Anomalies in the Radio Neutrino Observatory Greenland

MMS Annual Meeting

Zack Meyers

Rehovot, June 5, 2023

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

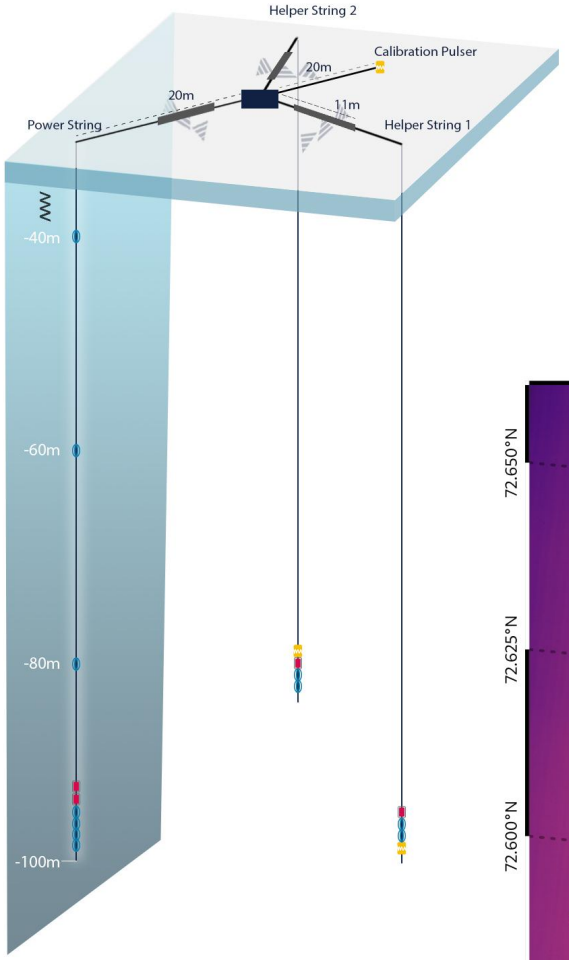
HELMHOLTZ WEIZMANN RESEARCH SCHOOL MULTIMESSENGER ASTRONOMY

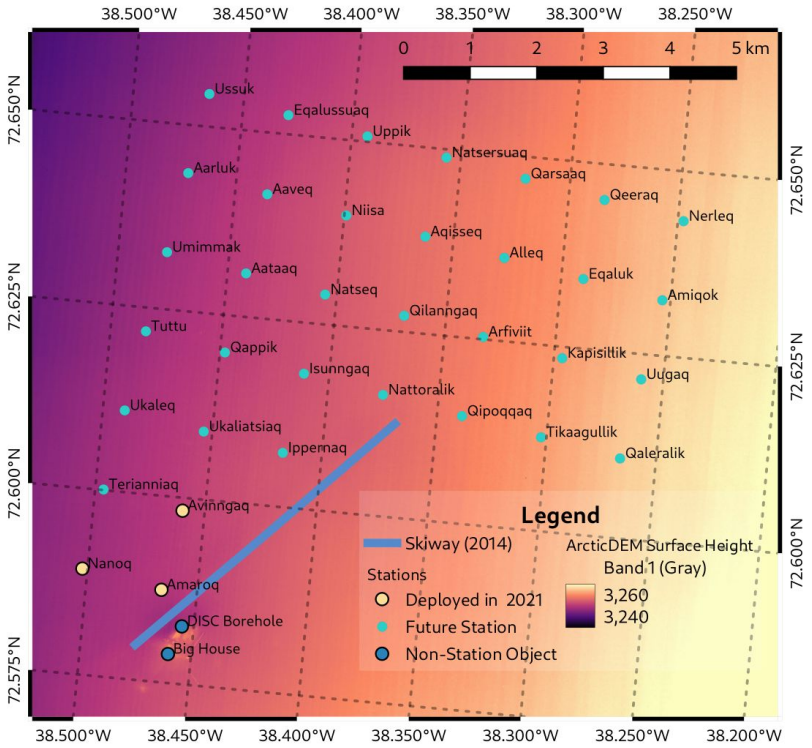
ECAP ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

DESY.

The Radio Neutrino Observatory Greenland

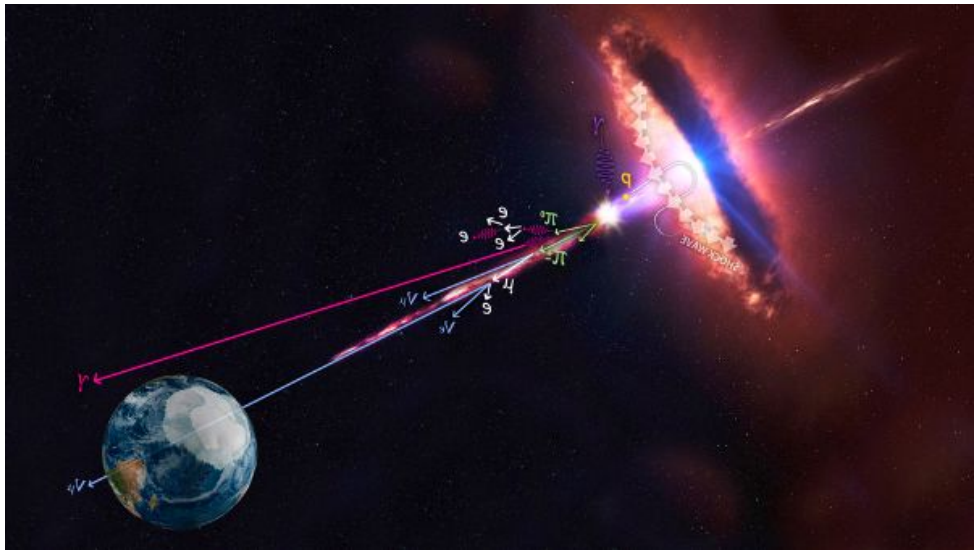
RNO-G





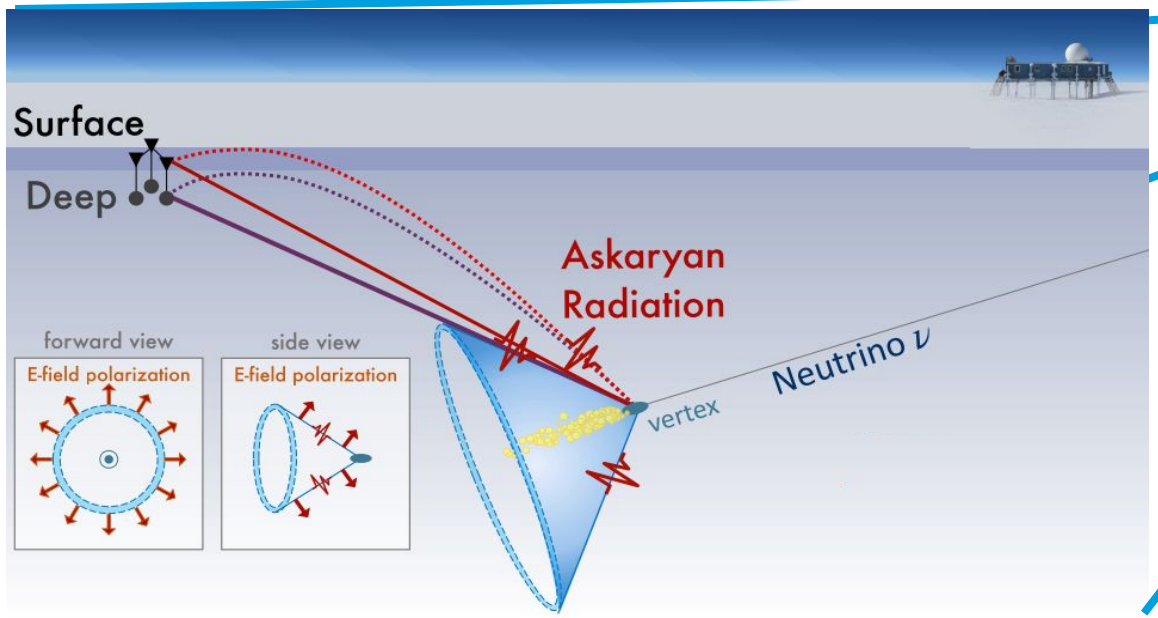
The Radio Neutrino Observatory Greenland

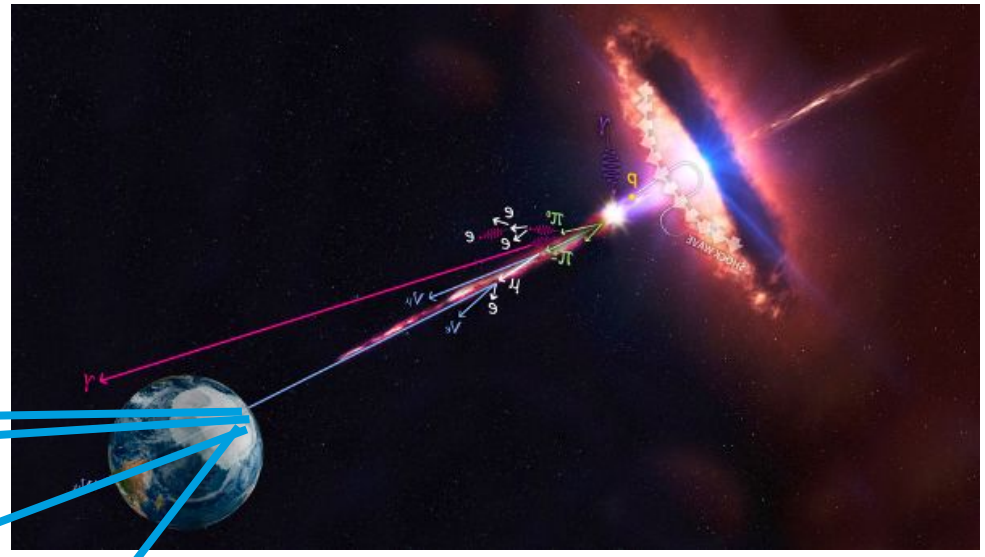
Why do we like Neutrinos



The Radio Neutrino Observatory Greenland

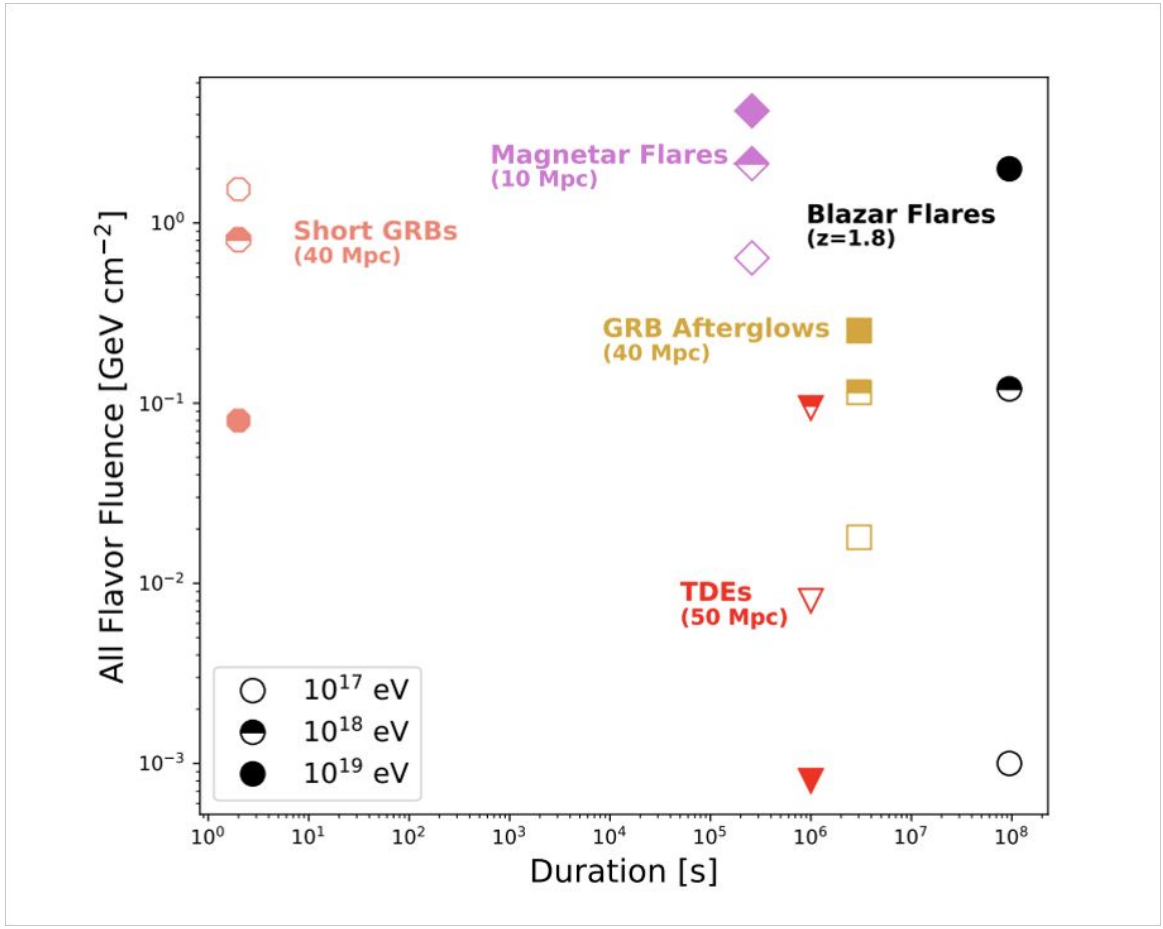
Askaryan Effect

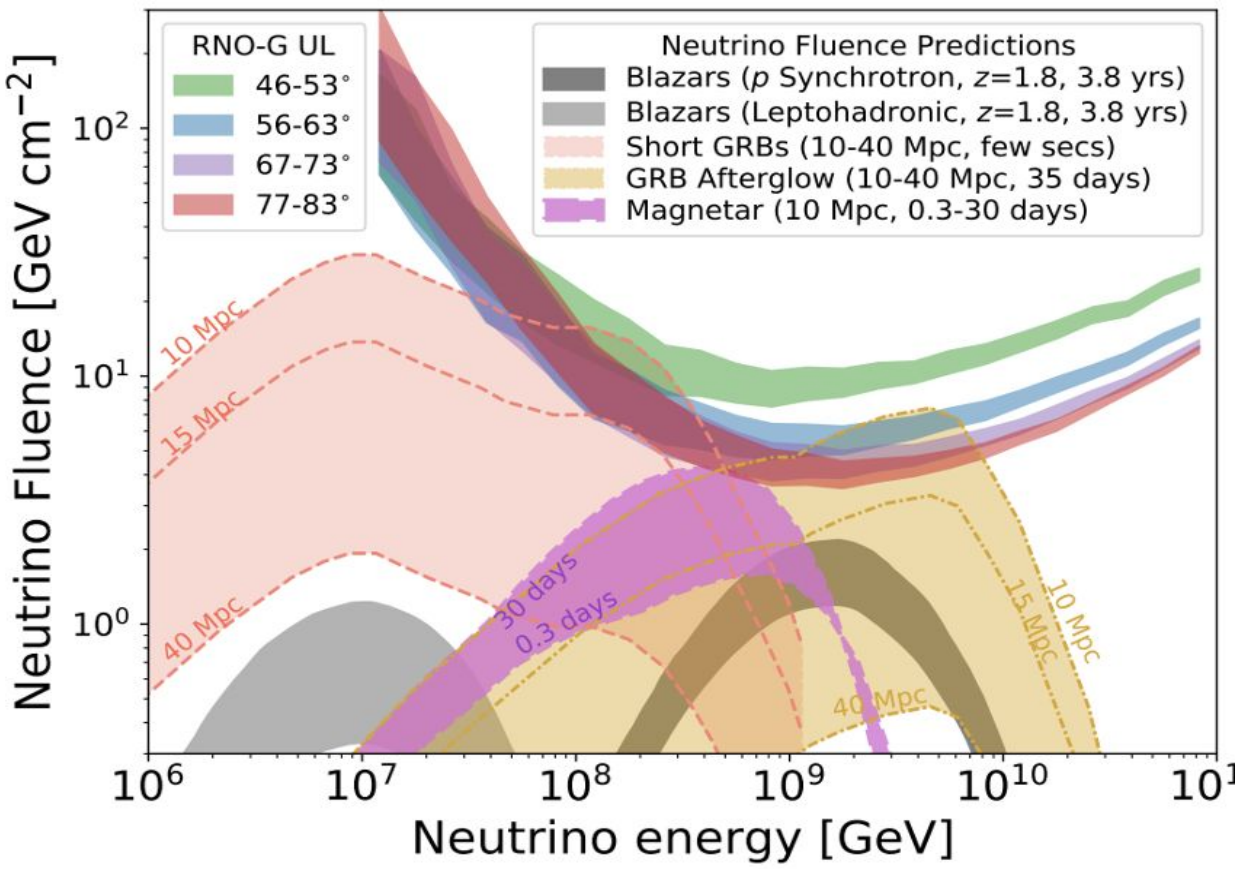




The Radio Neutrino Observatory Greenland

Progenitors and Sensitivities



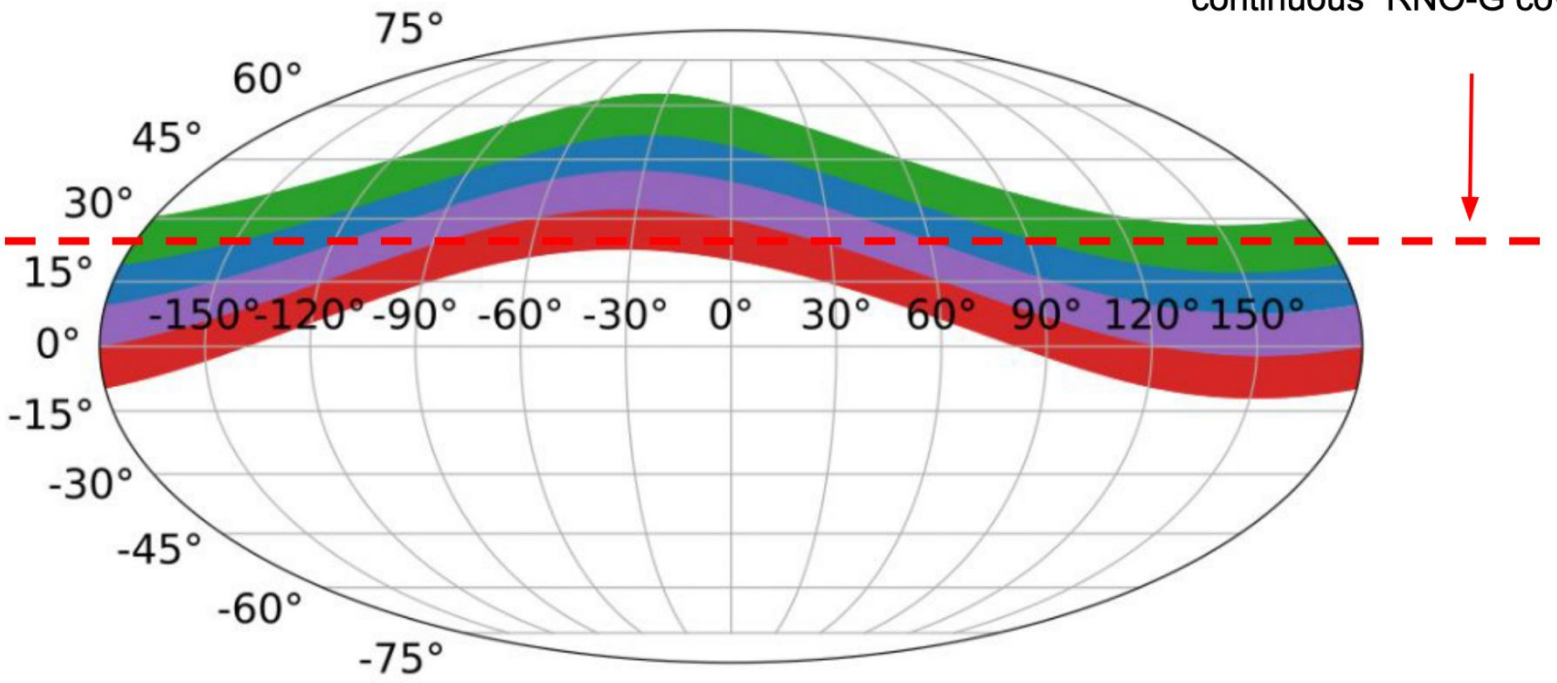


GRB 221009A

(non-)detection

GRB declination (19 deg)

One of the only dec bands with
“continuous” RNO-G coverage



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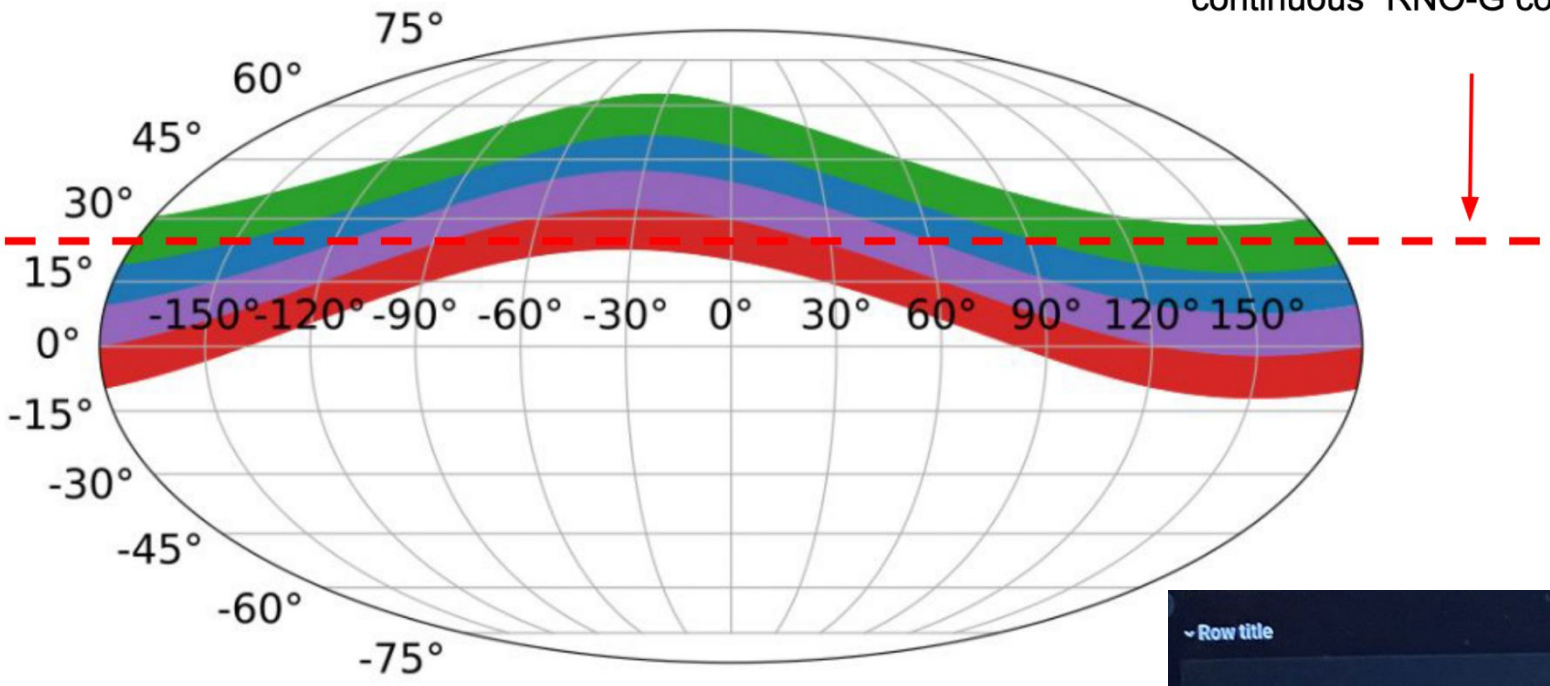
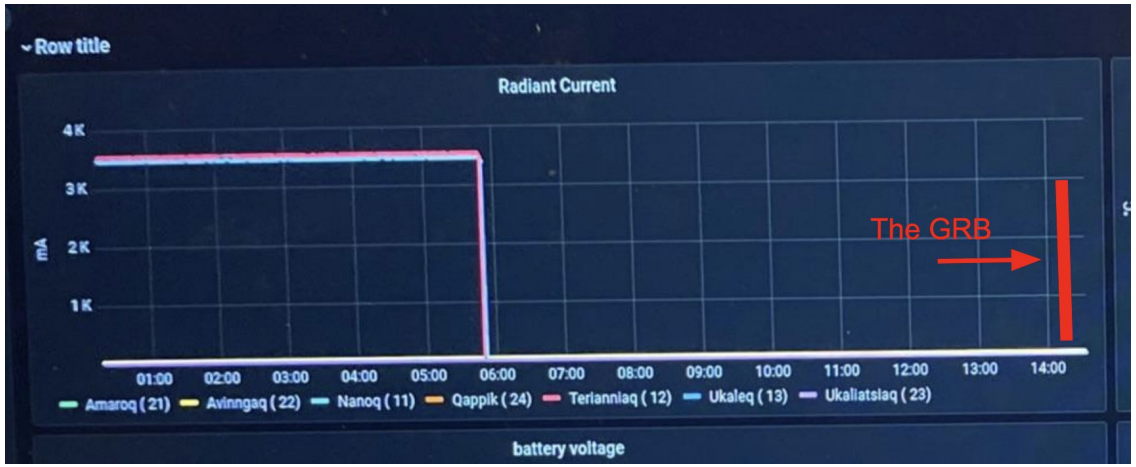
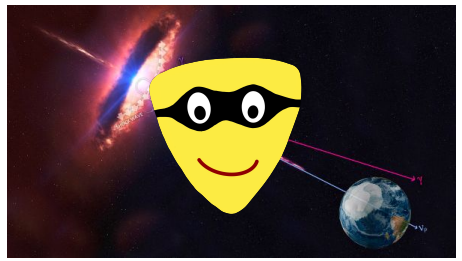


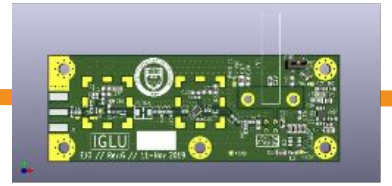
From B.Clark, 2022

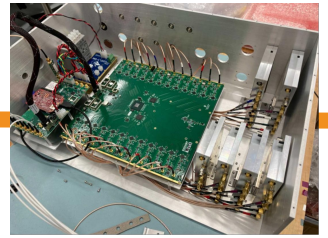


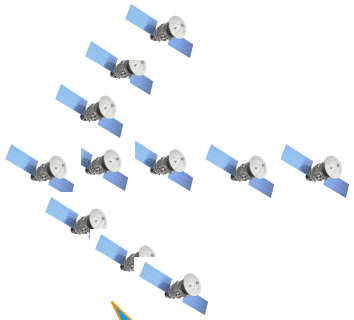
Signal Chain

From the cosmos to your computer









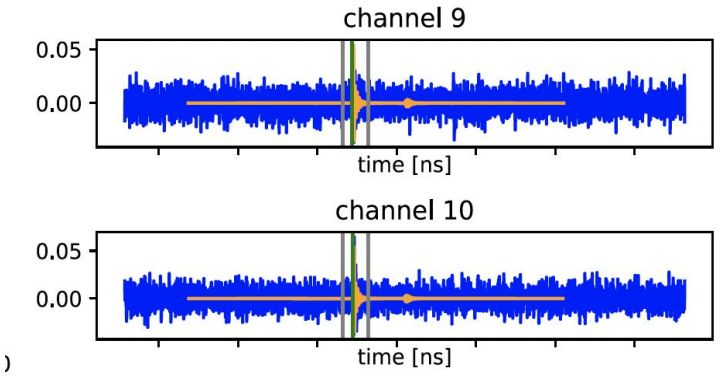
10%

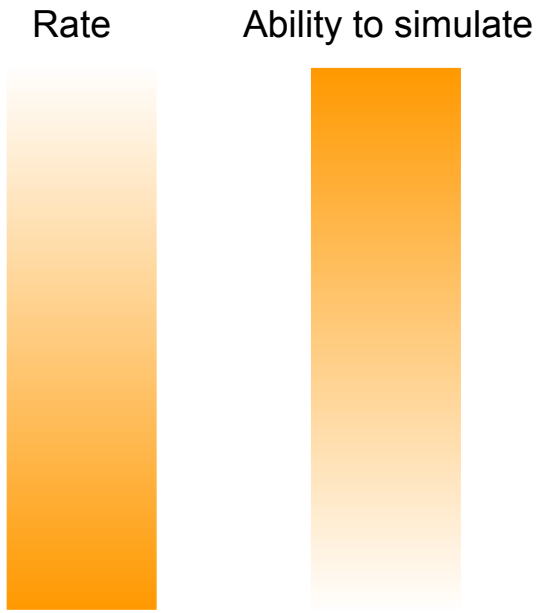
1% to 5%?

Data Overview

Data rates

- Most triggered events are noise:
  - Expect <~ 1 neutrino / full RNO-G / year
  - Expect O(1) cosmic ray events in surface component / day
  - other physics backgrounds: Sun, Galaxy
  - Thermal noise fluctuations
  - Anthropogenic and hardware induced noise (intermittent, up to ~10 Hz)



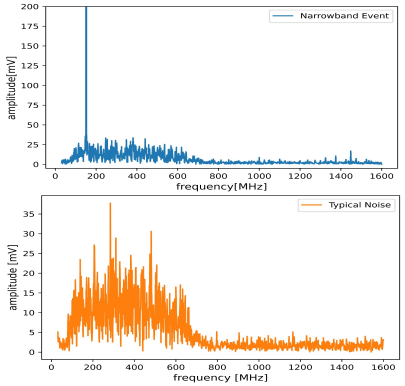


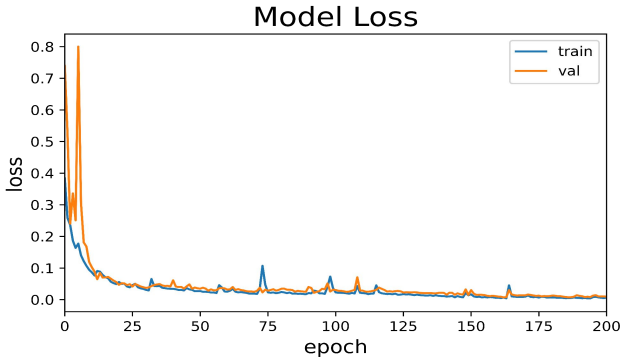
- Signal pulses near threshold
- Characteristic polarized bipolar pulses convovled with hardware response

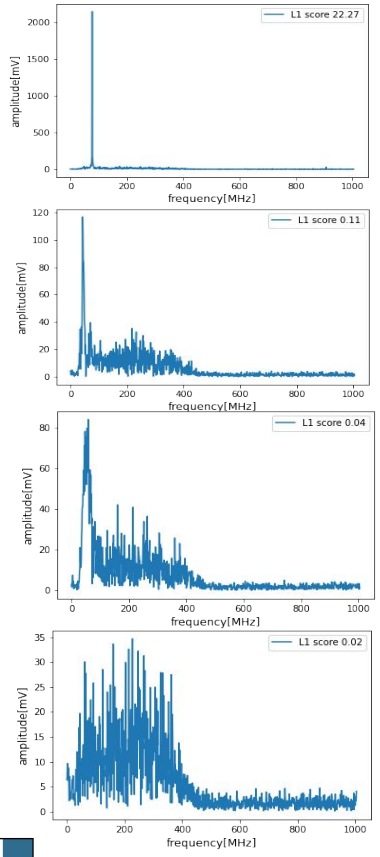
CW Noise

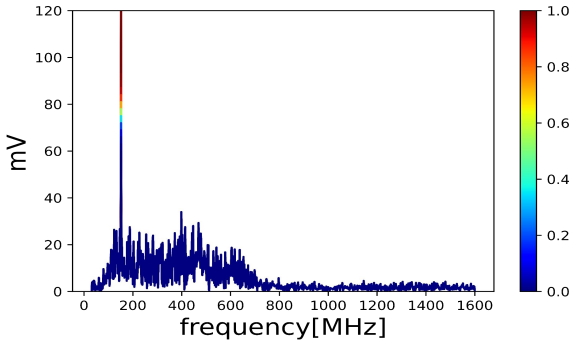
Simple CNN Classification

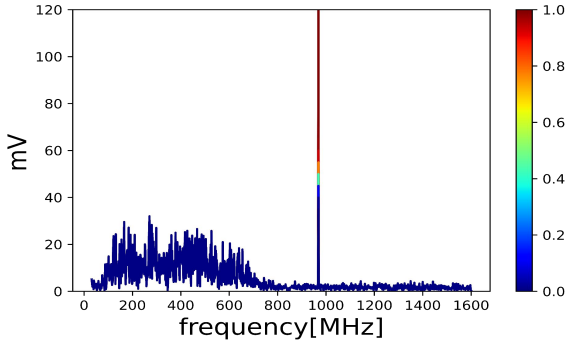
input_2: InputLayer	input:	[(None, 1005, 1)]
	output:	[(None, 1005, 1)]
conv1d_3: Conv1D	input:	(None, 1005, 1)
	output:	(None, 1005, 64)
batch_normalization_3: BatchNormalization	input:	(None, 1005, 64)
	output:	(None, 1005, 64)
re_lu_3: ReLU	input:	(None, 1005, 64)
	output:	(None, 1005, 64)
conv1d_4: Conv1D	input:	(None, 1005, 64)
	output:	(None, 1005, 64)
batch_normalization_4: BatchNormalization	input:	(None, 1005, 64)
	output:	(None, 1005, 64)
re_lu_4: ReLU	input:	(None, 1005, 64)
	output:	(None, 1005, 64)
conv1d_5: Conv1D	input:	(None, 1005, 64)
	output:	(None, 1005, 64)
batch_normalization_5: BatchNormalization	input:	(None, 1005, 64)
	output:	(None, 1005, 64)
re_lu_5: ReLU	input:	(None, 1005, 64)
	output:	(None, 1005, 64)
global_average_pooling1d_1: GlobalAveragePooling1D	input:	(None, 1005, 64)
	output:	(None, 64)
dense: Dense	input:	(None, 64)
	output:	(None, 2)

