Neutrino Vertex Reconstruction in South Pole Ice

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Optics in South Pole Ice

- Index of refraction a function of depth (firn layer)
  - radio waves bend away from surface

- Multiple paths possible
  - direct and reflected signals
  - horizontal / surface propagation not considered in this model

- Neutrino vertex reconstruction needs accurate time delays from raytracing results
  - first step for neutrino energy, direction reconstruction

\[ n(z) = n_{\text{deep}} + (n_{\text{surface}} - n_{\text{deep}}) e^{Cz} \quad \text{for } z < 0 \]

\[ n_{\text{deep}} = 1.78, \quad n_{\text{surface}} = 1.35, \quad C = 0.0132 \text{ m}^{-1} \]
Spline-Fitted Raytrace Tables

• Smoothly interpolate many-dimensional tables with B-splines

• Technical challenges
  – discontinuities due to firn shadow, air/ice boundary cause ringing
  – reflected solutions in addition to direct ray
  – solution: cylindrical coordinates + multi-step table lookup

source location hypothesis: $(z_{source}, r)$

NO SOLUTION
Example raytrace spline fits

- source in air: table points with fit
- source in ice: 2D residuals

- typical error is ~0.3 ns relative to full raytrace calculation
- spline evaluation is 500 times faster
Reconstruction of Simulated Events

- Cross-correlate over all sky using spline time delays for each direction
  - parallelized for GPUs with OpenCL

- Simulated $10^{18}$ eV neutrino vertex direction resolution:
  - $\sim0.3$ degree in zenith / azimuth
All-sky All-Distance Reconstruction

- Form cross-correlation skymap for all distances
  - “onion” reconstruction

- Distance reconstruction is very limited
  - curvature is negligible at O(km) distances
Deep Calibration Pulsers

ARA-2 top view

Vpol pulsers in IceCube holes

D. Seckel
Raytraced Radio Paths

Direct and refracted rays from IC-1 to ARA-2 (center)

total propagation time ~ 22 μs

ARA-2

IC-1 pulser

3.6 km

1.4 km

D. Seckel
Deep Pulser Event (IC-1 to ARA-2)

Both pulses observed: direct (upgoing) and refracted (downgoing)
Directional Reconstruction of Pulser

- cross-correlation reconstruction of direct pulses
  - sum of CC pairs for all directions in sky

- $O(\text{degree})$ directional resolution

- Distance reconstruction very difficult due to near-plane-wave timing
  - solution: use reflected ray

M.-Y Lu
Double-pulse Distance Reconstruction

- Separate direct and reflected pulses into “snippets”

- Include reflected pulses into cross-correlation
  - spline tables also support reflected rays

- Deep pulser distance reconstructed to 13%
  - systematic offset; statistical spread is much less
Double-Pulse Raytracing and Geometric Limitations
1. Time difference of direct pulse to two antennas gives receipt angle of ray
2D Idealized Example

1. Time difference of direct pulse to two antennas gives receipt angle of ray

2. Raytracing gives a path along which the vertex lies
1. Time difference of direct pulse to two antennas gives receipt angle of ray

2. Raytracing gives a path along which the vertex lies

3. Time from direct to reflected pulse in a single antenna identifies vertex

2D Idealized Example
Different Antenna Depths: Reverse Raytrace

allowed ray given measured receipt angle

vertex at \((r, z) = (500, -500)\) m

NB: assumes perfect measurement of receipt angle
Reflected Time Difference Lookup

Direct to reflected time difference along ray

Slope of curve maps time resolution to distance resolution — shallower is more challenging
Raytracing Launch Angle Difference

Smaller is better (more likely that both rays are near Cherenkov cone)
But the real story is more complicated (and 3D!)
Double-Pulse Efficiency in Full Neutrino Simulation
Double-Pulse Selection Algorithm

- Simulated neutrino waveform
- Autocorrelation
- Direct–reflected time difference
- Pulse “snippet” separation
- Cross-correlation

M. Beheler-Amass
10^{18} \text{ eV neutrinos, 25m station depth}
Vertex Distribution

simulated neutrino energy = $10^{18}$ eV, antenna $z = -50$ m, 1000 events

Cherenkov + raytracing geometry favorable in some fraction of cases
Double-Pulse Efficiency vs. Station Depth

Shallower is better for detecting more double pulses
Summary and Next Steps

• Spline framework provides fast raytracing approximation
  – enables all-sky, all-distance interferometric reconstruction

• Cross-correlation vertex directional resolution of $O(1)$ degree

• Additional information from reflected ray enables distance reconstruction
  – $O(10\%)$ distance resolution at several km distance
  – 10%-40% of simulated events have at least one double pulse

• To do: continue to evaluate antenna depth dependence
  – double-pulse efficiency decreases with depth
  – distance resolution increases with depth

• To do: full double-pulse vertex distance reconstruction using automated pulse snippet selection algorithm
Firn Boundary Spline Table

Firn boundary table: fast determination if source / receiver solution possible
Errors relative to raytracer

random sources in air

Gaussian Fit Differences Between Raytrace and Radiospline Delays, In Air

$\sigma = 0.08 (ns)$

random sources in ice

Gaussian Fit Differences Between Raytrace and Radiospline Delays, In Ice

$\sigma = 0.31 (ns)$

Agreement of in-air tables excellent; some outliers in ice (known issue with spline fits)

M. Beydler

6/13/18
radiospline Performance

Random source/target locations (2.3 GHz Core i7)

<table>
<thead>
<tr>
<th>Method</th>
<th>Average computation time / ray (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AraSim raytracer</td>
<td>0.21</td>
</tr>
<tr>
<td>radiospline</td>
<td>0.00037</td>
</tr>
</tbody>
</table>

Spline lookup+evaluation is > 500 times faster than full point-to-point raytrace calculation
Cherenkov Cone Angle Difference

double pulse efficiency estimate from simulation, no noise, cone angle selection

\[ |\theta_{\text{view}} - \theta_c| \leq 2.5^\circ \]

\begin{align*}
\text{log}(E/eV) = 16 & \quad \text{line color: blue} \\
\text{log}(E/eV) = 17 & \quad \text{line color: green} \\
\text{log}(E/eV) = 18 & \quad \text{line color: red} \\
\text{log}(E/eV) = 19 & \quad \text{line color: cyan} \\
\text{log}(E/eV) = 20 & \quad \text{line color: magenta} \\
\text{log}(E/eV) = 21 & \quad \text{line color: yellow}
\end{align*}

\text{M-Y. Lu}