Beam-formed Data with LOFAR

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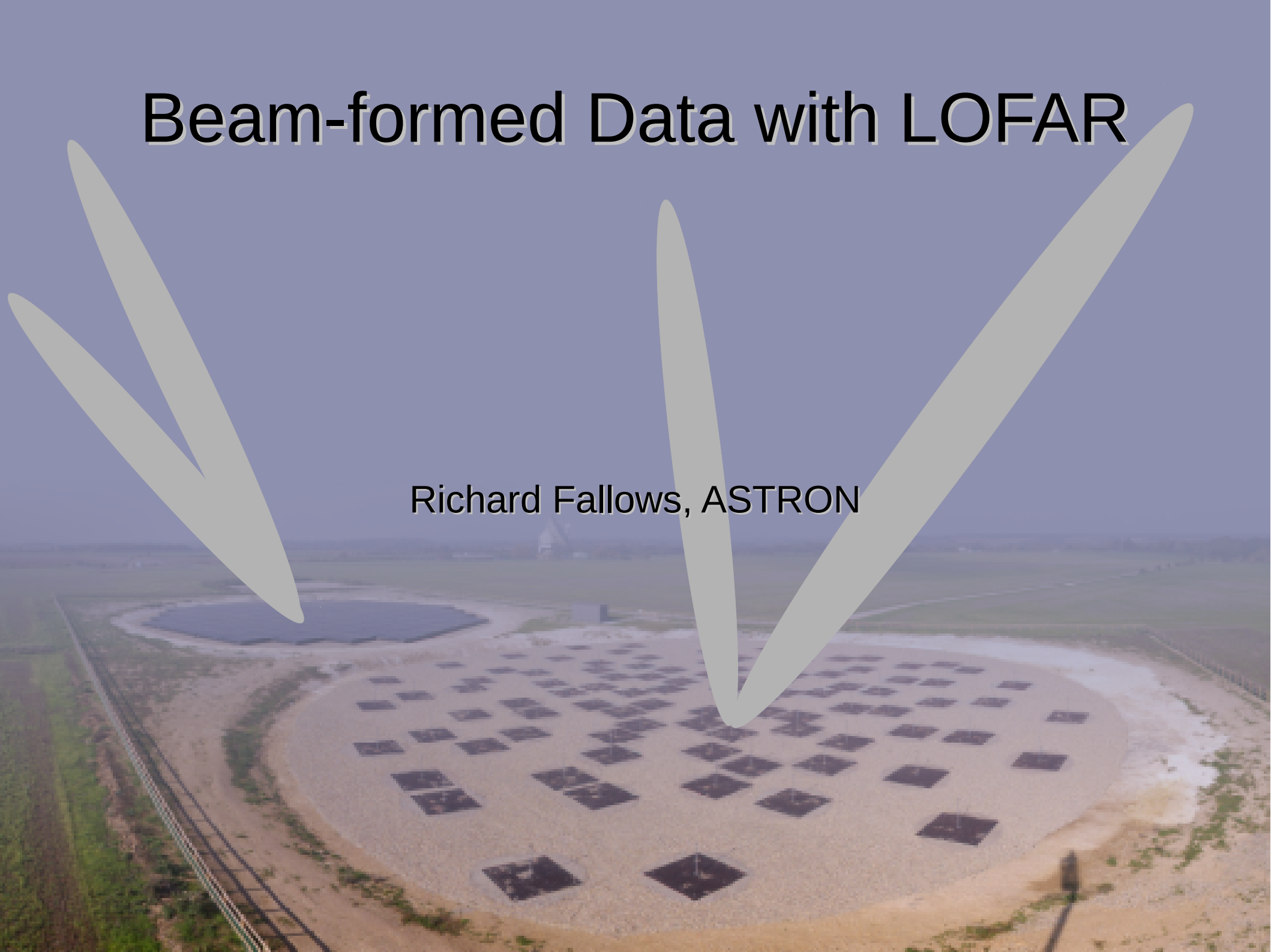
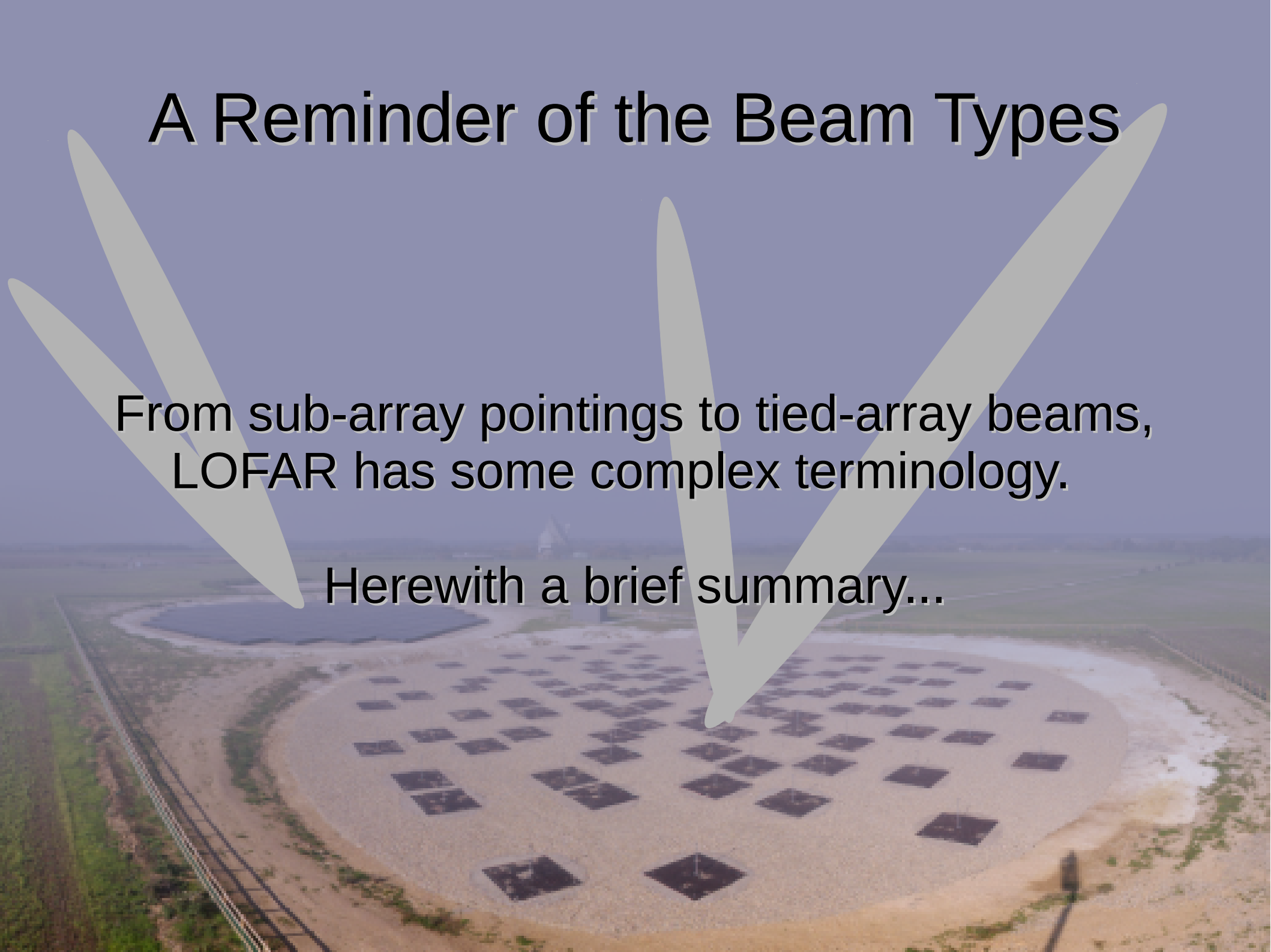


Beam-formed Data – Main Uses

- Pulsars – already covered
- Single-station science
- Dynamic spectra:
  - Solar radio bursts
  - Planetary emission
  - Scintillation
- “Imaging” diffuse objects:
  - Raster-style imaging
  - Useful for Sun and other wide objects

A Reminder of the Beam Types

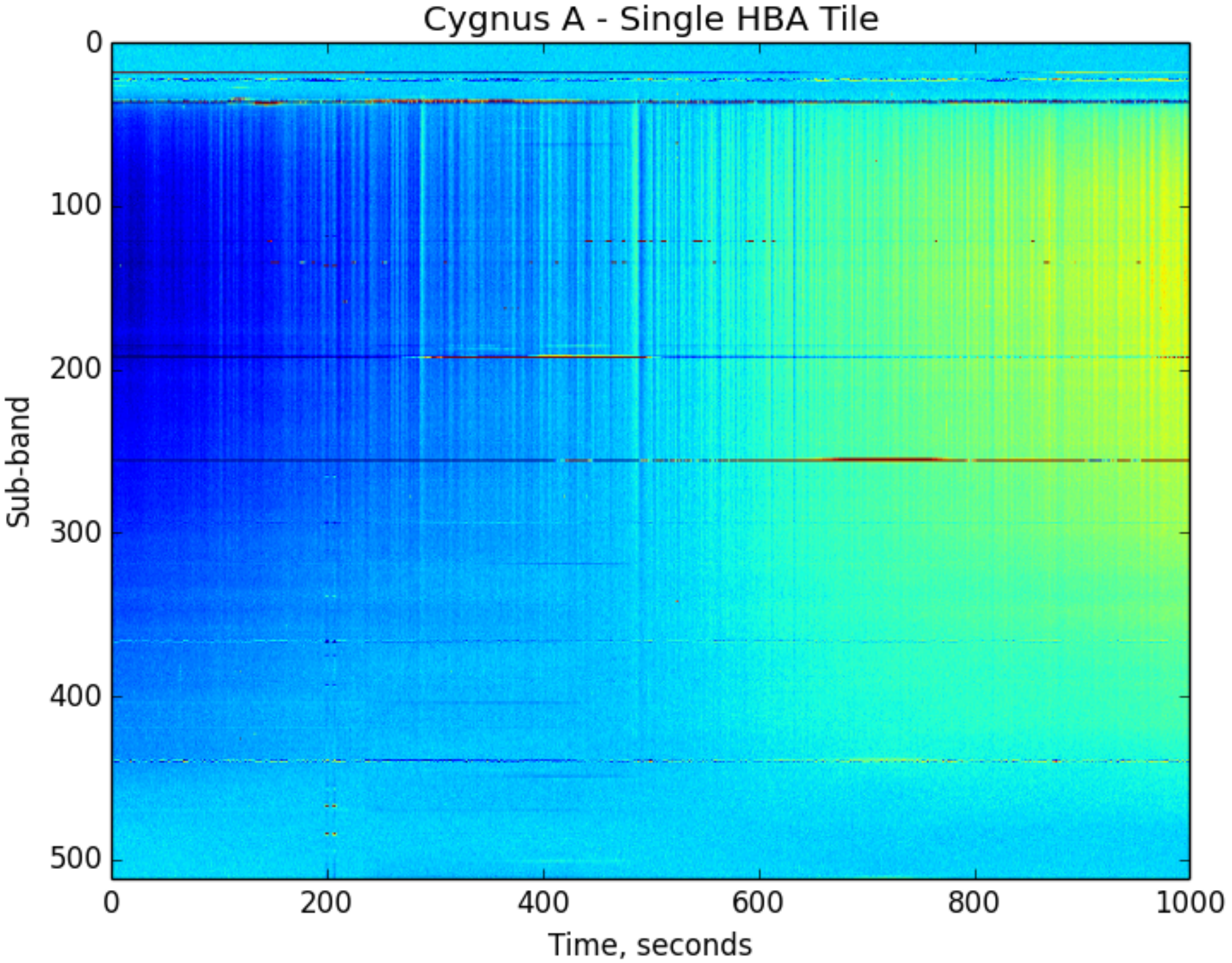


From sub-array pointings to tied-array beams, LOFAR has some complex terminology.

