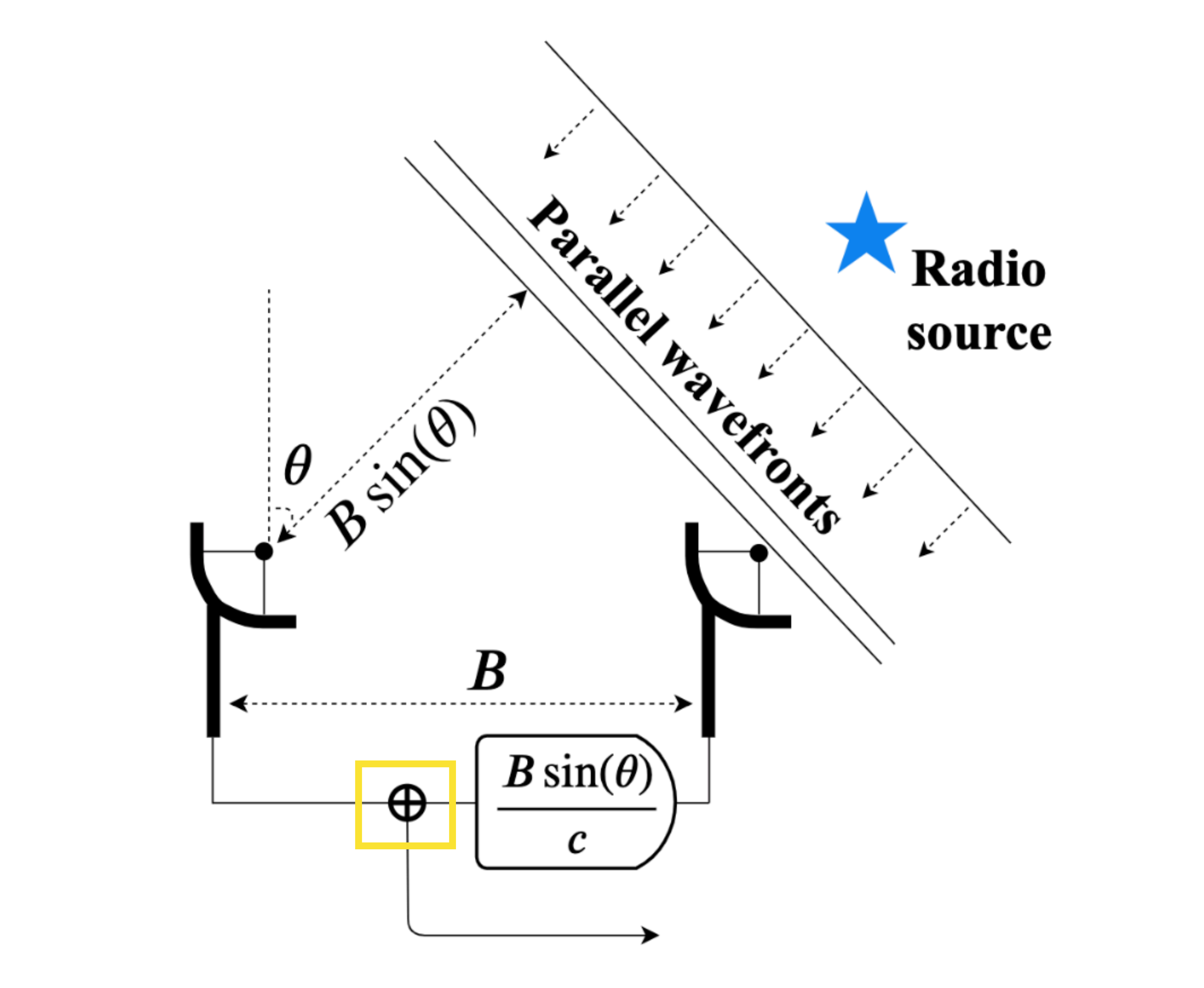
Updates on ATA beam-forming calibration

Wael Farah - interferometric SETI meeting

Simple Interferometer

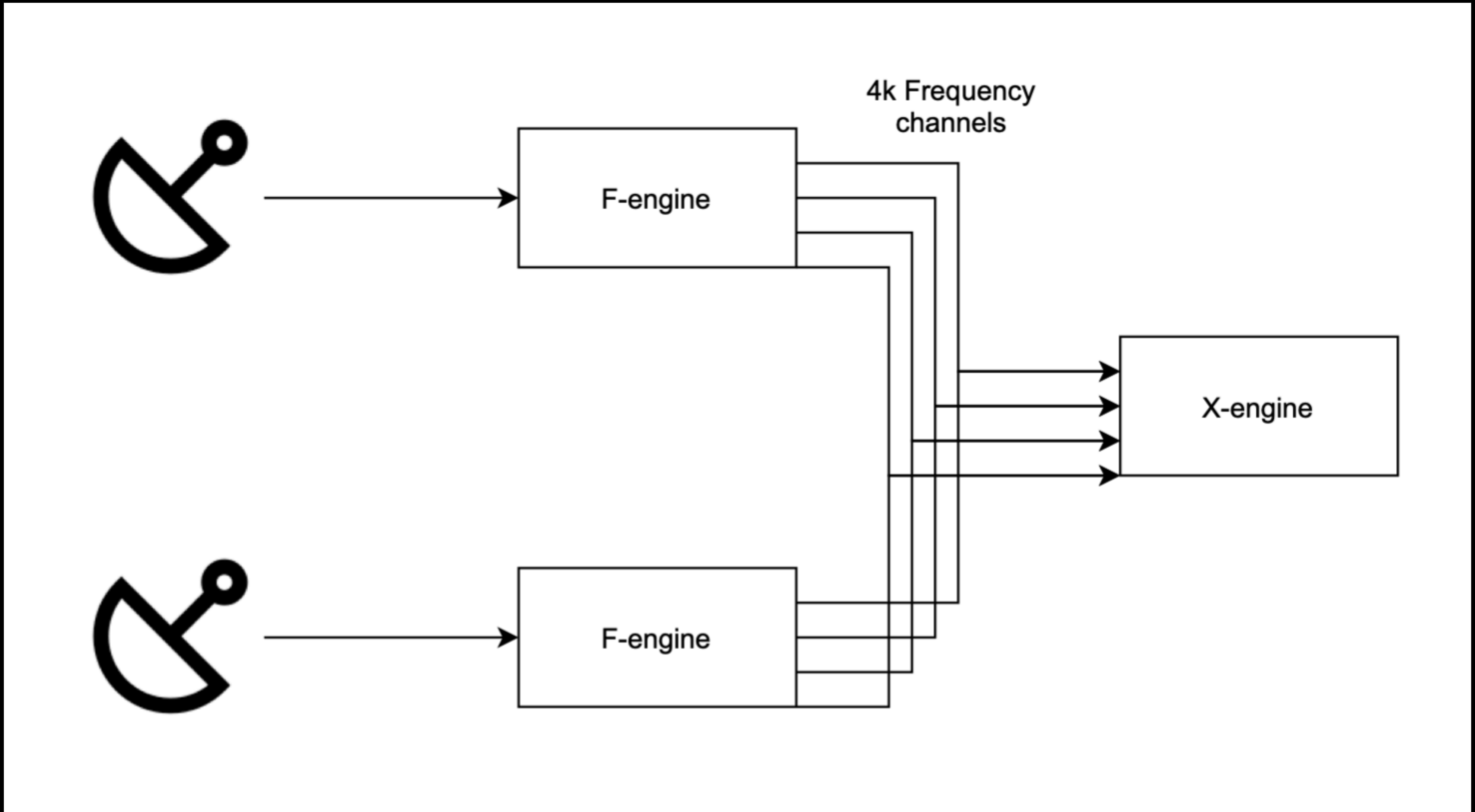
- 2 major operations:
  - Multiplication (aka correlation). Each antenna is multiplied by every other (including itself), forming baselines. 2D iFFT of this data product gives sky intensity distribution (i.e. image of the sky)
  - Addition (aka beamforming). Every antenna is compensated for the delay (with respect to a reference position) and instrumental phase, and then summed coherently to maximize the sensitivity of the array on a sky position



Sources of delay

- Geometric delay: the fact that antennas are spread geometrically on earth
- Fixed delay: Due to fiber/copper, can change over time/temperature.
- Instrumental phase: electronics + atmosphere (concern at higher frequencies) + …

