True Random Number Generation from Very Low Frequency Noise

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github.com/mateibarbu19/trng-methods

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Why?

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So, how do we choose a secret?

RANDOM.ORG [Haa25]

Figure 1: Version 1
(with whiskey bottles)

Figure 2: Version 2

Related Work

- A embedded prototyping approach [LL19]
  - Focused on maximizing entropy
  - Non i.i.d. variables
  - Comparison between compressed and uncompressed streams
  - Plots use are misleading
  - Leaked audio noise at acquisition
  - Good results when combining multiple sources

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  - Leaked audio noise at acquisition
  - Good results when combining multiple sources
- A on-chip 180nm approach [Kum+20]
  - Employed hybrid sources of entropy
    - QRNG based on optical phenomena
    - Un compressed radio captures
  - They propose an unconventional arbiter block
  - Important implementation details were left out

Research Objectives

- Reproducible results
- Modular design
- FIPS 140-2 validation

Very Low Frequency Radio

- 3-30kHz
- Ideally in a Radio Quiet Zone
- Data from **abelian.org**

> The atmospheric noise in VLF band is mainly impulse noise under the background of Gaussian white noise. Gaussian white noise is composed of the superposition of pulses formed by a large number of thunderstorms distributed around the world. Impulse noise is formed by the superposition of lightning electromagnetic pulses near the receiver. [LXC22]

Figure 3: Setting up an antenna in Alaska [Stu25]

