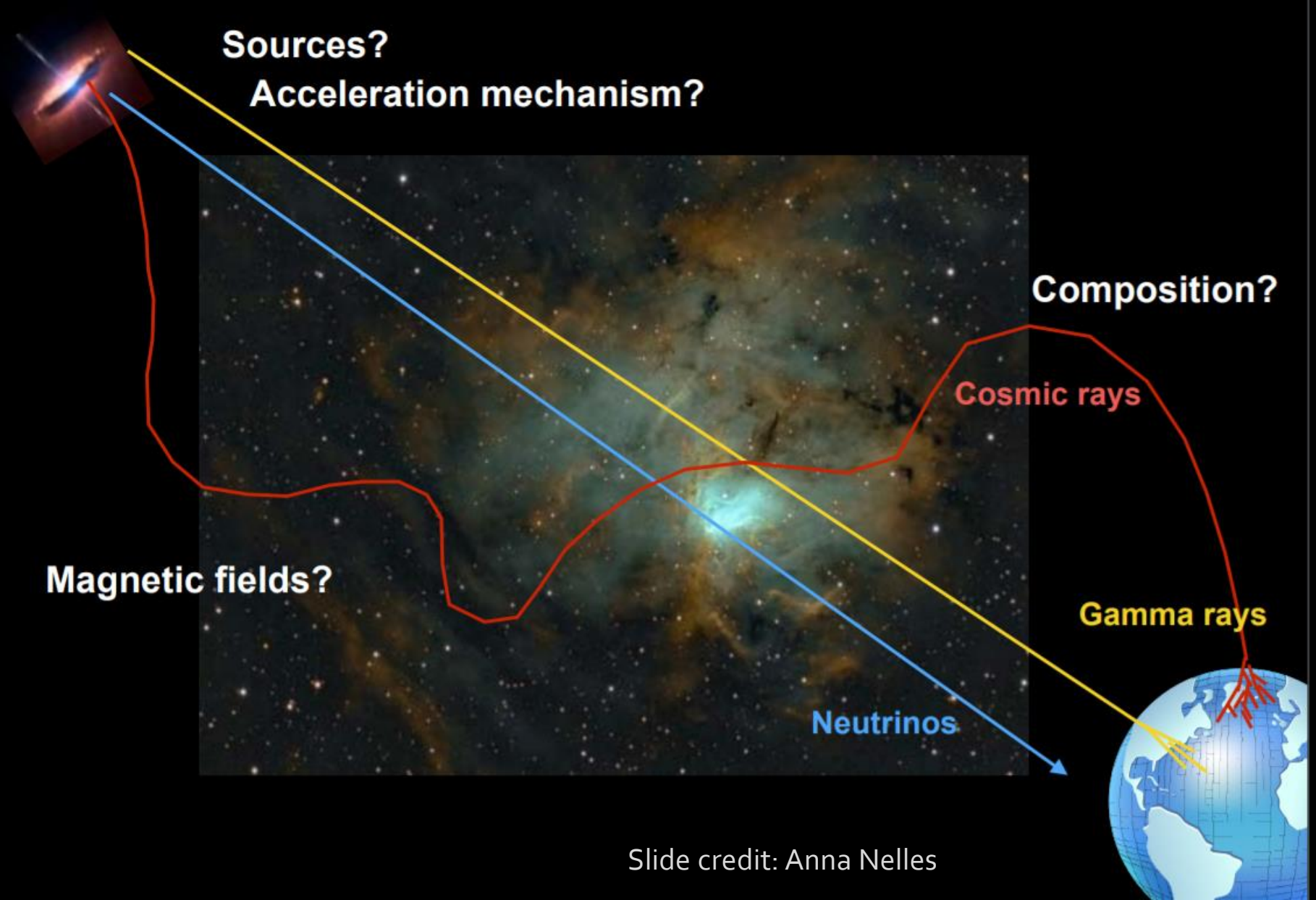
Direct detection of Cosmic Rays: Techniques, challenges and early results

Ryan Monroe, Anna Nelles, Gregg Hallinan,
Michael Eastwood , Marin Anderson,
and many others!

