DETERMINING DEEP ANTENNA POSITIONS AND UNCERTAINTIES WITH ARA STATION 5

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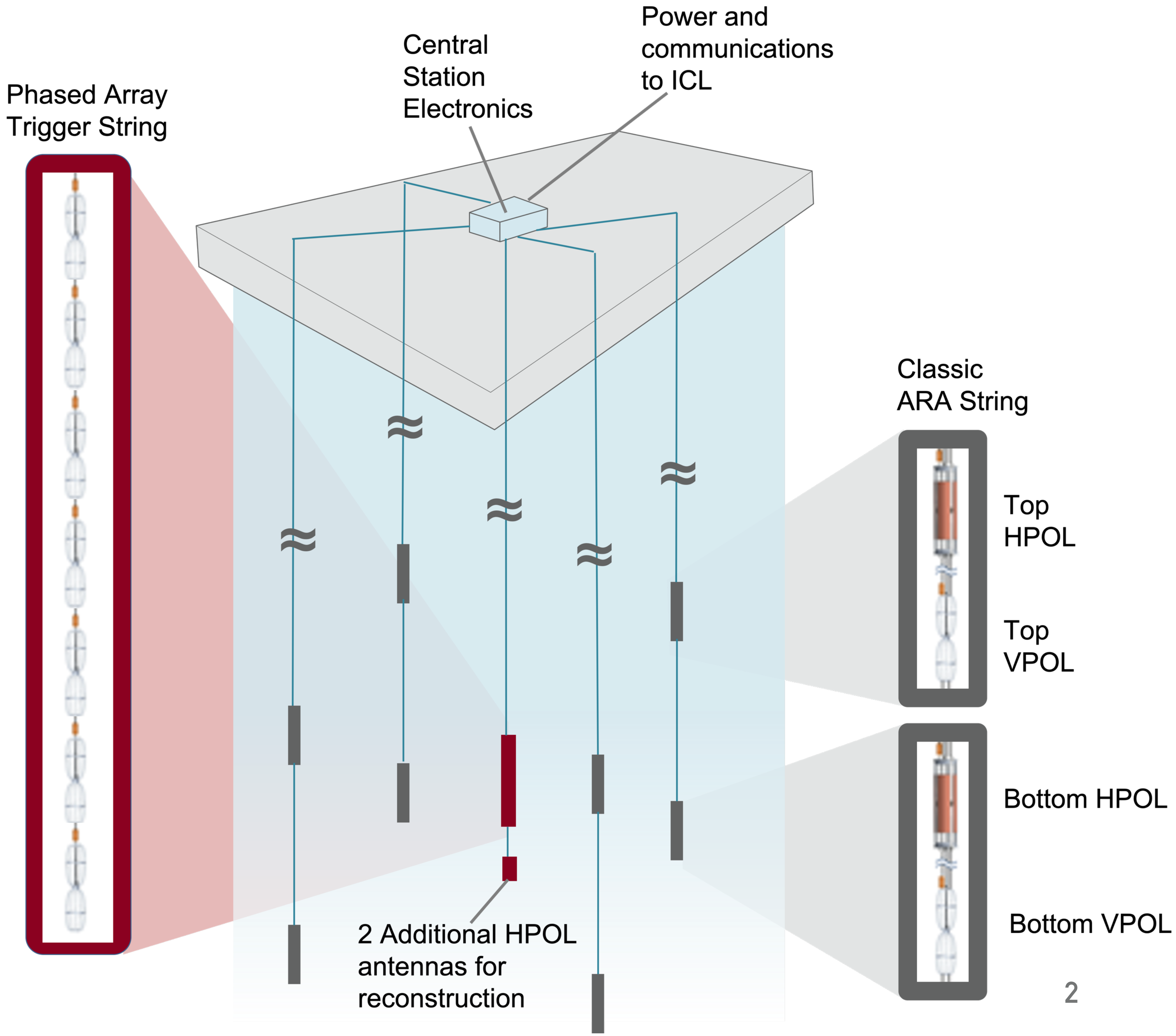
ARA STATION 5

- Two separate (but connected) experiments located in the same spot
- Phased Array: one string with 7 VPol antennas and 2 HPol antennas. It uses a phased array trigger on VPol antennas only.
- A5 Station: traditional ARA station with 4 strings. Each string has two VPol and two HPol antennas ~30 m apart. It uses a power threshold trigger
- One local calibration pulser
- **Goal: determine antenna locations to within 10 cm**



WHAT WE NEED FOR GEOMETRY CALIBRATION

	Description
Ice model	Index of refraction changes as a function of depth; big impact on distant calibration sources
Cable Delays	Relative delays due to different cable lengths + differences in bulk cable
Calculated time delays using calibration waveforms	Dependent on the quality of the digitizers, similarity of antenna impedances, and available in-situ measurements
Calibration Sources	Ideally, want sources at a variety of angles, as well as both local and distant. For ARA5 we have two sources: 1 local cal pulser + 1 SPIceCore drop

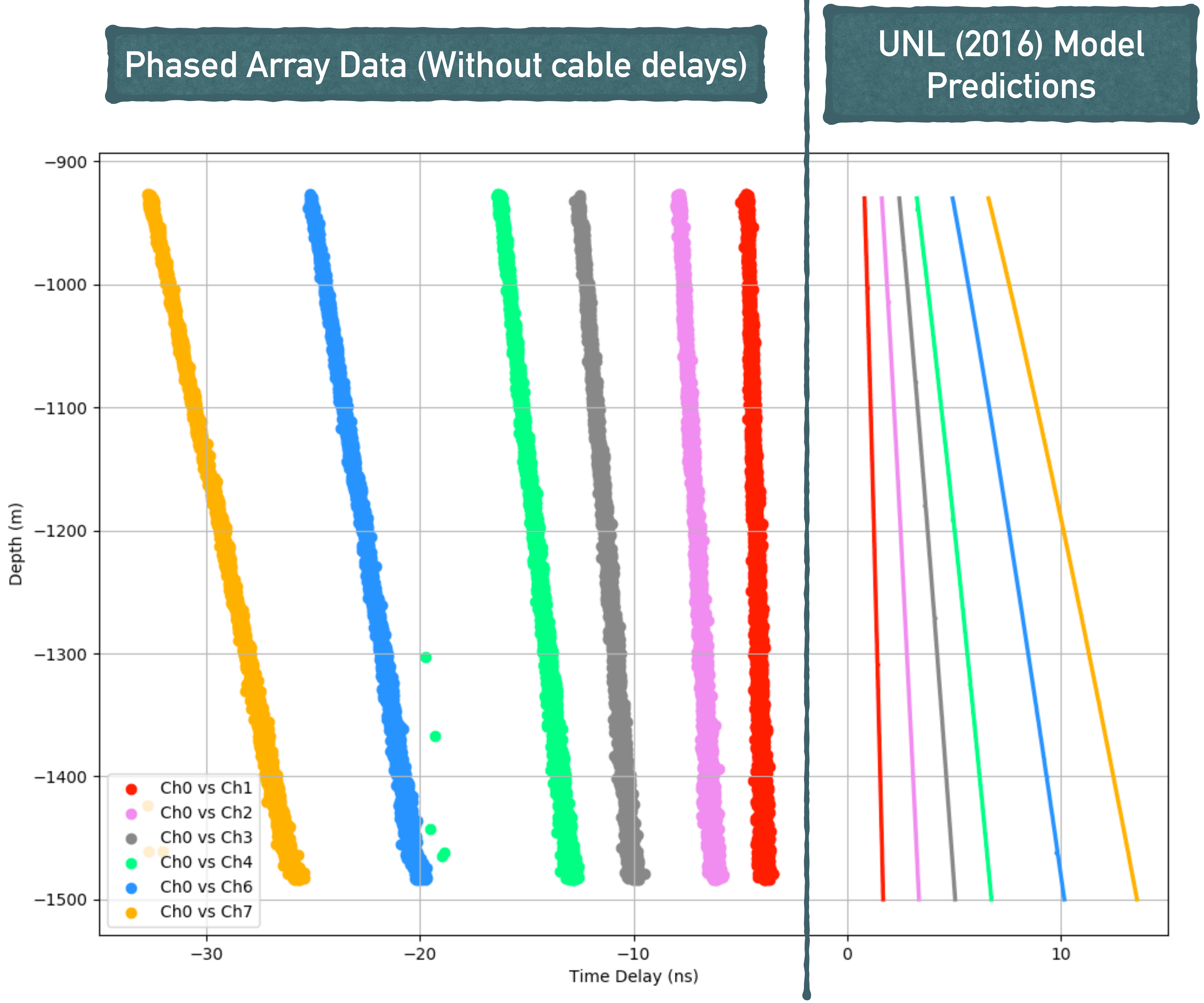
FITTING PROCESS FOR CALIBRATING ARA 5

1. Using only phased array antennas, solve simultaneously for best ice model and relative phased array cable delays
2. Using best ice model, calculate expected and measured time delays from:
   - Local calibration pulser
   - SPIceCore pulser
3. Input those time delays in a Minuit optimizer to find best antenna locations and ARA channel cable delays

