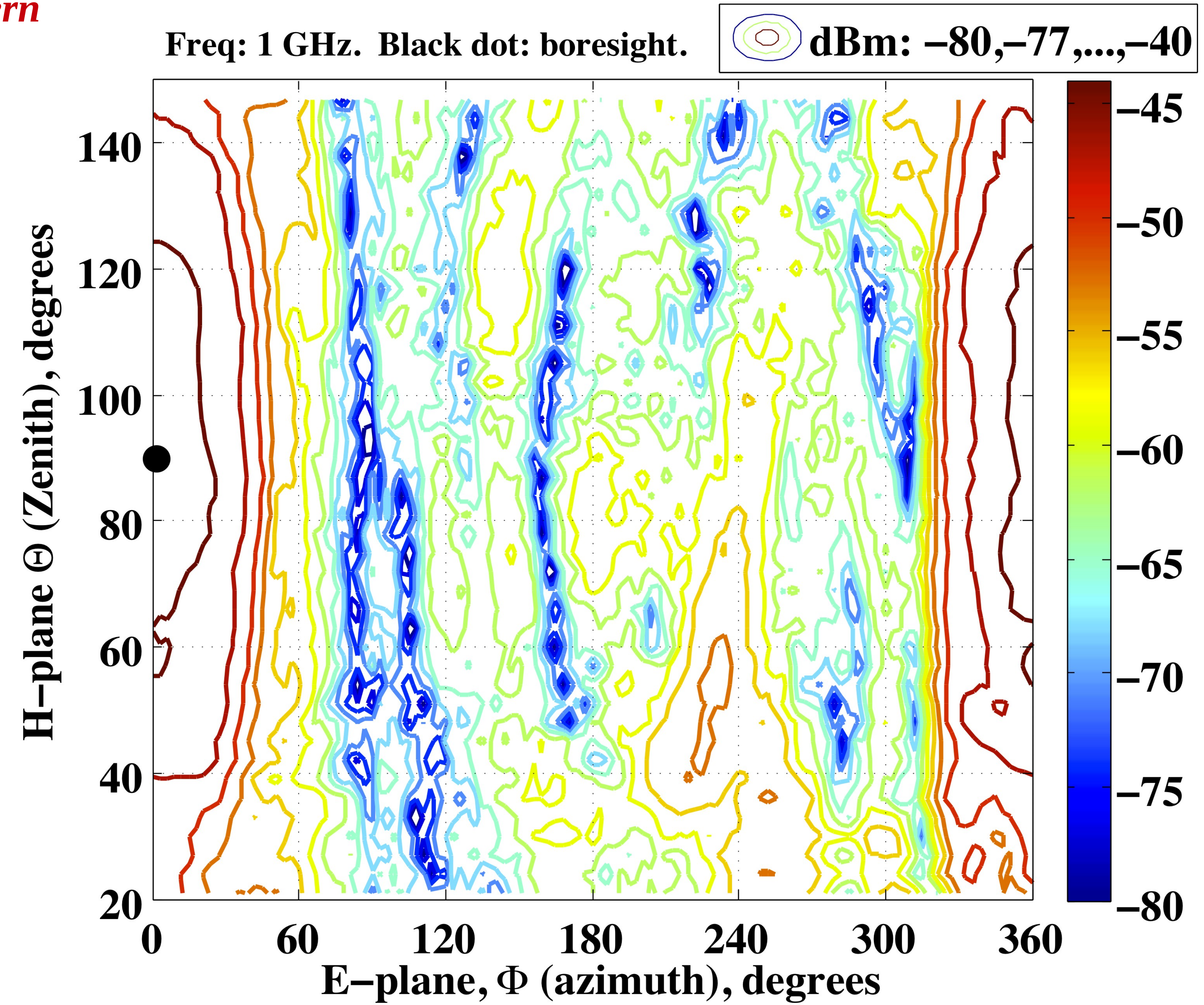
Experimental Setup: 3D radiation pattern, gain



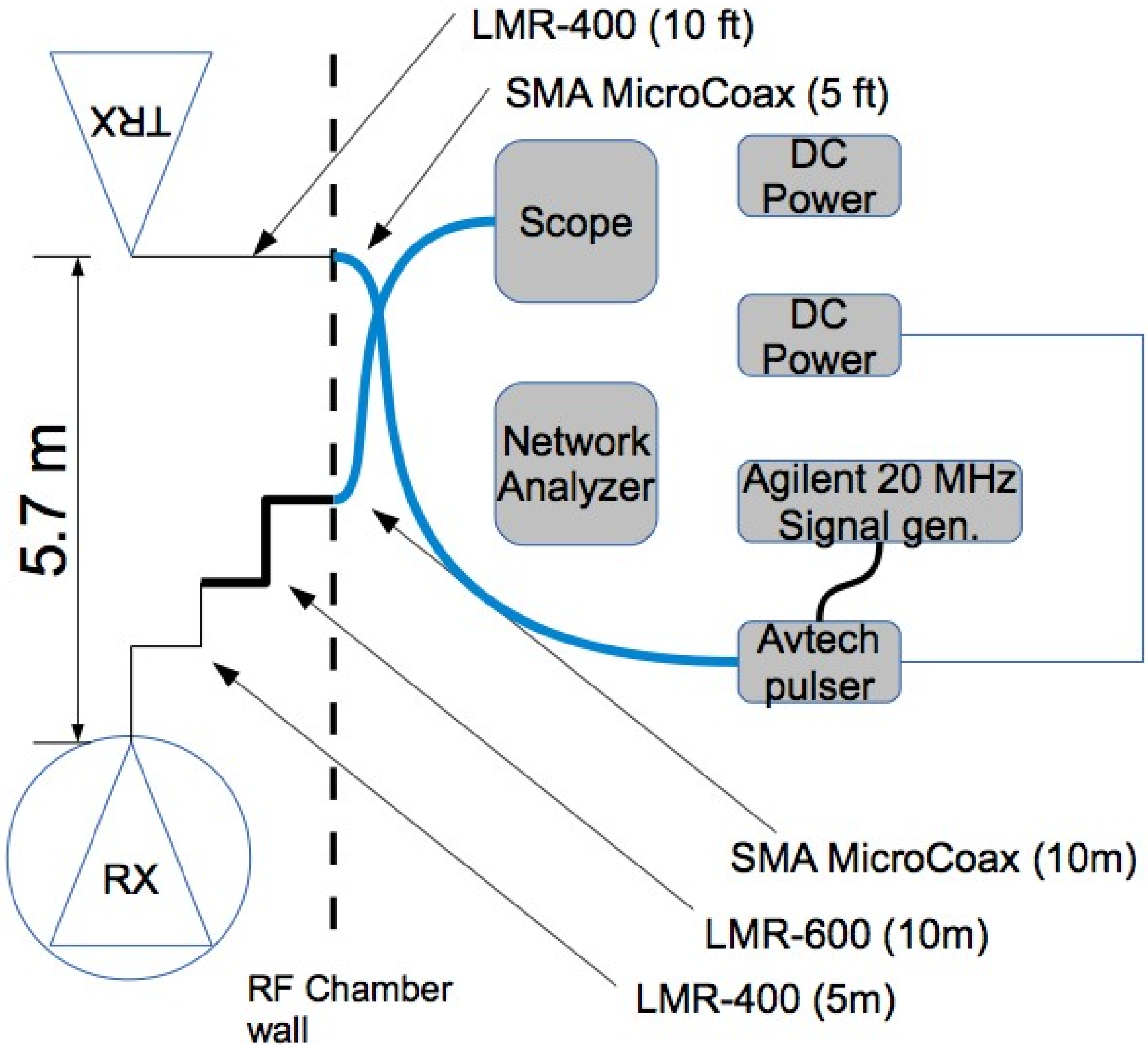
Measured the full radiation pattern vs. frequency, azimuth, and zenith angles.

