Radio instrumentation for neutrino detectors (mostly) using ice

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Disclaimers

- I'll be touching on various instrumentation for a lot of different experiments
  - ARA, ARIANNA, RNO-G, IceCube Gen2Radio, ANITA, PUEO, BEACON, GRAND, TAROGE ...
- I won't be able to capture every detail
- I "only" work on 6 of these experiments
- Fortunately there are a lot of commonalities

Outline

1. **General Overview of radio neutrino detectors**
   - Askaryan (In-ice, balloon-borne)
   - Earth-skimming (balloon-borne, terrestrial)
2. Details on status and prospects of specific subsystems
   - Detection medium
   - Antenna and RF-chain design
   - Trigger and Digitization Electronics
   - Deployment
   - Power
   - Communications and Control

Anatomy of an in-ice radio neutrino detector (ARA, ARIANNA, RNO-G, IceCube Gen2Radio)

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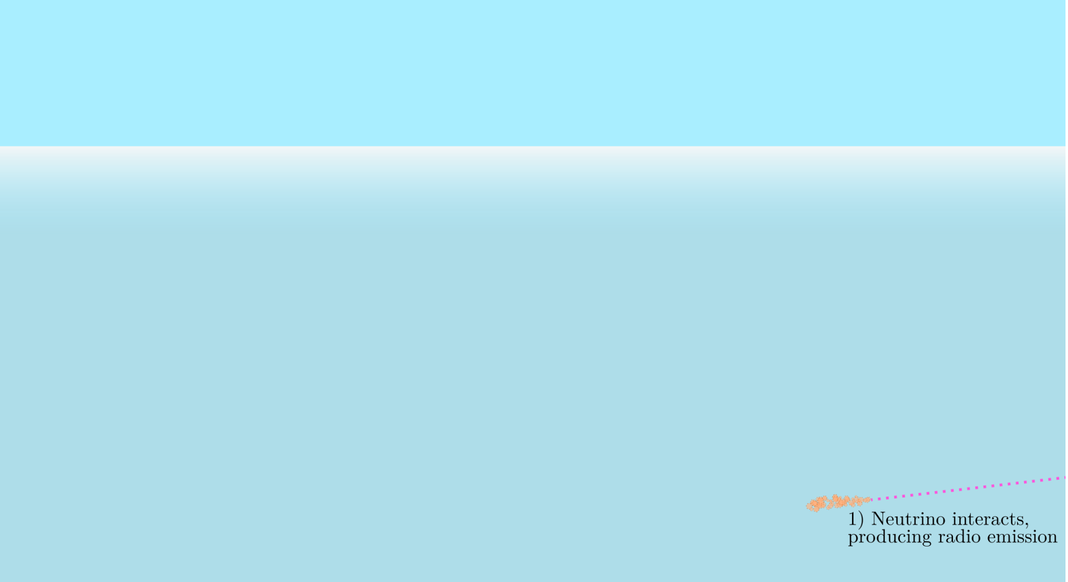

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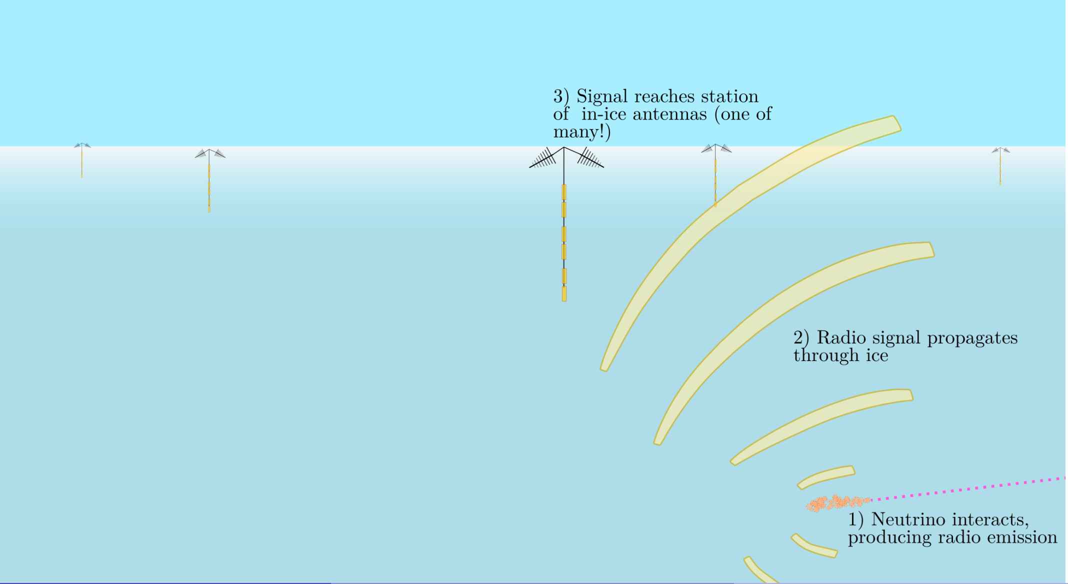