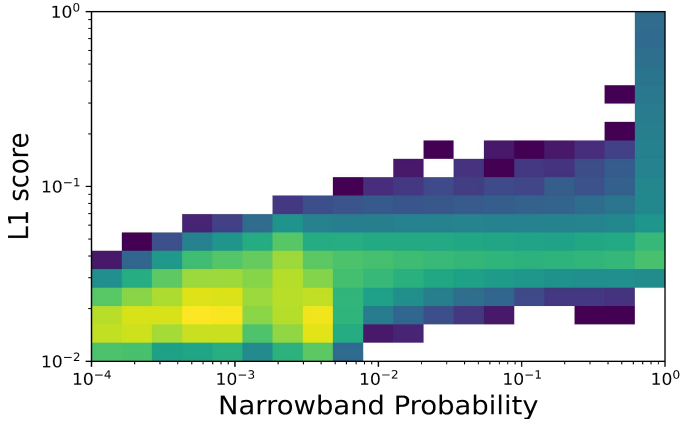


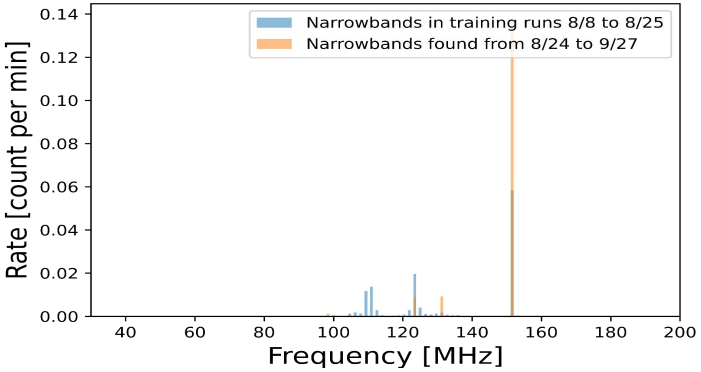






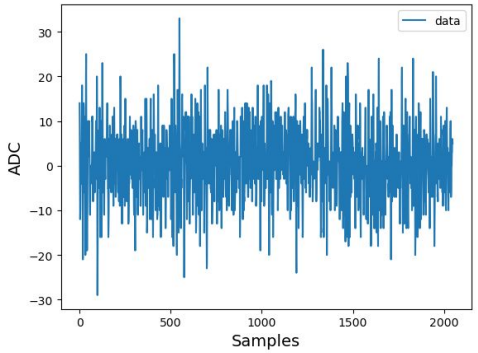






Anomaly Detection

Using STFT Mosaic of Phased Array



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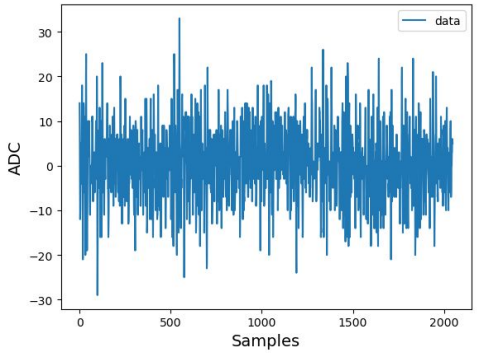

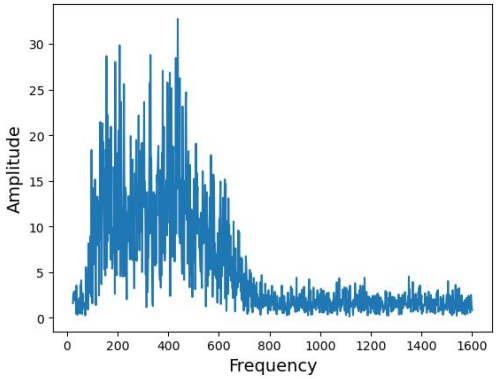

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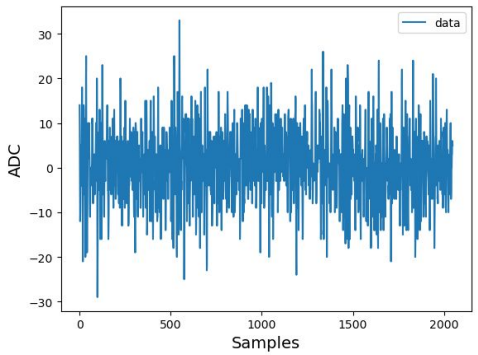

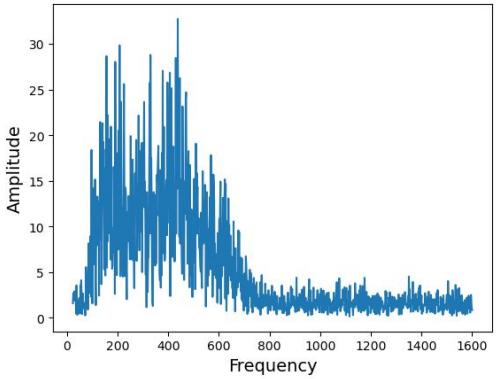

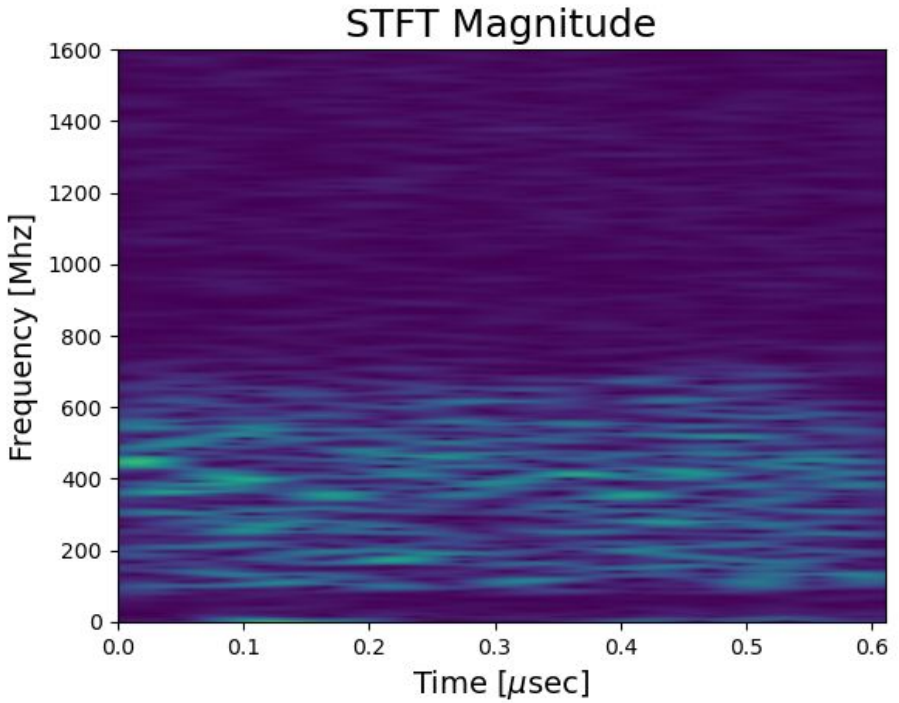

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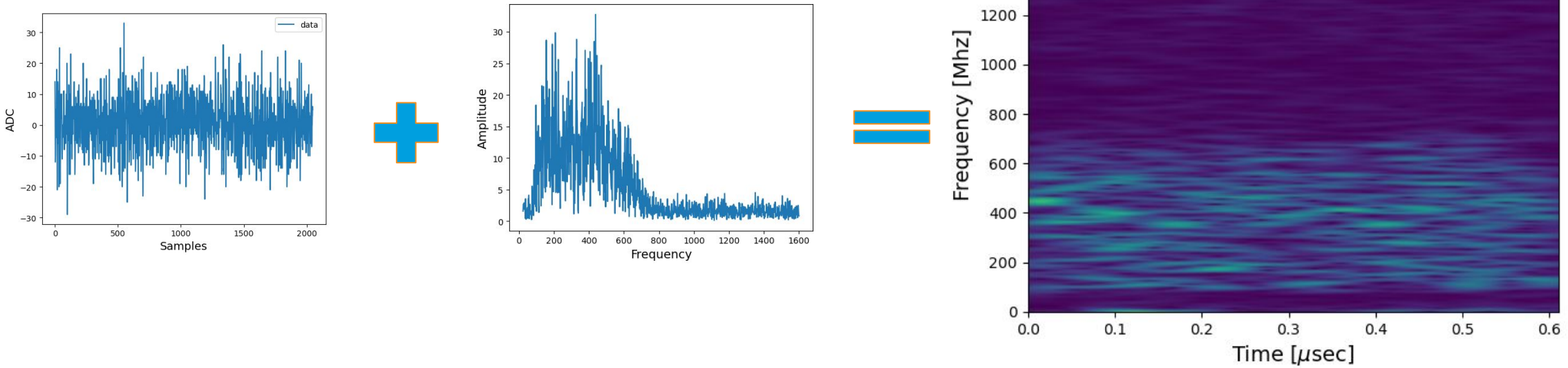

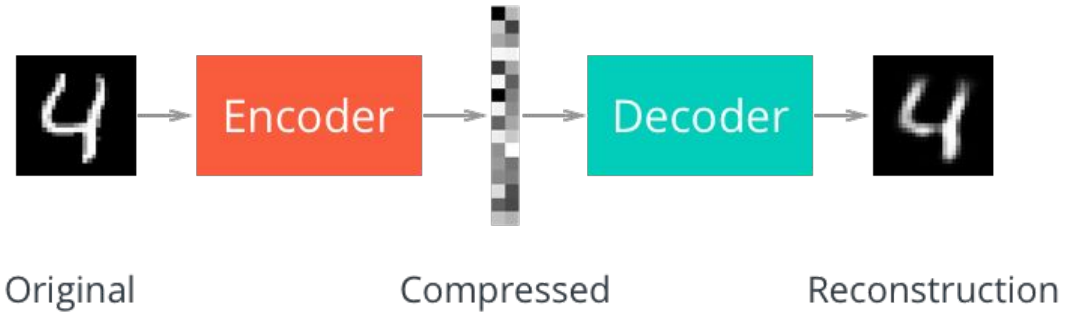

Anomaly Detection

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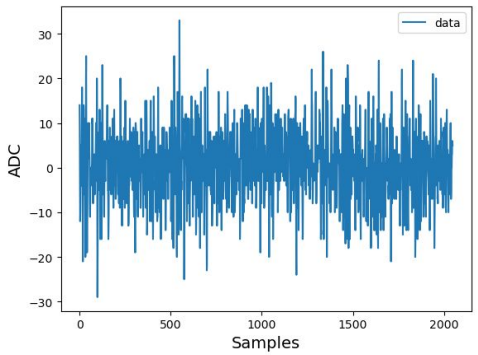
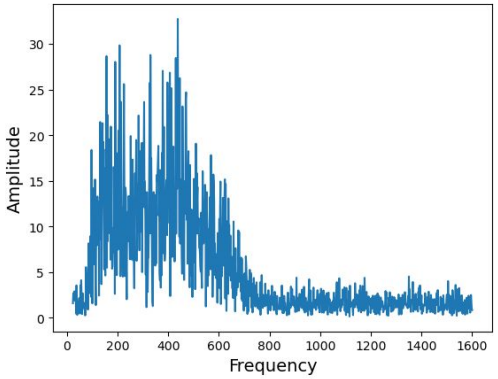
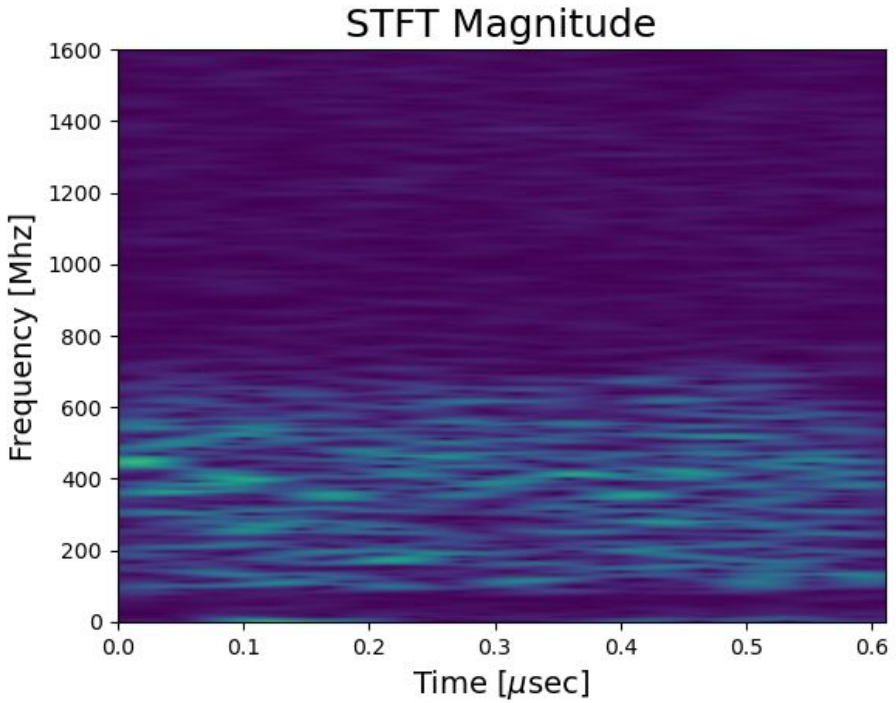
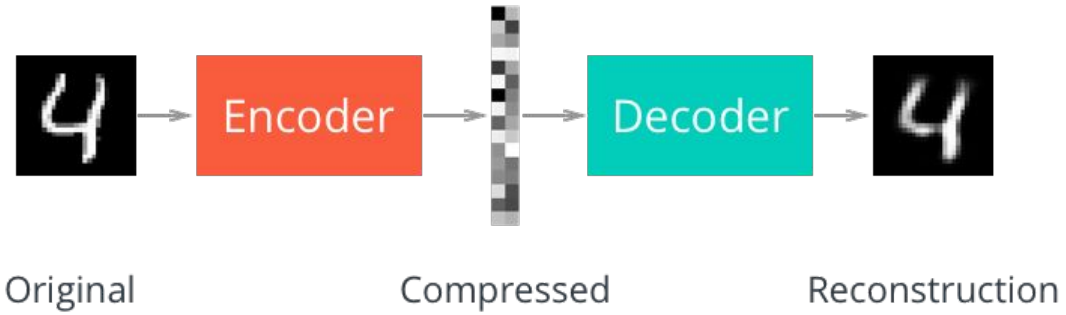
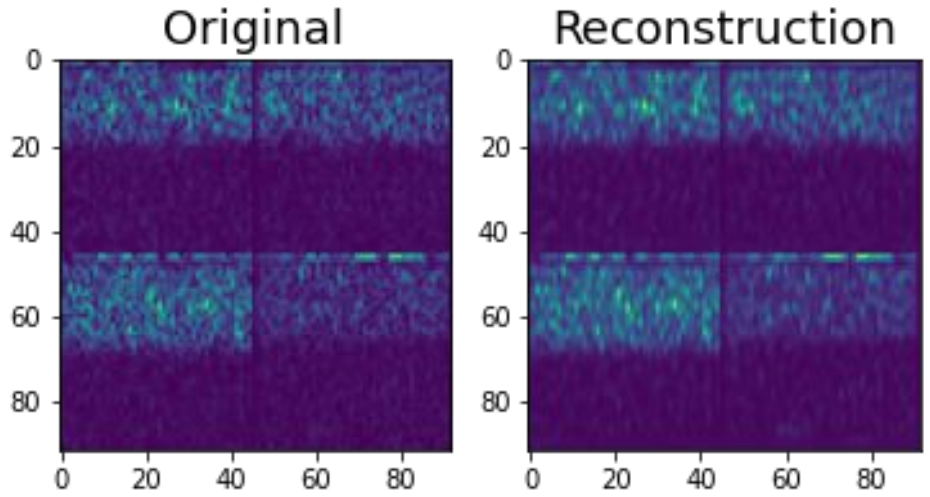




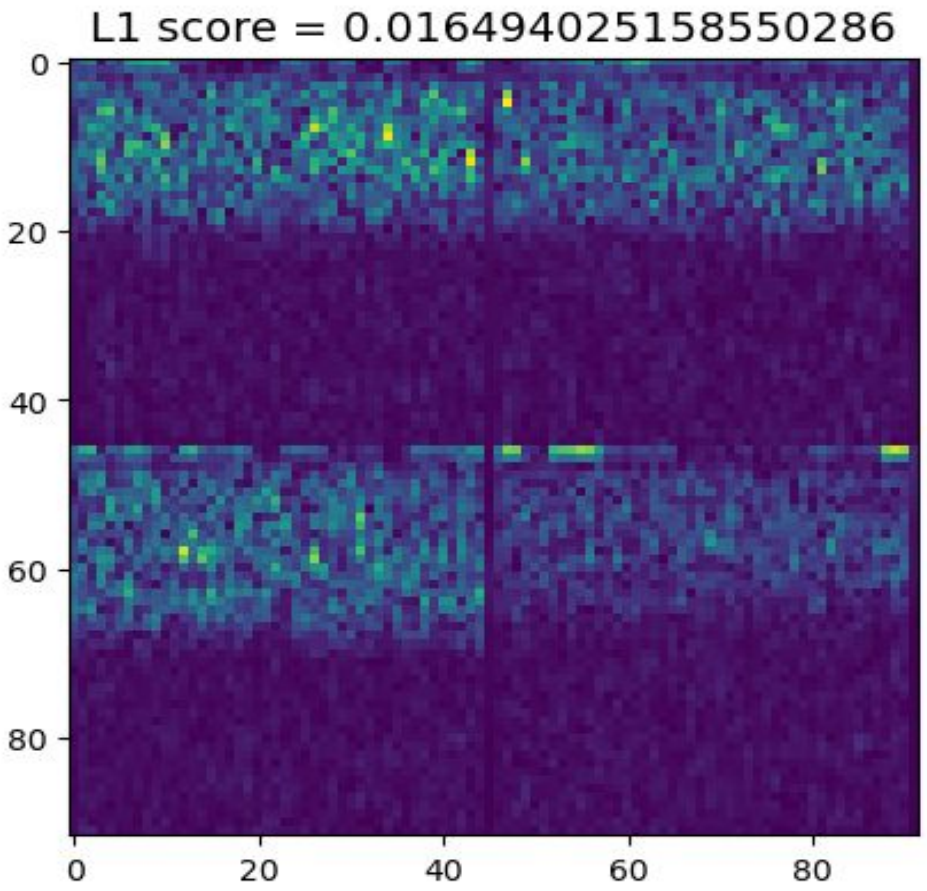


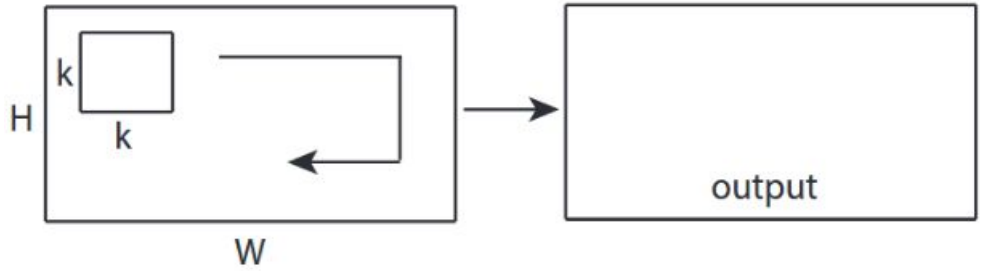


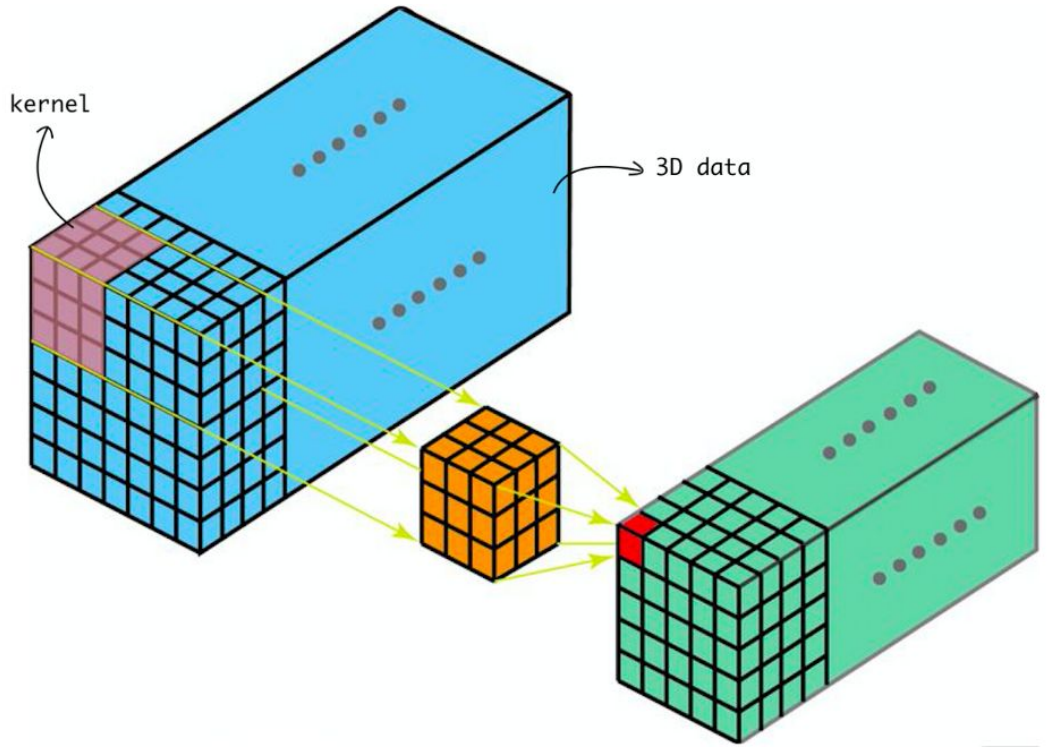


Anomaly Detection

Going 3D

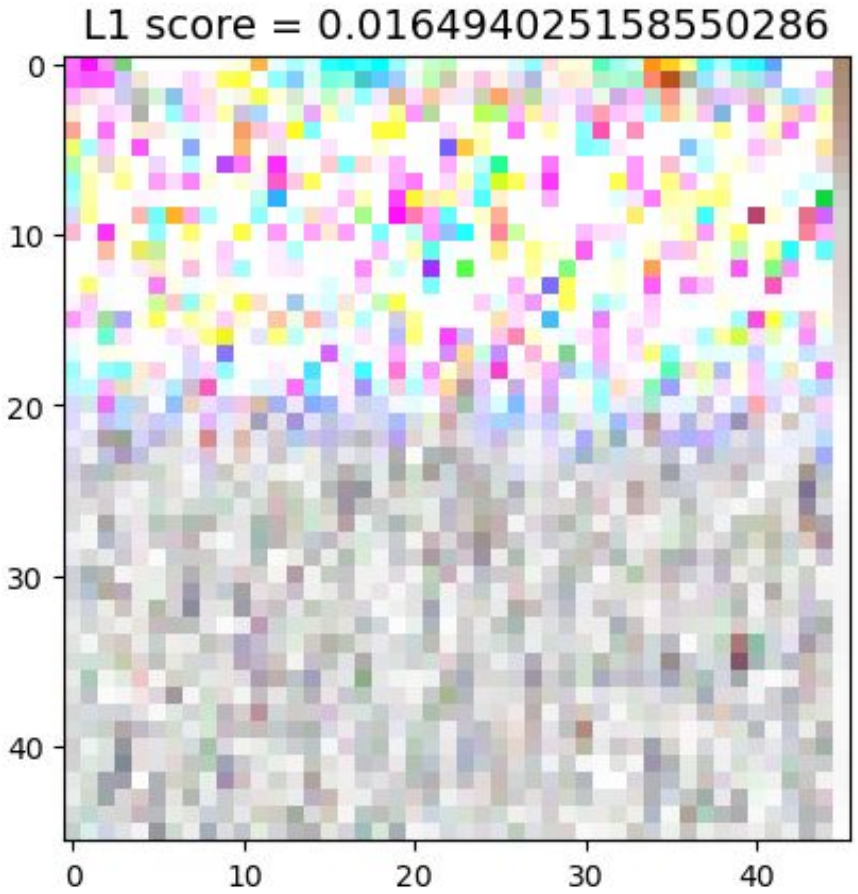


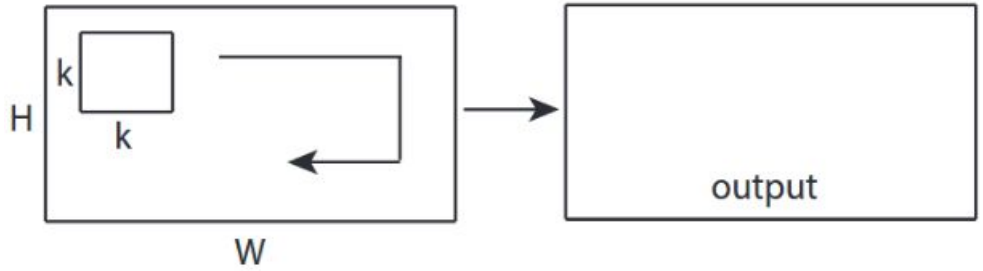


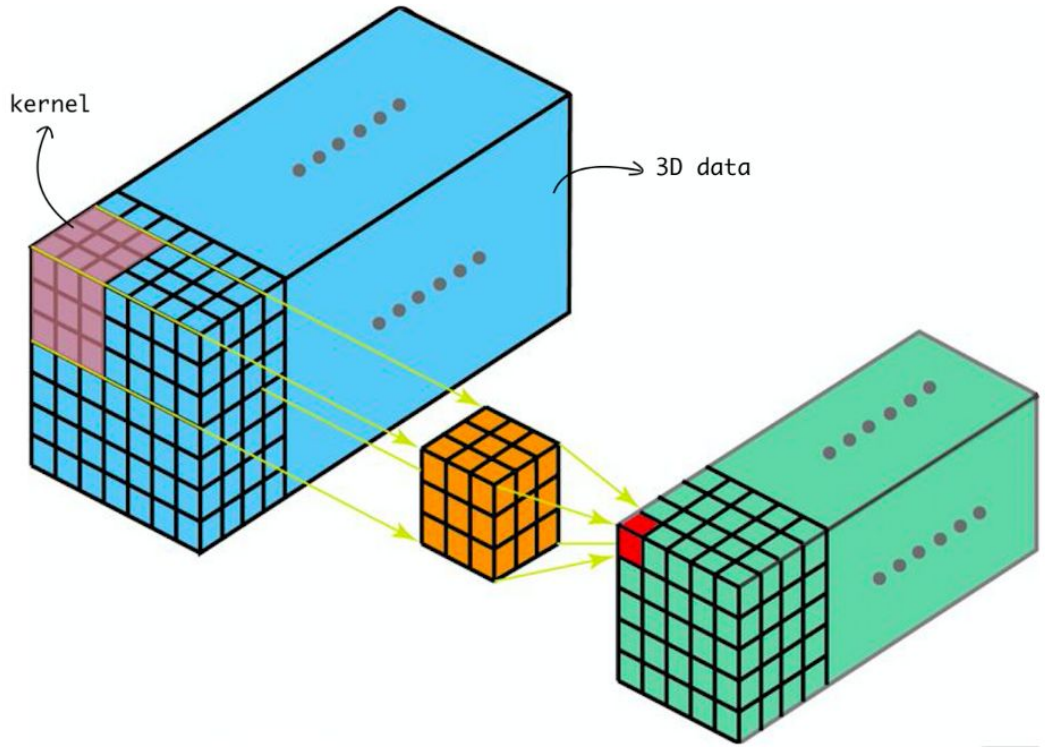


Anomaly Detection

Going 3D





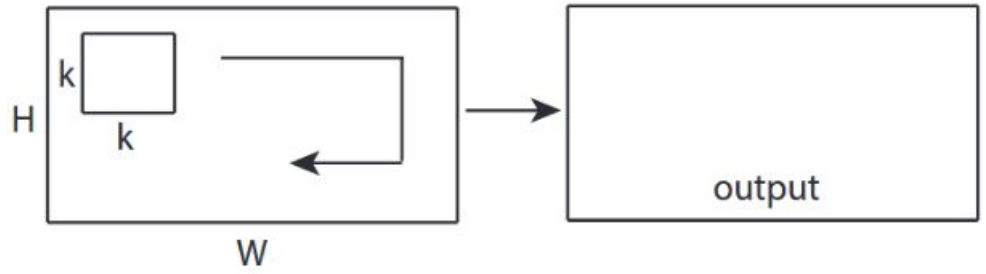


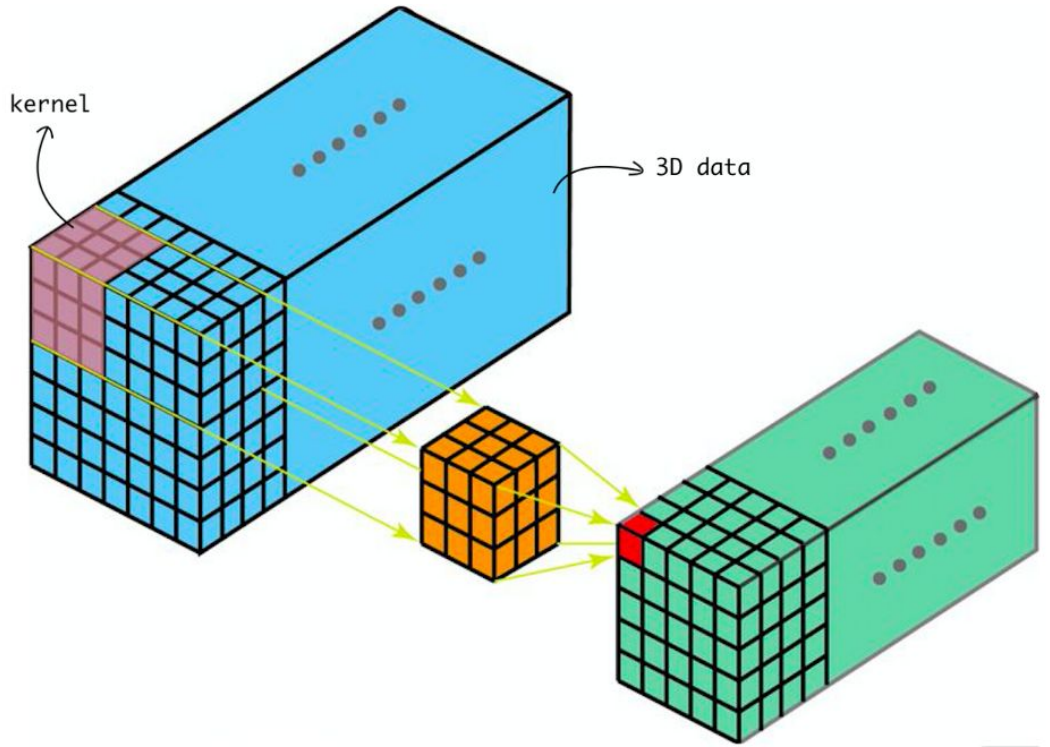
Anomaly Detection

Going 3D

```
Model: "sequential"
_________________________________________________________________
Layer (type)                 Output Shape              Param #
=================================================================
conv2d (Conv2D)              (None, 92, 92, 32)        2080
_________________________________________________________________
dropout (Dropout)            (None, 92, 92, 32)        0
_________________________________________________________________
conv2d_1 (Conv2D)            (None, 46, 46, 16)        131088
_________________________________________________________________
conv2d_transpose (Conv2DTran (None, 46, 46, 16)        65552
_________________________________________________________________
dropout_1 (Dropout)          (None, 46, 46, 16)        0
_________________________________________________________________
conv2d_transpose_1 (Conv2DTr (None, 92, 92, 32)        32800
_________________________________________________________________
conv2d_transpose_2 (Conv2DTr (None, 92, 92, 1)         33
=================================================================
Total params: 231,553
Trainable params: 231,553
Non-trainable params: 0
_________________________________________________________________
```

```
Model: "sequential_7"
_________________________________________________________________
Layer (type)                 Output Shape              Param #
=================================================================
conv3d_10 (Conv3D)           (None, 46, 46, 4, 32)     16416
_________________________________________________________________
dropout_14 (Dropout)         (None, 46, 46, 4, 32)     0
_________________________________________________________________
conv3d_11 (Conv3D)           (None, 23, 23, 2, 16)     2097168
_________________________________________________________________
conv3d_transpose_14 (Conv3DT (None, 46, 46, 4, 16)     1048592
_________________________________________________________________
dropout_15 (Dropout)         (None, 46, 46, 4, 16)     0
_________________________________________________________________
conv3d_transpose_15 (Conv3DT (None, 46, 46, 4, 32)     262176
_________________________________________________________________
conv3d_transpose_16 (Conv3DT (None, 46, 46, 4, 1)      2049
=================================================================
Total params: 3,426,401
Trainable params: 3,426,401
Non-trainable params: 0
_________________________________________________________________
```