Herewith a brief summary...

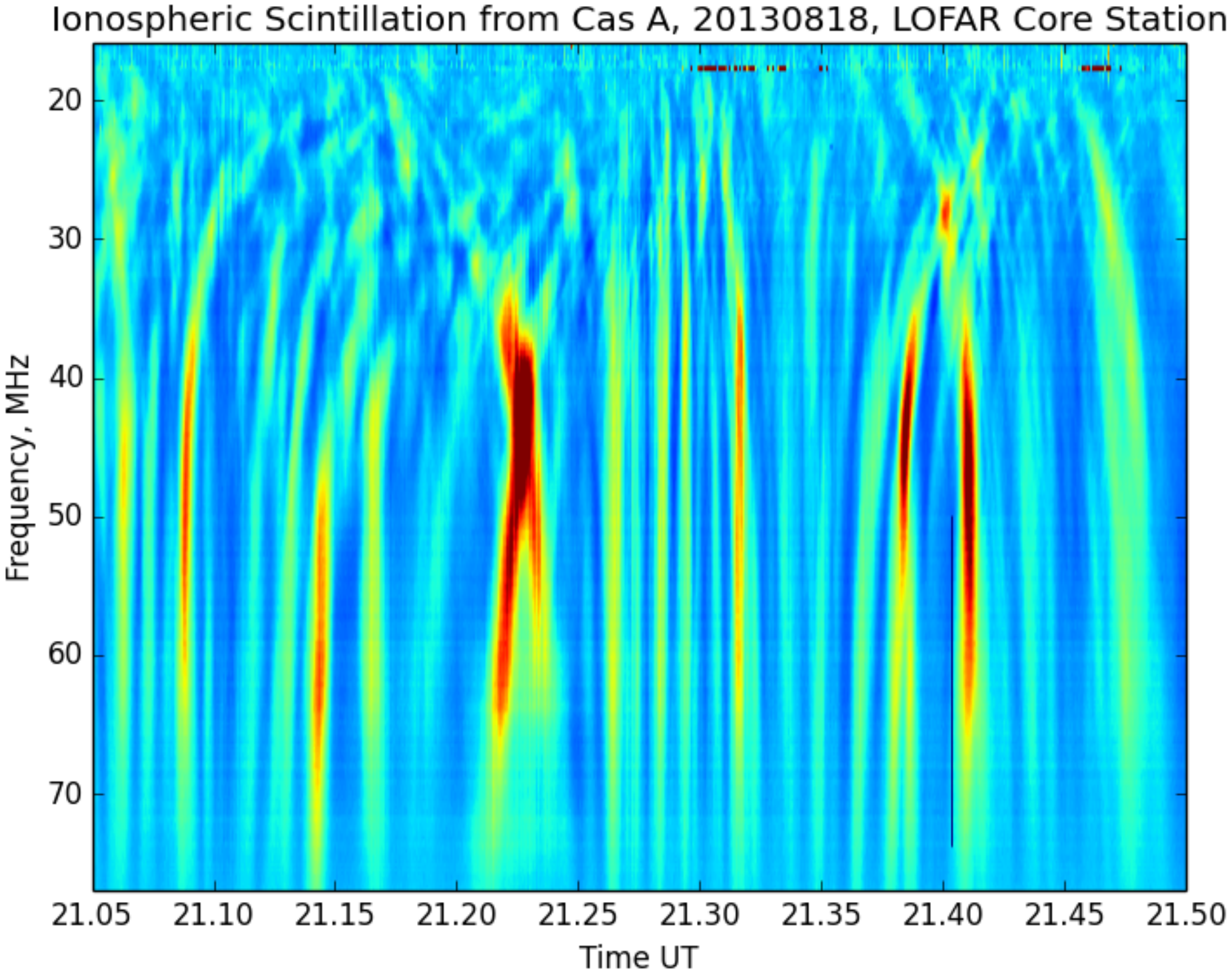
HBA Tile Beam

- Each HBA tile consists of a 4x4 grid of crossed-dipoles, controlled by an analogue beam-former
  - Can be “pointed” in only **one** direction at a time!
  - Baseline is 5m:
    - Beam diameter ranges from ~43° at 110MHz to 20° at 240MHz
- Central system: Pointing direction of tile specified by definition of first pointing.
- Single station use:
  - Define pointing how you wish
  - Sub-array station to point different tiles in different directions (with corresponding loss in sensitivity)


Cygnus A - Single HBA Tile
Sub-band
Time, seconds
0
100
200
300
400
500
0
200
400
600
800
1000

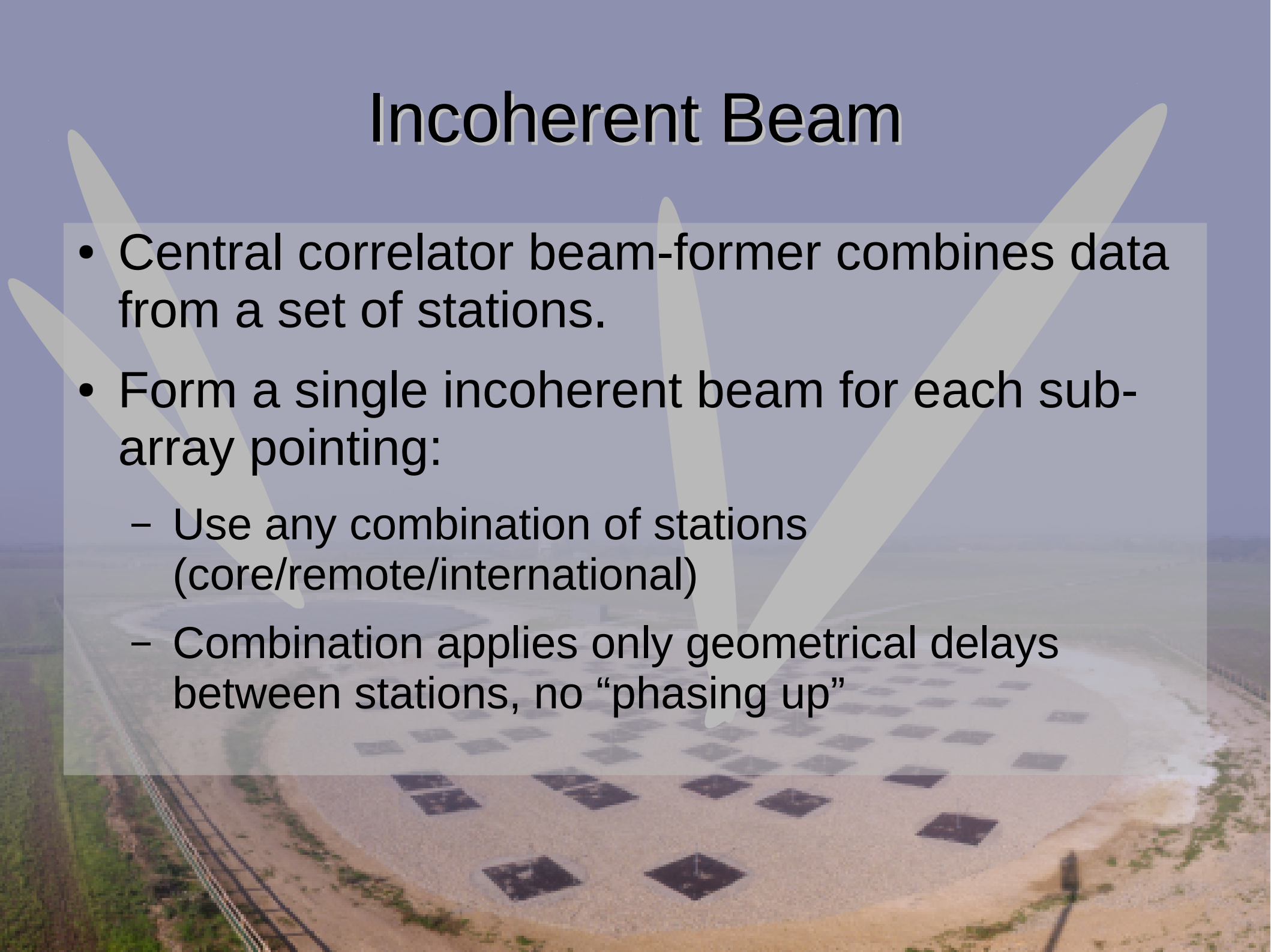
“Sub-Array Pointing” - Station Beam

- Dipoles/Tiles combined via station beam-former
  - Forms “beamlets” where each beamlet is a pointing for a single sub-band
  - Up to 488 beamlets can be formed (8-bit mode)
  - Beamlets can be pointed in any direction using any sub-band:
    - Use all beamlets to point in the same direction with full bandwidth
    - Have several/many different pointings with a corresponding trade-off in bandwidth.
- Any single pointing direction covering a set of sub-bands is known as a sub-array pointing, or station beam.
- If HBA is used, pointing only makes sense within the area covered by the tile beam.