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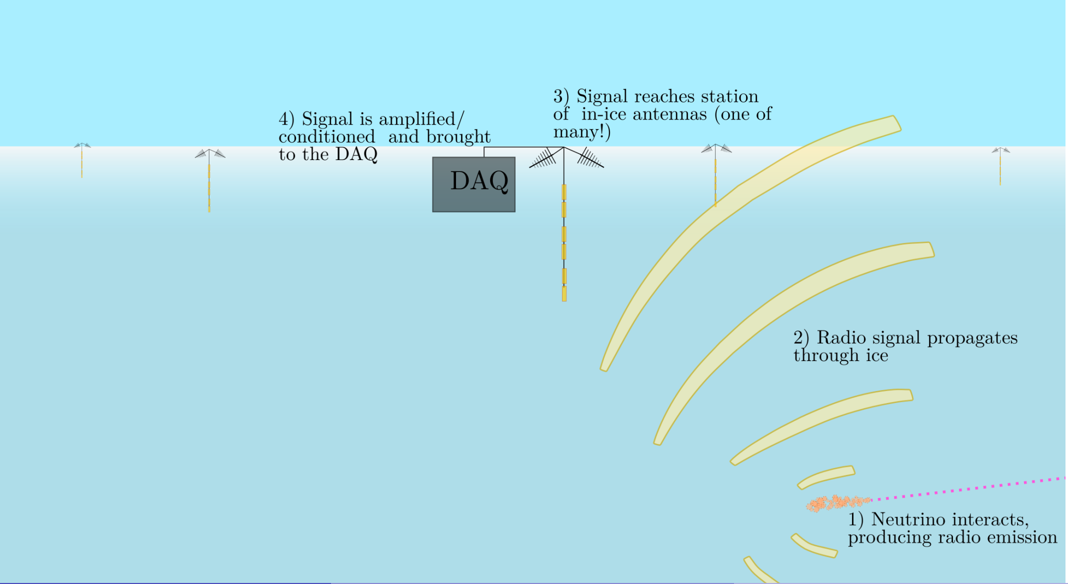

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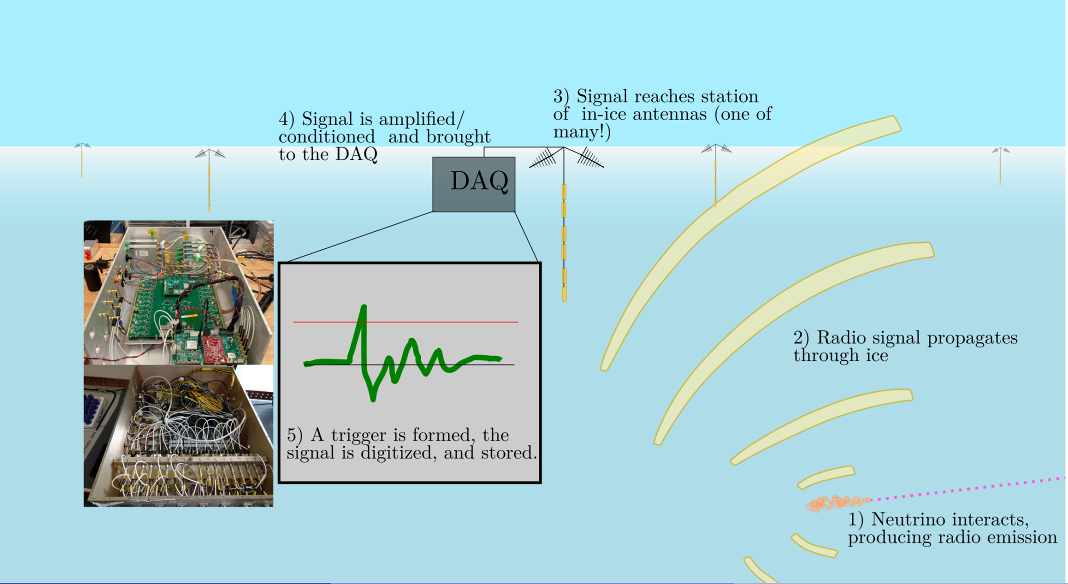

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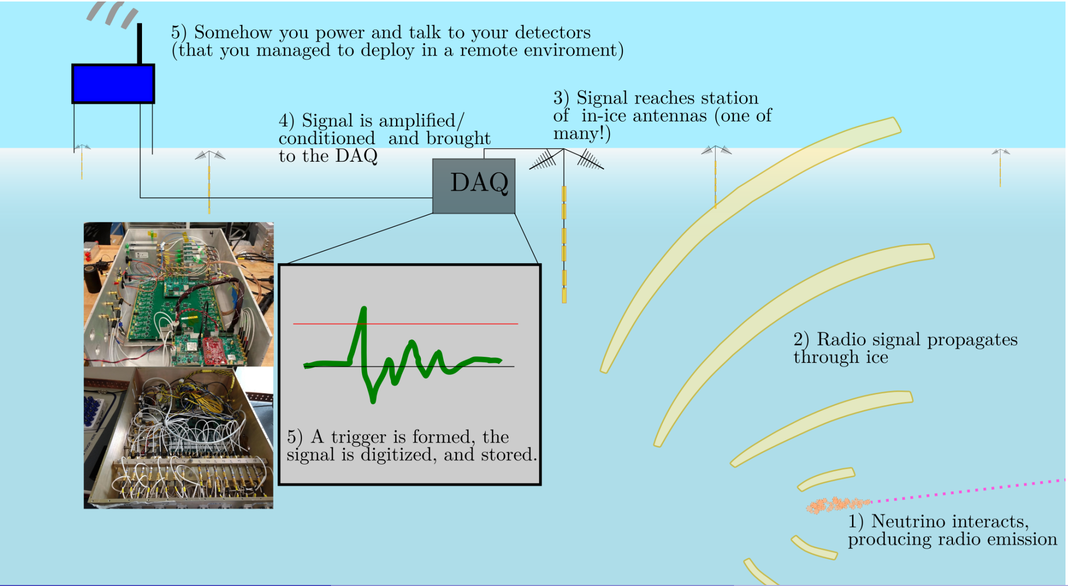