Backend Schematic



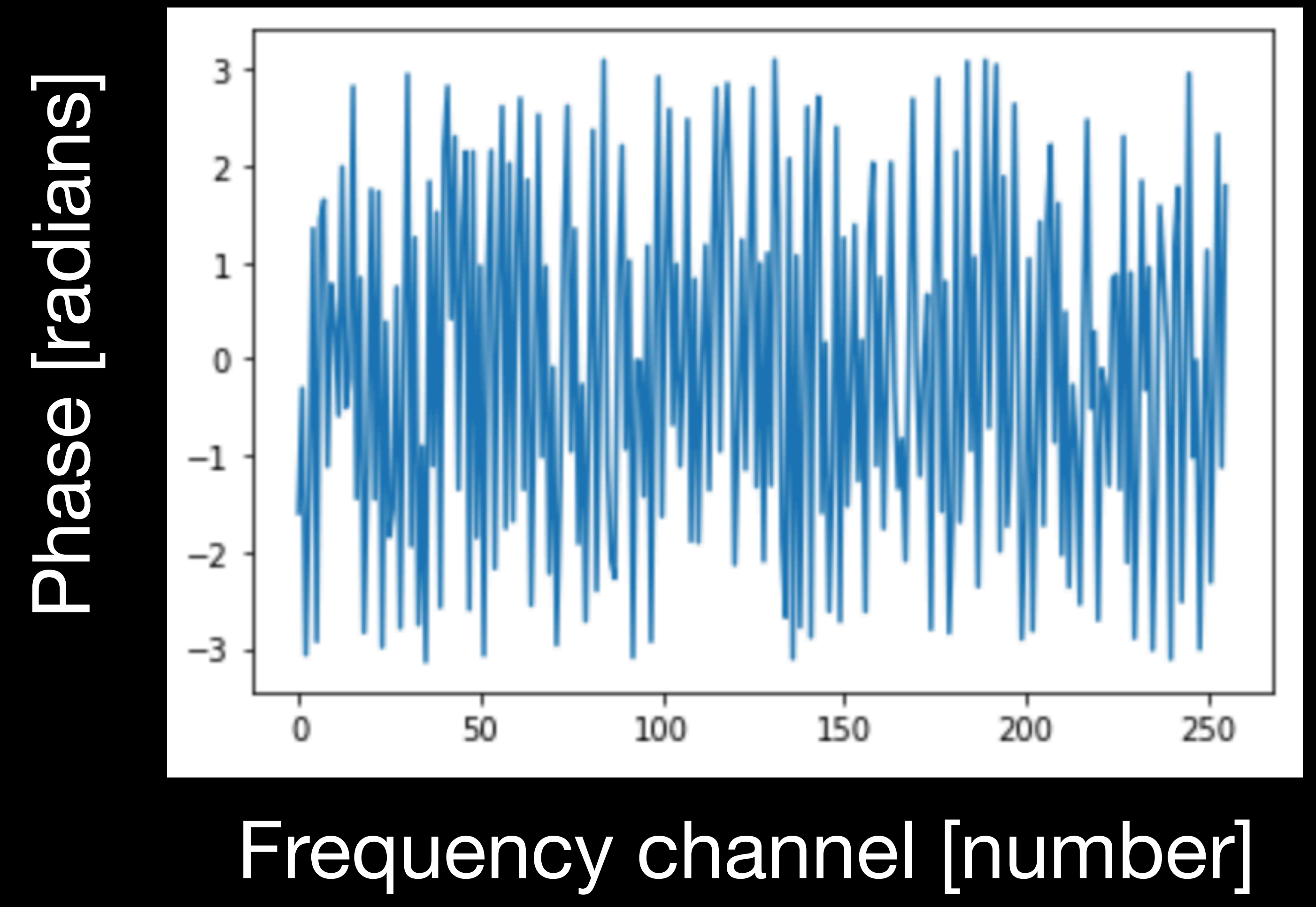
Calibration (delay+ phase) scheme

1. Cross-correlate antennas

$$F(\nu) = \sum_{t_i}^{T} V_a(t_i, \nu) \times V_b^*(t_i, \nu)$$

Where * represents the complex conjugate,
\nu is frequency
and “a” and “b” are antenna indices

1c <-> 5c baseline (x pol)

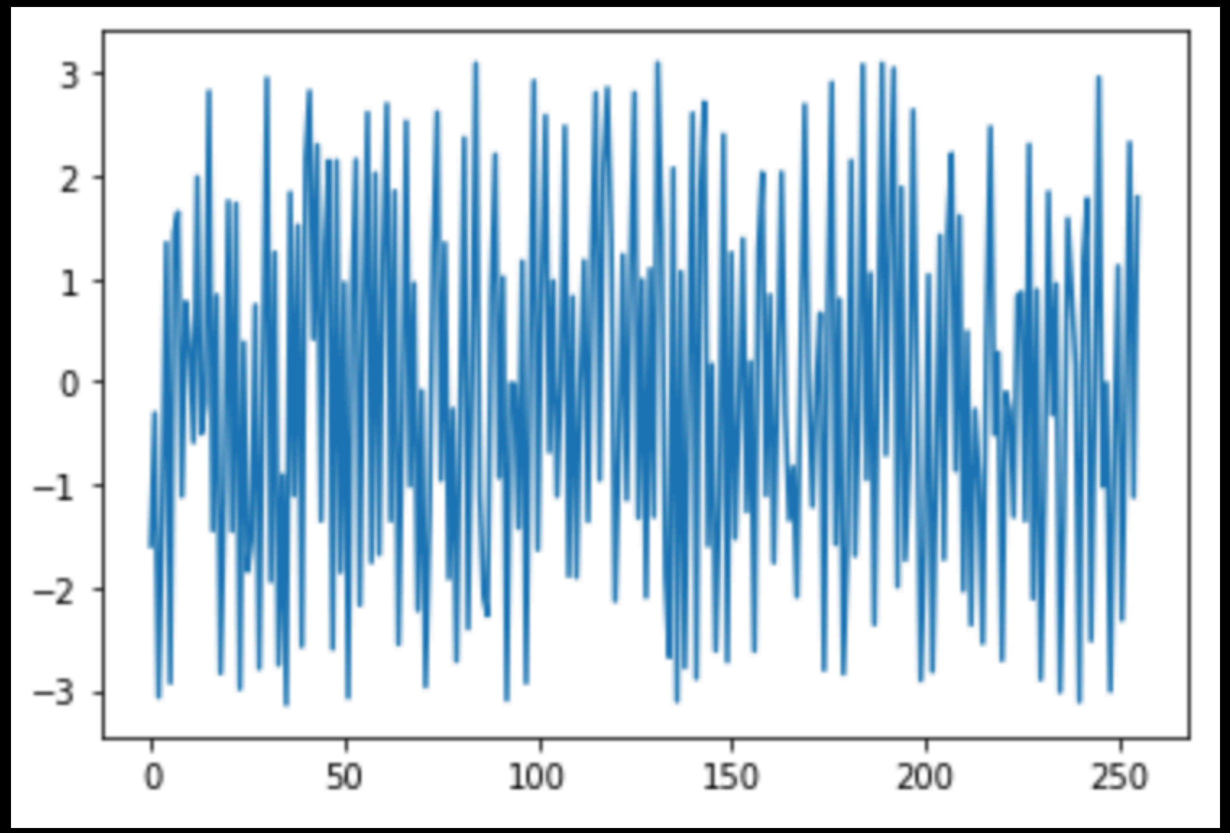


Calibration (delay+ phase) scheme

1. Cross-correlate antennas,
 display data + sanity checks

1c <-> 5c baseline (x pol)

Phase [radians]



Frequency channel [number]

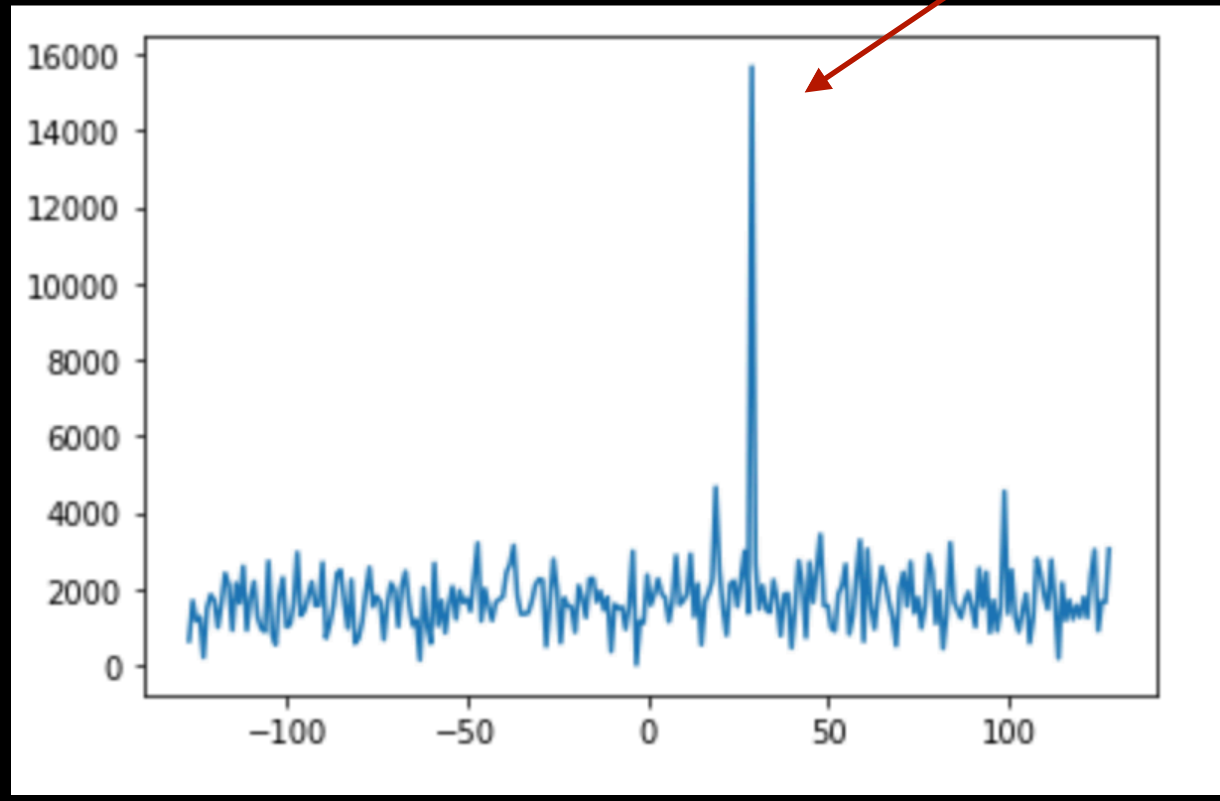
Lag in the time domain
=
fringe in the freq domain

iFFT

Spike in lag spectrum

Lag spectrum

Amplitude [arb.]

