Weak signal extraction using matrix decomposition: with application to detection of ultra high energy neutrinos

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outline

- motivation: weak signal extraction in radio-based experiments
  - what is `weak’?
- why radio? high-energy neutrinos
- matrix decomposition
- expansion in a basis and filtering
- application: experiment T576 at SLAC
  - Radar detection of an electron-beam induced particle cascade
- outlook for future analyses and discussion
weak signals in radio

- in radio analyses, we deal mainly with time series of voltage, power, or spectral information:
weak signals in radio

- Focusing on $V(t)$: what happens when a signal is 10% the size of the background? 1%?

- For experimentalists:
  - voltages on a scope

- For theorists:
  - vector of real-valued entries
weak signals in radio

- Why am i talking to you about radio?

at ultra-high energies, flux of cosmic rays and cosmic-ray neutrinos drops dramatically 1 km\(^{-2}\)century\(^{-1}\) at the highest energies!
detection of cosmic ray neutrinos remotely, via radio methods, is the way to extend up to the highest energies.

- The technique presented here applies to a new method to detect neutrinos with energies above 10\(^{15}\) eV: radar
weak signals in radio

- If backgrounds are known exactly, the only limit to extraction is noise. e.g.:
  \[ V_i = b_i + s_i + n_i \]
  where \( V \) is our data vector,
  \( b \) is a background vector,
  \( s \) is our signal vector, and
  \( n \) is uncorrelated (random) noise

- many techniques to ‘dig out’ signals from noise, if backgrounds are exact; then `weak’ is defined relative to (uncorrelated) noise.
  - only limits then are (generally) technical
- but... what if the backgrounds aren’t exact?
- what if they cannot be known a priori?
- what if the background variation is greater than the amplitude spread of the signal?
matrix decomposition

• let’s assume that our `data’ consists of:
  - random phase sine waves
  - impulsive radio bursts
  - uncorrelated noise
  - a very small (~1%) signal

• Then let’s assume we can generate `null data’ that mimics the real data, minus the signal
  - examples:

\[
V_{data}^i = b_i + c_i + n_i + s_i
\]

\[
V_{null}^i = b_i + c_i + n_i
\]
matrix decomposition

Matrix decomposition produces a \textit{basis of patterns} made from the null data itself. Similar methods exist in many disciplines: principal-component analysis, Karhunen-Loeve, etc.

Novel application to radio:
Bean, Ralston, Snow arXiv:1008.0029
filtering and expansion in a basis

To filter data, one expands a data vector $V_{data}$ in the filter basis, with vectors $f$,

$$c^0 = f^0 \cdot V_{data}$$

and

$$c^N = f^N \cdot V_{data}$$

where the expansion coefficients are labelled $c$. Then the expansion of this data vector, up to order $n$, in the filter basis, produces the filter vector $F$:

$$F_j^n = \sum_{i=0}^{n} c^i f_j^i$$

and then the filtered data $V_{filt}$ is simply

$$V_{filt} = V_{data} - F^n$$
filtering and expansion in a basis

\[ V_{\text{dat}} - F^n \]

addition of more basis patterns in the expansion improves the filter

\[ V_{\text{dat}}^i - (V_{\text{dat}} - F^n)^i \]

improvement becomes modest but continues to high \( n \)
filtering and expansion in a basis

to test our filter, we can inject a signal at \(~1\%\) background amplitude

we make it monochromatic at 2.1 GHz, and with random phase.
filtering and expansion in a basis

here we show the result of filtering this particular event.

we see a hint of a signal at the correct point, but other 'blobs' are of similar amplitude

the original data vector (with injected signal) and the remainder after filtration
filtering and expansion in a basis

averaging a hundred events, each with an injected signal with random phase, we see a distinct signal pop out of the background. we have extracted a random phase signal buried at ~1:100 in noise and random-phase background.
application: SLAC experiment T576

shower created in the target (HDPE)

10 GeV electron beam, N=10⁹

incident radio is reflected

Towards detecting ultra-high-energy neutrinos with radar

transmitter

receiver
application: SLAC experiment T576

results from first run (May 2018) are out
results from second run (November 2018) forthcoming! (ICRC2019)

Suggestion of Coherent Radio Reflections from an Electron-Beam Induced Particle Cascade

S Prohira\textsuperscript{1,2}, K. D. de Vries\textsuperscript{3}, D. Besson\textsuperscript{4,9}, A. Connolly\textsuperscript{1,2}, C. Hast\textsuperscript{5}, U. Latif\textsuperscript{4}, T. Meures\textsuperscript{6}, J.P. Ralston\textsuperscript{4}, Z. Riesen\textsuperscript{7}, D. Saltzberg\textsuperscript{8}, J. Torres\textsuperscript{1}, S. Wissel\textsuperscript{7}, and X. Zuo\textsuperscript{8}

+ A. Nozdrina, J. Beatty, J. Nam
Run 1 analysis finds evidence for a signal-region excess at 2.4 σ over a null hypothesis.

used the technique outlined here to extract a weak signal.
comparing to simulation, the agreement is quite good.
Established a signal excess at 2.4 sigma via sideband subtraction.
conclusions, next steps

- matrix decomposition methods are a powerful tool for pattern-based filtration of time-domain signals
- weak signals can be extracted from large backgrounds
- application to real data looks promising
- much more to be done...and more to learn!

thanks!
backup
why UHE neutrinos?

