21-cm Intensity Mapping

With GBT, Arecibo, and CRT

CMU Cylinder Telescope Prototype

Presented at
Cosmology on the Beach
By Jeff Peterson, CMU
Jan. 12, 2011

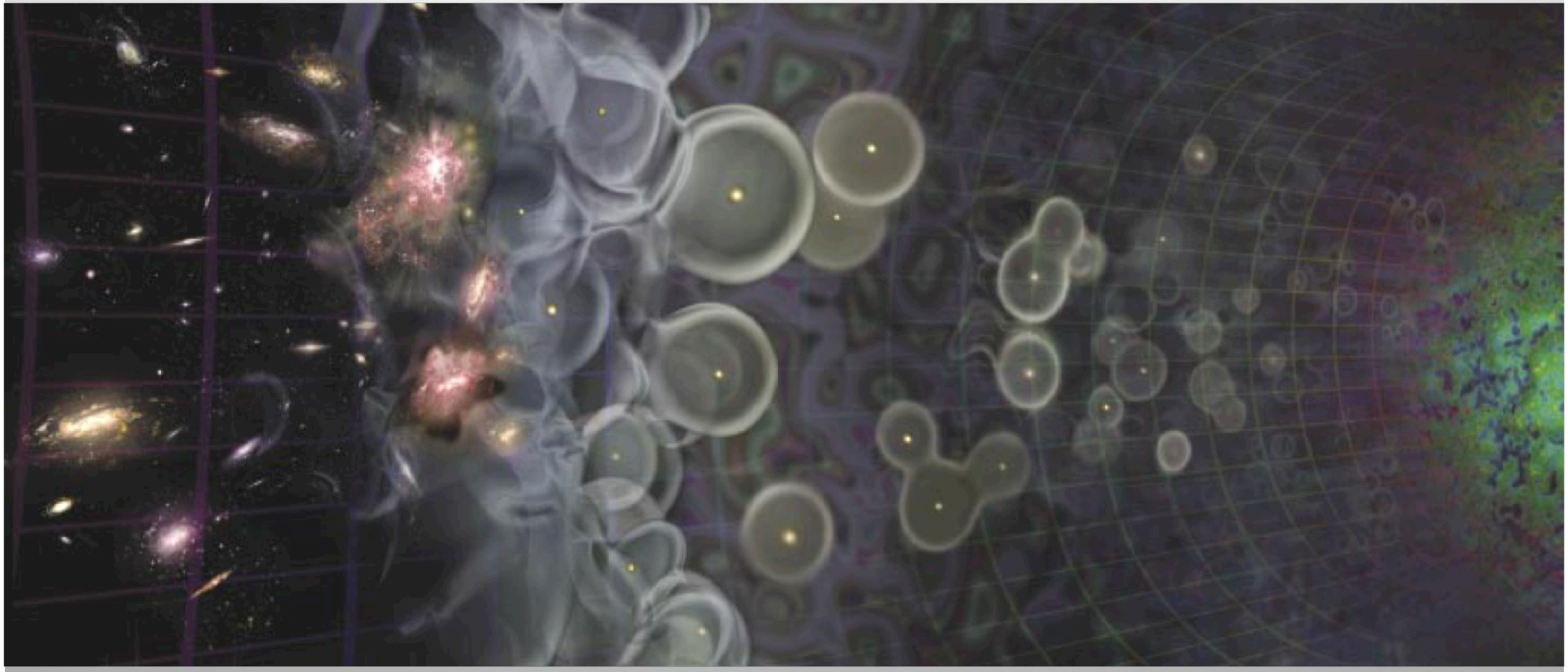
References

- Astrophysics from the Highly-Redshifted 21 cm Line, Furlinetto etal (arXiv:0902.3011)
- Cosmology from the Highly-Redshifted 21 cm Line , Furlinetto etal (arXiv:0902.3259)
- 21-cm Intensity Mapping, JP, etal (arXiv:0902.3091)
- Reionization and Cosmology with 21-cm Fluctuations, Morales & Wyithe (arXiv:0910.3010)
- Wouthuysen-Field coupling strength and application to high-redshift 21-cm radiation, Hirata, (arXiv:astro-ph/0507102)

Outline

- Cosmic History of Neutral Gas
- 21 cm Cosmology at redshift 1-3
- Baryon Acoustic Oscillations
- Intensity Mapping
- GBT Results
- GBT and Arecibo plans
- Cylinder Telescope Test Results
- Next Steps