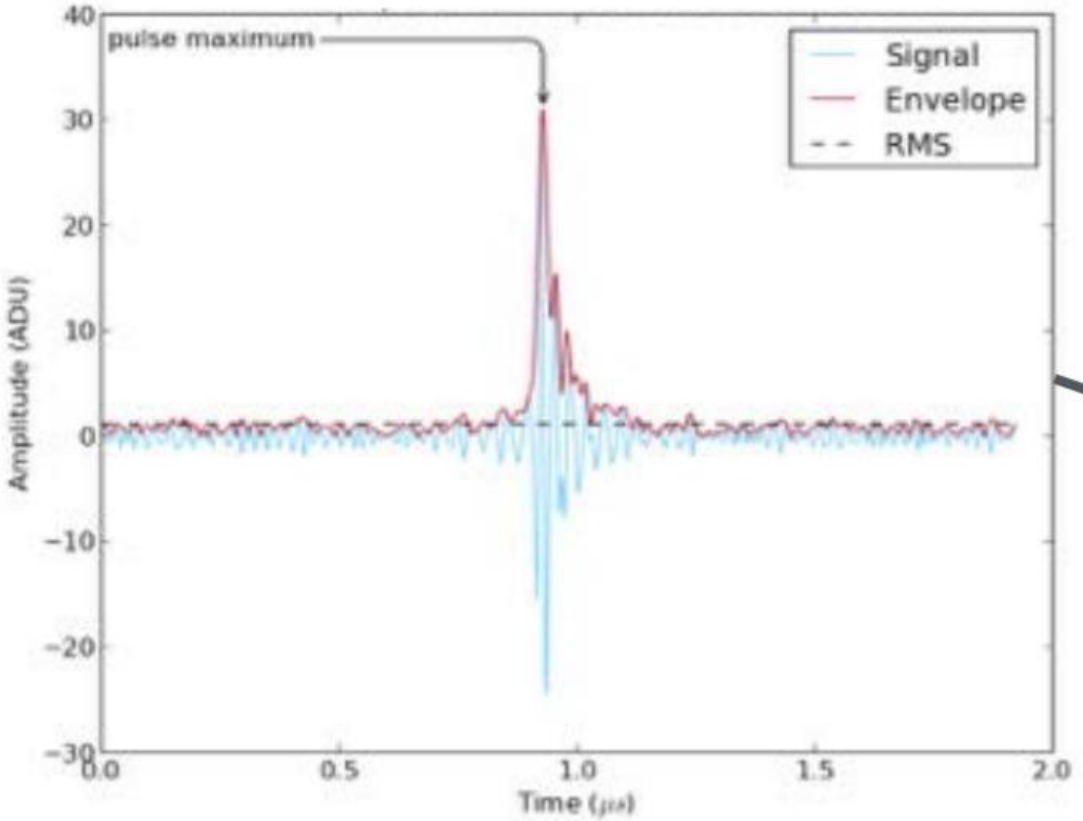
Astroparticle Physics

At the highest energies

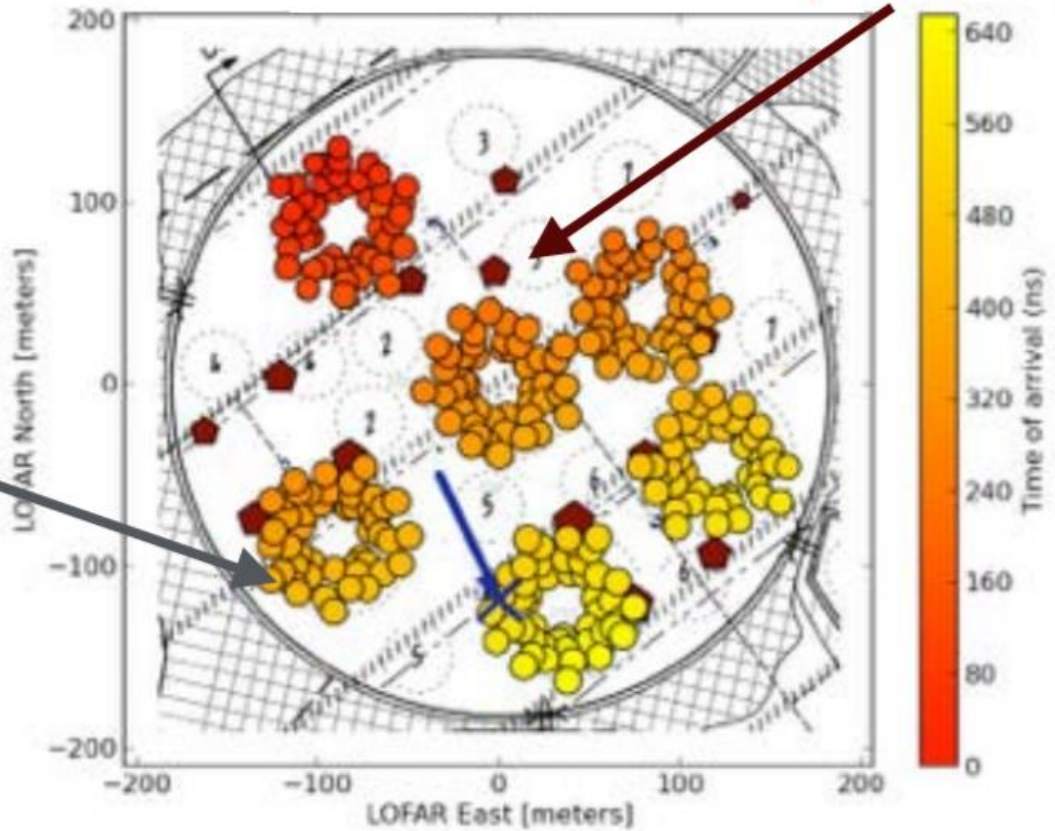


Slide credit: Anna Nelles

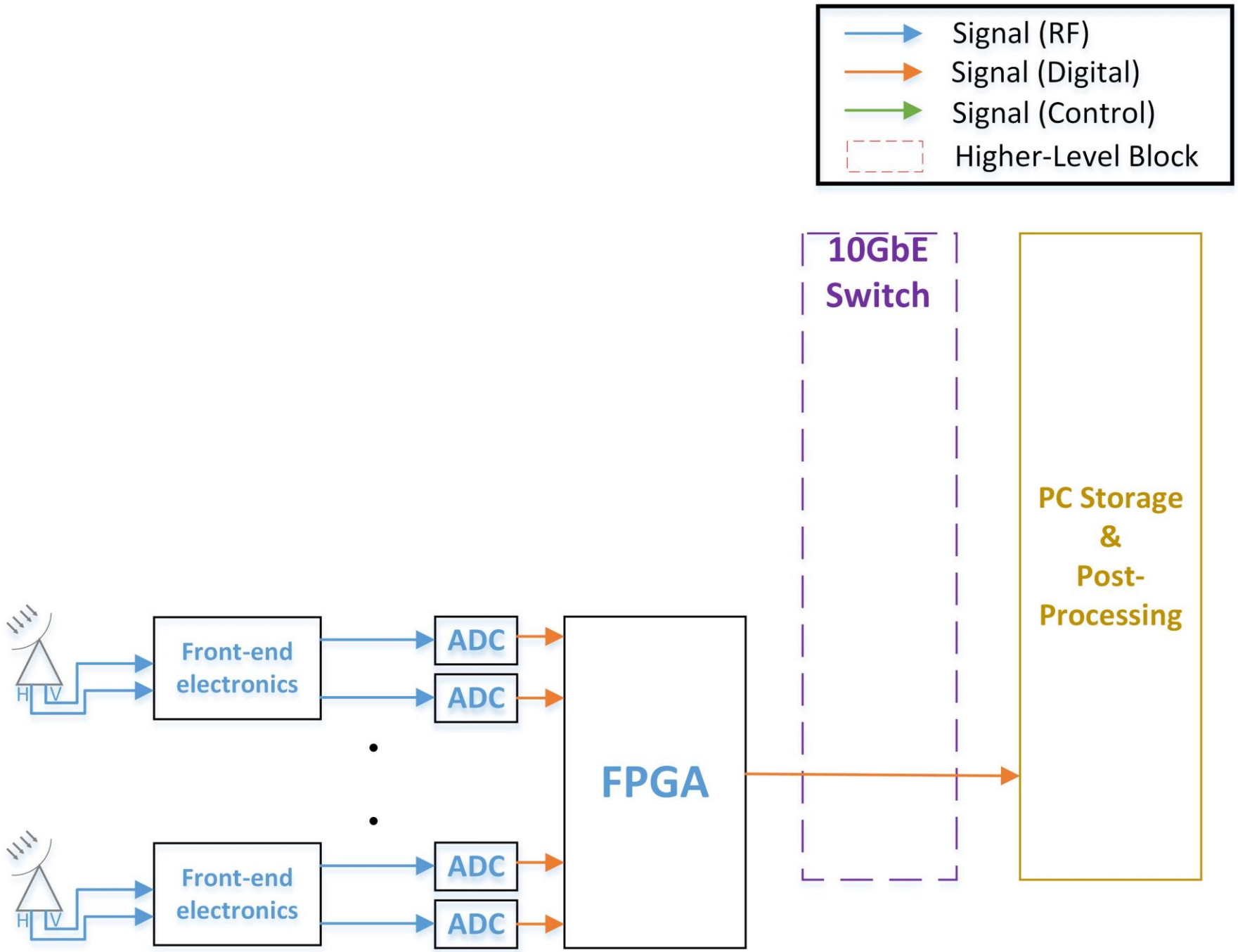
Single antenna data LOFAR 30-80 MHz

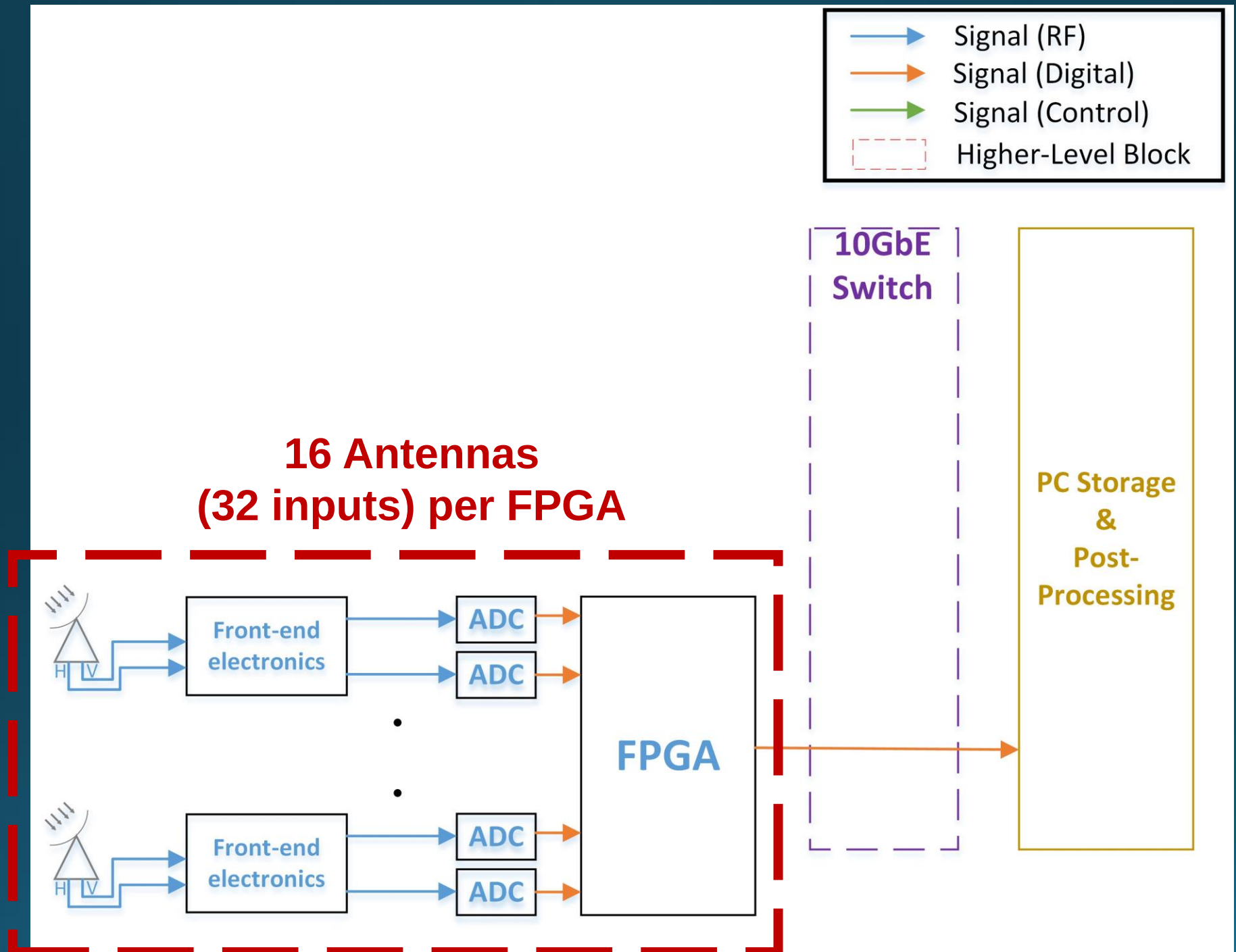


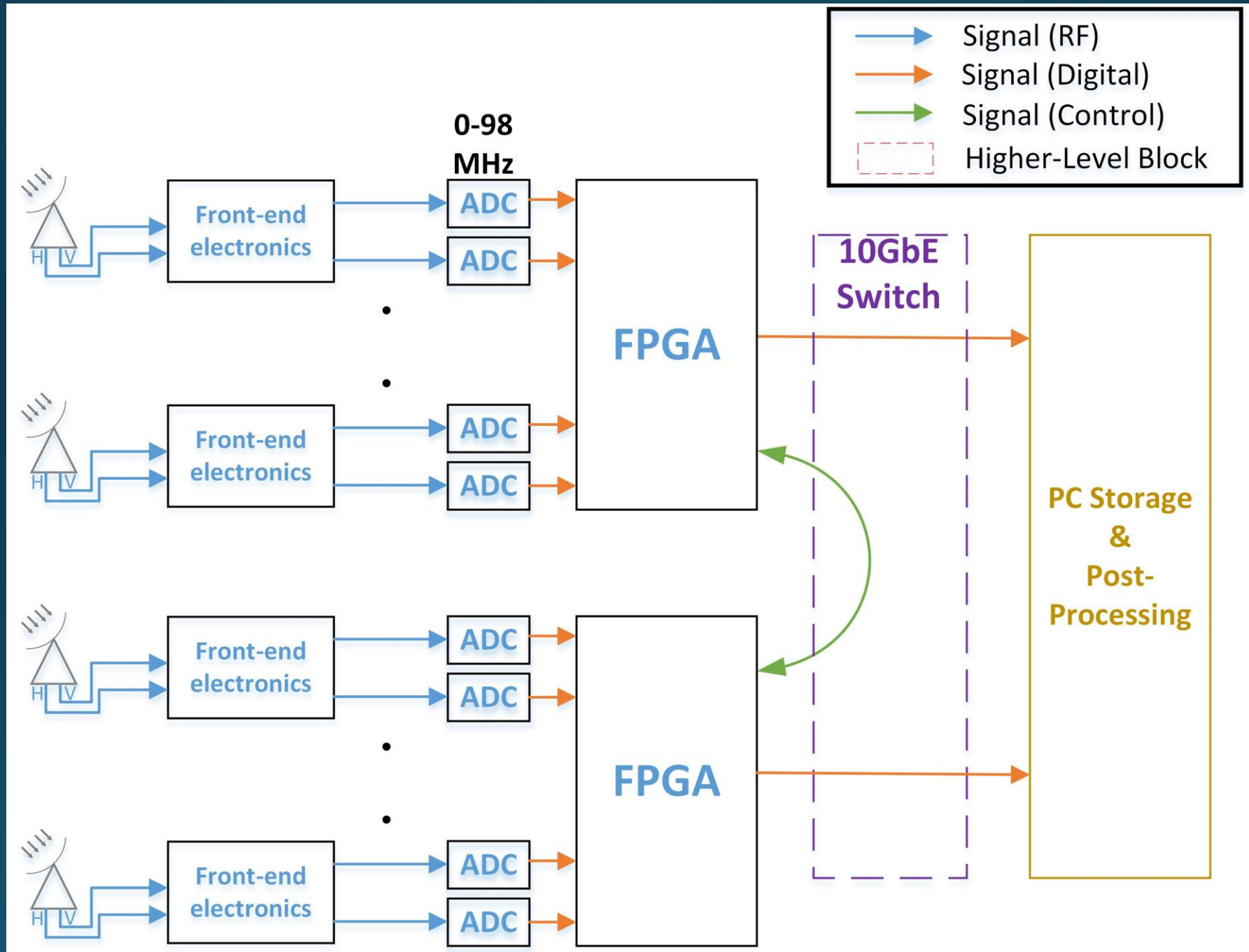
Particle detectors provide trigger

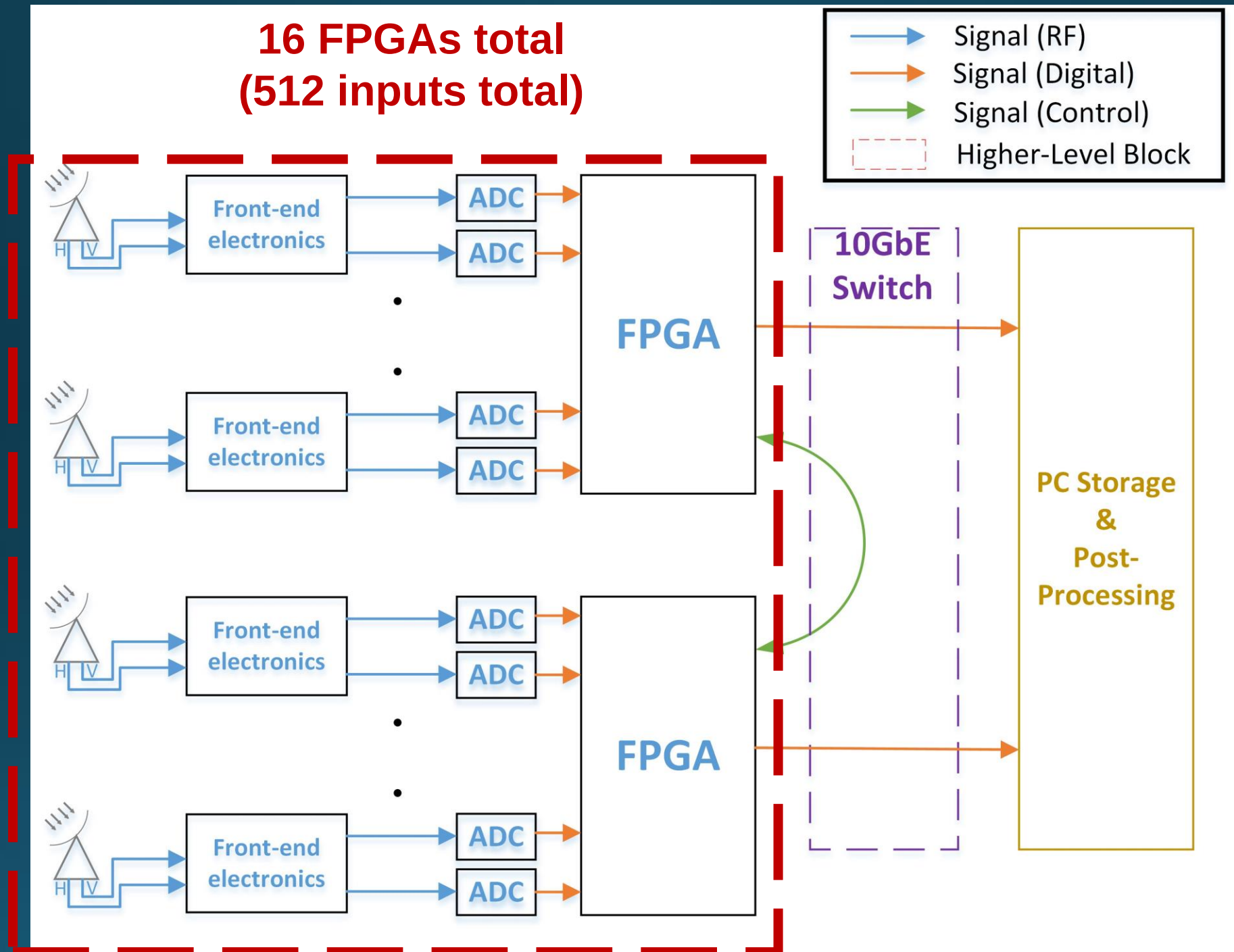


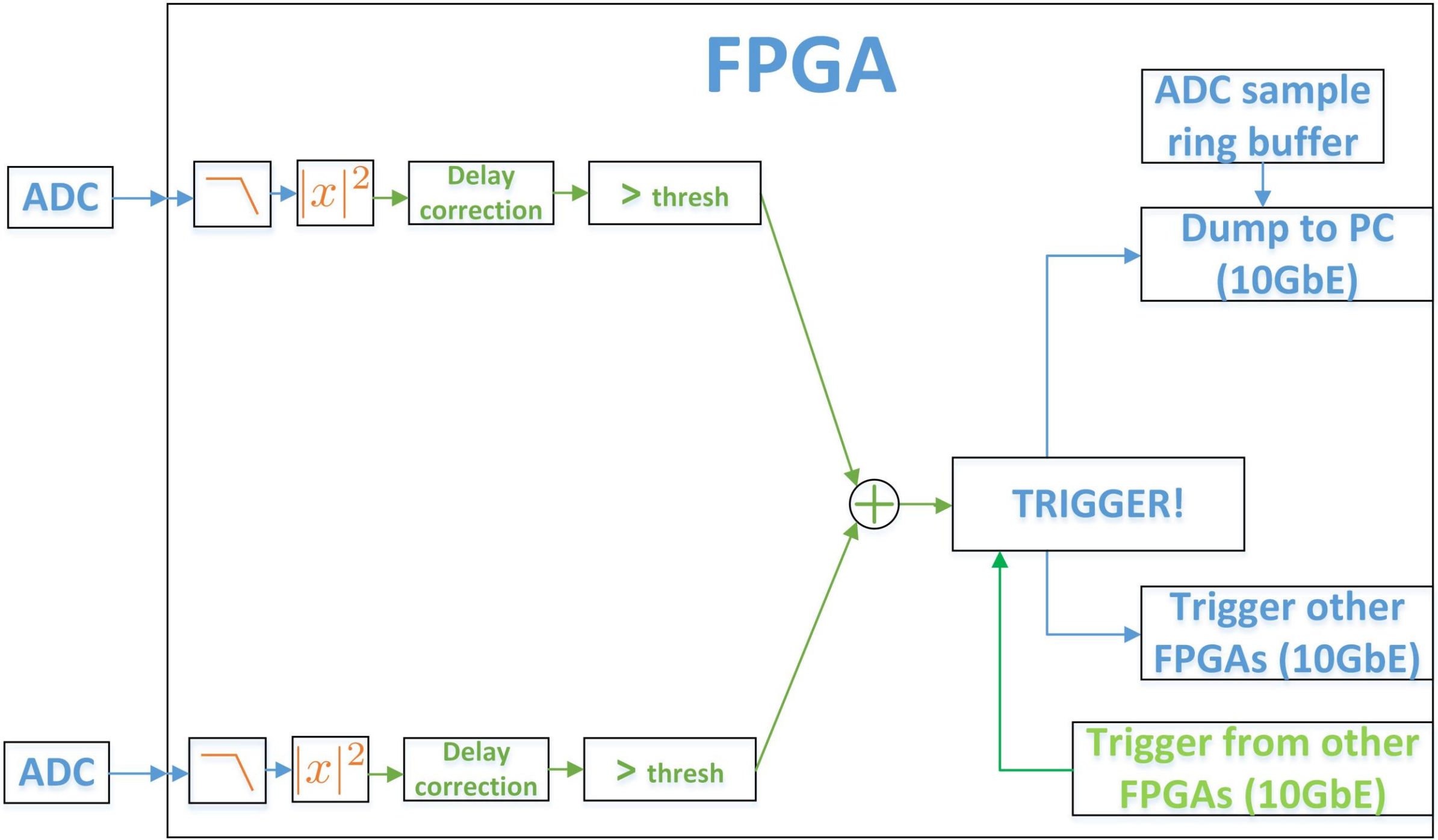
Slide credit: Anna Nelles


Signal (RF)
Signal (Digital)
Signal (Control)
Higher-Level Block
10GbE Switch
PC Storage & Post-Processing
Front-end electronics
Front-end electronics
ADC
ADC
ADC
ADC
FPGA
H
V
H
V


Signal (RF)
Signal (Digital)
Signal (Control)
Higher-Level Block
10GbE Switch
PC Storage & Post-Processing
16 Antennas
(32 inputs) per FPGA
Front-end electronics
ADC
ADC
FPGA
Front-end electronics
ADC
ADC
H
V
H
V

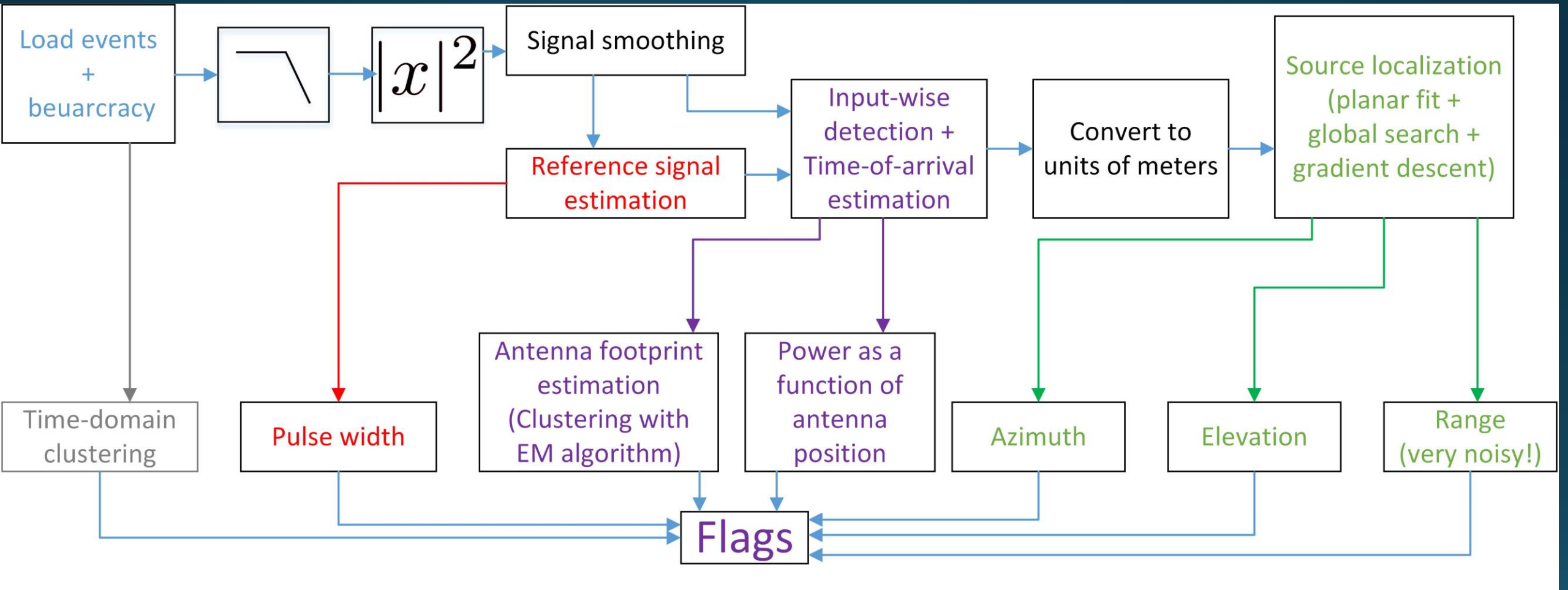

Signal (RF)
Signal (Digital)
Signal (Control)
Higher-Level Block
0-98 MHz
Front-end electronics
ADC
FPGA
10GbE Switch
PC Storage & Post-Processing
H
V

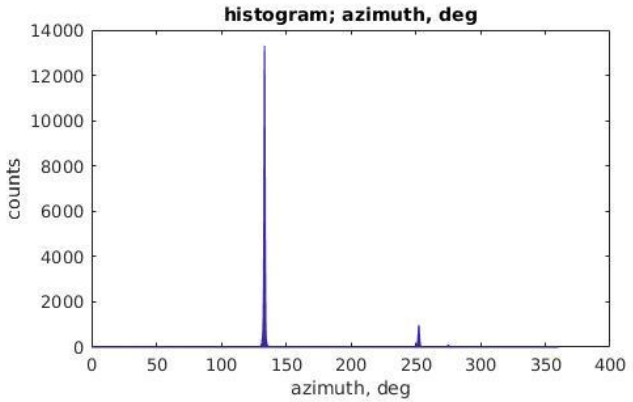

16 FPGAs total
(512 inputs total)
Signal (RF)
Signal (Digital)
Signal (Control)
Higher-Level Block
Front-end electronics
ADC
FPGA
10GbE Switch
PC Storage & Post-Processing
H
V

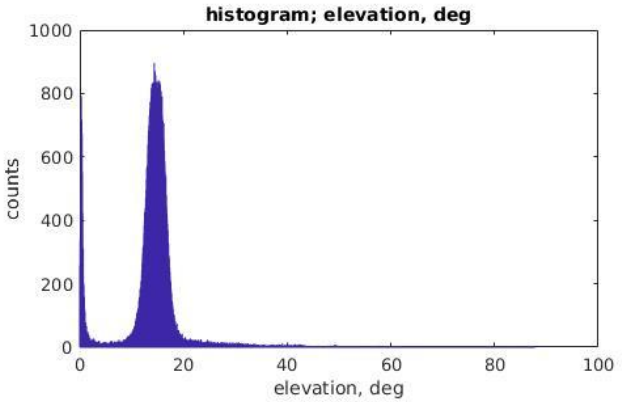

FPGA
ADC sample ring buffer
ADC
$|x|^2$
Delay correction
> thresh
Dump to PC (10GbE)
TRIGGER!
Trigger other FPGAs (10GbE)
ADC
$|x|^2$
Delay correction
> thresh
Trigger from other FPGAs (10GbE)