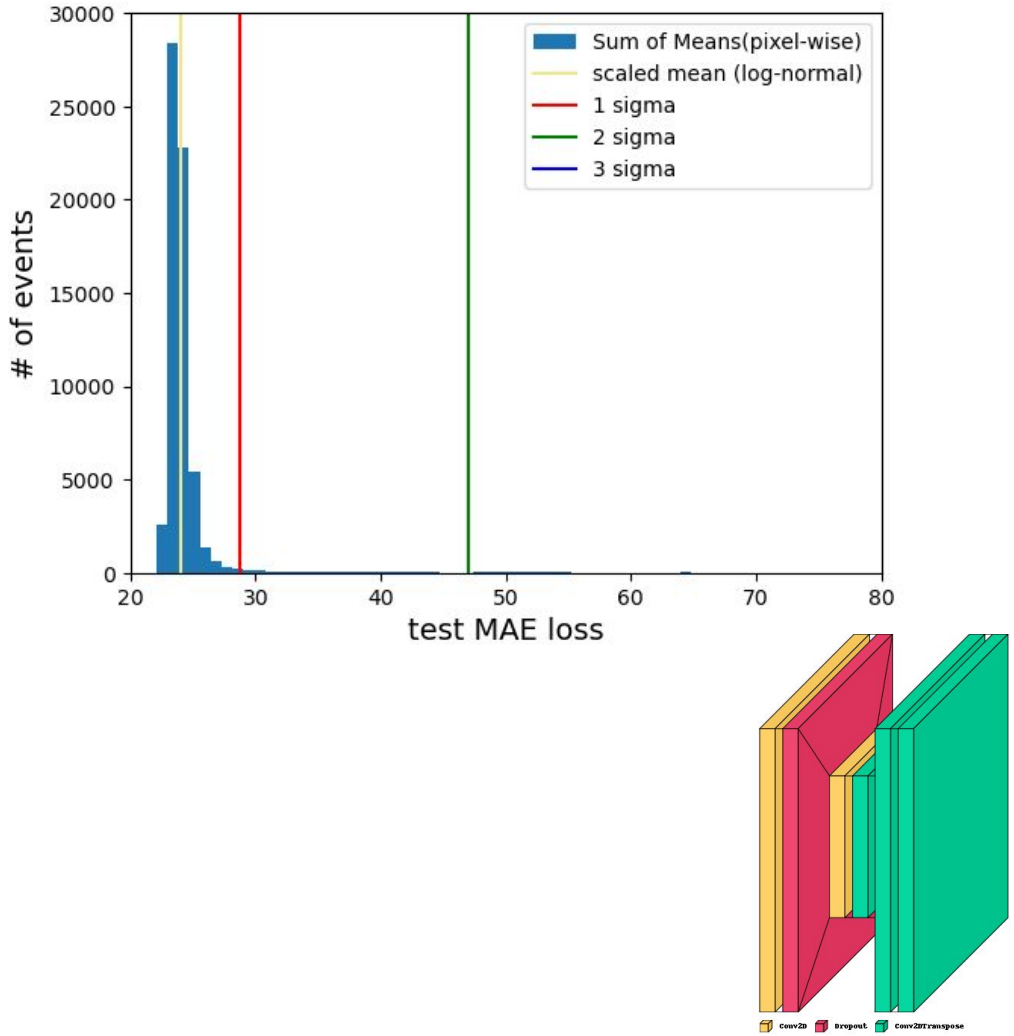




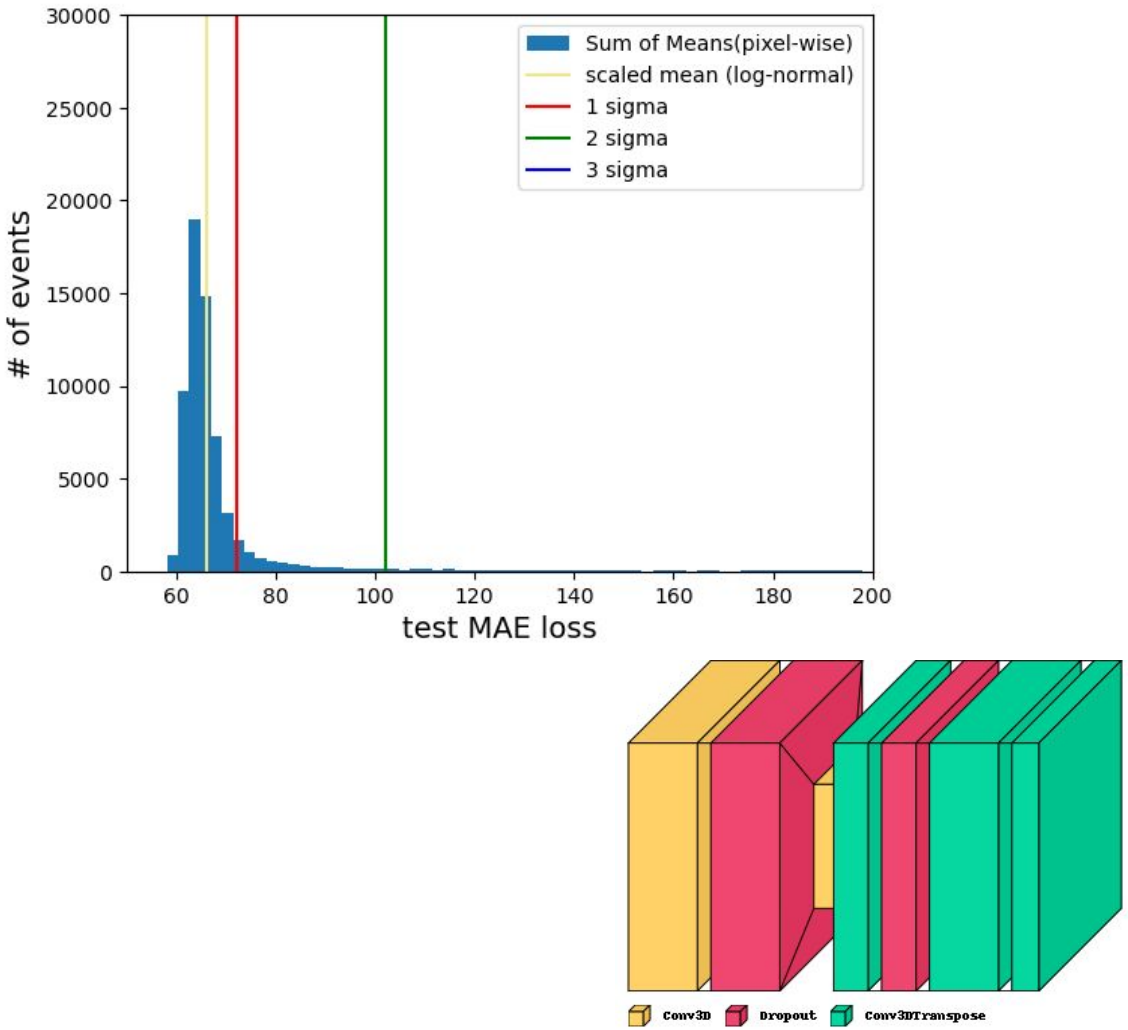
Anomaly Detection Update

Going 3D

2D Mosaic

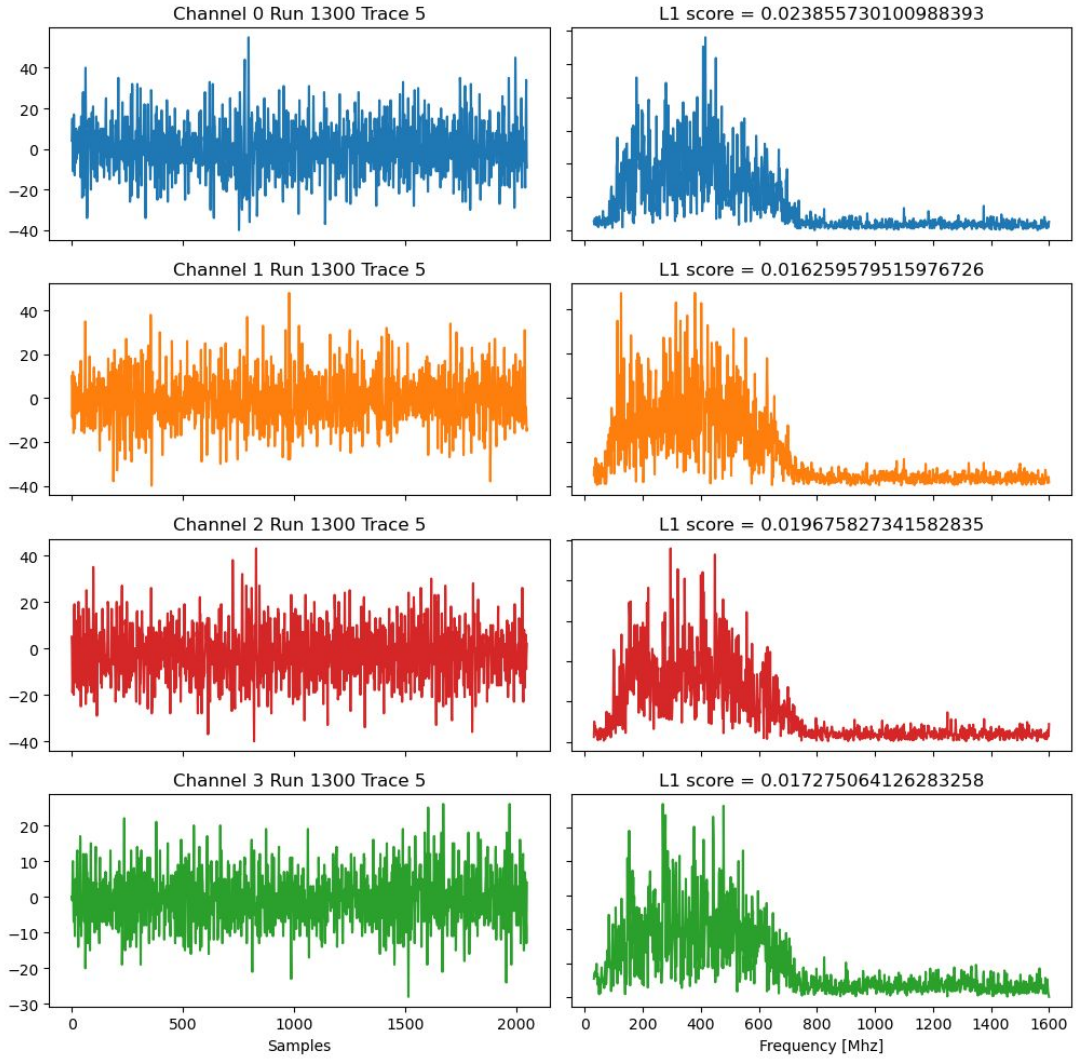


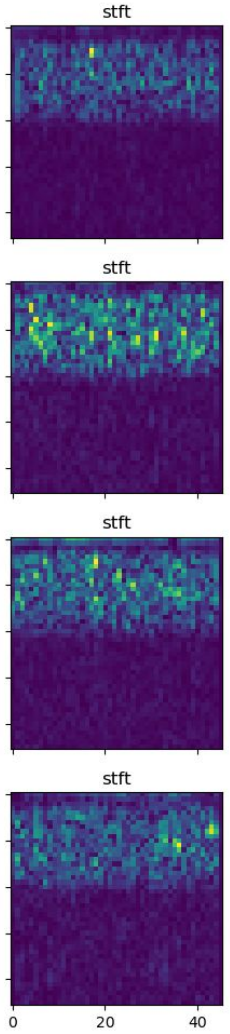
3D Tensor

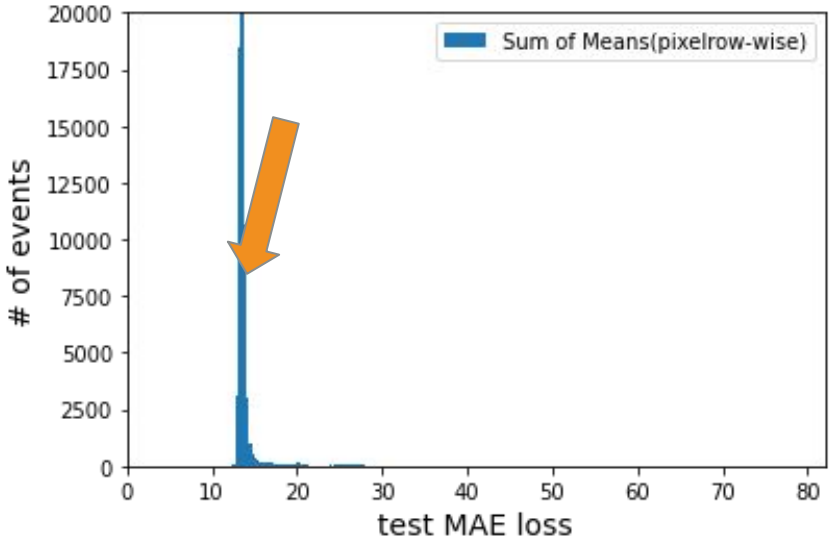


Anomaly Detection

Thermal Noise

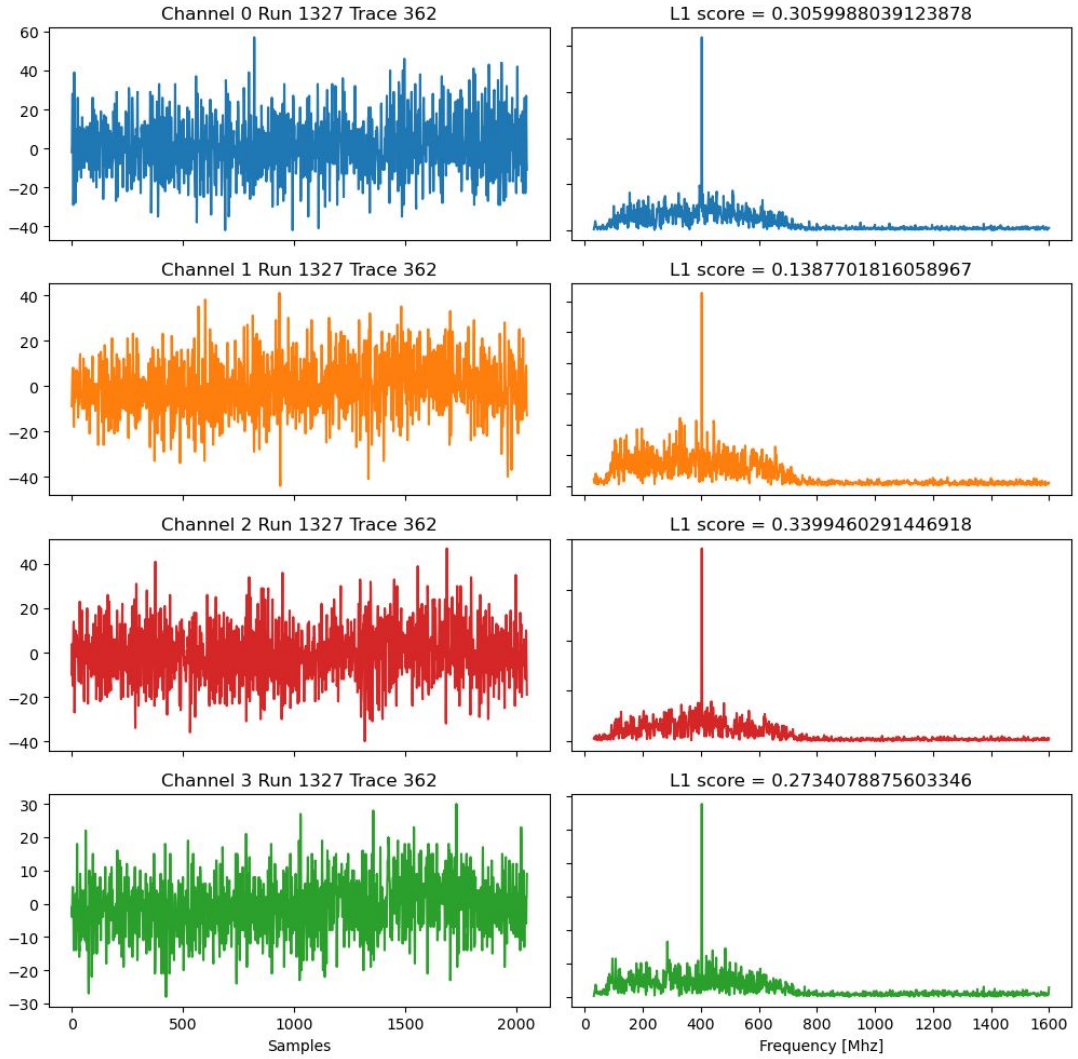


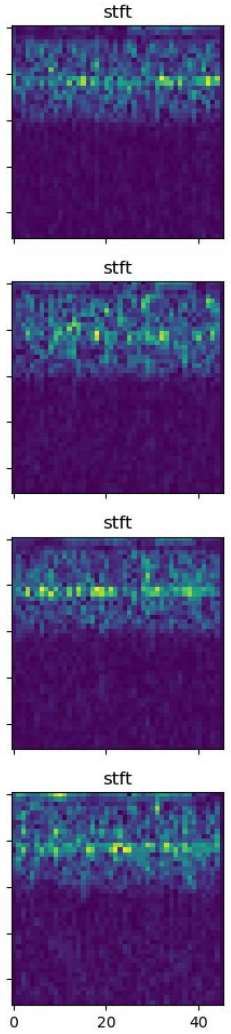


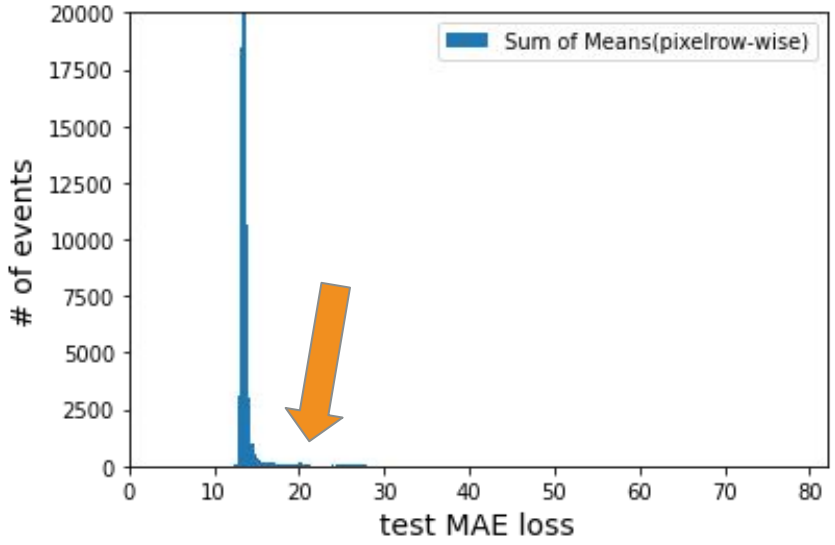


Anomaly Detection

Weak Continuous Wave (CW)