The History of Hydrogen Gas



1 10 redshift 100 1000

CRT
GBT
Arecibo

LOFAR
MWA
PAPER
GMRT
PaST/21CMA

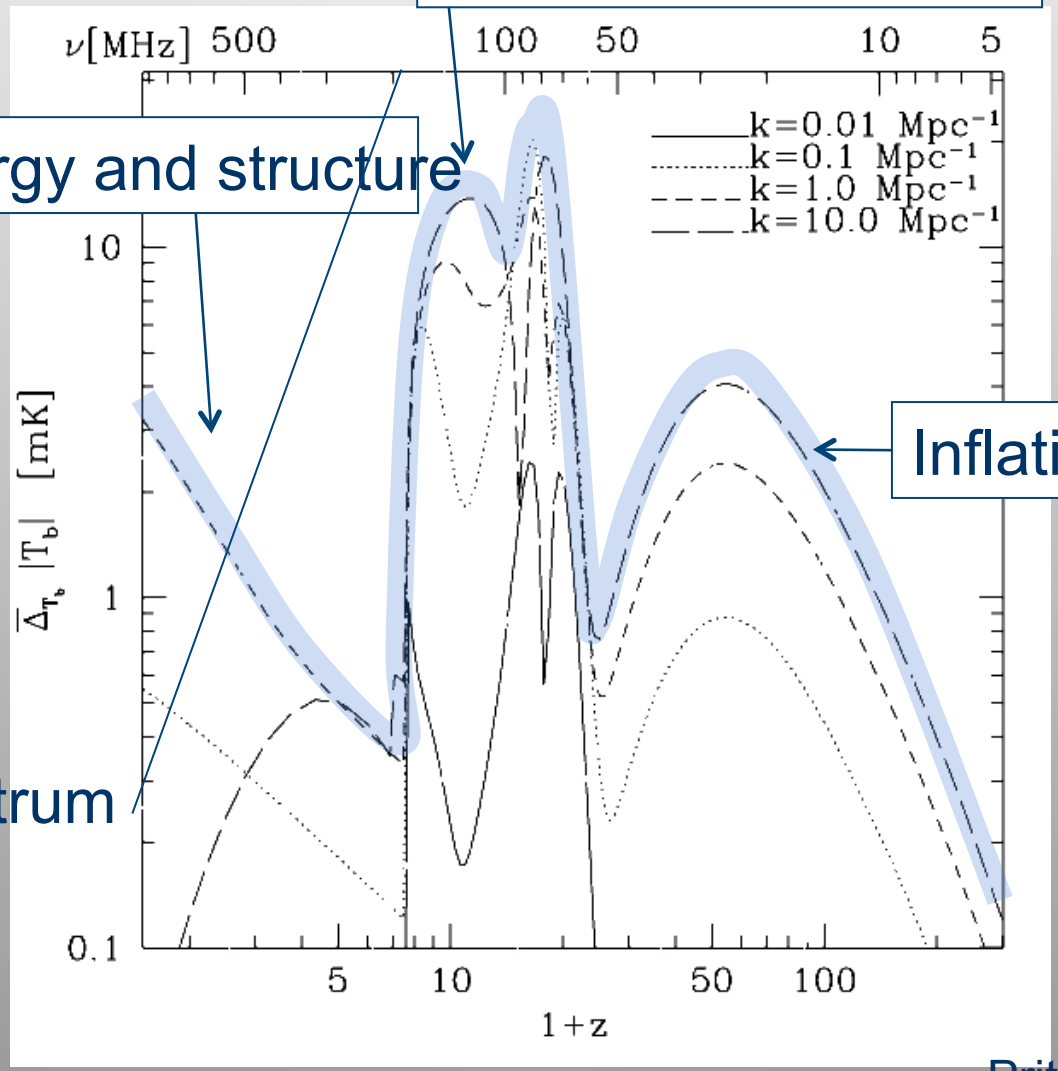
Lunar or
Antarctic Array

Image: Scientific American 2006

21 cm power s shift

Reionization/dark ages

Dark Energy and structure

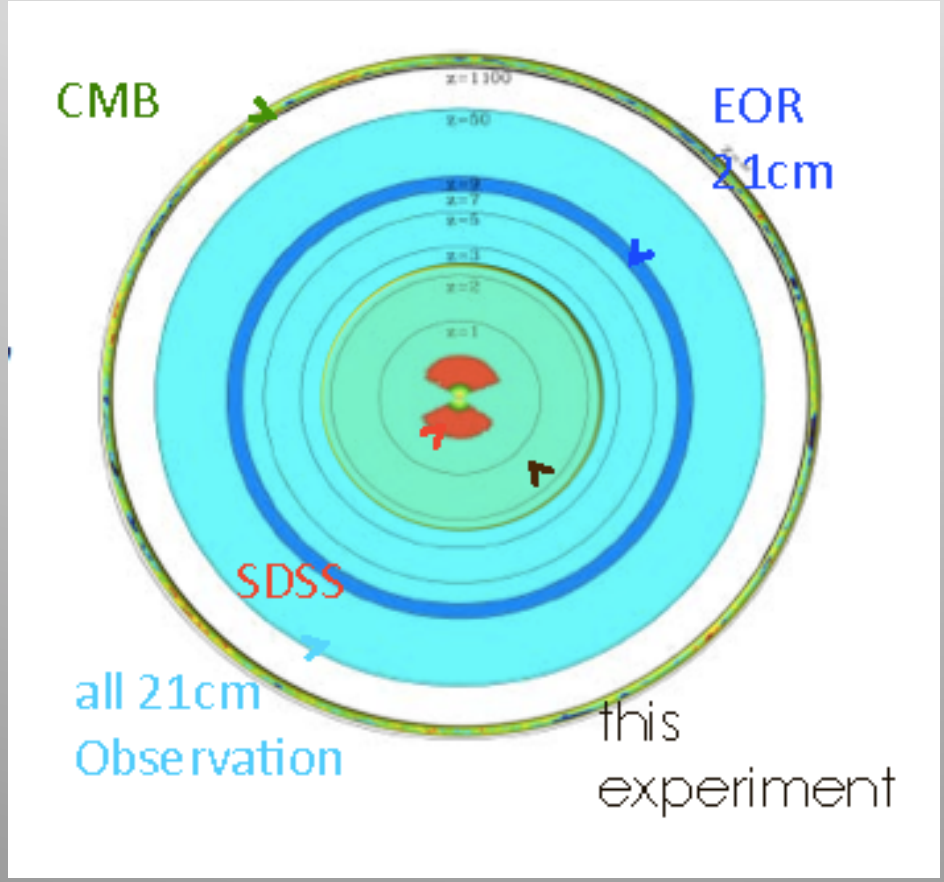


Inflationary physics

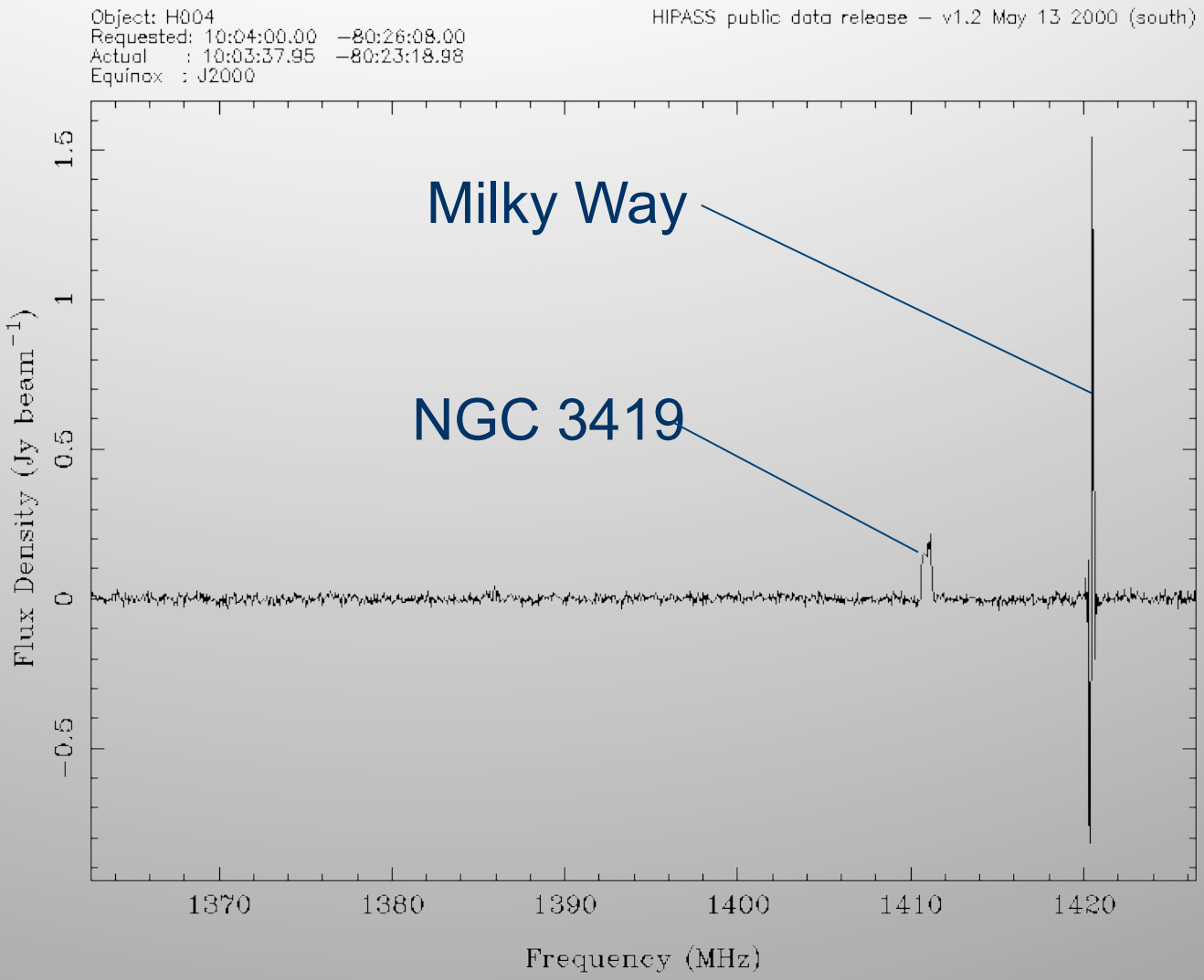
Synch. spectrum

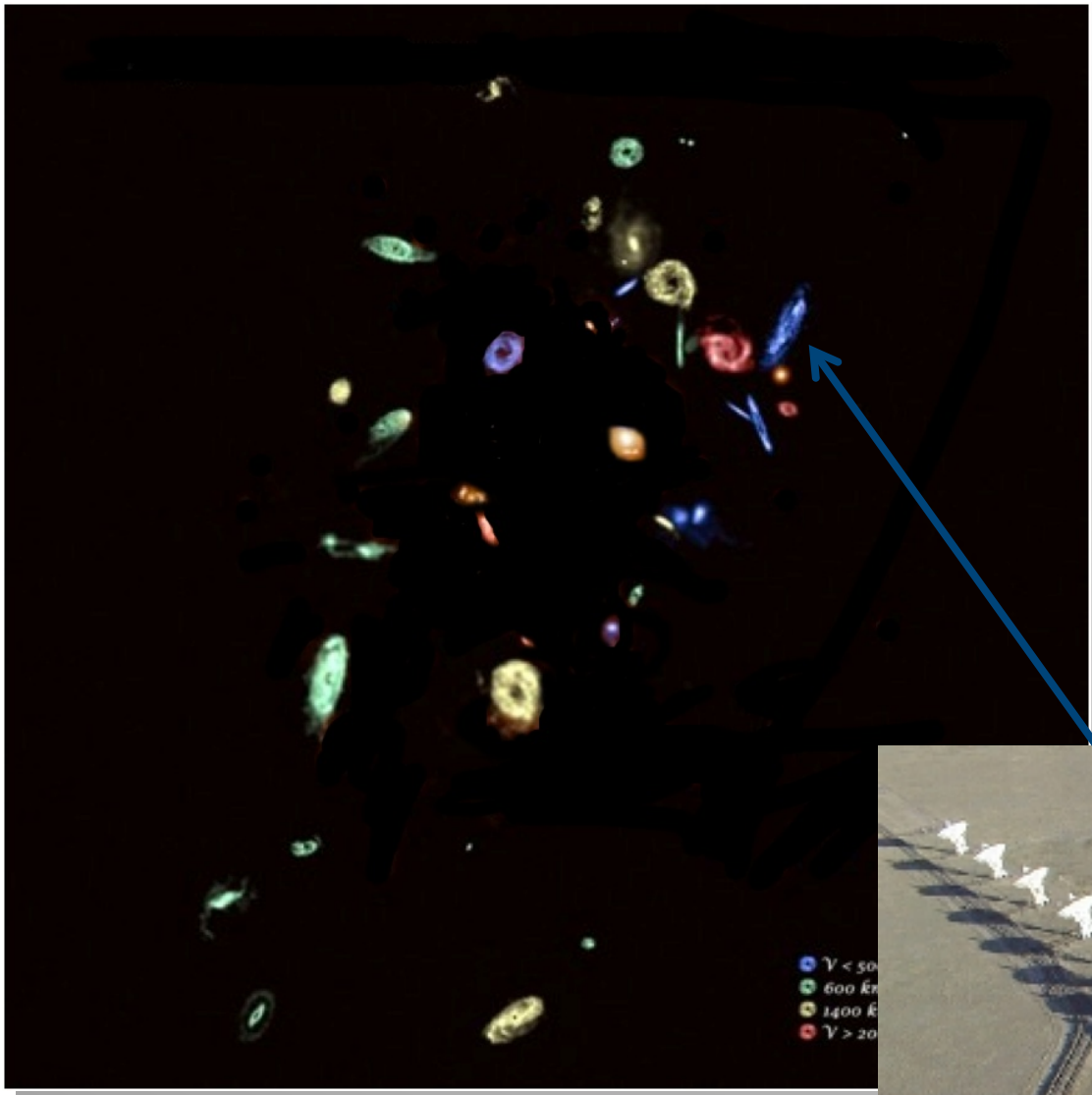
Pritchard & Loeb 2008

21-cm observations are three dimensional and can cover huge co-moving volumes



Data from Parkes Telescope

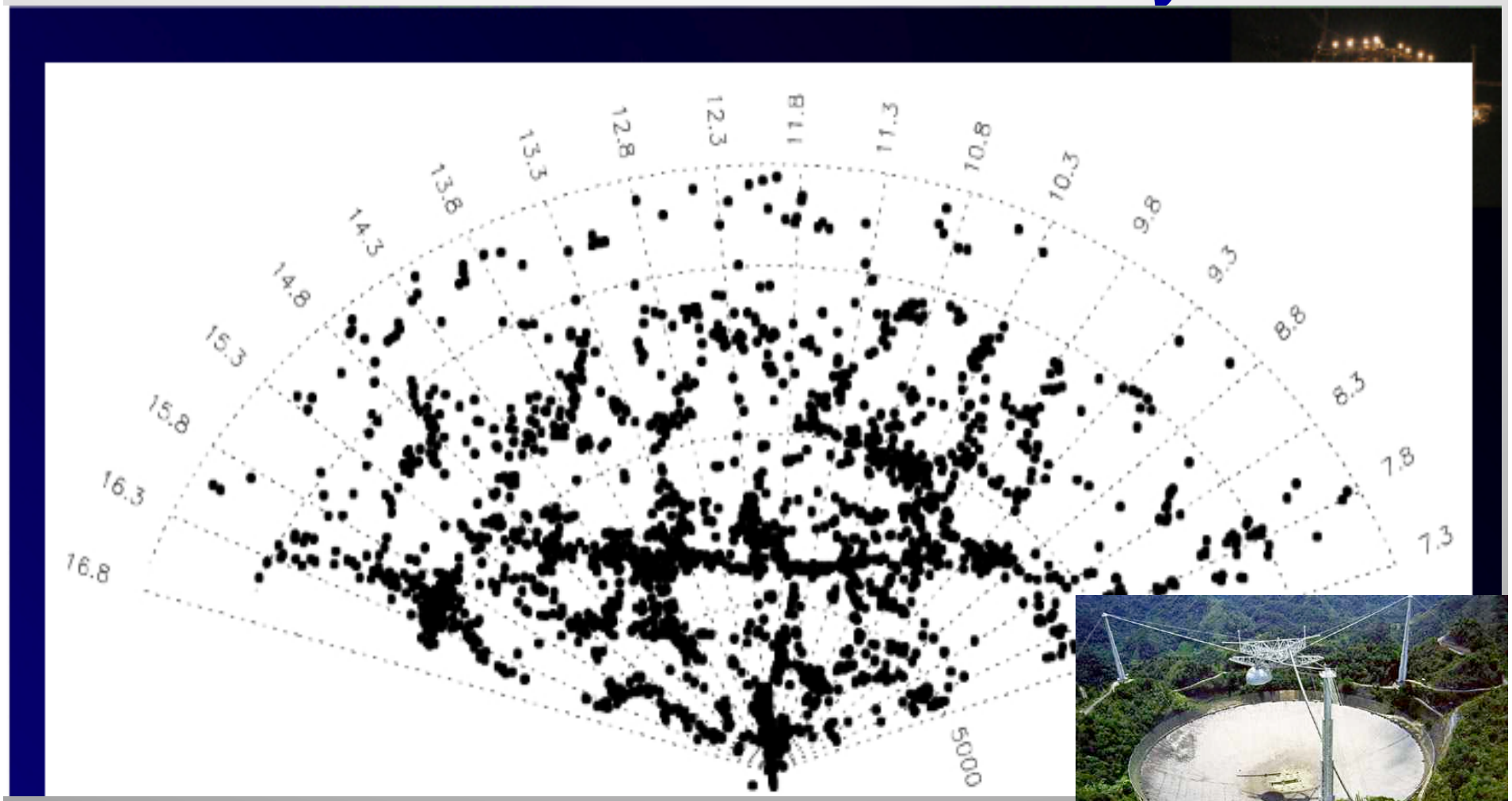




Very Large Array

21 cm galaxy images,
Form the VIVA project.