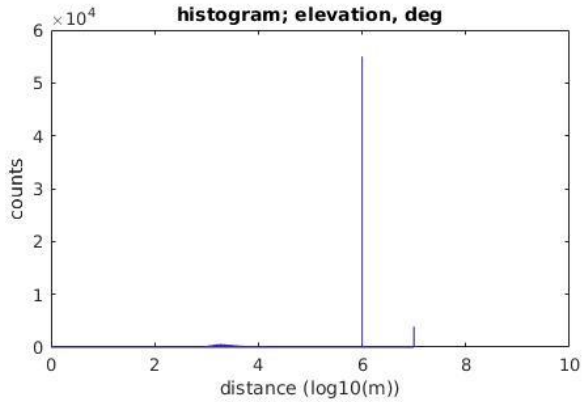
PC Post-Processing

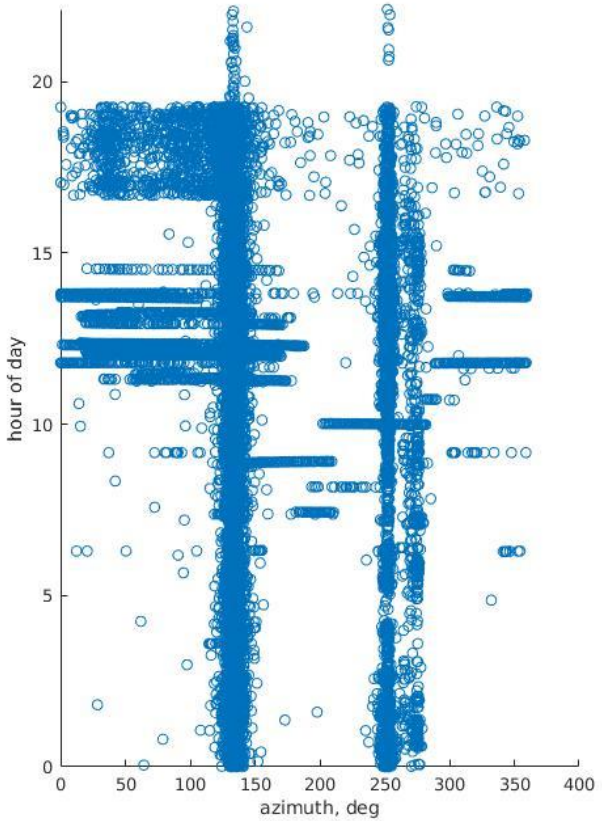
Challenge: No strong priors on CRs until we have successful detections

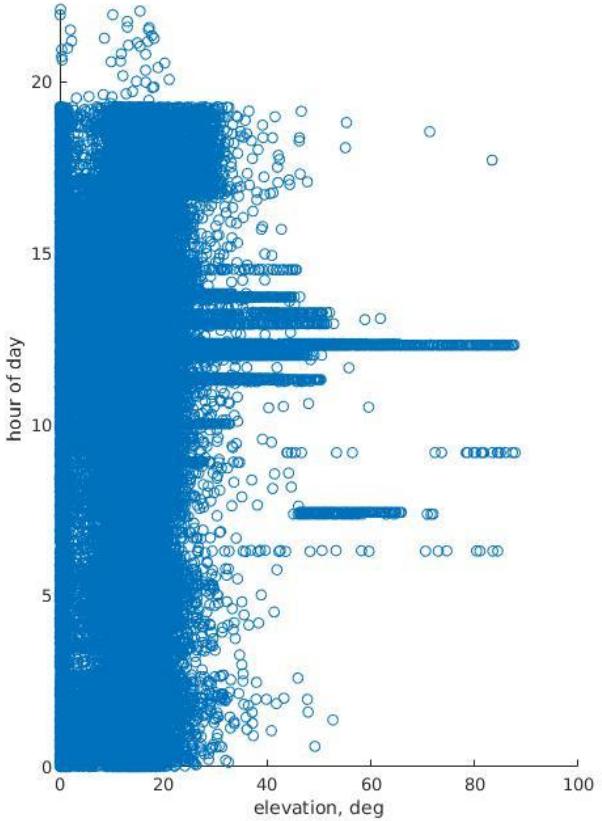


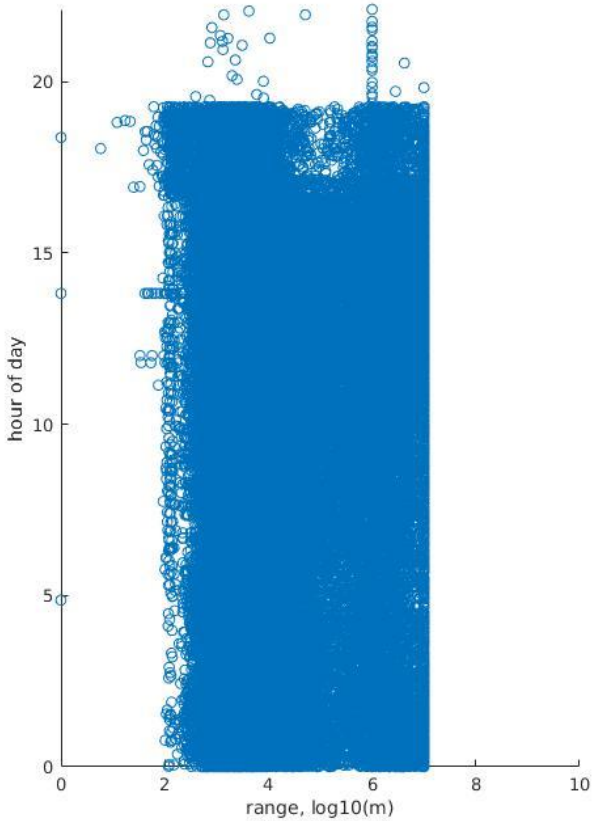

histogram; azimuth, deg
counts
azimuth, deg

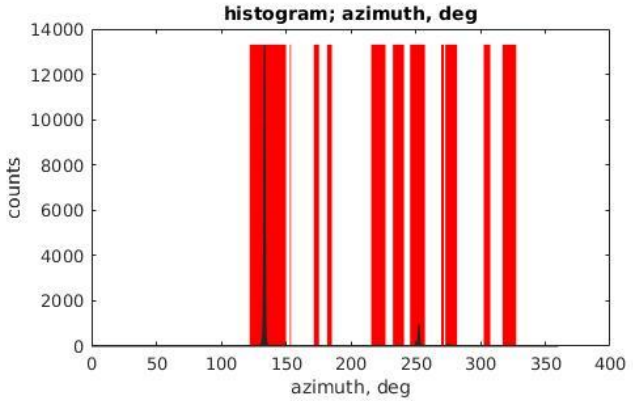

histogram; elevation, deg
counts
elevation, deg

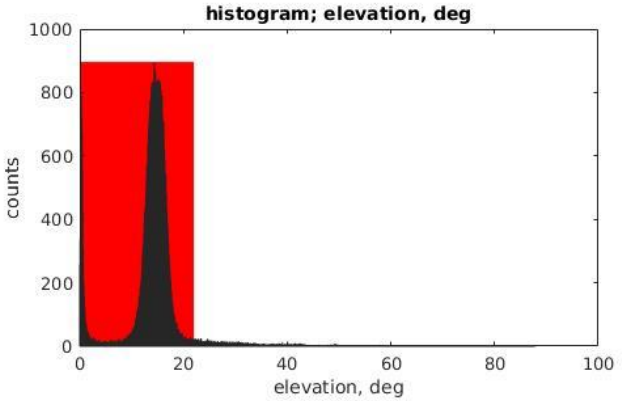

histogram; elevation, deg
counts
distance (log10(m))

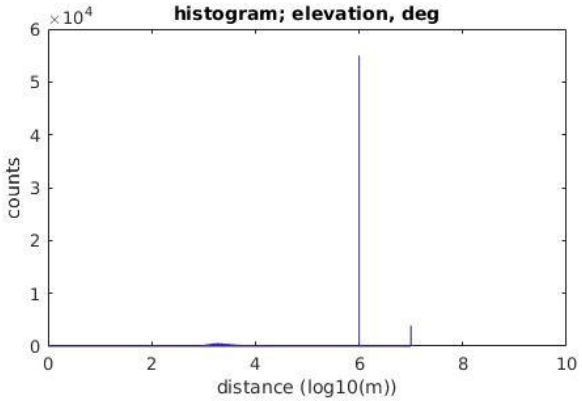

hour of day
azimuth, deg

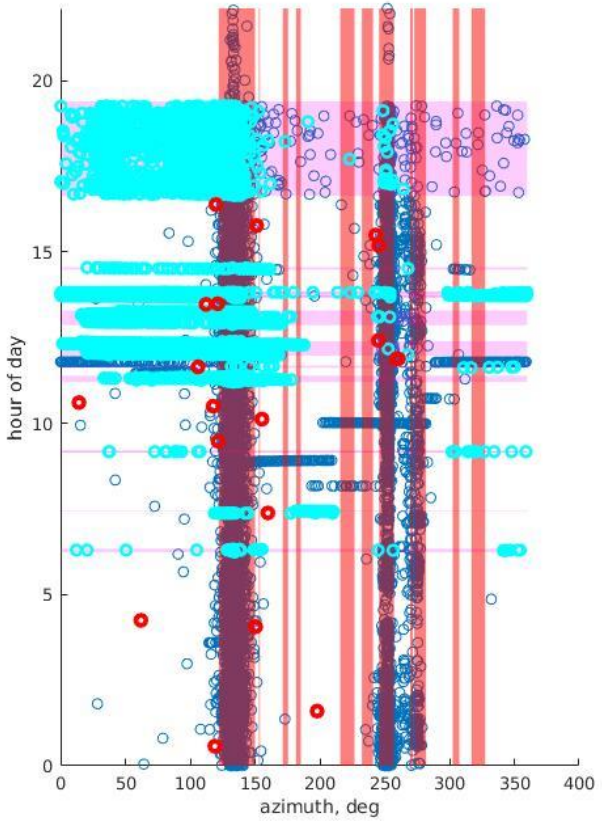

hour of day
elevation, deg

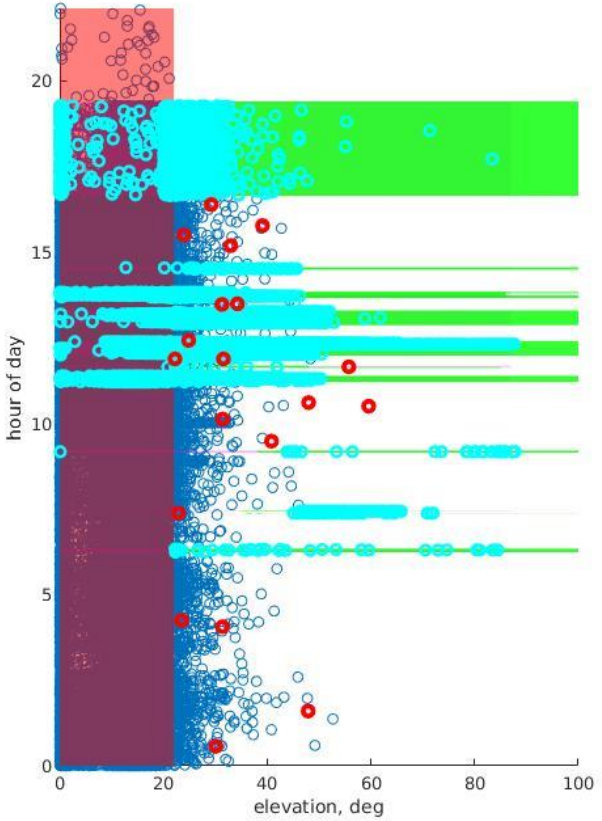

hour of day
range, log10(m)

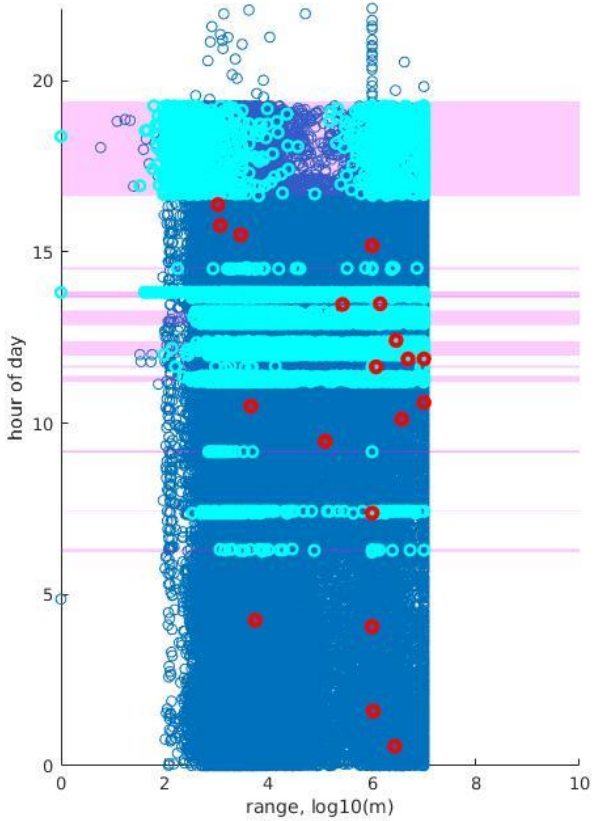

histogram; azimuth, deg
counts
azimuth, deg

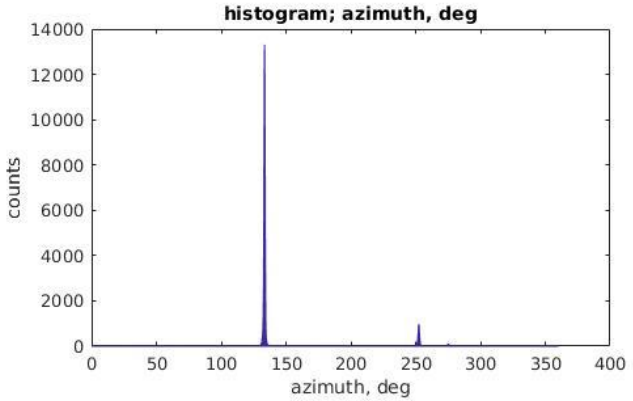

histogram; elevation, deg
counts
elevation, deg

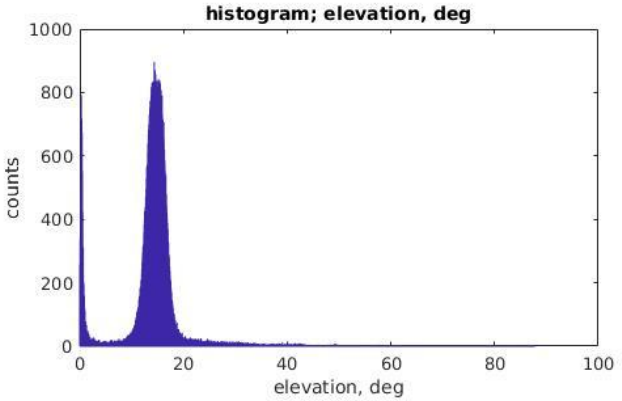

histogram; elevation, deg
counts
distance (log10(m))