VLF Characteristics I

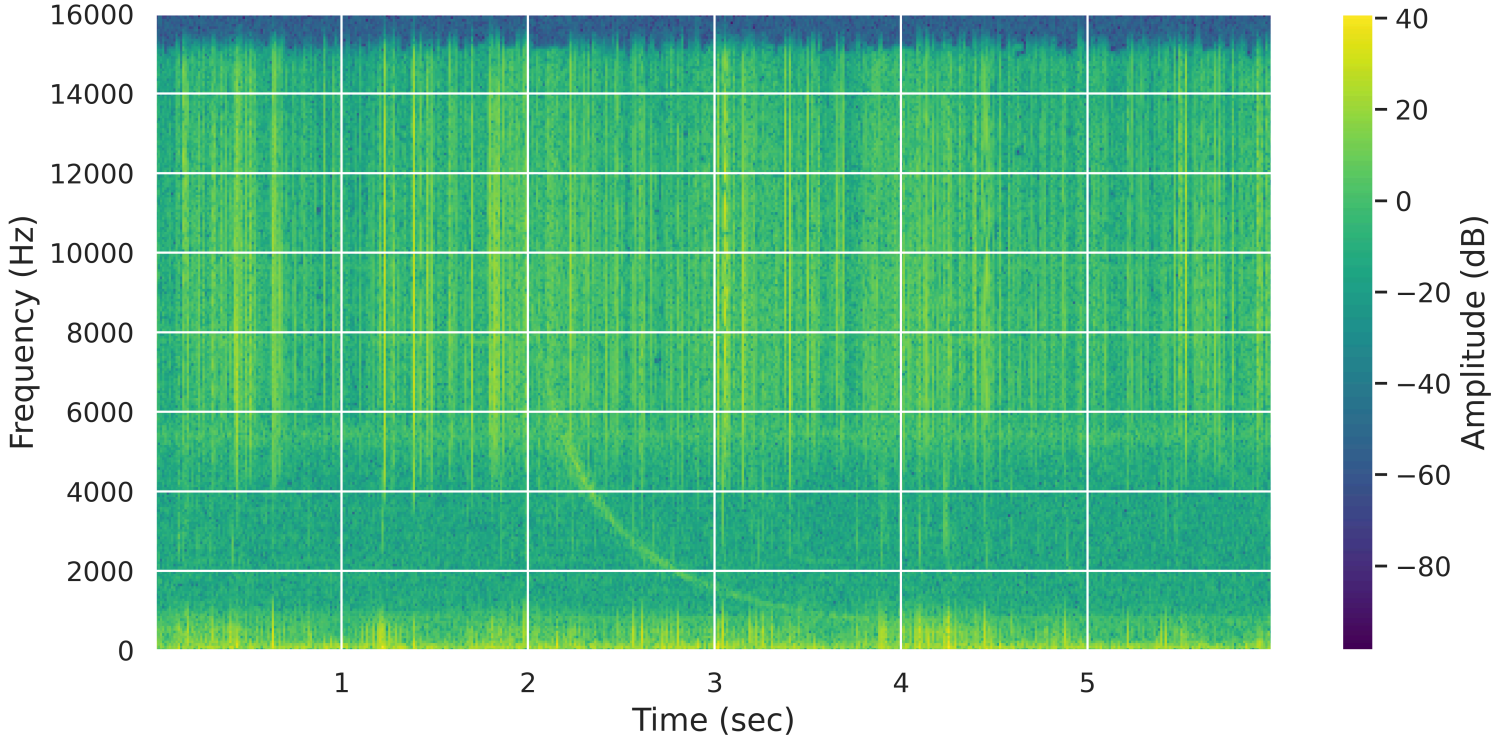

Figure 4: General spectrogram pattern for VLF captures. Whistler portrayed in the center bottom. Lightning events depicted by vertical yellow bars.

VLF Characteristics II

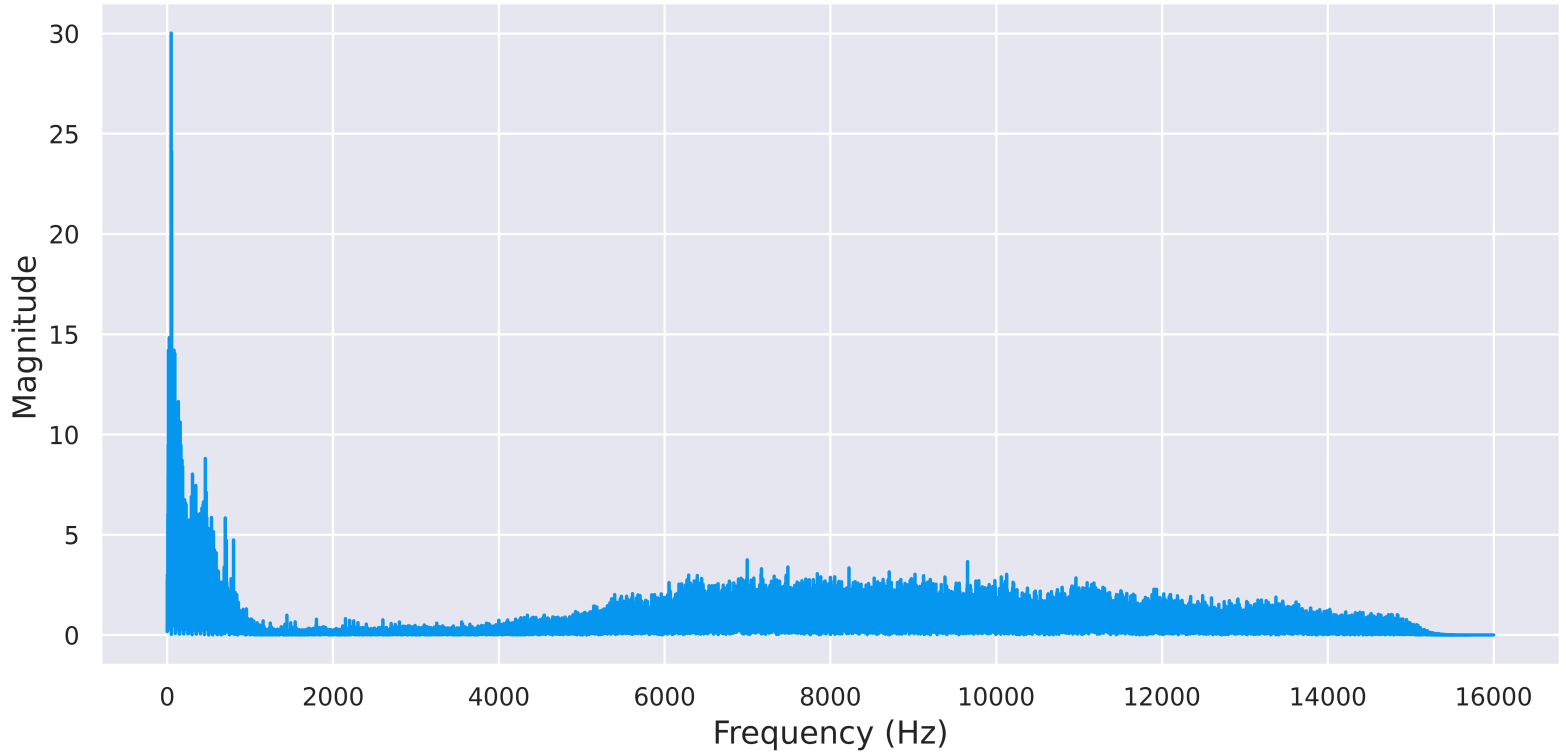

Figure 5: General spectrum pattern for VLF captures.