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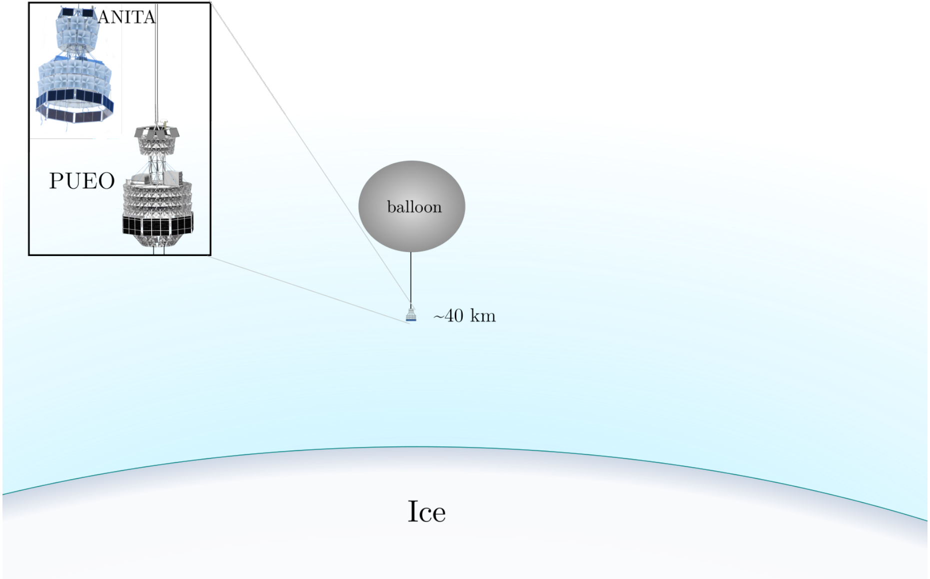

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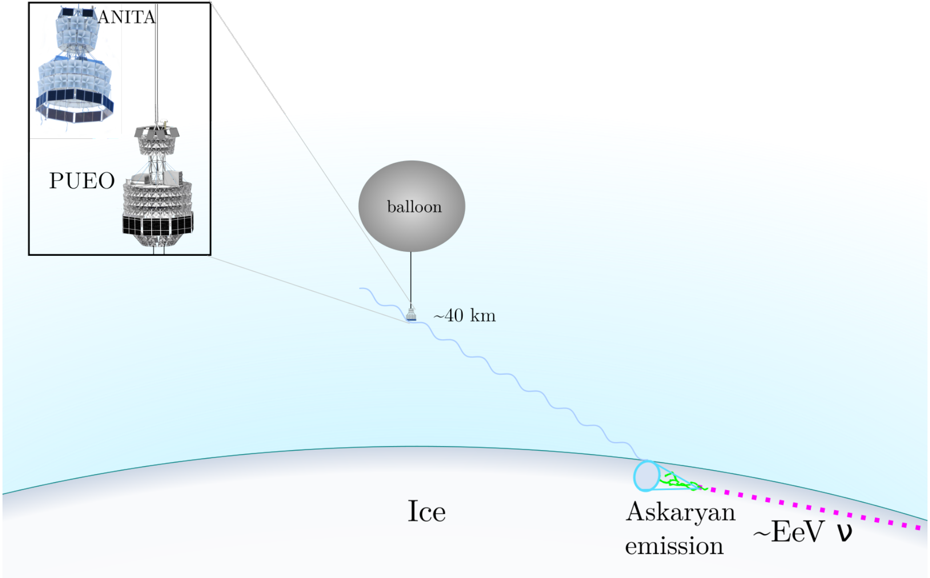

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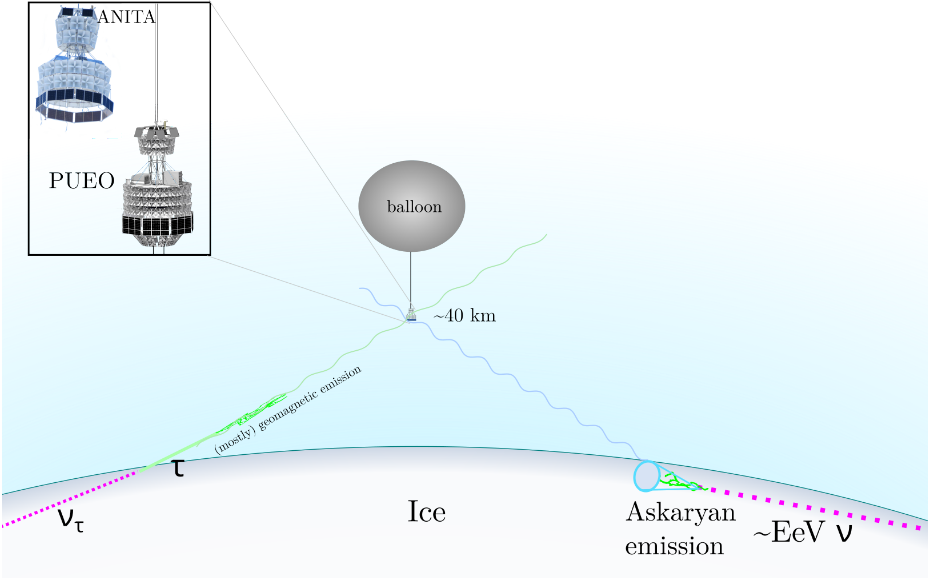

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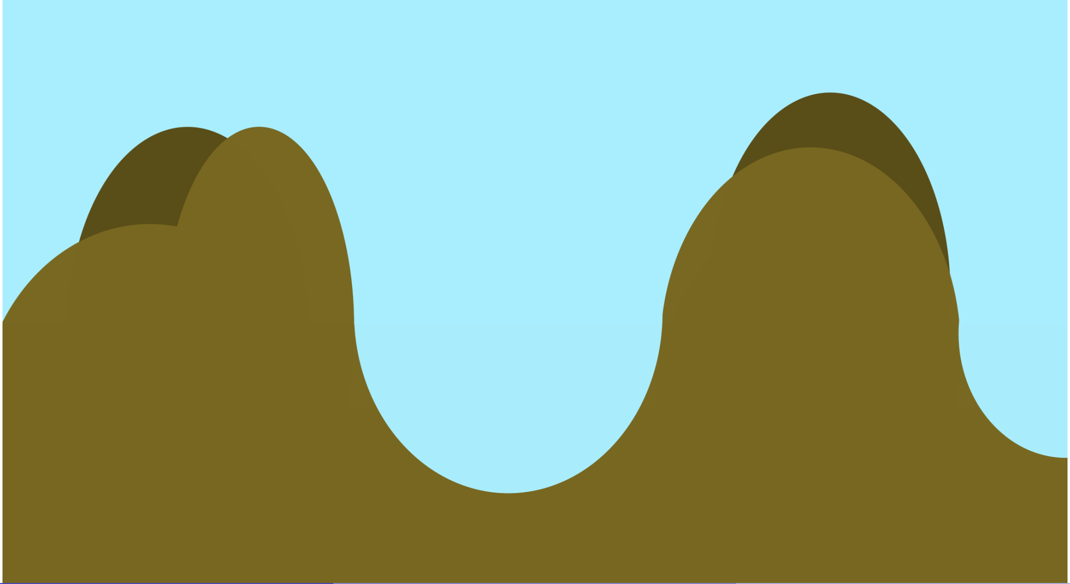