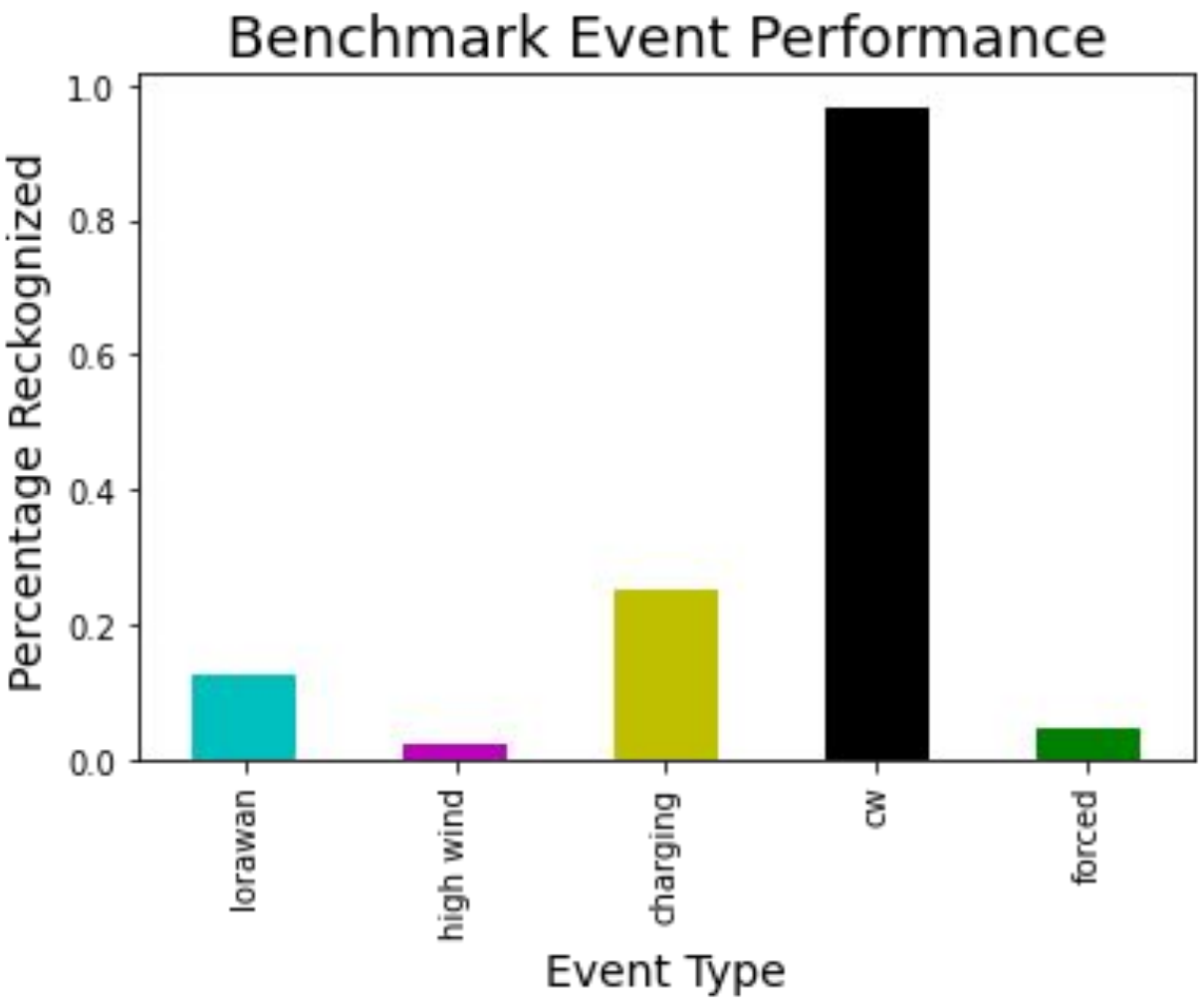


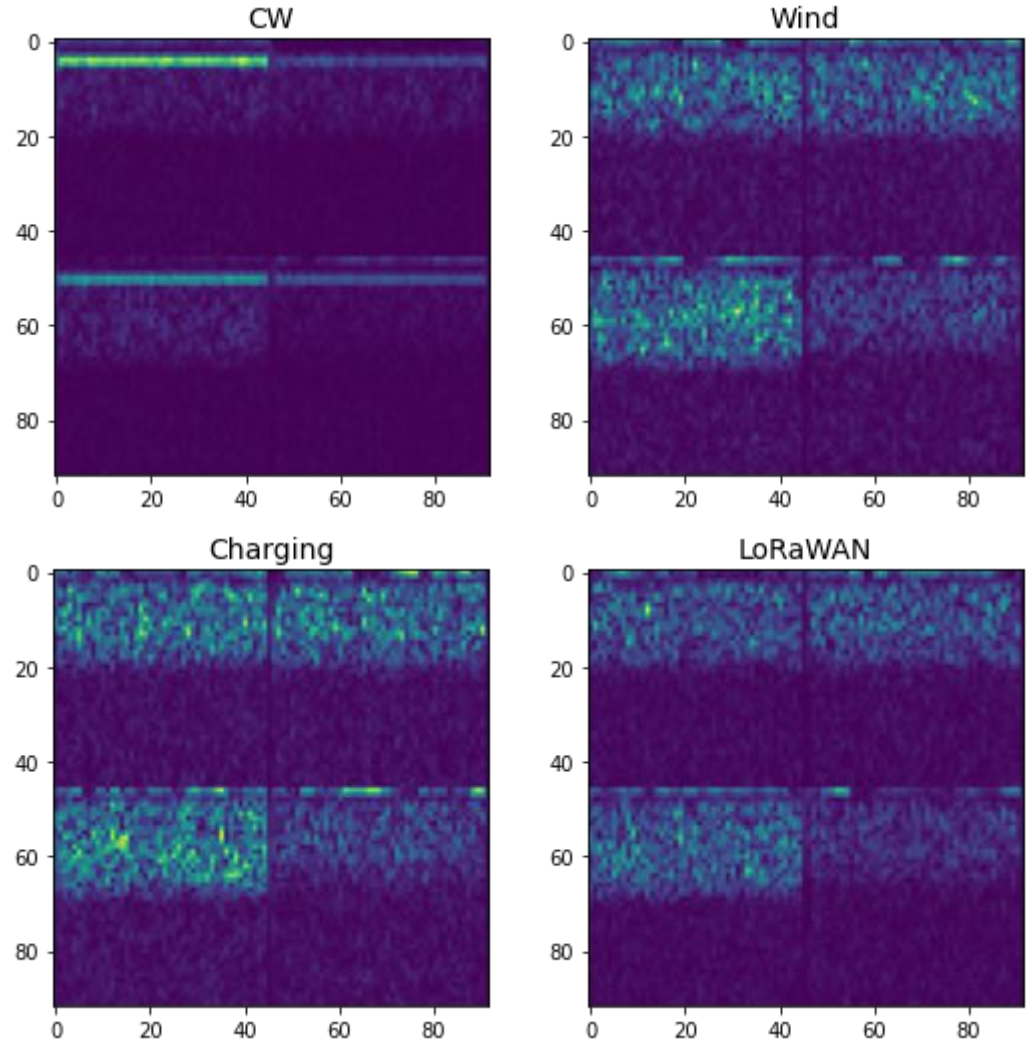




Anomaly Detection

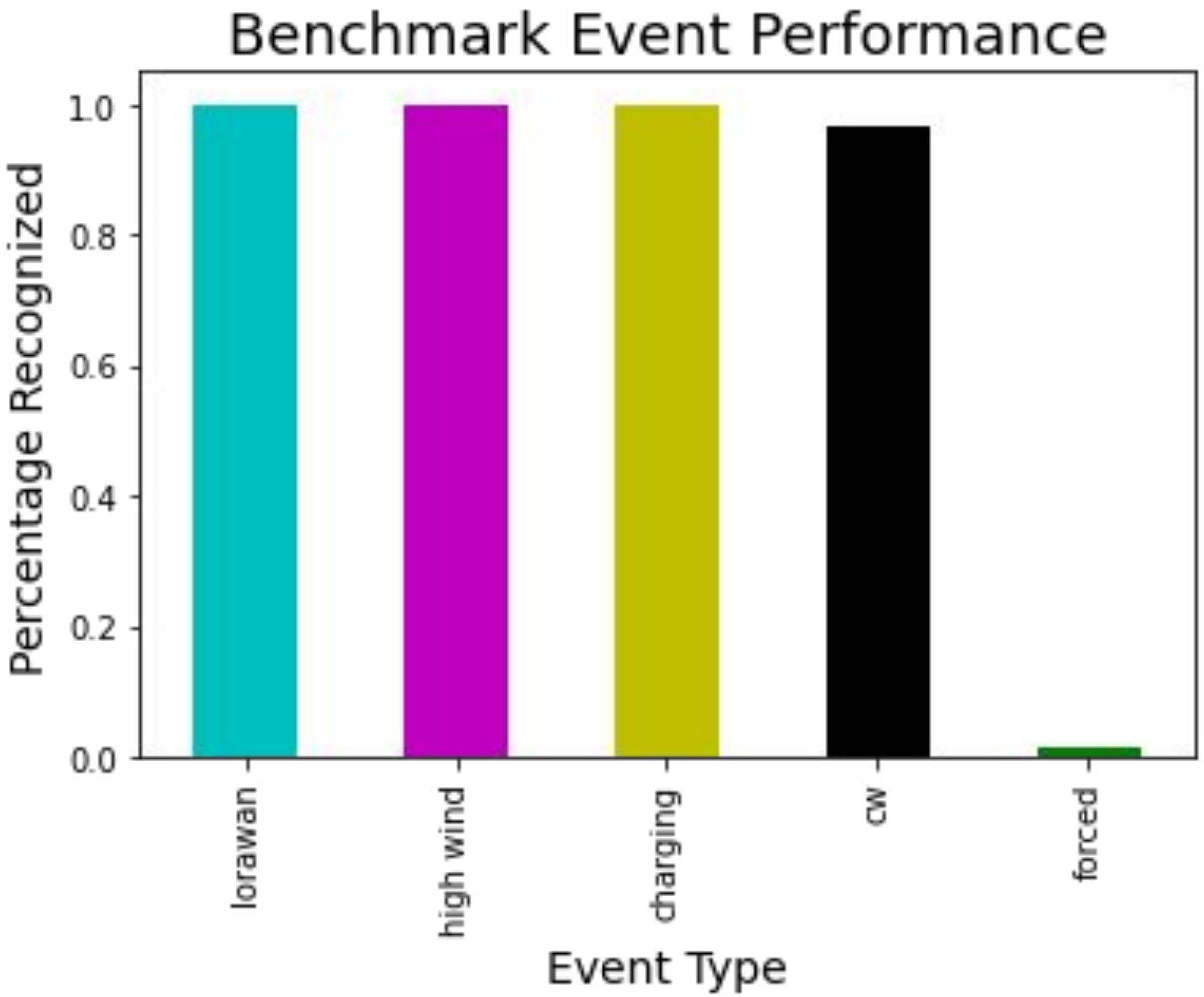
Deep Benchmarks

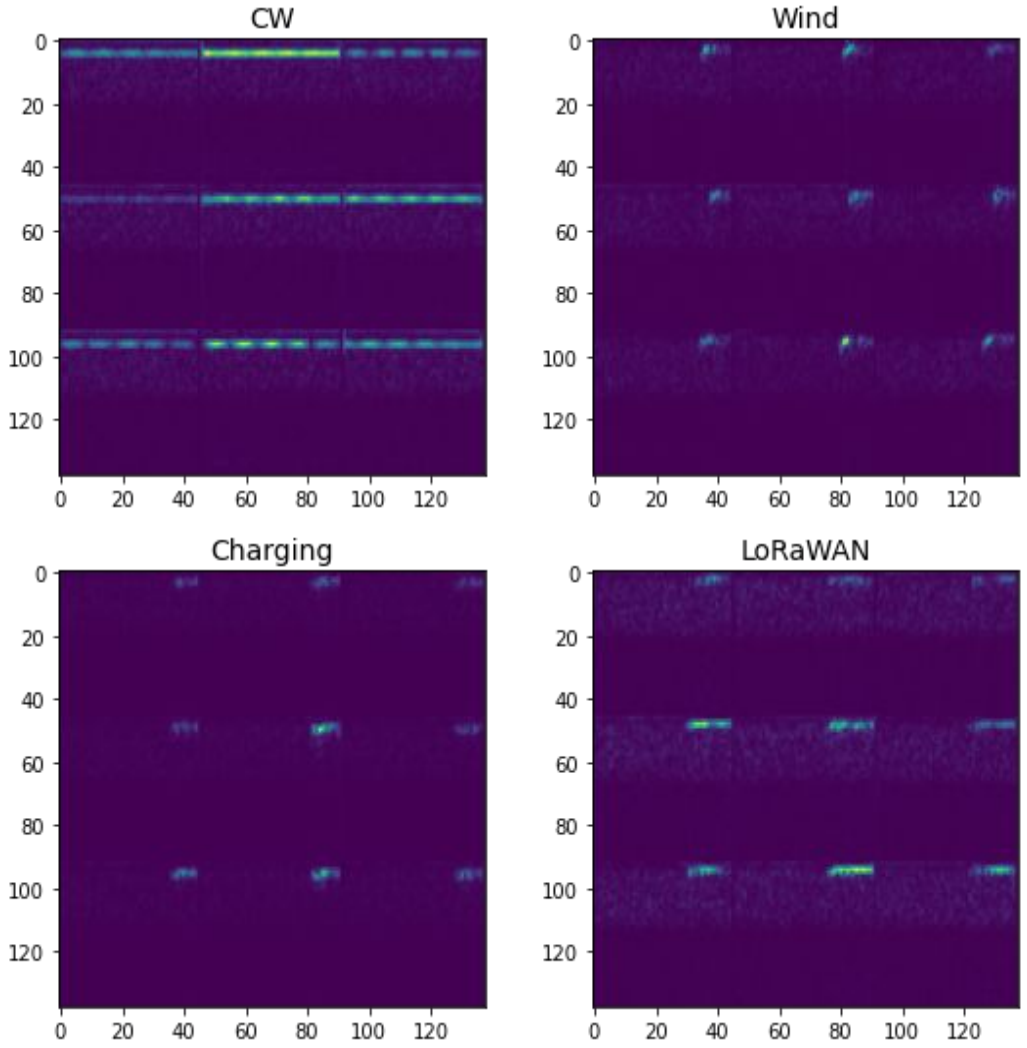




Anomaly Detection

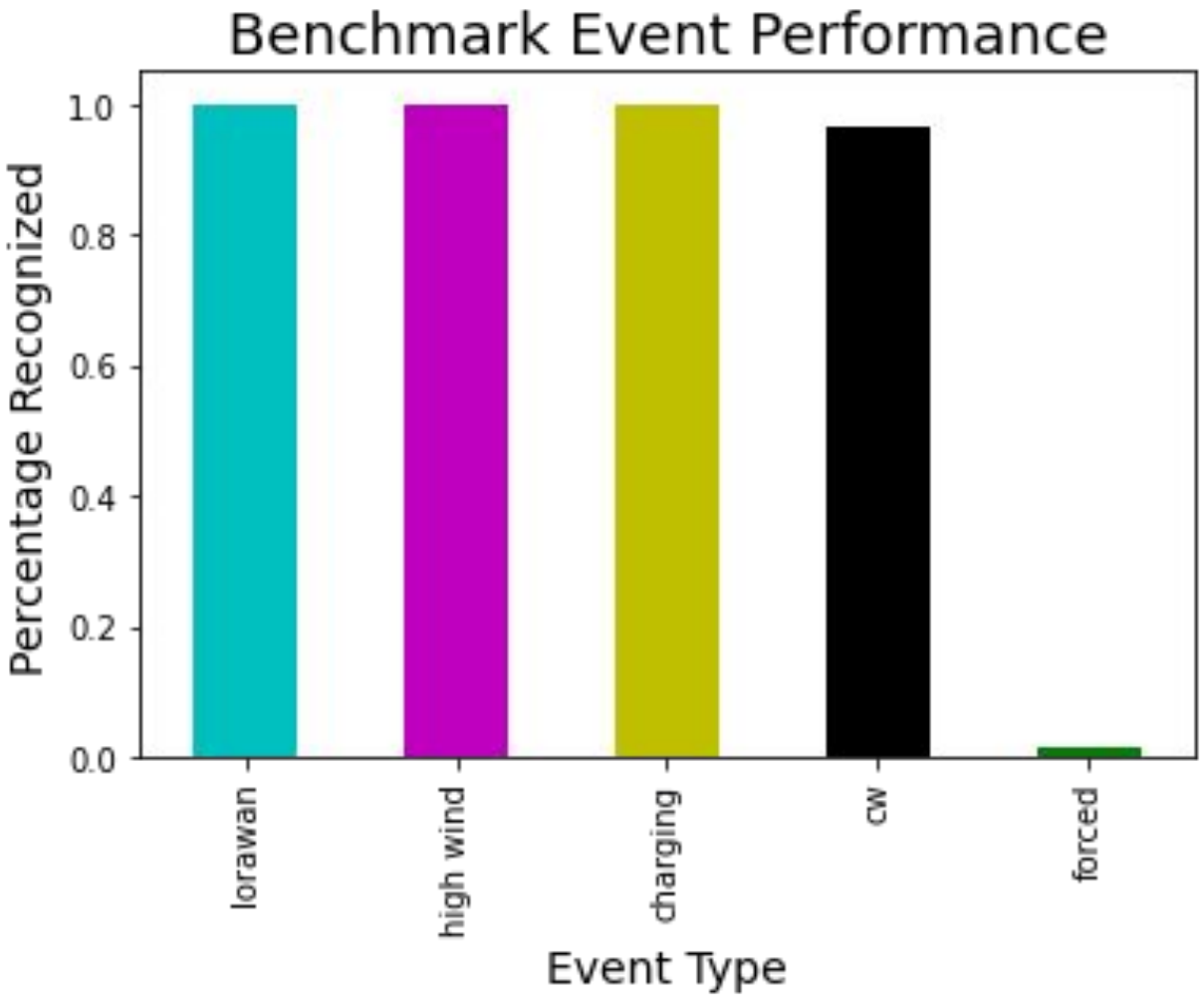
Surface Noise Benchmarks

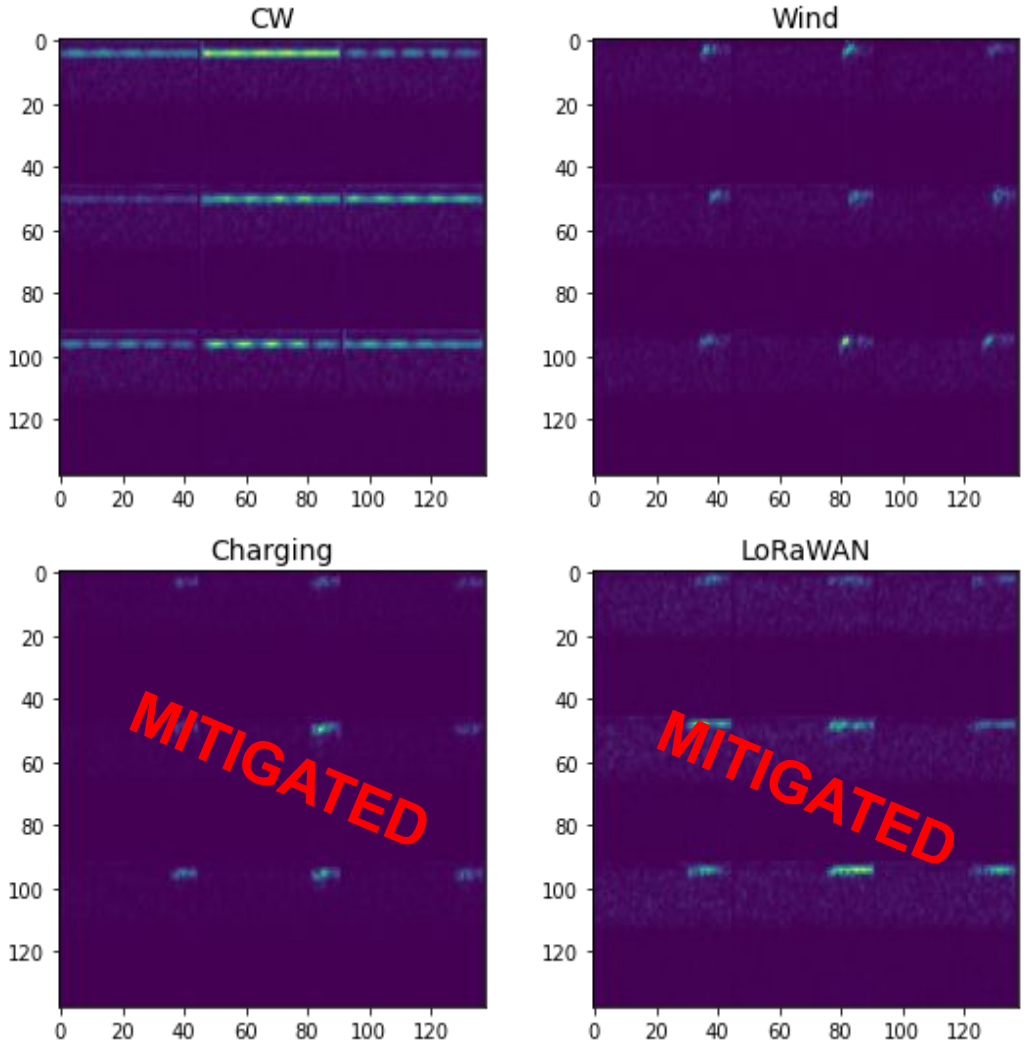




Anomaly Detection

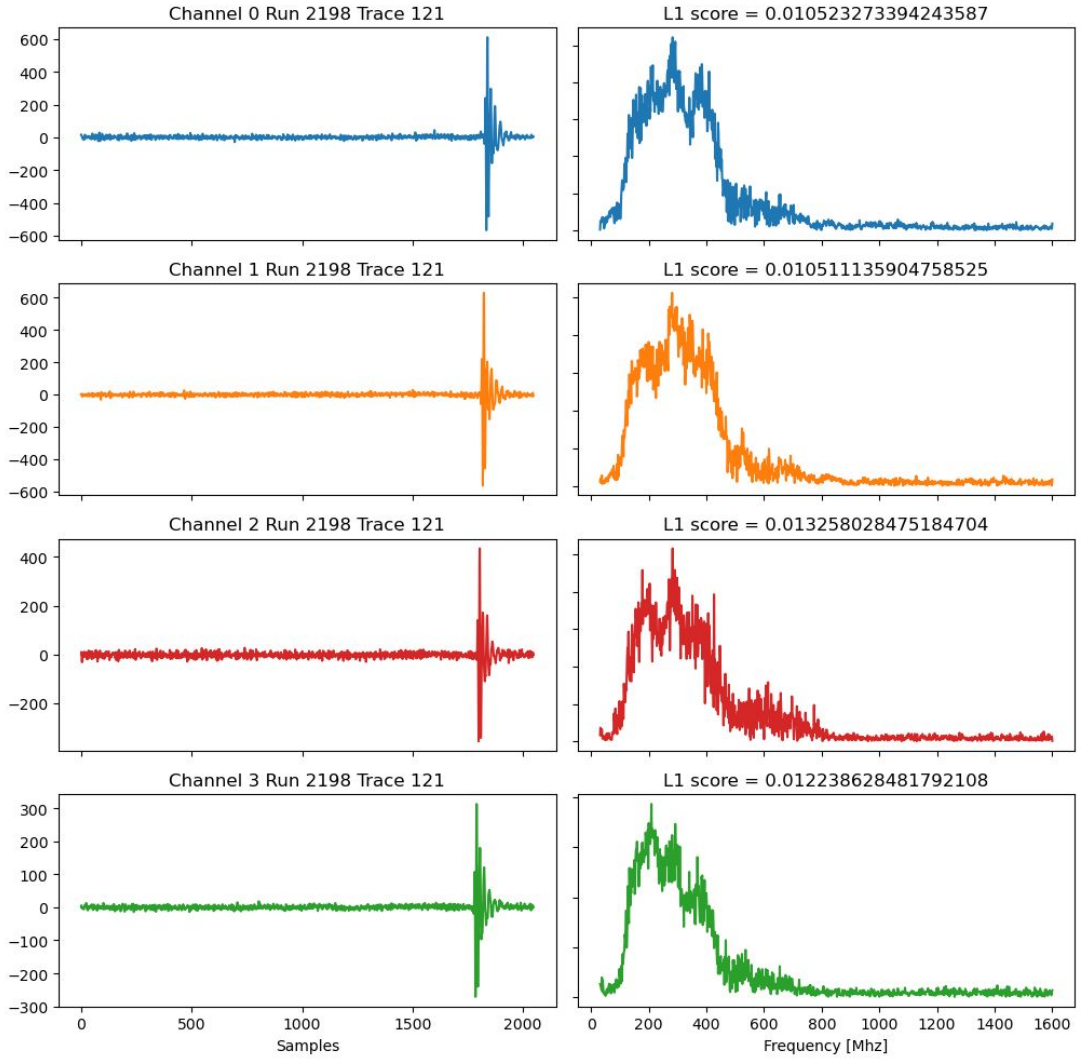
Surface Noise Benchmarks

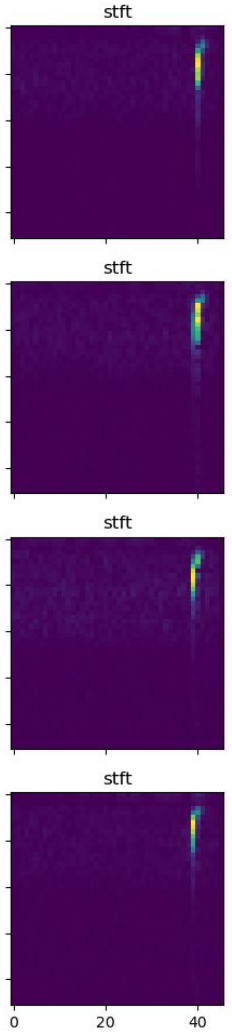


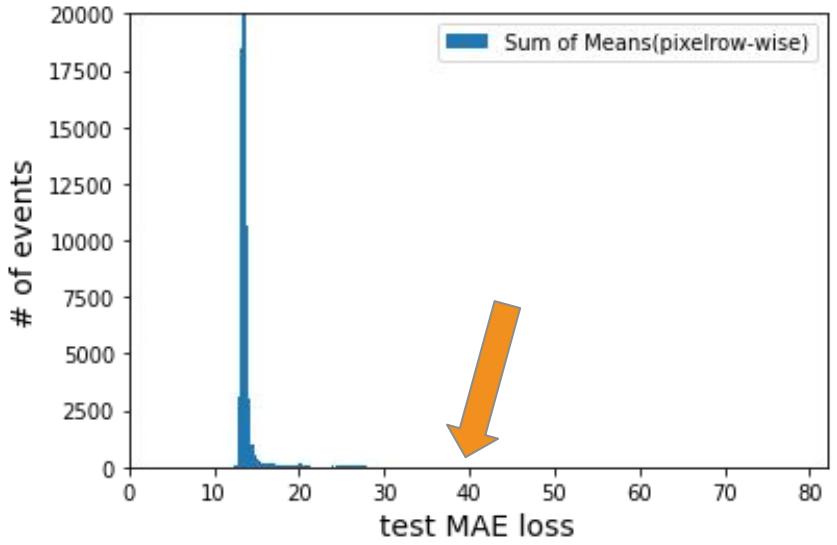


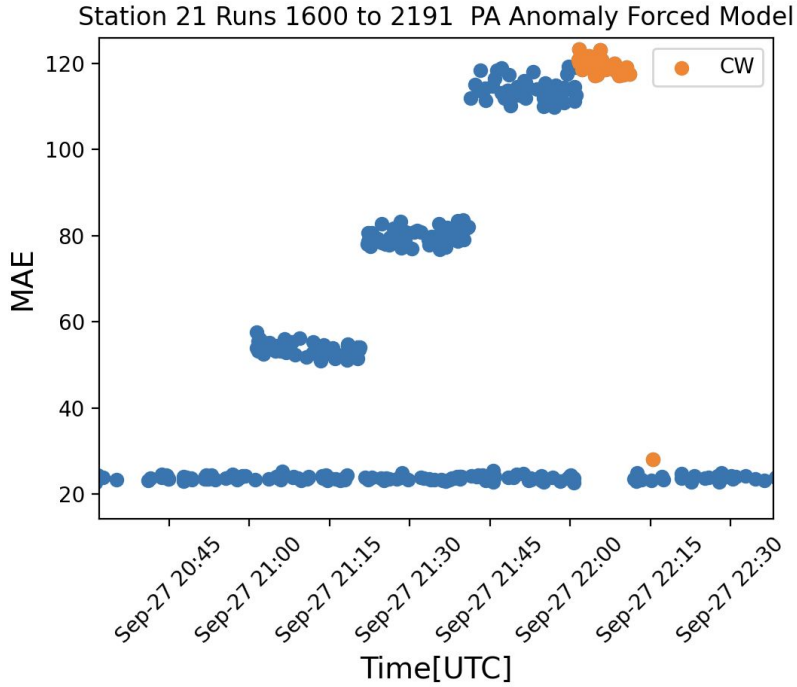
Anomaly Detection

Calibration Pulsing



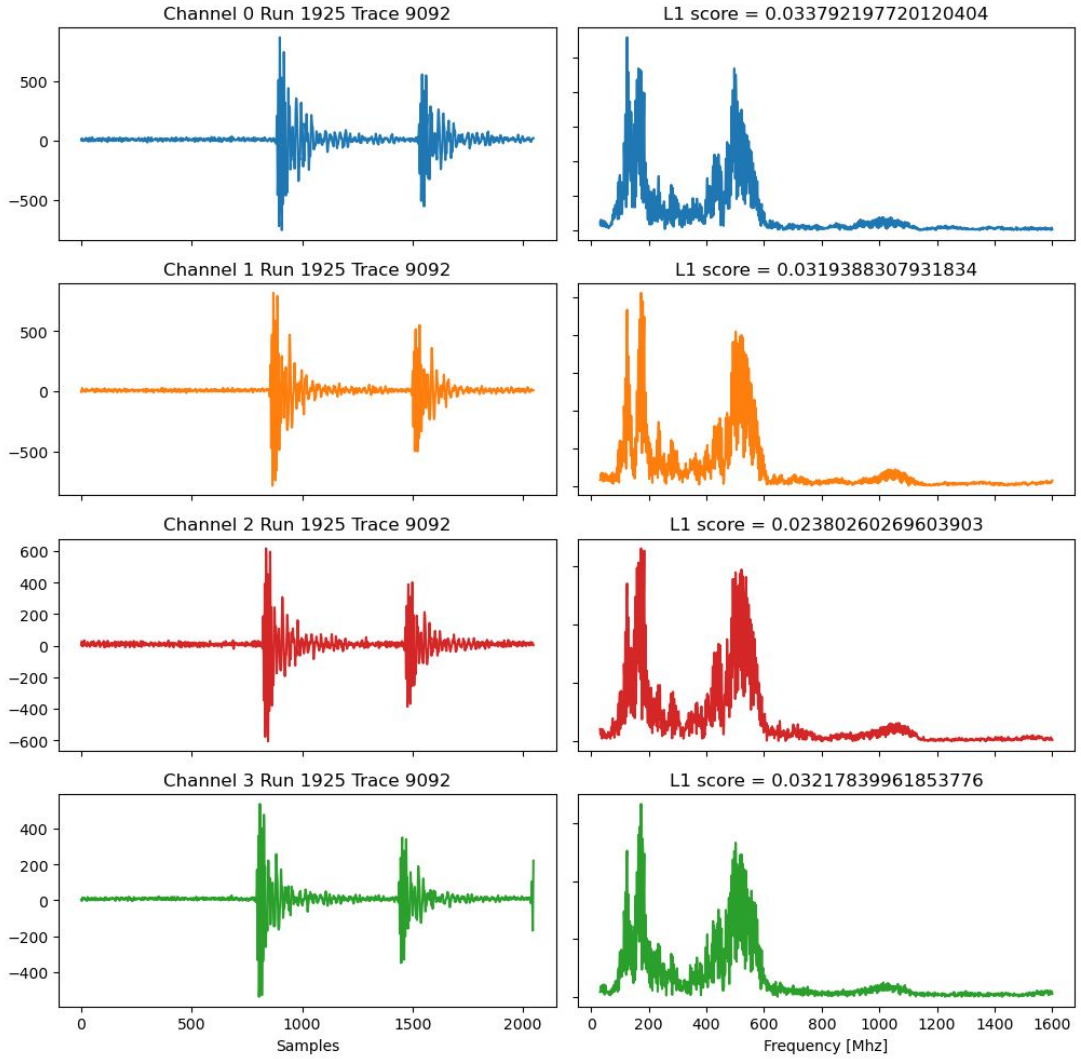


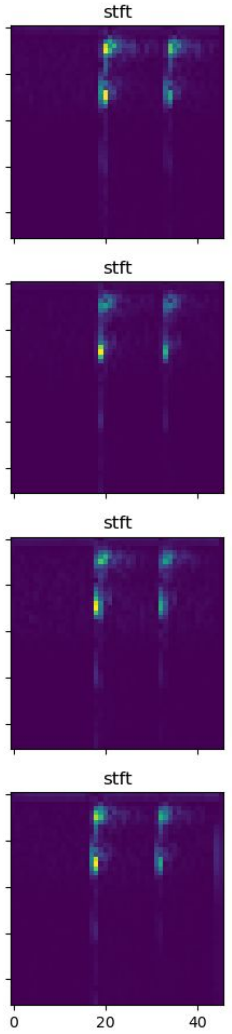


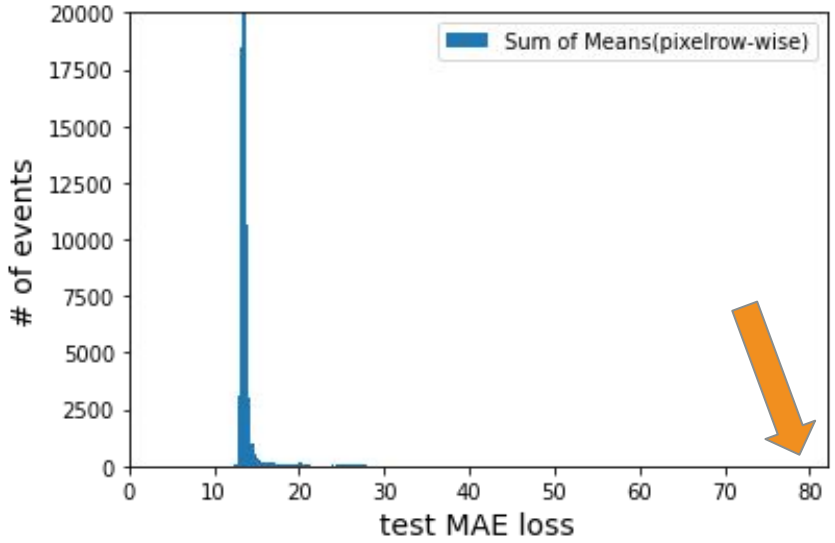


Anomaly Detection

Storm? Ice Quakes?

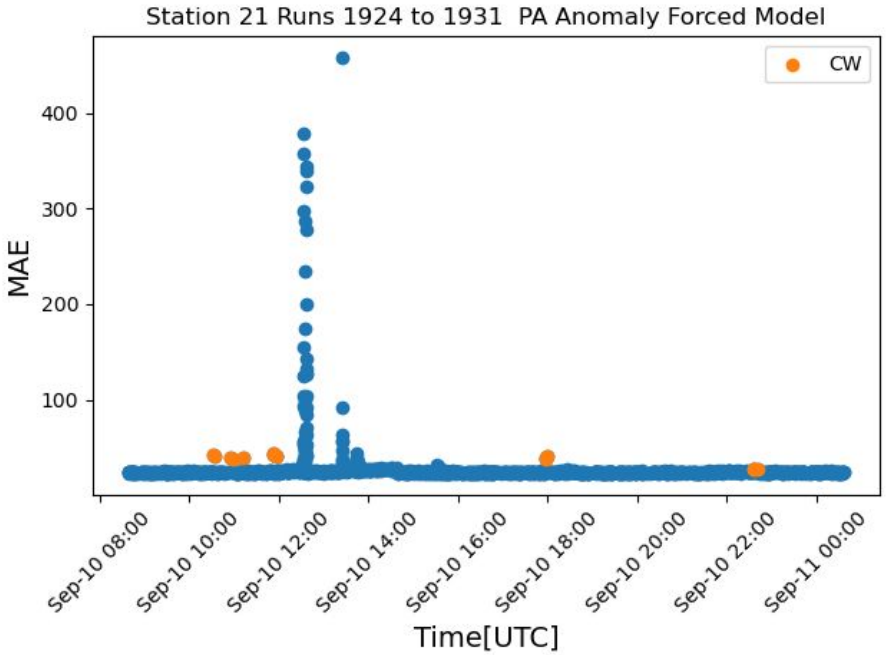


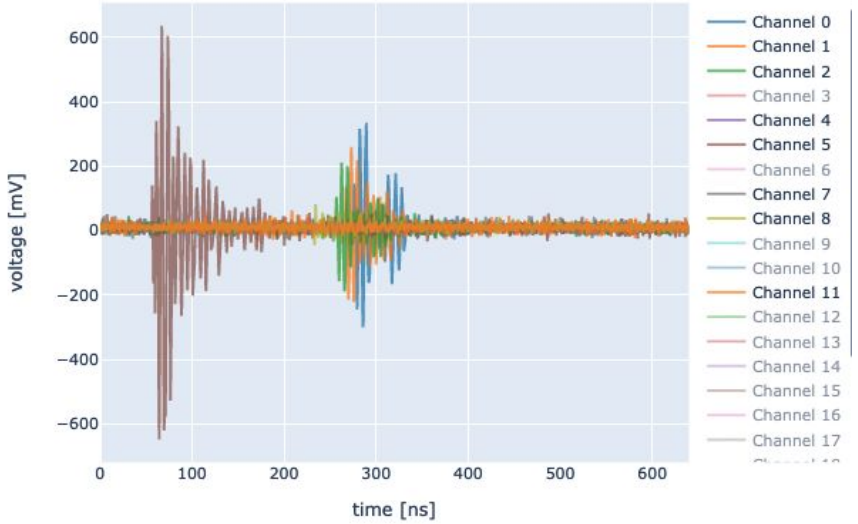


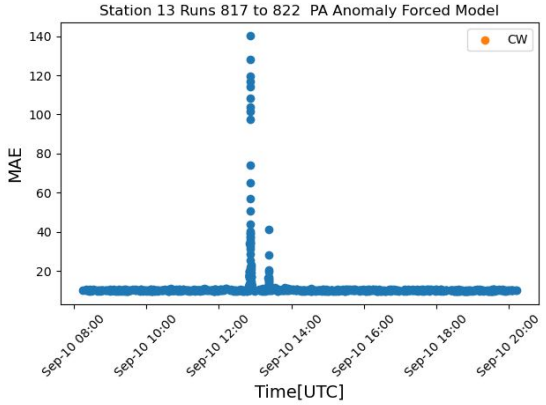


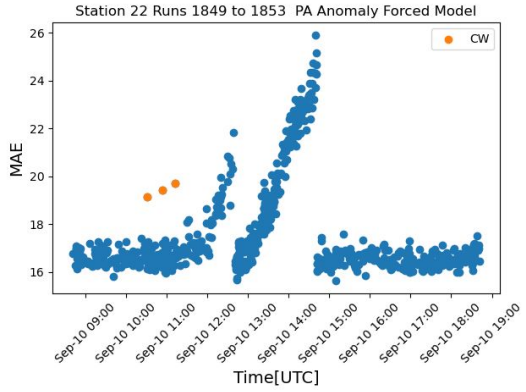
Snowmobiles?

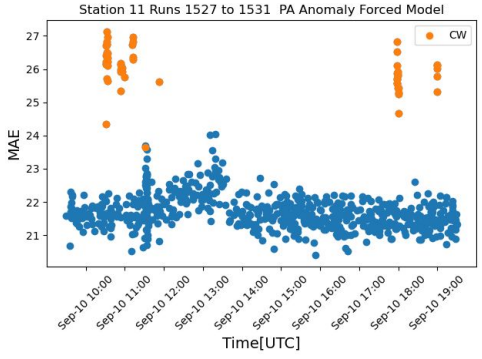
September 10th – Snowmobile?

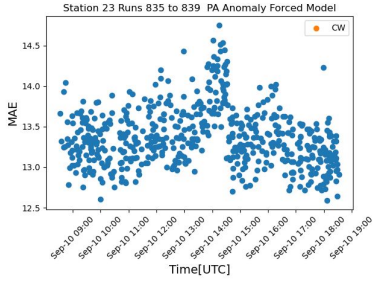


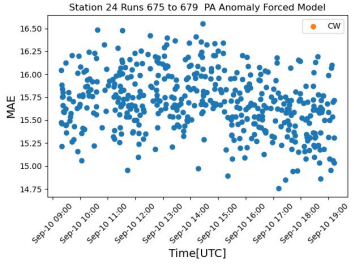






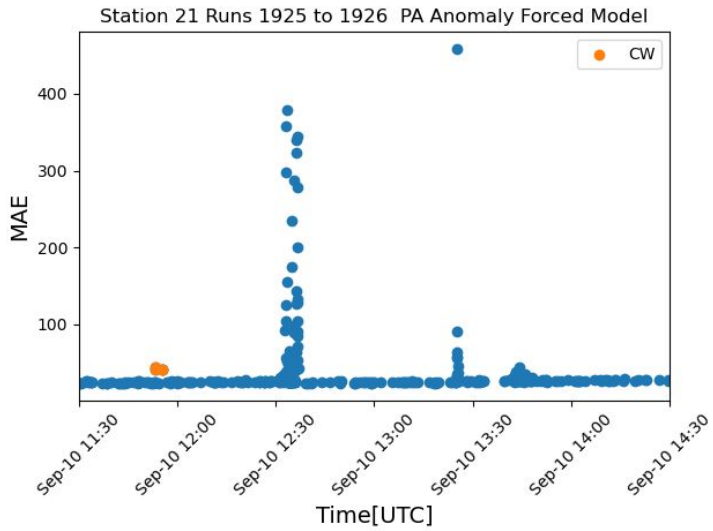


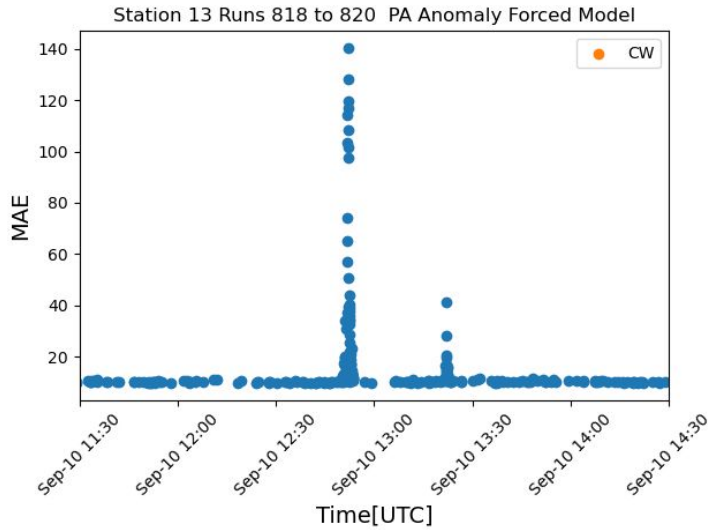




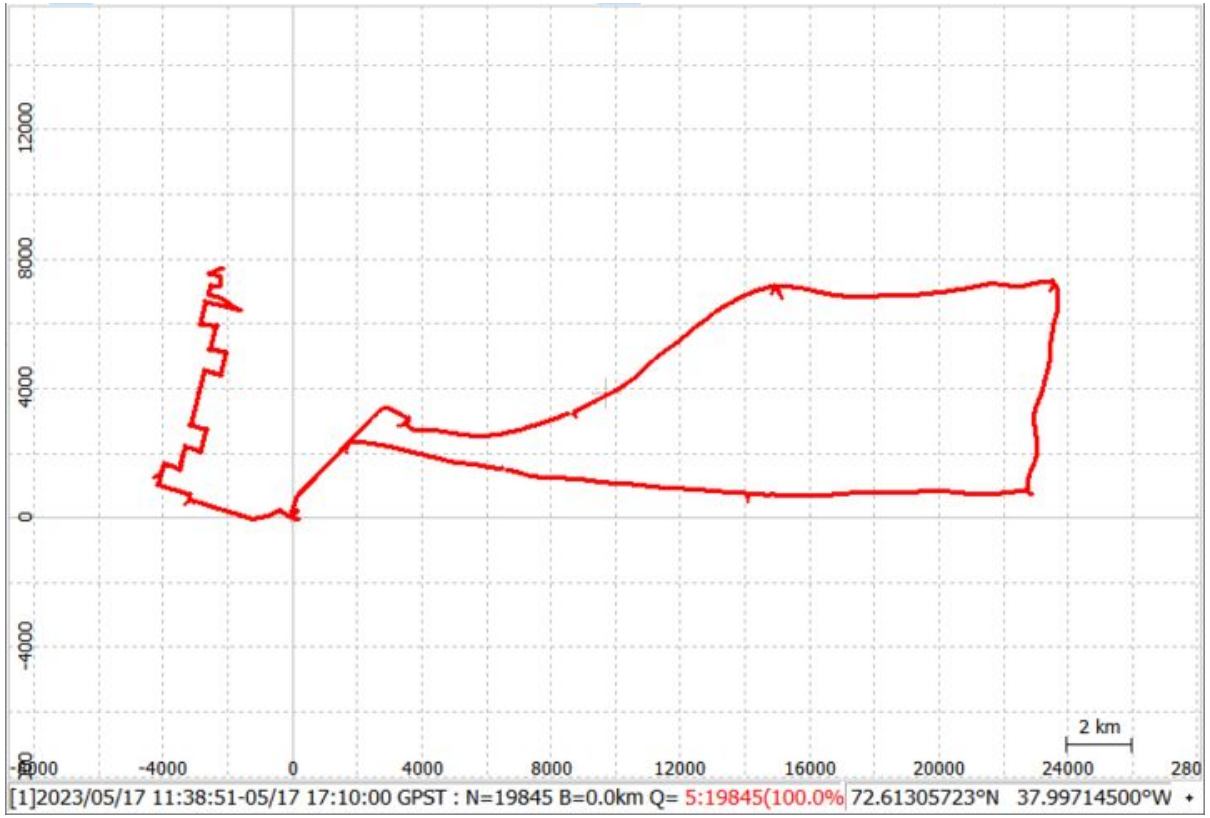
Snowmobiles!

Ice Sat Traverse



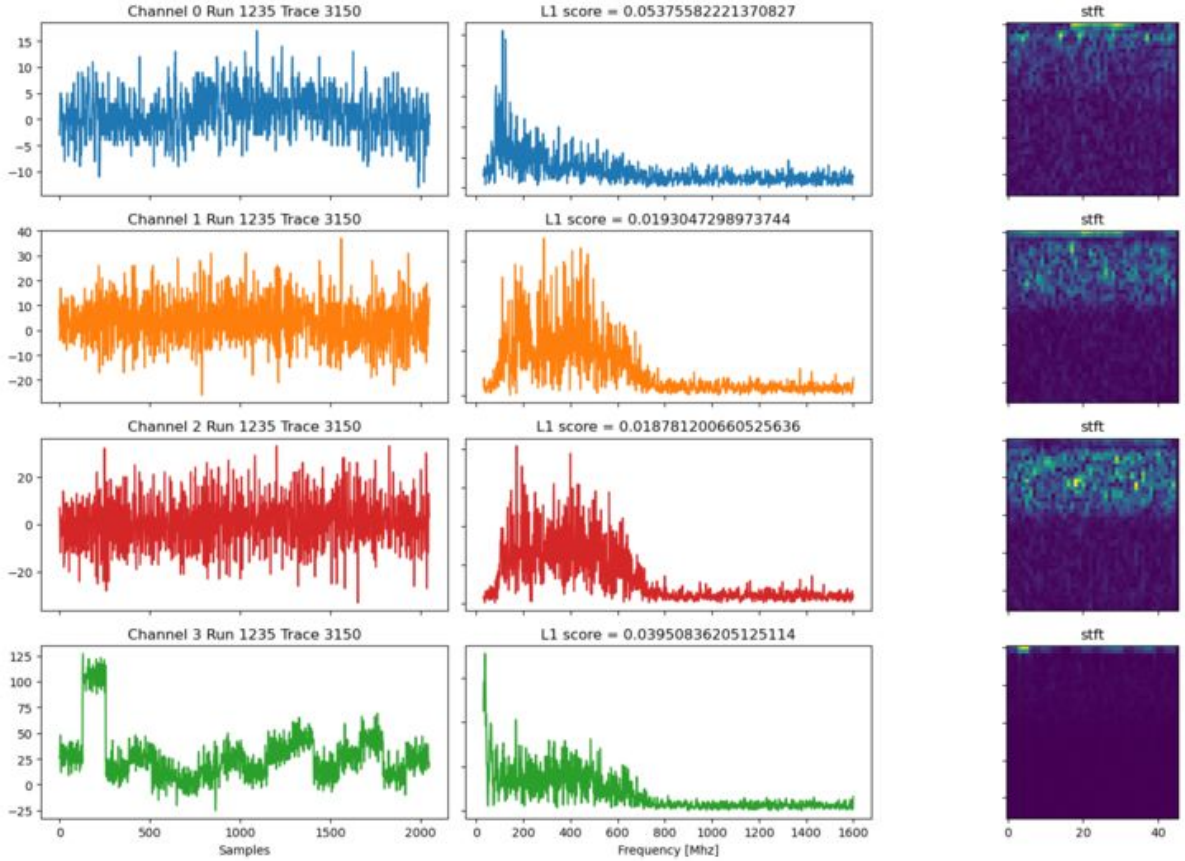


ICESat-2
ICE, CLOUD, AND LAND ELEVATION SATELLITE-2



Block Offsets

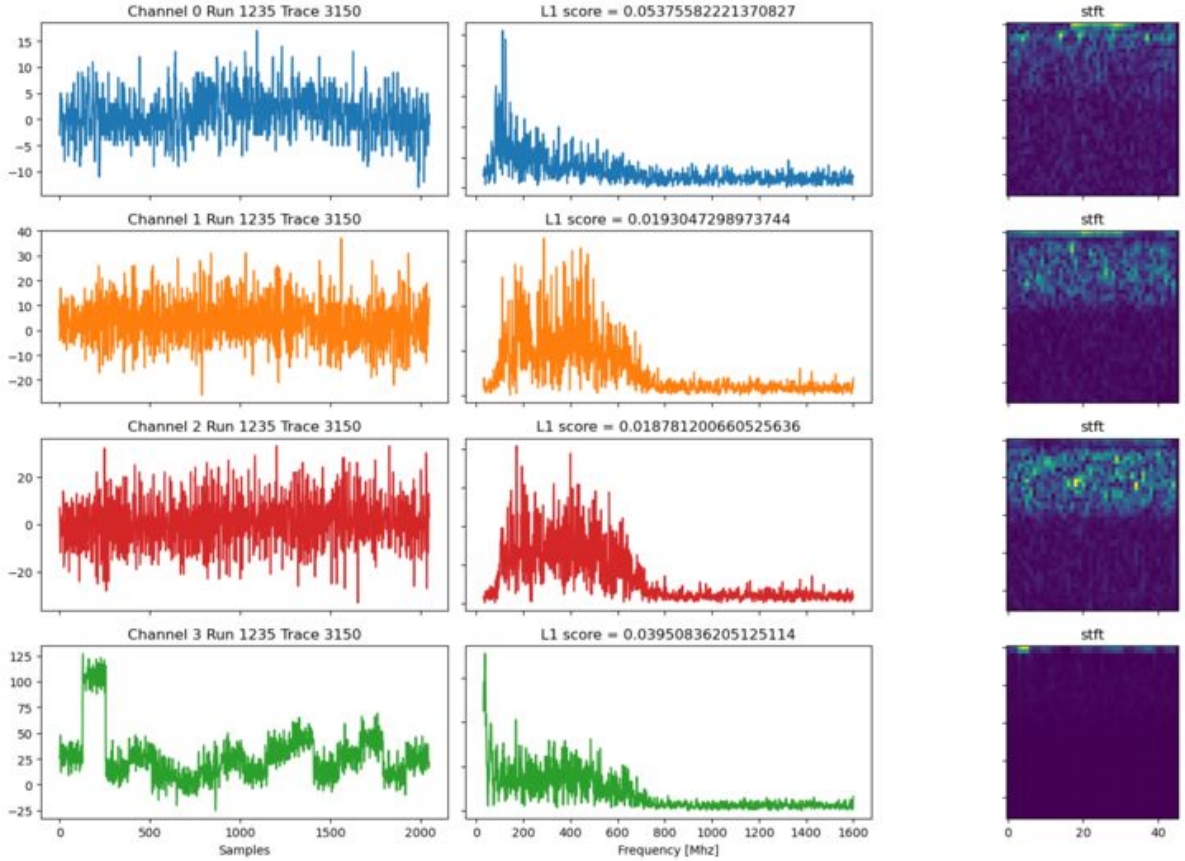
Station 13 channel 3 suffers from frequent block offsets



- **LAB4D digitizes in 16 blocks of 128 samples**
- **Probably due to unstable bias in the supplied voltage**
- **Fixable in level 1 calibration**

Block Offsets

Station 13 channel 3 suffers from frequent block offsets

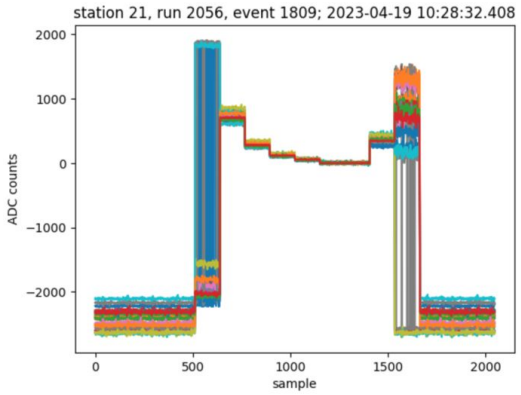


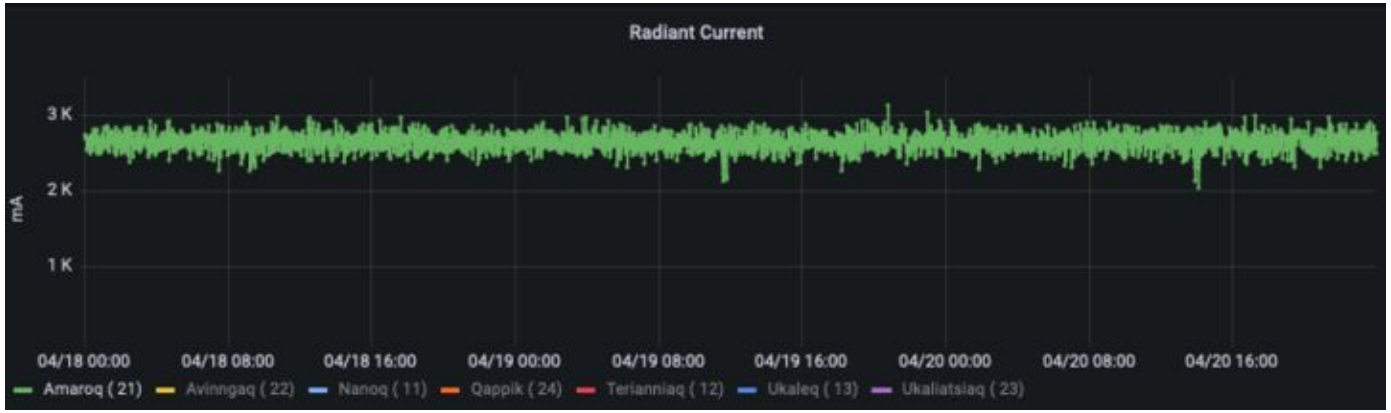
- **LAB4D digitizes in 16 blocks of 128 samples**
- **Probably due to unstable bias in the supplied voltage**
- **Fixable in level 1 calibration**