VLF Characteristics III

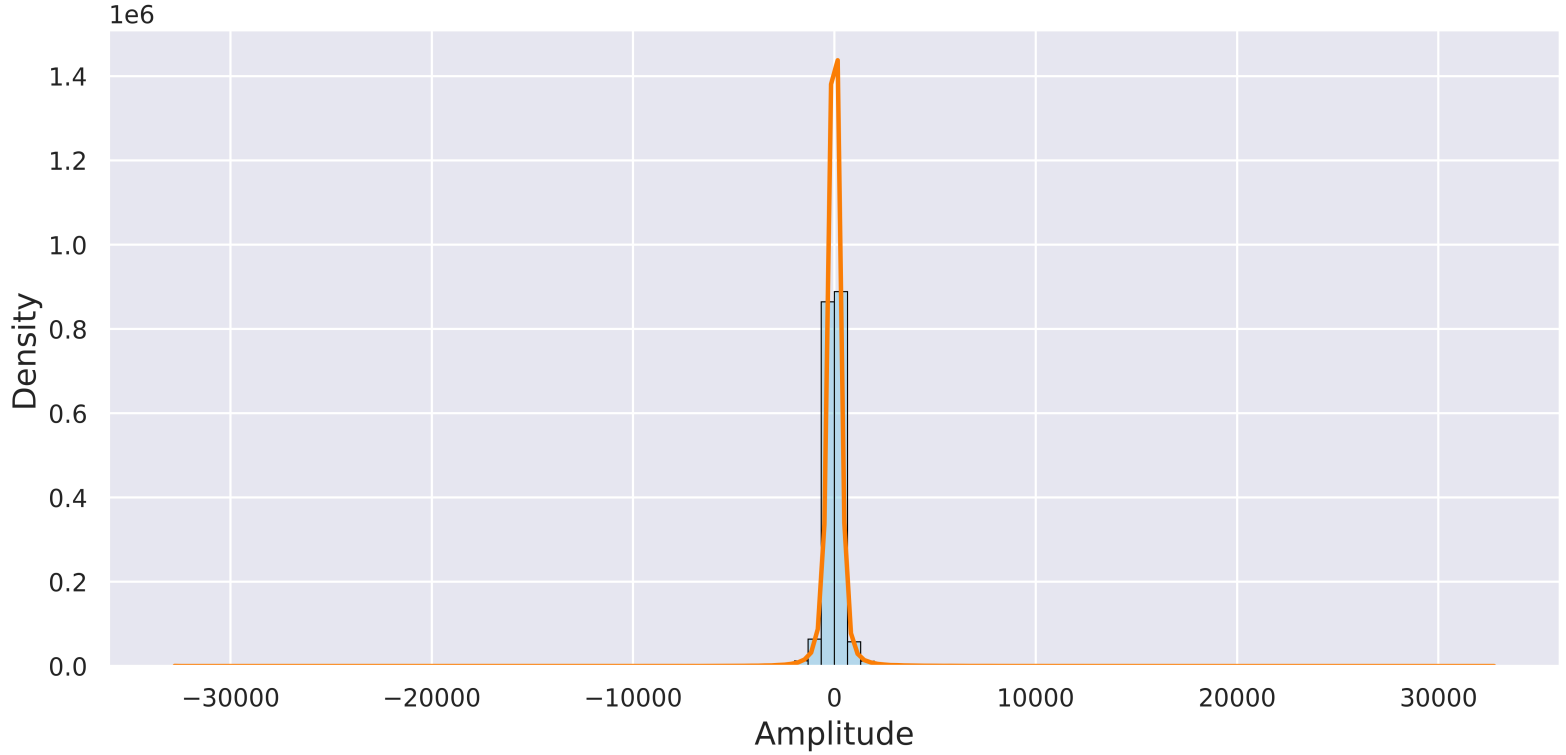

Figure 6: General distribution pattern for VLF captures.

