Plans for radio transmitters in distant holes in the Gen2 radio array

- Want full-circuit gain calibration using calibrated Tx over full range of $(\phi_{Tx \rightarrow Rx}, \theta_{Tx \rightarrow Rx})$
- To get incidence angles to ν vertex, need to precisely measure relative timing/antenna positions
  - Precision measurements of cable delays at < 100ps
  - Precision measurements of group delays as f(θ, ϕ)
    - Pre-deployment in-lab calibration as f(temperature)
    - Post-deployment *in situ* with at least subset of antennas (assuming identical)⇒equip some Rx with scalar NWA-on-a-chip to monitor.
    - If possible, record azimuthal orientation and in-hole tilt of Rx after deployment
- 10 cm/yr snow accumulation will change n(z)⇒re-calibrate surface antennas year-to-year (Jakob B)
  - Can use ARIANNA trick to precisely measure accumulation if equip w/ near-surface Tx

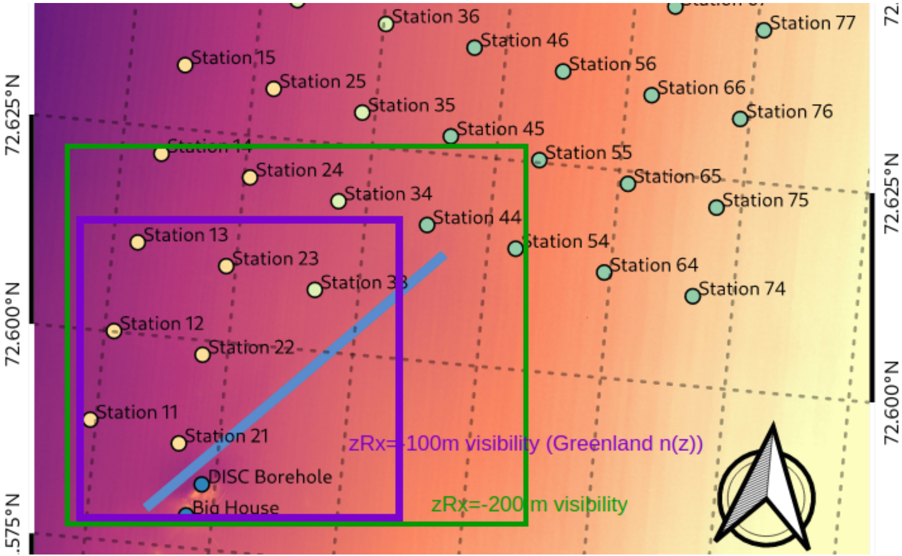
Prior calibration status/lessons (see MyoungChul, Steve B. and Kaeli talks!)

- MyoungChul calibrate ARA to thermal noise
- Ch-to-ch variation in Rx using multiple distant Tx
  - ICL rooftop + deep pulsers + surface pulsing + SPICE core + WB
  - $\delta\mathcal{G}_{VPol}$ ~25%
  - $\delta\mathcal{G}_{HPol}$ ~30%
    - ARA Calibration to UHECR flux still TBD
  - Ilya and Giri (UNL) currently putting ARA Tx into nuRadioMC

What will we have learned by 2025?

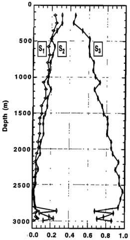
- additional SPICE core runs (2022-23?):
  - incl. frequency sweep at Higher amplitude than 2019-20 run
    - most direct measure of $L_{atten}(\omega)$
  - with dedicated HPol transmitter to understand odd pattern of H:V in ARA data
- Surface survey over 2π in azimuth (ARA & RNO-G)
  - Near-surface Tx (both VPol and HPol)$\rightarrow$both shallow and deep Rx
    - Can we use R rays only for neutrino reconstruction?

RNO-G DISC hole - SPICE, redux



What else will we learn from RNO-G calibration?