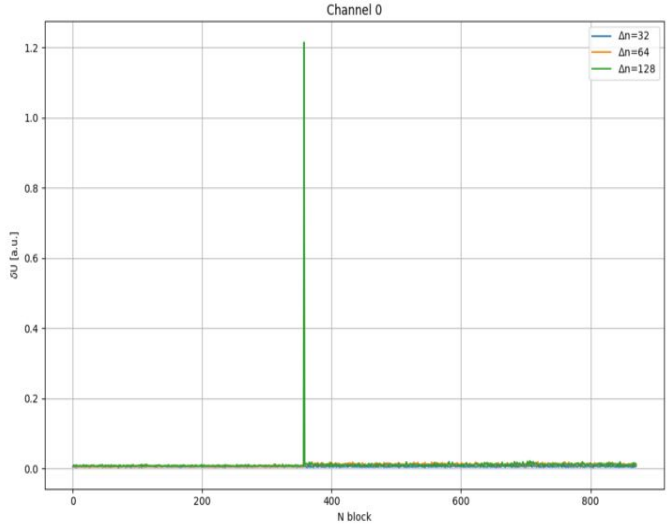
MITIGATED

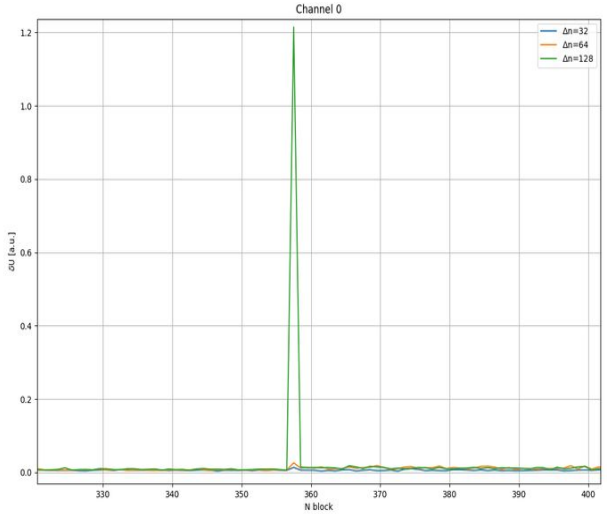
Another Anomalous Event in 21 on April 19

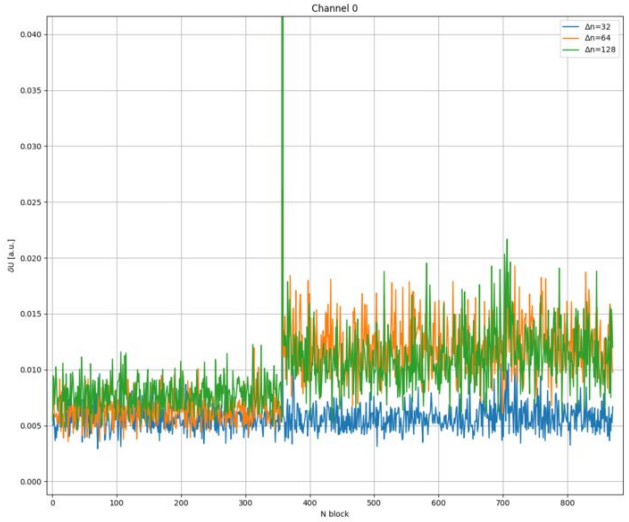
MEGA Block offsets. Glitching can occur





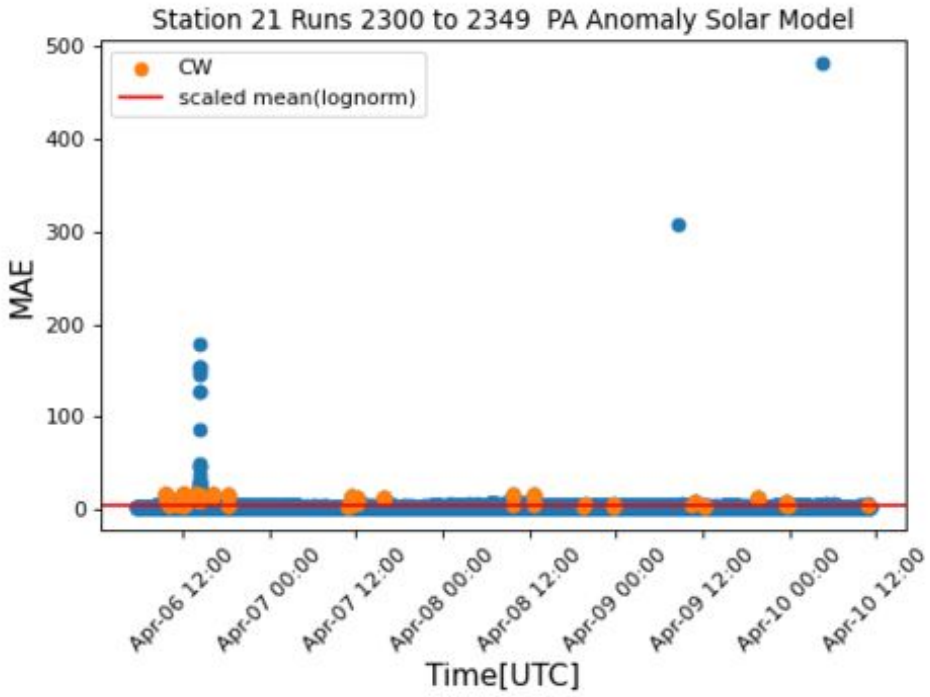


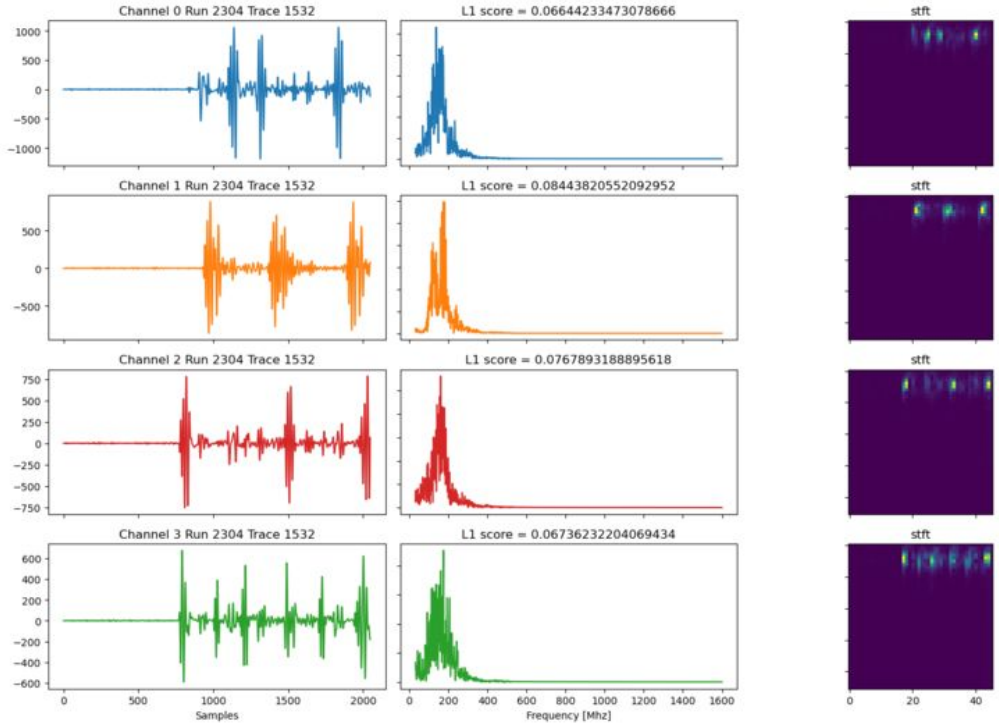


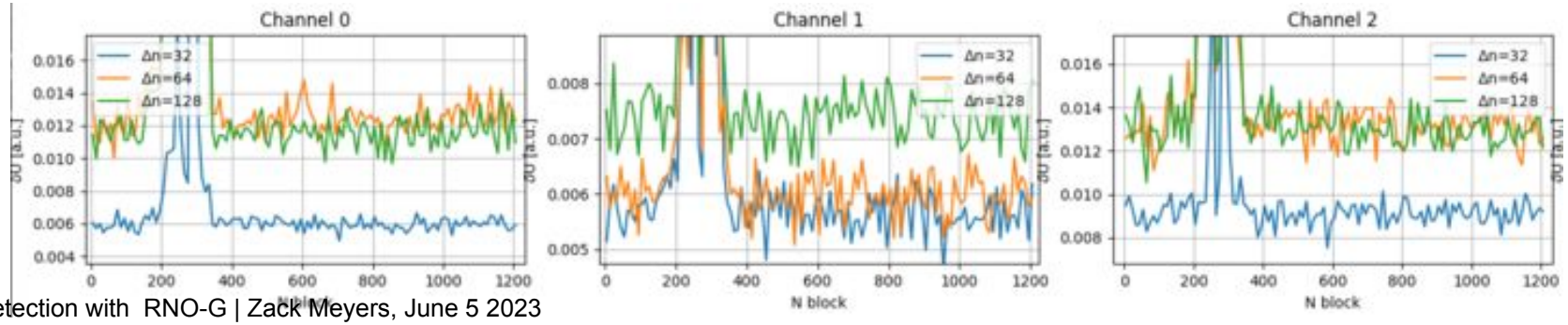


Another Anomalous Event in 21 on April 19

MEGA Block offsets. Caused by loss of power?







Turning on Station 21

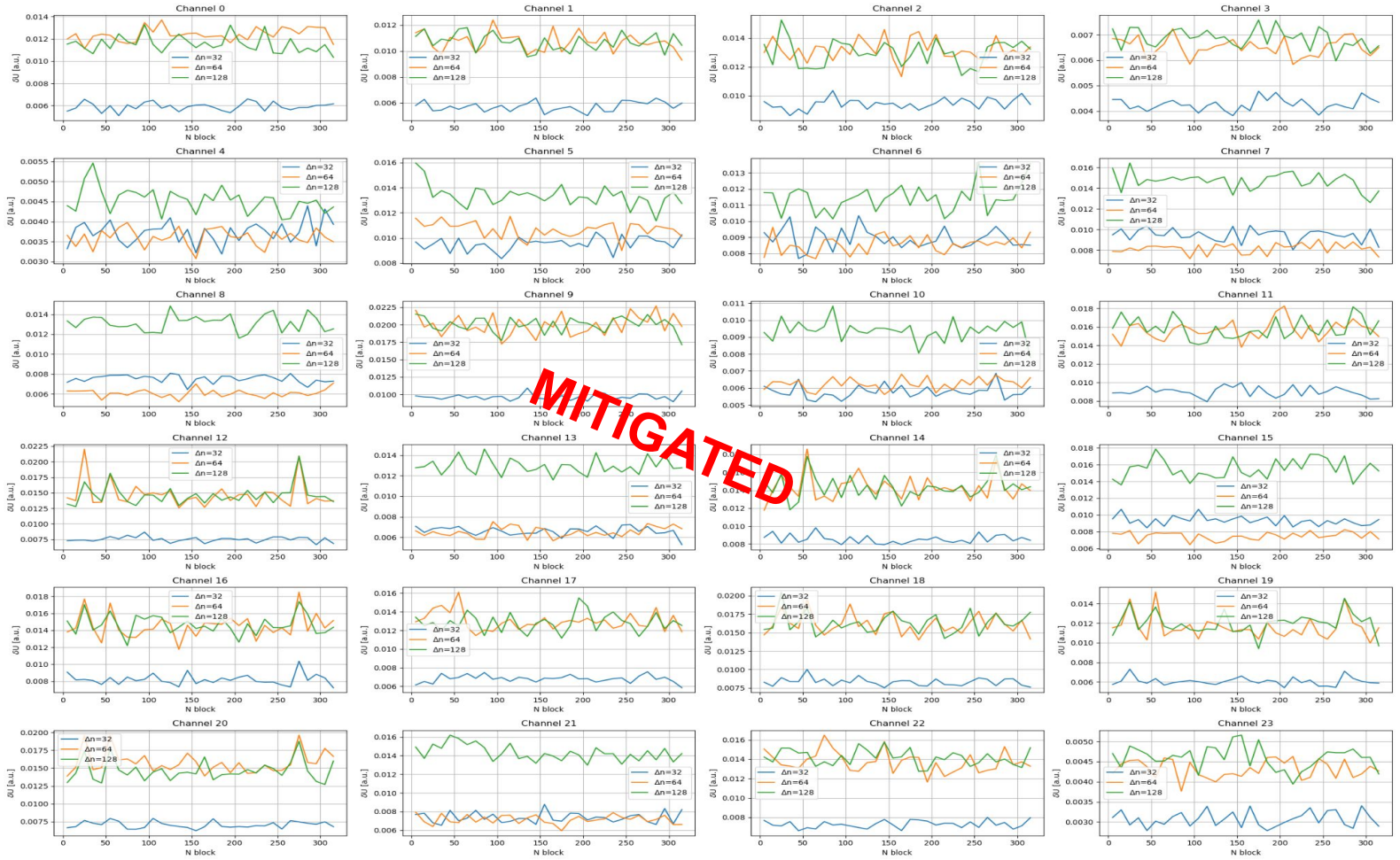
First 2023 run (2234)

Turning on Station 21

Later 2023 run (2500)

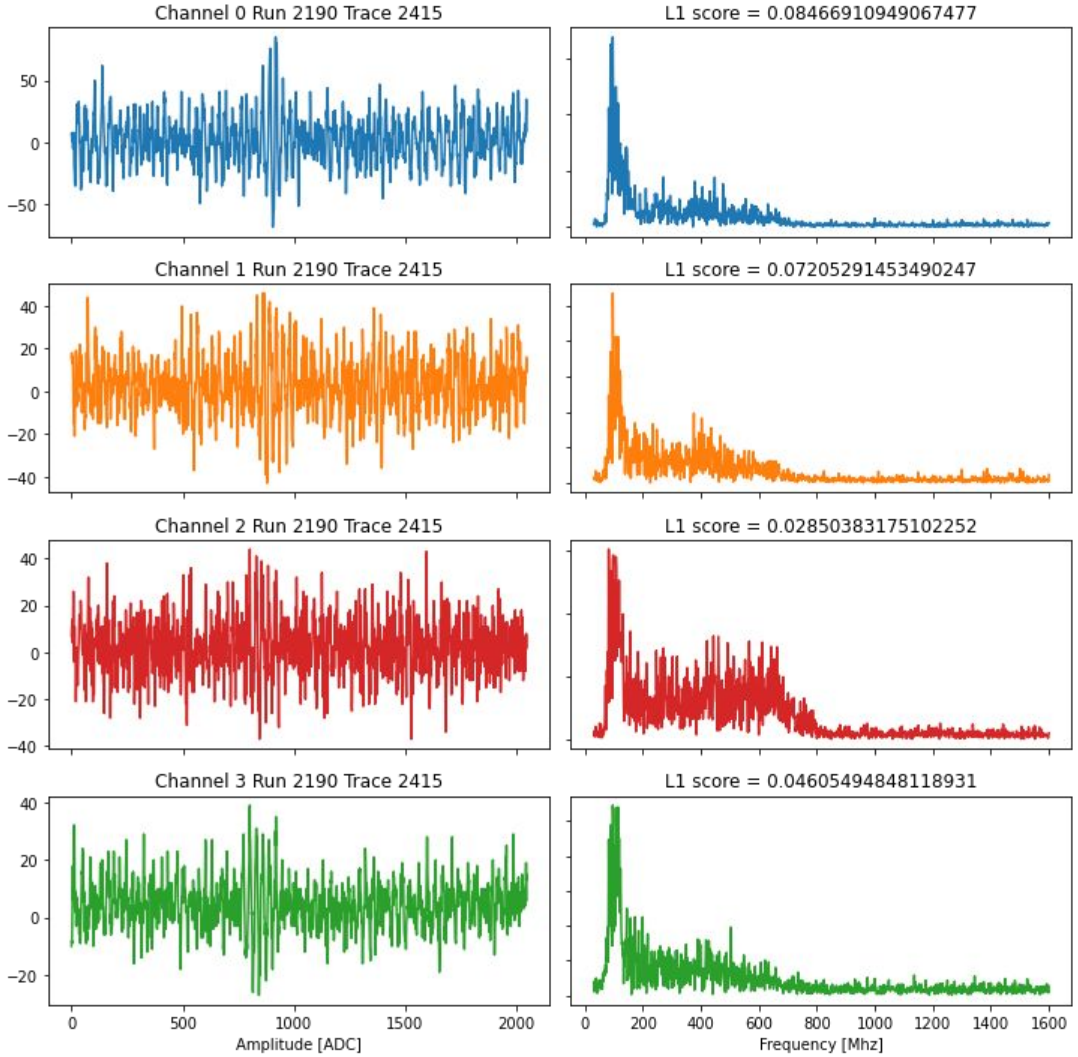
Turning on Station 21

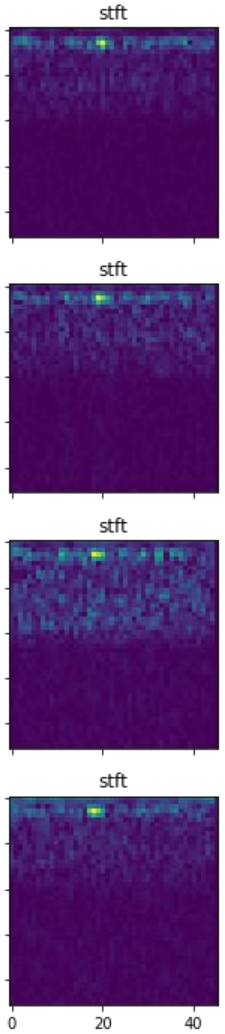
Later 2023 run (2500)

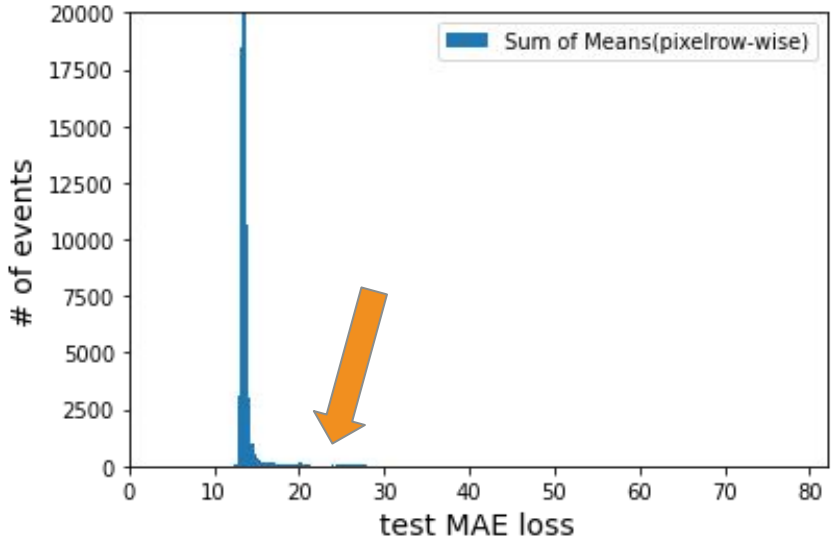


Anomaly Detection

Anomalous Low Threshold Event

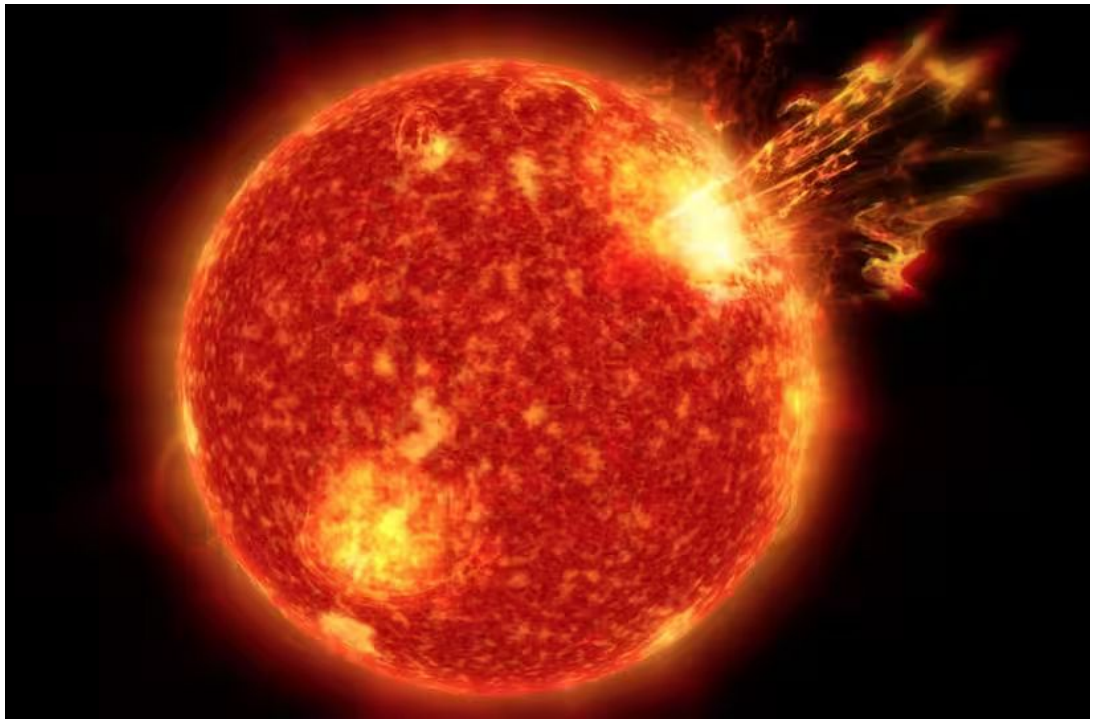


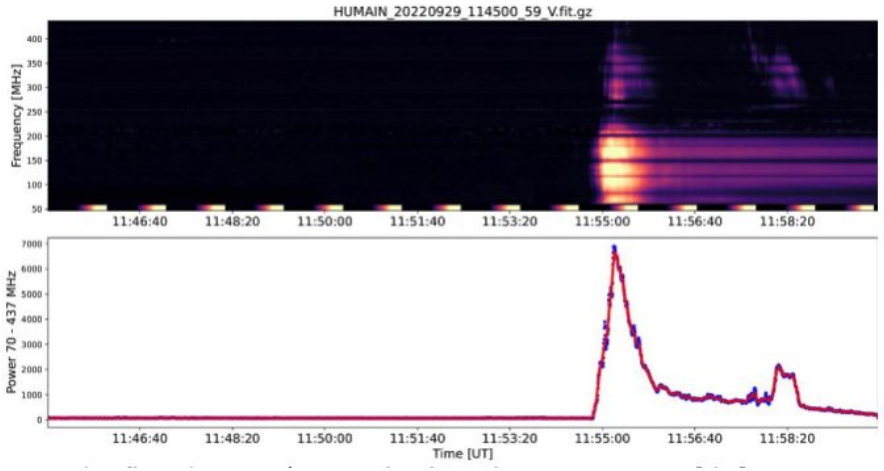


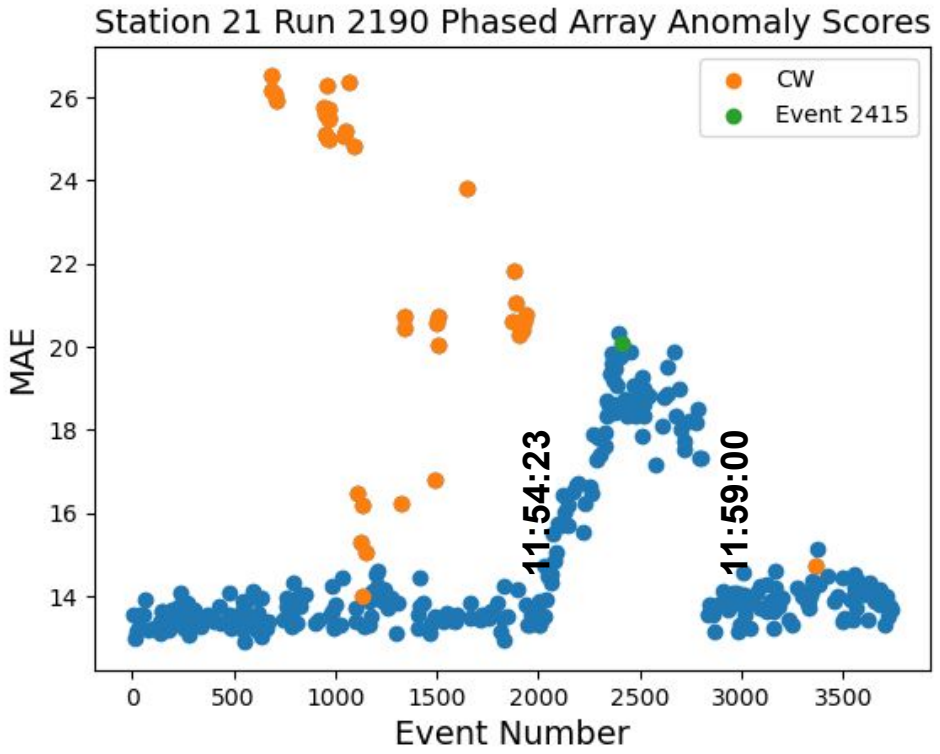


“Anomalous Low Threshold event”

Type II Solar Flare

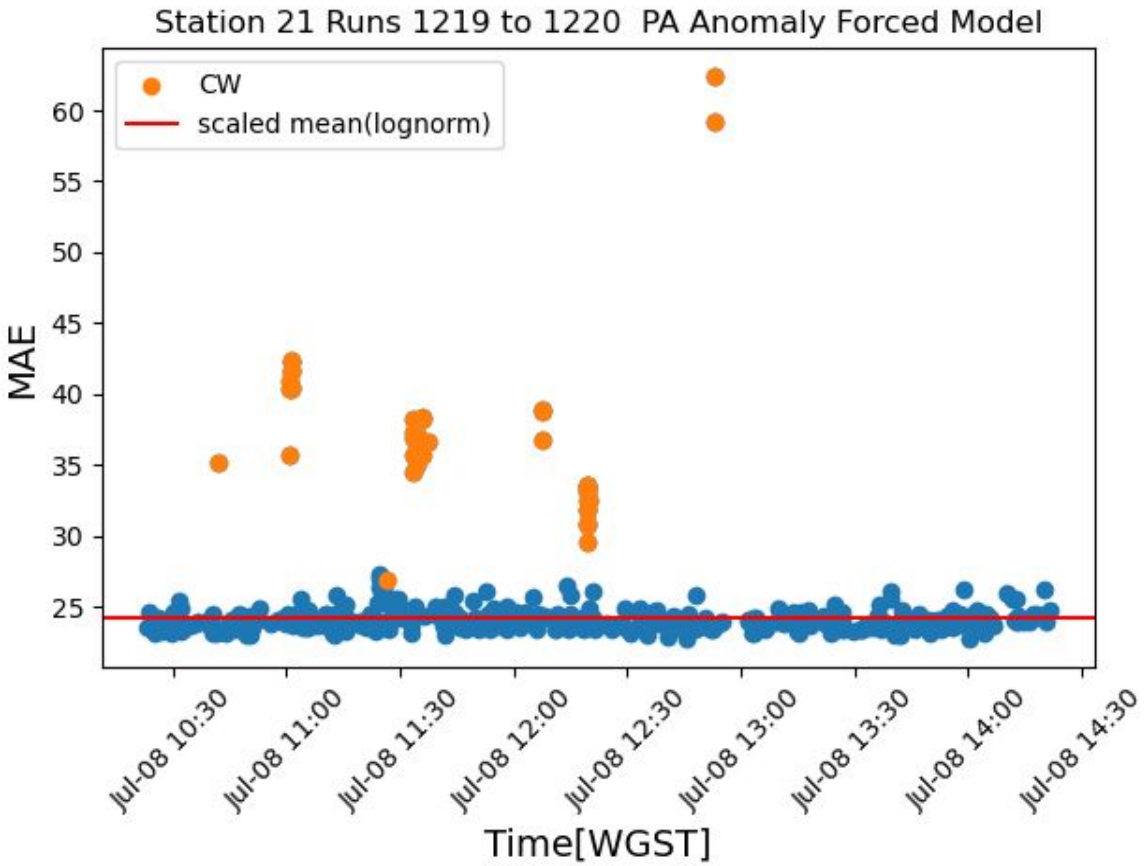


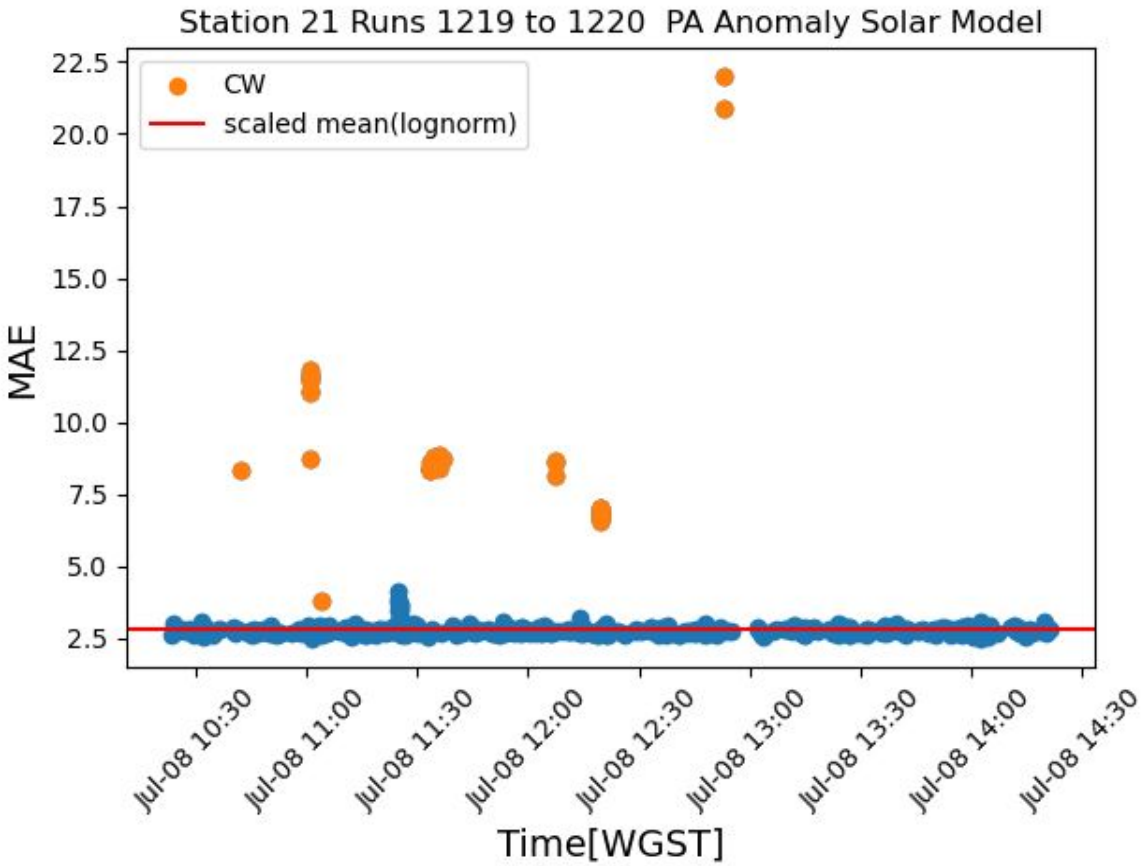




“Solar Model”

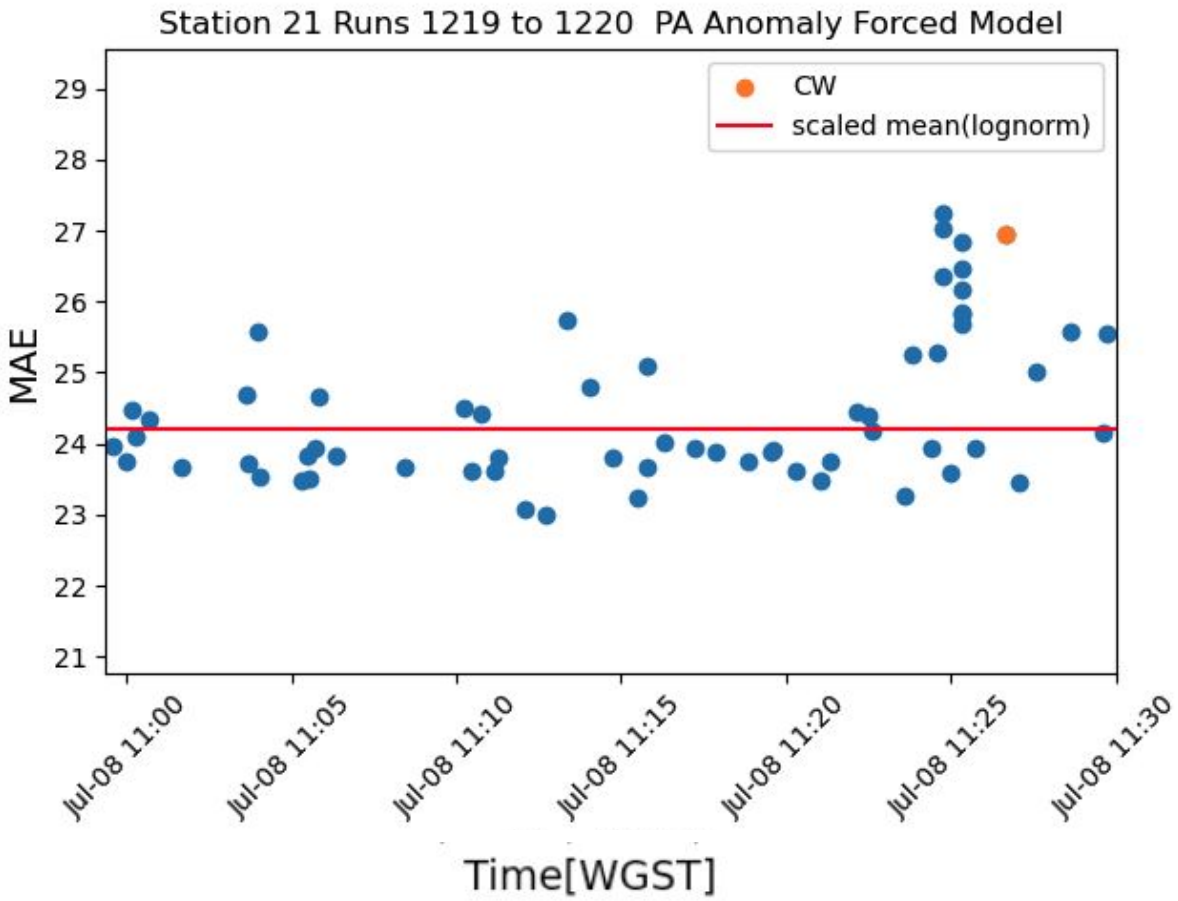
Butterworth filter 25 - 250 MHz

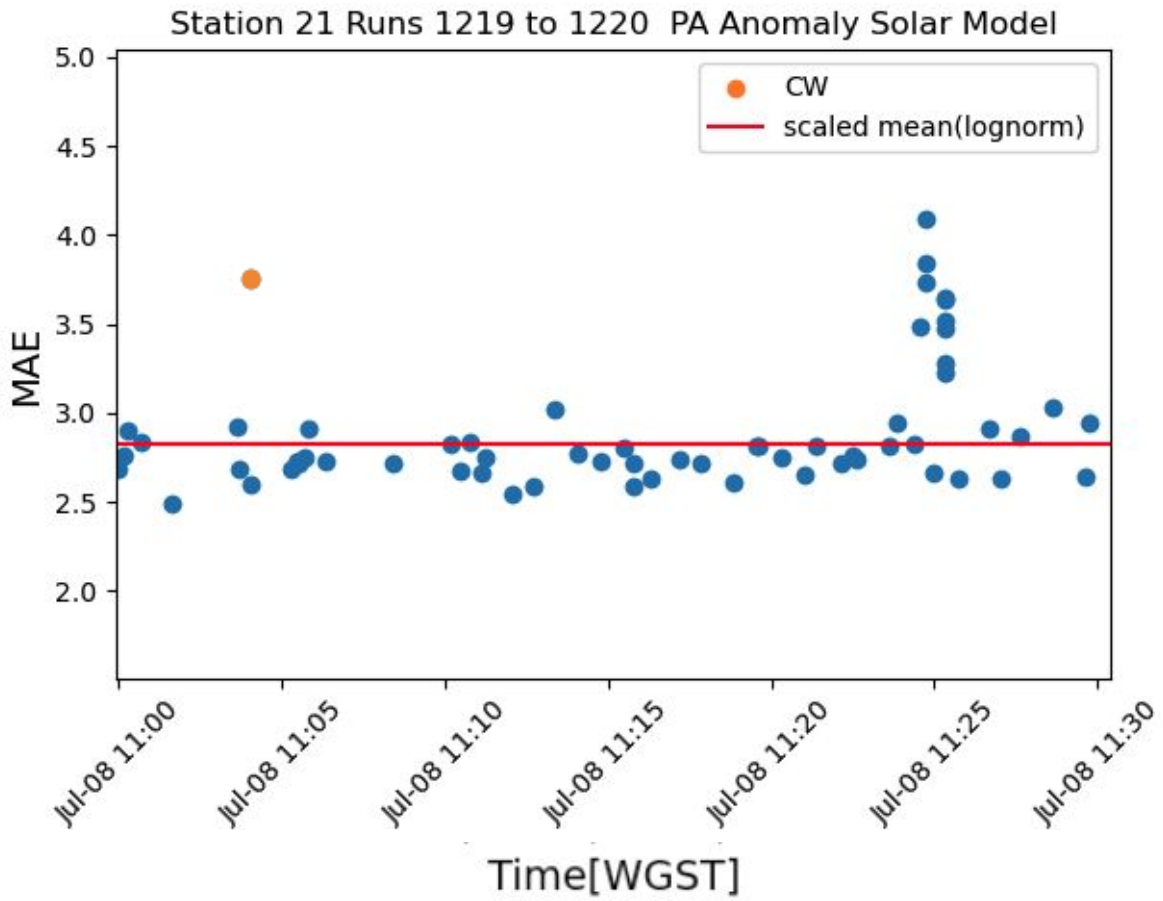




“Solar Model”