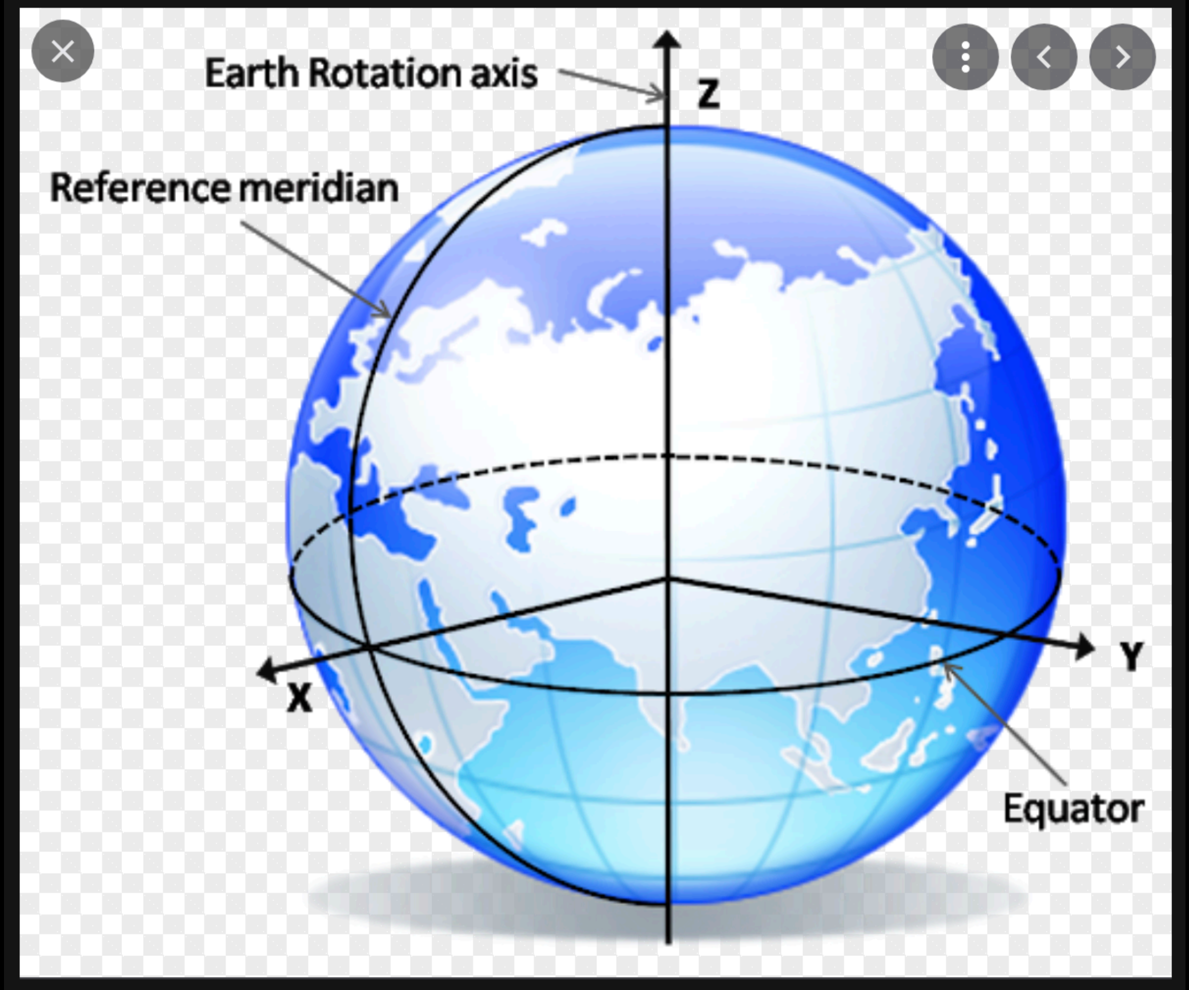


Samples [1/64MHz = 15.625 ns]

Calibration (delay+ phase) scheme

1. Cross-correlate antennas, display data + sanity checks

2. Calculate **geometric delays** given the position of antennas + position of source (and a reference antenna position)



ITRF (ECEF; earth centered earth fixed) antenna positions XYZ

	x	y	z
1A	-2.524136e+06	-4.123448e+06	4.147709e+06
1F	-2.524193e+06	-4.123464e+06	4.147658e+06
1C	-2.524141e+06	-4.123508e+06	4.147649e+06
2A	-2.524086e+06	-4.123417e+06	4.147769e+06
4J	-2.523998e+06	-4.123376e+06	4.147863e+06
2H	-2.524174e+06	-4.123388e+06	4.147745e+06
3D	-2.524045e+06	-4.123400e+06	4.147811e+06
5B	-2.523924e+06	-4.123448e+06	4.147837e+06
1K	-2.524156e+06	-4.123435e+06	4.147709e+06
5C	-2.523925e+06	-4.123461e+06	4.147824e+06
1H	-2.524203e+06	-4.123431e+06	4.147685e+06
2B	-2.524070e+06	-4.123435e+06	4.147761e+06

Calibration (delay+ phase) scheme

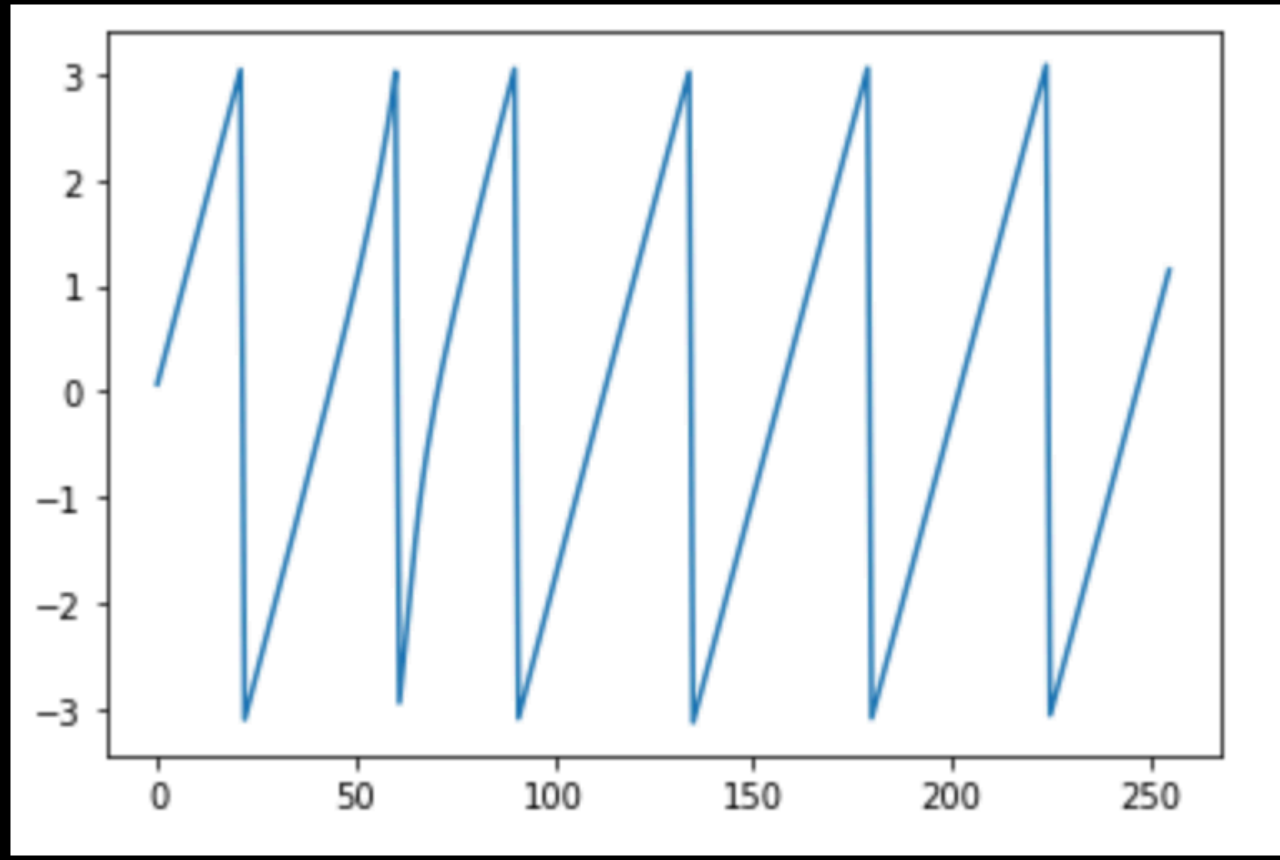
1. Cross-correlate antennas,
 display data + sanity checks

2. Calculate **geometric delays**
 given the position of antennas +
 position of source (and a reference
 antenna position)

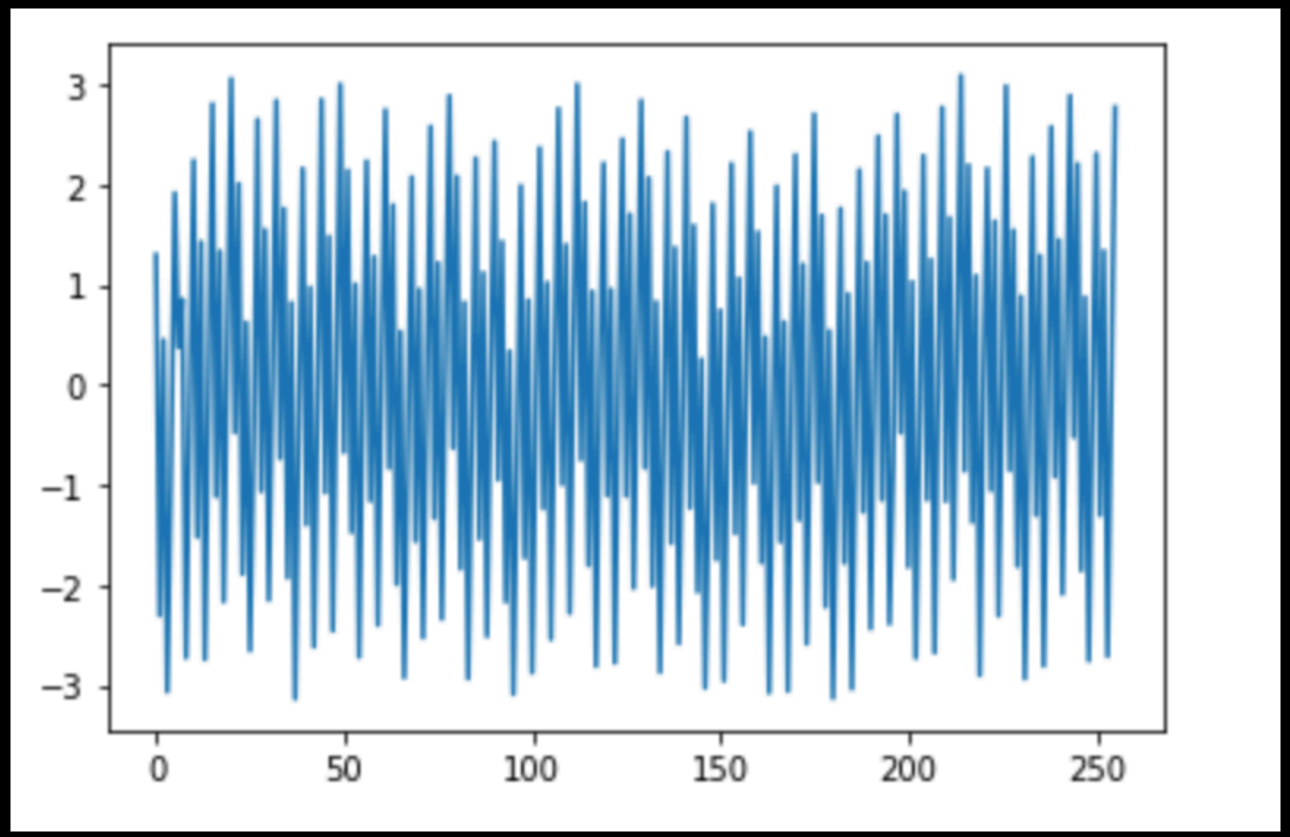
3. Apply geometric delays:

~6 samples
~ 93.75 ns

Geometric
delay phasor:

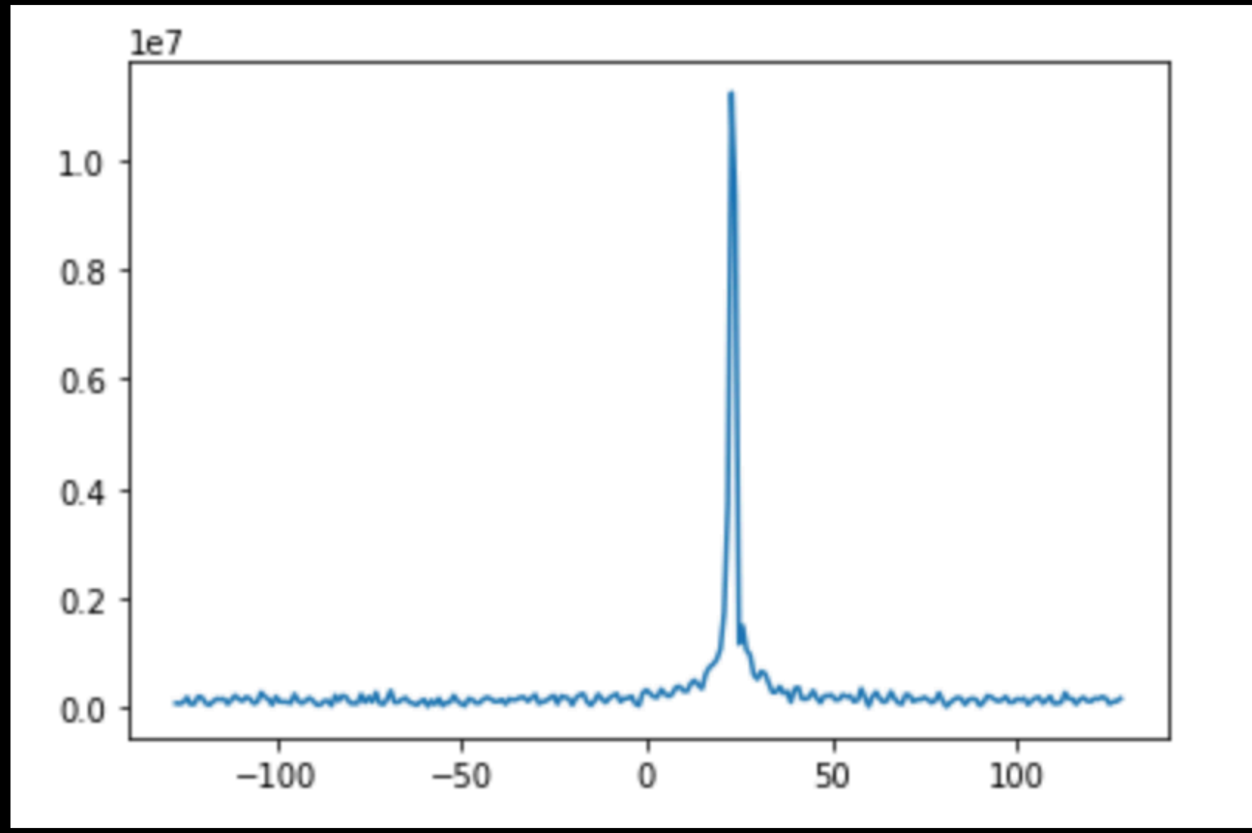


1c <-> 5c baseline



iFFT

Lag spectrum



Calibration (delay+ phase) scheme

1. Cross-correlate antennas, display data + sanity checks

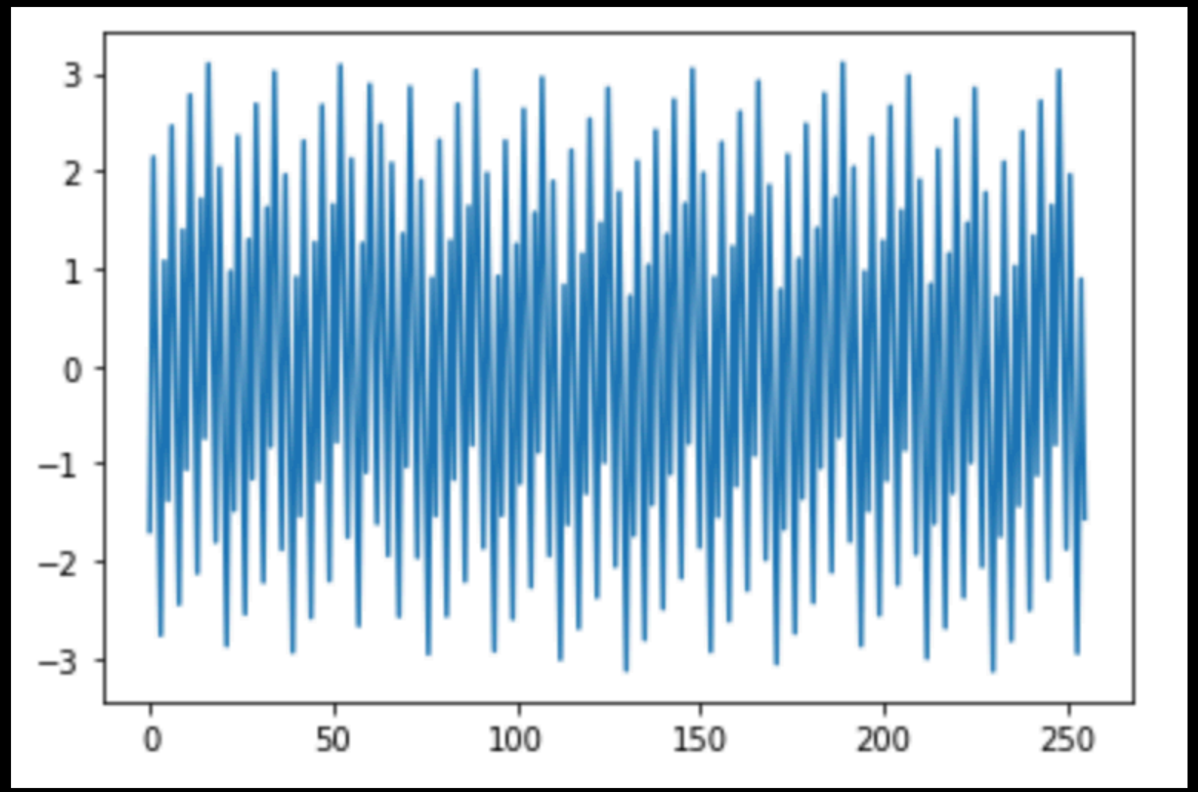
2. Calculate **geometric delays** given the position of antennas + position of source (and a reference antenna position)

3. Apply geometric delays

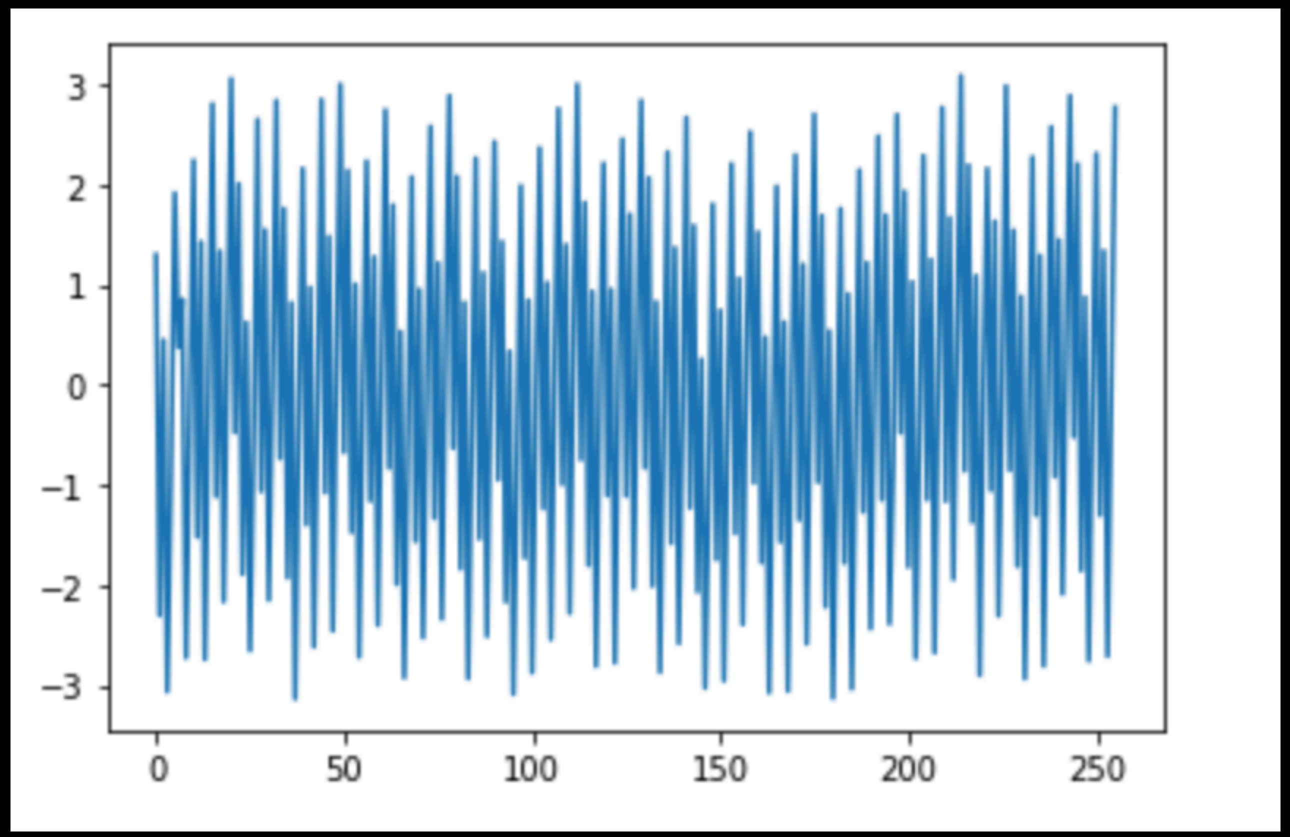
4. Measure integer-sample **fixed delays** from lag spectrum.