ASSUMPTIONS MADE FOR ARA STATION 5

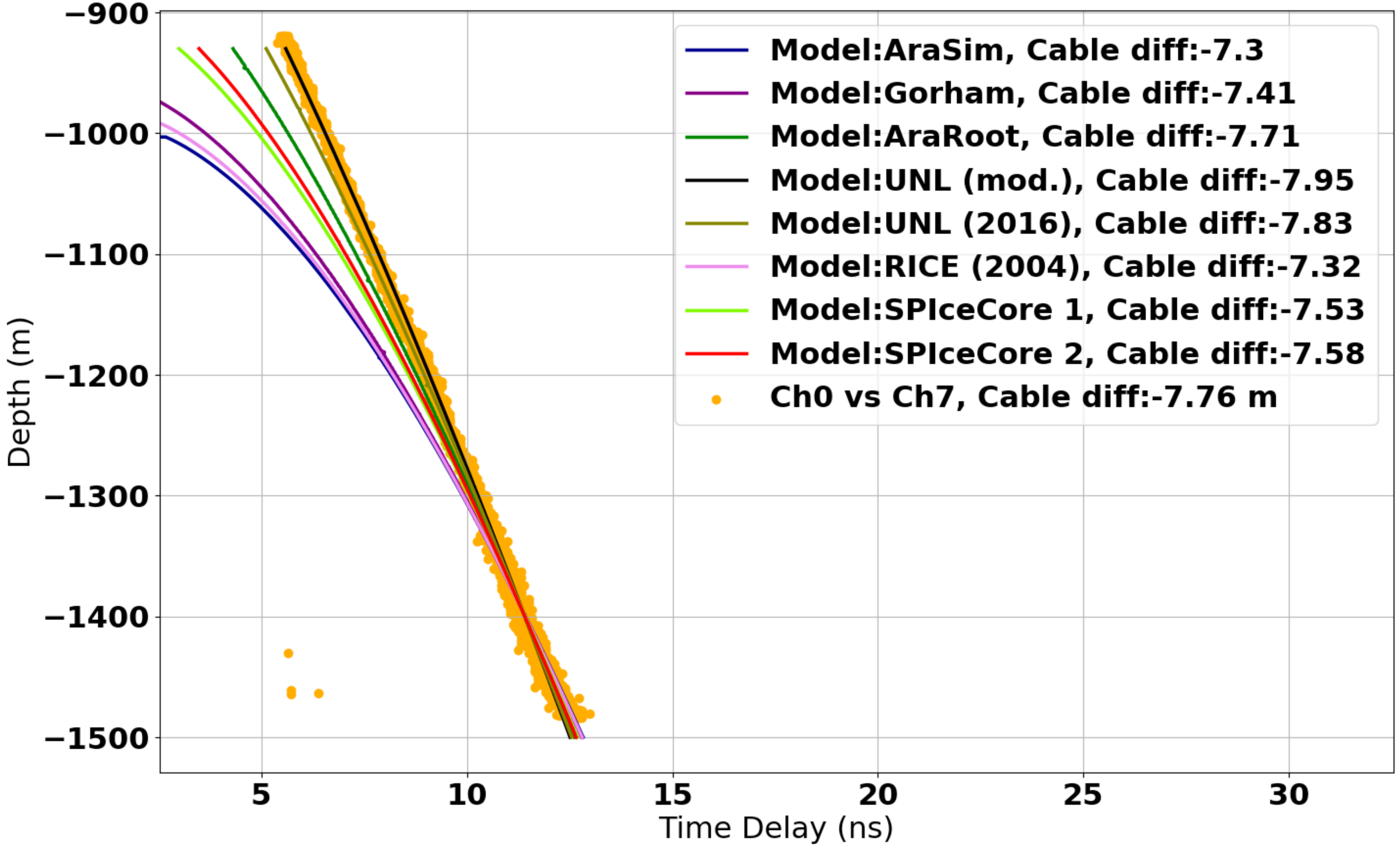
- **We know the depth of the phased array exactly.**
  - This is a reasonable assumption because the phased array antennas are deployed compactly, within ∼10 m of each other, so likely the relative depths are very accurate.
- **We know the depth of the SPIceCore pulser as a function of time.**
  - This was measured carefully during the SPIceCore run
  - Any uncertainties here are absorbed by the fit for ice model
- **The Phased Array and the SPIceCore holes are approximately parallel.**

USING SPICECORE TO FIND BEST ICE MODEL AND CABLE DELAYS



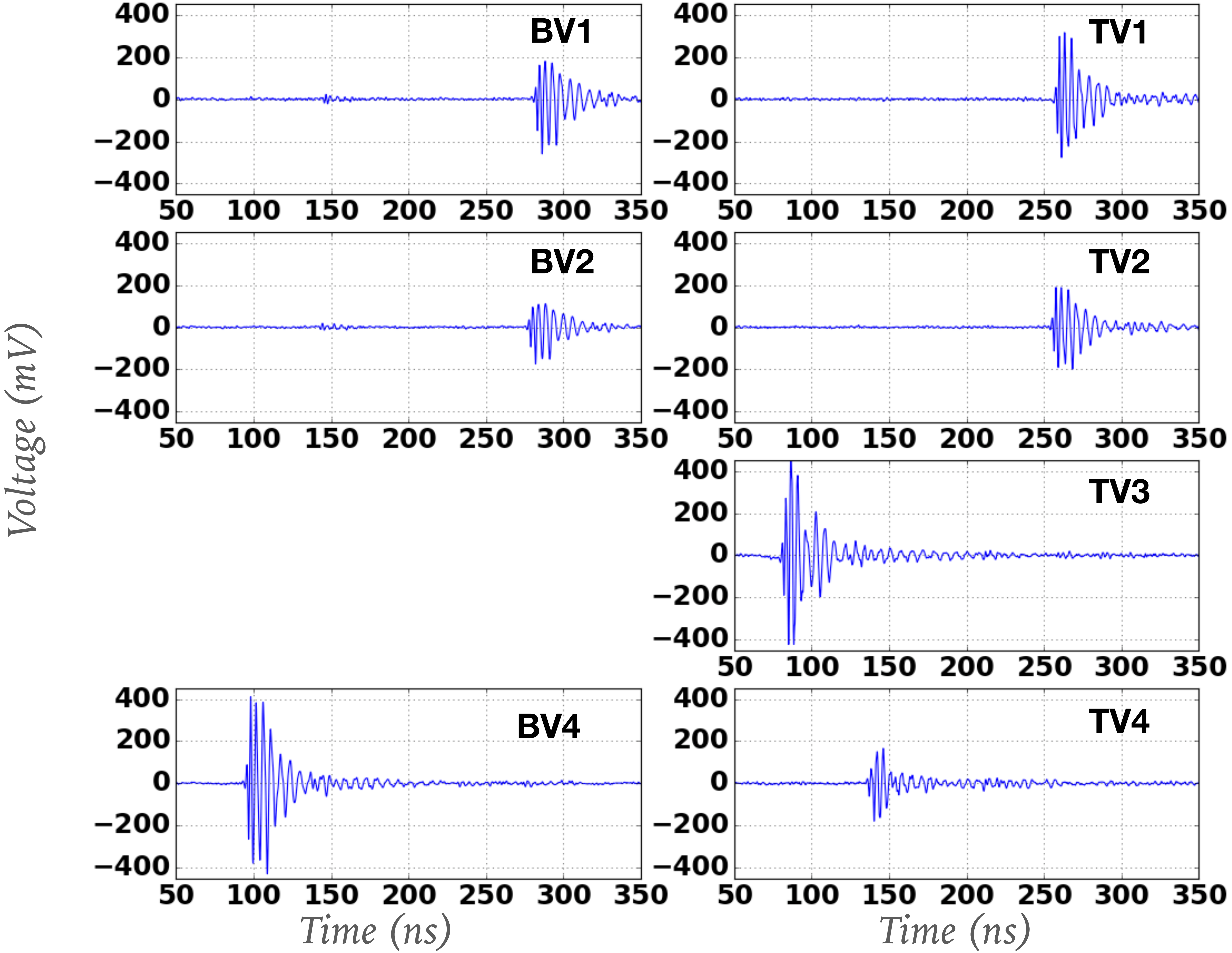
- Because we didn't have individual cable delay measurements, we had to use SPIceCore data to solve for ice model and cable delays simultaneously
- As the SPIceCore pulser dropped, the time delays between channels changes
- Plotted here are time delays as a function of depth- no cable delays included. Data is on left, model prediction is on the right
- Difference between model (right) and data (left) is one way to find the cable delay
  - For example, difference between red data and model is 5.1 ns. Using nominal speed = 0.202 m/ns we can get cable length of 1.03 m (compared to 1.0 m predicted)