Achieved 73% coverage of the unit sphere (limited in zenith angle by the mounting stock in the chamber)

Main Result #2: Radiation Pattern



Experimental Setup: impulse response



Derivation of effective height using this experimental setup:

r = antenna separation,

c = light speed,

V_L = antenna voltage delivered to load,

Z_L = load resistance (and coaxial line resistance, 50 Ohms),

Z_{in} = antenna input resistance (~50 Ohms),

Z_0 = impedance of free space (120π Ohms) *(c.f. P. Miocinonic, 2006)*

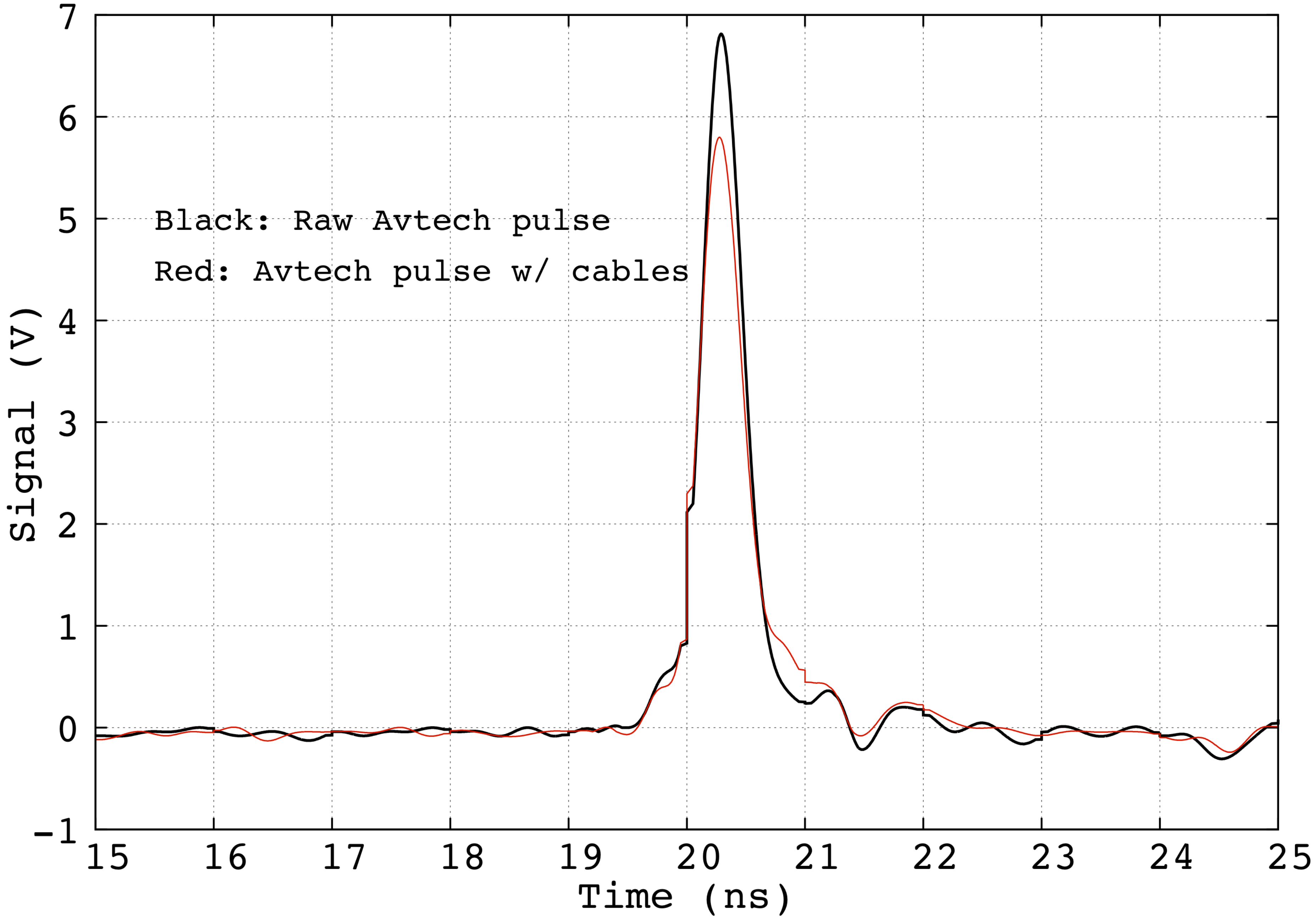
$$V_L(t) = 2\left(\frac{Z_L}{Z_L + Z_{\text{in}}}\right)\vec{h}_{rx}(t) \circ \vec{E}(t)$$

$$\vec{E}(t) = \frac{2}{4\pi r c}\left(\frac{Z_{\text{in}}}{Z_{\text{in}} + Z_L}\right)\frac{Z_0}{Z_{\text{in}}}\vec{h}_{tx} \circ V_{\text{src}}(t)$$

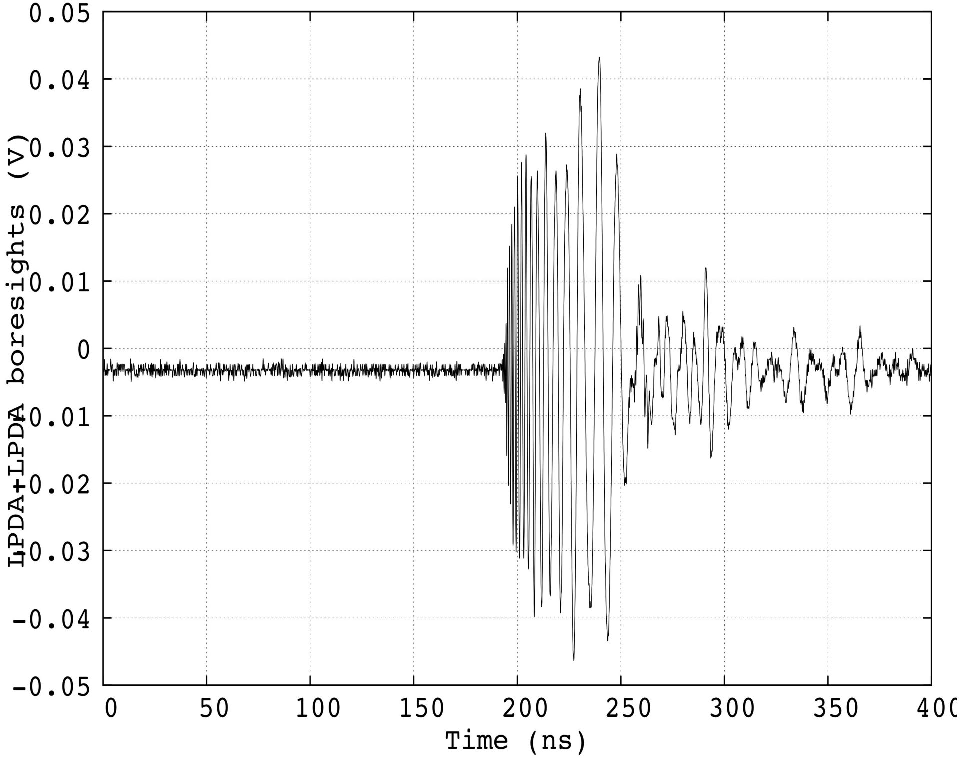
$$V_L(t) = \frac{1}{(2\pi r c)}\frac{Z_0}{Z_L}\vec{h}_{rx}(t) \circ \vec{h}_{rx}(t) \circ \partial_t V_{src}(t) \qquad \left(\vec{h}_{tx} = -2\,\partial_t \vec{h}_{rx}(t)\right)$$