Ionospheric Scintillation from Cas A, 20130818, LOFAR Core Station
Frequency, MHz
20
30
40
50
60
70
21.05
21.10
21.15
21.20
21.25
21.30
21.35
21.40
21.45
21.50
Time UT

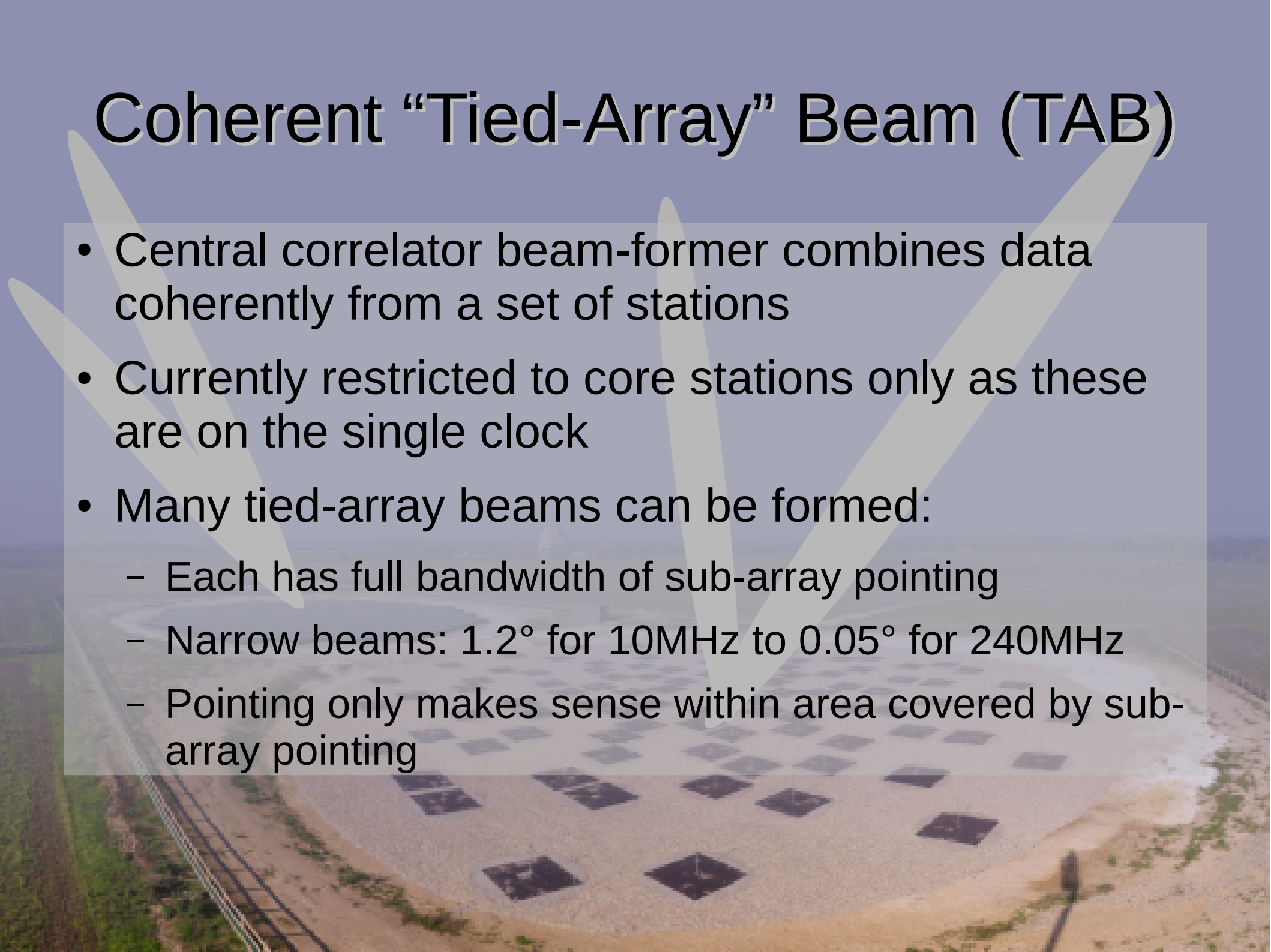
Incoherent Beam

- Central correlator beam-former combines data from a set of stations.
- Form a single incoherent beam for each sub-array pointing:
  - Use any combination of stations (core/remote/international)
  - Combination applies only geometrical delays between stations, no “phasing up”

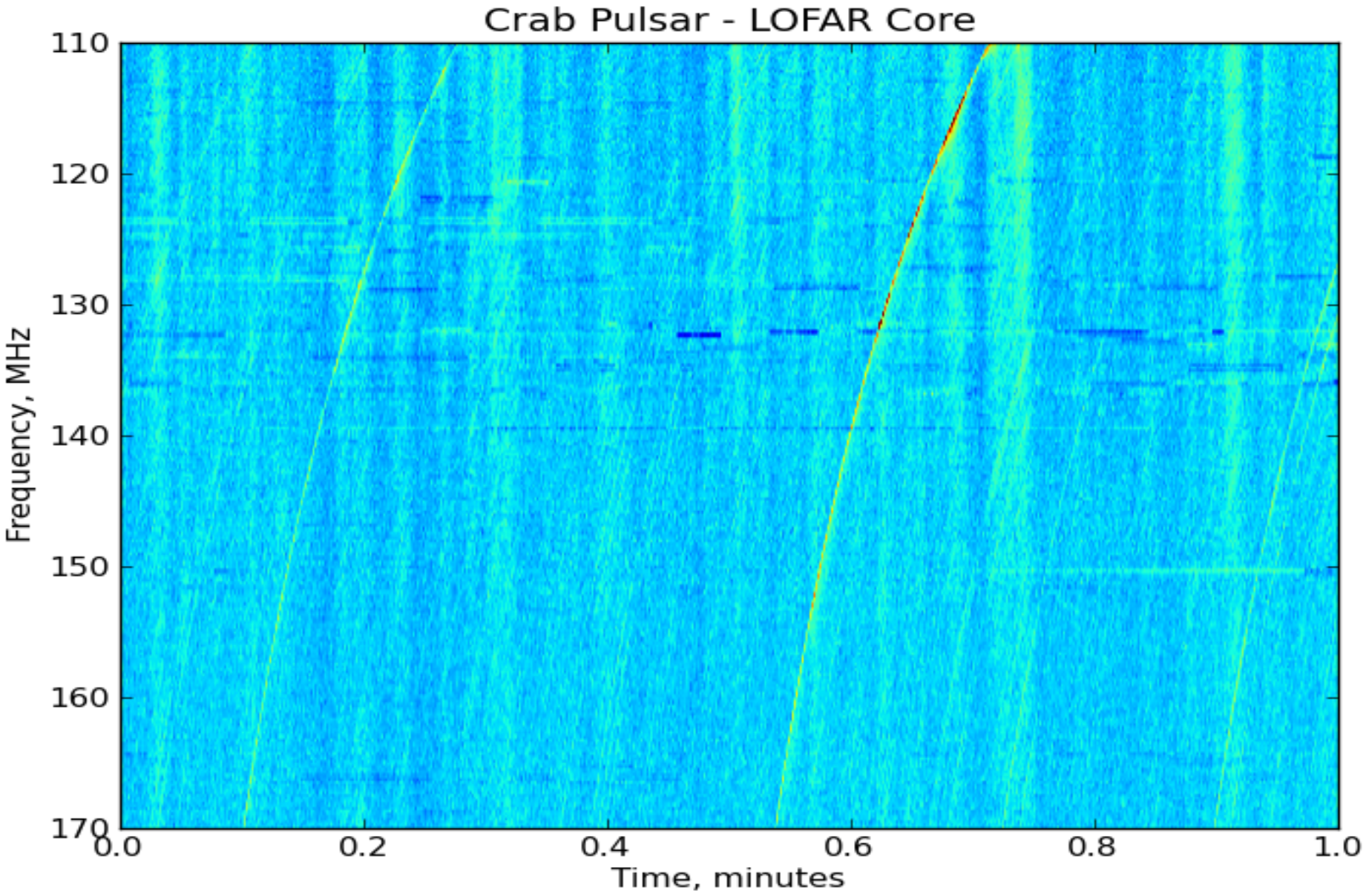


Coherent “Tied-Array” Beam (TAB)

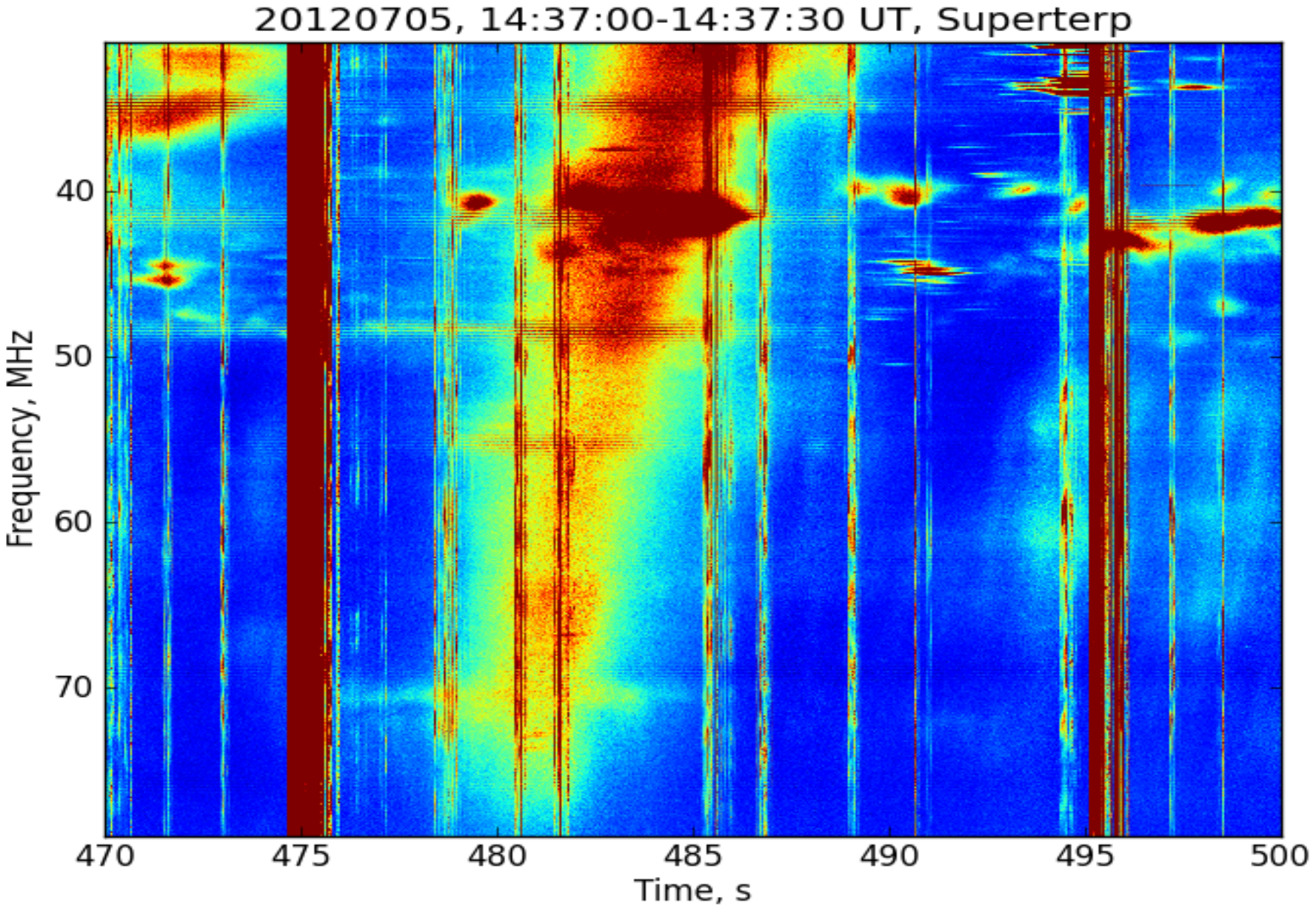
- Central correlator beam-former combines data coherently from a set of stations
- Currently restricted to core stations only as these are on the single clock
- Many tied-array beams can be formed:
  - Each has full bandwidth of sub-array pointing
  - Narrow beams: 1.2° for 10MHz to 0.05° for 240MHz
  - Pointing only makes sense within area covered by sub-array pointing