COMPARING MULTIPLE MODELS



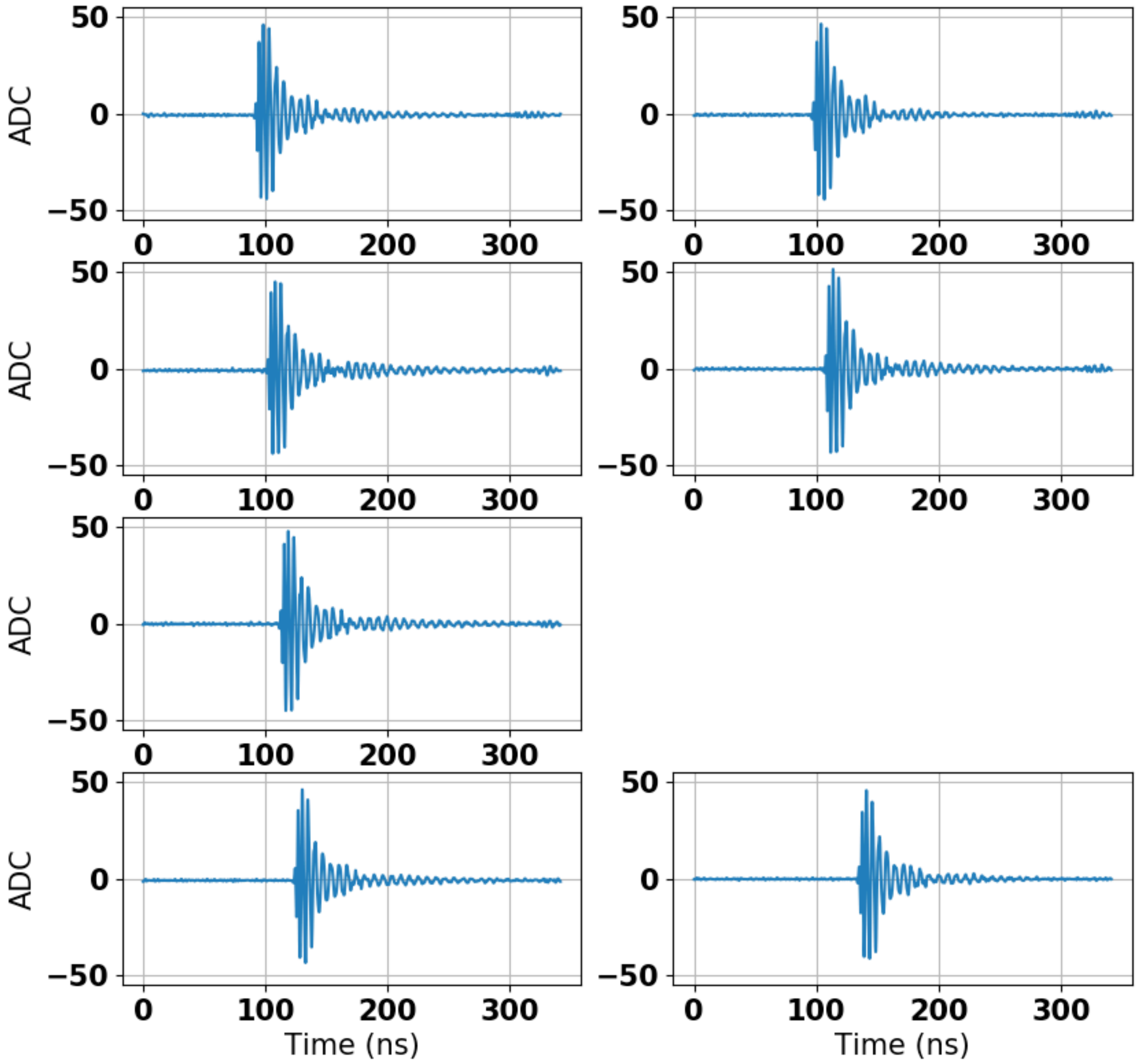
- While a shift in the x axis can account for the cable delay, the shape of the curve determines the ice model
- Here, I've forced all models to overlap data at -1400 m to easily compare
- Only UNL (2016) gets close to describing data accurately
- Solution: modify UNL (2016) to get new best ice model

AVERAGE LOCAL CALIBRATION PULSER- A5 ANTENNAS



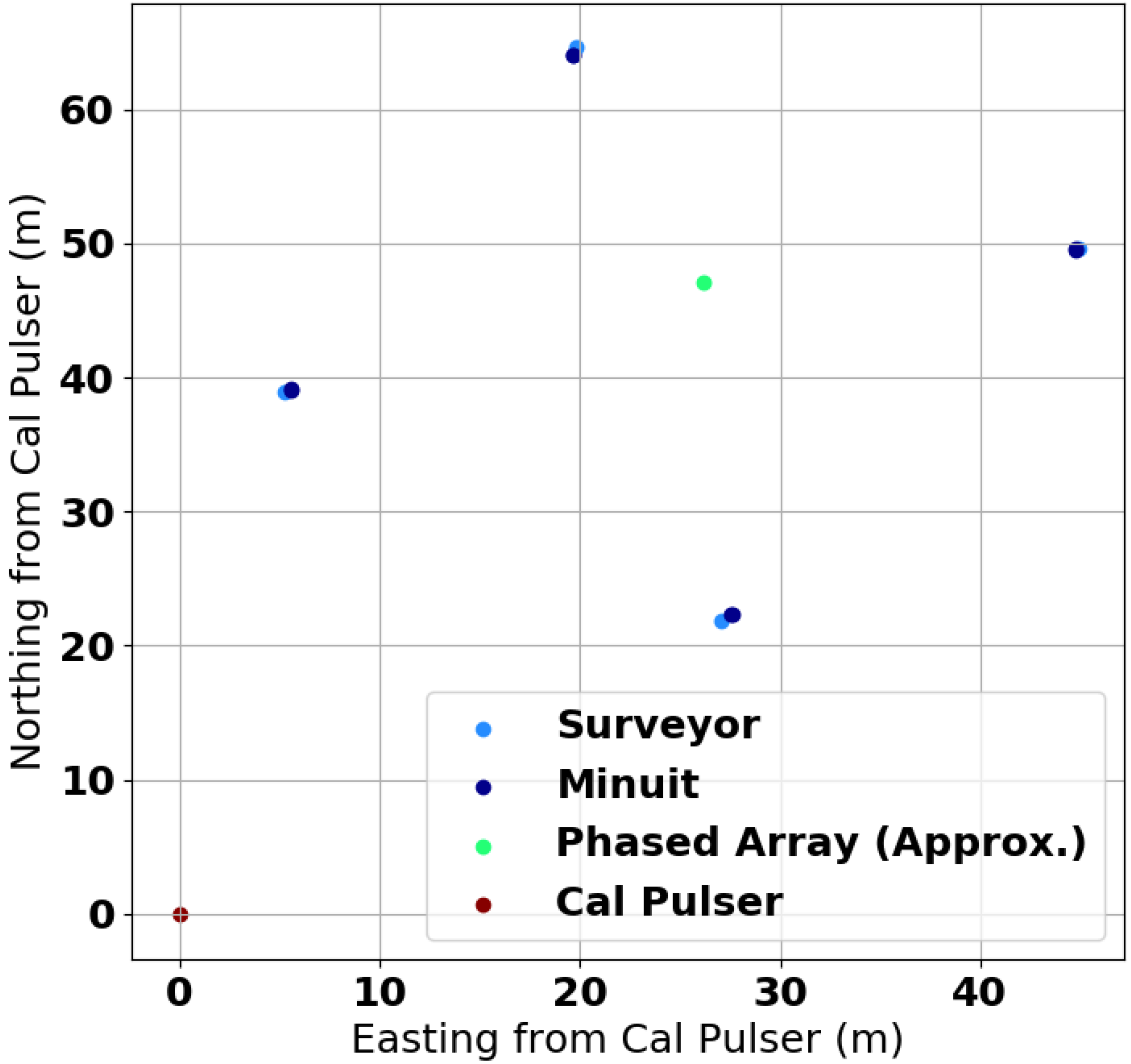
- Averages for 7/8 VPol antennas for a local calibration pulser
- Differences between channels caused by two main things:
  - Non-identical impedances and non-identical impulse responses
  - Angular dependence of both transmitting + receiving antenna
- Average calculated time delay error: 82 ps