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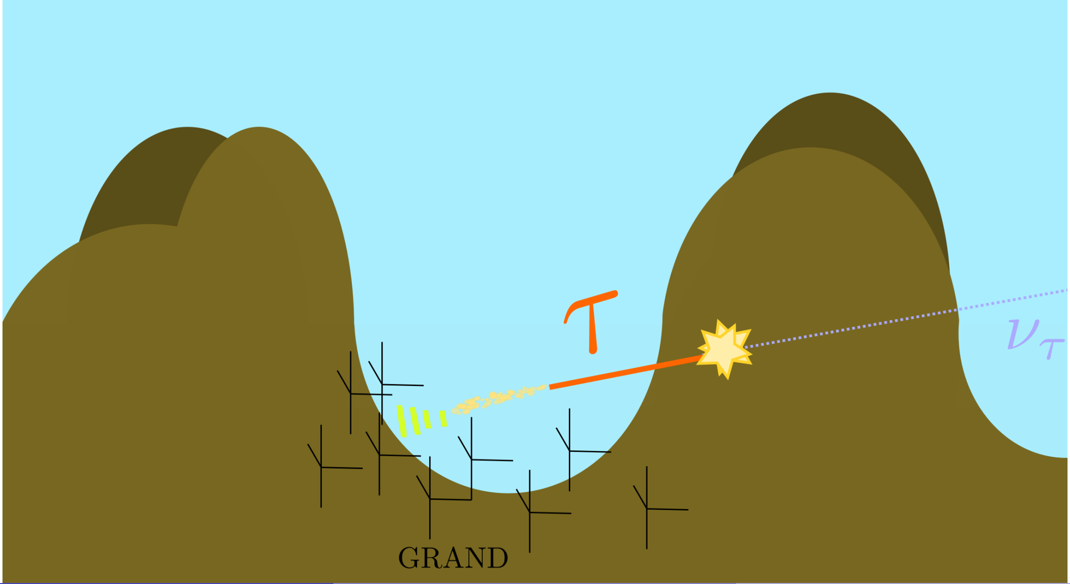

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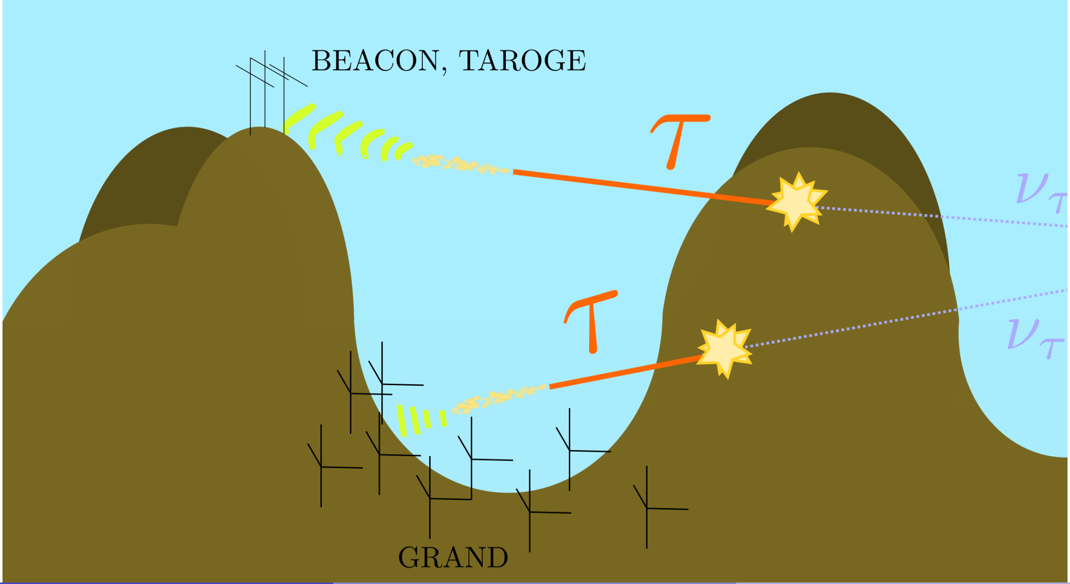
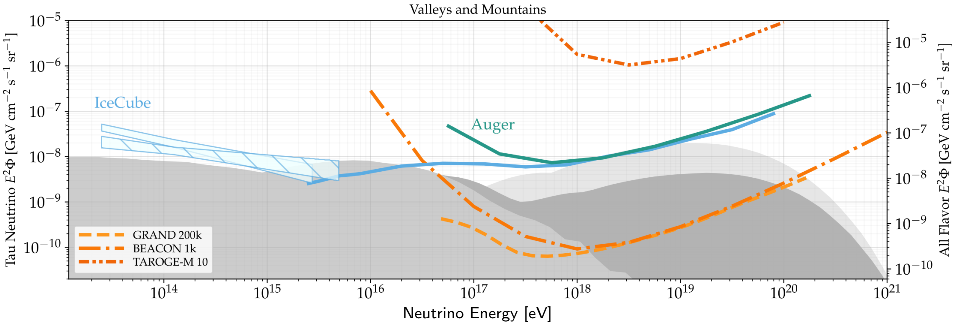


Earth-skimming Radio Detectors

- Only sensitive to τ neutrinos (and cosmic rays)
  - See N. Otte's talk for more on Earth-skimming technique (not limited to radio!)
- Can be located anywhere with mountains (that is radio quiet)
  - GRAND location is Tien Shan Mountains in China
  - BEACON prototype in White Mountains of California
  - TAROGE in Taiwan, TAROGE-M on Mt. Melbourne in Antarctica
- But much of instrument design mirrors Askaryan detectors
  - Prototypes for BEACON and TAROGE literally use electronics from ARA and ARIANNA.