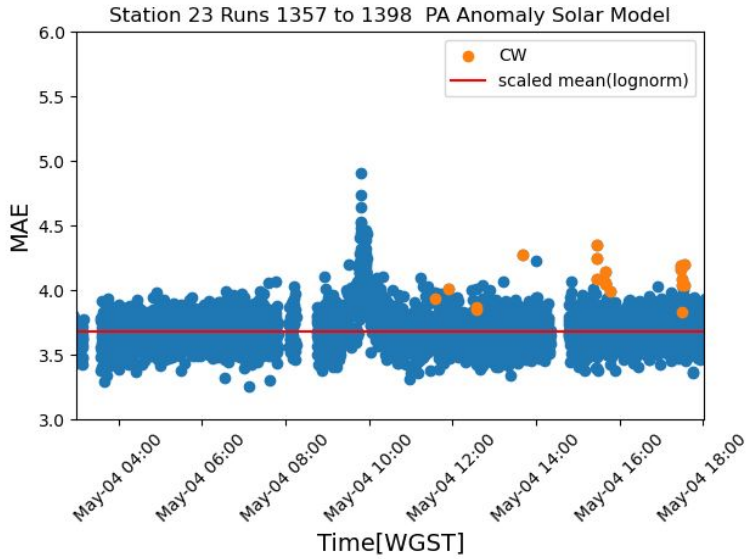
Butterworth filter 25 - 250 MHz

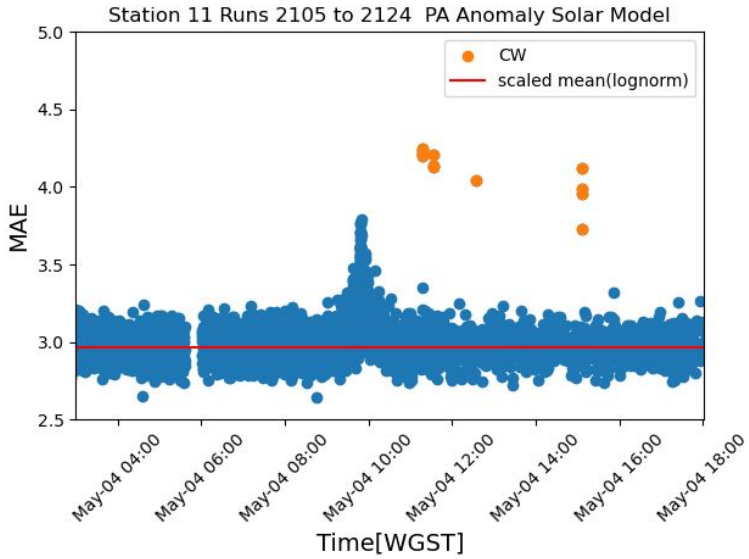


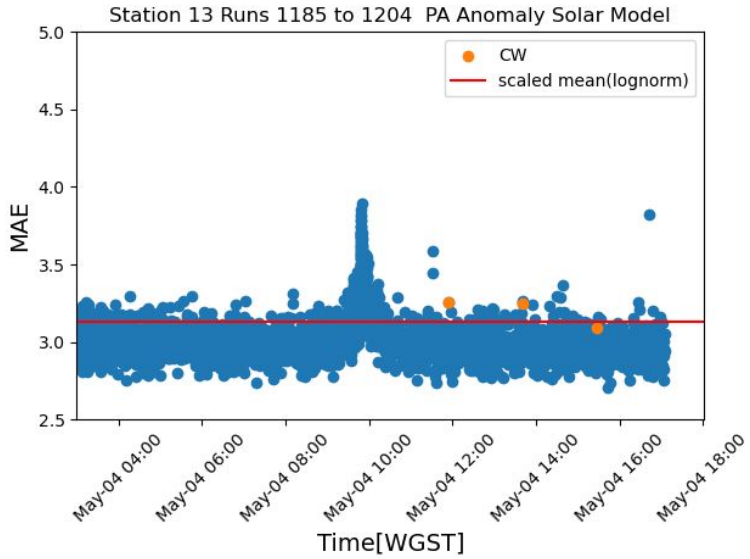


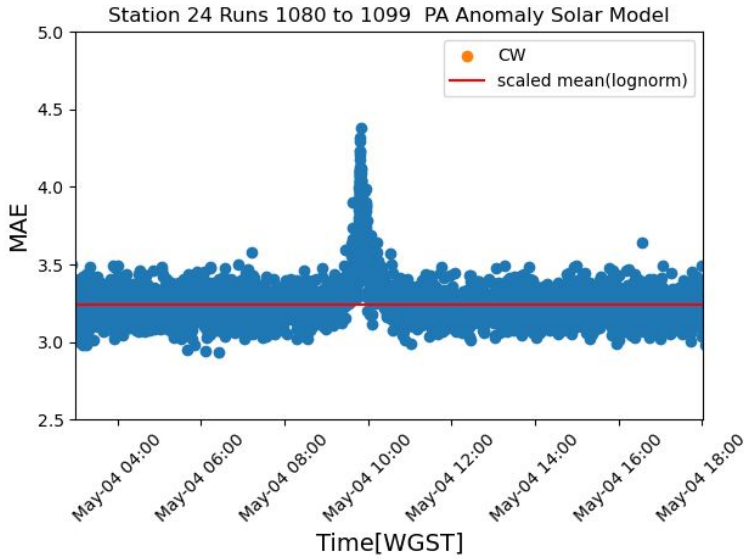
More Solar Bursts

Another strong event



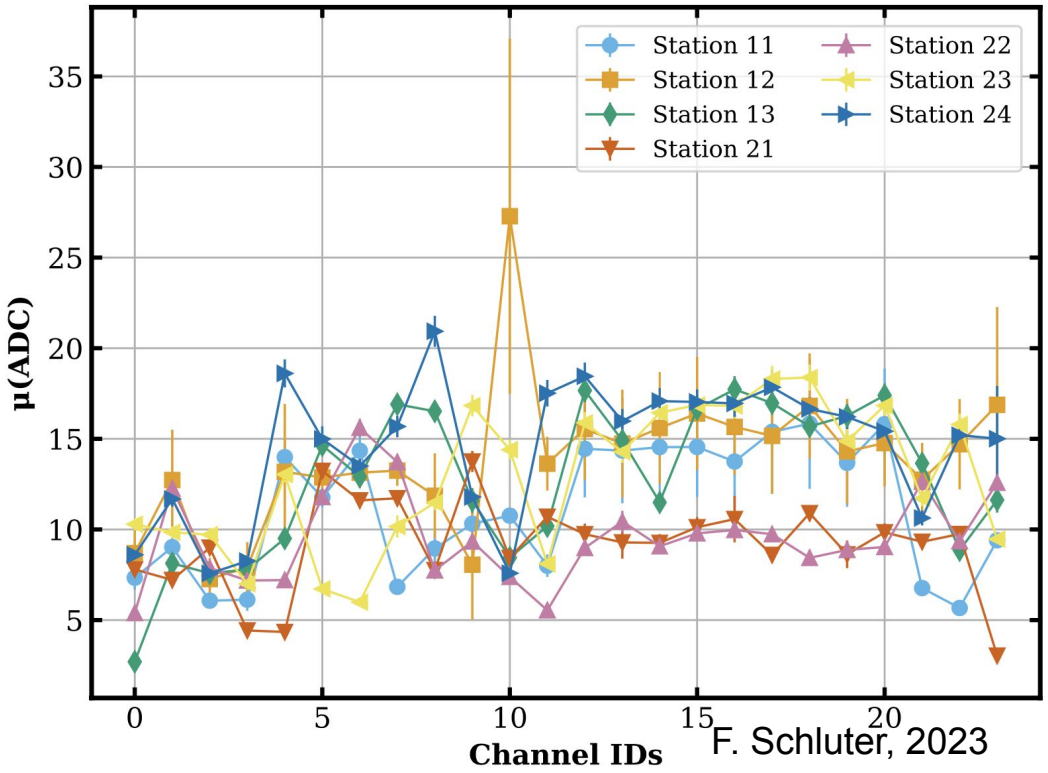


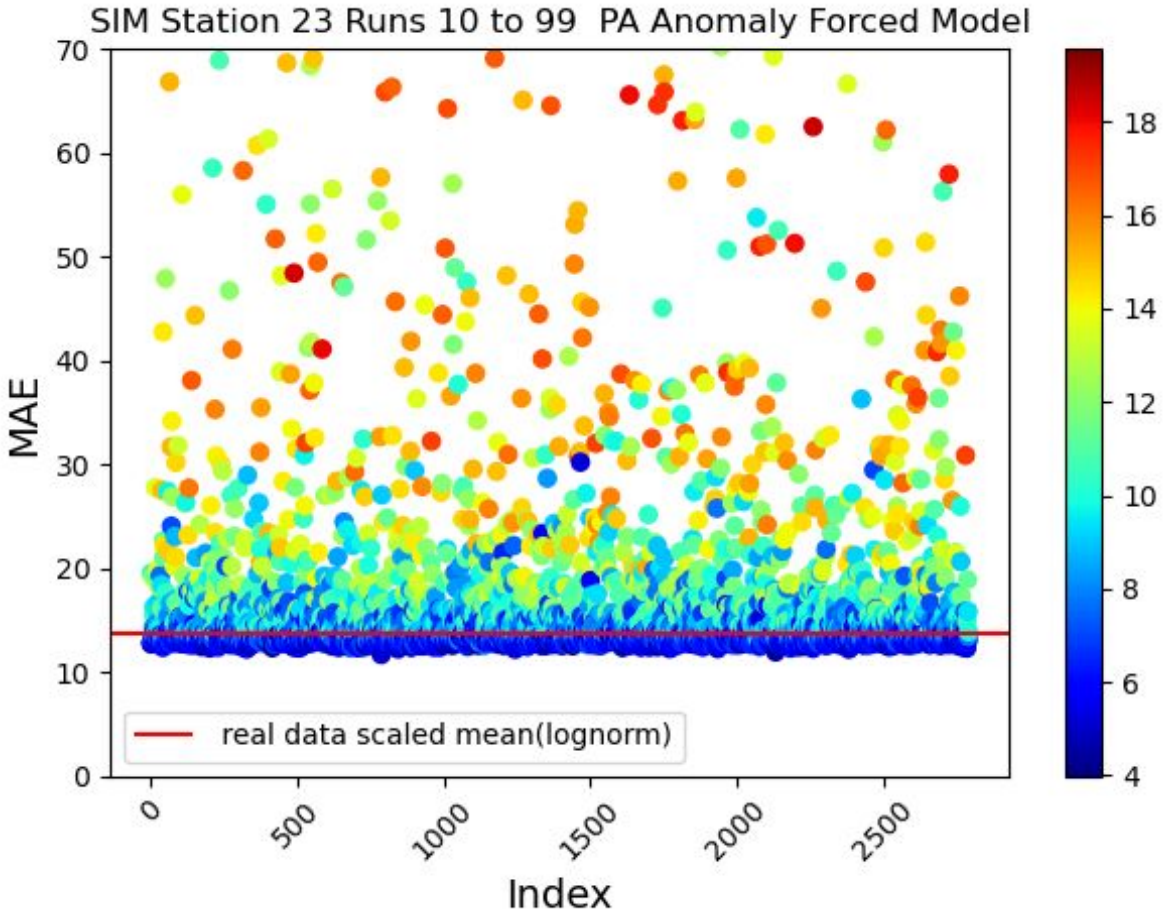




Sim Station 23

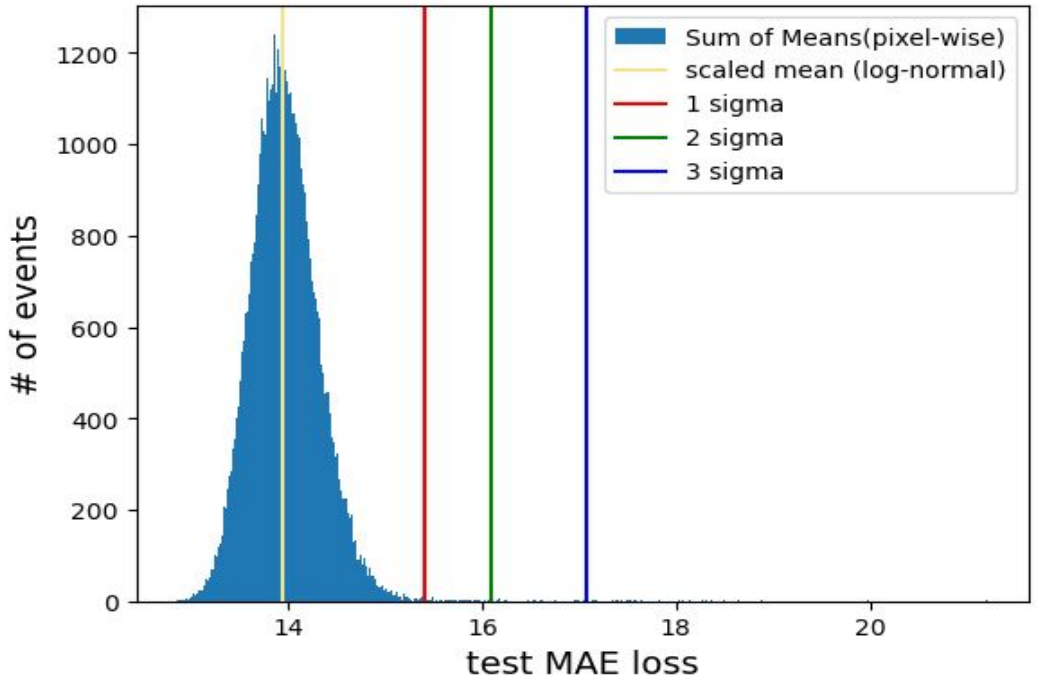
Are Neutrinos Anomalous





Prioritization

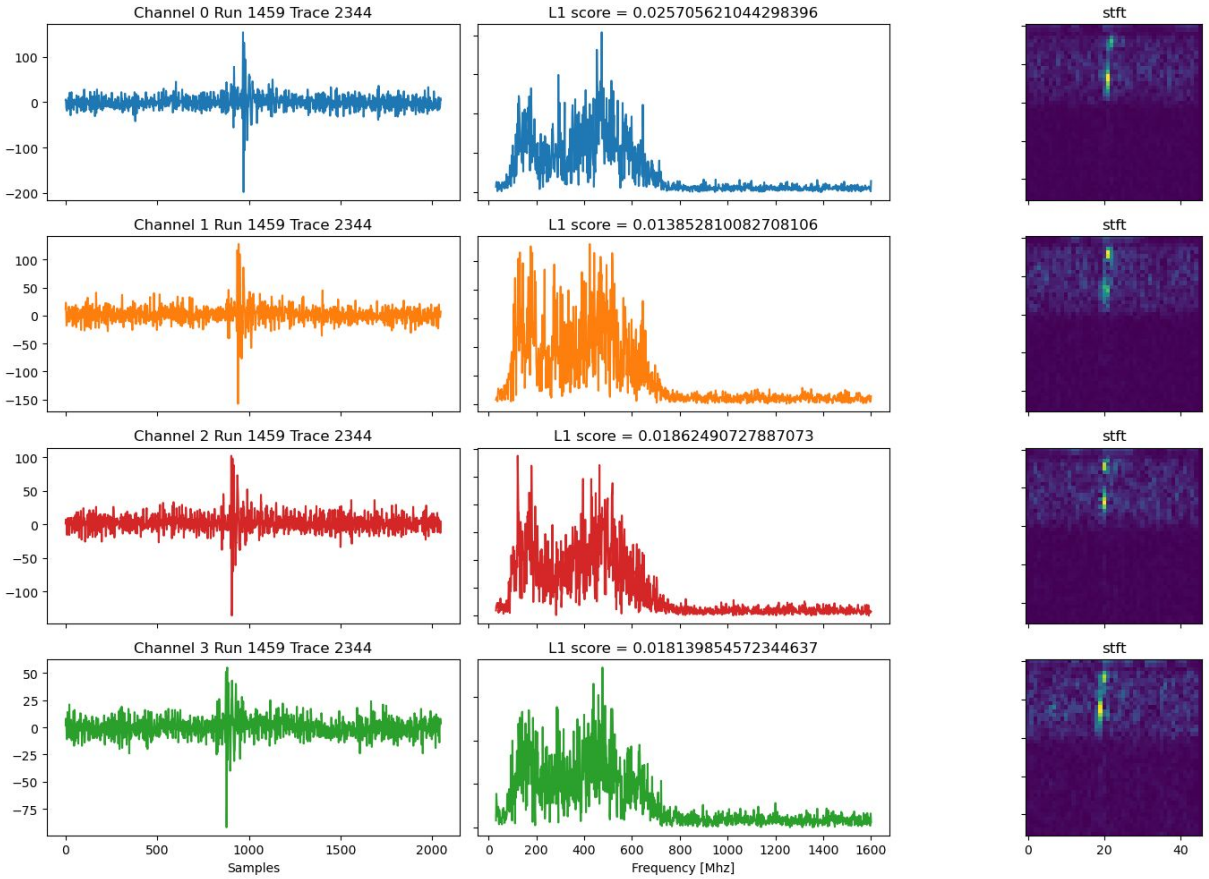
Neutrinos left over in the sample

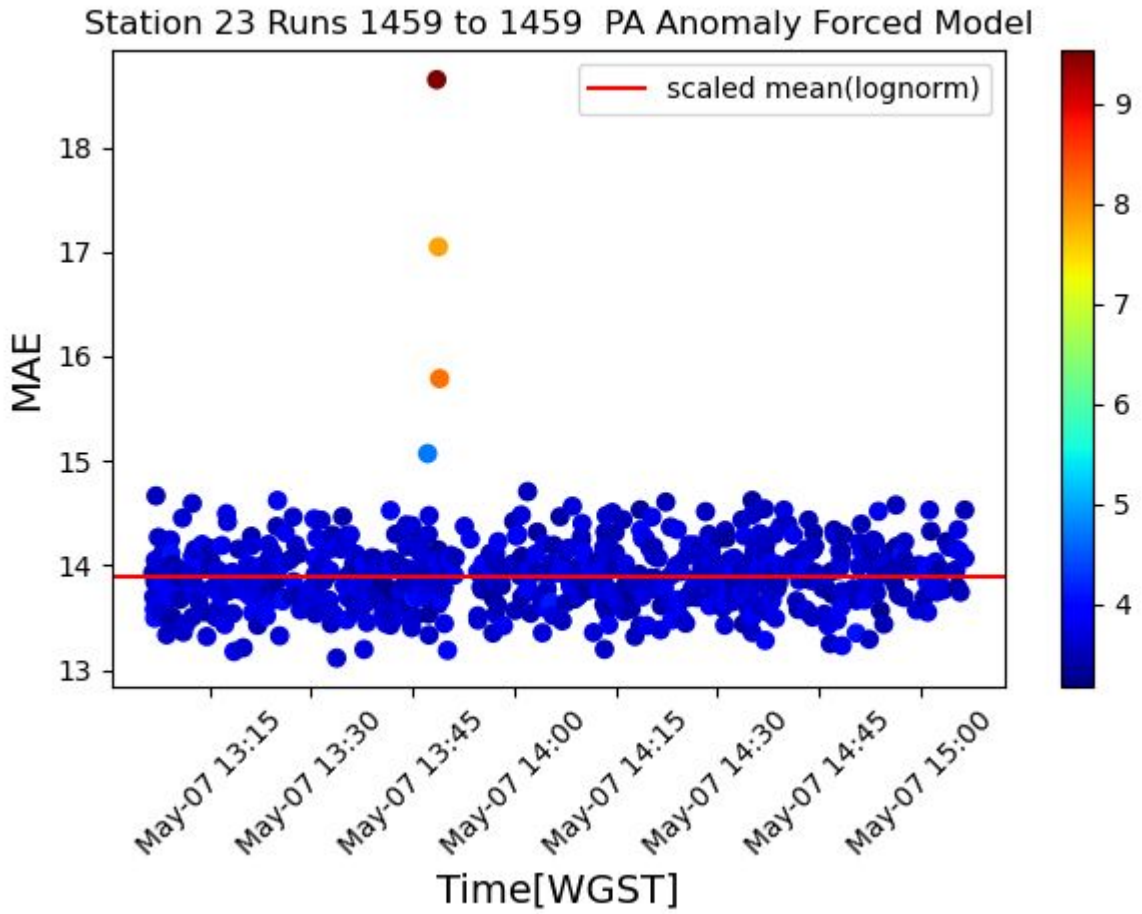


	# of events	# of simulated Neutrinos	Neutrino Ratio
Full Sample	58546	2794	0.048
MAE cut mean	25701	1565	0.061
MAE cut aggressive	392	1201	3.064

Neutrino-ish Signal

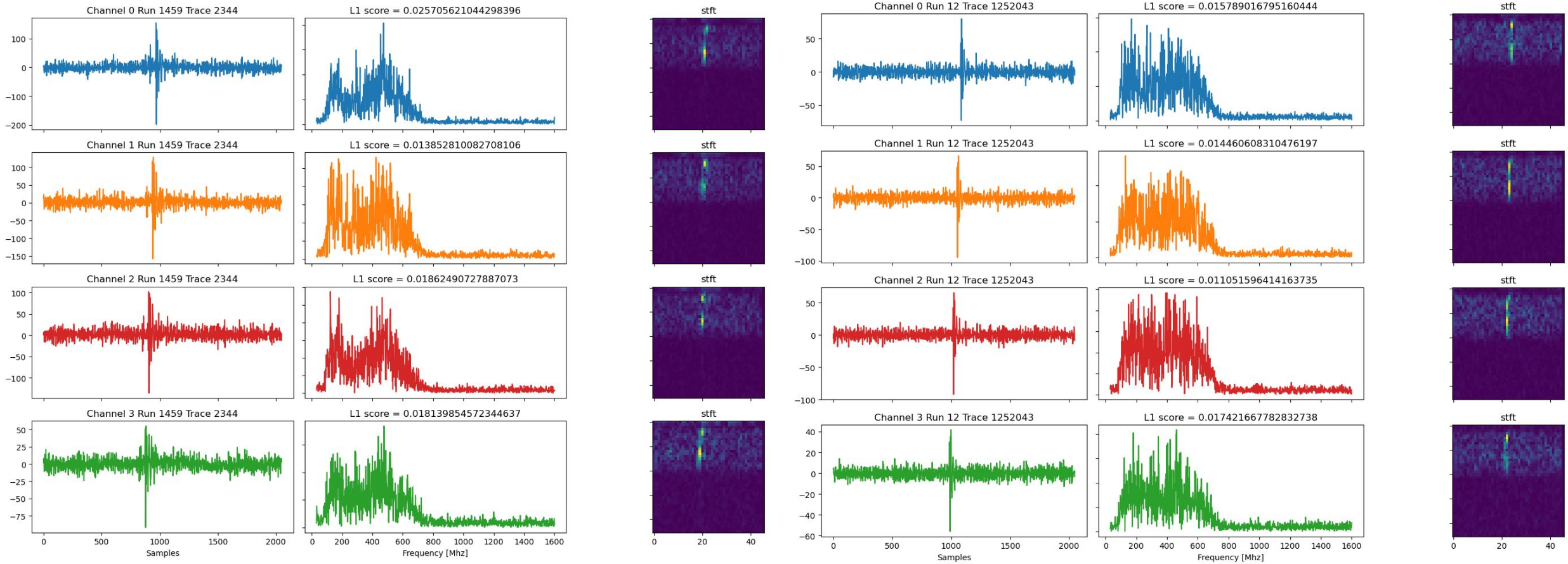
THIS IS NOT A NEUTRINO





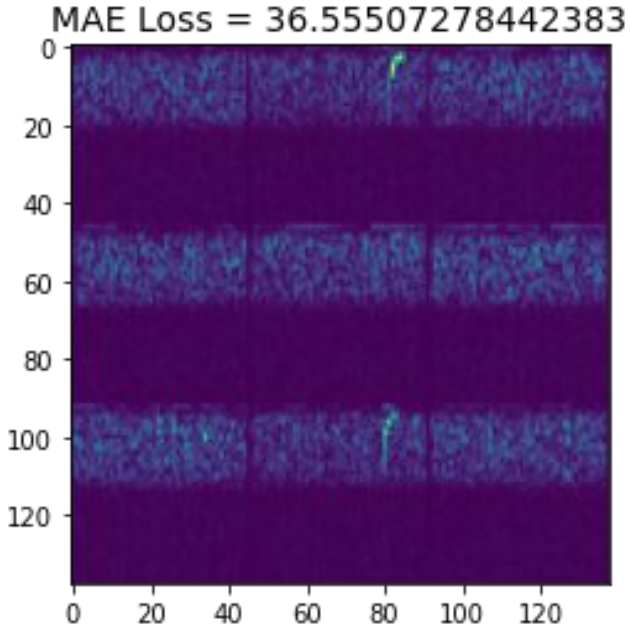
Neutrino-ish Signal

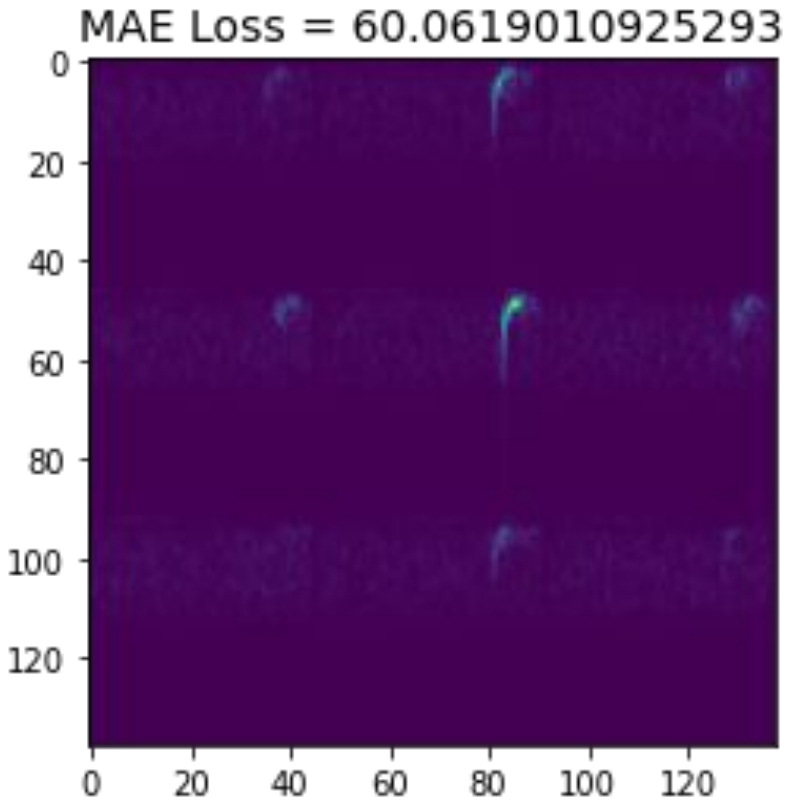
….but it does kind of look like one

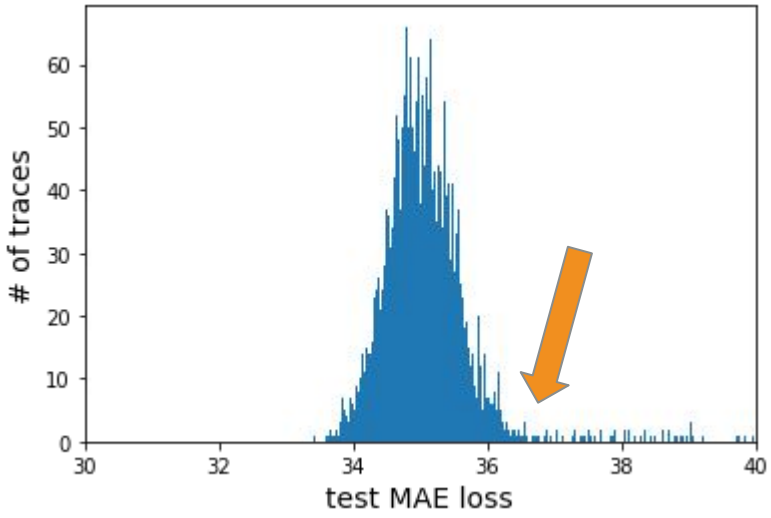


Cosmic Ray Candidates

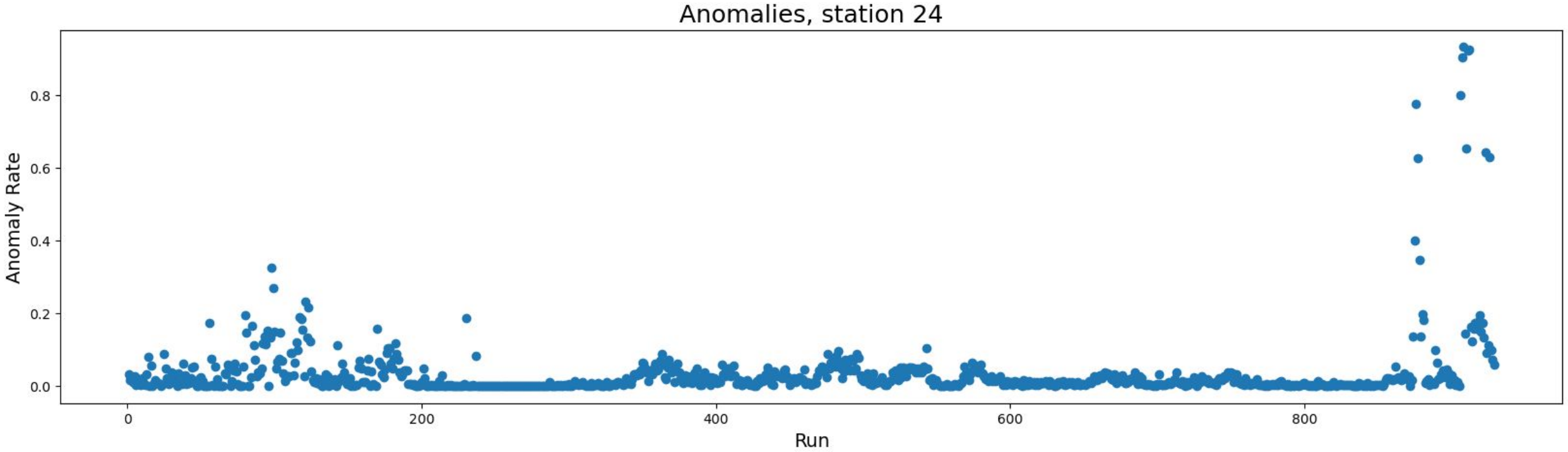
Surface Candidates (748 run 793(*Aldrin* .69)) (1718 run 1091(*Armstrong* .87))