PHASED ARRAY WAVEFORMS



- What changed?
  - Better digitizers
  - Antenna impedances and impulse responses extremely similar
  - Compact array means antenna angular response less pronounced
- Average time delay error: 30 ps

USING MINUIT TO FIND POSITIONS



Measured time delay from cross correlation (including cable delays)

Expected time delay from RayTracer

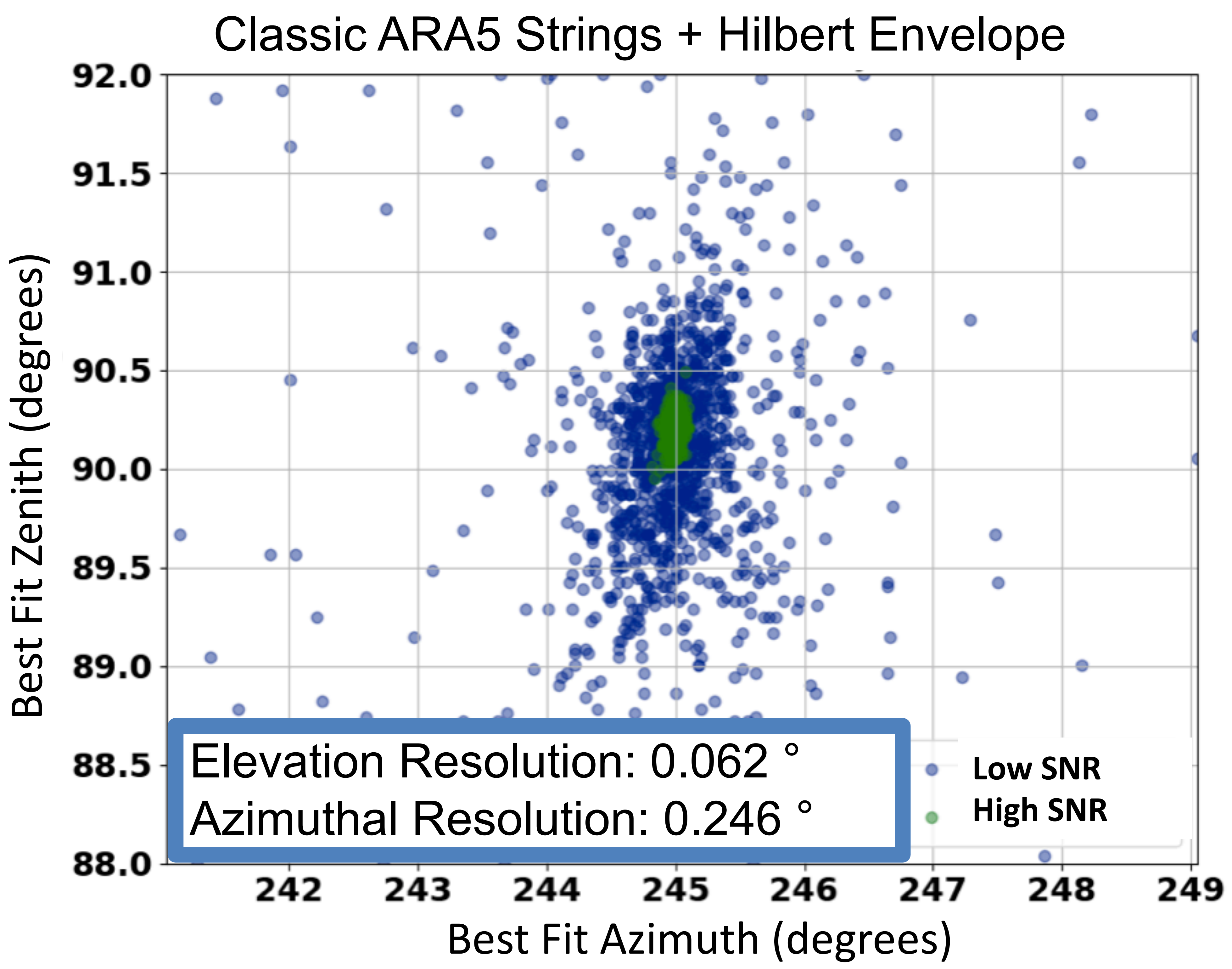
$$\chi^2 = \sum_{pairs} \frac{(\Delta t - RayTracer(r_1, r_2, z_1, z_2))^2}{\sigma^2}$$

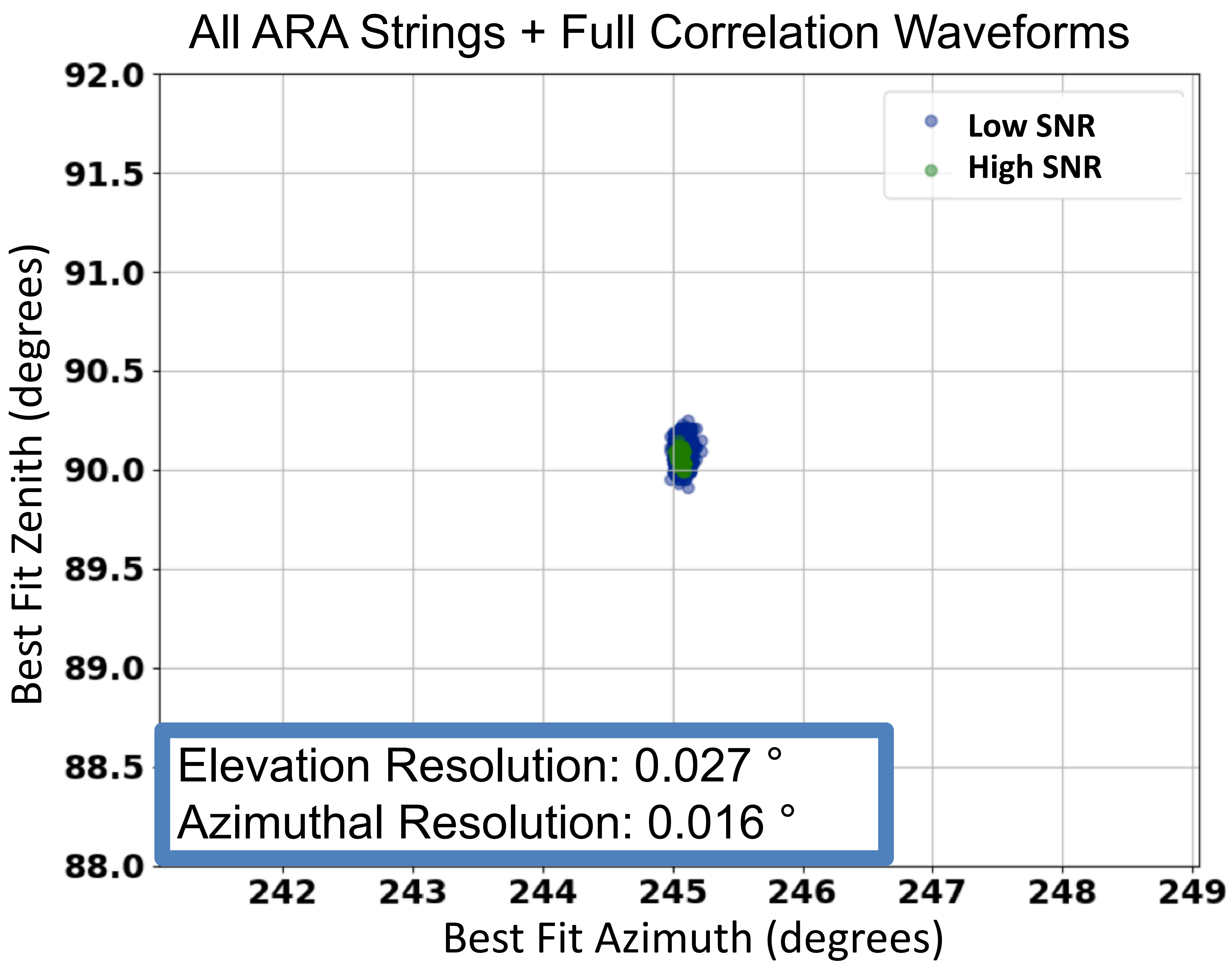
Variance from time delay calculation

- Two main steps:
  1. Build a library of time delays, using all available calibration sources
  2. Minimize the above equation in two steps: once assuming holes are straight/parallel, then allowing holes to tilt
- Errors on fit calculated using built-in Hessian error functionality- all below 5 cm