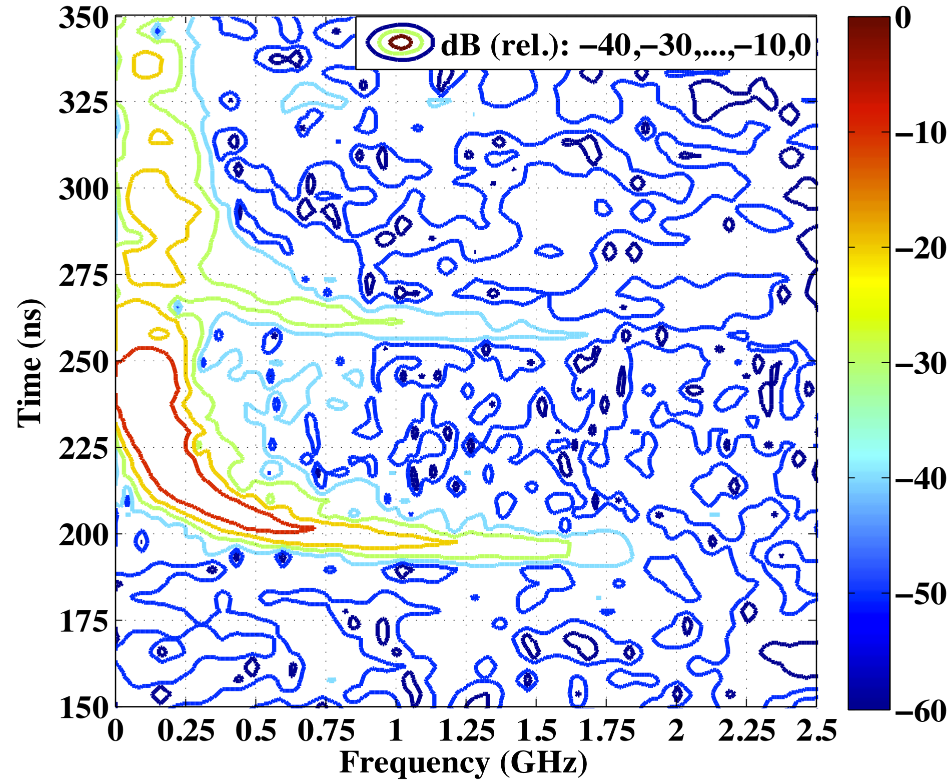
Avtech (pulser) signal

Reception bandwidth > 1 GHz



Time-domain Results: raw, bore-sight case





Left: Bore-sight signal data.

Right: Spectrogram of the data on the left; magnitude of the short-time Fourier transform in dB (color scale).

Method for Obtaining $h_{rx}(t)$

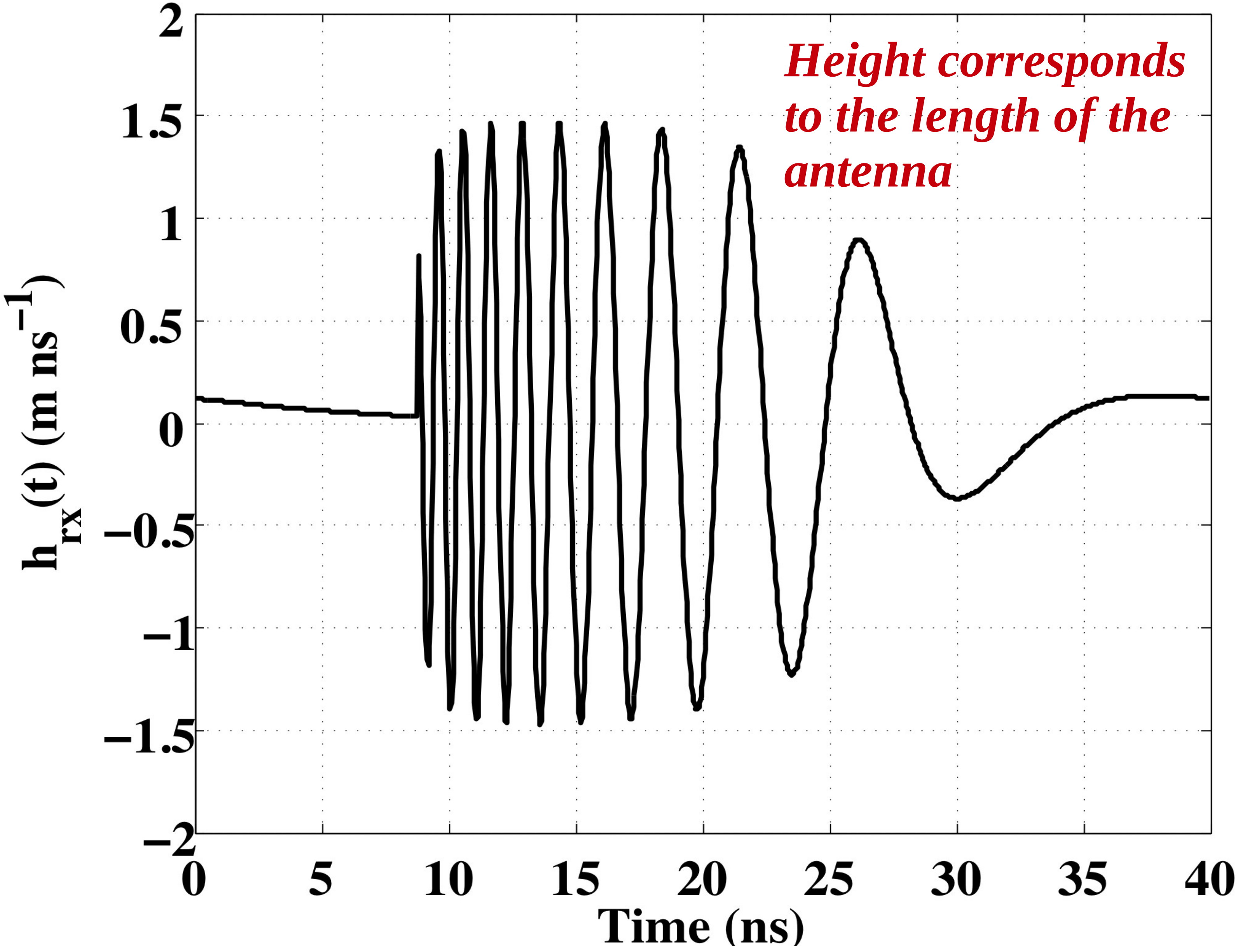
- ***Rotating to Fourier domain and back amplifies noise***
- ***Assume a trial function with parameters, a(t) chosen to turn on/off the function***
- ***Perform a fit that minimizes R after scanning the full parameter space***