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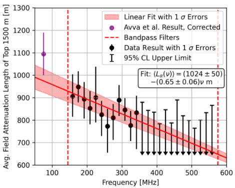
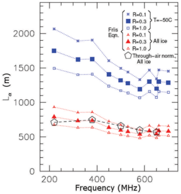
Ice as a Radio Detection Medium

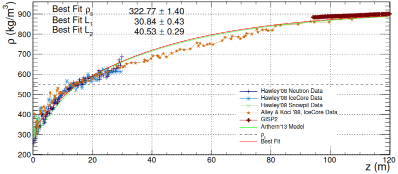
- Glacial ice is abundant in Antarctica and Greenland, and basic properties are well understood
- Radio attenuation length is temperature and chemical composition dependent, but is $\mathcal{O}(1\text{ km})$ at relevant frequencies
- Index of refraction approximately constant except near surface in the "firn," the transition layer between surface snow and deep ice.
  - Size of firn varies from location to location, $\mathcal{O}(100\text{ m})$ in Greenland, $\mathcal{O}(200\text{ m})$ at South Pole
  - This changing index of refraction is the main motivation for burying antennas (larger aperture due to ray bending, more well understood ice)
- Studies ongoing on more subtle properties of ice (e.g. birefringence)

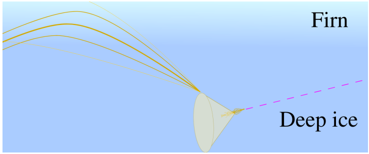
Left: Greenland Attenuation (arXiv:2201.07846), Right: SP Attenuation(doi:10.3189/172756505781829467)



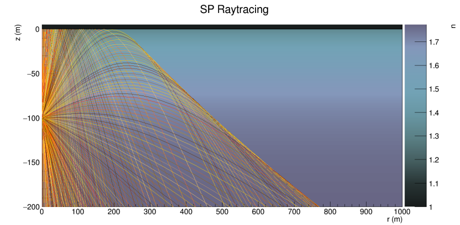


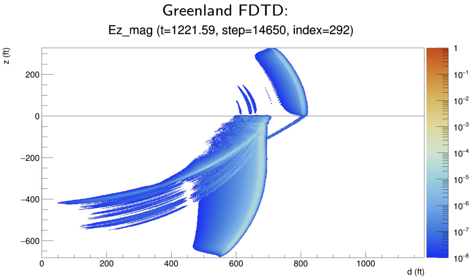
Greenland Ice Density (arXiv:1805.12576)





Modeling propagation in ice





- Raytracing (infinite frequency) approximation works reasonably well in deep, mostly homogeneous ice
- Near the surface, density structures similar to wavelength (and the ice surface) start to matter
- This is particularly important in the in-ice case as it allows backgrounds to couple into the ice in unusual ways (for balloons, these details are largely unimportant)
- Improved modeling using Finite-Difference Time Domain (arXiv:1805.12576) or Parabolic Equations (arXiv:2011.05997) an important development in understanding propagation

The atmosphere as a Radio Detection Medium

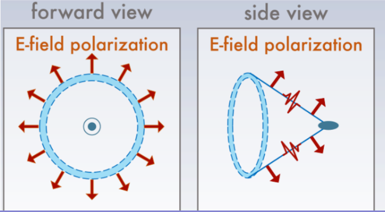
- For air showers, the atmosphere is very well understood and constantly globally monitored for meteorology
- Refractivity gradient is small, often negligible for propagation (other than inversions)
- What is more difficult is modeling reflections and diffraction off the ground
  - Since reflected cosmic ray emission can look like upward going τ emission, this is crucial!
  - But since Fresnel zone is relatively large, usually signal would just be attenuated rather than distorted

FDTD simulation of plane wave reflecting off a rough ice with under-ice layers:

(Some) Antenna Parameters

- Gain (or directivity): how pointy an antennas beam pattern is
  - A higher-gain antenna can recover smaller signals in direction of peak gain, but need multiple antennas to cover 2π
  - In analysis (and even in trigger) can combine antennas to synthesize higher-gain antennas
- Band: What frequencies may be matched well
  - More bandwidth is better. Typically lower frequencies propagate better and can see signal from farther from Cerenkov angle, but require physically larger antennas for good matching
- Dispersion: How much group delay is added to signal
- Physical size: Larger antennas are more difficult to deploy, especially in boreholes
- Polarization: What polarizations the antenna is sensitive to
  - Polarization is important for background rejection and for neutrino direction reconstruction

Polarization from Askaryan radiation:

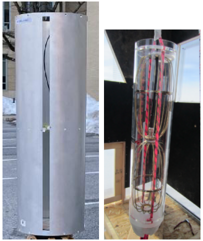


In-ice experiment antennas

- If not constrained by geometry (i.e near surface), Log-Periodic Dipole Antennas (LPDAs) reasonable.
  - Moderate gain, wideband(100 MHz - 1 GHz), but dispersive
  - Planar geometry makes for easy deployment; Can be rotated to cover different polarizations
- In a borehole, geometry is severely constrained
- Deep VPol antennas are still relatively easy:
  - Bicone "birdcages" (e.g. ARA) and fat dipole (e.g. RNO-G, RICE) antennas have been used.
  - Reasonable bandwidth (150 MHz - 600 MHz) , low dispersion
- Deep HPol antennas are hard
  - Slot antennas fit, but difficult to make broadband
    - ⋆ Adding ferrites (e.g. ARA) can help, at cost of loss of efficiency, linearity
  - Lots of room for improvement here, or new ideas (circularly polarized antennas?)