Our Proposal

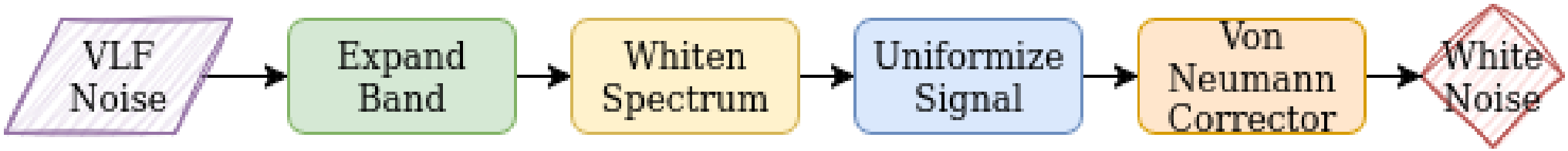

Figure 7: Post-processing pipeline for a VLF entropy source

Our Proposal

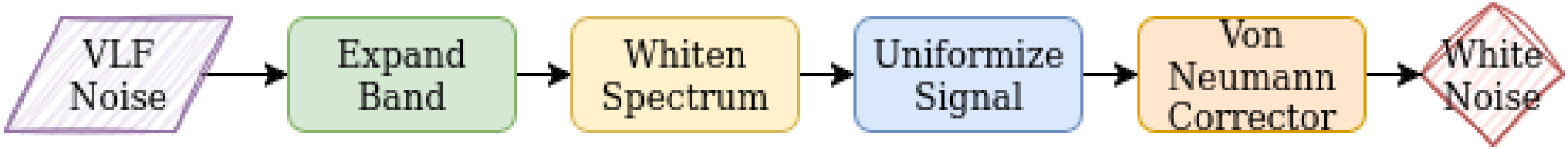

Figure 7: Post-processing pipeline for a VLF entropy source

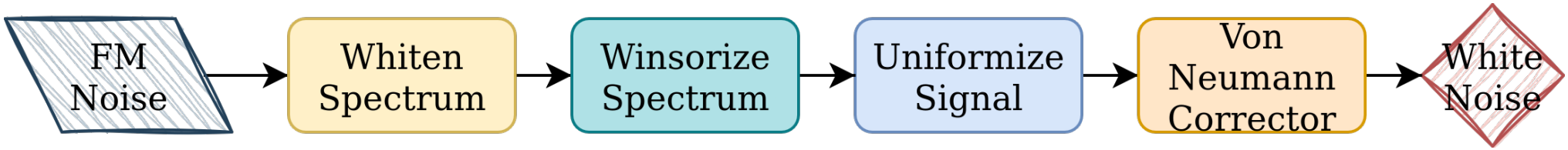

Figure 8: Post-processing pipeline for a FM entropy source

Experiments

Host Id	Location	Coordinate
15	Cumiana, NW Italy	44.96N,7.42E
35	Forest, Virginia	37.34385N,79.28818W
41	Heidelberg, Germany	49.443N,8.695E

Table 1: Chosen VLF hosts from abelian.org

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Table 1: Chosen VLF hosts from abelian.org

Host Id	Entropy (b/B)	Optimum compression reduction (%)	Arithmetic mean	Monte Carlo Pi error (%)	Serial correlation coefficient
15	6.151641	23	126.6439	30.24	0.124103
35	4.797632	40	126.6439	14.82	0.493773
41	6.708163	16	127.6324	27.95	0.026920

Note. Chi squared percentage of 0.01% on all sources.

Table 2: Evaluation of VLF entropy sources distributions

Results

High entropy (~8b/B), unbiased, low correlated outputs.
On average, the VLF pipeline failed about 300-400 tests out of ~425000, resulting in an 0.0008 error rate. Which is comparable to the $p = 0.001$ threshold within the SP800 STS suite.