Alfalfa redshift survey

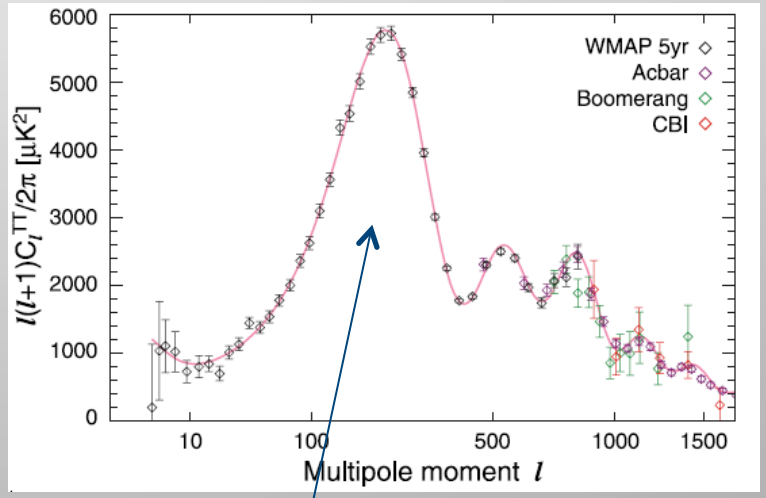


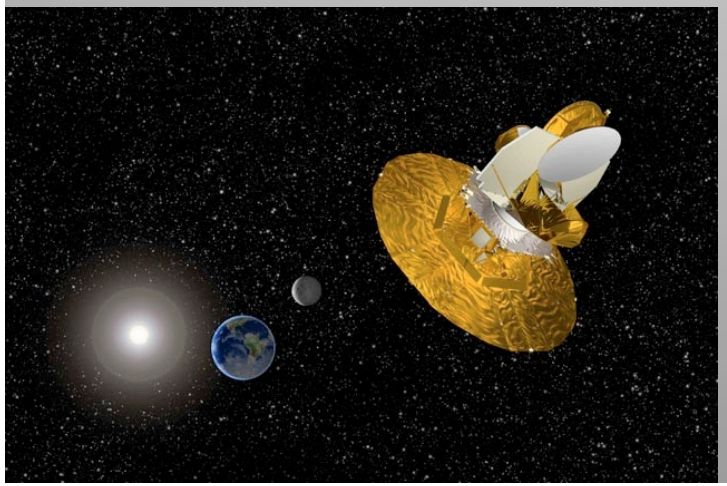
Large scale structure matches optical surveys

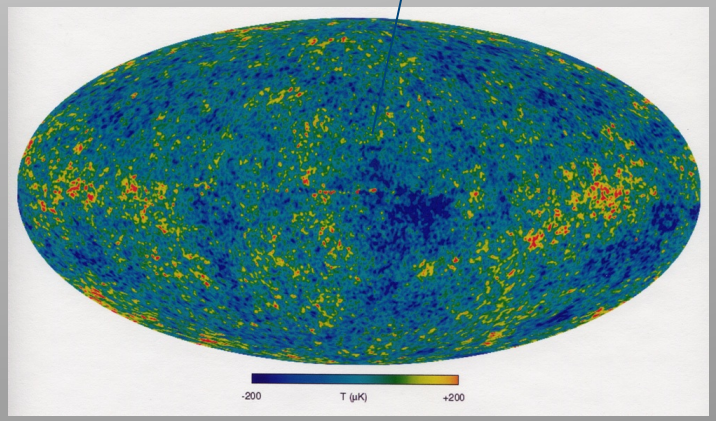
Baryon Acoustic Oscillations – Dark Energy Probe

- CMB acoustic oscillations: imprinted standard ruler, 400 Mly.

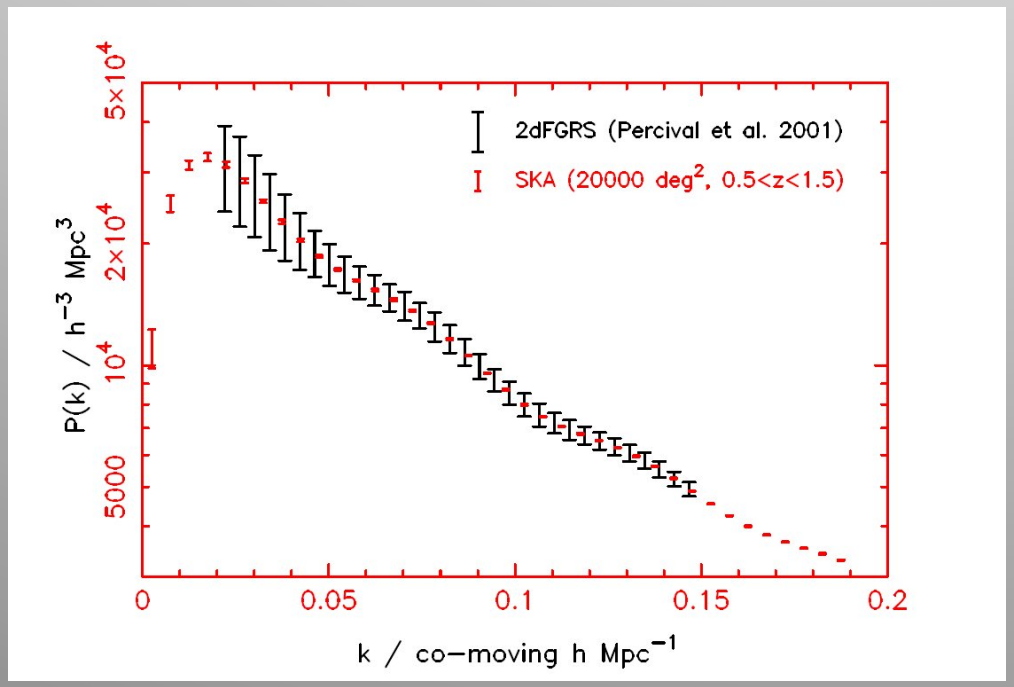
WMAP5 and other, Nolta et al (2008)