22 samples = 343.75ns

Fixed delay phasor:

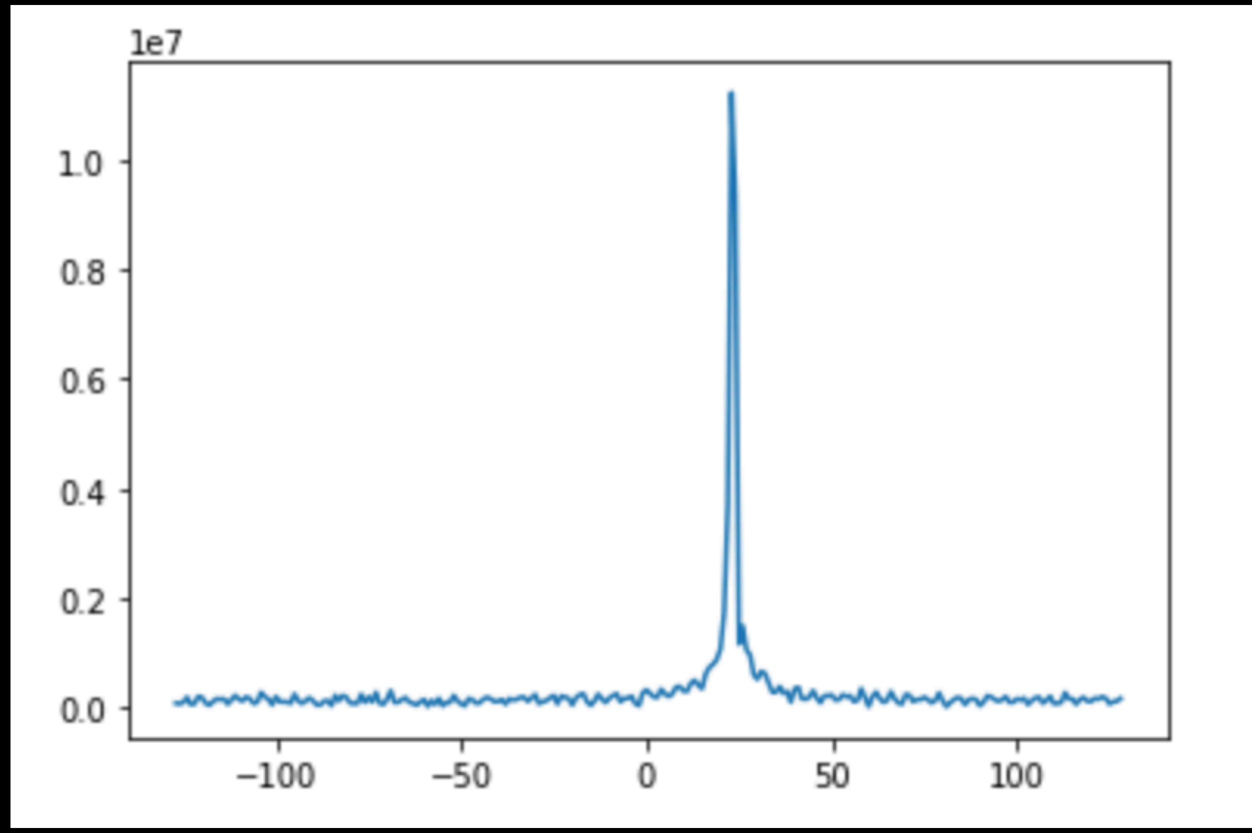


1c <-> 5c baseline



iFFT

Lag spectrum



Calibration (delay+ phase) scheme

1. Cross-correlate antennas, display data + sanity checks

2. Calculate **<u>geometric delays</u>** given the position of antennas + position of source (and a reference antenna position)

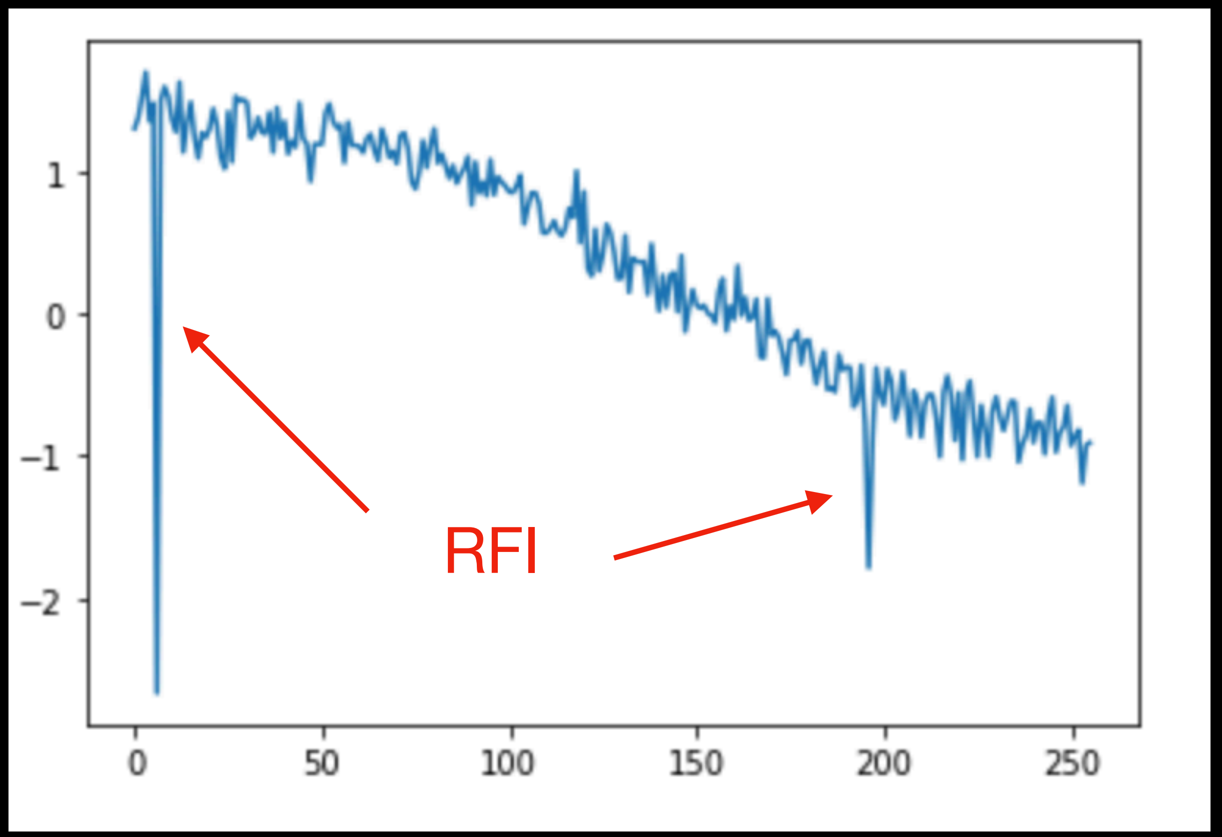
3. Apply geometric delays

4. Measure integer-sample **<u>fixed delays</u>** from lag spectrum.

5. Apply <u>fixed sample delays:</u>

1c <-> 5c baseline

Phase [radians]