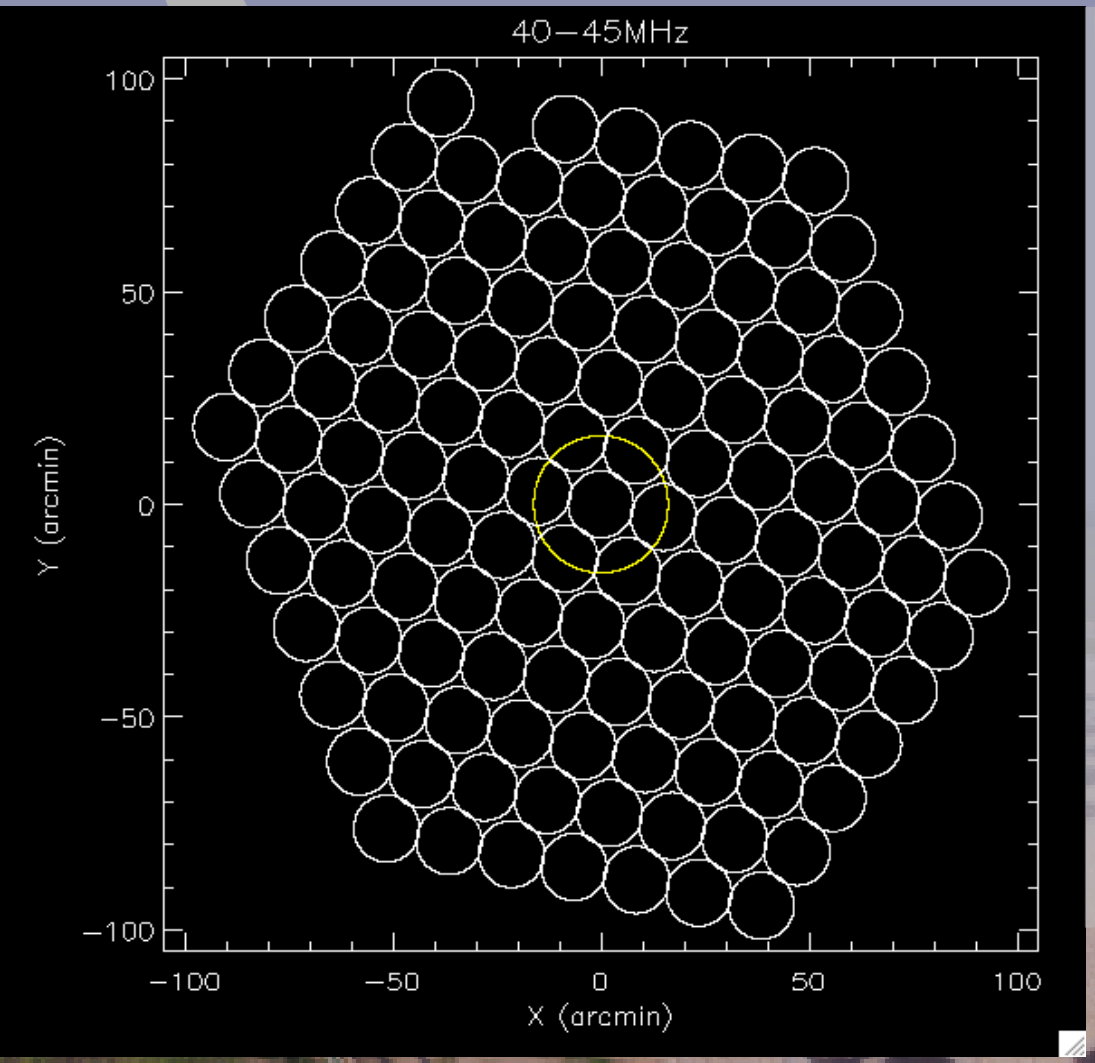
TAB Example: Crab pulsar scintillating through the solar wind



TAB Example: solar radio burst seen through a thunderstorm – superterp stations

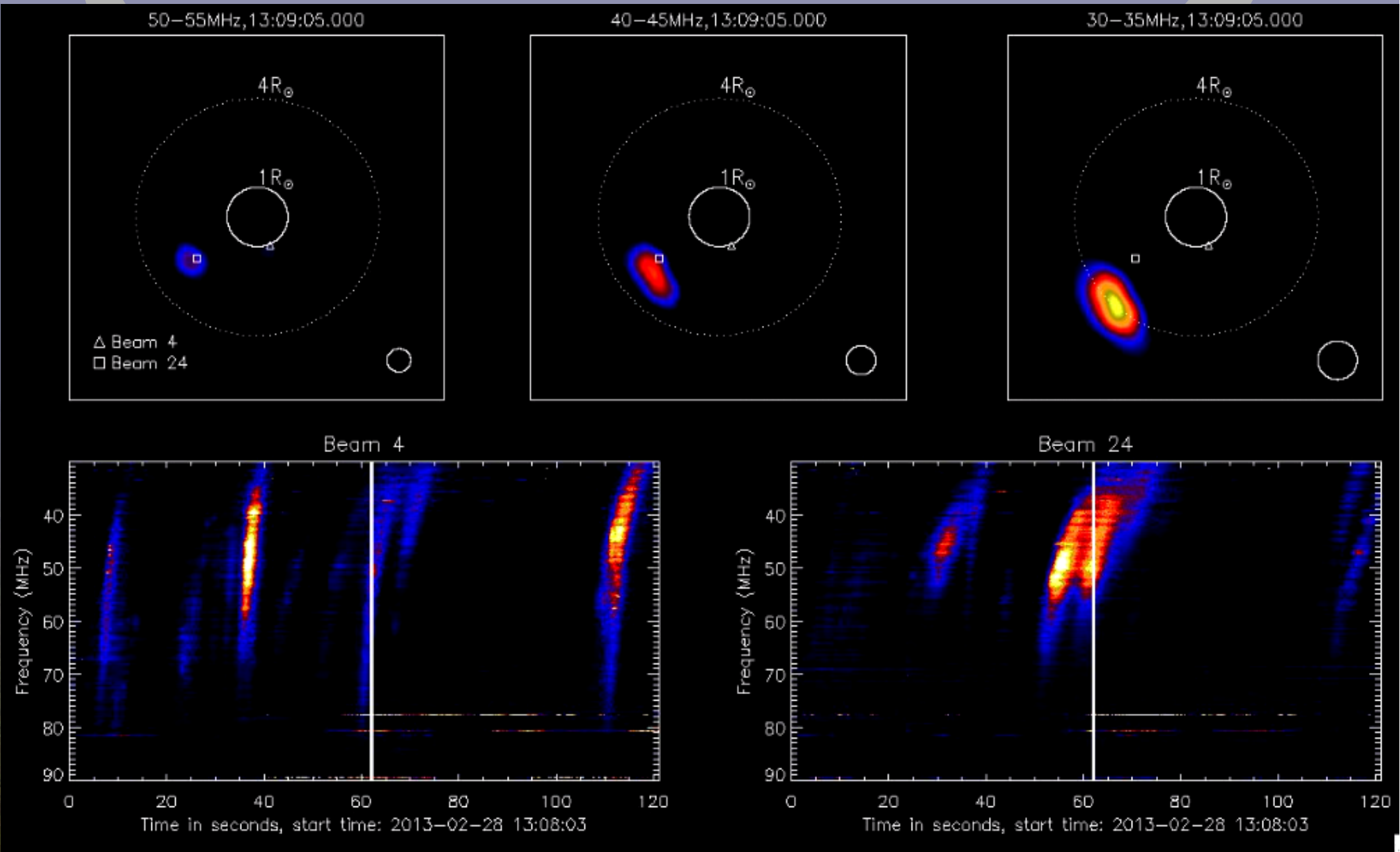


TAB Example: multiple TABs mapping the Sun



- Can form concentric 'rings' of beams on and around an object.
- Try it to see if solar radio bursts can be mapped with this technique.
- Advantage over traditional imaging of very high time and frequency resolution and ready access to a dynamic spectrum for each beam.