RESULTING RESOLUTION: POINTING BACK TO THE LOCAL CALIBRATION PULSER

- Very successful at pointing events back to local calibration pulser
- But, this is expected, since we used this data for calibrating!
- Ideally, would have a third, separate calibration source to test the geometry



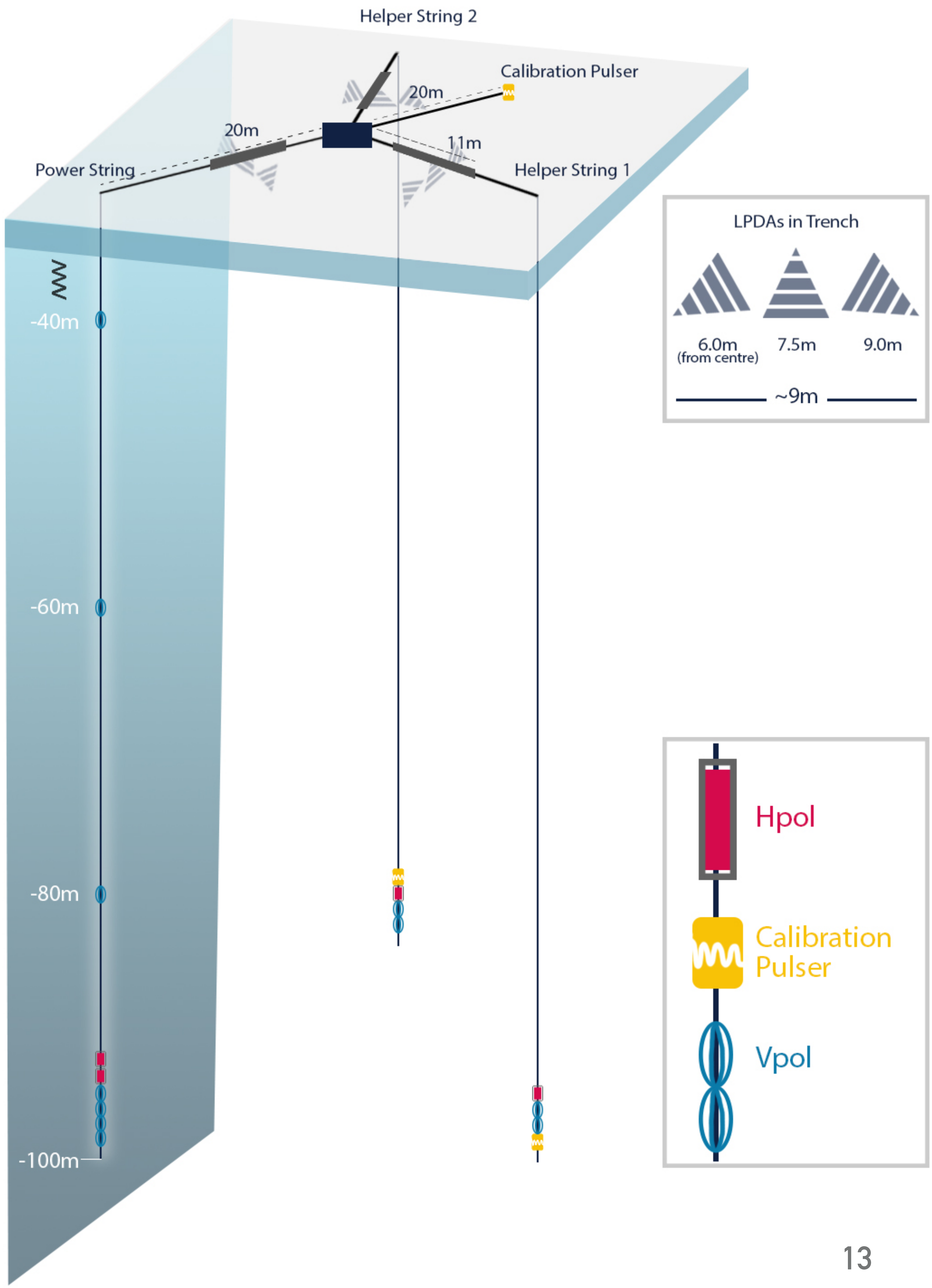


SUMMARY OF PRECISION

	Estimated error	How to improve
Ice model	+/- 0.05 ns; additional systematic offset	More precise measurements of cable lengths and cable speeds at cold temperatures prior to deployment
A5 calibration pulse time delays	+/- 0.082 ns	More identical antenna impedances; better in situ measurements; improved digitizers
Phased array calibration pulse time delays	+/- 0.03 ns	
Minuit fit	<5 cm	Orthogonal calibration pulsers would likely make it easier to minimize

FUTURE PLANS

- RNO-G: first stations to be deployed this summer
- Upgrades:
  - Multiple local calibration pulsers
  - All fibers and cables measured
  - New VPol and HPol antenna designs
  - Better digitizers
- Other calibration sources also planned (DISC borehole, snowmobile surface pulsing, maybe others)