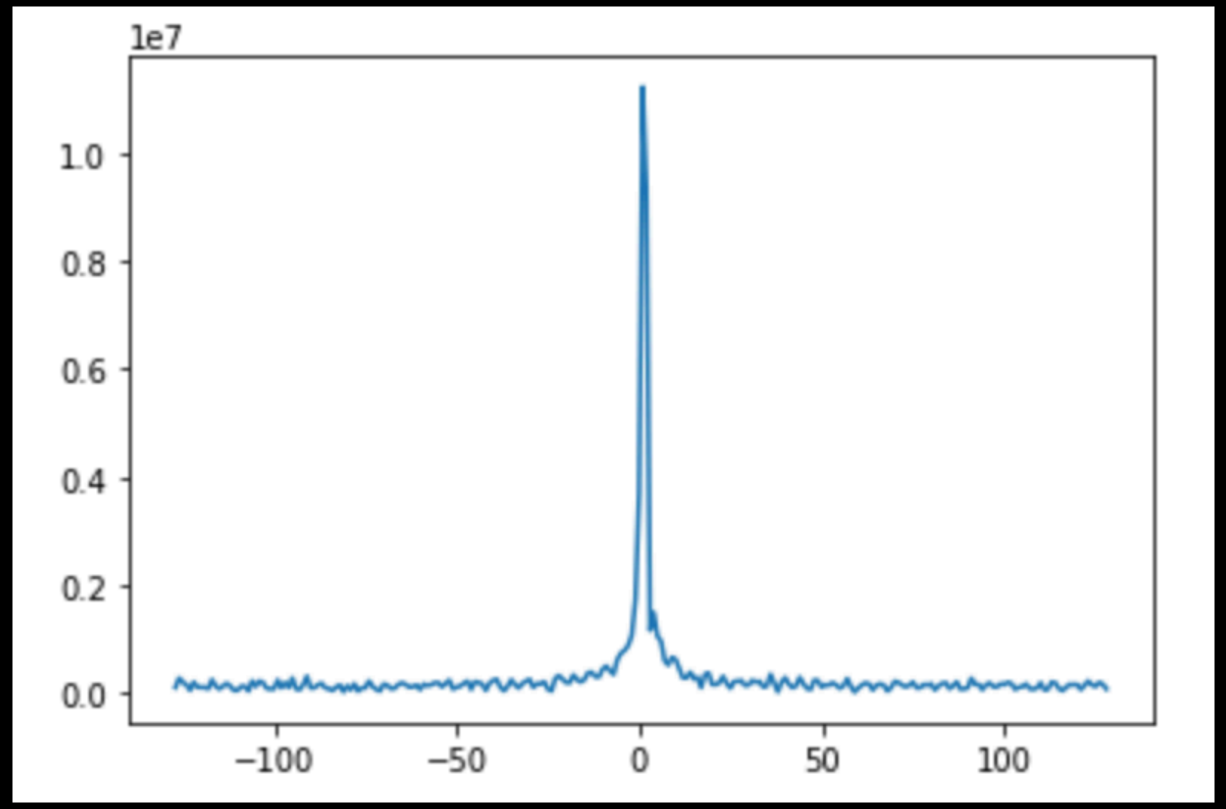


Frequency channel [number]

iFFT

Lag spectrum

Amplitude [arb.]



Samples [1/64MHz = 15.625 ns]

Calibration (delay+ phase) scheme

1. Cross-correlate antennas, display data
 + sanity checks

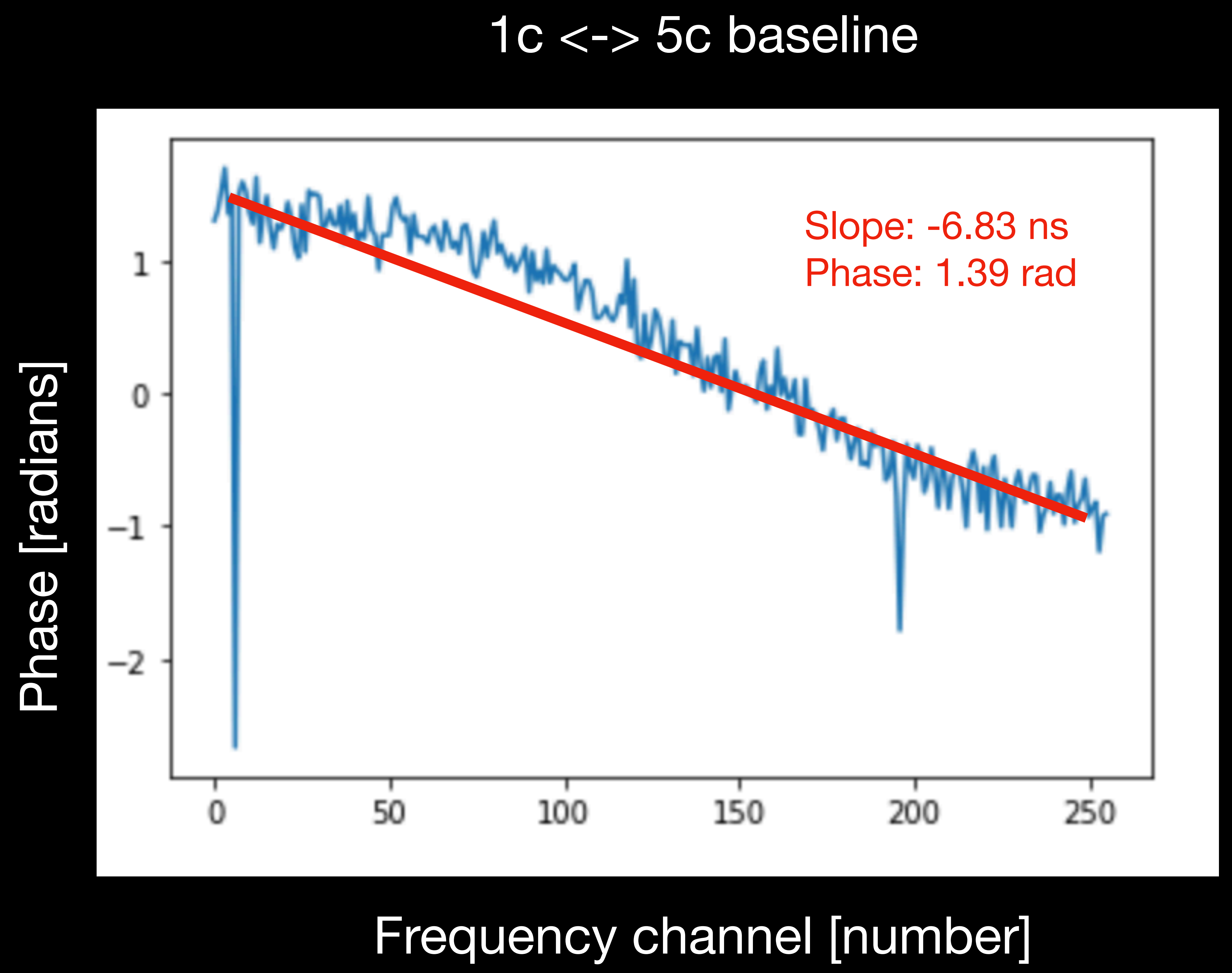
2. Calculate **geometric delays** given the
 position of antennas + position of source
 (and a reference antenna position)

3. Apply geometric delays

4. Measure integer-sample **fixed delays**
 from lag spectrum.

5. Apply fixed sample delays

6. Measure sub-sample delay (slope)
 and
 measure phase (intercept)



Calibration (delay+ phase) scheme

1. Cross-correlate antennas, display data + sanity checks

2. Calculate **<u>geometric delays</u>** given the position of antennas + position of source (and a reference antenna position)