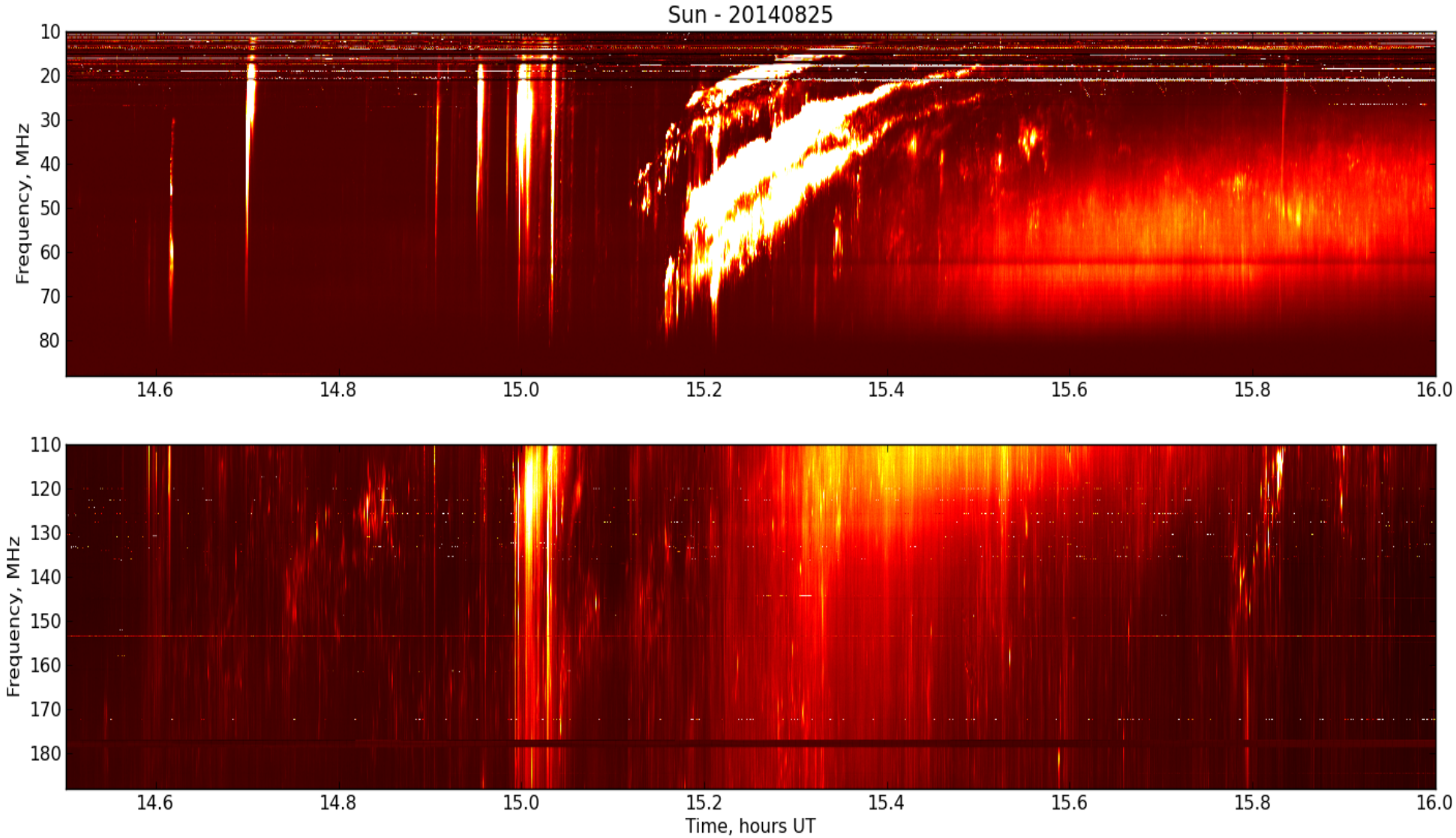
TAB Example: multiple TABs mapping the Sun



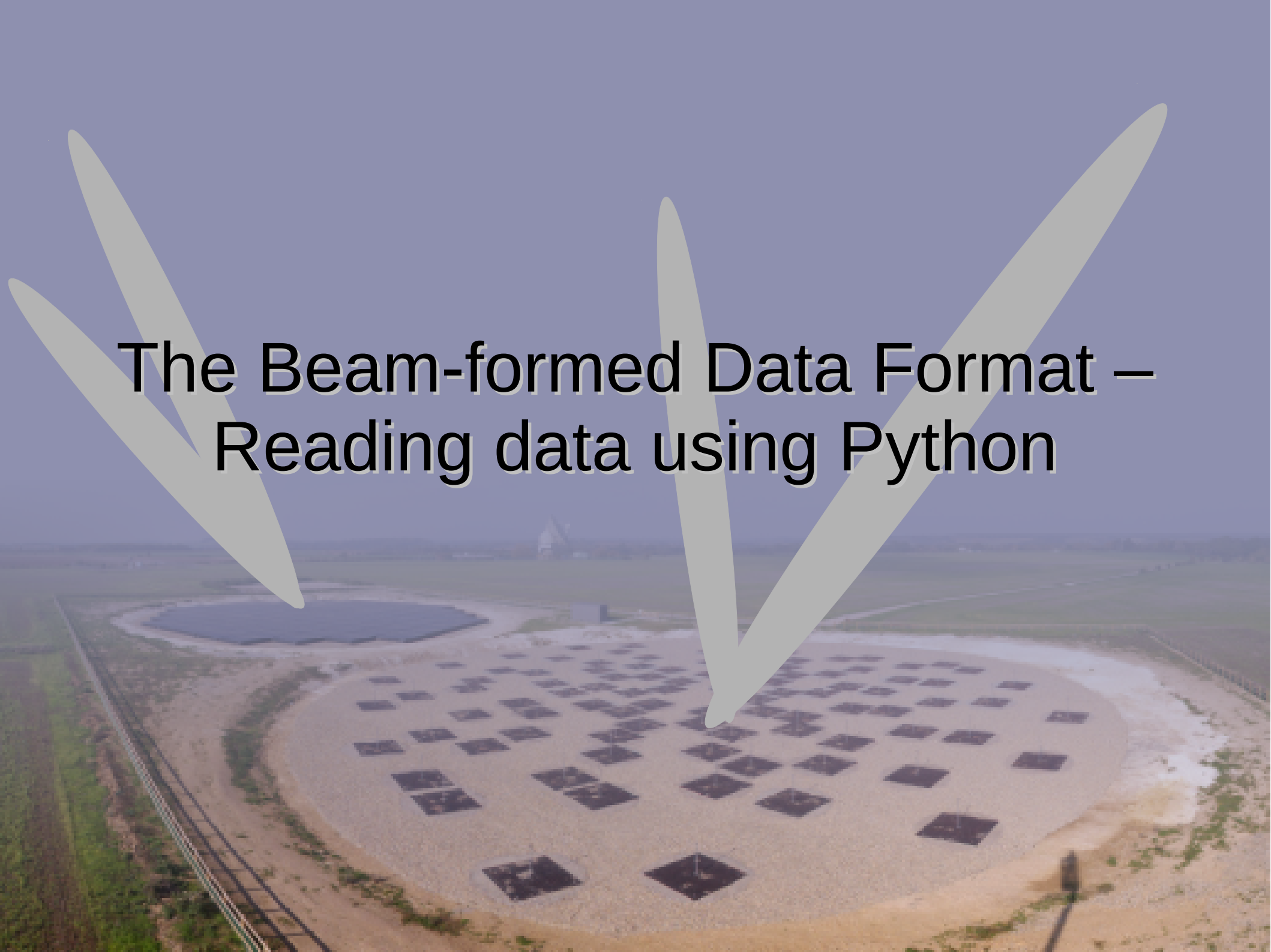
Recording Single Station Data

- “Fly's Eye” mode
- Correlator outputs sub-array pointing data from each station individually
- Possible applications:
  - Off-line correlation of raw complex voltages (VLBI for example)
  - Recording high time-resolution time series' for later correlation (interplanetary scintillation for example)
  - Future: Parallel observations, different stations pointing in different directions, or observing different frequency ranges.

Simultaneous LBA/HBA Observation of the Sun



The Beam-formed Data Format – Reading data using Python



Beam-formed Data Files

- Data are accessible via HDF5
- Consist of **two** files:
  - *.h5: HDF5 file containing the meta-data plus a data array **linked** to:
  - *.raw: The data themselves in a binary format.
- Data can be read using any HDF5 library routines or file reader (e.g., hdfview) by opening only the h5 file.
  - **But** both files must be stored in the same place and you must be reading them from that place

Beam-formed Data Files

- File name structure:

  <ObsID>_SAPxxx_BEAMxxx_Sx_Pxxx.h5/raw

  - ObsID is the observation ID, Lxxxxxx
  - SAPxxx is a sequential sub-array pointing number, e.g., SAP000
  - BEAMxxx is a sequential beam number, e.g., BEAM000
  - Sx refers to Stokes parameter: S0-S3 for Stokes I,Q,U,V respectively
  - Pxxx is a sequential part number for cases where data for various sub-band blocks are split over several files.
    - If sub-bands are all in the same files, only P000 is used.

Beam-formed Data Files

For example, Stokes Q data from observation with ID number L246143 for the 10th labelled beam number of the second station beam will have the file names:

L246143_SAP001_BEAM009_S1_P000.h5

L246143_SAP001_BEAM009_S1_P000.raw

If the observation contains 400 sub-bands recorded as 20 sub-bands per file, part numbers would be P000 to P019.

Beam-formed Data Files

- Note on BEAM numbers:
- The order is important:
  - Coherent tied-array beams are numbered first
  - Specified pointing directions numbered ahead of those calculated from tied-array `rings'.
  - Incoherent Stokes beams are numbered next
  - Fly's Eye beams numbered last.
- No numbers are reserved for particular cases, so all available beams will be numbered sequentially and the experiment setup needs to be known to determine which numbers refer to which coherent, incoherent or fly's eye beam.

H5 File Structure

- HDF5 file structure is a hierarchical structure of “folders”/”directories” each containing meta-data and/or data:

  /SUB_ARRAY_POINTING_xxx

  /SUB_ARRAY_POINTING_xxx/BEAM_xxx

  /SUB_ARRAY_POINTING_xxx/BEAM_xxx/STOKES_x

  /SUB_ARRAY_POINTING_xxx/BEAM_xxx/COORDINATES

- The data are found by opening the STOKES_x folder.

Reading Data Using Python

- Use h5py library to read HDF5 files
  - >> import h5py
  - >> f = h5py.File('BF_file.h5')
- To list folders:
  - >> f['/'].items()

```
Out[..]:
[(u'SUB_ARRAY_POINTING_000',
  <HDF5 group "/SUB_ARRAY_POINTING_000" (2 members)>),
'SYS_LOG', <HDF5 group "/SYS_LOG" (0 members)>)]
```

Reading Data Using Python

- To list meta-data (“attributes”):
  - >> f['/'].attrs.items()

    Out[..]:

    [(u'DOC_VERSION', '2.5.0'),

    'OBSERVATION_NOF_SUB_ARRAY_POINTINGS', 1),

    ...
- To get a known attribute:
  - >> f['/'].attrs.get('TELESCOPE')

    Out[..]: 'LOFAR'
- To list keys:
  - >> f['/'].attrs.keys()

    Out[..]:

    [u'DOC_VERSION',

    u'OBSERVATION_NOF_SUB_ARRAY_POINTINGS',

    ...