Summary

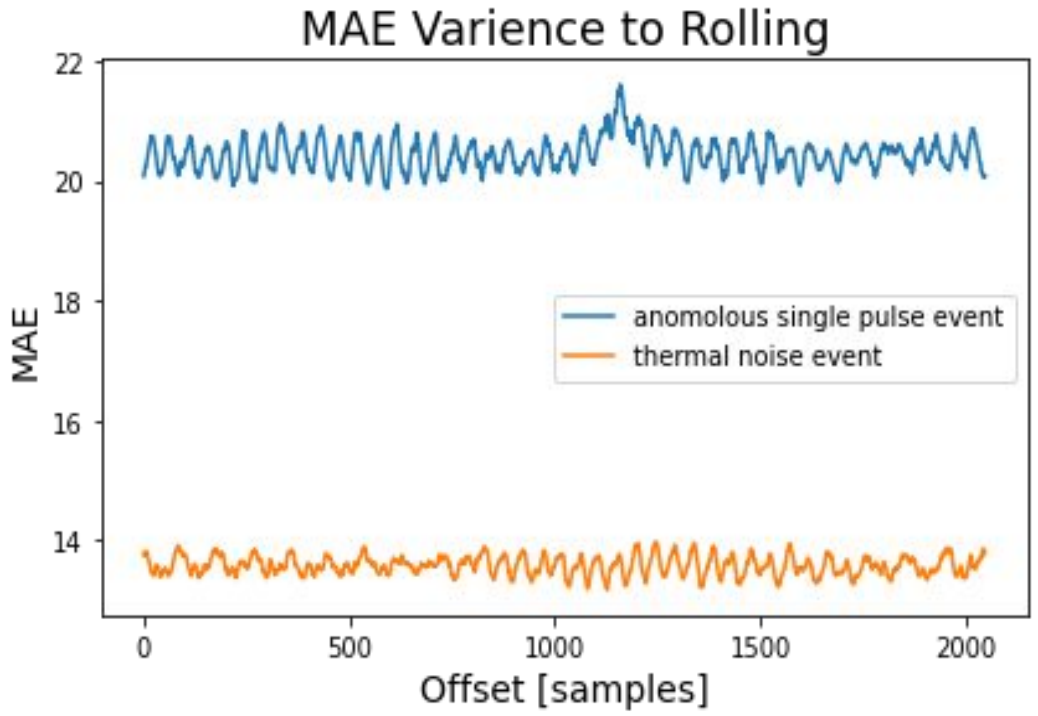


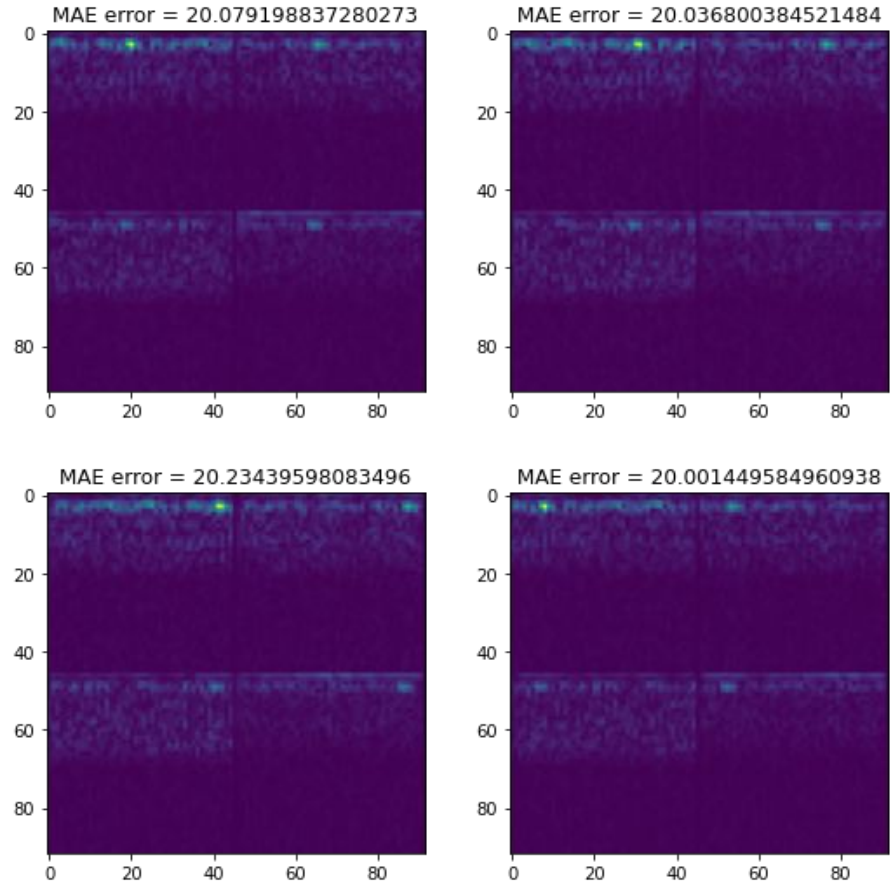
- **Neutrinos (simulated) and Cosmic Ray Candidates are highly anomalous**
- **New noise classes / glitches discovered and mitigated**
- **Active Sun can be used as calibration source, characteristic burst shapes**
- **Only one component of filtering and Multi-Messenger Response**
- **Models are simple – more complex 3D and Clustering for better efficiency**

Bonus Slides

Anomaly Detection Update

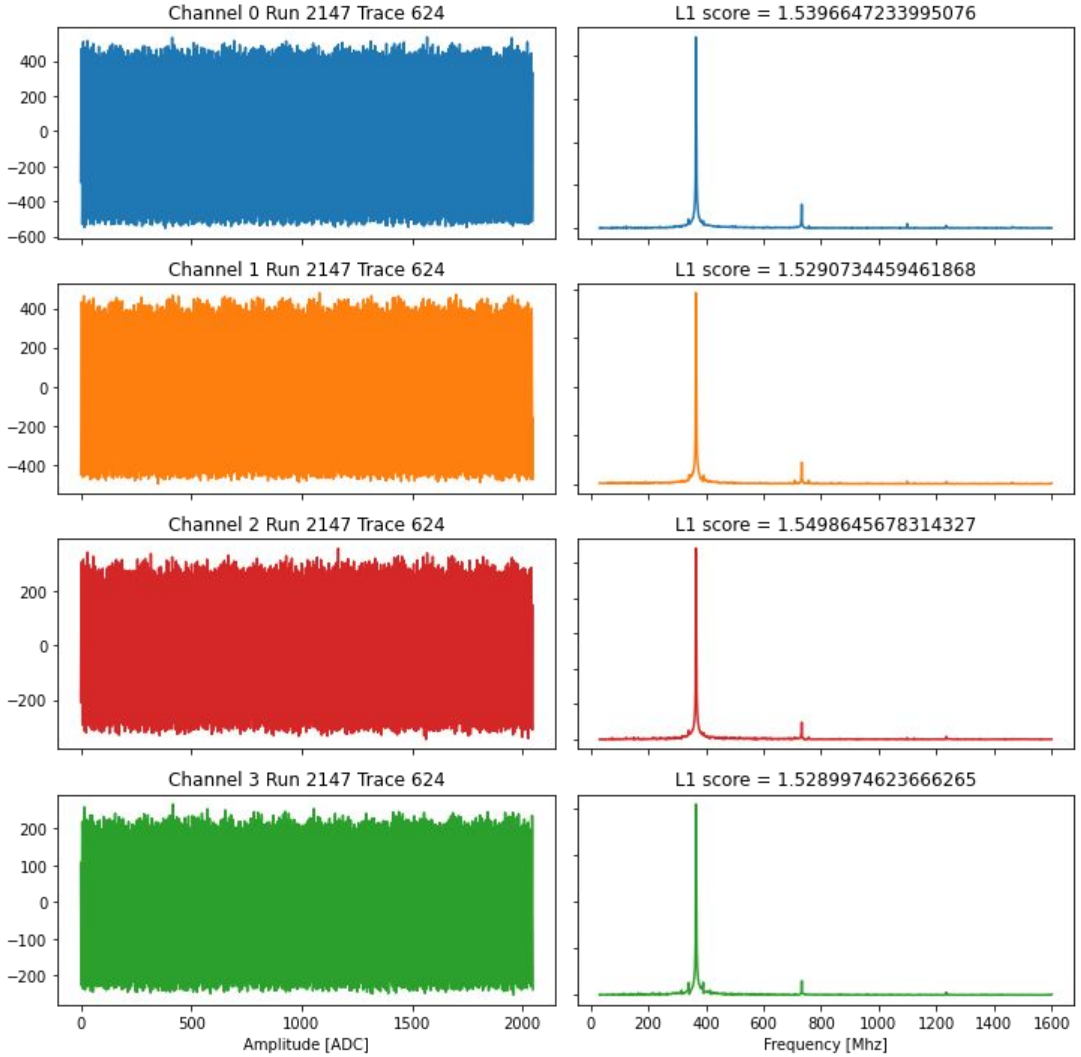
Anomalous Event Rolling Invariance

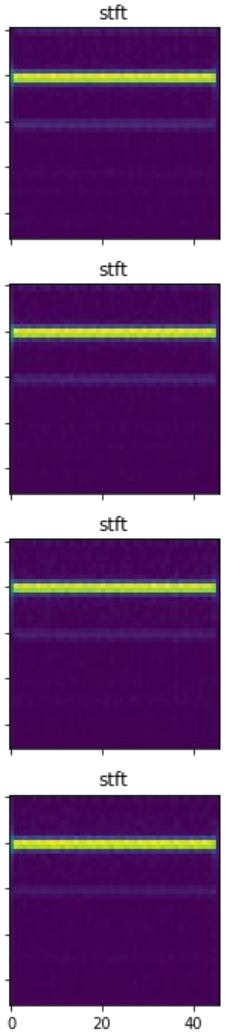


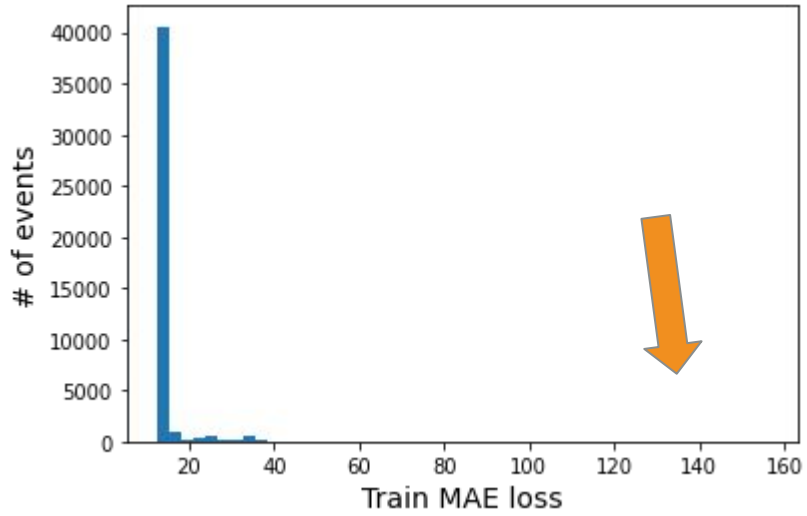


Anomaly Detection

Strong CW

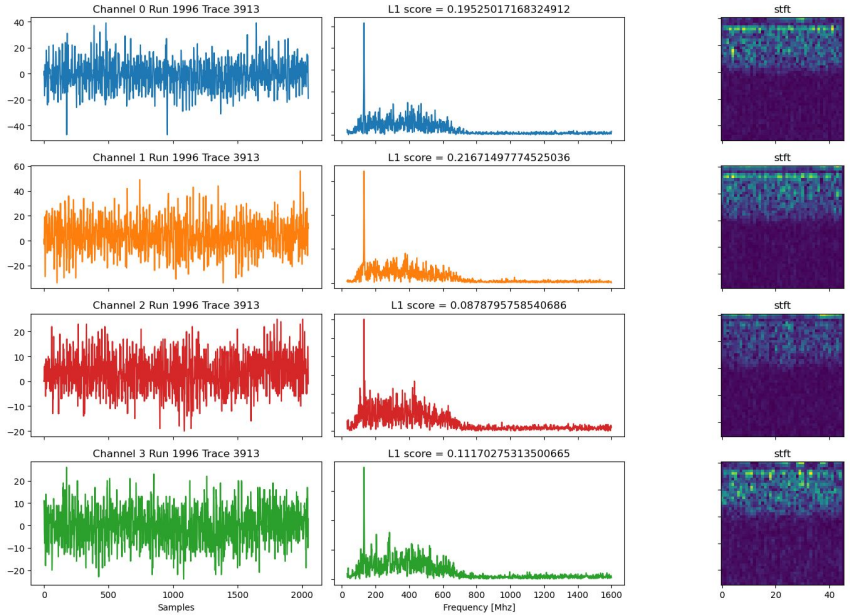


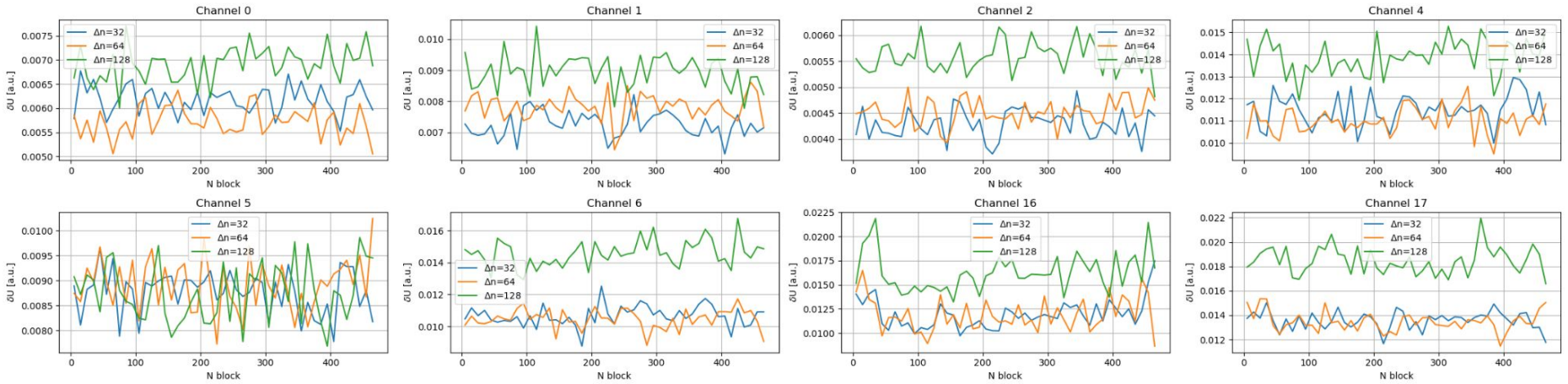




Solar Storm April 23

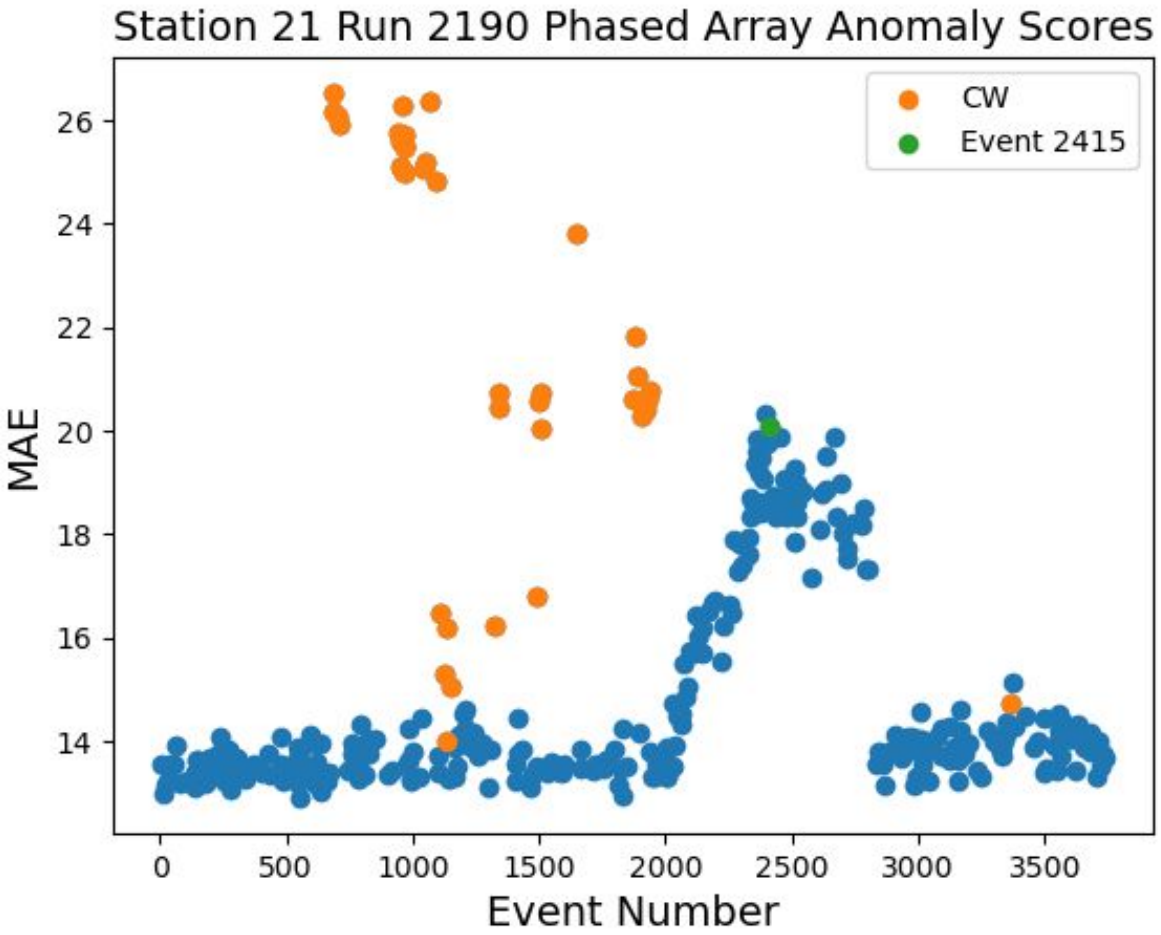
Station 11 after CW-like event

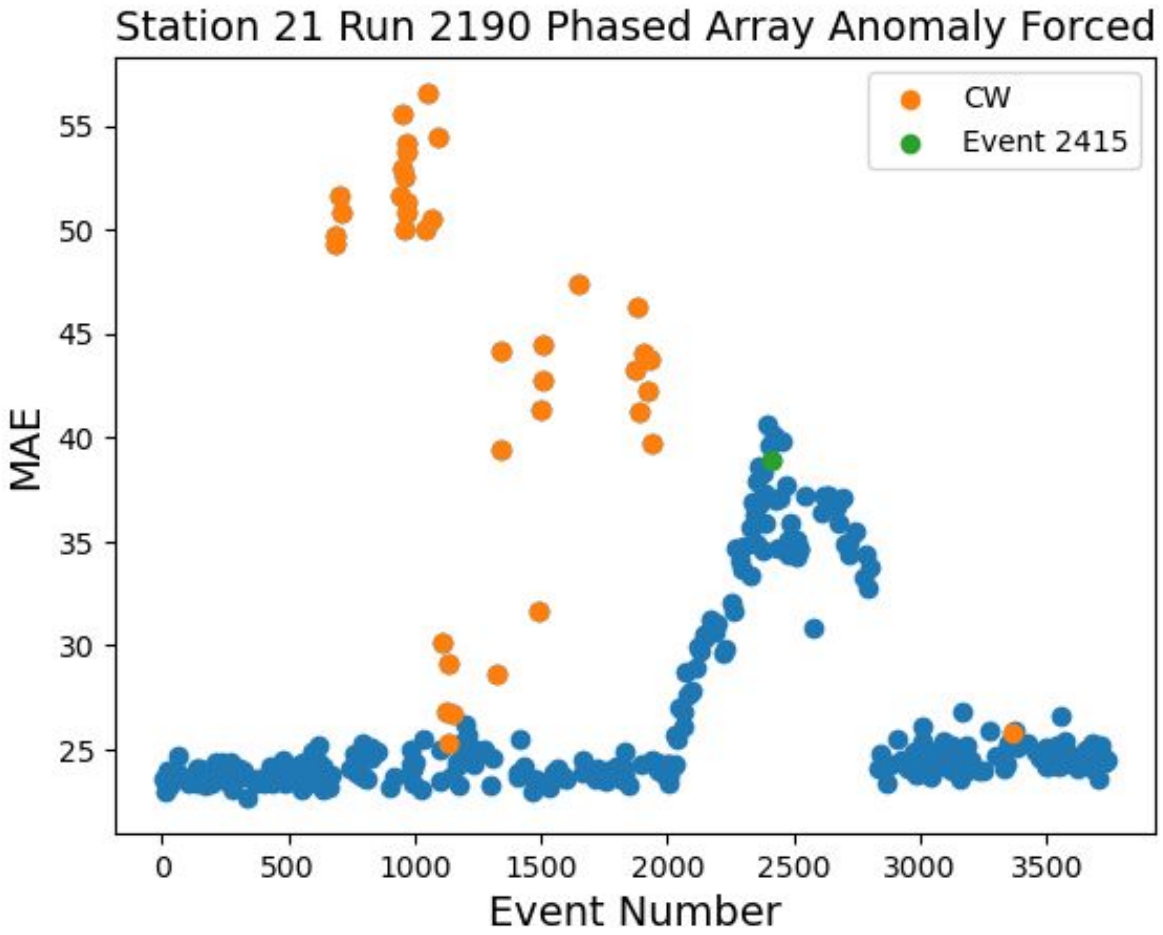




“Anomalous Low Threshold Event”

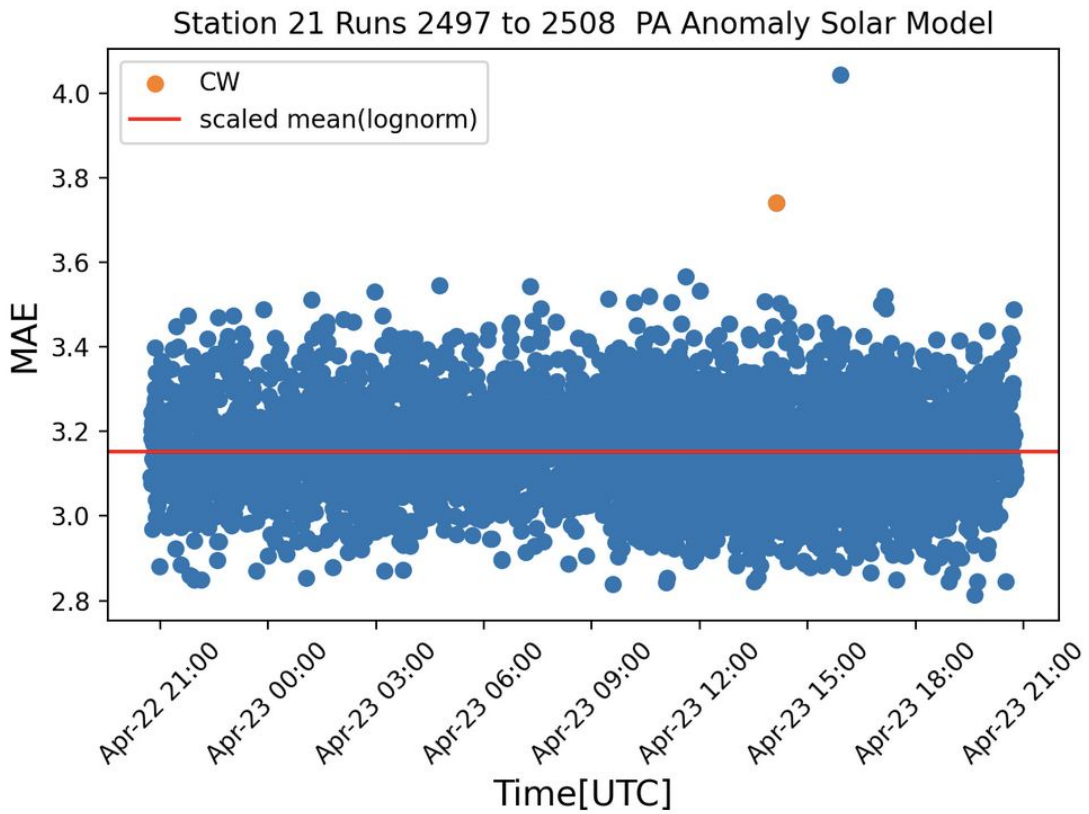
Forced triggers vs “Quiet Periods”

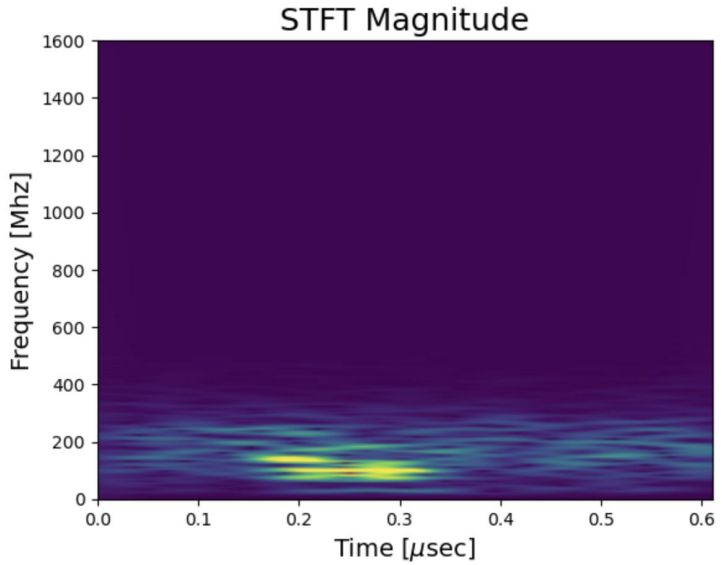


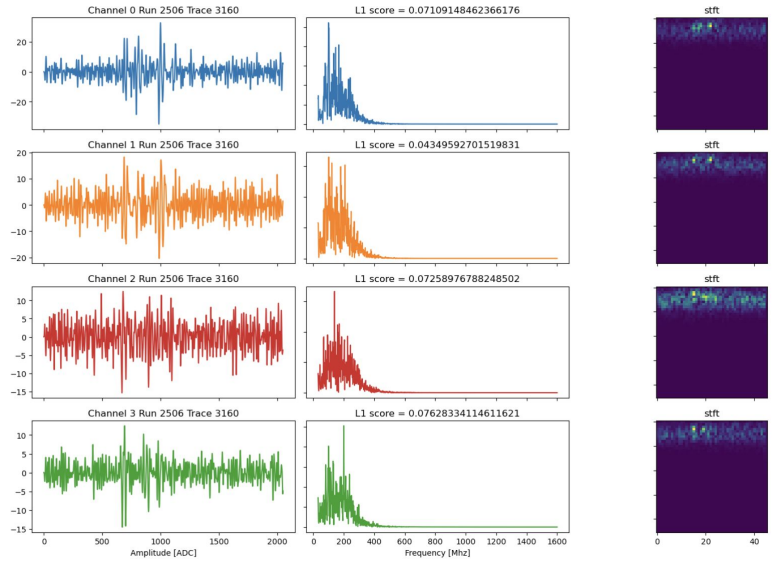


Solar Storm April 23

Station 21

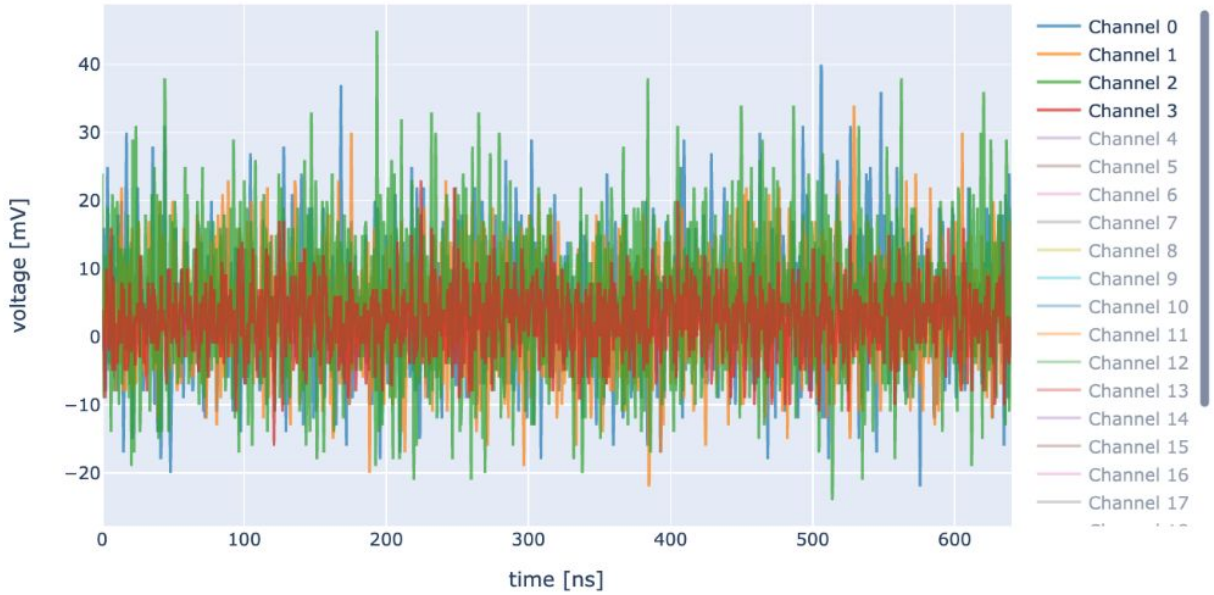


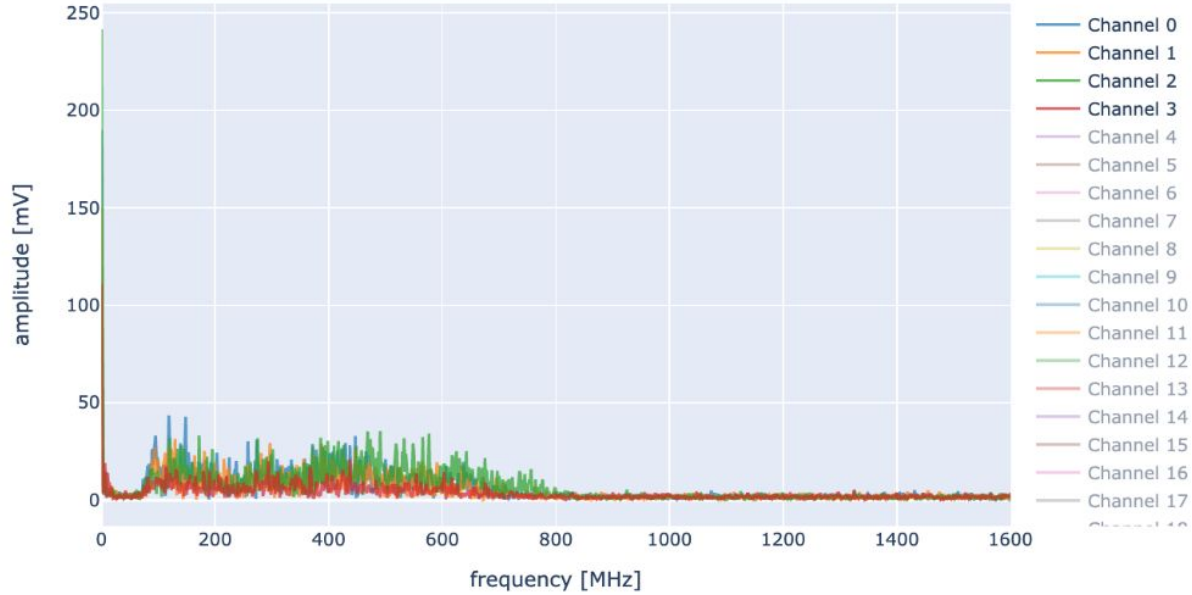


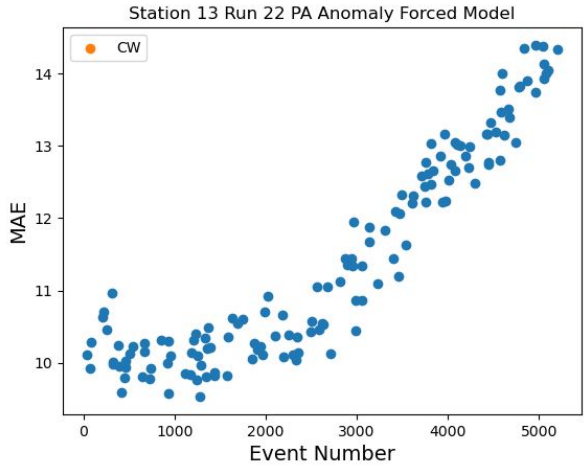


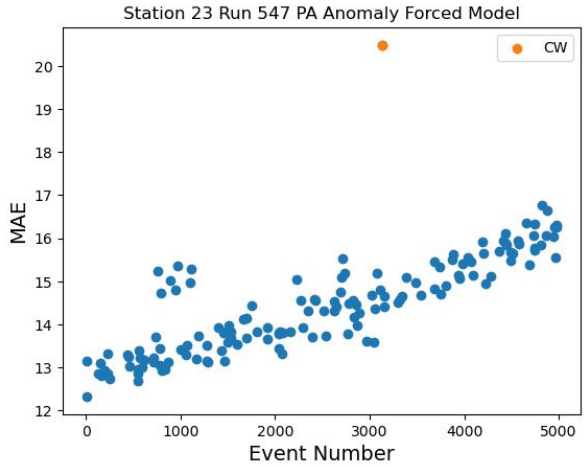
“Solar Model”

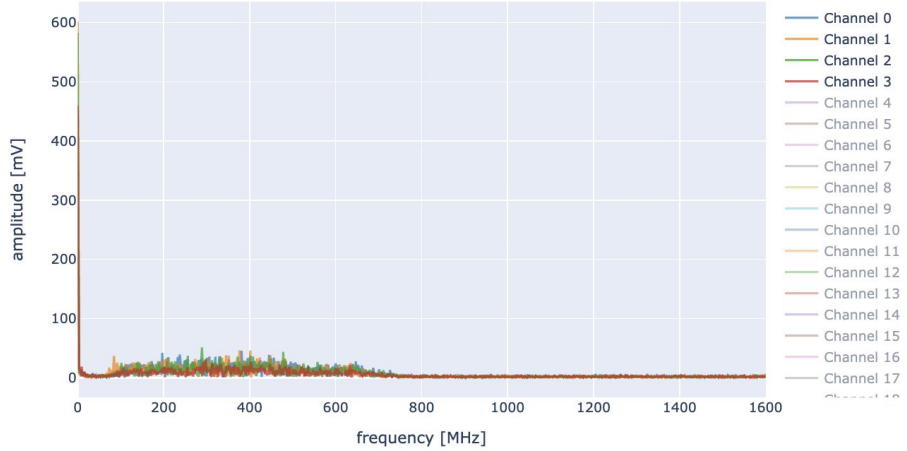
Butterworth filter 25 - 250 MHz





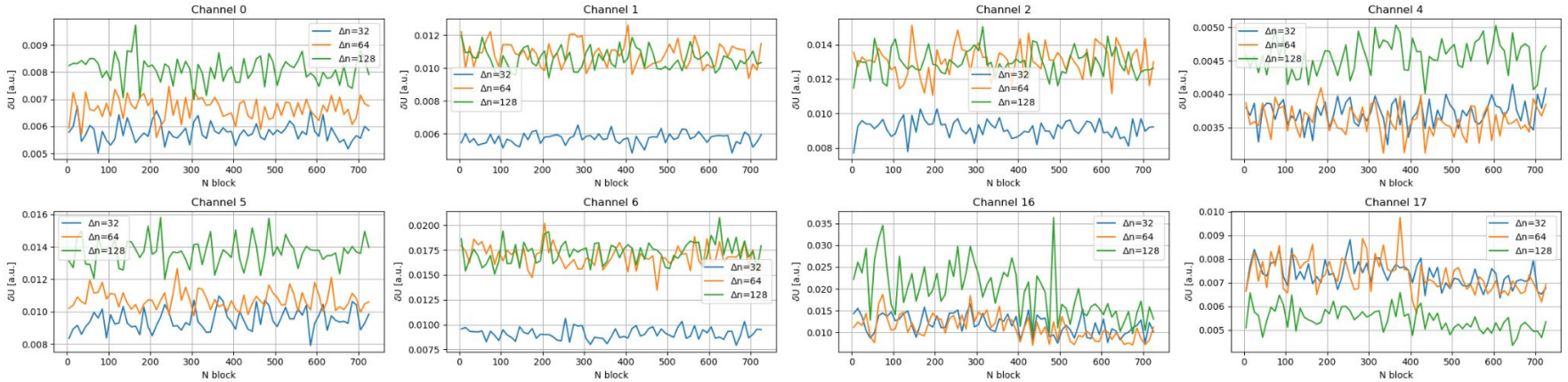


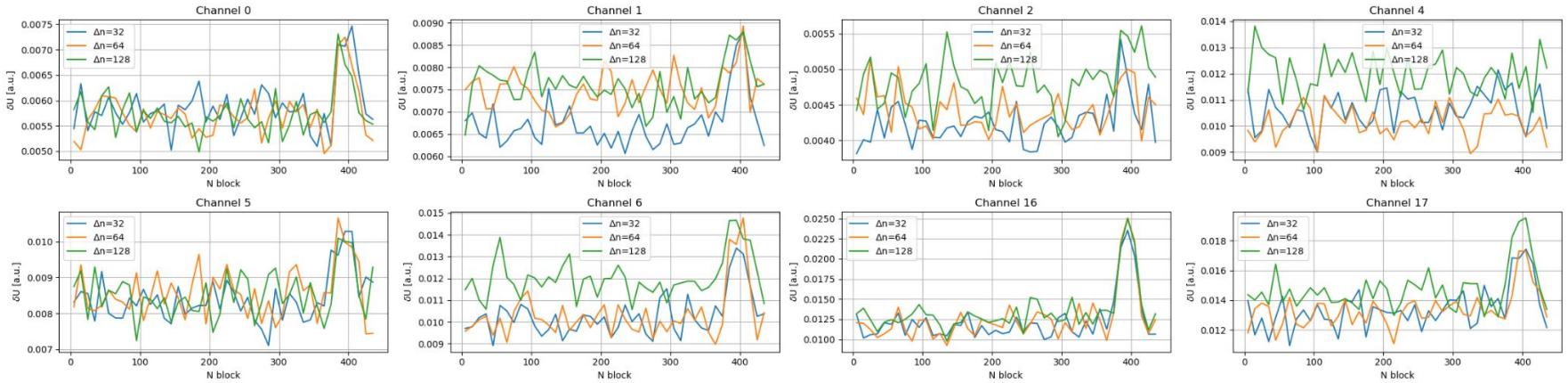




Solar Storm April 23

Station 21 (top) 11 (bottom)