$$h_{rx}(t) = A\,a(t)\cos(2\pi\, k \ln(t/t_{\mathrm{end}}))$$

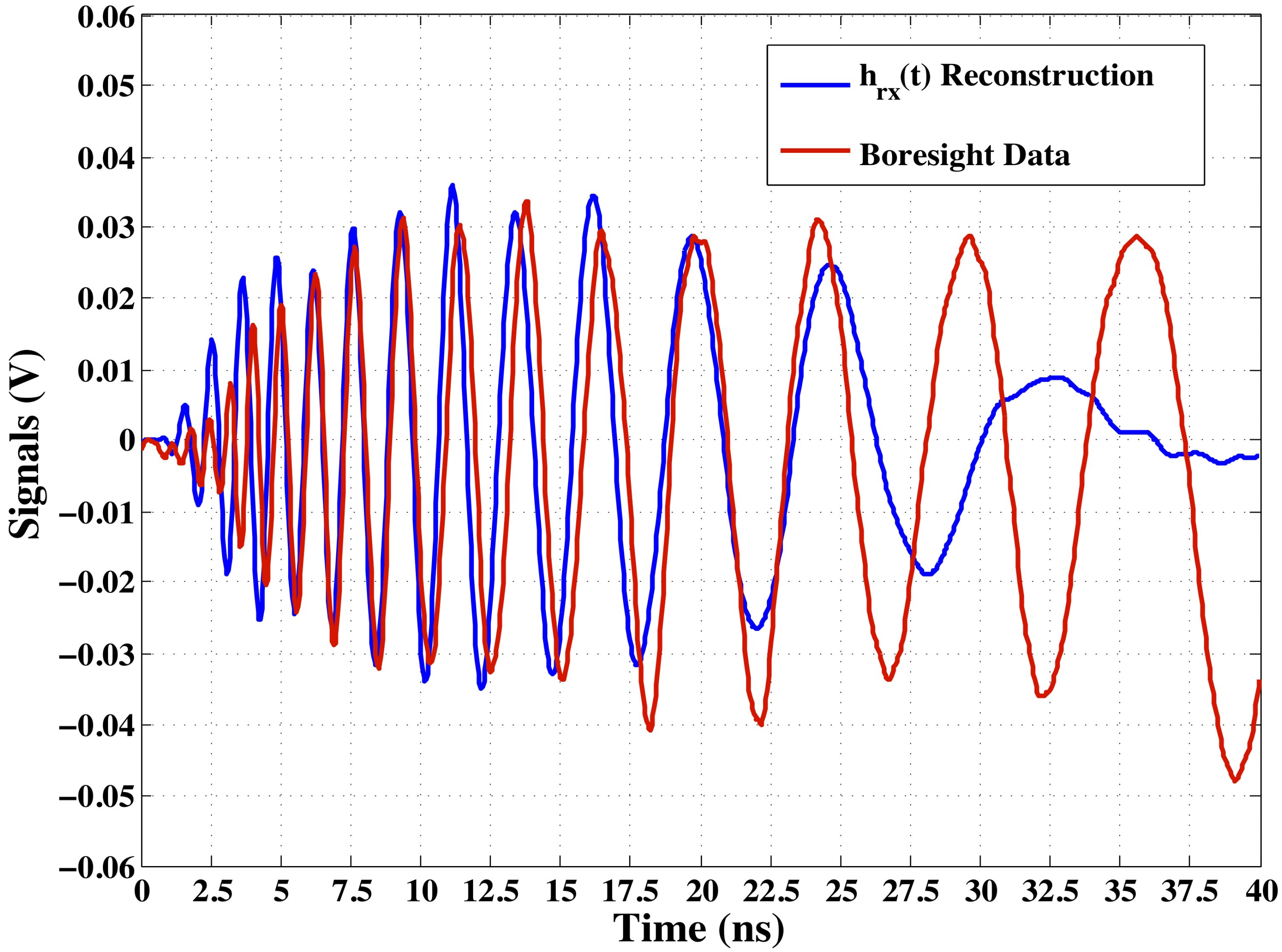
$$a(t) = (2/\pi)^2 \tan^{-1}(t/t_0)\tan^{-1}(-(t-t_{\mathrm{end}})/t_1)$$

$$R = \frac{1}{N}\sum_i^N \left(f_{\mathrm{data}}(t_i) - f_{\mathrm{model}}(t_i)\right)^2$$