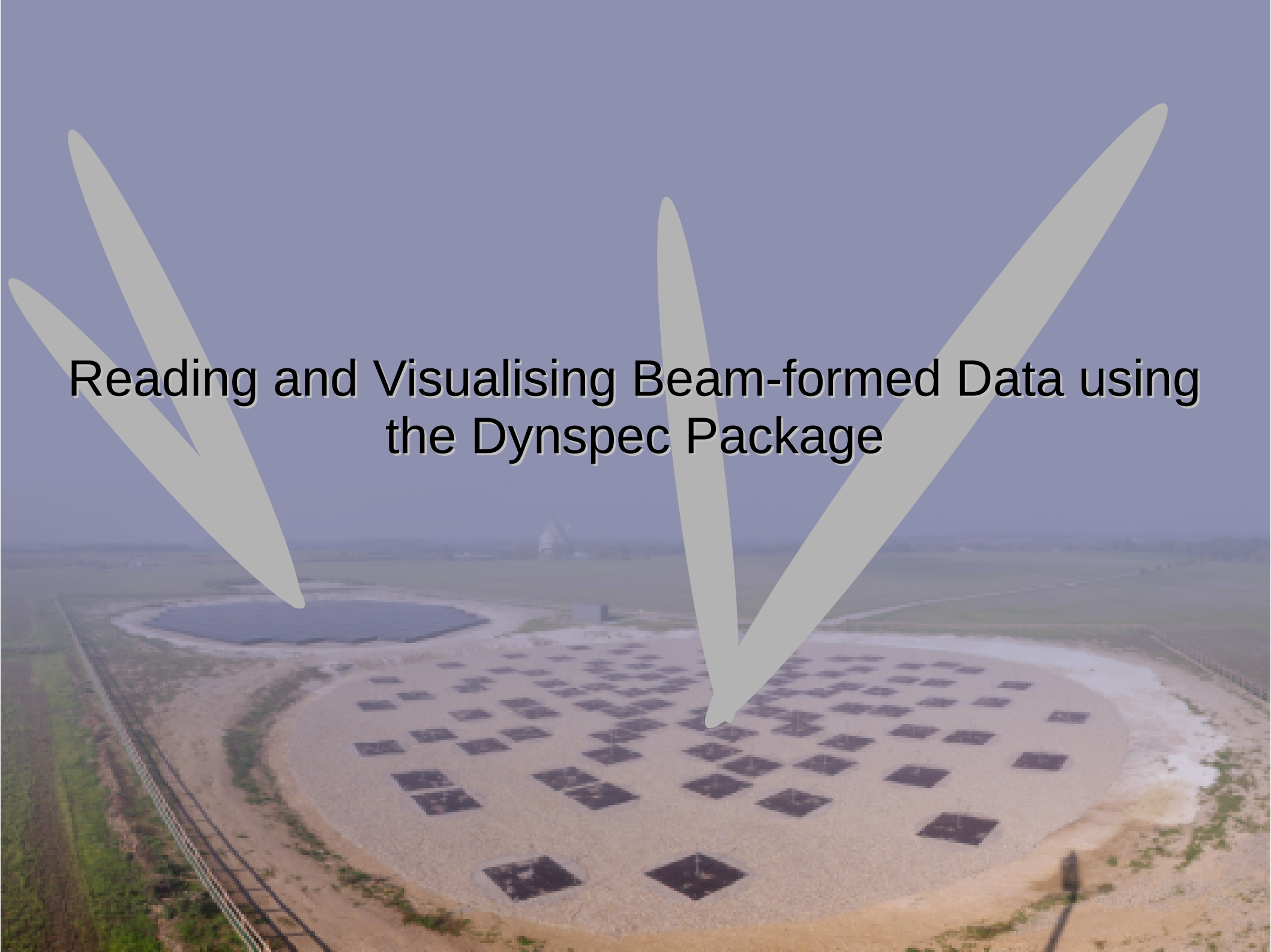
Reading Data Using Python

- Put meta-data into Python dictionary:
  - >> parameters = dict(f['/'].attrs.items())
  - >> parameters['TELESCOPE']

    Out[..]: 'LOFAR'
- Read data:
  - >> data = f['/SUB_ARRAY_POINTING_000/BEAM_005/STOKES_0']
  - >> data.shape

    Out[..]: (3232896, 6400)
- Data are stored as a 2-D array of [time,frequency]

Reading and Visualising Beam-formed Data using the Dynspec Package



The Dynamic Spectrum Toolkit

- The Dynamic spectrum Toolkit Container (DTC) is a complete package of tools to reduce, process and visualise LOFAR beam-formed data:
  - “Quicklook” tool to obtain quicklook images
  - Extract particular time and frequency ranges of interest
  - Rebin the data to average in time and/or frequency
  - “Subtraction” tool to subtract one beam from another (for example to subtract an off-source beam from an on-source) using Z=X-(k*Y) where k is a free scaling factor
  - “LinPol” tool, to convert I,Q,U,V dynamic spectra to I,linear,PA,Total dynamic spectra
  - Visualisation tool to explore the data

The Dynamic Spectrum Toolkit

- Full details for installing and running can be found at:

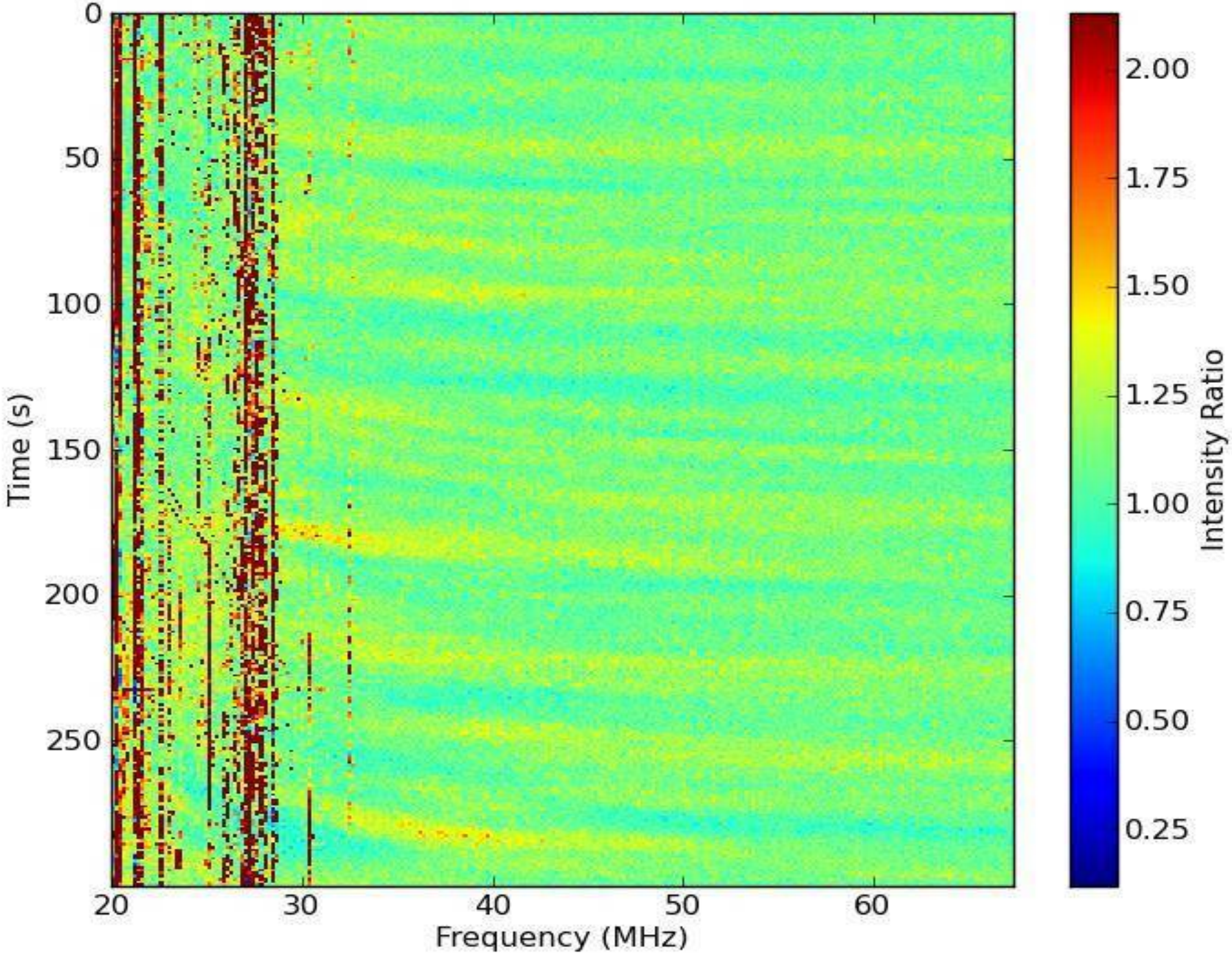
  http://www.lofar.org/operations/doku.php?id=public:user_software:dynspec

Quicklook Plots

- Run Beam2Dynspec-Quick

  Usage: Beam2Dynspec-Quick --id=Lxxx --obsDIR= --outputDIR= --percentTimeData=[0->1] --percentSpectralData=[0->1] --transpose=[yes or no] --nofPart=

- Uses percentage of data to create jpg files of dynamic spectra.