(Connolly and Bustamante 2019)

- above ~few PeV, scattering cross section and flux (and source) of UHE nu not constrained by experiment.
- neutrinos travel on straight lines and through matter-probe into now-unseeable parts of the universe.

(IceCube)

(Connolly and Bustamante 2019)
why UHE neutrinos?

"Because it's* there."
-G. Mallory

*probably
why UHE neutrinos?

"Because it's* there."
-G. Mallory

- cosmogenic nu flux from UHECR interaction with CMB photons
- UHECR flux at earth extends up to the GZK limit, UHE neutrinos are probably there to be detected

*probably
how to detect UHE neutrinos

- collision between a high energy particle (like a neutrino) and a water ice molecule produces a shower of secondaries (as below)
- if this shower happens in a region that a detector is sensitive to... detected!

- 2 ways to detect shower (really the same):
  - optical
  - radio frequency (RF)
- cannot directly measure the primary nu, must reconstruct primary based on the properties of the detected shower.
how to detect UHE neutrinos

- **Optical:**
  - AMANDA, IceCube

- **Askaryan/Radio:**
  - RICE, ARA, ANITA, ARIANNA

detect the primary indirectly by detecting the cascade produced from the original nu interaction.

IceCube (~$10^{15}$ eV)  
ANITA (10$^{21}$eV)
how to detect UHE neutrinos

- **Optical:**
  - AMANDA, IceCube

optical regime: UHE neutrino creates a cascade which emits Cherenkov light. Light is detected by optical modules.

IceCube (~10^{15} eV)
how to detect UHE neutrinos

Askaryan effect is coherent radio-frequency Cherenkov pulses as above (P. Gorham et. al. ANITA) can be detected by RICE/ARA/ANITA

\[ P(W) \sim N^2 \]
why radio?

- Askaryan/Radio:
  - RICE, ARA, ANITA, ARIANNA

- up at 100Mhz-1Ghz frequencies, the attenuation of RF fields is very low relative to optical
- can “see” further, and therefore instrument a larger volume.

ANITA (10^21eV)
why radar?

- **Optical:**
  - AMANDA, IceCube

- **Askaryan/Radio:**
  - RICE, ARA, ANITA, ARIANNA

*Optical has upper limit due to volume
*Radio has lower limit due to physics and limited aperture!

RADAR is the best bet for bridging the gap

IceCube (~$10^{15}$ eV)

ENERGY

ANITA ($10^{21}$ eV)
what is radar UHE detection?

Shower created in material volume is interrogated with RF

incident particle

plasma

medium

reflected signal

interrogating wave

antenna

Scattered signal is coherent

(nothing to scale)
can it work?

Assuming transmitter (TX) broadcasting continuous-wave (CW), scattered field from a single electron (label A) is:

\[ \mathbf{E}_A = \frac{\alpha E_I}{R} \hat{n} \times \hat{n} \times \epsilon_A \]  

the vectors are simply for polarization, and \( E_I \) is the incident field, from the TX, at the electron A with all of the propagation through the medium and the plasma folded in. \( \alpha \) is the reflection coefficient, with units of length,

\[ \alpha = \frac{q^2 \omega}{c^2 m(\omega + i\nu_c)} \]
can it work?

Then, summing over all the particles ($E_A$ from last slide now indexed with $n$) in a shower gives:

$$Re [E_{tot}] = \frac{1}{T} \sum_{n=1}^{N} \int_{t}^{t+T} \Theta(t' - t_n)\Theta(t_n^f - t') Re [E_n(t)] \, dt,$$

(1)

Simulation (RadioScatter arXiv:1710.02883) shows that things look pretty good...
does it work?
does it work?

run 2 dataset contained multiple DAQs, many more channels, and data taken for several ‘smoking guns’. (sorry, can’t show results yet...)

12-channel DAQ developed at OSU (P. Allison et al) represented by open circles, to characterize the signal as a function of azimuth.
what would a future detector look like?

Effective volume: Measure of the amount of sensitive material for your detector for radio, it is the volume of the area to which your receivers are sensitive.

simulations show radar is competitive with icecube above 1PeV, and better than any existing tech up to ~1EeV using same settings as simulation which matched run 1 result.
what would a future detector look like?

sensitivity curves on previous slides for a similar layout.

deep detectors in ice, larger than icecube but same if not better sensitivity with .001 the # of detectors!

large ice sheet is needed, preferably location far away from other experiments.
raw data
plasma lifetime

signals vary based on the free electron (plasma) lifetime.

simulation shows return signals for very short lifetimes.
geometric acceptance

trigger threshold curves for a static shower and TX RX is moved around the solid angle of the shower

left: vertical polarization
right: horizontal polarization

red: geometric acceptance for 5 sigma Askaryan signal in ice (~5 degrees)
attenuation length in ice

measurements from CReSIS experiment at KU
why radio?

- up at 100Mhz-1Ghz frequencies, the attenuation of RF fields is very low relative to optical
- can “see” further, and therefore instrument a larger volume.