3. Apply geometric delays

4. Measure integer-sample **<u>fixed delays</u>** from lag spectrum.

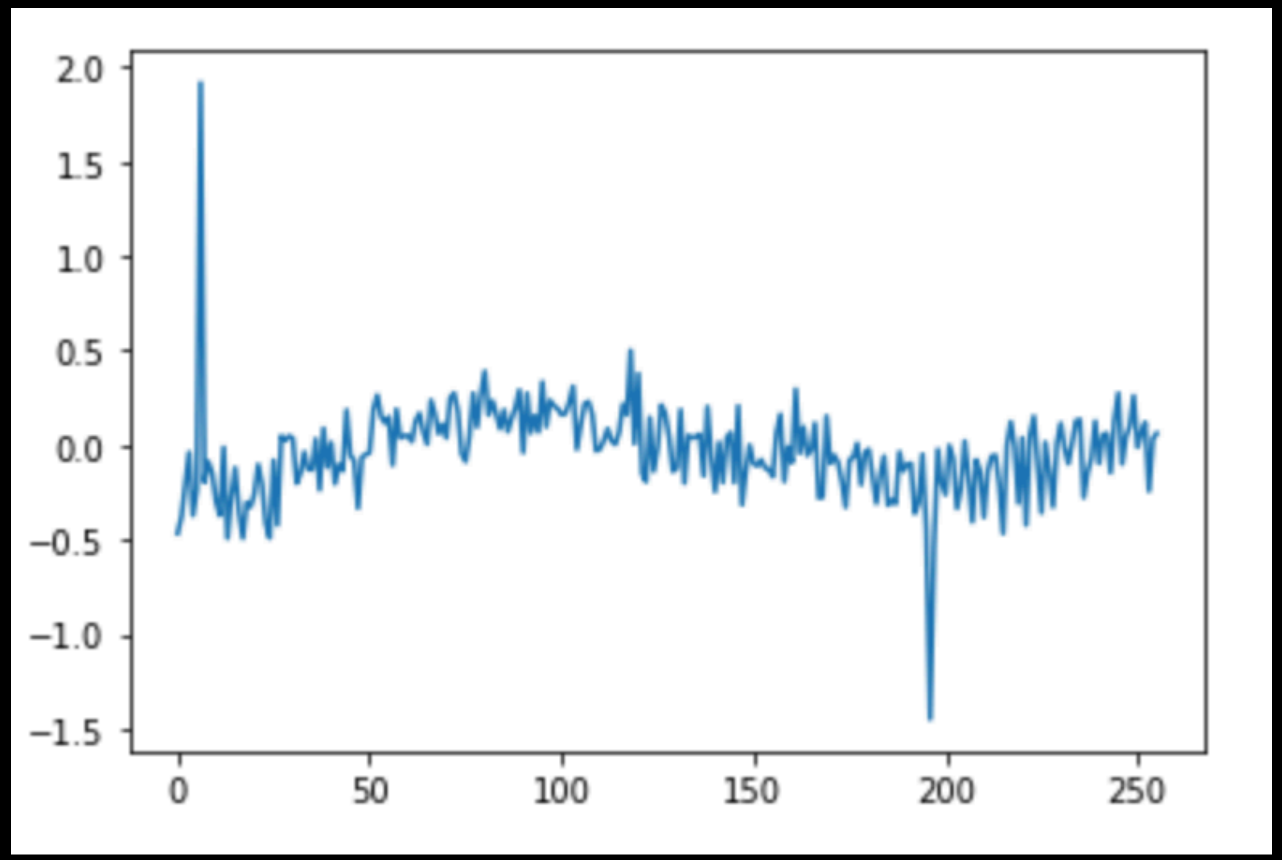
5. Apply <u>fixed sample delays</u>

6. Measure <u>sub-sample delay</u> (slope)
   and
   measure <u>phase</u> (intercept)

7. Apply <u>sub-sample delay</u> + <u>phase</u>

8. Do the above for all other antennas

1c <-> 5c baseline

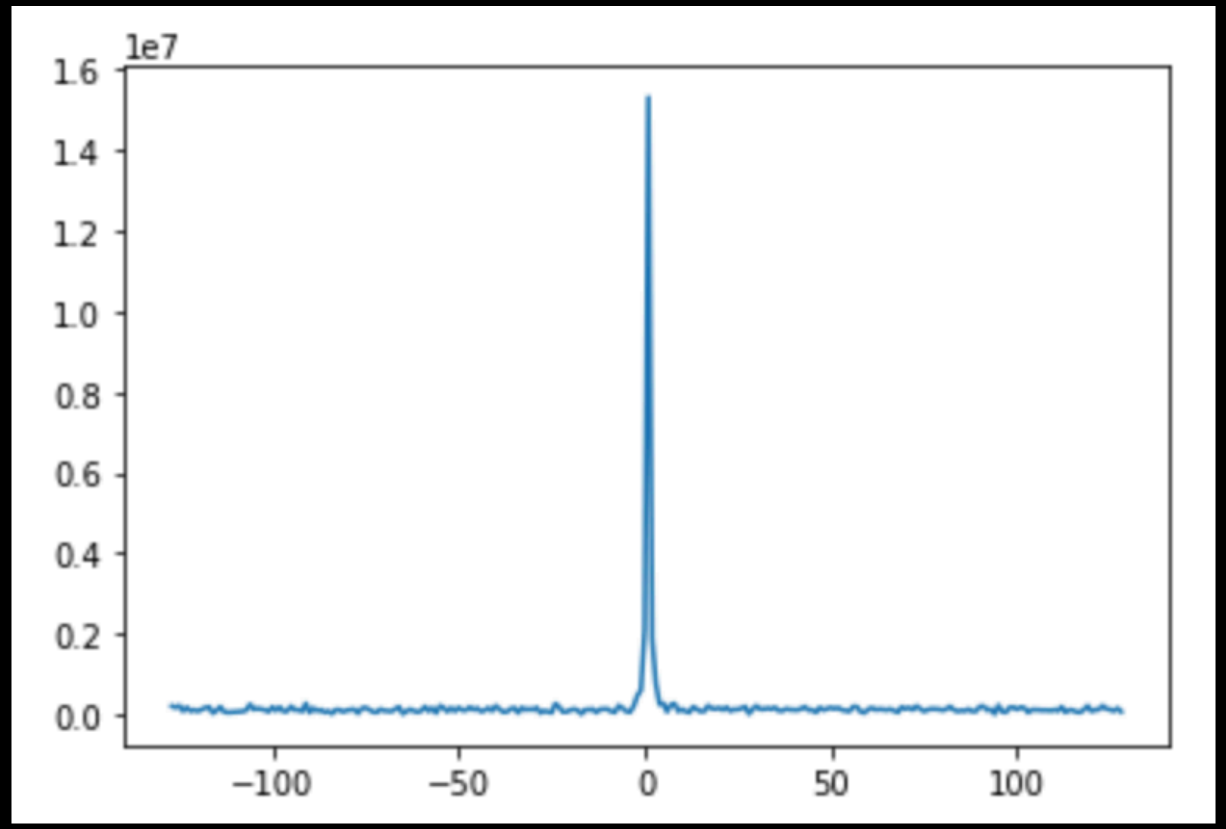


Phase [radians]

Frequency channel [number]

iFFT

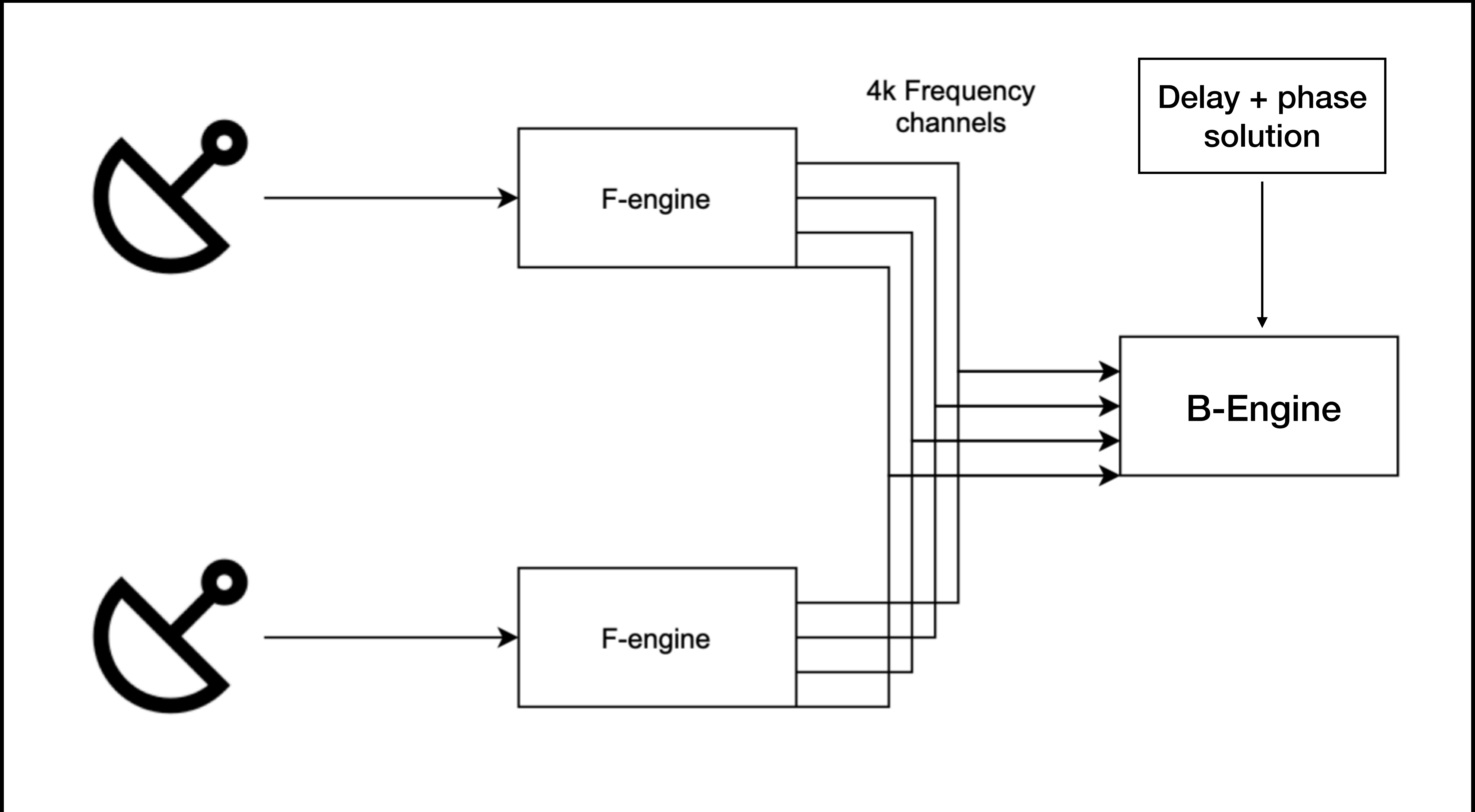
Lag spectrum



Amplitude [arb.]

Samples [1/64MHz = 15.625 ns]

Replace Correlator with Beamformer



(Python/offline)Beamform on sky source

1. Apply geometric + fixed delays + phase offset

   (no gain, nor bandpass calibration applied)

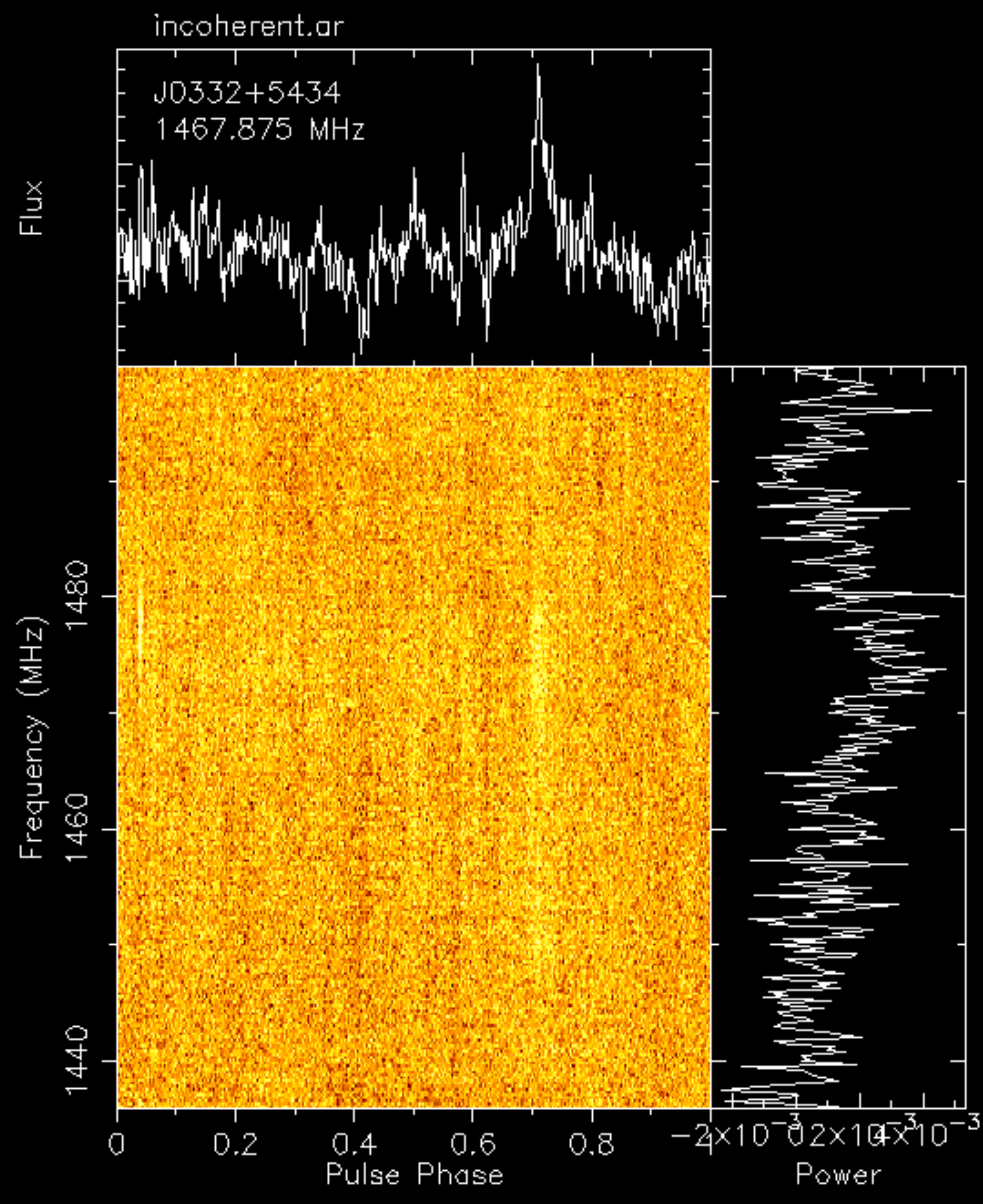
2. Coherent summation (in phase)