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Host Id	Passed	Failed	Weak	Percentage
15	100	11	3	87%
35	101	10	3	88%
41	92	12	10	80%

Table 3: Dieharder results for our TRNG pipeline on VLF sources

Comments

- Von Neumann corrector is the “weak link” in the chain
  - output bitrate $\approx 25\%$ input bit rate
  - too generic
  - causes some `dieharder` tests to fail
- Noise up to 4kHz is discarded
- Multiple FFTs on blocks of different sizes

Further Improvements

- Optimize parameters
  - Data representation size
  - Sample rate
  - Block sizes
- Replace algorithms with more performative ones
  - E.g. Von Neumann corrector with a cryptographic hash function
  - Reduce operations on spectrum
- Dynamically determine the shape of the Gaussian white noise envelope

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- Optimize parameters
  - Data representation size
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- Replace algorithms with more performative ones
  - E.g. Von Neumann corrector with a cryptographic hash function
  - Reduce operations on spectrum
- Dynamically determine the shape of the Gaussian white noise envelope
- Use higher quality VLF sources

Thank you for listening!

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github.com/mateibarbu19/trng-methods

> Randomness works well in search sometimes better than humans.
>
> – Nassim Nicholas Taleb

Bibliography

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FM as an Entropy Source

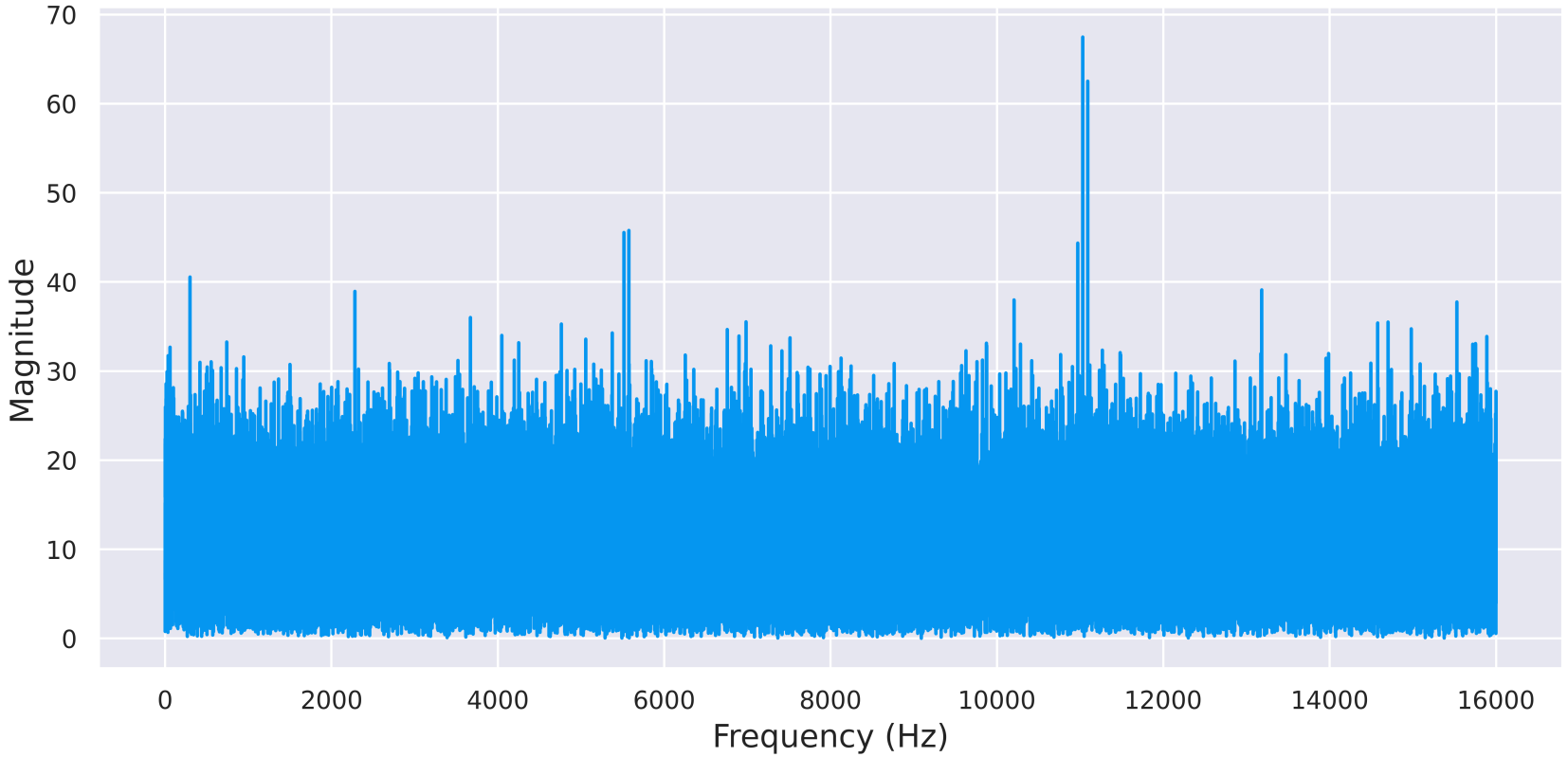


Figure 11: General spectrum pattern for an FM source

FM as an Entropy Source

Frequency (MHz)	Entropy (b/B)	Optimum compression reduction (%)	Arithmetic mean	Monte Carlo Pi error (%)	Serial correlation coefficient
80	7.300621	8	127.1270	21.81	0.015797
160	7.473322	6	129.8854	21.42	0.008358
230	7.343521	8	127.7567	21.70	0.013876

Note. Chi squared percentage of 0.01% on all sources.

Table 4: Evaluation of FM entropy sources distributions

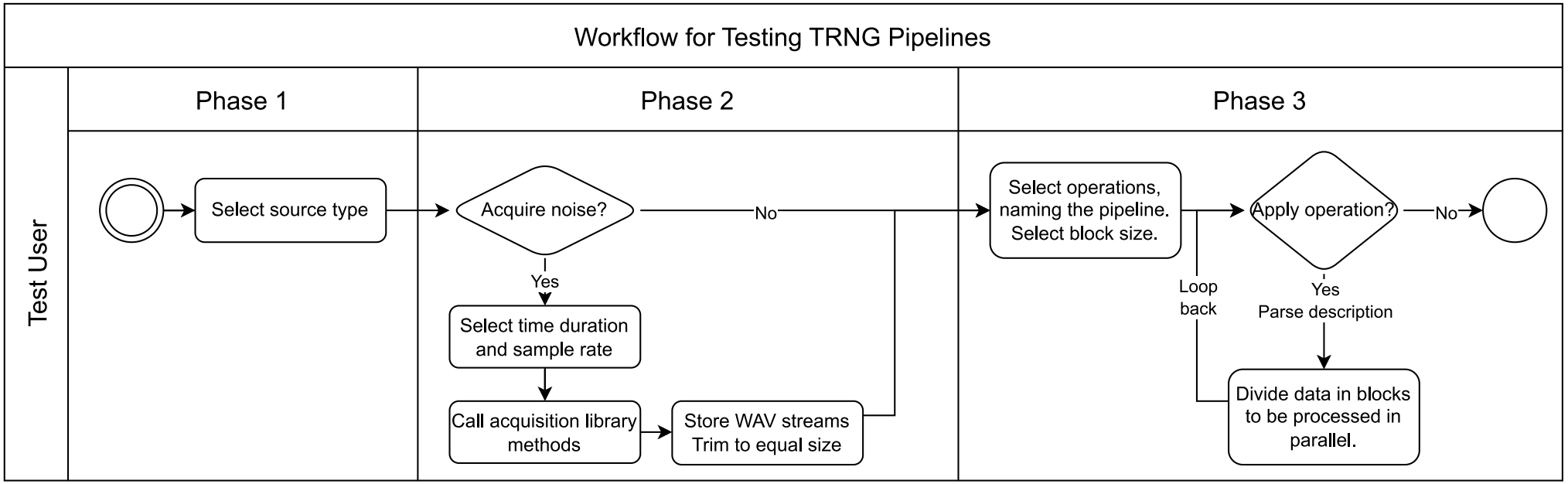
FM as an Entropy Source

Frequency (MHz)	Monobit	Poker	Runs	Long Run	Continuous run	Total
80	3	1	8	9	0	20
160	5	2	5	4	0	16
230	1	1	3	7	0	12

Note. Mesured with `rngtest`.