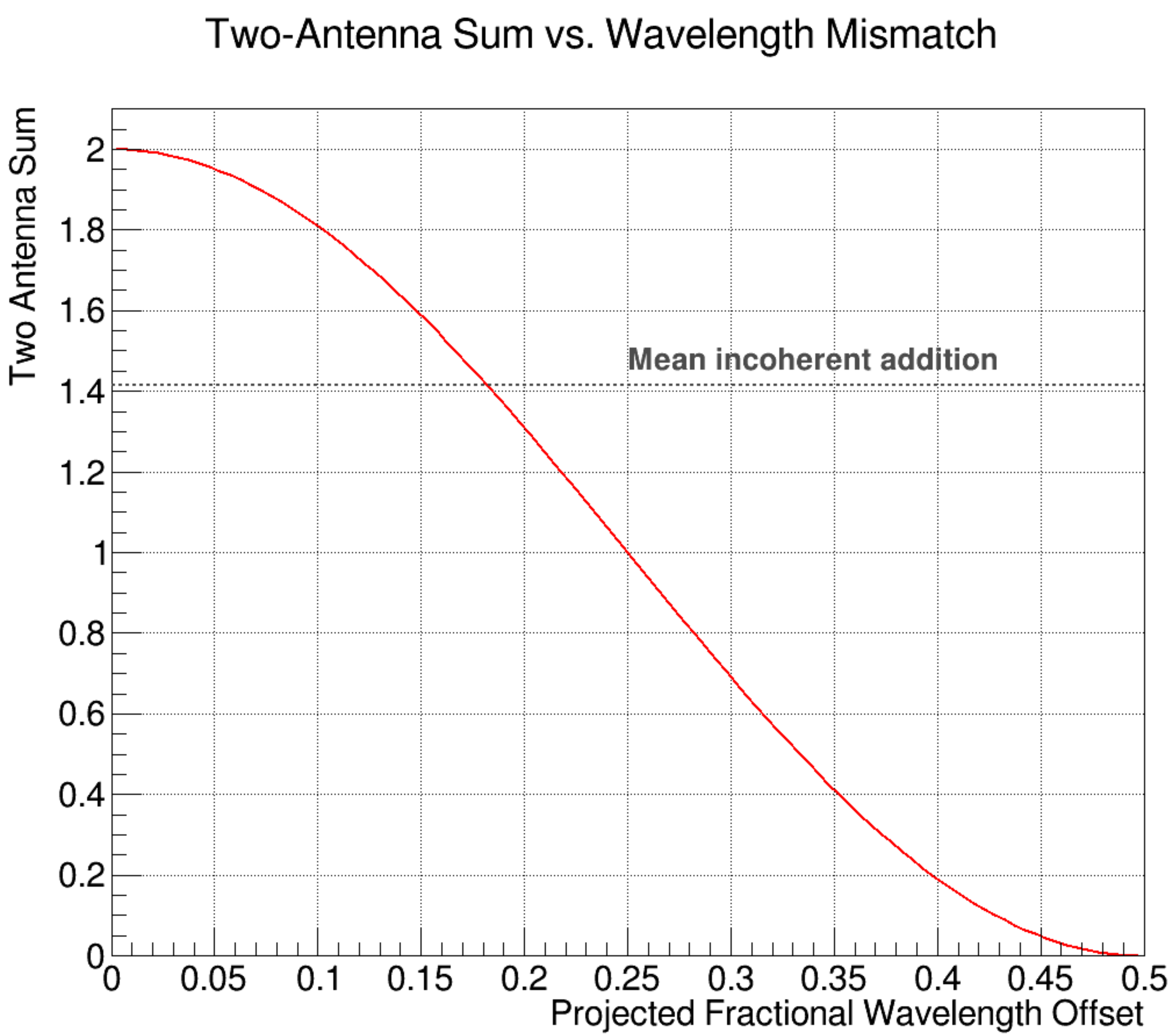
BACKUP

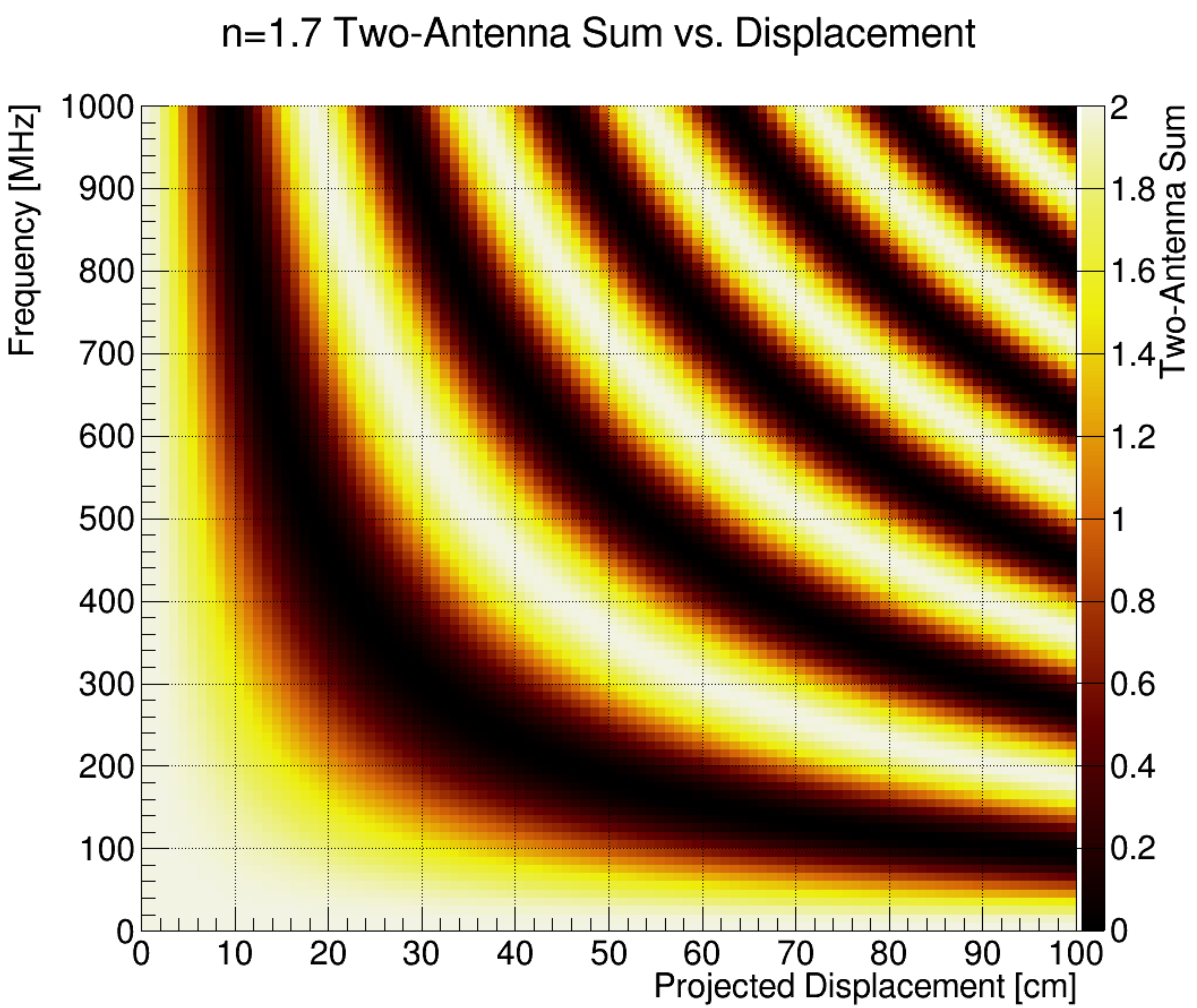
UNKNOWN AND KNOWN PARAMETERS

Quantity	Unknown Parameters	Known Parameters
(x, y, z) of each A5 VPol antenna	24	
(x, y, z) of local Calibration Pulser	3	
(x, y) of SPIceCore hole	2	
(x, y) of Phased Array	2	
Cable delays for each A5 VPol antenna	8	
Cable delays for each Phased Array VPol antenna	7	
Ice Model	3	
Time Delays from A5 baselines + local calibration pulser		28
Time Delays from A5 baselines + SPIceCore		28
(z) of Phased Array		7
z(t) of SPIceCore pulser		1
Total	49	64

The relationship between time delays and position is not linear- so very hard to know when you have "enough" known parameters

HOW GOOD DOES THE POSITION FIT NEED TO BE?





To use full waveforms, need to have errors below 10 cm

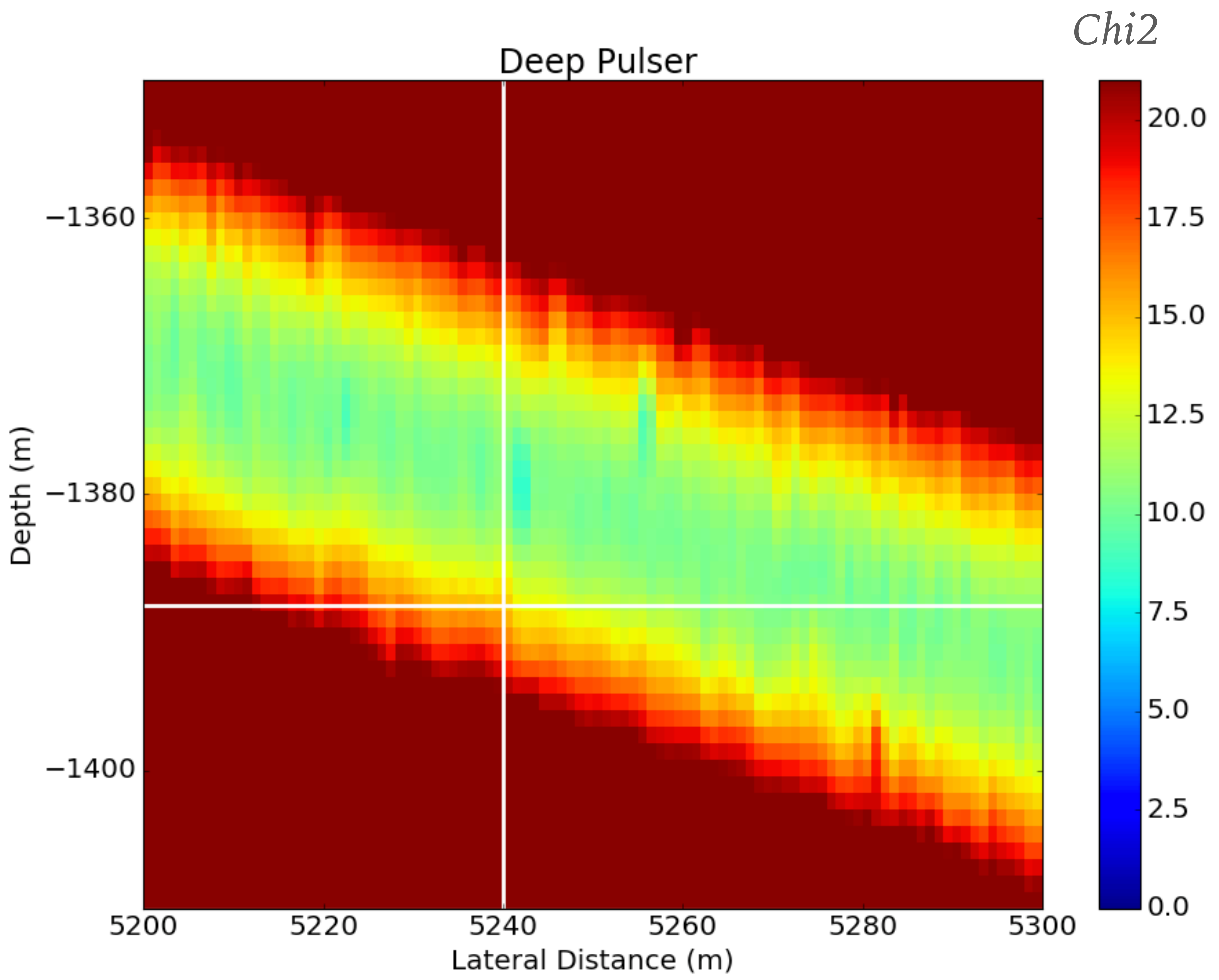
POTENTIAL ICE MODELS

$$n(z) = A - (A - B)e^{Cz}$$

Model Name	A	B	C
AraSim	1.78	1.35	0.0132
Gorham	1.788	1.325	0.0140
AraRoot	1.78	1.353	0.0160
UNL 2016	1.78	1.326	0.0182
UNL 2016, modified	1.78	1.326	0.0202
RICE (2004)	1.78	1.36	0.0132
SPIceCore 1	1.774	1.293	0.0154
SPIceCore 2	1.774	1.249	0.0163
Uzair	1.78	1.17054	0.0171774