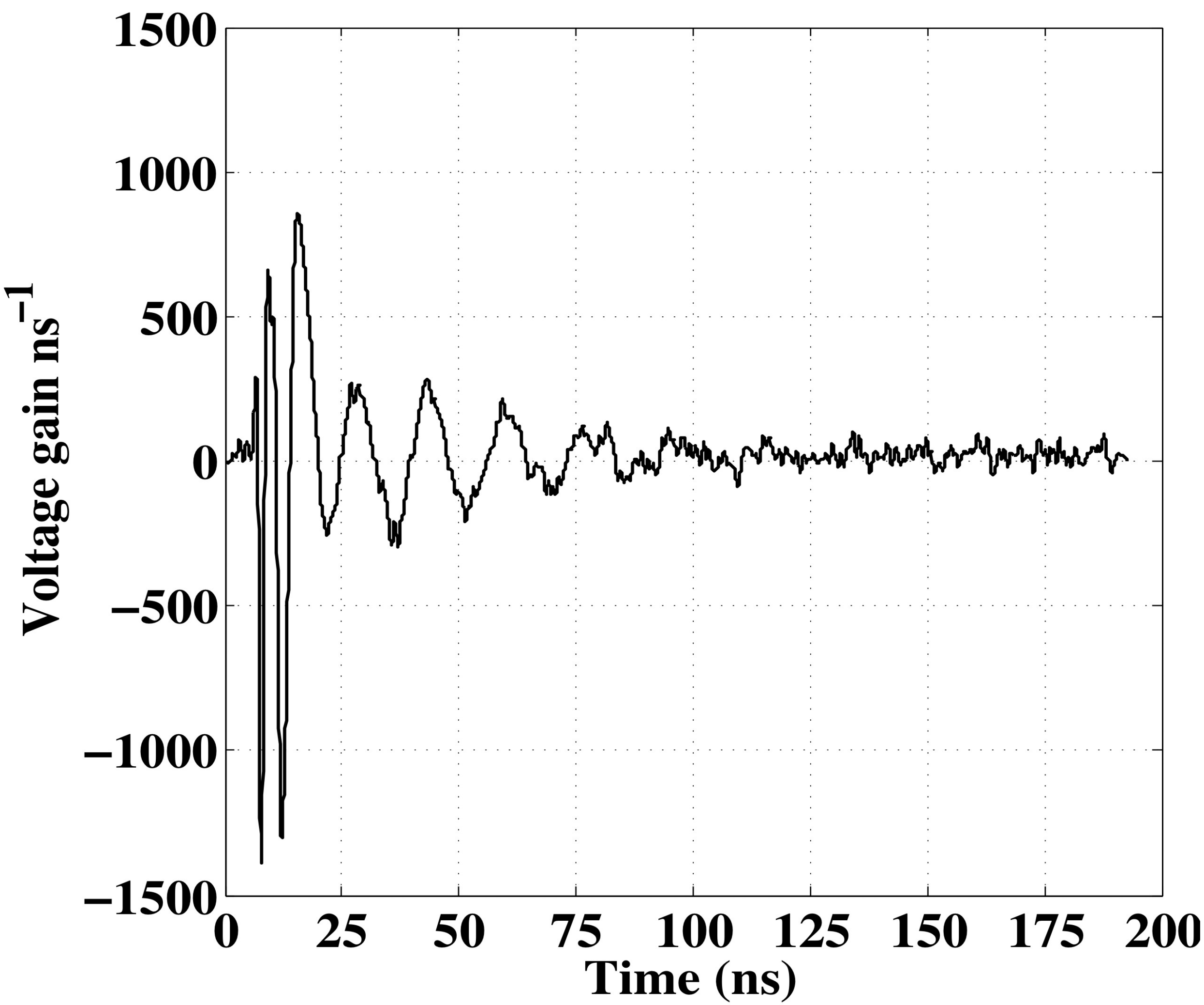
Main Result #3: Bore-sight $h_{rx}(t)$



Main Result #3: Bore-sight $h_{rx}(t)$



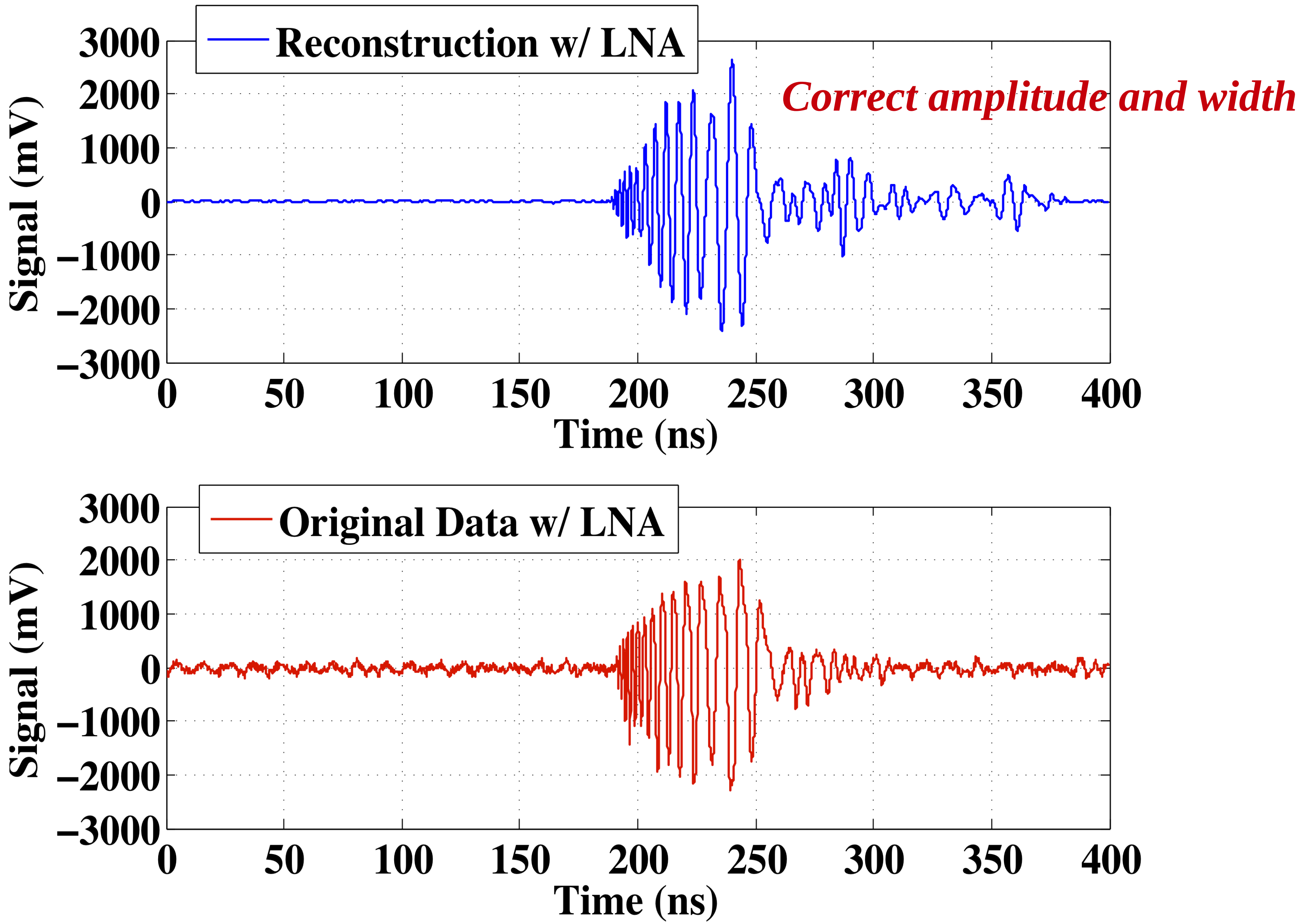
Main Result #4: Bore-sight $h_{rx}(t)$ w/ Amplifier



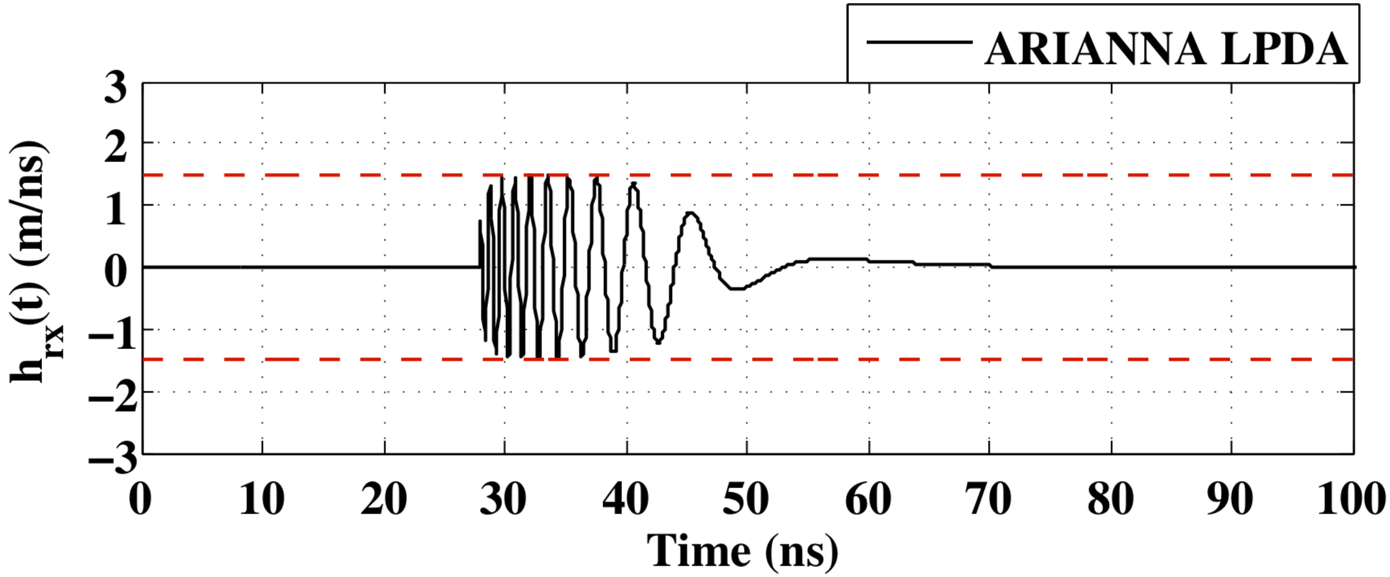
Credit: James Walker and Steve Barwick, UCI