0
50
100
150
200
250
Time (s)
20
30
40
50
60
Frequency (MHz)
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
Intensity Ratio

Rebin Tool

- Run Beam2Dynspec-Rebin

  Usage: Beam2Dynspec-Rebin --id=Lxxx --obsDIR=

  --outputDIR= --tmin= --tmax= --tscale= --fmin=

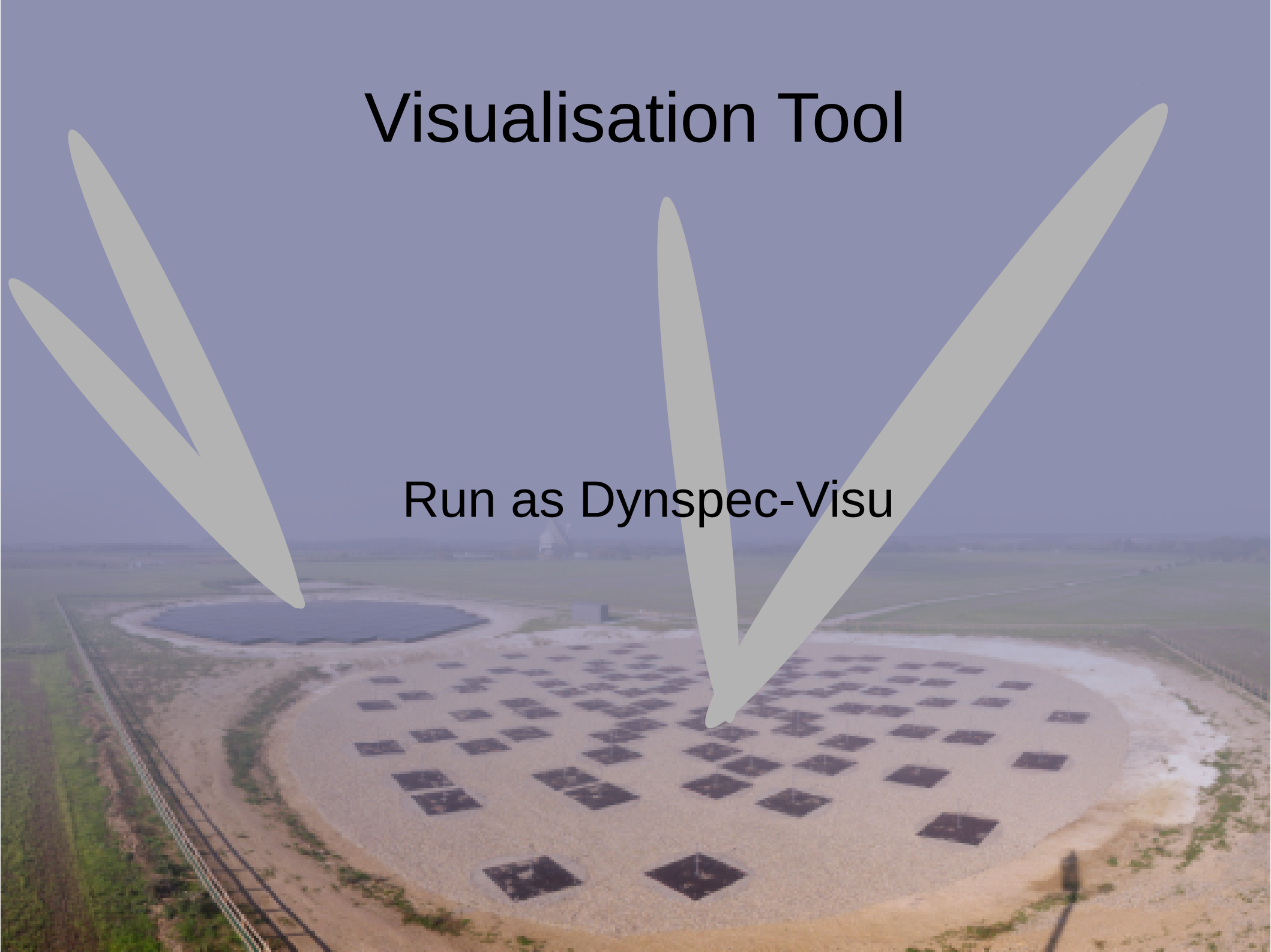
  --fmax= --chanPerSubband= --RAM=(x in Gb) --Npart= --RebinAll=(yes or no)

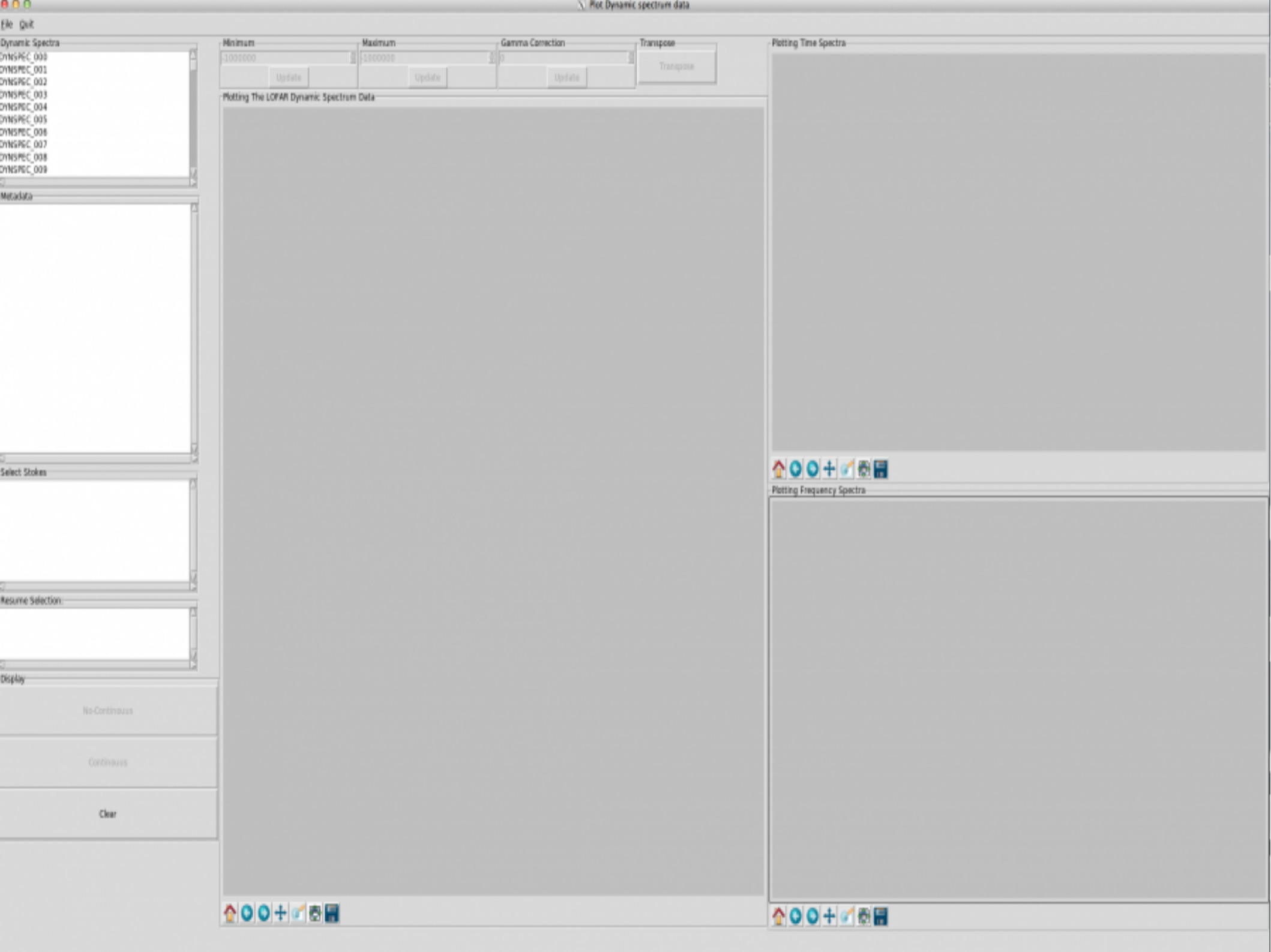
  [if Rebinall=yes default => 0: else –NSAP=]

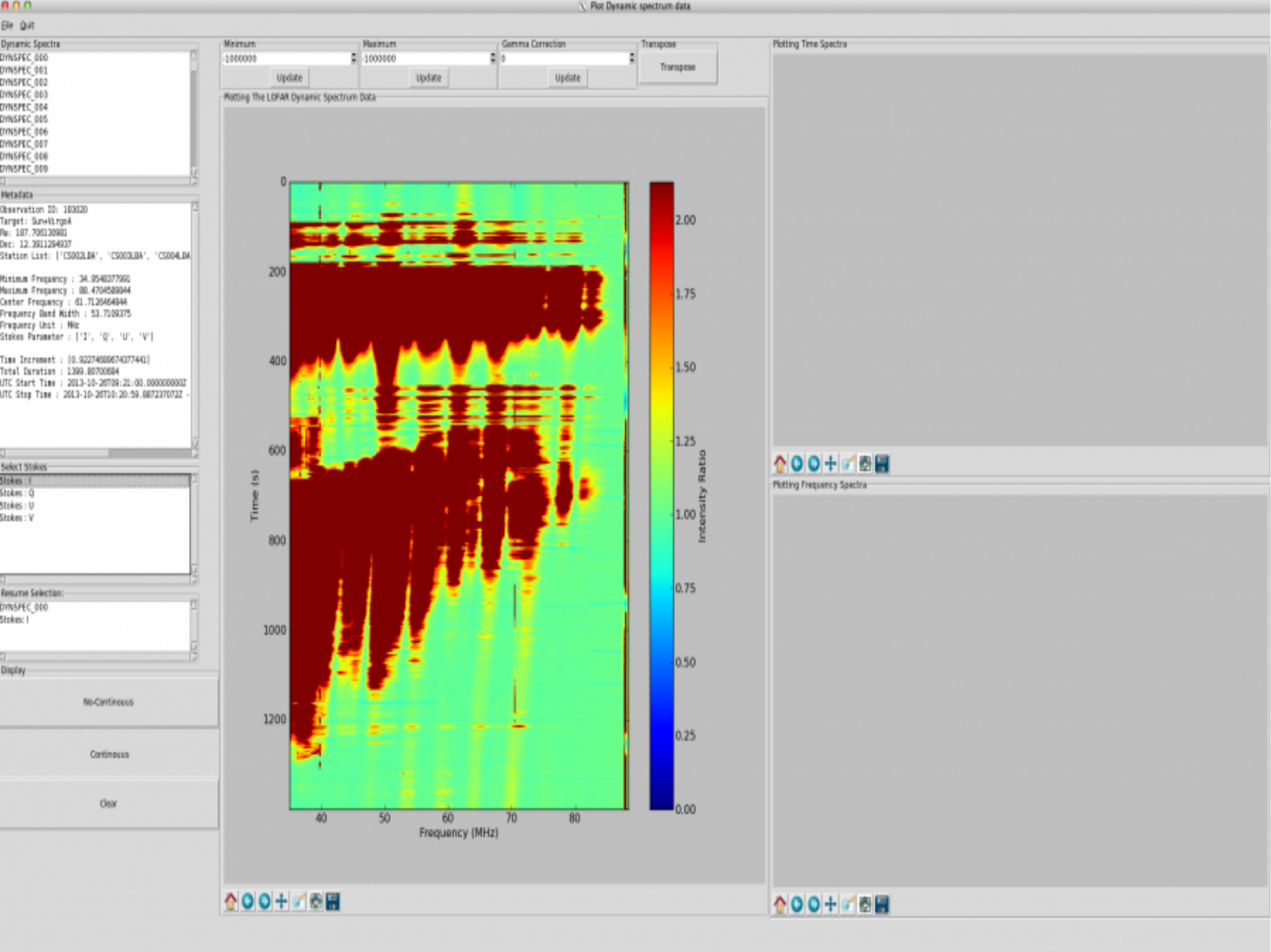
- Rebins data to desired time/frequency resolution and outputs data from all beams in a “dynspec” HDF5 format.