I use this model

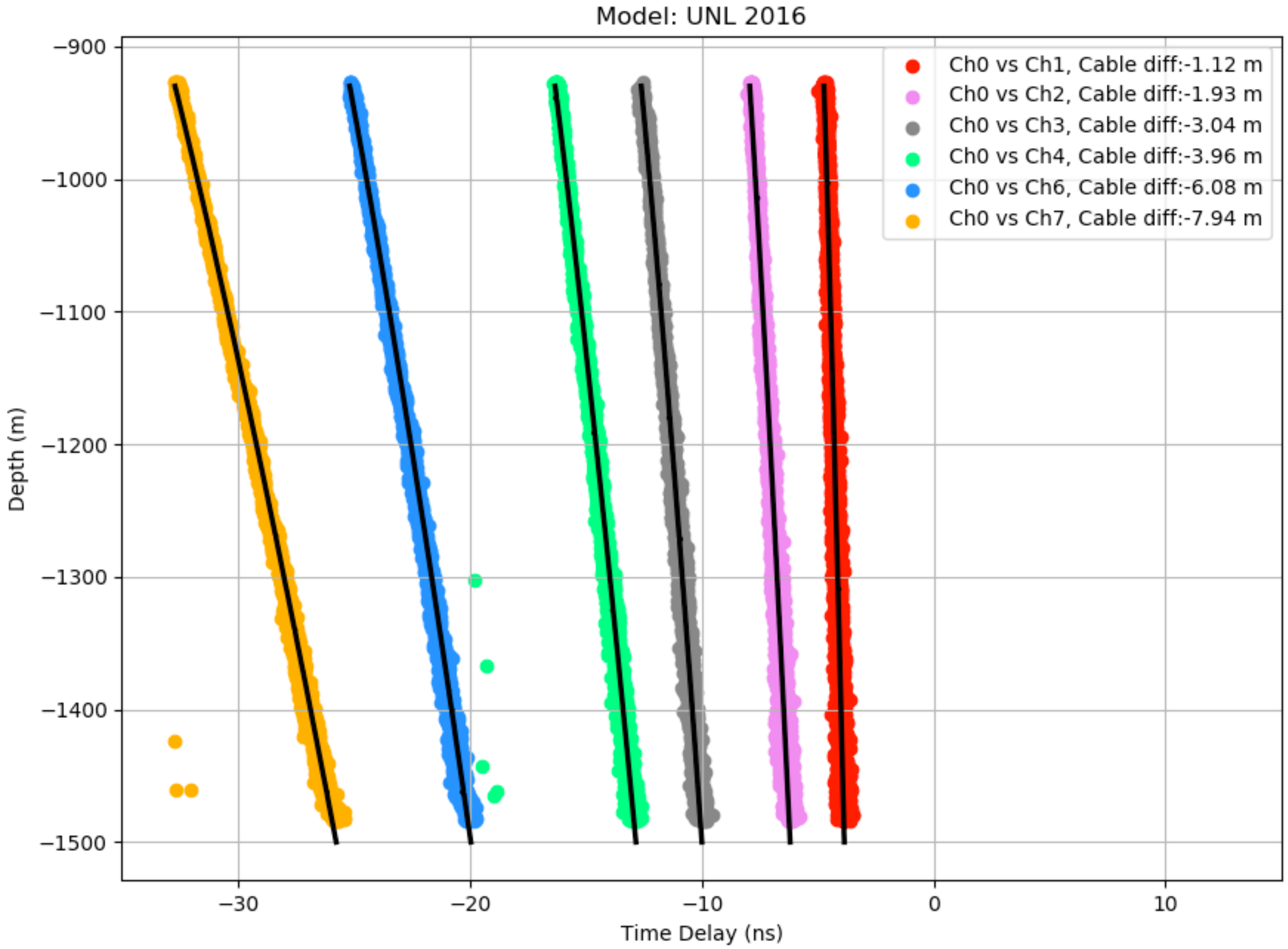
DOES DEEP PULSER RECONSTRUCT WITH THIS ICE MODEL? YES



- Ice model: UNL (2016) modified
- Using only phased array, deep pulser reconstructs to approximately correct location