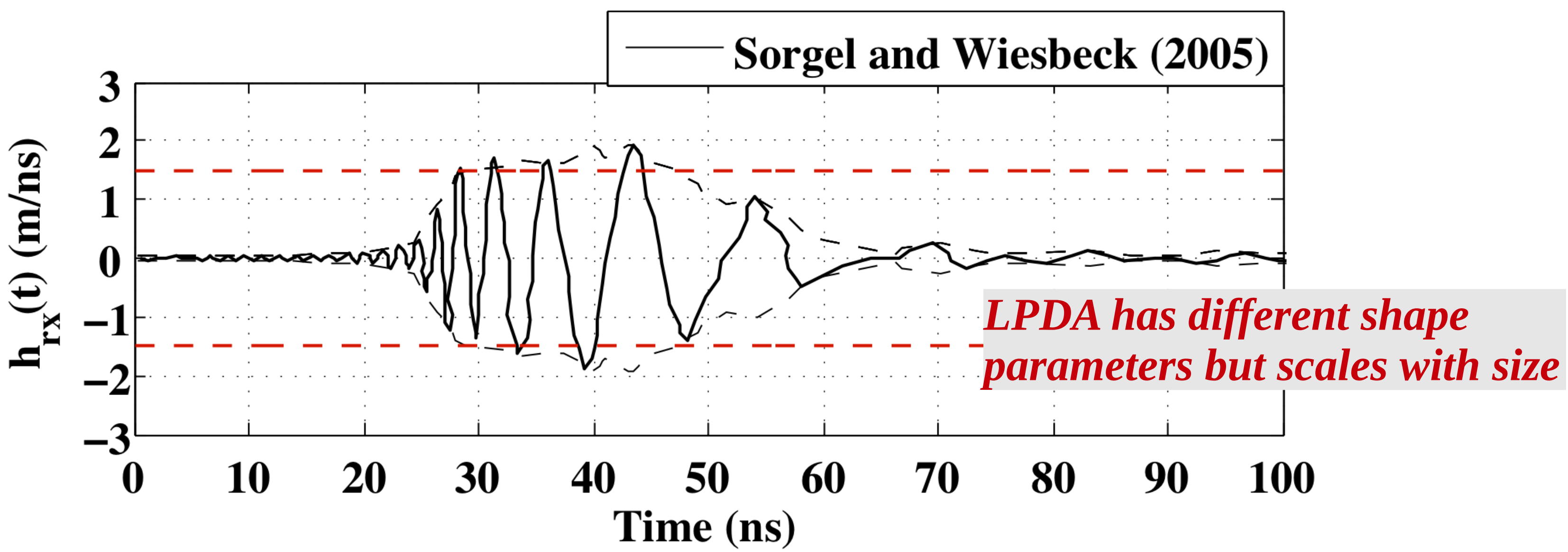
$$V_L(t) = \frac{1}{(2\pi r c)} \frac{Z_0}{Z_L} H_{\text{amp}}(t) \circ \vec{h}_{rx}(t) \circ \vec{h}_{rx}(t) \circ \partial_t V_{src}(t)$$

Main Result #4: Bore-sight $h_{rx}(t)$ w/ Amplifier



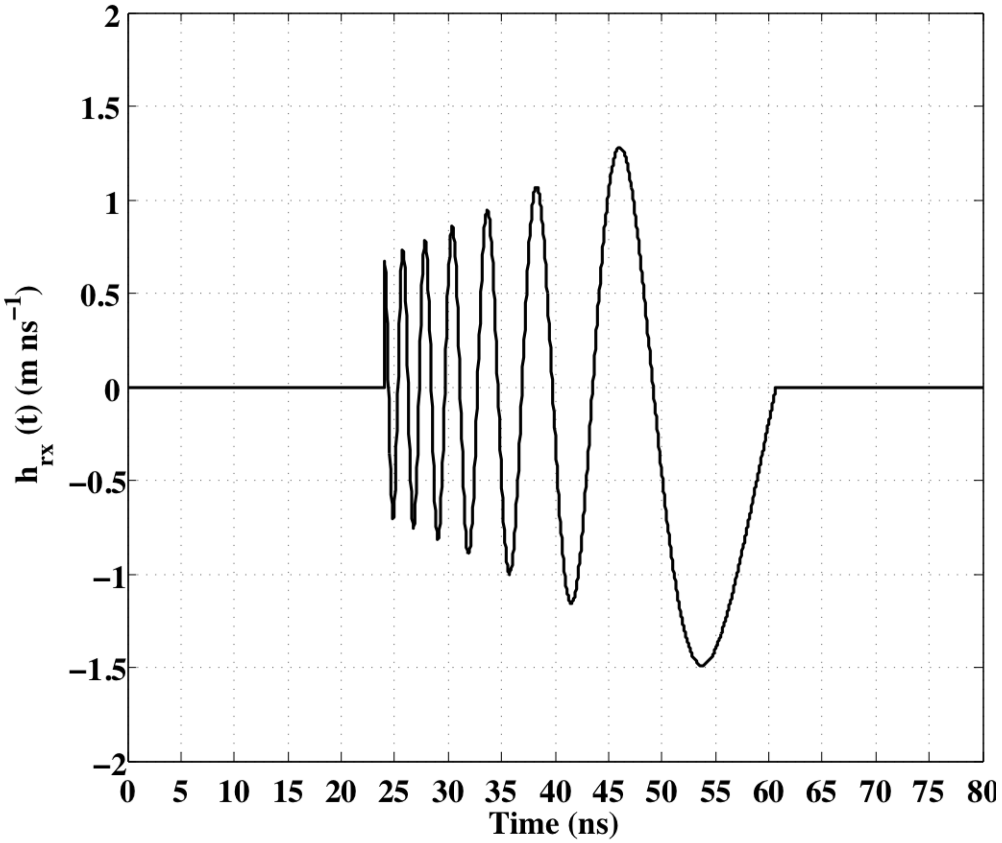
Comparing Effective Height to Others' Results

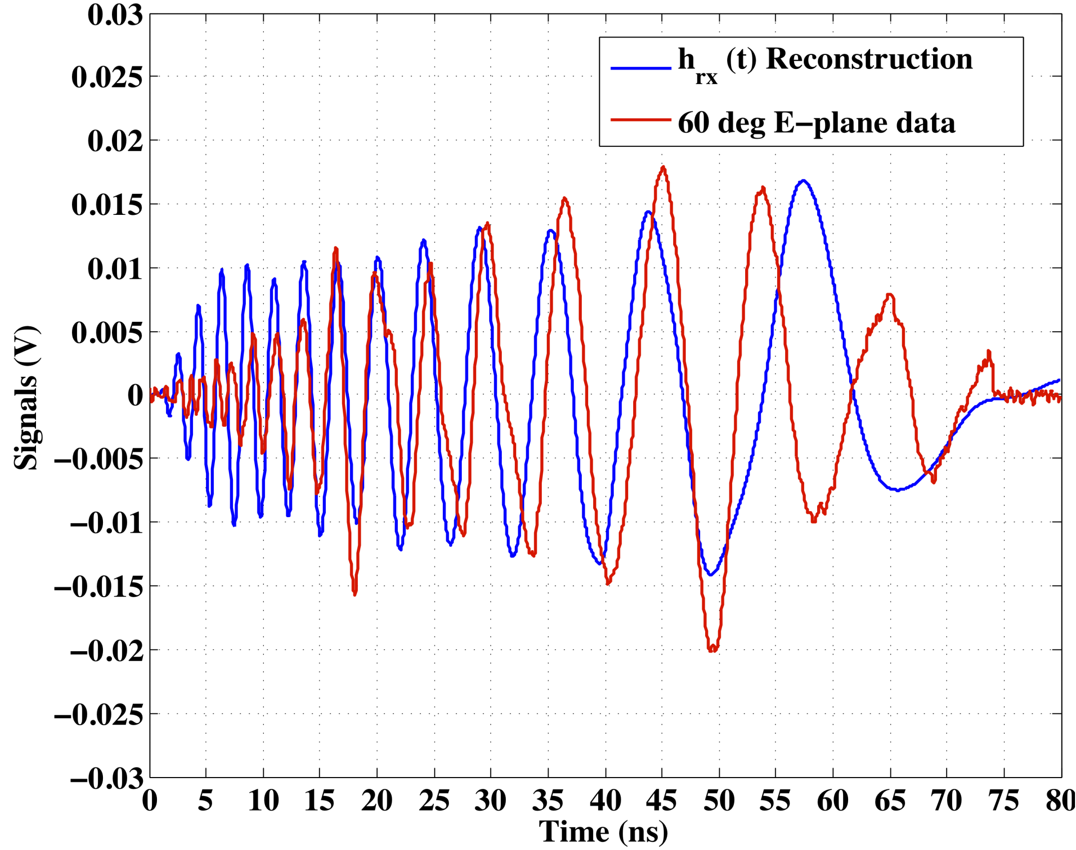




Note: data from this reference has been scaled to match LPDA sizes.