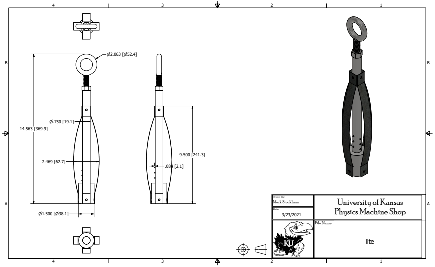
- Advance RF cal techniques & pulser hardware
  - Measure density fluctuations
- Numerical results on permittivity likely site-specific
  - E.g., birefringent asymmetry expected at Summit (no flow$\Rightarrow n_1 \approx n_2$):



https://agupubs.onlinelibrary.wiley.com/doi/pdfdirect/10.1029/97JC00161

Will also prototype Hole logging (closure?)

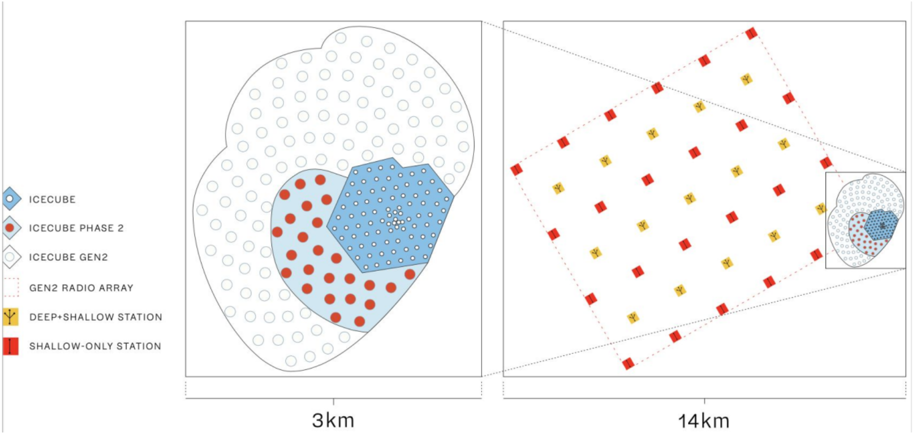
- Commercial acoustic loggers https://mountsopris.com/ql40-abi-2g-acoustic-televiewer: $60K + cold-hardening ($4K) + software ($4K) + maintenance ($2K)
- cheap KU custom (BoraBora)
  - Mechanically find minimum ID +optical/Hall effect sensors→time constriction passed



ARA local CP model

- $+$ Local cal pulser, 1–2 per station, in separate boreholes, gives:
  - $+$ 'heartbeat' to measure livetime
    - $+$ 'Standard' waveforms to measure constancy of response (although not done methodically)
  - $+$ Estimate of $\epsilon_{trigger}(SNR)$ using attenuators on cal pulser transmitters
  - $+$ Measures of XPol response
- – Nearby disallows training on DnR
- – baselines too short to see biref effects
- – Timestamps occasionally off⇒filtering ex post facto
- – Requires dedicated boreholes
  - ⇒*Add local CP Tx to each Rx borehole (RNO-G)*

ICG2R Geometry



Cal Tower+Hole

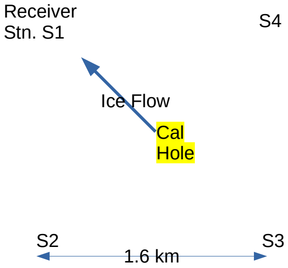
- Propose that, for every N (=32? =16?) stations, drill one dedicated 'calibration' hole at inter-station grid center
  - distances more typical of true neutrinos than local CP
- zTx(z=-100m)→zRx(z=-200m) horizon at ∼1 km.
  - For 1.6 km station spacing on square grid, need z∼-300 m to safely illuminate NN from centrally-located Tx calibration hole
    - Caution: For vertical PA z=-100→-80 m, prominent caustic effects
    - Surface Rx horizon much more limited than in-ice
- 'Permanent' instrumentation in most (2/3?) cal holes
  - DS: Possibly including two Tx separated by multi-meter scales
- Tx operated in either pulsed, tone (of variable duration), or CW mode (autonomously-powered)
  - L_{atten} not possible via near/far measurement, will require absolute dead-reckoned P_{Rx}/P_{Tx}
  - Remaining holes left empty: periodic S11(z_{Rx}) measurements, $V_{Rx}(z_{Tx})$
    - But how to stand-off closure?