DoF = 21

UNL (2016) MODIFIED: HOW THIS LOOKS ACROSS CHANNELS

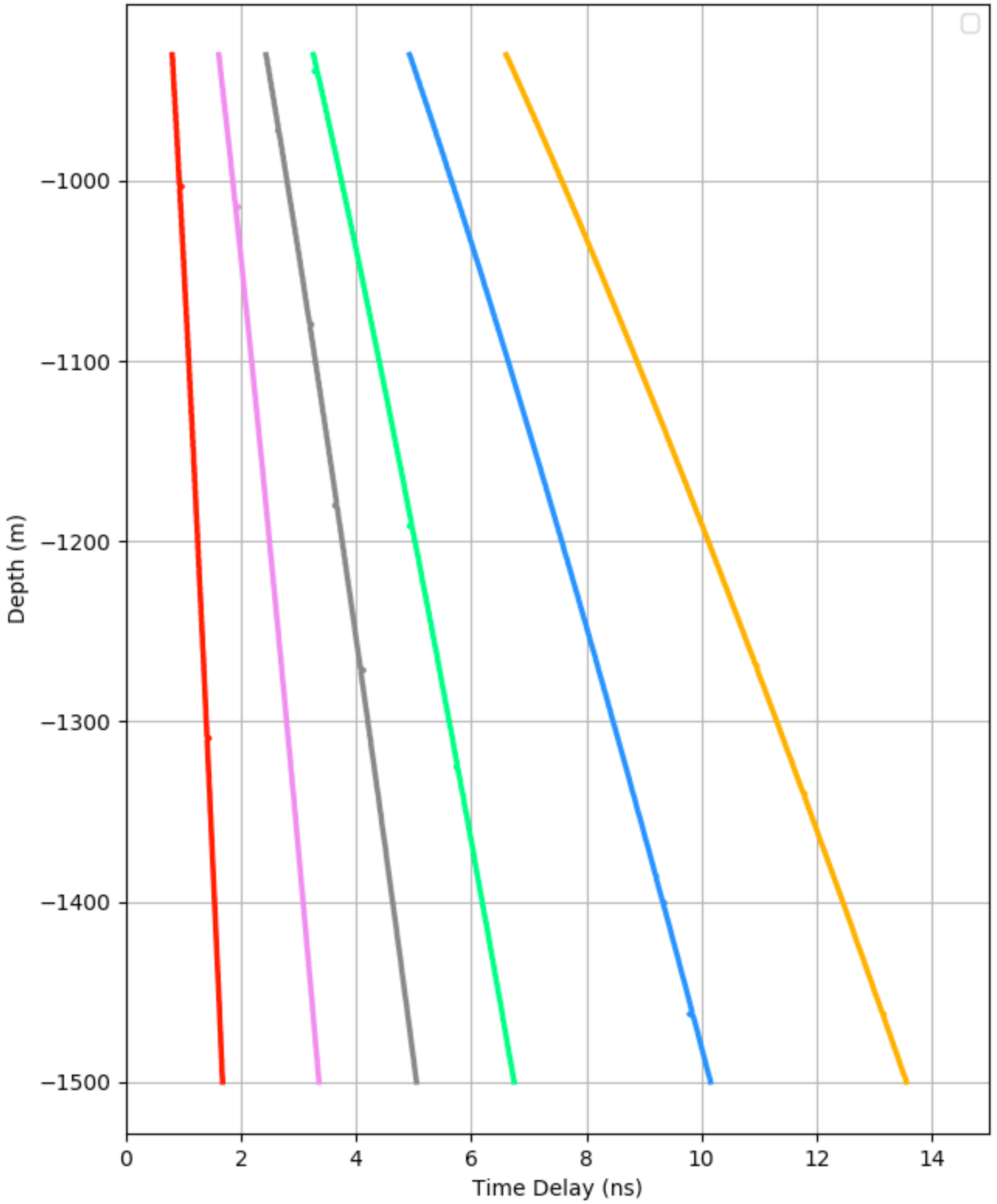


- Modified UNL fits all pairs of channels
- Six pairs of channels shown here

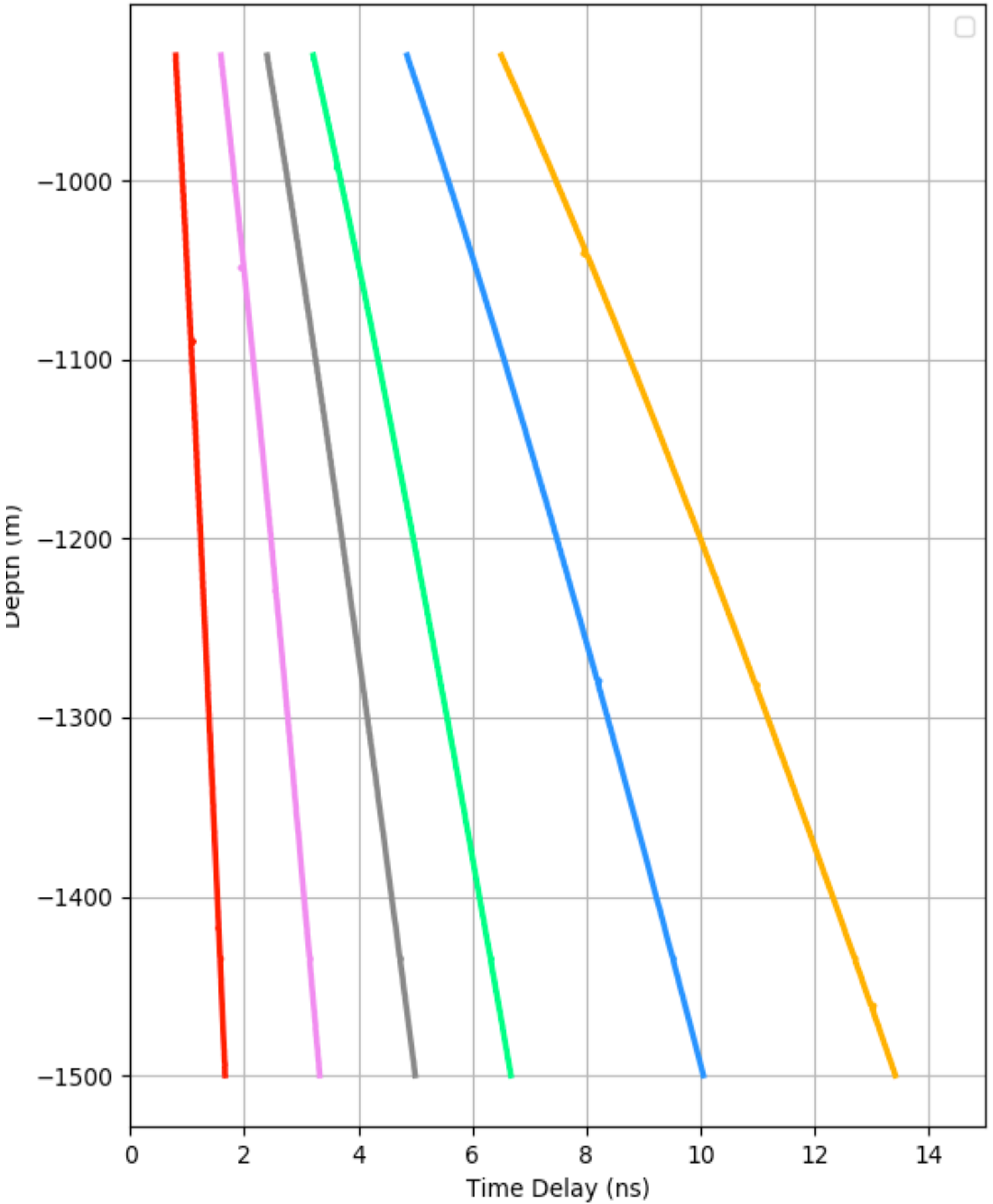
COULD THIS BE A DISTANCE EFFECT? NOT PRIMARILY

Plotting the model for two different SPIceCore distances does not change answer much

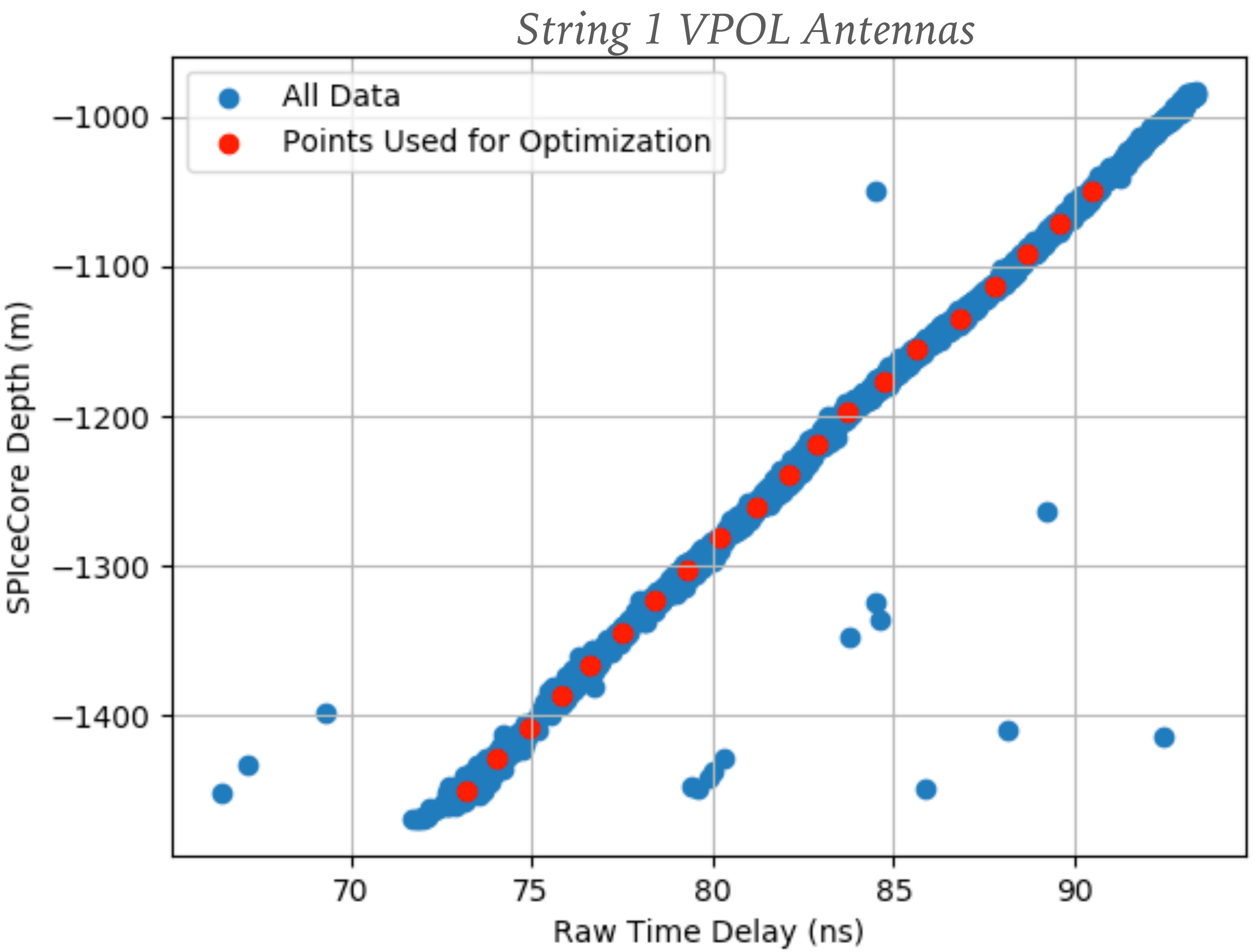
Nominal SPIceCore Distance (4150 m)



SPIceCore Distance = 4190 m



USING SPICECORE FOR CALIBRATION– A5 CHANNELS



- For a single antenna pair, plot all time delays as a function of depth of SPIceCore
- Interpolate to find 20 points at specific depths
- Repeat for all baselines
- Note: cable delays here have not been added

MAP OF ARA STATION 5