Visualisation Tool

Run as Dynspec-Visu




Plot Dynamic spectrum data
File Quit
Dynamic Spectra
DYNSPEC_000
DYNSPEC_001
DYNSPEC_002
DYNSPEC_003
DYNSPEC_004
DYNSPEC_005
DYNSPEC_006
DYNSPEC_007
DYNSPEC_008
DYNSPEC_009
Metadata
Select Stokes
Resume Selection
Display
No Continuous
Continuous
Clear
Minimum
-1000000
Update
Maximum
1000000
Update
Gamma Correction
0
Update
Transpose
Transpose
Plotting The LOFAR Dynamic Spectrum Data
Plotting Time Spectra
Plotting Frequency Spectra


Plot Dynamic spectrum data
File Quit
Dynamic Spectra
DYNSPEC_000
DYNSPEC_001
DYNSPEC_002
DYNSPEC_003
DYNSPEC_004
DYNSPEC_005
DYNSPEC_006
DYNSPEC_007
DYNSPEC_008
DYNSPEC_009
Metadata
Observation ID: 183020
Target: Sun+VirgoA
Ra: 187.706130981
Dec: 12.3911294937
Station List: ['CS002LBA', 'CS003LBA', 'CS004LBA
Minimum Frequency : 34.9548377991
Maximum Frequency : 88.4704589844
Center Frequency : 61.7126464844
Frequency Band Width : 53.7109375
Frequency Unit : MHz
Stokes Parameter : ['I', 'Q', 'U', 'V']
Time Increment : [0.92274688674377441]
Total Duration : 1399.88700684
UTC Start Time : 2013-10-26T09:21:00.000000000Z
UTC Stop Time : 2013-10-26T10:20:59.887237072Z -
Select Stokes
Stokes : I
Stokes : Q
Stokes : U
Stokes : V
Resume Selection:
DYNSPEC_000
Stokes: I
Display
No-Continuous
Continuous
Clear
Minimum
-1000000
Update
Maximum
-1000000
Update
Gamma Correction
0
Update
Transpose
Transpose
Plotting The LOFAR Dynamic Spectrum Data
Time (s)
0
200
400
600
800
1000
1200
Frequency (MHz)
40
50
60
70
80
Intensity Ratio
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
Plotting Time Spectra
Plotting Frequency Spectra

Plot Dynamic spectrum data

File Quit

Dynamic Spectra

DYNSPEC_000

Metadata

Observation ID: 249607
Target: Cas A
Ra: 350.850006104
Dec: 58.8149980267
Station List: ['CS002LBA', 'CS003LBA', 'CS004LBA

Minimum Frequency : 29.9987773895
Maximum Frequency : 60.0260761719
Center Frequency : 45.0134277344
Frequency Band Width : 30.078125
Frequency Unit : MHz
Stokes Parameter : ['I', 'Q', 'U', 'V']

Time Increment : [0.0843718433557780457]
Total Duration : 150.051208496
UTC Start Time : 2014-10-16T13:20:00.000000000Z
UTC Stop Time : 2014-10-16T13:24:59.979622105Z

Select Stokes

Stokes : I
Stokes : Q
Stokes : U
Stokes : V

Resume Selection:

DYNSPEC_000
Stokes: I

Display

No-Continous

Continous

Clear

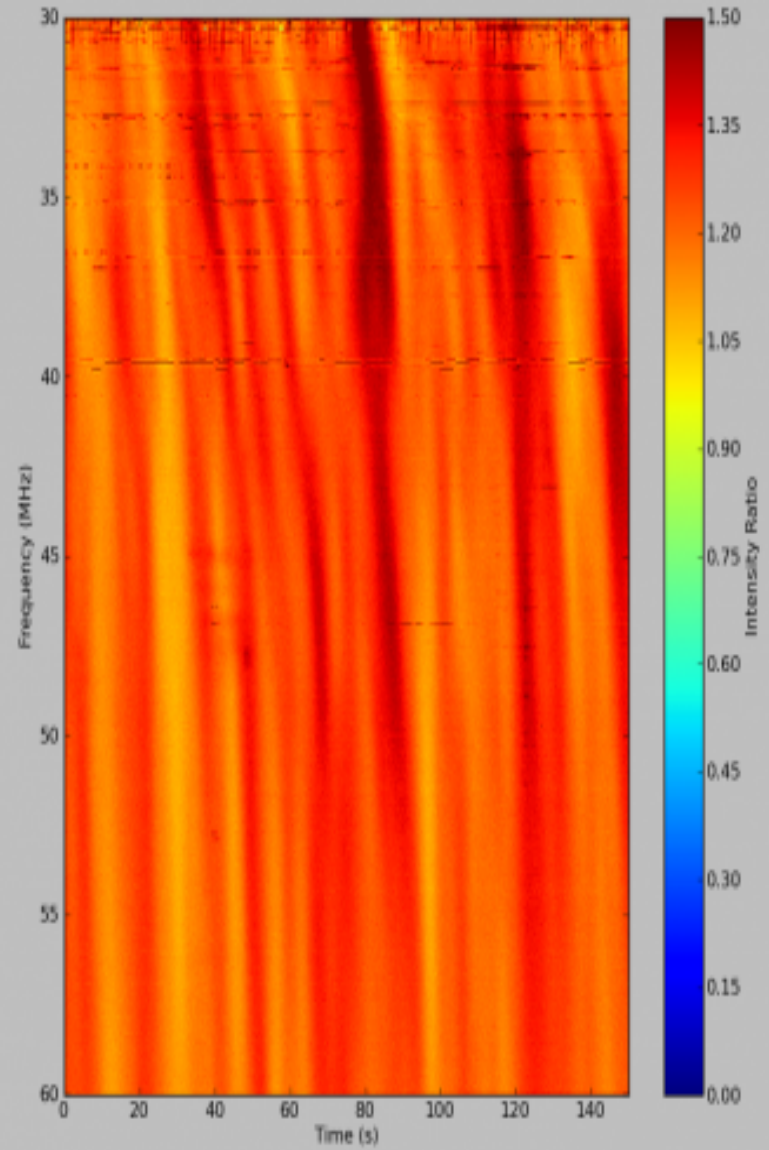
Minimum: 0 Update

Maximum: 1.5 Update

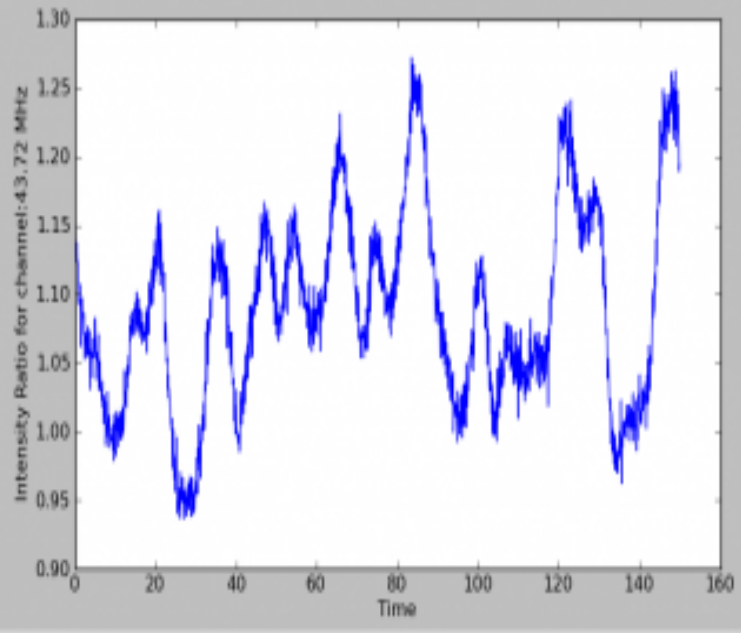
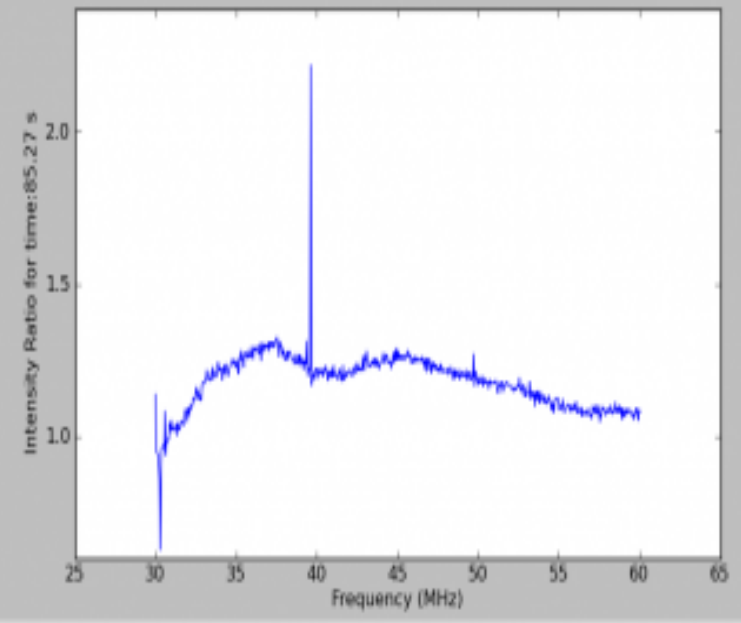
Gamma Correction: 0.95 Update

Transpose

Plotting The LOFAR Dynamic Spectrum Data



Plotting Time Spectra



Plotting Frequency Spectra