Field of View

Diurnally Averaged

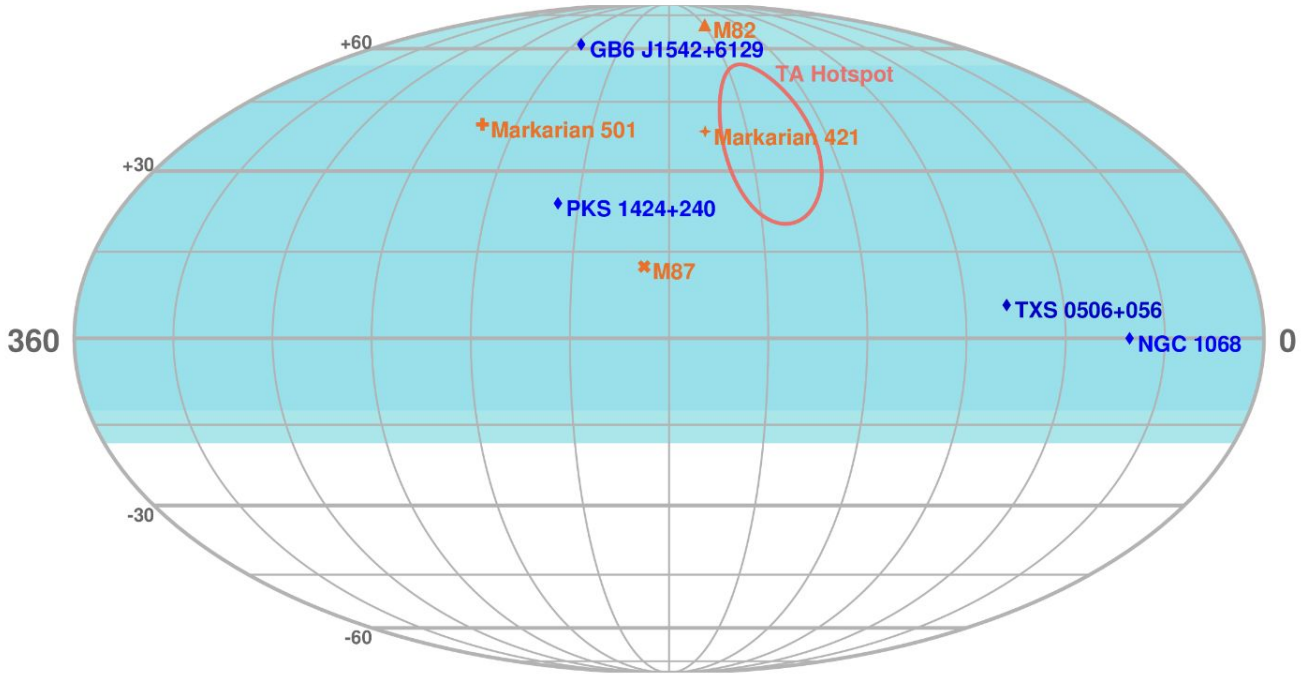
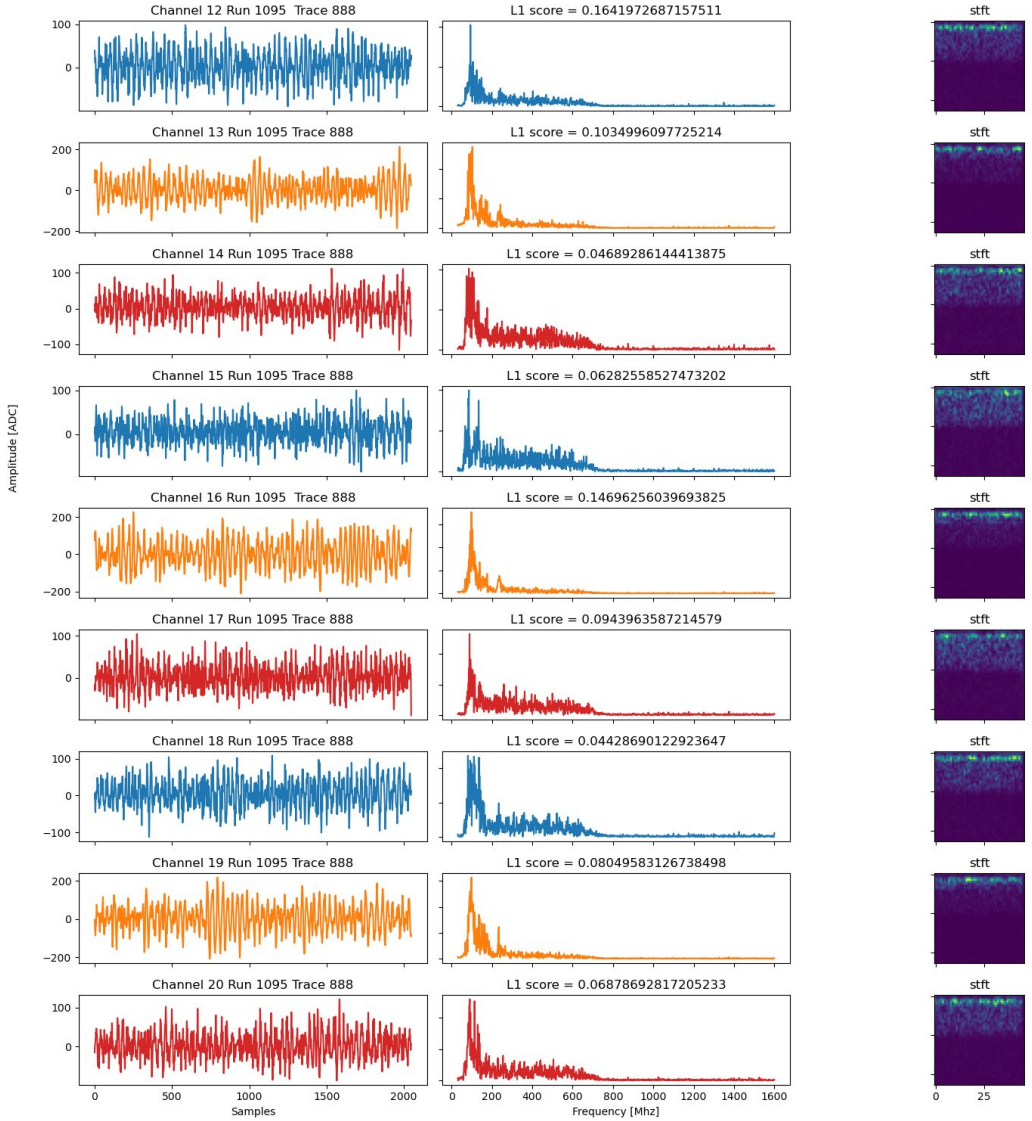
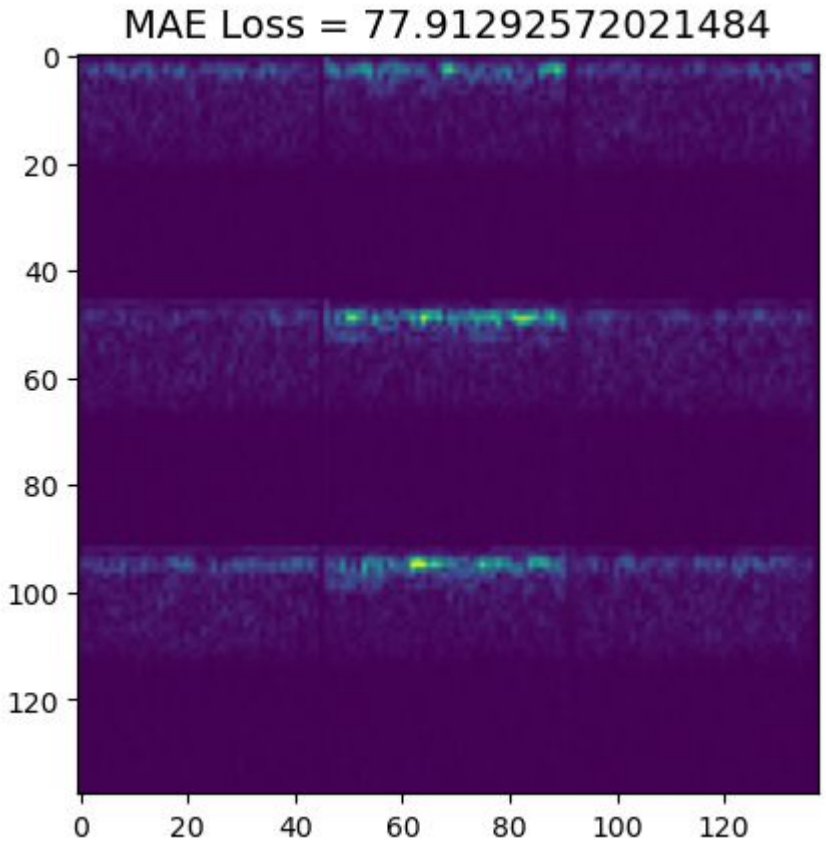


Figure 2. The field of view, in equatorial coordinates, of an in-ice radio detector for neutrinos in Greenland. The colored background represents the diurnally-averaged total field of view of the detector. Also shown are targets with interesting multi-messenger implications. The blue sources are those seen by IceCube as the most significant sources in a point-source search [78]. In orange, we show other interesting candidates, with strong γ-ray emission and/or radio emission. Furthermore, we indicate what is known as the *TA hotspot* as indicated by the anisotropy measurement in cosmic ray measured with the Telescope Array [79].

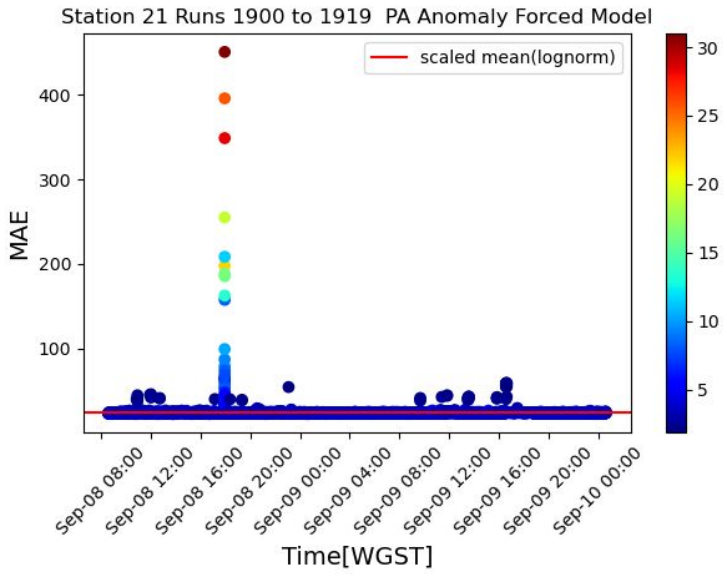
Masha's Surface Events

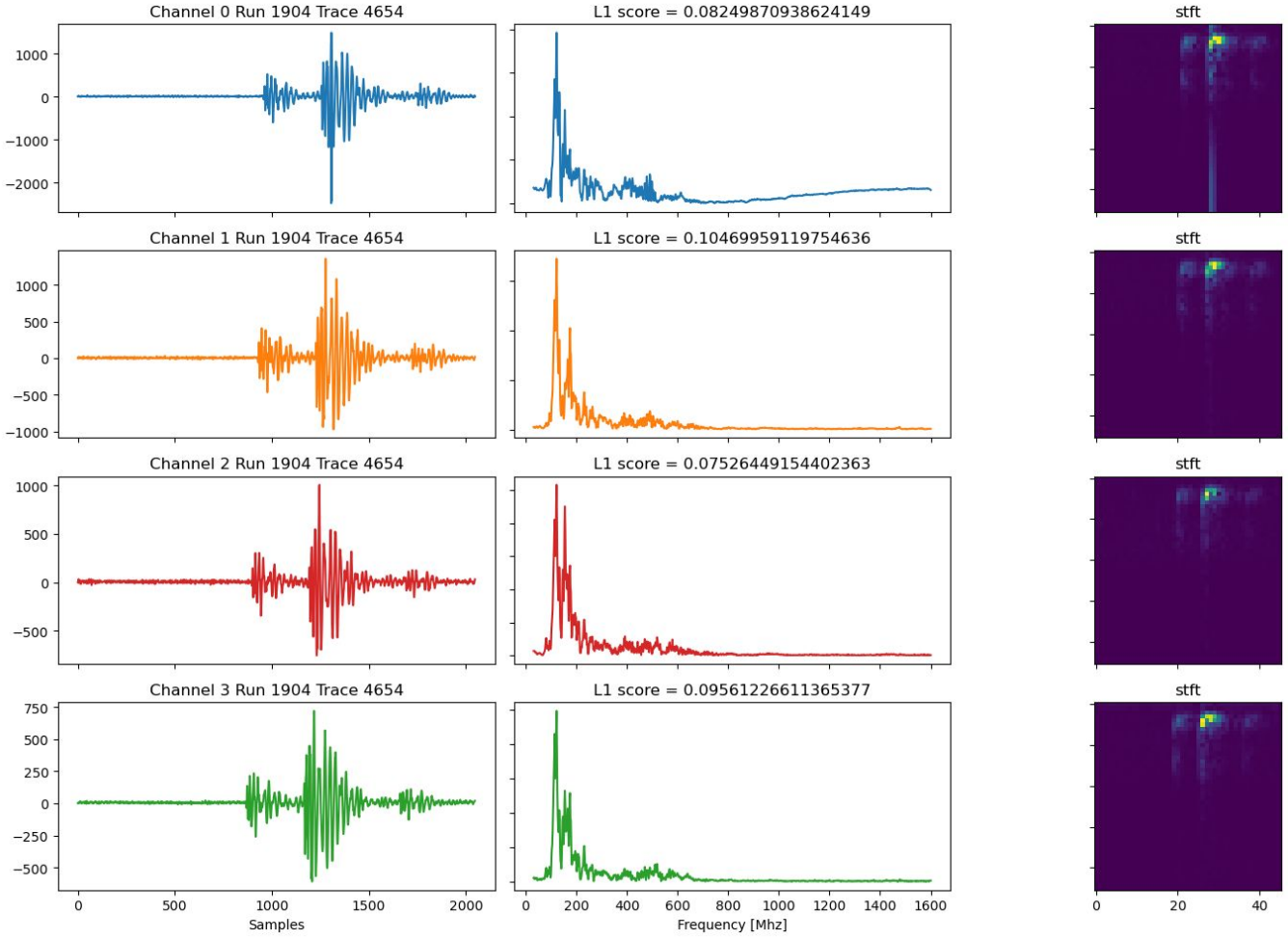
Station 23





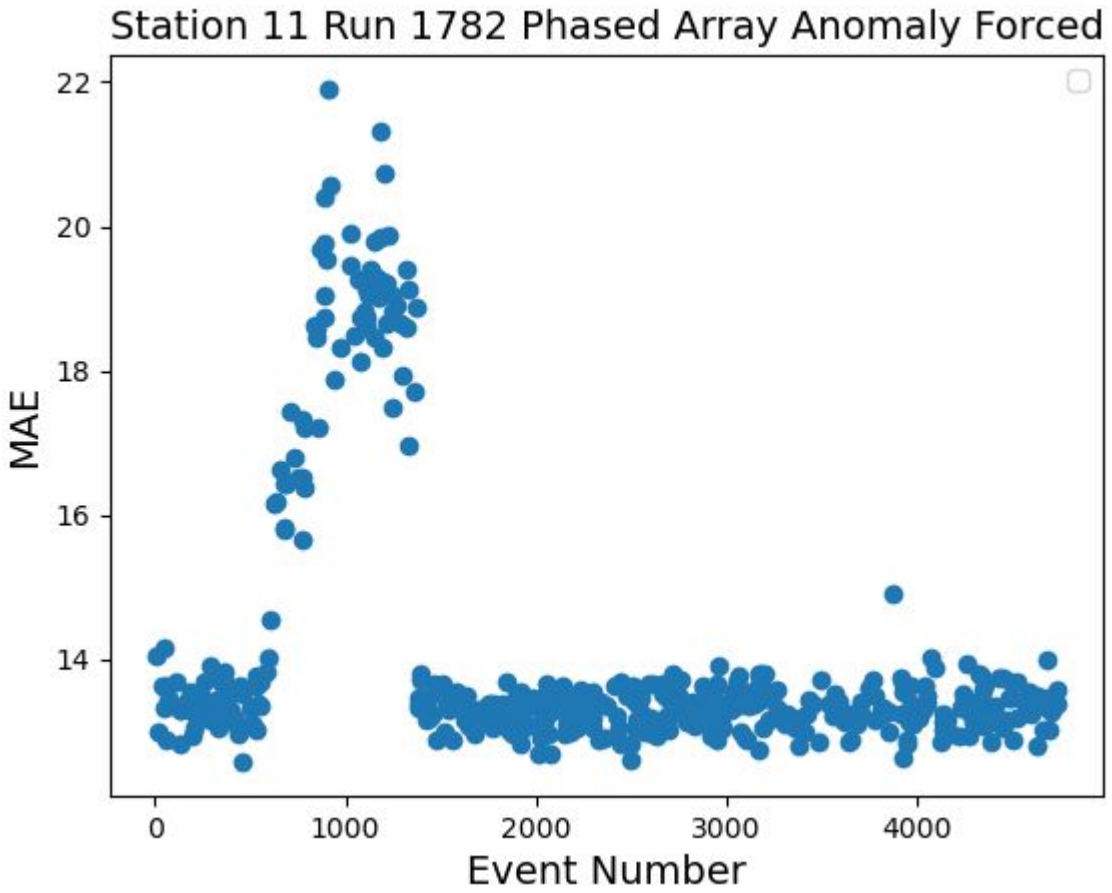
Snowmobiles / Ice Sat Traverse

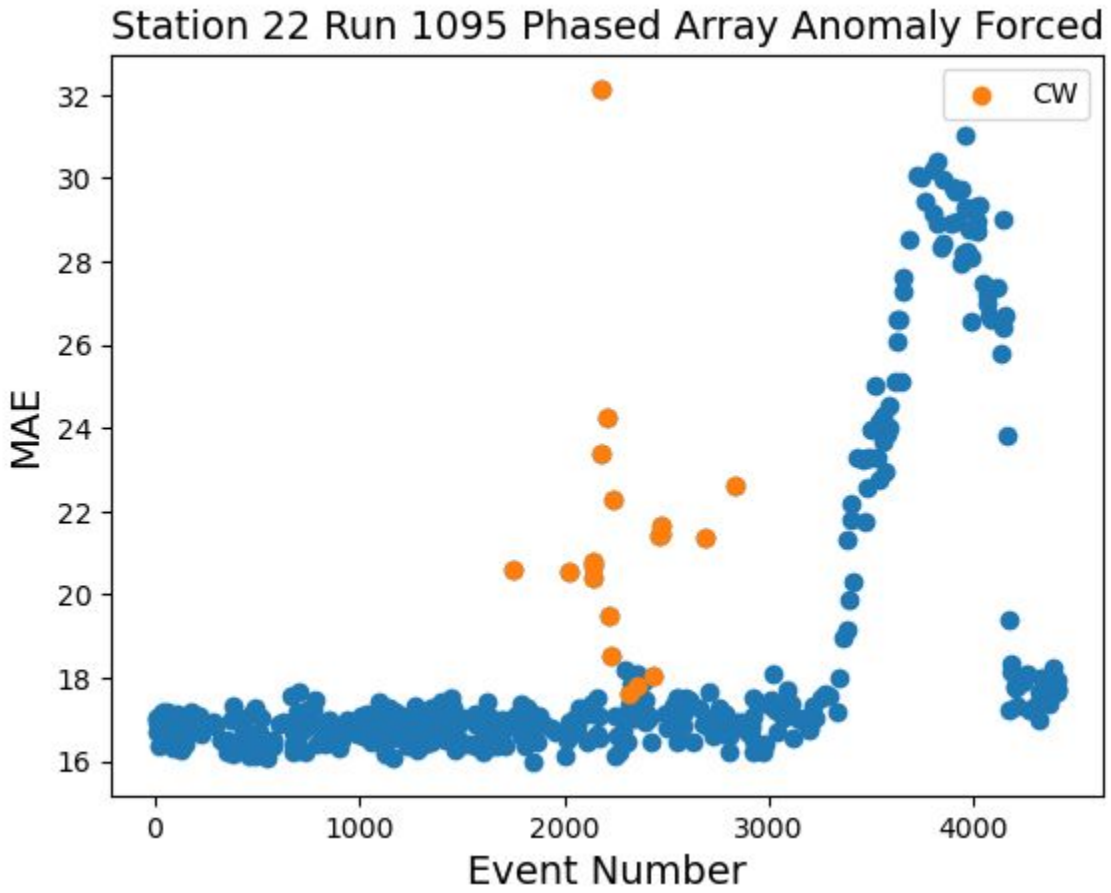




Station 23 and 22

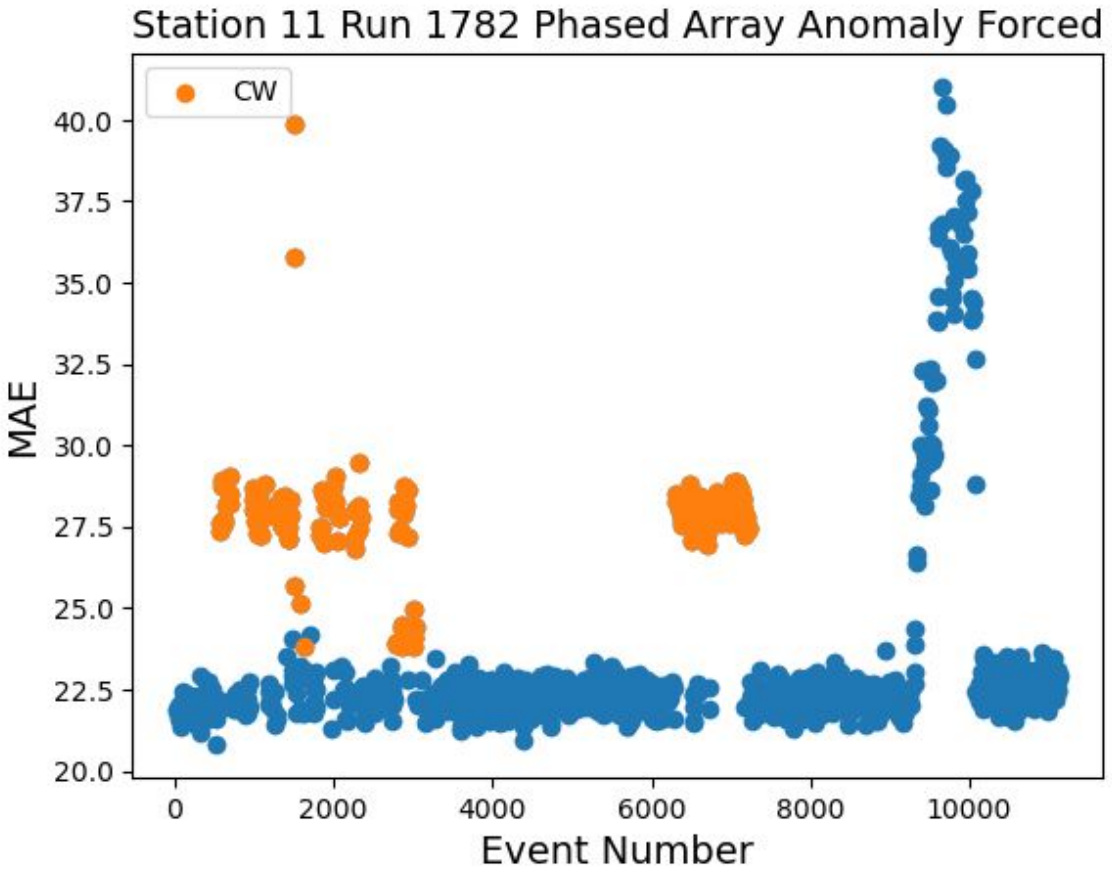
Forced Trigger Models

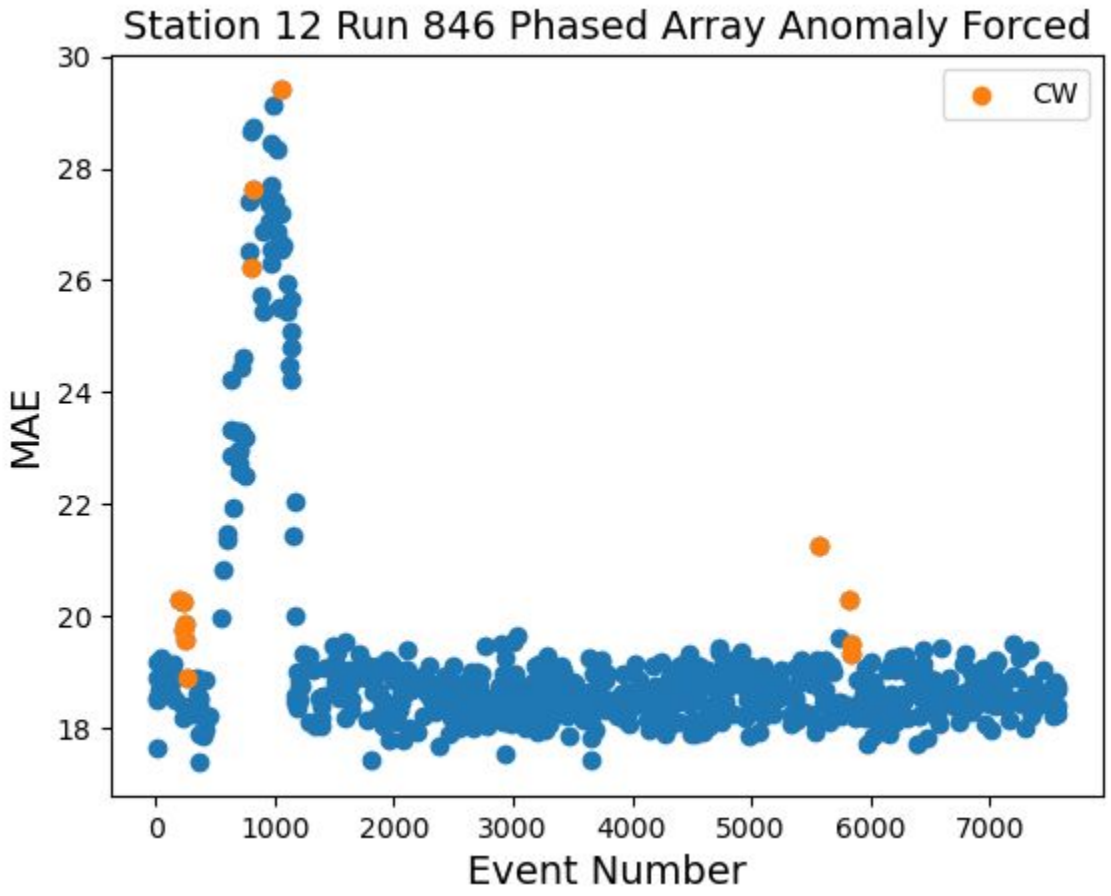




Station 11 and 12

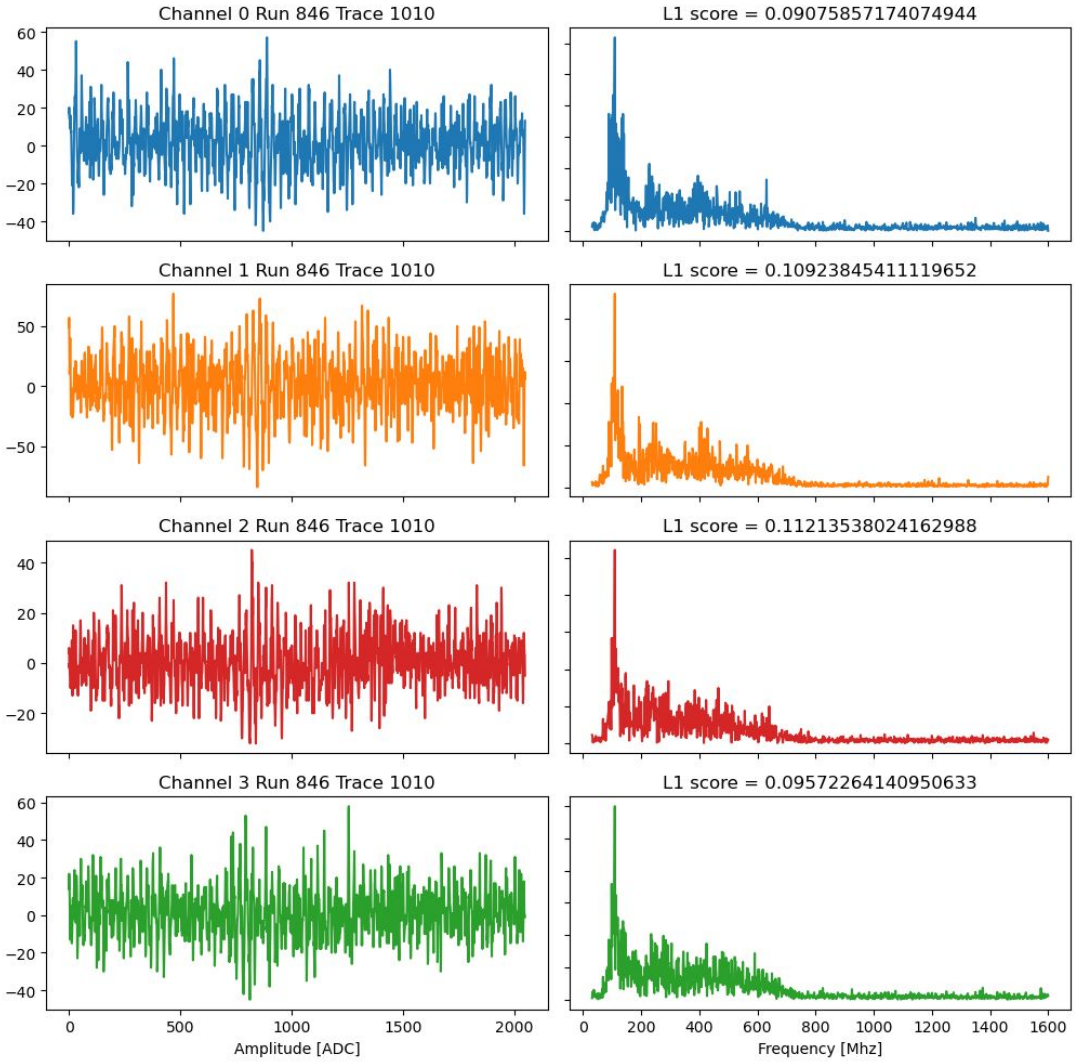
Forced Trigger Models, 13 and 24 not running during flare

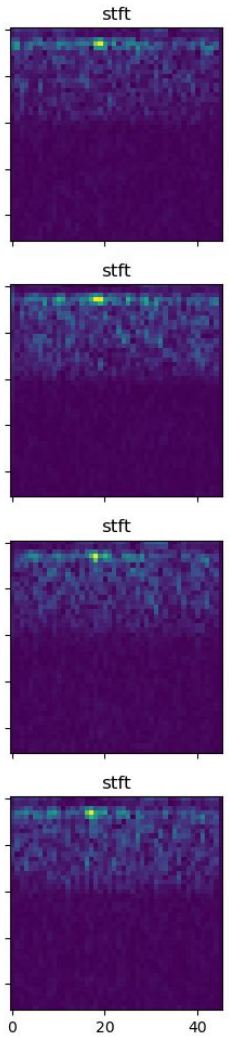


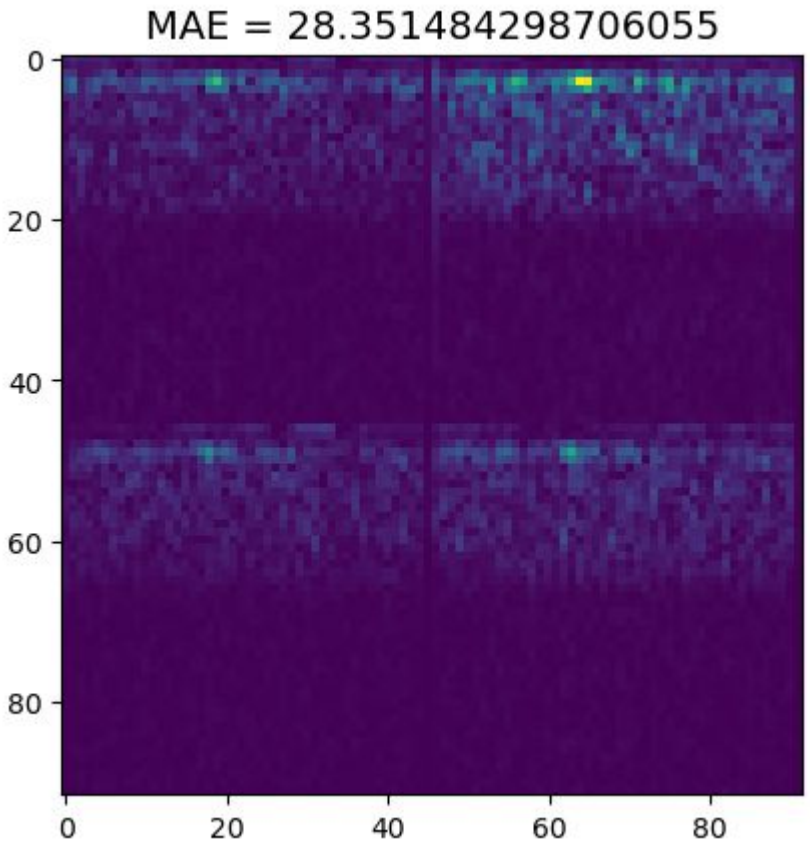


CW during the flare?

Or is the flare characteristically narrow?







“Anomalous Low Threshold Event”

Reconstruction / Coming from above

Channel 0

Channel 5