3. Incoherent sum (for comparison)

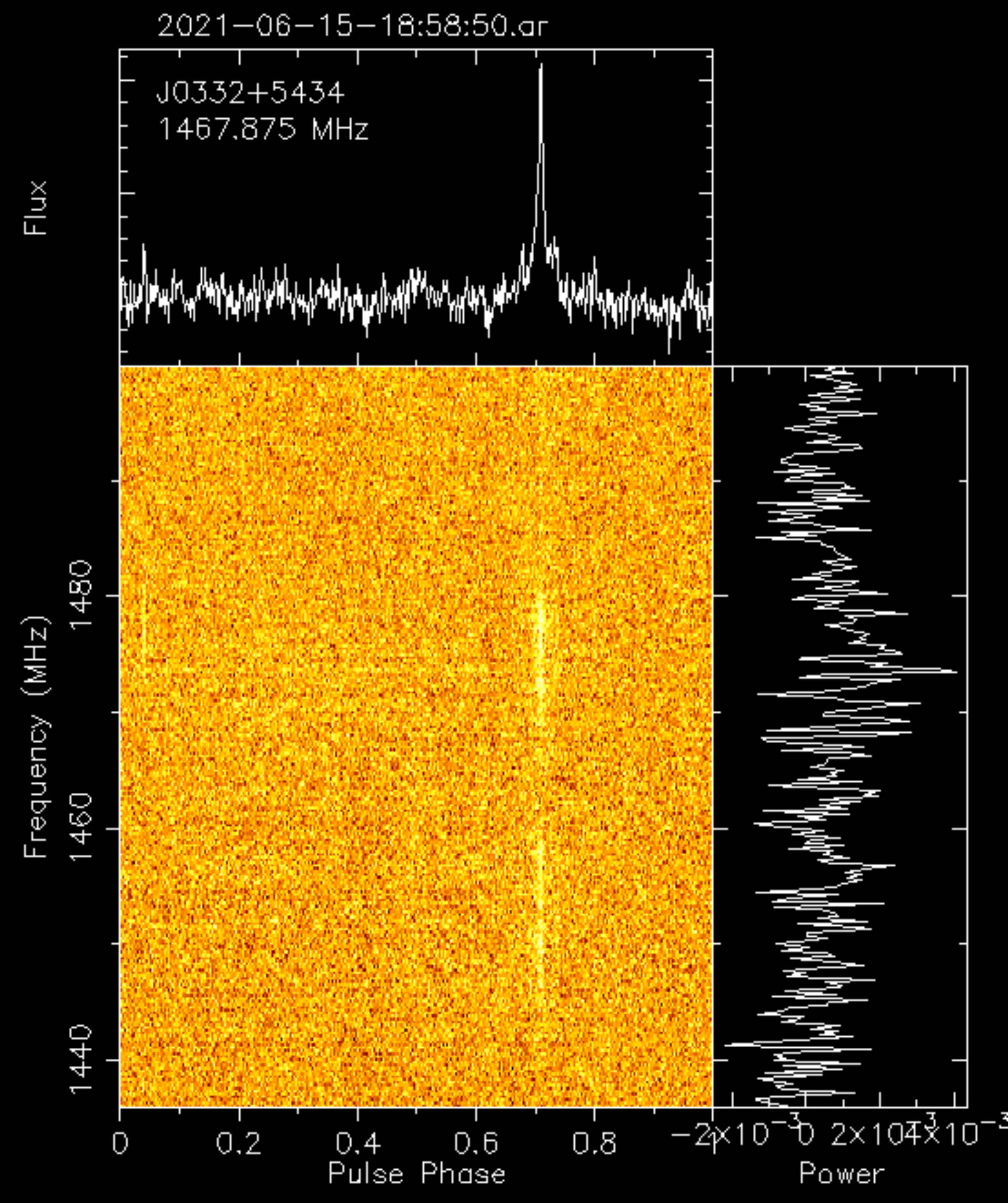
4. Pulsar processing (5 mins obs)

5. ~ factor of 2 improvement in S/N (Theoretical improvement is sqrt(Nants) = sqrt(11) = 3.3, with perfect beam forming efficiency)

Incoherent sum



coherent sum



Beamform on sky source (pol-dependent solution)

1. Apply geometric + fixed delays + phase offset

   (no gain, nor bandpass calibration applied)

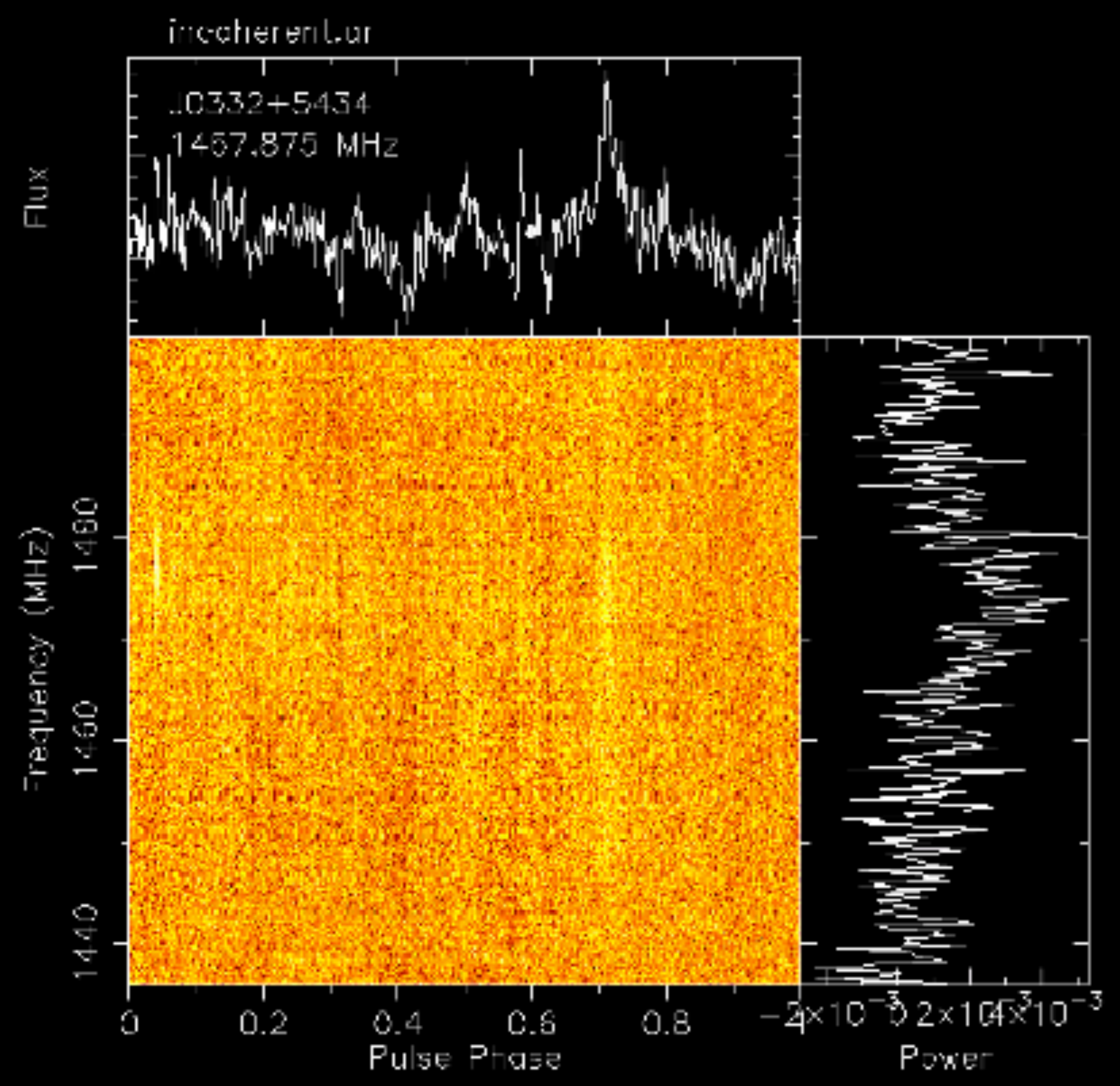
2. Coherent summation (in phase)

3. Incoherent sum (for comparison)

4. Pulsar processing (5 mins obs)

5. Using polarisation-dependent phase solution. S/N scales correctly with number of antpols

Incoherent sum



coherent sum