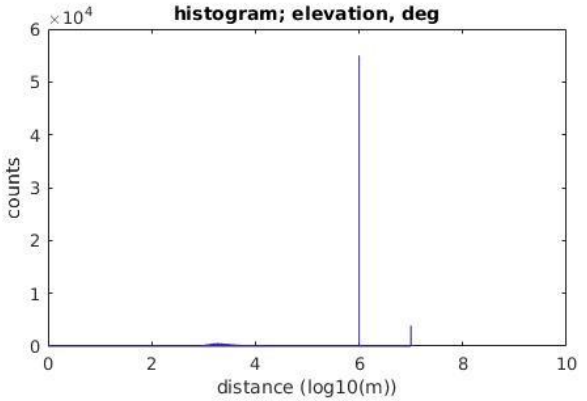

hour of day
azimuth, deg

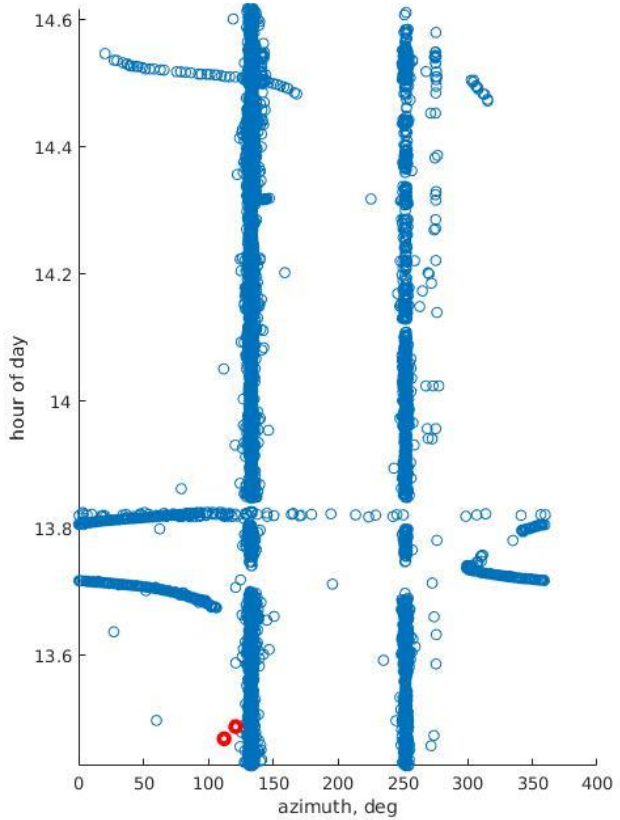

hour of day
elevation, deg

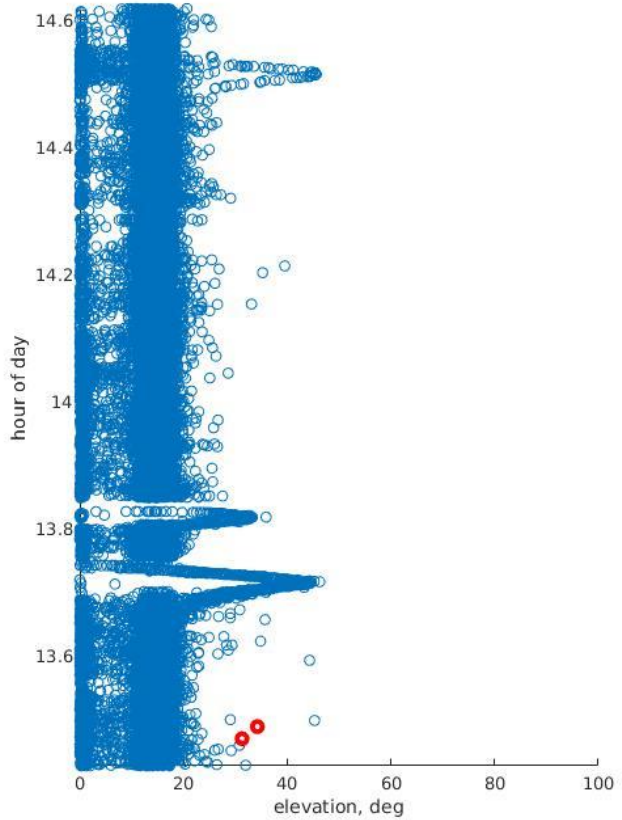

hour of day
range, log10(m)

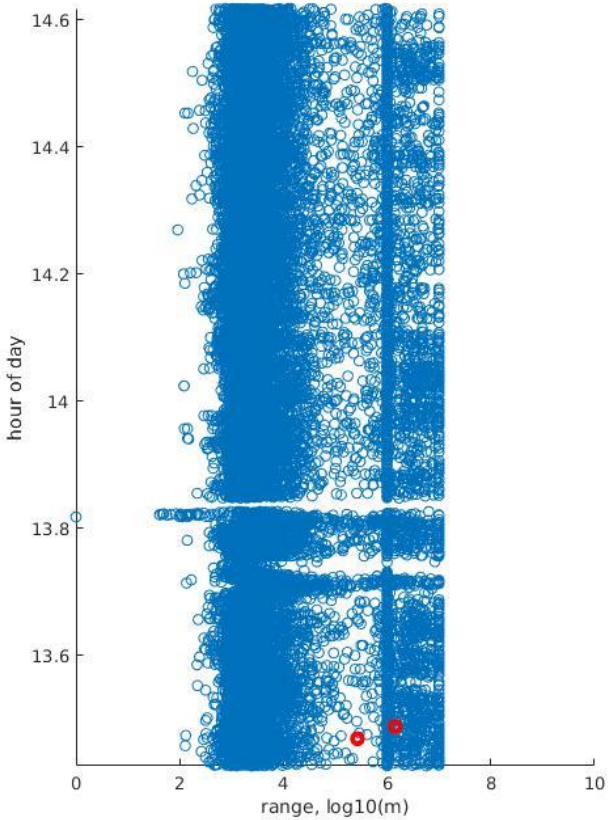

histogram; azimuth, deg
counts
azimuth, deg

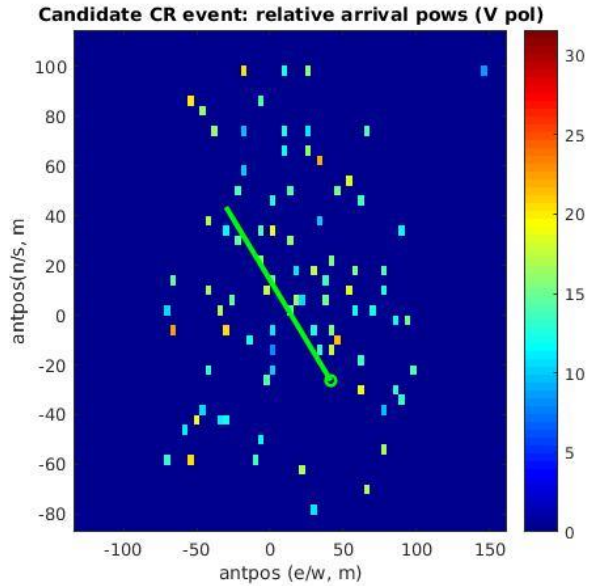

histogram; elevation, deg
counts
elevation, deg

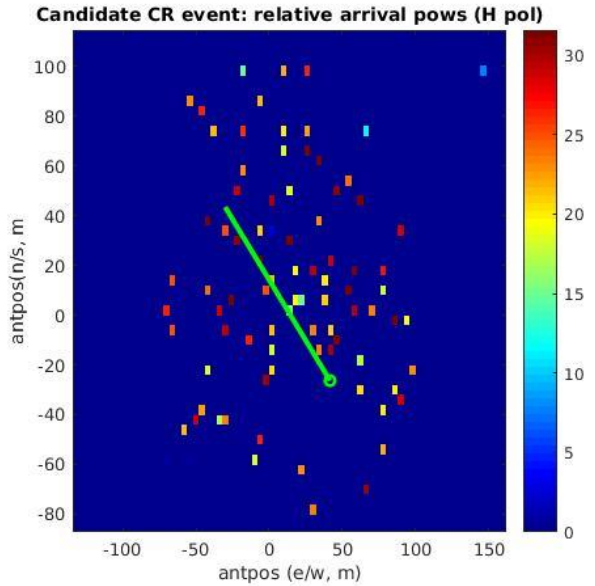

histogram; elevation, deg
counts
distance (log10(m))

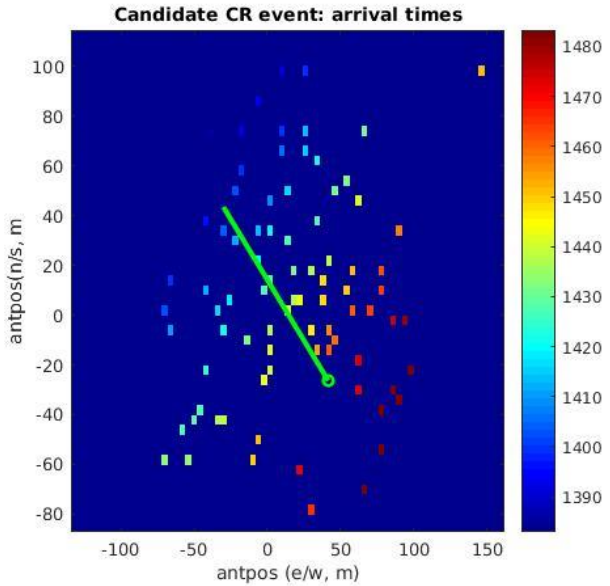

hour of day
azimuth, deg

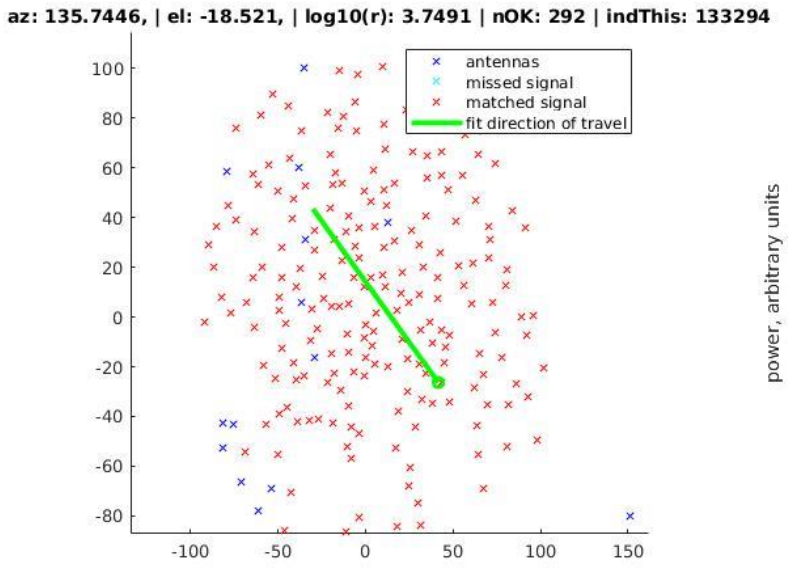

hour of day
elevation, deg

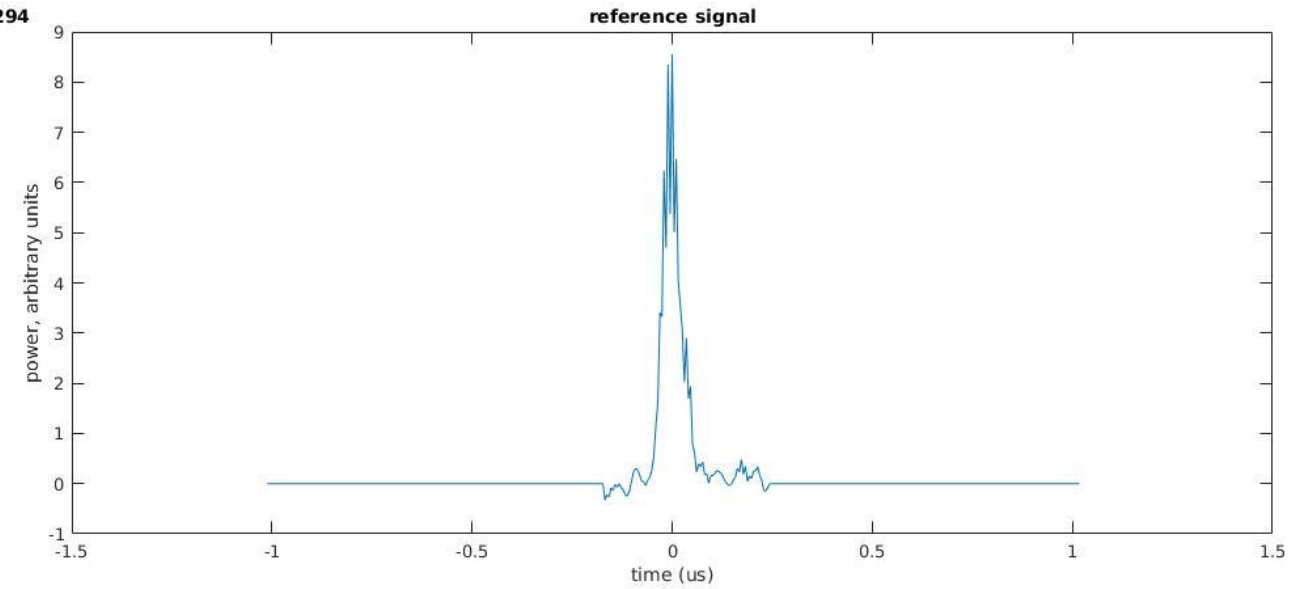

hour of day
range, log10(m)

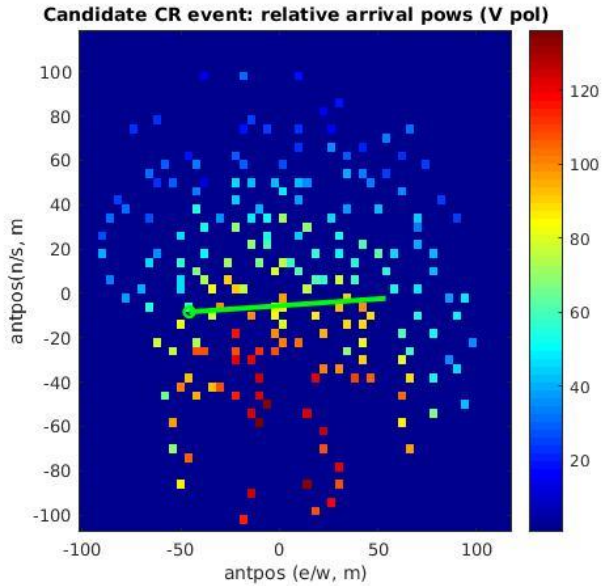

Candidate CR event: relative arrival pows (V pol)
antpos(n/s, m
antpos (e/w, m)

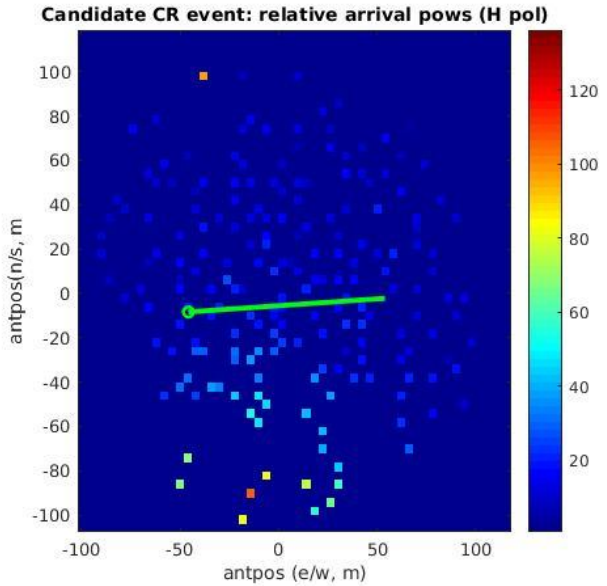

Candidate CR event: relative arrival pows (H pol)
antpos(n/s, m
antpos (e/w, m)

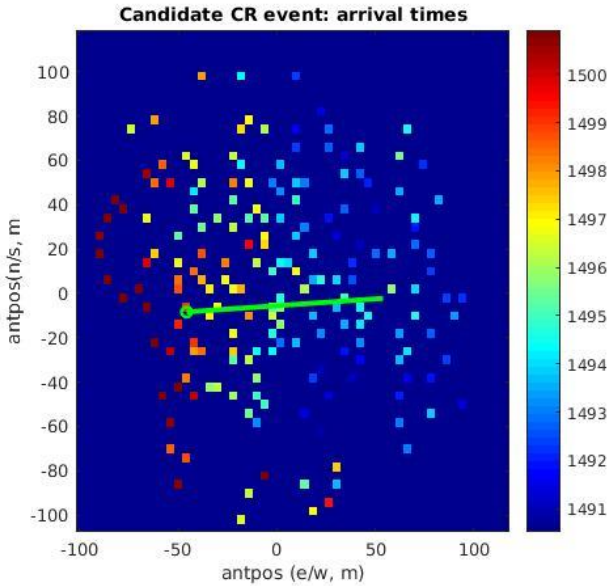

Candidate CR event: arrival times
antpos(n/s, m
antpos (e/w, m)

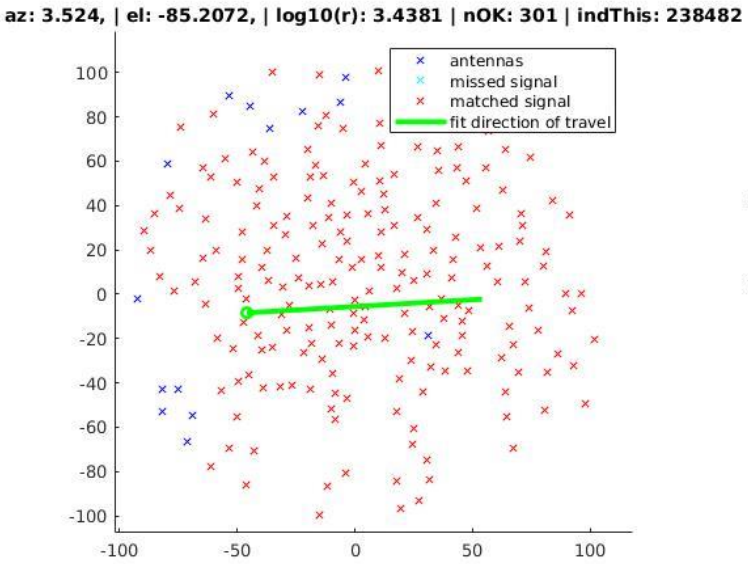

az: 135.7446, | el: -18.521, | log10(r): 3.7491 | nOK: 292 | indThis: 133294
antennas
missed signal
matched signal
fit direction of travel