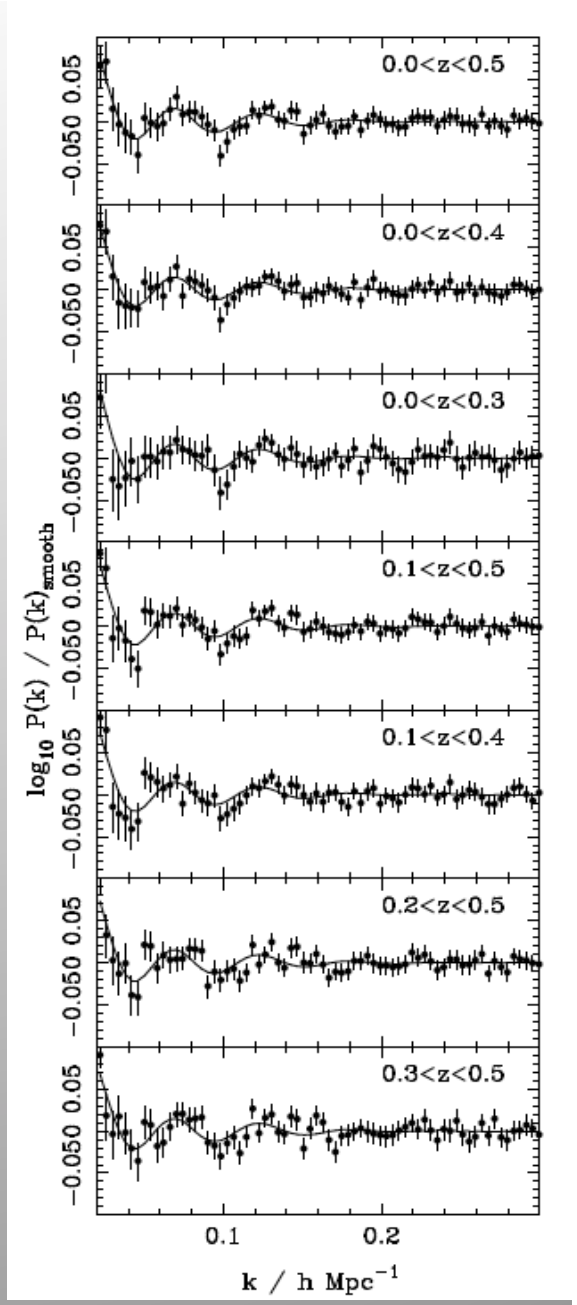






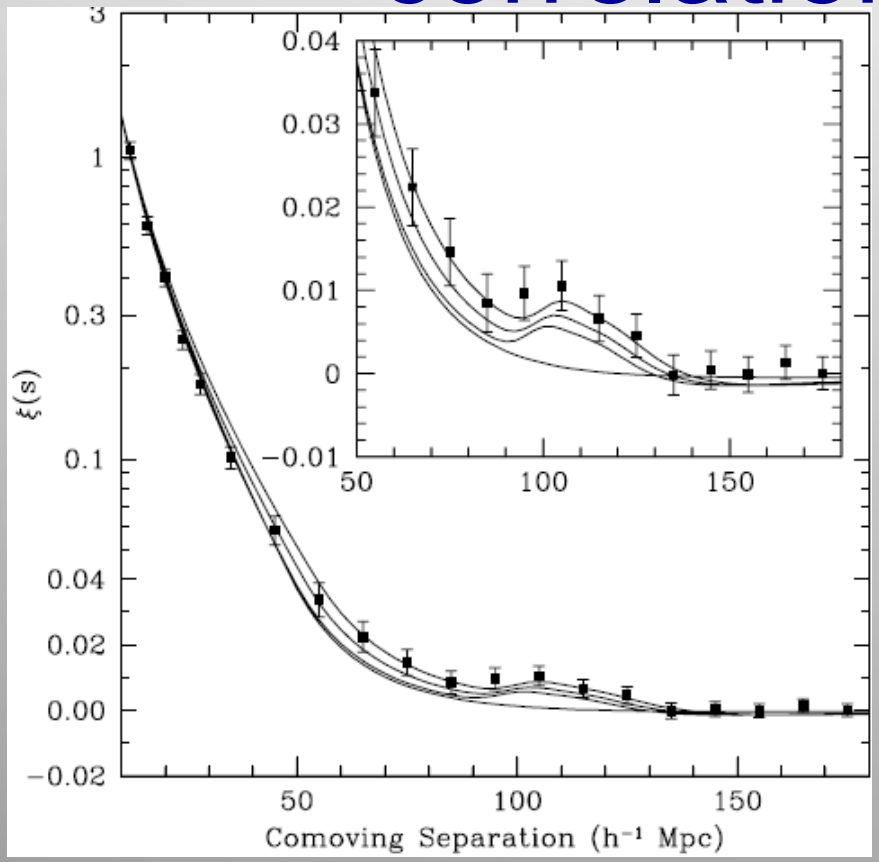
Baryon Wiggles Detected by SDSS and 2df

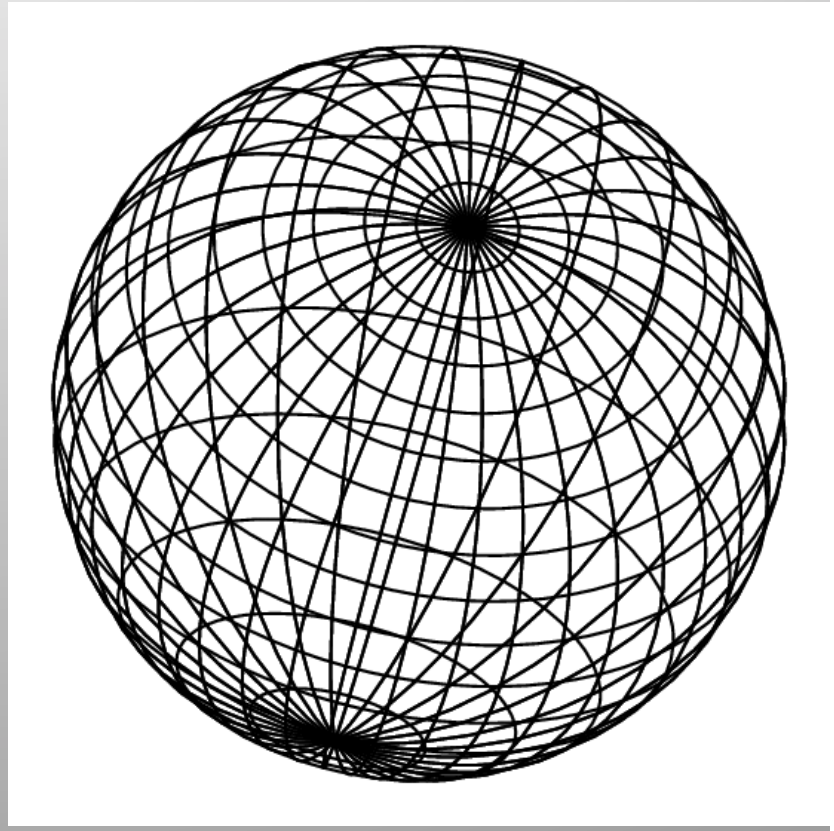




Eisenstein etal 2009

Spherical Shell in 3d correlation space.





Intensity Mapping

- Sethi, 2005
- Chang, Pen, JP, McDonald 2008
- Loeb, A. & Wyithe 2008

www.jpl.nasa.gov

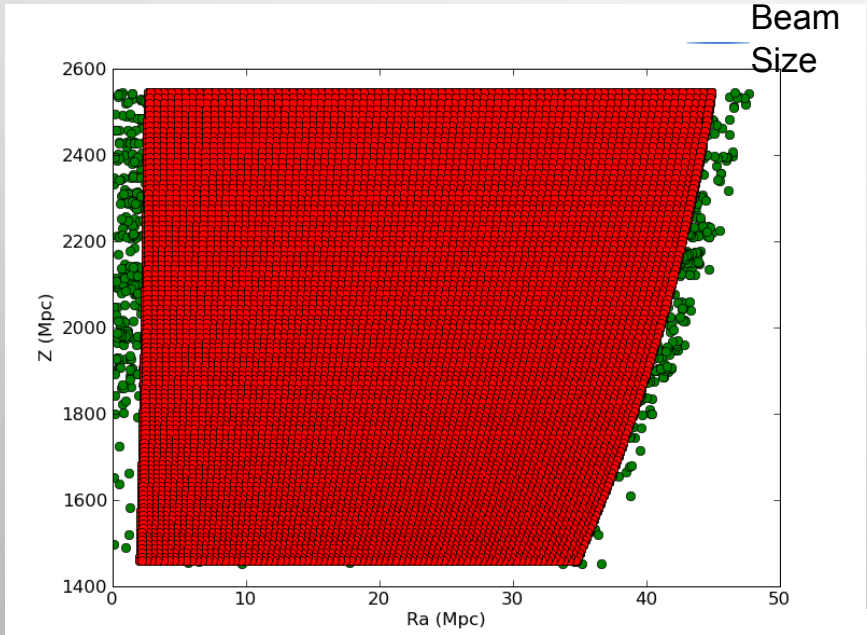
Green Bank Telescope
West Virginia

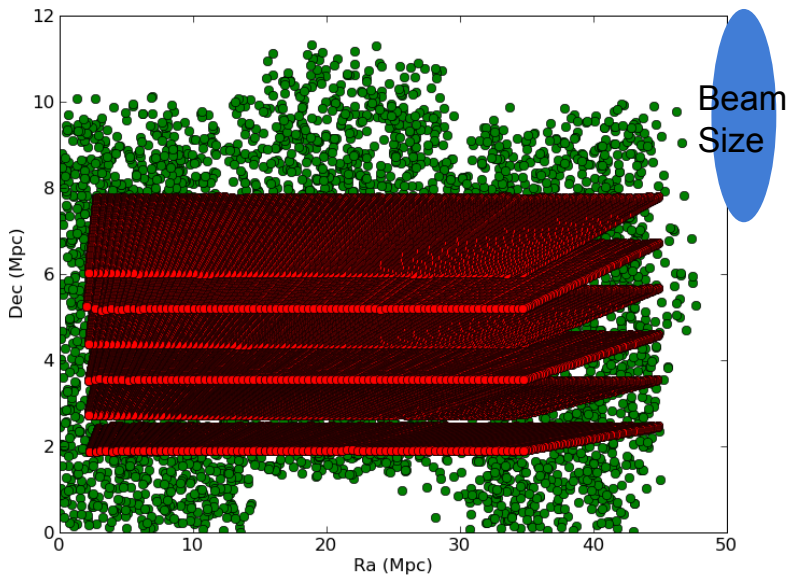
- 50 hours observation at z=1
- 10 hours at z=1.5

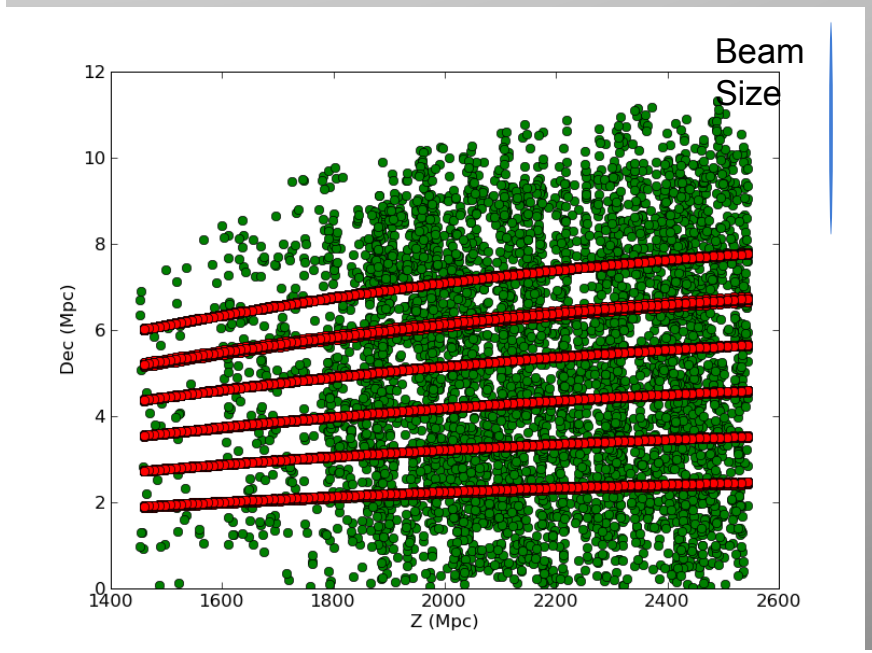
- DEEP2 Fields 2,4 deg x 0.5 deg fields

- 15 arcmin angular resolution at z=1

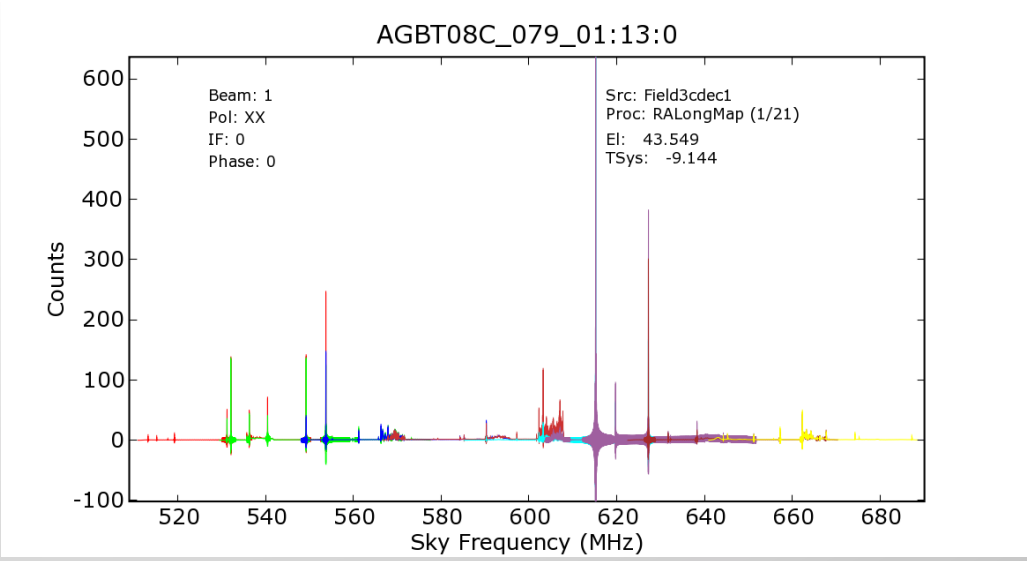
RA-Long Map


Beam
Size
Z (Mpc)
Ra (Mpc)


Beam
Size
Dec (Mpc)
Ra (Mpc)