Checking off-axis: 60 degrees in E-plane





***Effective height**: Similar height at late times and lower frequencies, but frequency modes above 600 MHz are missing (early times).*

***Reconstruction**: Early times (500-600 MHz) are large, but excellent match after 15 ns. The overall signal is much longer.*

Interactions with Askaryan Electric Fields, Comparisons with Monte Carlo simulation

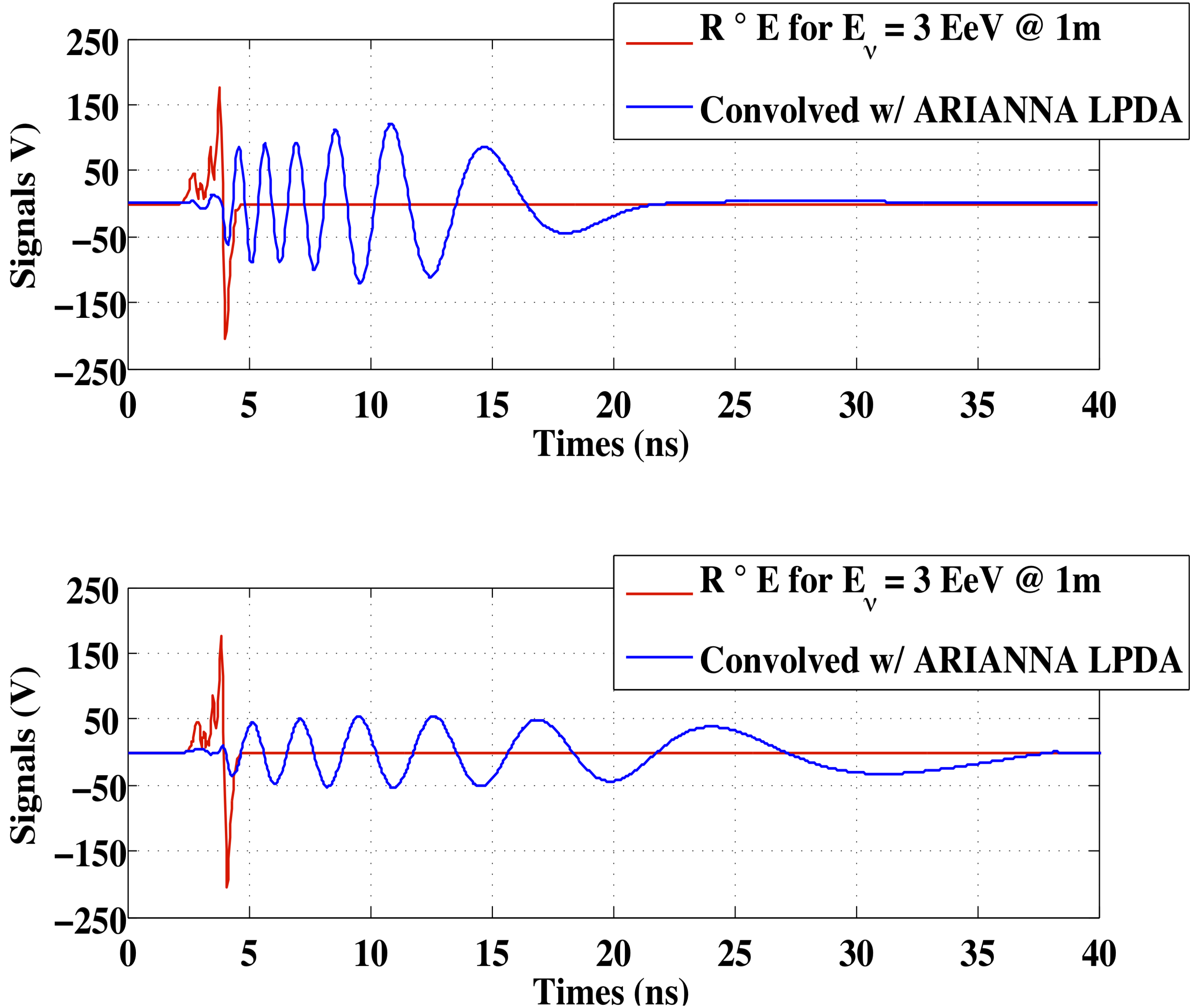
- ***Electric field strength typically parameterized from data, with respect to energy and frequency (Saltzberg et al., 2000), (Alvarez-Munis et al., 2010)***
- ***Observed strength depends on viewing-angle with respect to Cherenkov angle***
- ***Propagation and attenuation (lambda = attenuation length)***
- ***Signal voltage depends on viewing angle of the antenna***

$$E_{1m} = \frac{2.53\times 10^{-7} E_{\nu}[TeV](\nu/\nu_0)}{1+(\nu/\nu_0)^{1.44}} \quad \left(V\, m^{-1}\, MHz^{-1}\right)$$

$$E_{1m}(\theta_\nu) = E_{1m}\frac{\sin(\theta_\nu)}{\sin(\theta_C)}\exp\left(-\ln 2\left((\theta_\nu - \theta_C)/\Delta\theta\right)^2\right) \quad \left(V\, m^{-1}\, MHz^{-1}\right)$$

$$V_{\mathrm{LPDA}} = P(\theta_\nu)\frac{\Delta \nu}{\sqrt{2}}\frac{\sin\theta_\nu}{\sin\theta_C}\exp\frac{-r/\lambda}{r}\sum_i E_{1m}(\theta_\nu)\, h_{\mathrm{eff}}(\nu_i)$$

Main Result #5: Comparing Monte Carlo with Time-Domain Calculation



Conclusion

- **Discussed UHE neutrinos, the Askaryan Effect**
- **Mathematics of converting electric field waveform to voltage waveform**
- **Measured antenna properties, including conversion from E-field to voltage waveform**
- **Demonstrated angular monte carlo agreement, and computed neutrino waveforms entering ARIANNA DAQ.**
- **Future work: must span the angular space to generalize the fits, improve high-frequency agreement**

References

Alvarez-Muniz, Romero-Wolfe, and Zas. "Cherenkov radio pulses from electromagnetic showers in the time-domain." Phys. Rev. D, 2010.

Alvarez-Muniz, Romero-Wolfe, and Zas. "Practical and accurate calculations of Askaryan radiation." Phys. Rev. D, 2011.

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C. Baum. "General Properties of Antennas." IEEE Transactions on Electromagnetic Compatibility, 2002.

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P. Miocinovic, R. Field, P. Gorham, E. Guillian, R. Milincic, D. Saltzberg, D. Walz, and D. Williams. Time-domain measurement of broadband coherent cherenkov radiation. Phys. Rev. D, 2006.