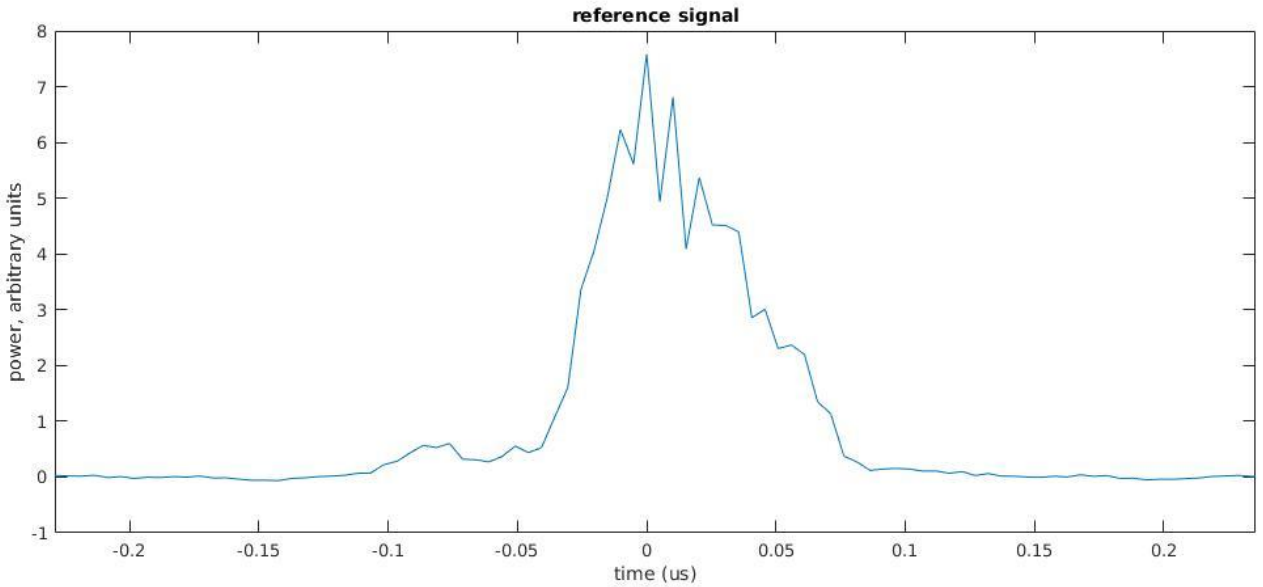

reference signal
power, arbitrary units
time (us)

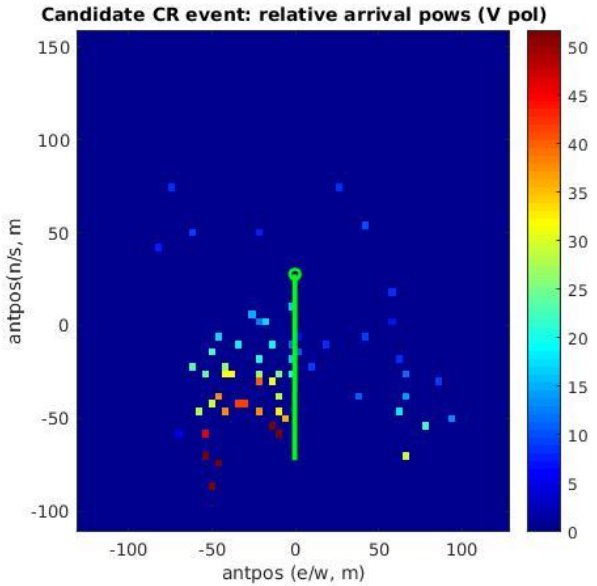

Candidate CR event: relative arrival pows (V pol)
antpos(n/s, m
antpos (e/w, m)

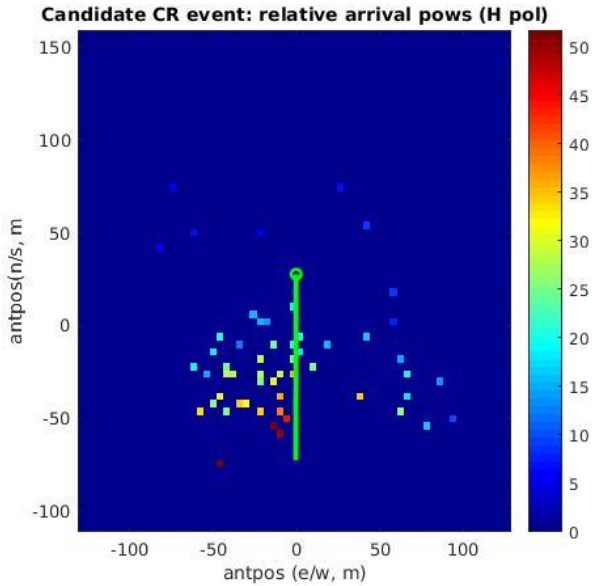

Candidate CR event: relative arrival pows (H pol)
antpos(n/s, m
antpos (e/w, m)

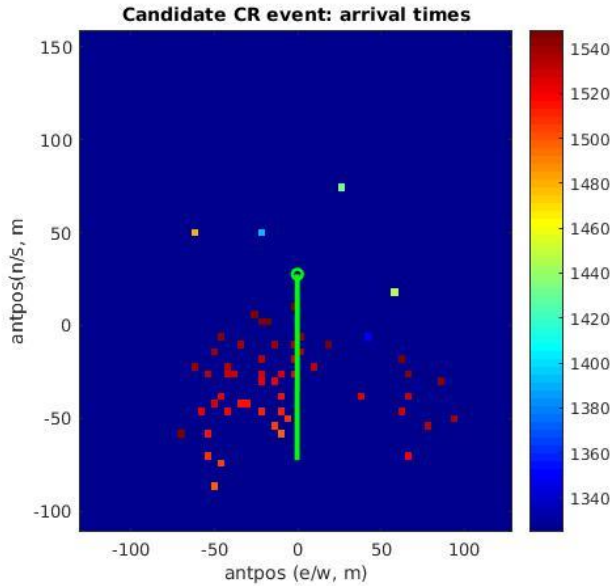

Candidate CR event: arrival times
antpos(n/s, m
antpos (e/w, m)

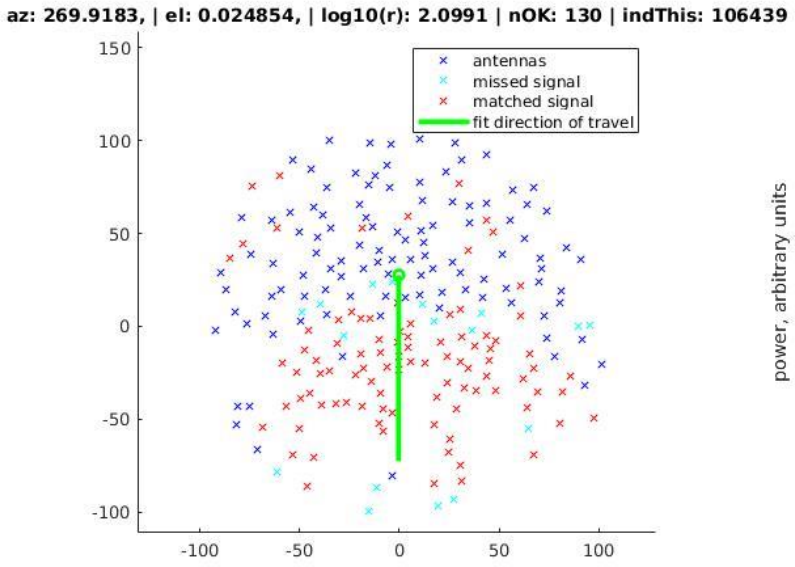

az: 3.524, | el: -85.2072, | log10(r): 3.4381 | nOK: 301 | indThis: 238482
antennas
missed signal
matched signal
fit direction of travel

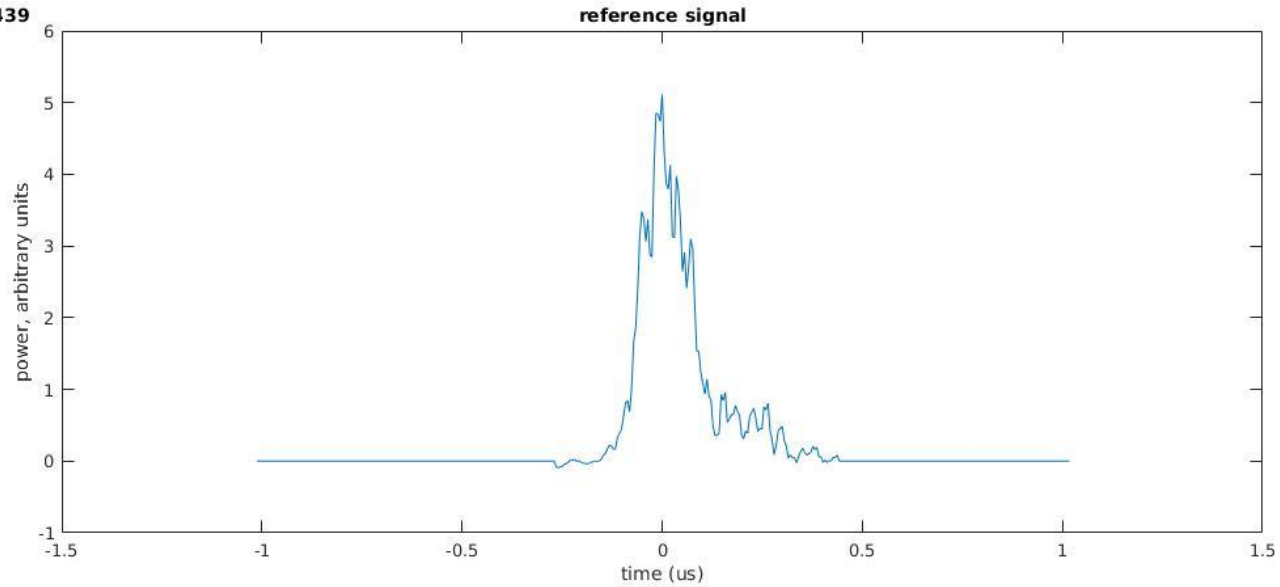

reference signal
power, arbitrary units
time (us)

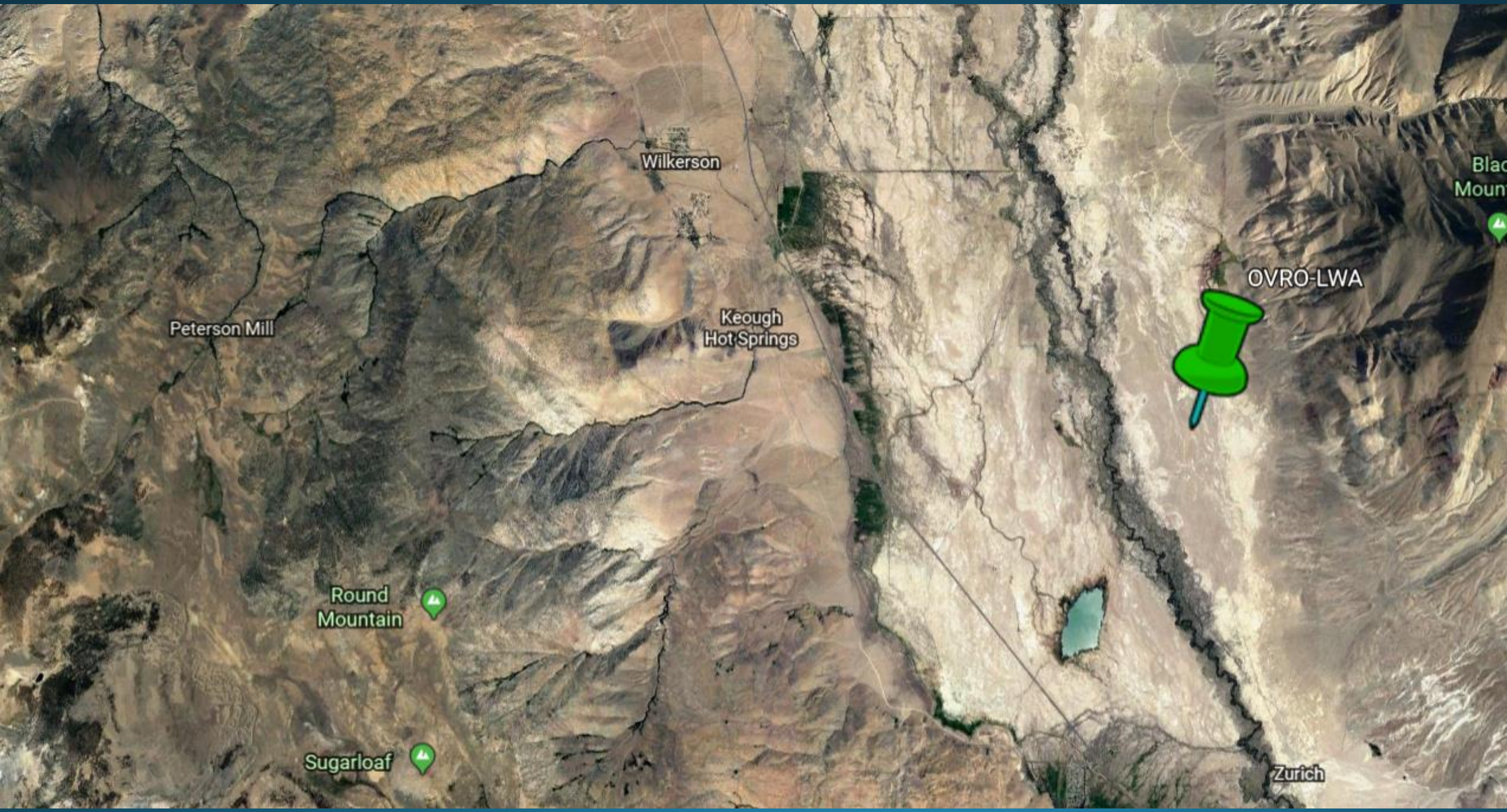

Candidate CR event: relative arrival pows (V pol)
antpos(n/s, m
antpos (e/w, m)

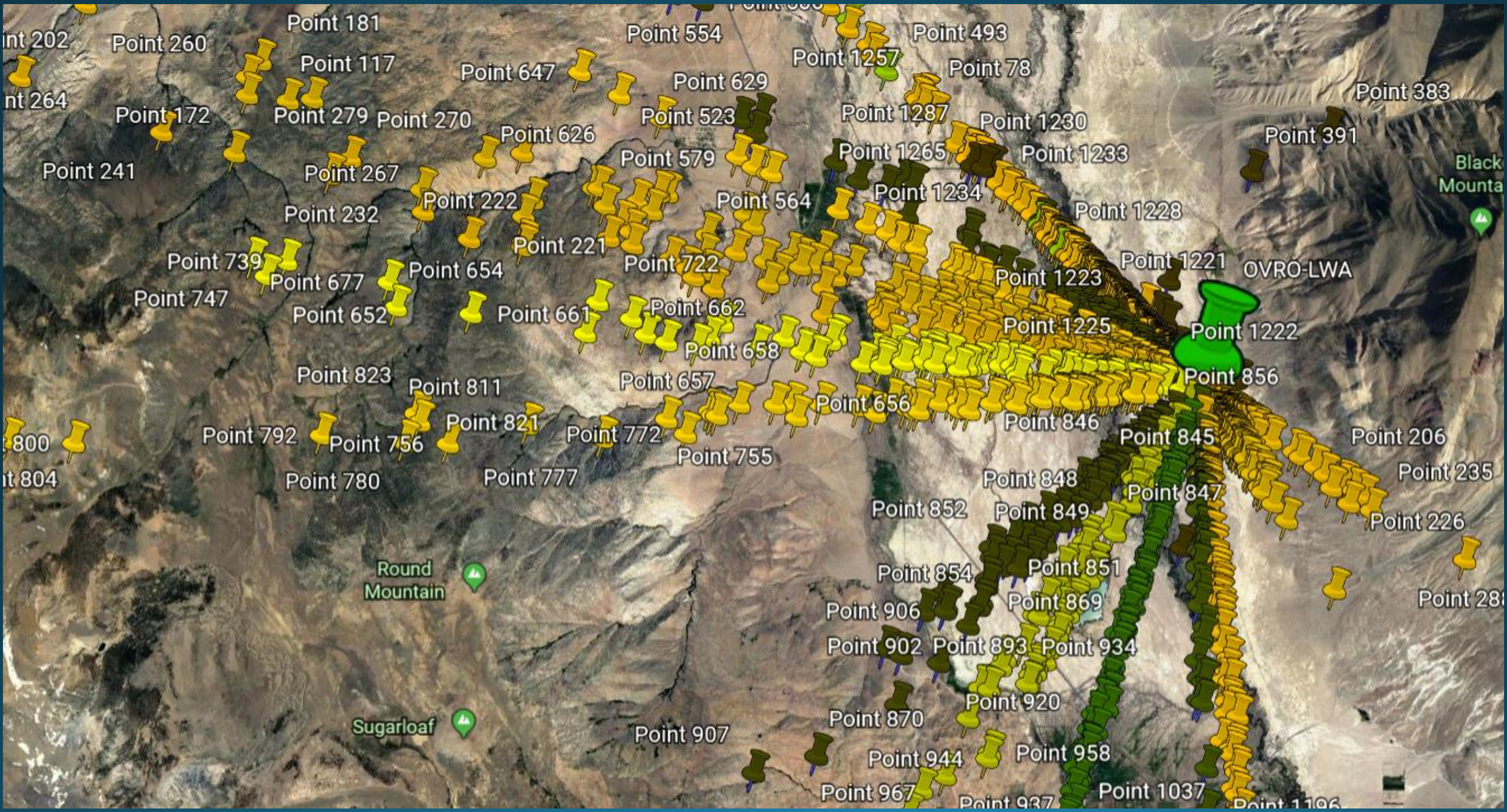

Candidate CR event: relative arrival pows (H pol)
antpos(n/s, m
antpos (e/w, m)