Table 5: Failed FIPS 140-2 tests out of 23024 for the FM pipeline

Software flow



Algorithms

Algorithm 1: Expand Band

1 spectrum ← FFT(data)
2 band_spectrum ← spectrum[start:end]
3 factor ← $\frac{\text{spectrum.size}}{\text{end}-\text{start}}$
4 spline_degree ← 5
5 enlarged_spectrum ← ZOOM(band_spectrum, factor, spline_degree)
6 adjusted_data ← IFFT(enlarged_spectrum)

Algorithms

Algorithm 2: Quantile Normalization For Uniform Distribution

1 max $\leftarrow$ MAXIMUM(ABS(data))
2 data $\leftarrow \frac{\text{data}}{\text{max}}$
3 ranked_data $\leftarrow$ RANK(data)
4 uniform_data $\leftarrow \frac{\text{ranked\_data}}{\text{ranked\_data.len}}$

More on VLF receivers [Gu+22]

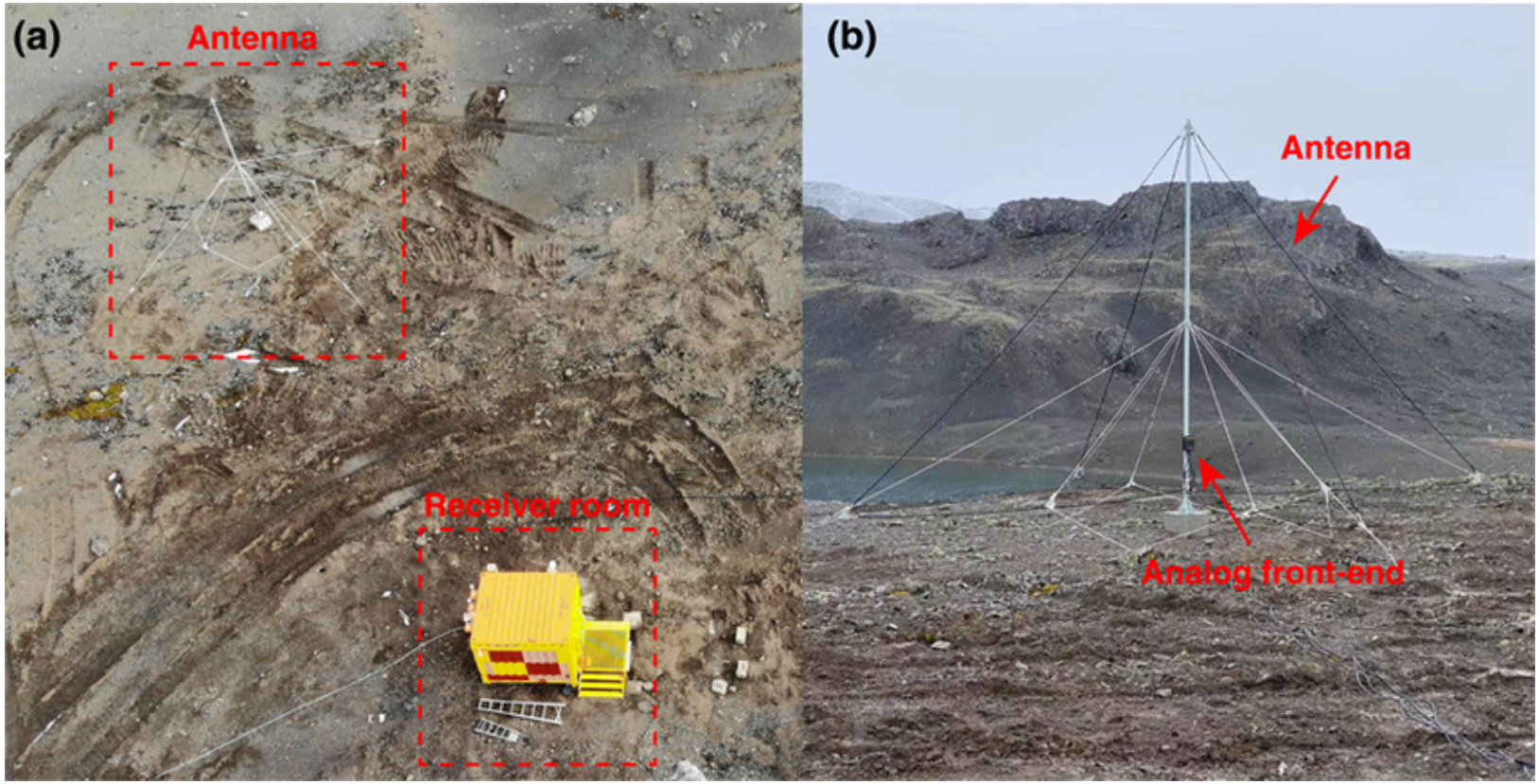


Figure 12: Photos of the Extremely Low Frequency/Very Low Frequency receiving system at the Great Wall station in Antarctica, (a) Layout and (b) antenna structure.