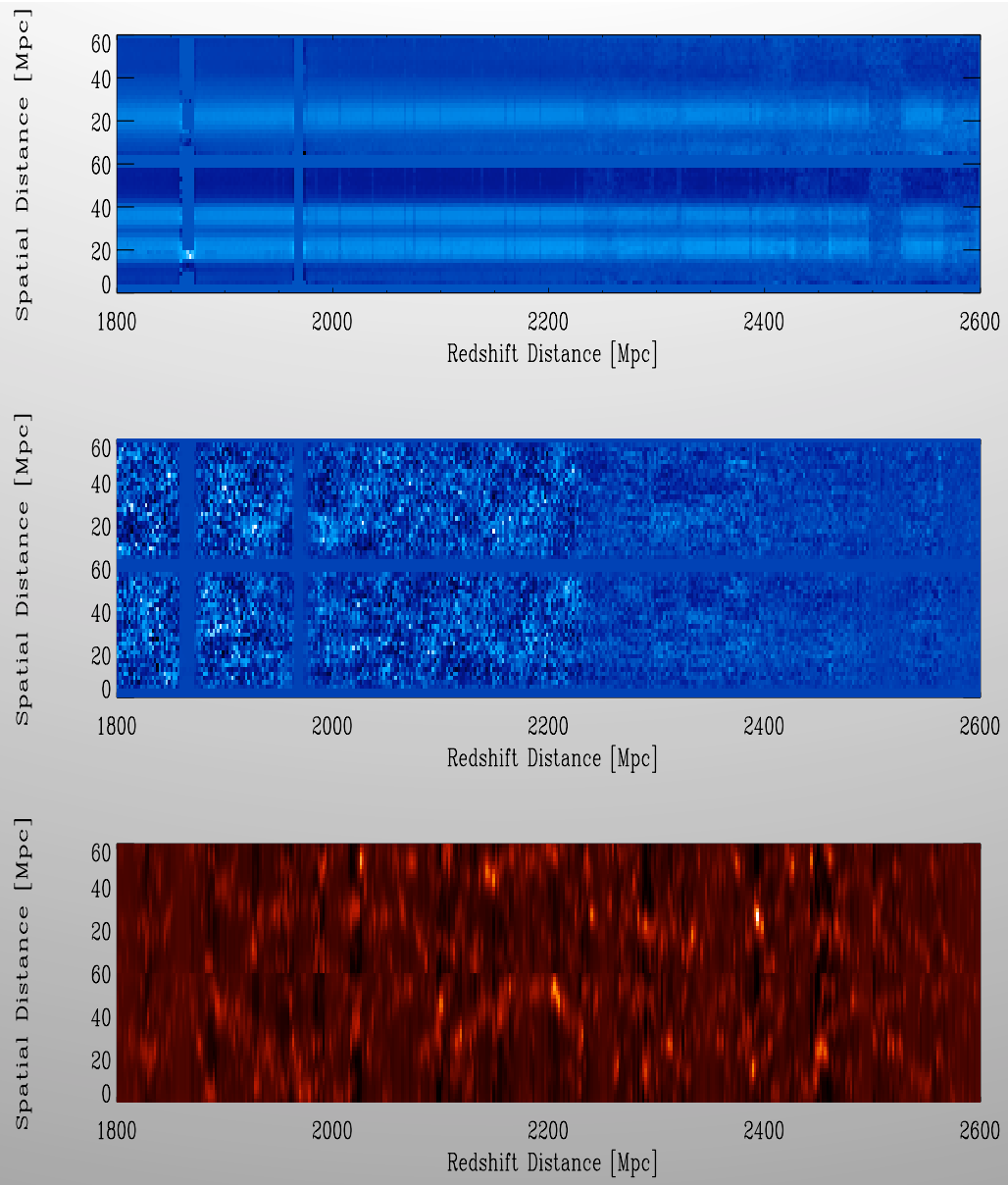

Beam
Size
Dec (Mpc)
Z (Mpc)

Raw spectra GBT (pre-June 2009)

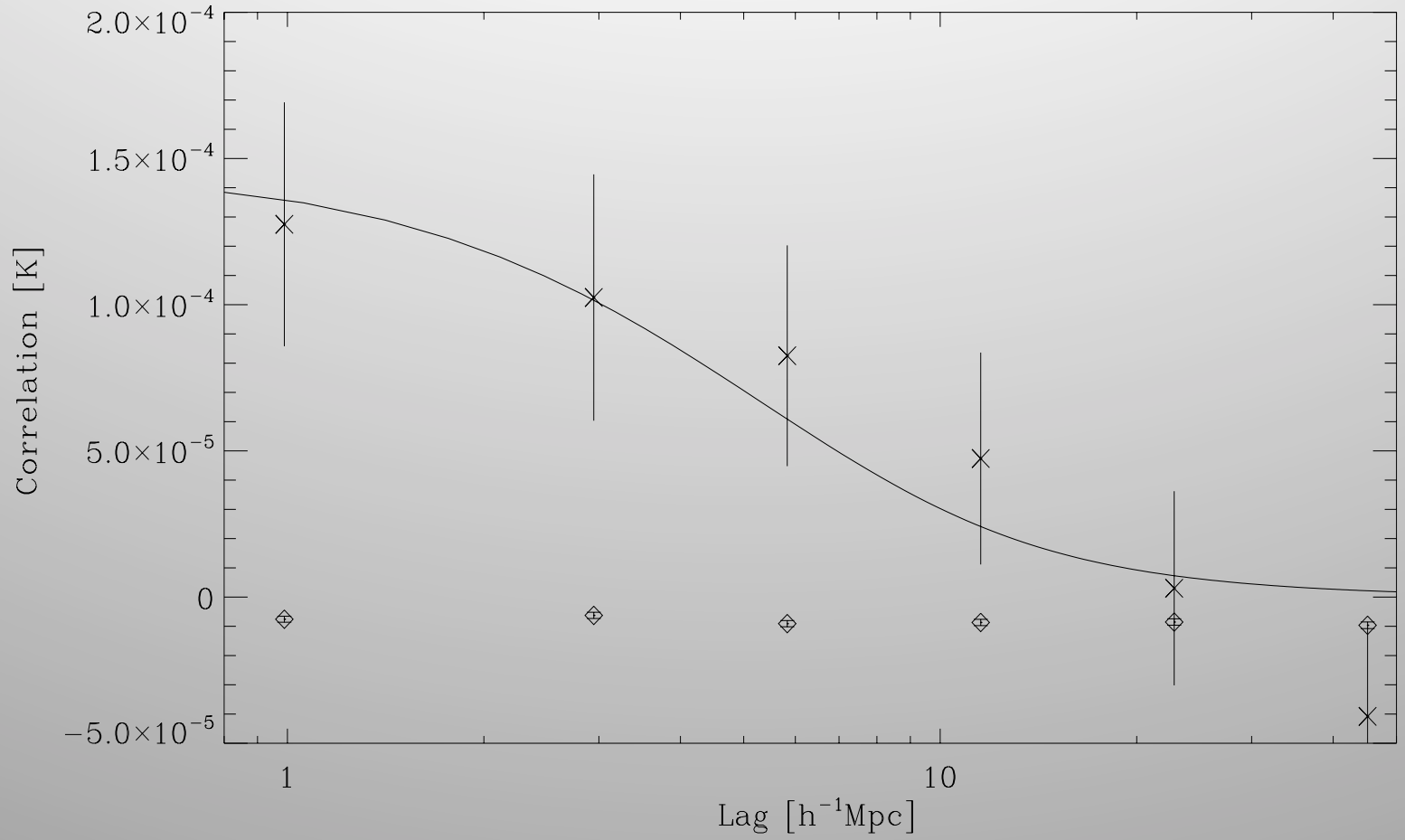


Analysis:

- Deal with instrument instabilities
- Remove RFI
- Remove Foregrounds
  - Galactic Synchrotron


Spatial Distance [Mpc]
60
40
20
60
40
20
0
1800
2000
2200
2400
2600
Redshift Distance [Mpc]
Spatial Distance [Mpc]
60
40
20
60
40
20
0
1800
2000
2200
2400
2600
Redshift Distance [Mpc]
Spatial Distance [Mpc]
60
40
20
60
40
20
0
1800
2000
2200
2400
2600
Redshift Distance [Mpc]

21cm – DEEP2 cross correlation



Chang, Pen, Bandura, JP, 2010

Results from GBT

- 2 x 10^14 solar masses HI detected at z~0.8
- Omega HI ~4.5 10^-4
- Intensity Mapping seems productive

Current program at GBT

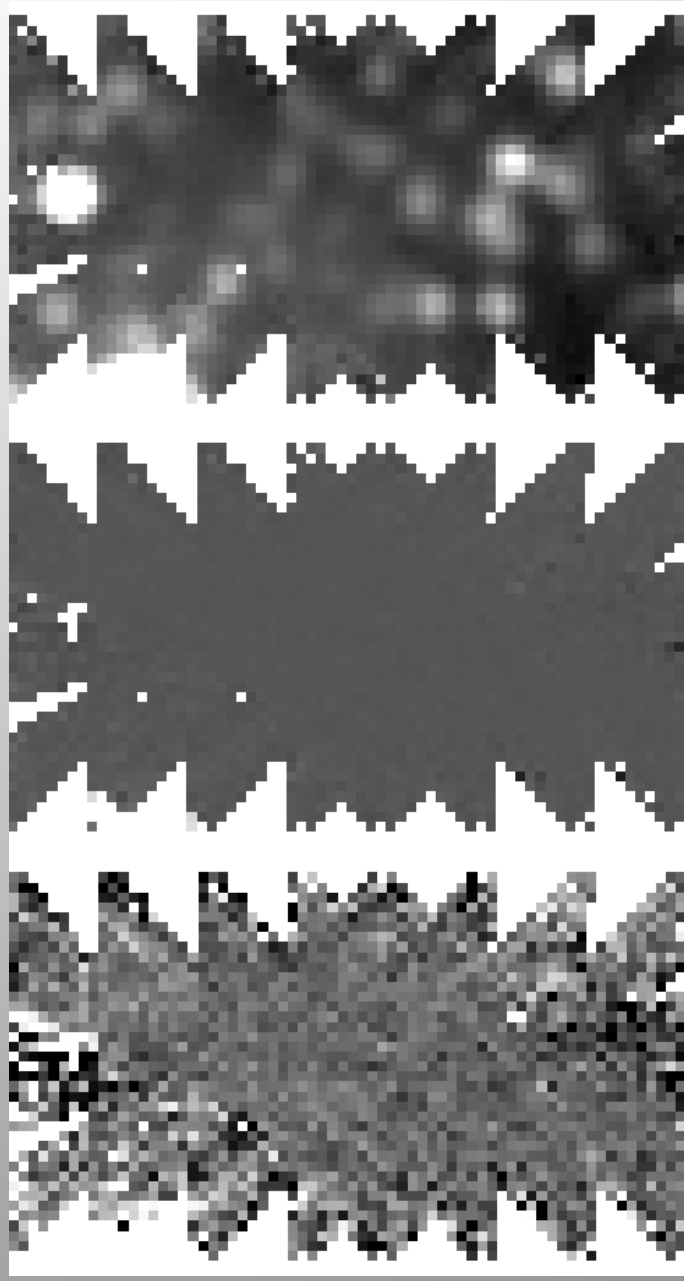
-Attempt to detect 21 cm structure without use of optical survey