Candidate CR event: arrival times
antpos(n/s, m
antpos (e/w, m)


az: 269.9183, | el: 0.024854, | log10(r): 2.0991 | nOK: 130 | indThis: 106439
antennas
missed signal
matched signal
fit direction of travel


reference signal
power, arbitrary units
time (us)


Wilkerson
Peterson Mill
Keough
Hot Springs
OVRO-LWA
Round
Mountain
Sugarloaf
Zurich


Point 181
Point 260
Point 117
Point 647
Point 554
Point 493
Point 1257
Point 78
Point 629
Point 523
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Point 1230
Point 383
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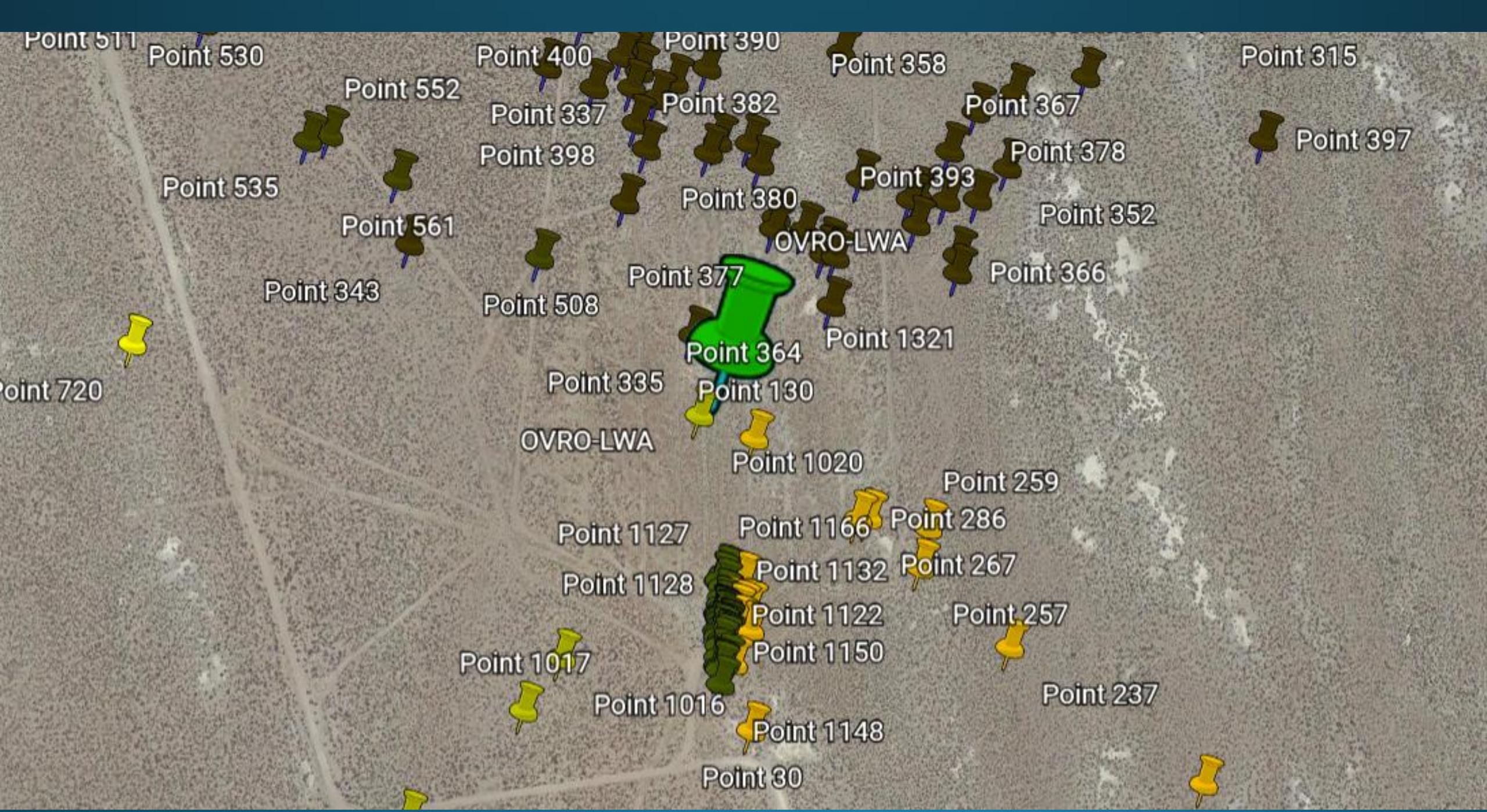
Point 279
Point 270
Point 626
Point 579
Point 1265
Point 1233
Point 241
Point 267
Point 222
Point 564
Point 1234
Point 1228
Point 232
Point 221
Point 739
Point 722
Point 1221
OVRO-LWA
Point 677
Point 654
Point 1223
Point 747
Point 652
Point 661
Point 662
Point 1225
Point 1222
Point 658
Point 823
Point 811
Point 657
Point 856
Point 656
Point 792
Point 821
Point 772
Point 846
Point 845
Point 206
Point 756
Point 755
Point 780
Point 777
Point 848
Point 847
Point 235
Point 852
Point 849
Point 226
Round Mountain
Point 854
Point 851
Point 906
Point 869
Point 902
Point 893
Point 934
Point 920
Point 870
Sugarloaf
Point 907
Point 944
Point 958
Point 967
Point 1037
Black Mounta


Point 511
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Point 390
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Point 561
OVRO-LWA
Point 377
Point 366
Point 343
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Point 335
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OVRO-LWA
Point 1020
Point 259
Point 1127
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Point 257
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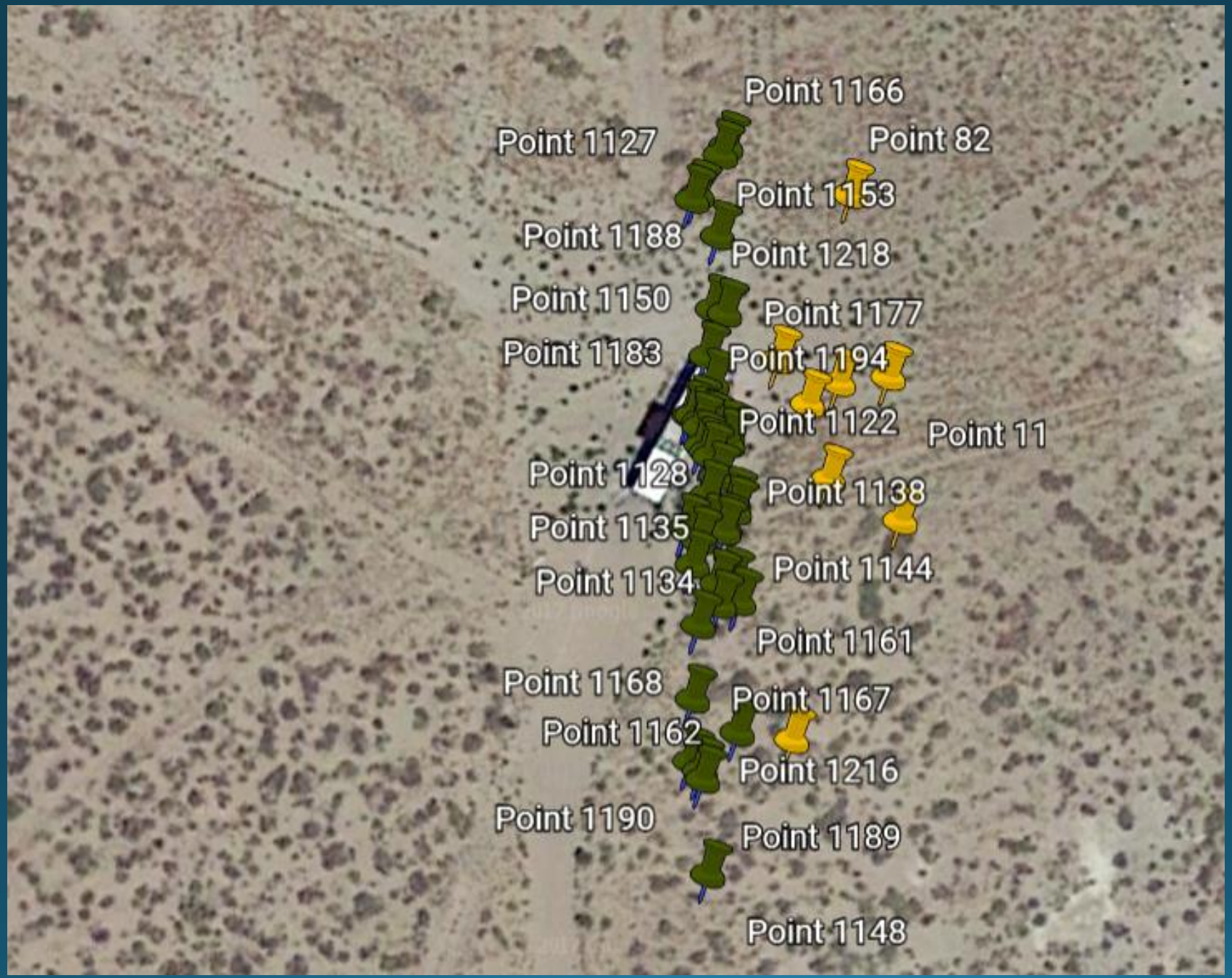
Point 1017
Point 237
Point 1016
Point 1148
Point 30


Point 1166
Point 1127
Point 82
Point 1153
Point 1188
Point 1218
Point 1150
Point 1177
Point 1183
Point 1194
Point 1122
Point 11
Point 1128
Point 1138
Point 1135
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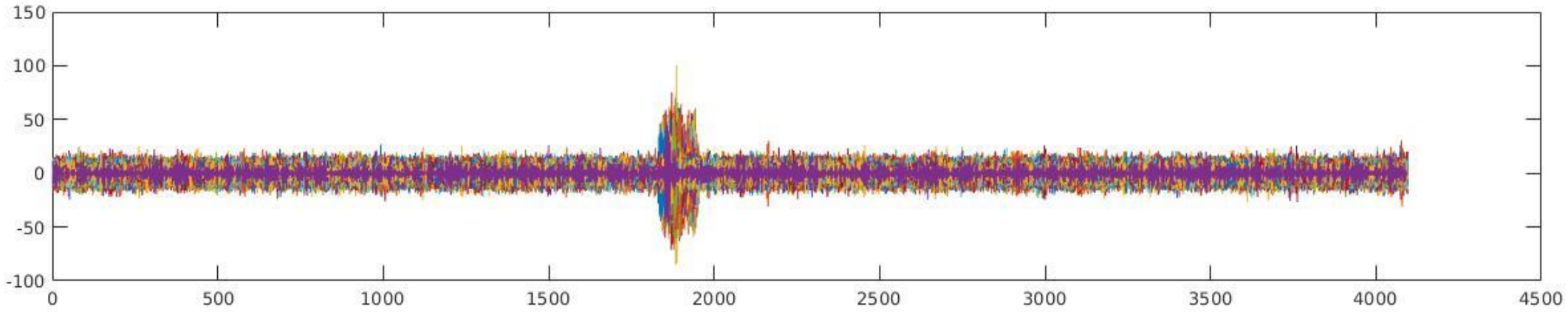
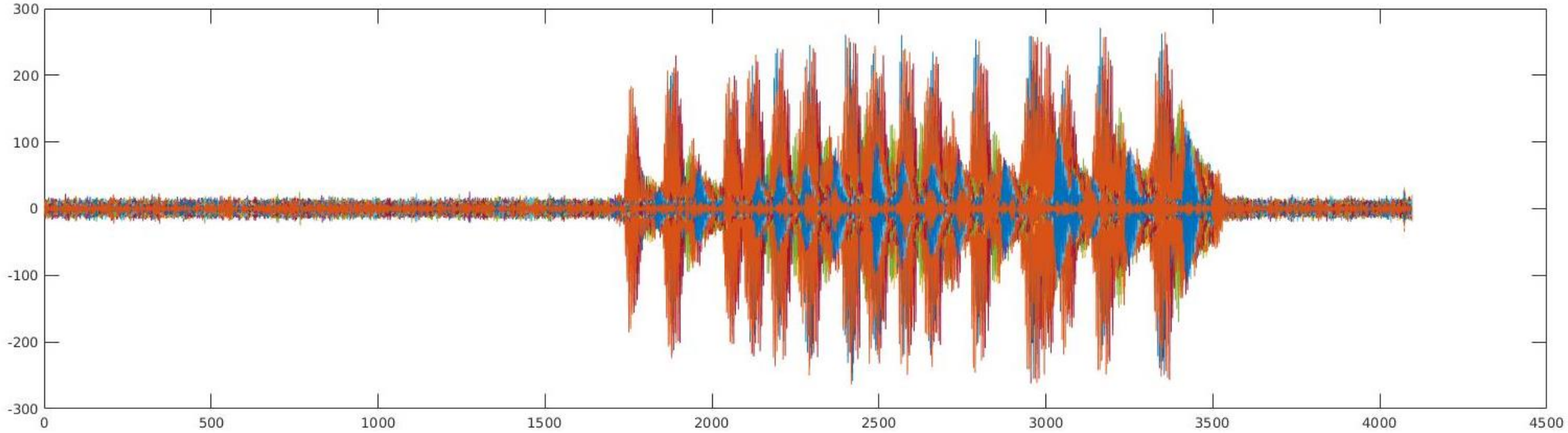
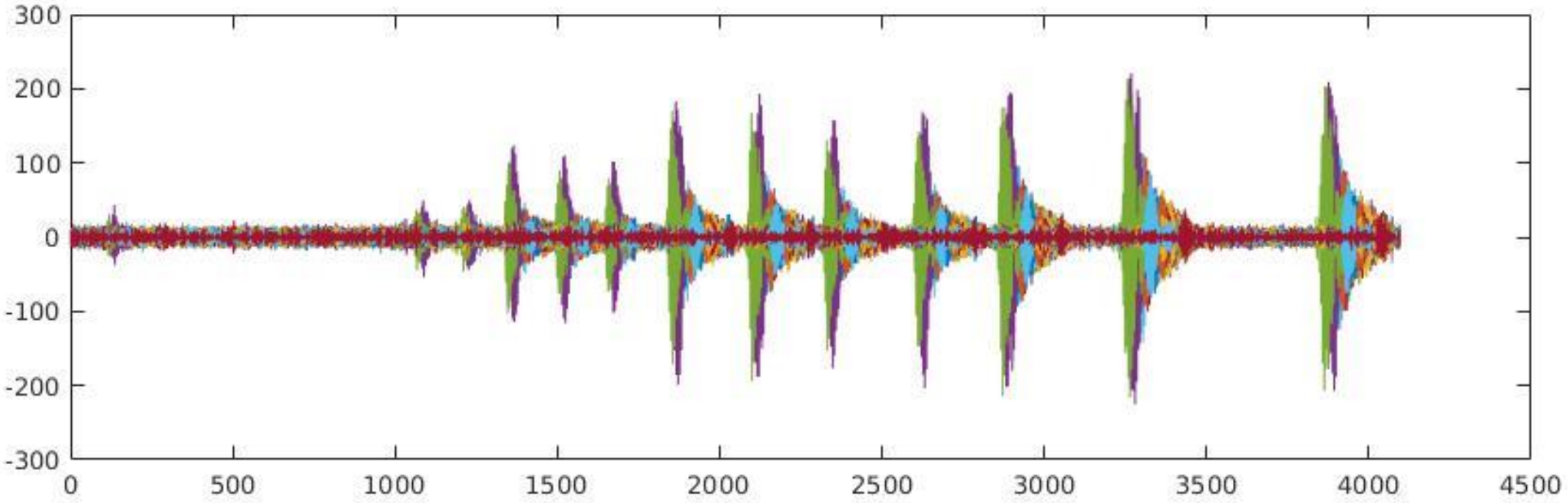
Point 1134
Point 1161
Point 1168
Point 1167
Point 1162
Point 1216
Point 1190
Point 1189
Point 1148