RNO-G Fat Dipole VPol (left) + LPDA (right):

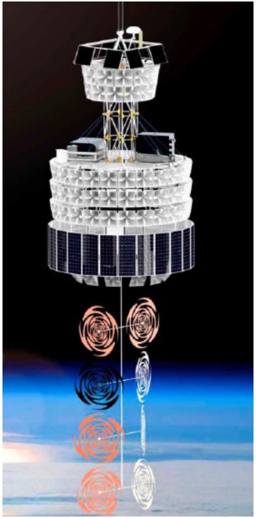
RNO-G quad-slot HPol (left), ARA VPol Bicone (right) :



Balloon-borne antennas

ANITA-III + ALFA dropdown:

PUEO, including low-frequency dropdowns:



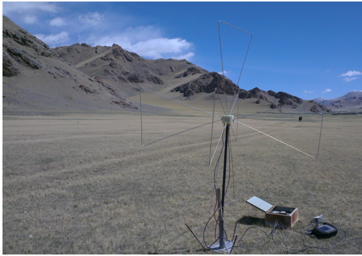
- Limited to one payload with constrained geometry (from launch envelope)
- Maximize gain for surface area → use dual-polarization quad-ridge horn (10 dBi) antennas
  - Well-matched across wide band, low dispersion, symmetric in polarization
  - But need to read out a LOT of channels
- Tradeoff between lower frequency cutoff and antenna size (PUEO will have more, smaller antennas targeting 300-1200 MHz, as opposed to 200-1200 MHz on ANITA)
- To extend to low frequency, drop down larger antennas after launch
  - Wire discone (ALFA) on ANITA-III
  - Sinuous dropdowns planned on PUEO

Earth-skimming antennas

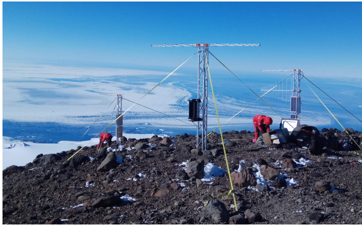
- Due to different emission spectrum, greater potential for interference, Earth-skimming radio experiments typically target lower band
- At these frequencies, galactic noise is significant, so ok to use electrically-short antennas
- Antennas must be raised high enough to avoid ground interference effects
    - Deployability and survivability are very important

BEACON short crossed-dipoles

GRAND bowties:



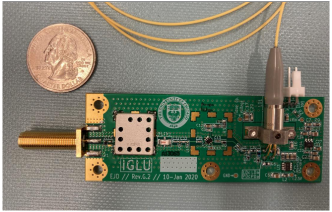
TAROGE-M LPDAs:

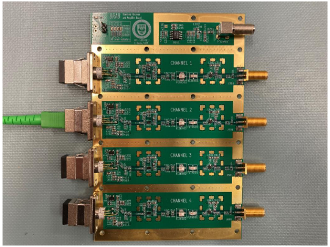


The rest of the RF Chain

- All experiments now using low-noise amplifiers very close to antenna to reduce noise figure
  - Noise requirements given by environment, but nothing too fancy is required since ice, ground is warm relative to 0 K
  - Custom LNAs can be designed to use less power
- Filters at frontend to define passband, in some cases remove RFI (e.g. handheld radios at Pole)
- Then signal transmitted either via coax (with DC bias) or RF-over-Fiber (RFoF)
  - Coax is ok for short distances or lower frequencies
  - For broadband antennas located far from DAQ box (e.g. down a borehole), RFoF is necessary to avoid excessive weight, gain slope (though still need copper for power)
  - Custom integrated LNA and RFoF transmitter developed for RNO-G much more cost-effective and power-efficient than commercial solutions

RNO-G combined LNA and RFoF transmitter + receiver / second stage amplifiers in 0.25 W/channel

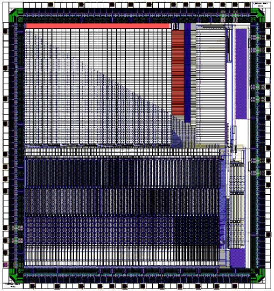




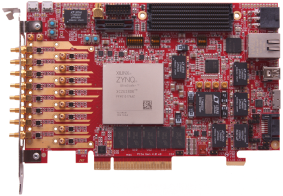
E. Oberla

Digitization

LAB4d chip (arXiv:1803.04600)



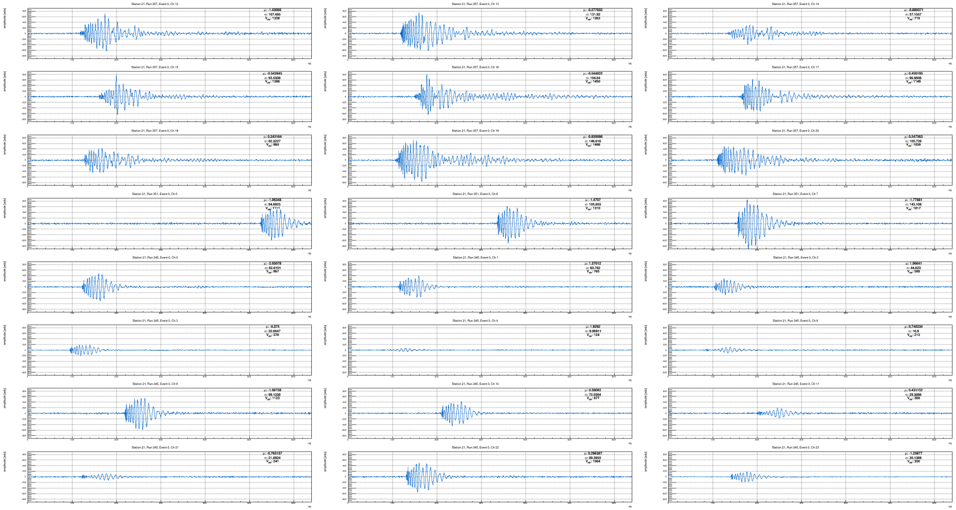
An RFSoC dev board:



- Flash ADCs (i.e. what you have in your oscilloscope) expensive and power hungry at high bandwidth, have not been scaleable to large channel counts under power, cost constraints.
  - But can be fine for lower bandwidths, smaller numbers of antennas (e.g. BEACON), especially with newer chips (e.g. HMCAD1511)
- Field has traditionally used custom Switched Capacitor Arrays (SCAs), where signal is recorded to analog buffer and then read out slowly when triggered
  - SST (ARIANNA, 4 channel/chip, 256 samples, ∼2 GSa/s), limited buffer depth for large stations
  - LAB3 (ANITA, 4 channel/chip, 260 samples, 2.6 GSa/s), complicated calibration, uneven sampling
  - IRS2 (ARA, 4 channel/chip, up to 32768 samples, 3.2 GSa/s), complicated calibration, uneven sampling
  - LAB4 (RNO-G, 1 channel/chip, 4096 samples (double buffered), 2.4-3.2 GSa/s), builtin compensation for uneven sampling!
  - New Multichannel chip of Gen2Radio?
- The Xilinx RFSoC is a new FPGA with built in 4 GSa/s ADCs that has emerged recently (thanks 5G!)
  - Still, cost and power consumption are too high for a scalable in-ice array, but will be used for PUEO!

What does data look like

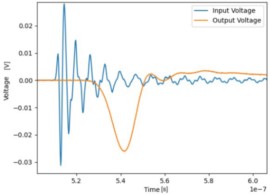
A bunch of waveforms (calibration pulser in RNO-G)



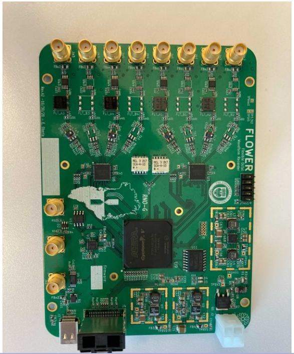
Triggering

- Goal is low threshold without maxing out data rate (most triggers thermal noise)
- Traditionally, analog coincidence triggering within causal time window used, with discriminators (ARIANNA) or square-law diode detectors (ANITA, ARA, RNO-G surface trigger)
  - Can play tricks with polarization (e.g. convert to LCP/RCP)
  - Optimal trigger bandwidth not necessarily the same as digitization bandwidth
  - Thresholds typically dynamically adjusted (at least on ANITA, ARA, RNO-G) to maintain data rate.
- Digital triggering is much more flexible, but requires streaming digitizer
  - But not necessary on all channels; can use on a subset of channels at lower bandwidth as demonstrated in RNO-G.
  - Flexible digital streaming board developed for RNO-G, planned to be used in BEACON

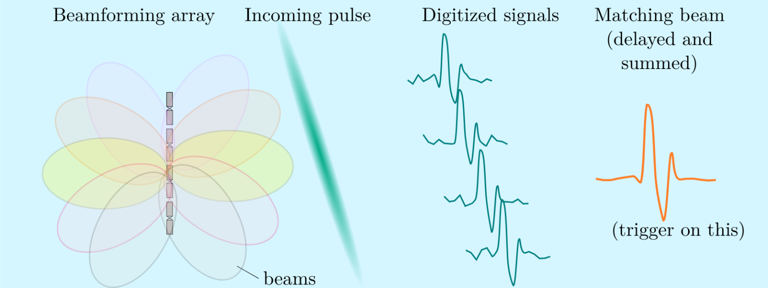
RNO-G trigger diode output:



Flexible digital streaming trigger board:



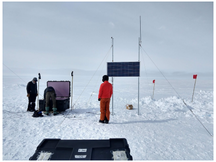
Beamforming Trigger



- With digital trigger, can synthesize multiple high-gain "beams" from low-gain antennas
- Take multiple antennas and combine signals with time delays to enhance certain directions (beams), then trigger on the beam
  - Technique demonstrated at South Pole with Askaryan Radio Array (see arXiv:1809.04573, arXiv:2202.07080)
  - Used in BEACON (including RFI masking)
  - Will be used in PUEO with RFSoCs
  - Will be used with subset of antennas (bottom 4) in RNO-G, Gen2Radio

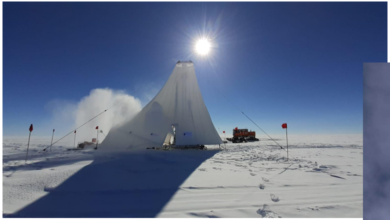
Instrument Deployment

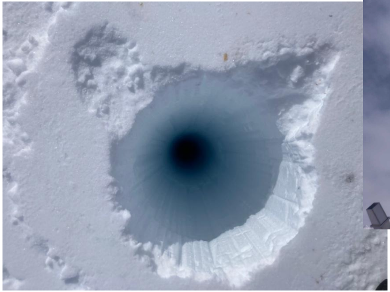
- For balloon, deployment is on standard long-duration balloon platform (balloons already fly in Antarctica), so problem solved by NASA
- Other types of detector require placing detectors in remote environment
  - Polar regions are remote, require long distance travel from stations for large arrays, shelter from cold.
  - For mountain-top detectors, need to find remote mountain ranges with vehicular access for realistic deployment
- Trend towards simplification of detector deployment (fewer holes, etc.) to allow for scalability
- Keeping track of which components are deployed where is also essential



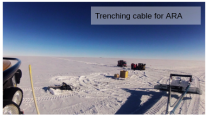
Drilling

- ARA used hot water drill to reach 200 m
  - Worked, but slow (hard to scale)
- RNO-G using new mechanical “BigRAID” auger drilled developed by BAS, first deployed last year
  - Some teething pains (e.g. controller software bugs to be ironed out), but demonstrated drilling down to 100 m (target depth for RNO-G, Gen2Radio) in a single day.