-Sweep Horizontally across Wigglz fields, rising, setting and transit

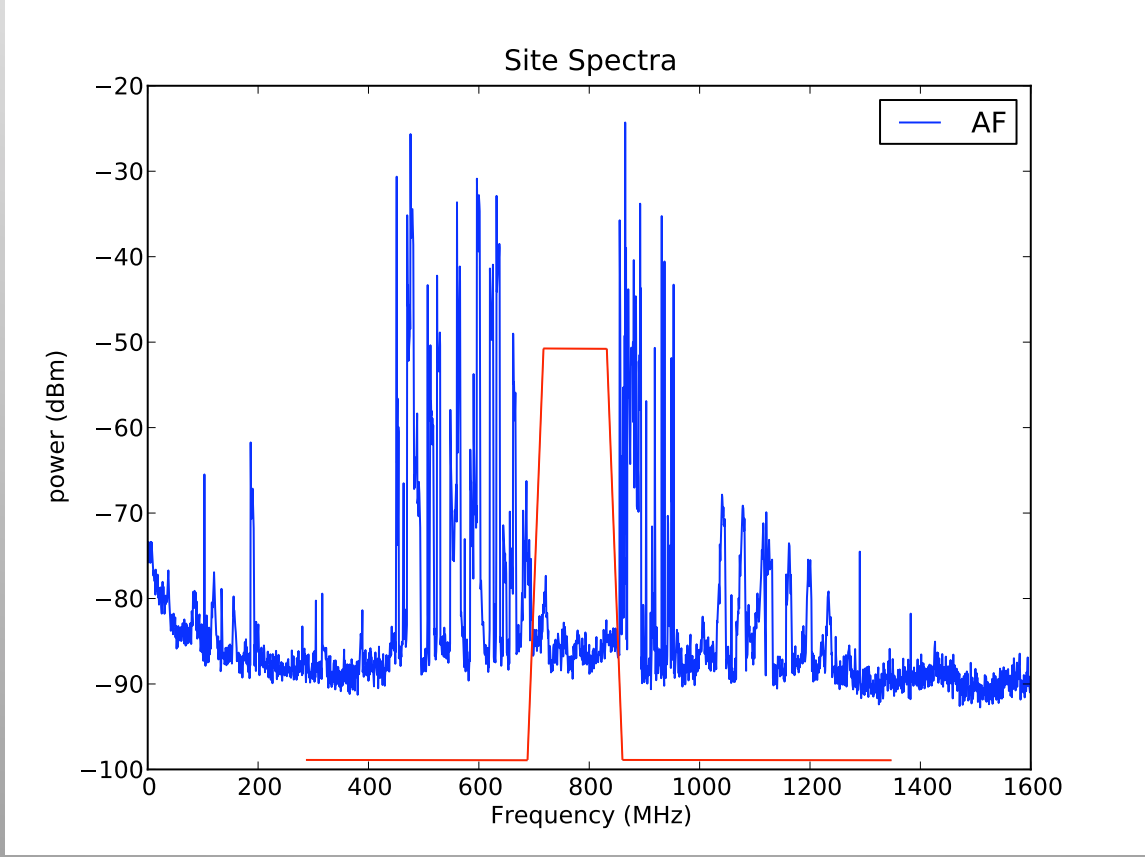
-Use CMB cross linked imaging algorithm

-Use PCA to remove modes with common Freq. structure.

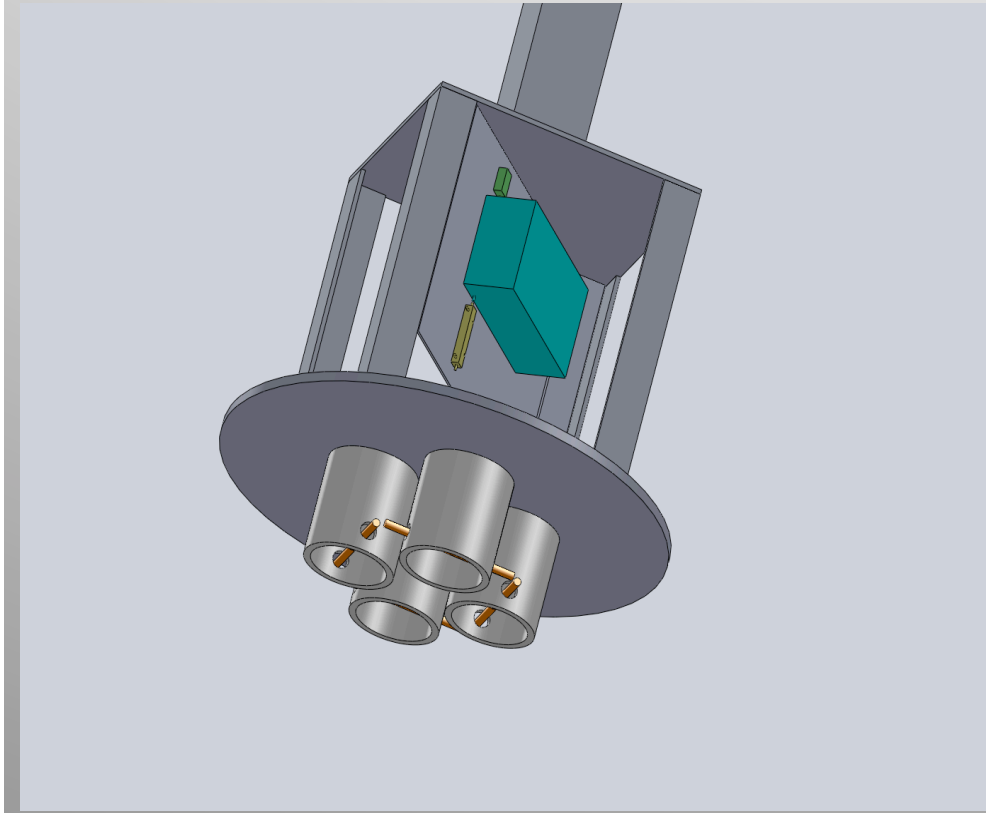
-Residual rms about twice the expected 21 cm signal.



Arecibo RFI


Site Spectra
AF
power (dBm)
Frequency (MHz)
−20
−30
−40
−50
−60
−70
−80
−90
−100
0
200
400
600
800
1000
1200
1400
1600

CMU 800 MHz feed at Arecibo



Use compact feed to fill the first fresnel zone of the spherical surface

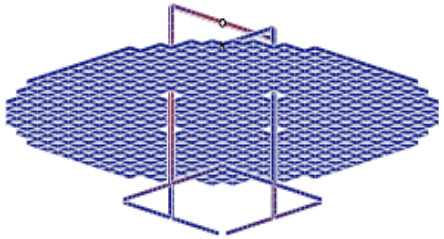
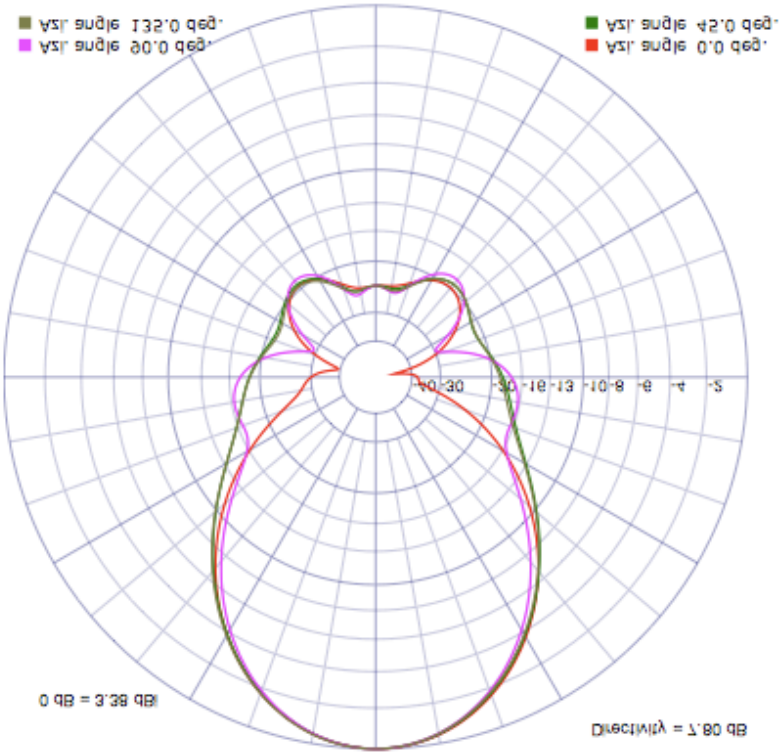
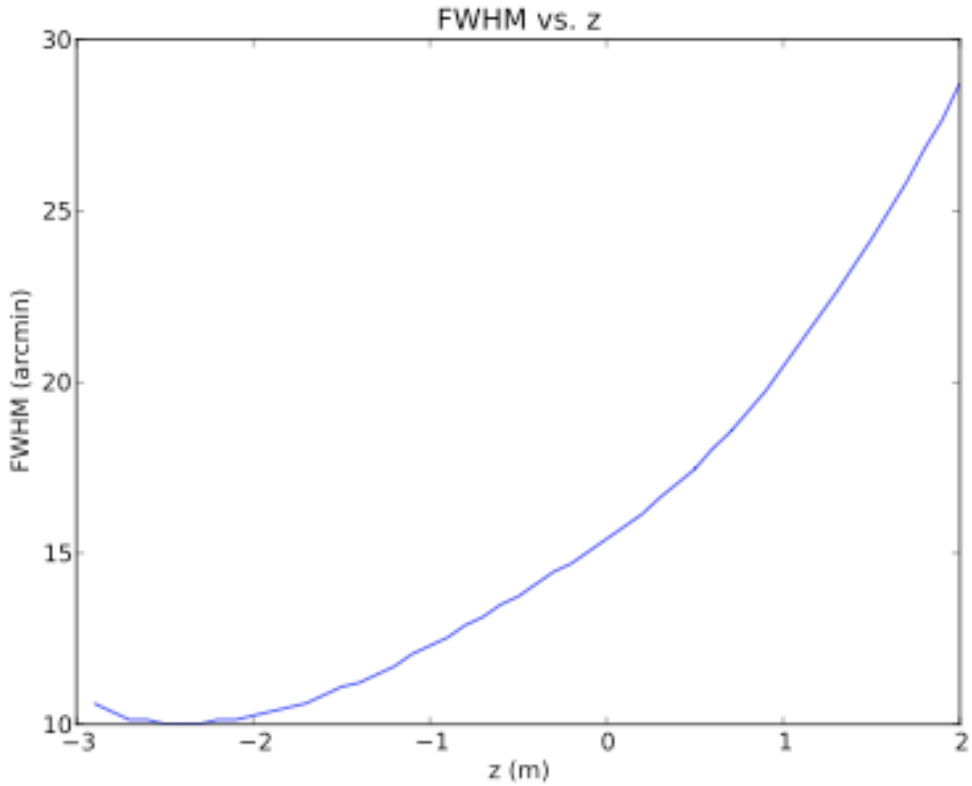
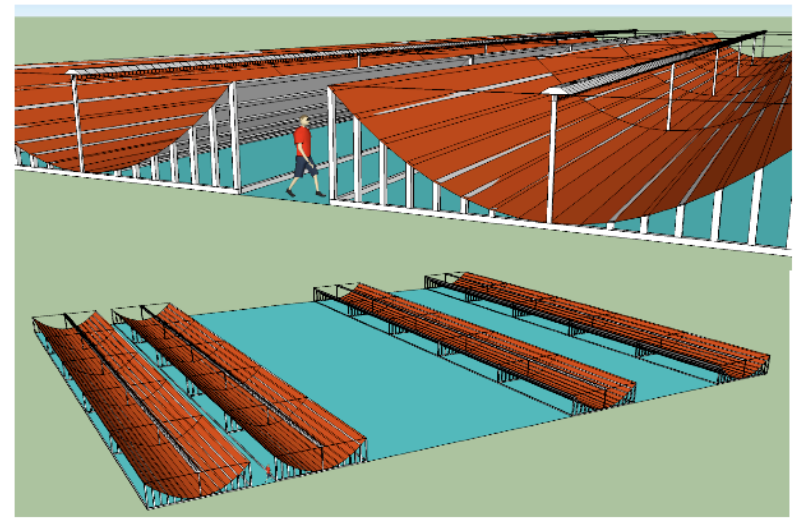