150
100
50
0
-50
-100
0
500
1000
1500
2000
2500
3000
3500
4000
4500


300
200
100
0
-100
-200
-300
0
500
1000
1500
2000
2500
3000
3500
4000
4500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100
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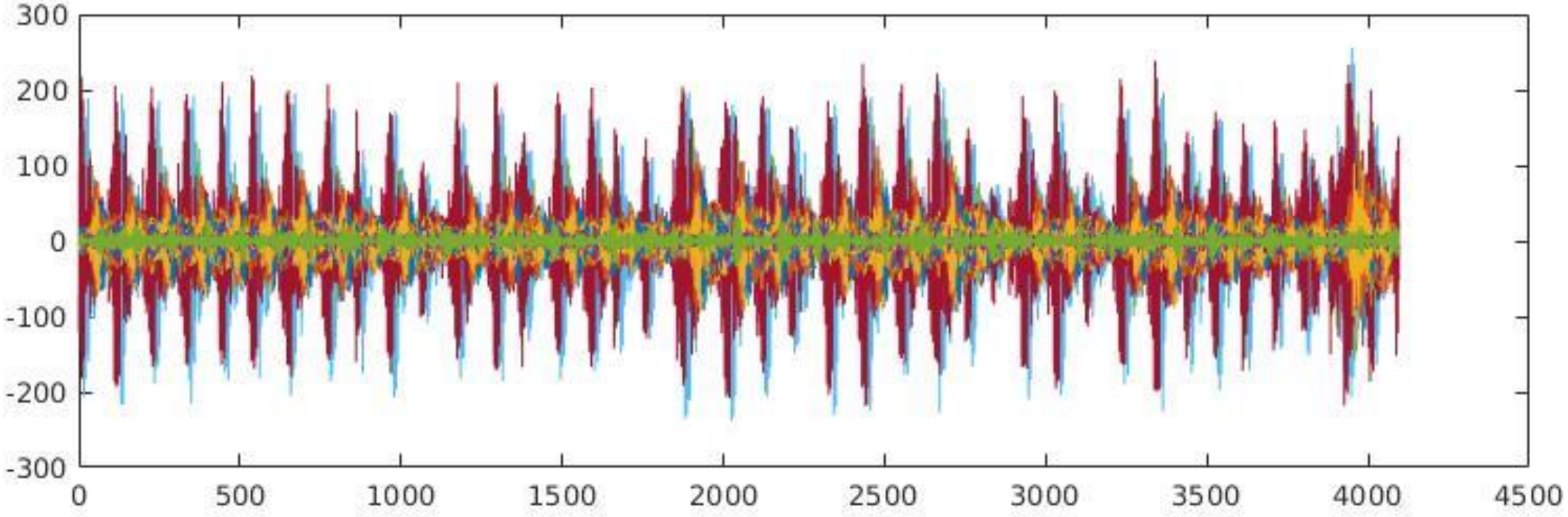
500
1000
1500
2000
2500
3000
3500
4000
4500


300
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100
0
-100
-200
-300
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1500
2000
2500
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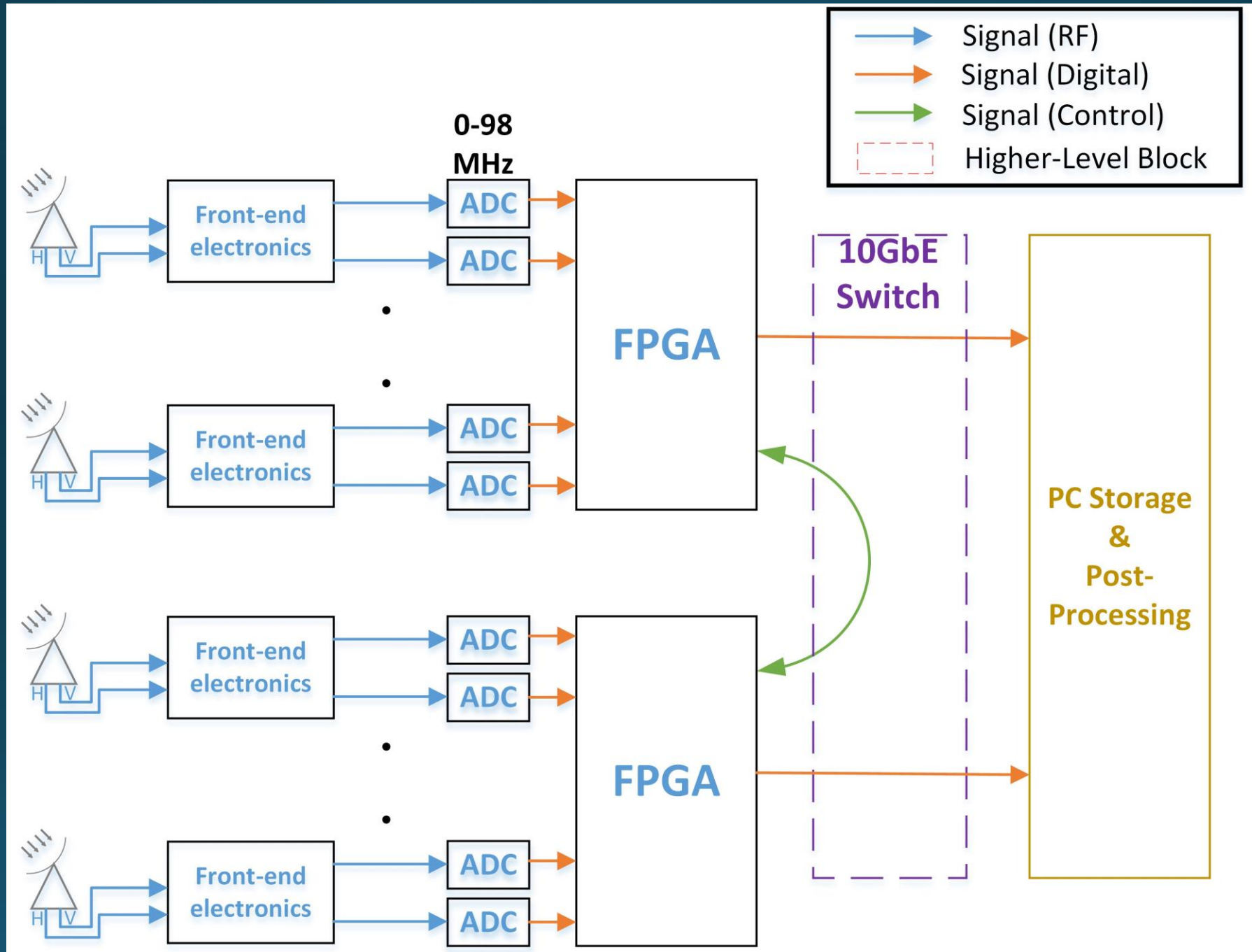
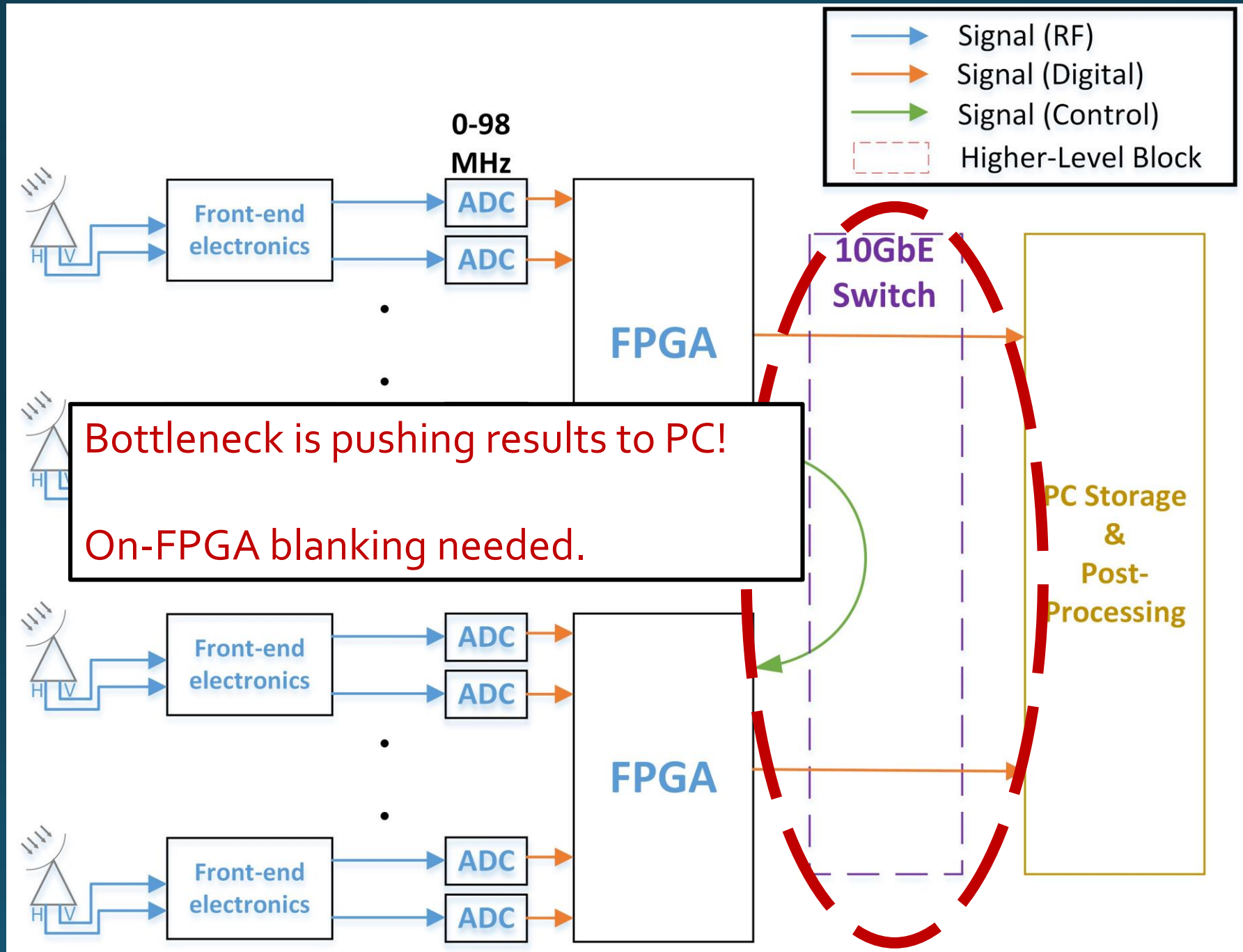
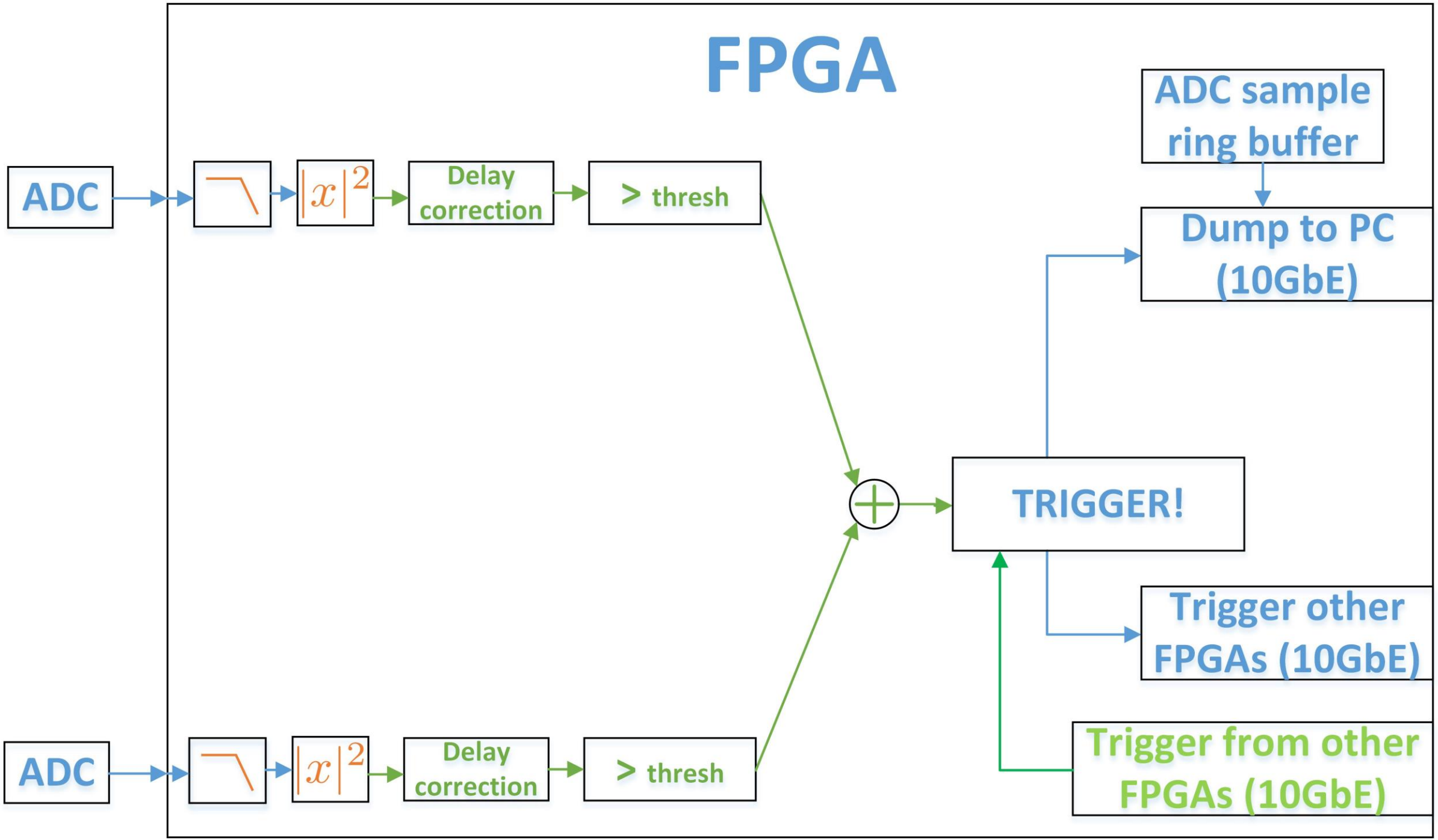
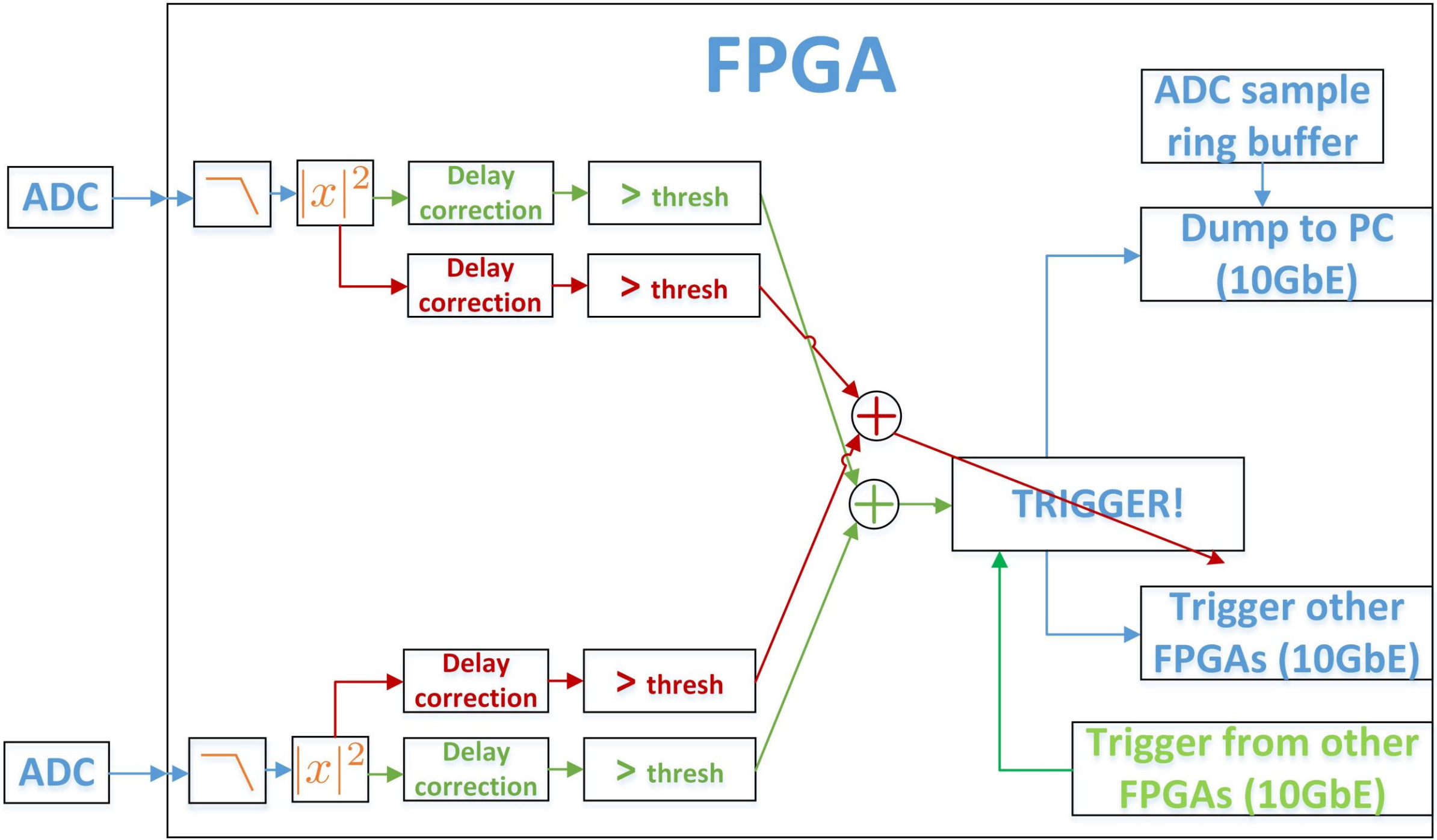
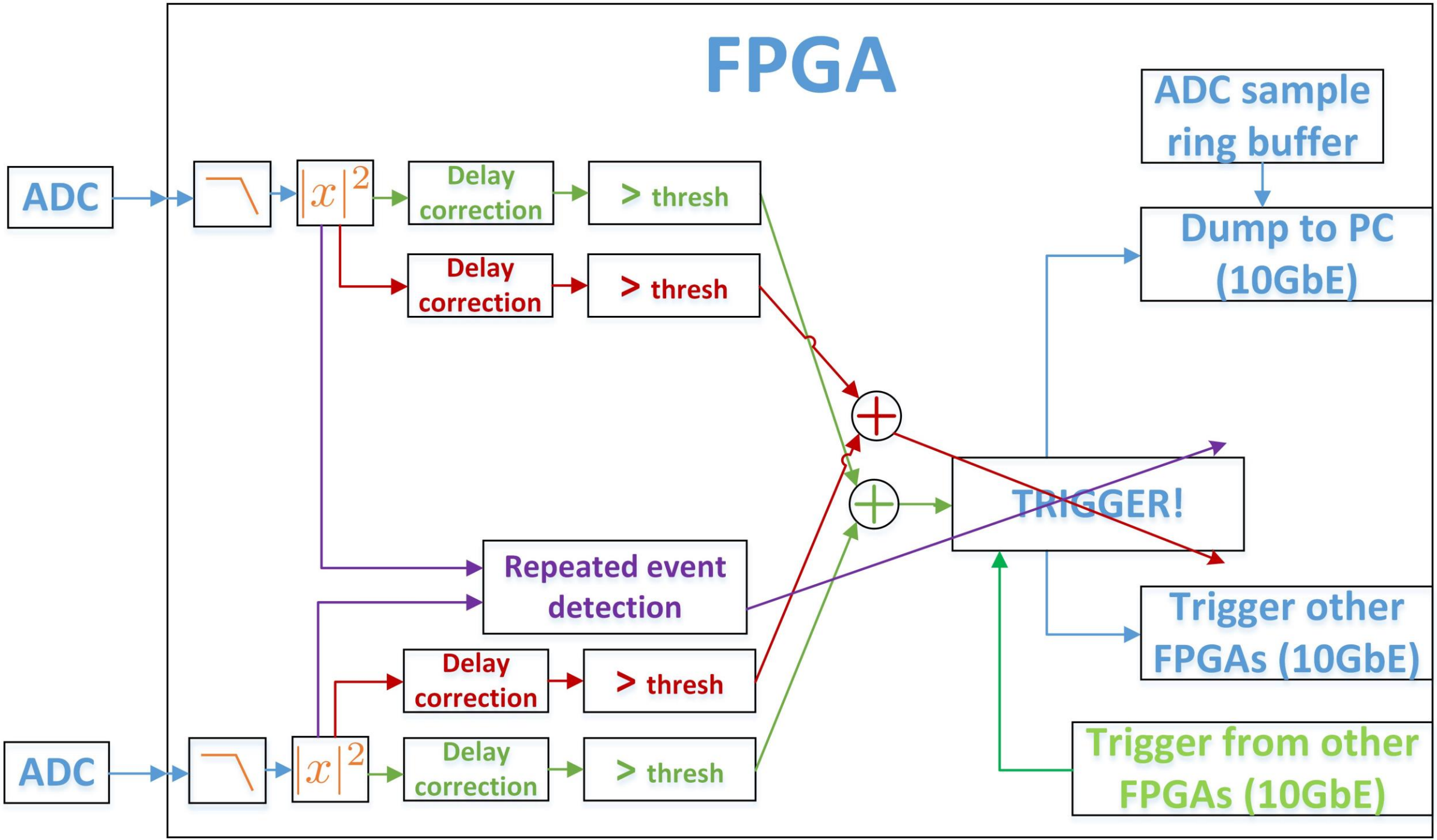
3500
4000
4500