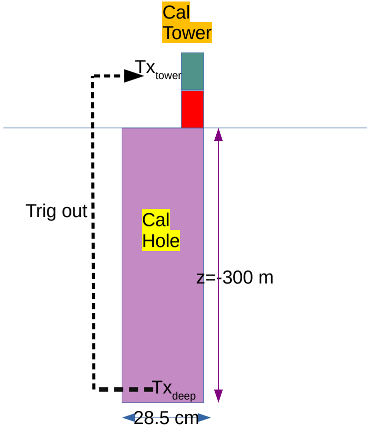
Prioritize deploying a calibration station in first season (before you realize there is a calibration issue you didn't anticipate how to address)

Station synchronization/averaging⇒Cal Tower

- Need to synchronize DAQ clocks on surface - currently, GPS (tricks can help)
  - Current ARA intra-station timing resolution ∼1–2 microseconds
    - To determine $\delta n/n < 0.001$ ⇒5–10 ns absolute
- ⇒Propose put VPol/HPol Tx atop calibration tower (4-5 m adequate, modulo snow accumulation)
  - "Segmented tower" to anticipate accumulation?
- For ice properties measurements over long baselines, would like to have waveform-averaging capabilities for low-SNR signals⇒trigger locked to high-SNR surface dipole→in-ice Rx pulses.
- If this can be locked in, possibility of measuring L_{atten} via bottom bounce!
- Can also use a drone (a la' TAROGE-M [Jordan]) to verify $\epsilon(\theta)$, although does not facilitate signal averaging
  - tethered balloon?
  - HiCalX on a cubesat?
- Ice Properties↔Tx characteristics require redundancy!

CalibrationTowerHole





Costing

- In-hole pulser (IDL/HVSP): 500 USD (dominated by DC→DC converter)
- Above-hole pulser (IDL/HVSP): 500
- 300 m LMR-400 trigger line cable + N-connectors: 1000
- In-ice trigger generator w/ external input: 100
- GPS boards (in-ice + above-hole): 100
- Arduino data loggers down-hole and above surface (200)
  - Send data up over LMR-400 to surface?
- Aluminum tower: 1000
- Two dipole antennas + 1 LPDA (home-built): 500
- Solar panels: 400

Total: ∼5K/station + labor (50K, total) + hole-drilling (?) + drill-fluid (10000) + hole-logger (5000/pc)
Extras: comms tower for turning on/off during winter? (a la' Mt. Discovery or TARA model)

Other ?

- CATH remote control/telemetry and/or local only (power via ICG2R grid)
- Can Gen2 Surface Radio Array fill some of calibration functionality needs?
- What can we get out of the SPICE core hole?
  - Optical (radio?) quality degrades with each drop.
  - Need to monitor hole closure!
- What can we get from a dedicated deep (2400 m?) calibration hole (a la' SPICE) to-be-drilled for ICG2?
  - Can we get one dedicated deep calibration hole at center of ICG2R array?
  - Jeff Severinghaus/Dale Winebrenner drill: 2400 m/48 hrs/89 mm diameter
    - But up to 10 degree walk⇒400 m at bottom of hole!
- What calibration sources can be used parasitically? (Cosmin)
  - Twice-daily weather balloon flights broadcast @405 MHz

One-line summary

Since IceCube Gen2 Radio is an instrument which targets neutrino astronomy over an unprecedented length scale and over an unprecedented duration, the calibration effort should match the science goals of tens of neutrinos detected, rather than just ID of the first UHE neutrino.