Figure 5: Feed Elevation biplot





Parameters of CRT



- Aperture filling: ~50%
- Size: 50-100 m
- Sky coverage: >10,000 sq degrees
- Number of data streams: 64-8,000
- Freq Range: start at ~700 MHz, allow 300-1500
- Instantaneous Bandwidth 100 MHz

The Cylinder Radio Telescope Consortium

- Jeff Peterson (CMU)
- Kevin Bandura,
- Bruce Taylor
- Jim McGee
- Florence Liu
- Deena Kim
- Bruce McWilliams

- Ue-LI Pen (CITA)

- Uros Seljak (U. C Berkeley)
- Hee Jong Seo

- Peter Timbie (U. Wisc.)

- Scott Dodelson (FNAL)
- John Marriner
- Dave McGinnis
- Albert Stebbins

- Tzu-Ching Chang (IAA Taipei)
- Kris Sigurdson (UBC)

- Chen Xuelei (NAOC)
- Shi Huli
- Wang Yougang
- Wu Fangquan

- Chen Zhiping (Hangzhou Dianzi University)
- Rui Lui

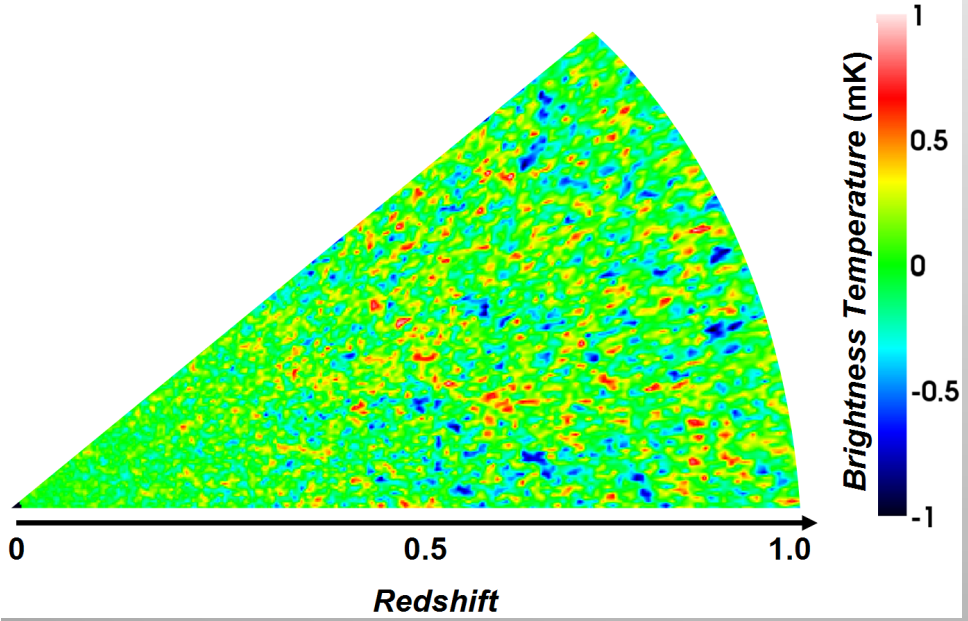
- Hassane Darhmouai (AUI)
- Rachid Benmouktar

- Christope Yeche (CEA)
- Christohpe Magneville
- Jim Rich
- 2 FTE engineer

- Reza Ansari (LAL)
- Marc Moniez
- 2 FTE engineer

- Jon Bunton (CSIRO)

Simulated Results



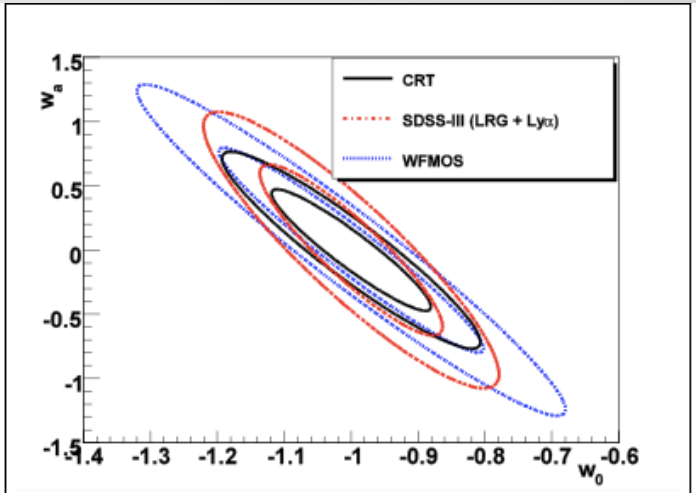
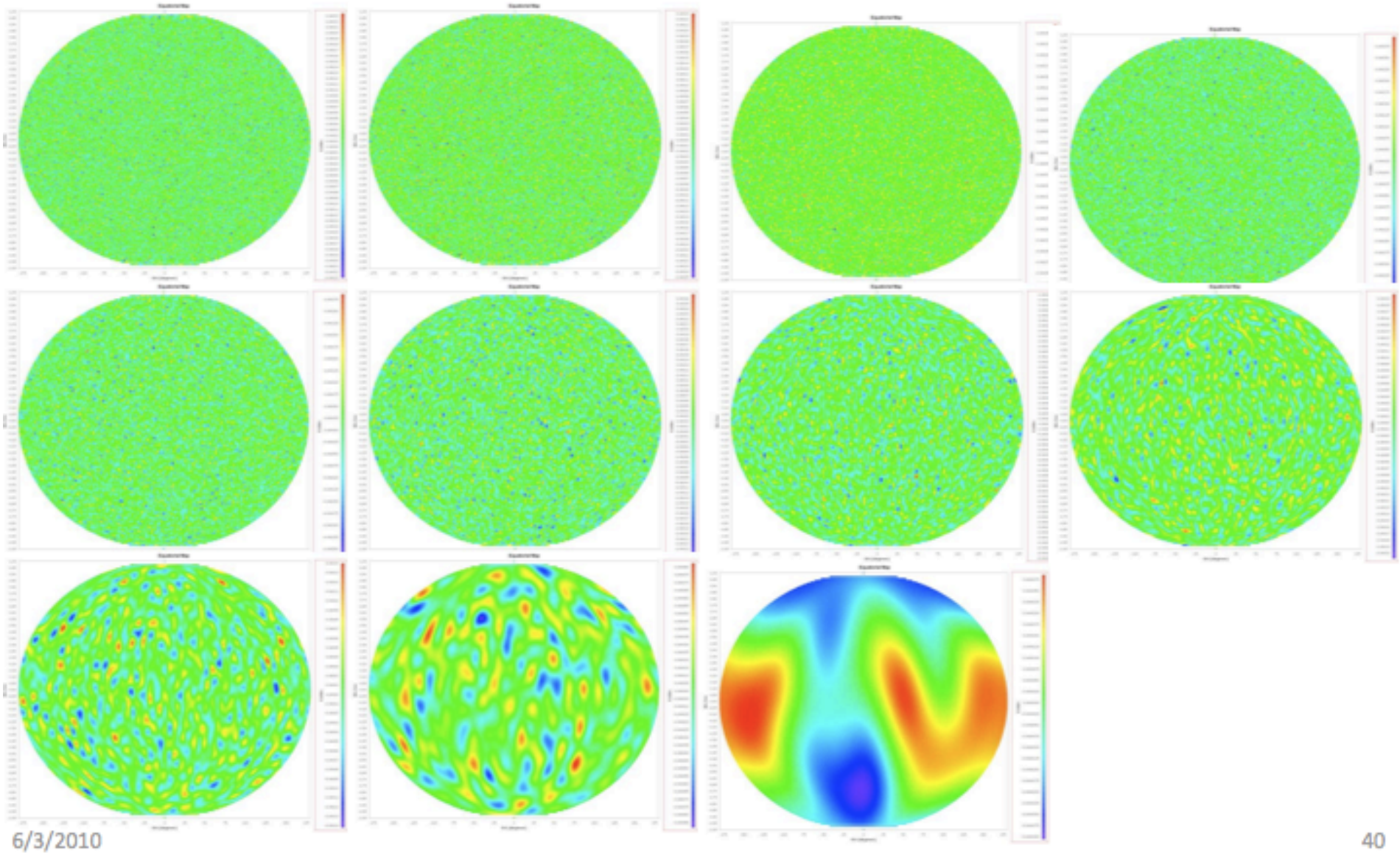


Figure 1. Sensitivity to Dark Energy Models. The plot shows projected error ellipses in the parameter space laid out by the Dark Energy Task Force. $w_0 = p/\rho$ is the dark energy equation of state, and w_a is the first derivative of w. Plotted in black are 1-σ and 2-σ contours for HI Intensity Mapping assuming a Cylinder Radio Telescope of area 10,000 sq meters. Also plotted are contours for the optical BAO experiments SDSS-III after combining the Large Red Galaxy and Lyman-alpha surveys (red) and WFMOS (blue).