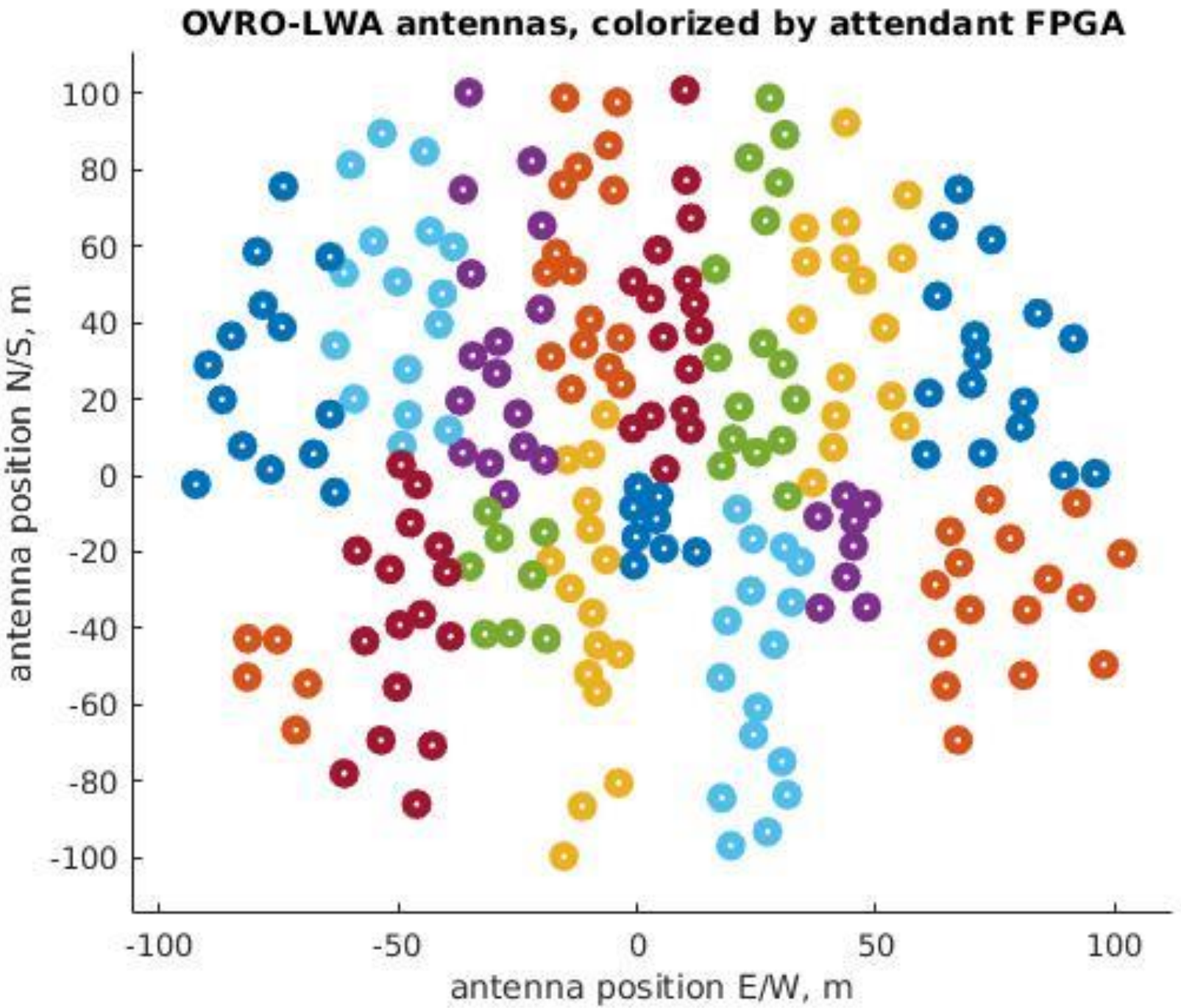

Signal (RF)
Signal (Digital)
Signal (Control)
Higher-Level Block
0-98 MHz
Front-end electronics
ADC
FPGA
10GbE Switch
PC Storage & Post-Processing
H
V

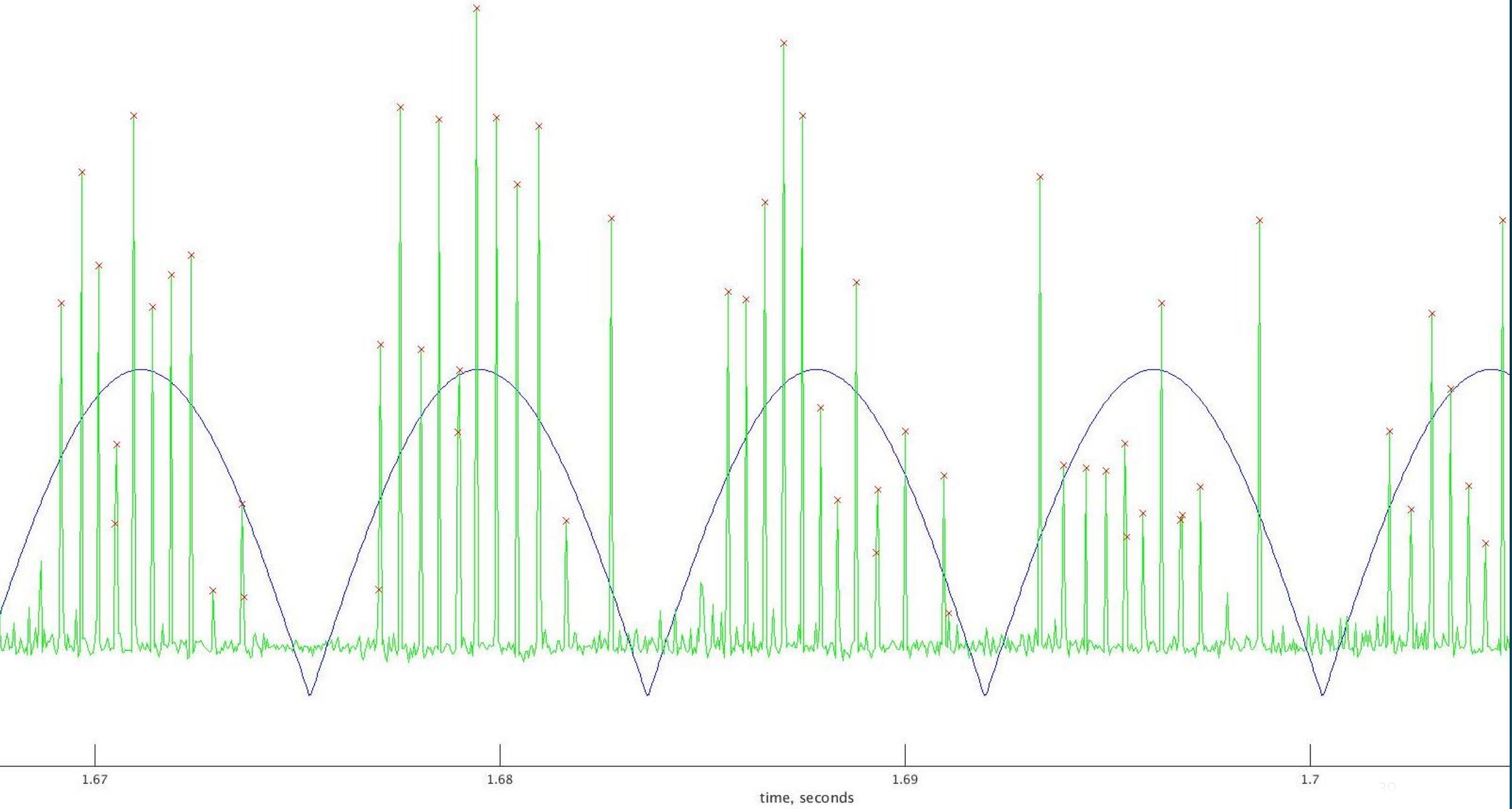

Signal (RF)
Signal (Digital)
Signal (Control)
Higher-Level Block
0-98 MHz
Front-end electronics
ADC
ADC
FPGA
10GbE Switch
PC Storage & Post-Processing
Bottleneck is pushing results to PC!
On-FPGA blanking needed.
Front-end electronics
ADC
ADC
FPGA
Front-end electronics
ADC
ADC


FPGA
ADC sample ring buffer
ADC
$|x|^2$
Delay correction
> thresh
Dump to PC (10GbE)
TRIGGER!
Trigger other FPGAs (10GbE)
ADC
$|x|^2$
Delay correction
> thresh
Trigger from other FPGAs (10GbE)

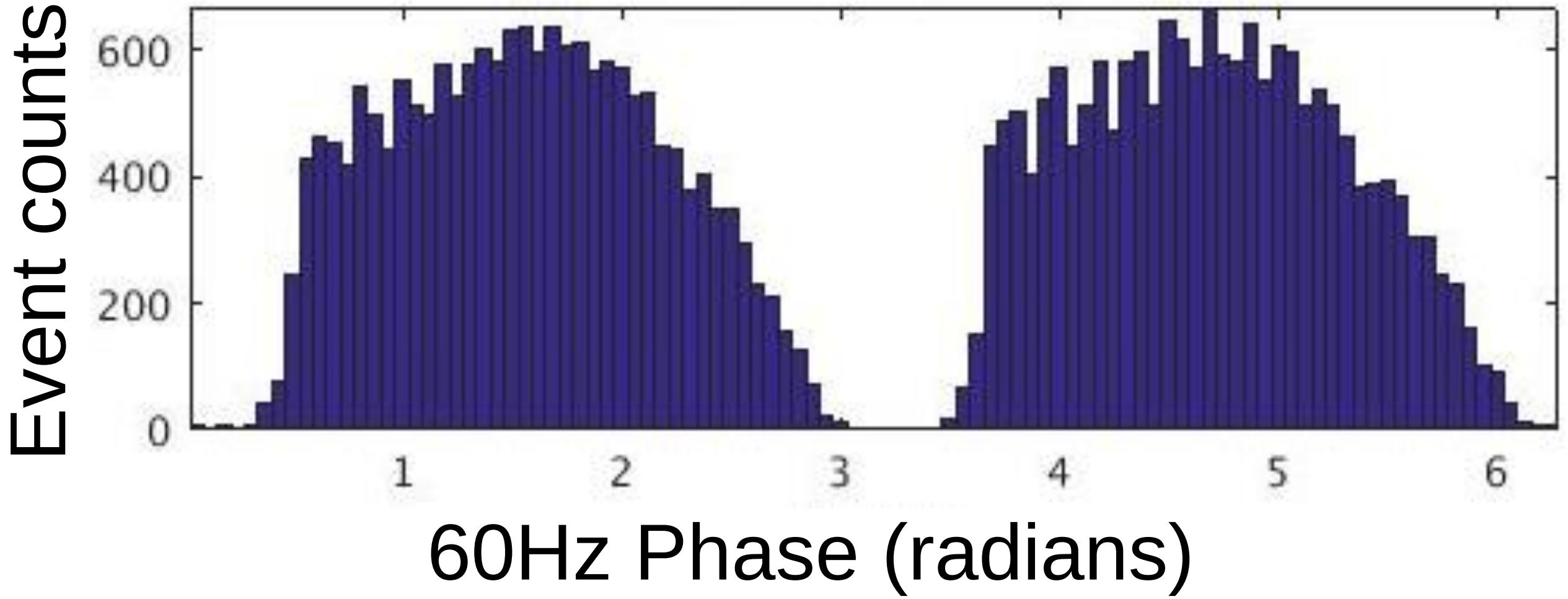

FPGA
ADC
ADC
$|x|^2$
$|x|^2$
Delay correction
Delay correction
Delay correction
Delay correction
> thresh
> thresh
> thresh
> thresh
ADC sample ring buffer
Dump to PC (10GbE)
TRIGGER!
Trigger other FPGAs (10GbE)
Trigger from other FPGAs (10GbE)


FPGA
ADC
ADC
$|x|^2$
$|x|^2$
Delay correction
Delay correction
Delay correction
Delay correction
> thresh
> thresh
> thresh
> thresh
Repeated event detection
ADC sample ring buffer
Dump to PC (10GbE)
TRIGGER!
Trigger other FPGAs (10GbE)
Trigger from other FPGAs (10GbE)


OVRO-LWA antennas, colorized by attendant FPGA
antenna position N/S, m
100
80
60
40
20
0
-20
-40
-60
-80
-100
-100
-50
0
50
100
antenna position E/W, m


1.67
1.68
1.69
1.7
time, seconds

Power line RFI histogram vs voltage phase



Next Steps

- Voltage time of arrival solutions only good to RMS 3 samples
  - Improvement = better localization
- 1.6M events; probably 15 CRs in data
  - How to convince self that detection is actually cosmic ray?
- "More (or better) data trumps better algorithms"
  - Work on fixing bad RFI sources

Takeaways

- RFI is a problem.
  - Planes preclude a fully automatic pipeline
  - Could we run from much of our RFI by tracking the AC voltage?
  - This tool is very powerful for localizing RFI!

- Need a system which is matched to the CR detection task
  - Bring all the voltages home
  - Ideally, process all the voltages in the same location

- I am very close!