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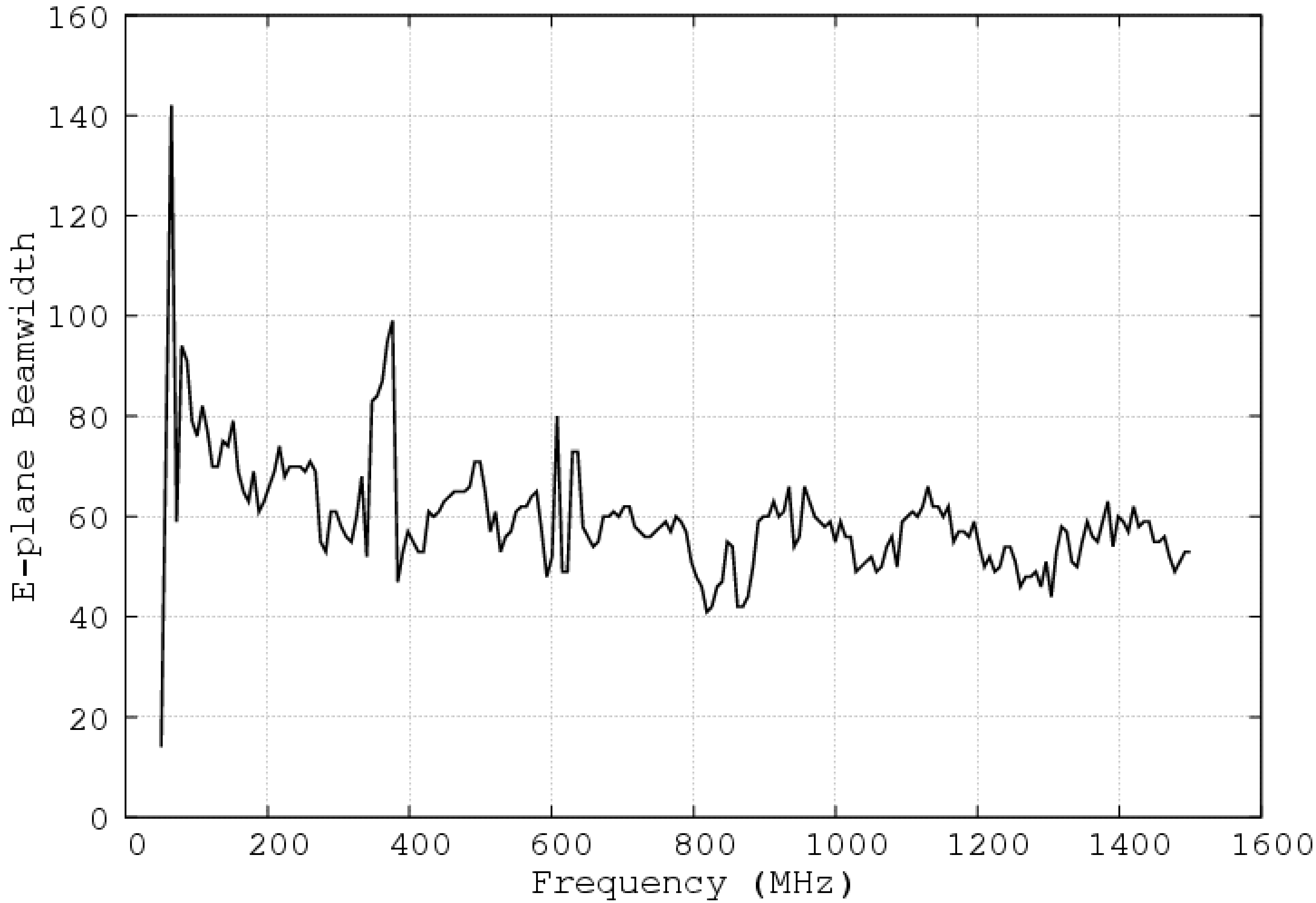
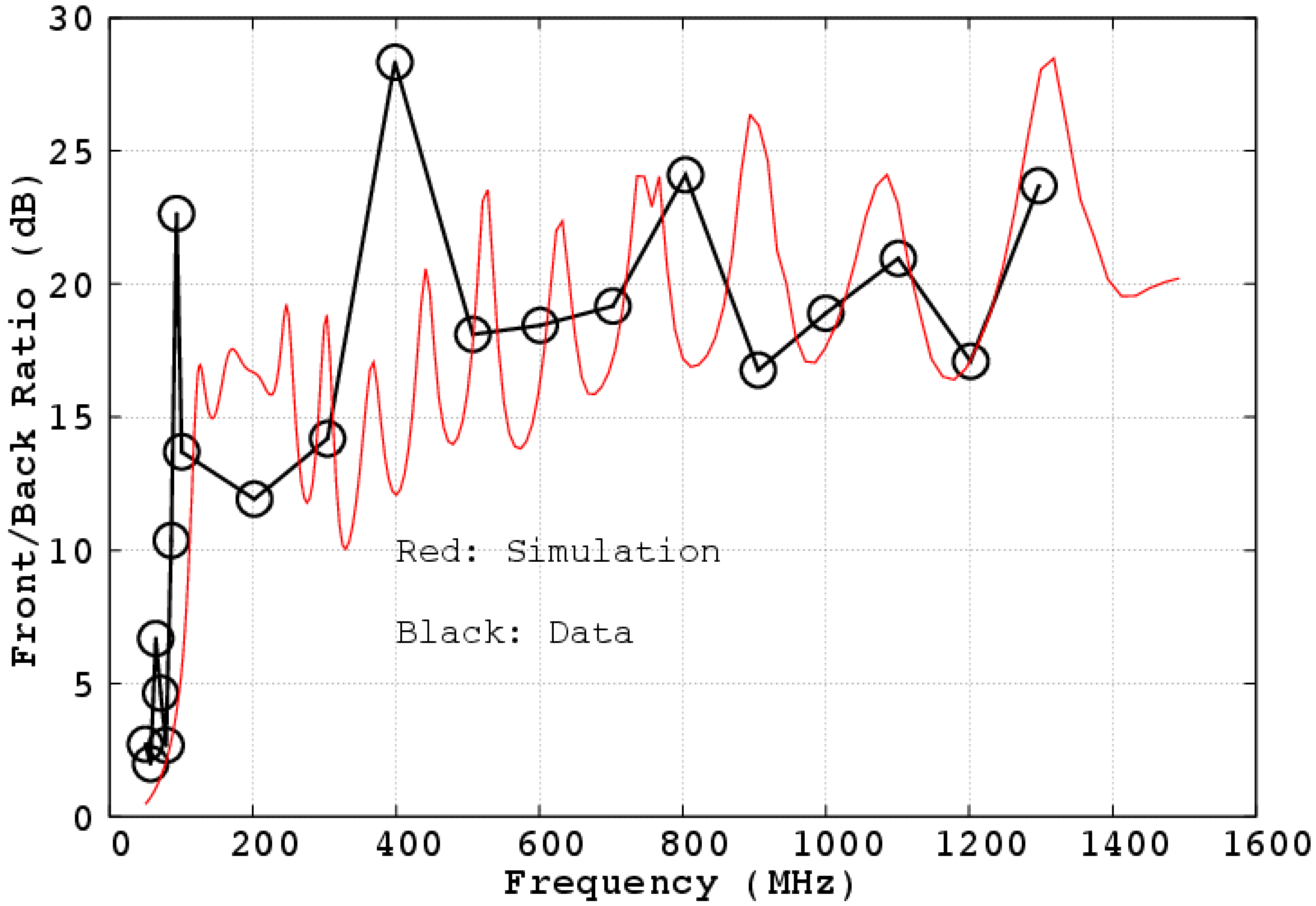
W. Sorgel and W. Wiesbeck. Influence of the antennas on the ultra- wideband transmission. EURASIP Journal on Applied Signal Processing, 2005.

Backup slides

E-Plane beam-width ~ 60 degrees



Front-Back Ratio ~ -15 dB



Gain vs. Frequency