Power



- Balloon is least constrained (multiple kW of solar)
- In-ice arrays and earth-skimming arrays require many stations in remote places, so power is one of the primary constraint on designs
  - Cabled power
    - Available if near large research facility (e.g. South Pole, for ARA or Gen2Radio; or White Mountain Research Center for BEACON prototype)
    - Power available for a large array not unlimited, due to transmission losses, weight and power plant limitations
    - Trenching in ice well-demonstrated by ARA
  - Autonomous power:
    - Solar panels + batteries work well most places, but limited uptime in Polar regions
    - Wind power under development to improve uptime in winter.

Communications

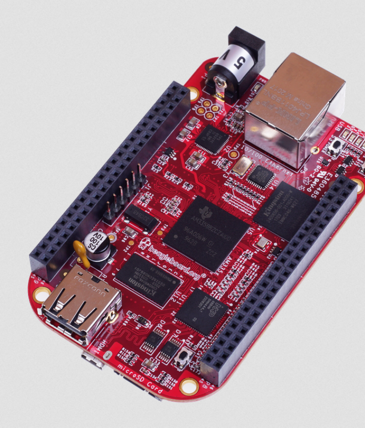
- Cabled, fiber or copper (or combination).
  - Highest bandwidth, infrastructure burden.
  - Work ongoing on low-power, robust to failure, fiber connectivity.
- Satellite
  - Satellites are far away, implies either low bandwidth or too high power per station.
- Terrestrial Wireless
  - Point to point wireless (e.g. 5 GHz WiFi, balloon LOS) an option, though typically higher-power
  - Cellular technology reduces power at station, though either requires having cell access available or deploying a cell network (as we did for RNO-G!)
  - Low-power IOT networks like LoRaWAN can be used as backup control path and housekeeping data
  - Main problem is regulatory

RNO-G LTE network demonstrated to have 9 km range!

Computing, Storage, Timekeeping

- Each balloon, in-ice or earth-skimming radio station has a computer (or in the case of ARIANNA/TAROGE, a microcontroller) managing data taking, communications, and slow control.
- Data also stored locally, either transiently until transmitted off, or sometimes it's impractical to get all the data off (ARIANNA, balloon experiments), so only a subset of data is sent for monitoring, but the rest must be picked up.
  - In case of experiments at South Pole and Greenland, while data gets transferred from each detector, there is not sufficient bandwidth to send it all home, so hard drives get picked up.
  - Industrial SD cards work well for local station storage, helium drives work well in ballooning
- GPS can be used for timing, with precision of around 10 ns.

The BeagleBoneBlack Industrial single-board computer is used on RNO-G, BEACON, and the ARA phased array



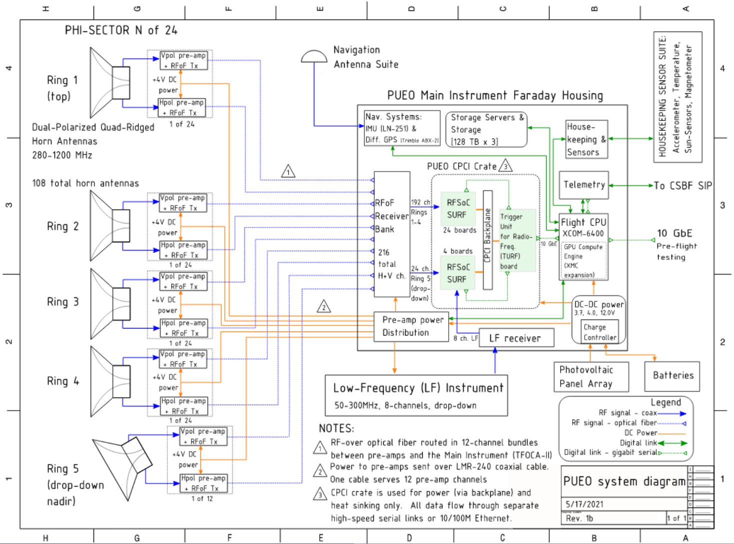
Conclusion

- The technology necessary for deploying radio neutrino detectors is now reasonably mature with all components demonstrated at some level
- The balloon-borne platform is mature and the next-generation balloon payload (PUEO) is already being built.
- Some room for optimization, simplification, improved reliabilitly, and further power savings, but the technology to build a large-scale in-ice array like Gen2Radio is ready today.
- Earth-skimming radio detectors are also progressing rapidly (and not constrained by Polar logistics).

Backup slides

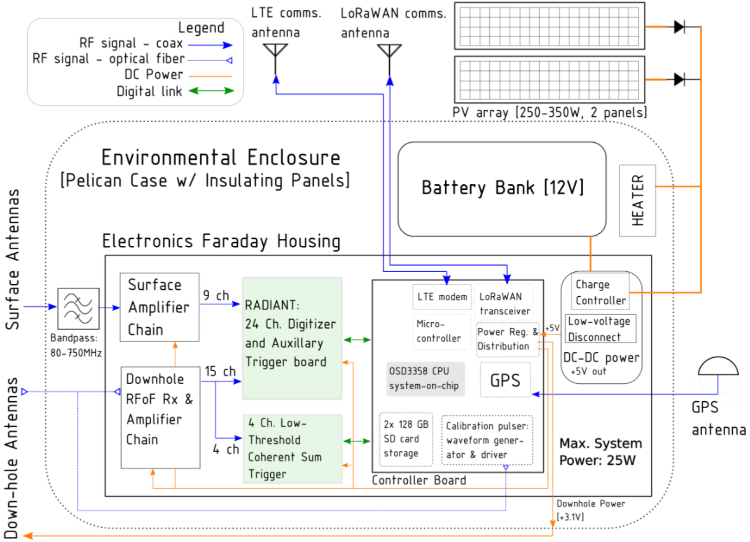
PUEO System Diagram

arXiv:2010.02892



RNO-G System Diagram

RNO-G System



BEACON System Diagram

The BEACON Prototype Instrument