N. Gnedin

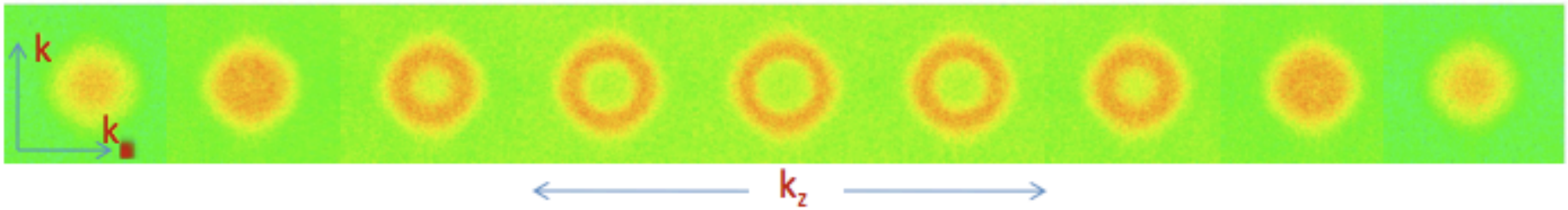
R. Ansari, etal

BAO Signal First Peak from 400-1400MHz

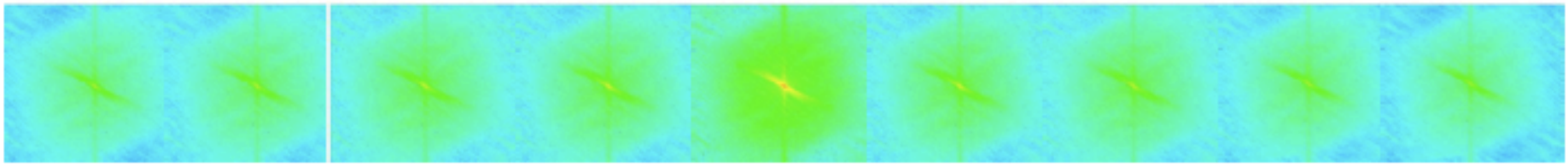


Foreground Removal (Fermilab)

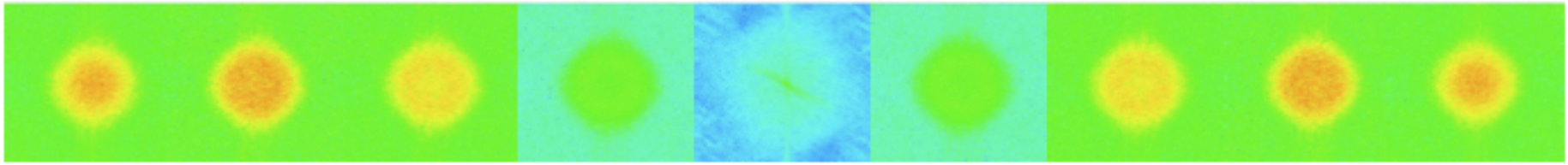
BAO First Peak in 3-D k-Space (Gnedin)



BAO First Peak and Foreground in 3-D k-Space



BAO First Peak and Foreground with Foreground Removal in 3-D k-Space



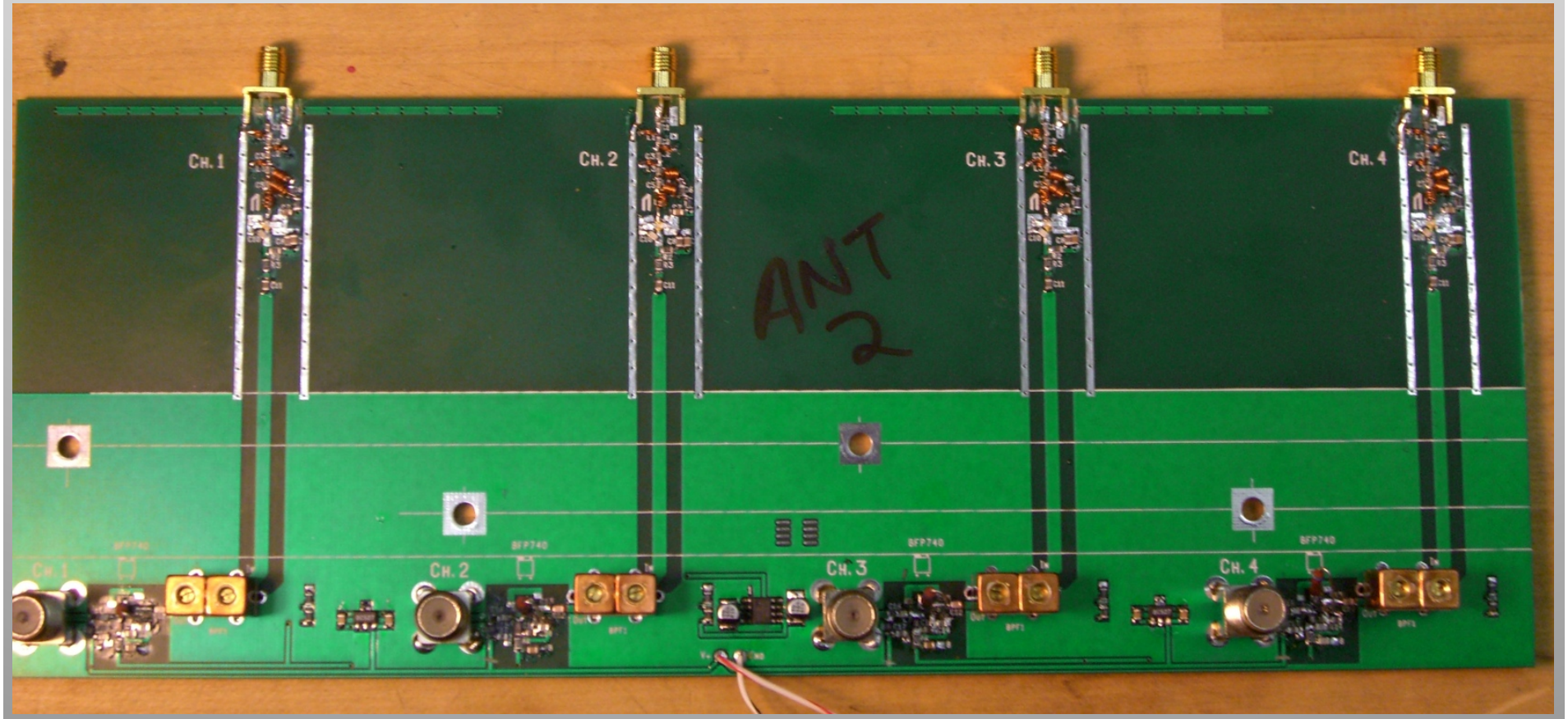
Other Science Goals for CRT

- Pulsar Search
- Map Magnetic Fields via Rotation Measure
- SETI
- Stepping stone for HERA
- Cutting-edge high-throughput radio astronomy

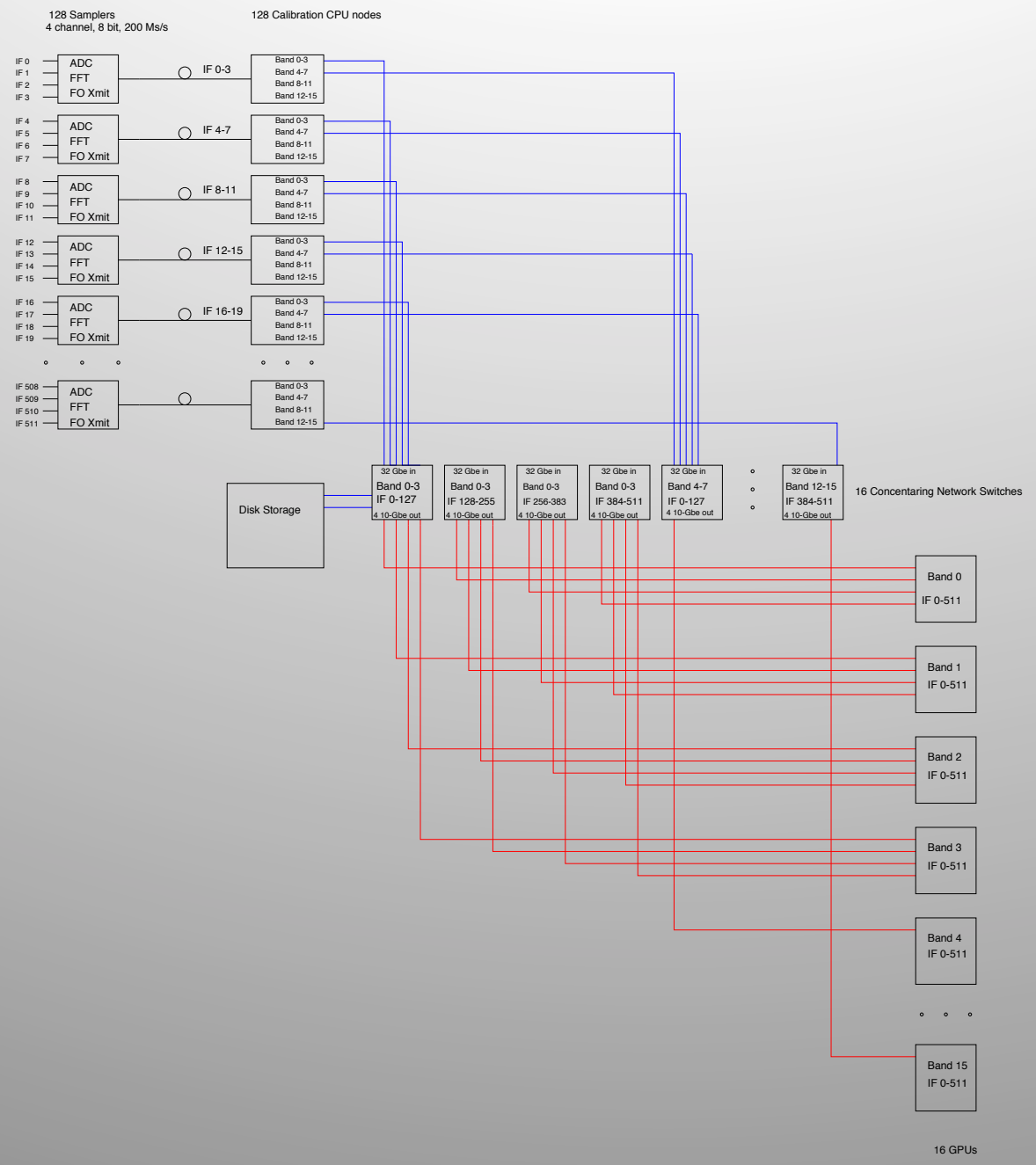
CMU cylinders in operation:
J. Peterson, K. Bandura, U-L Pen, K. Sigurdson, U
Seljak

STATE
JUNIATA
SUBARU

Antenna and LNA



Correlaltion computer (Sigurdson)


128 Samplers
4 channel, 8 bit, 200 Ms/s
128 Calibration CPU nodes
IF 0
IF 1
IF 2
IF 3
ADC
FFT
FO Xmit
IF 0-3
Band 0-3
Band 4-7
Band 8-11
Band 12-15
IF 4
IF 5
IF 6
IF 7
IF 4-7
IF 8
IF 9
IF 10
IF 11
IF 8-11
IF 12
IF 13
IF 14
IF 15
IF 12-15
IF 16
IF 17
IF 18
IF 19
IF 16-19
IF 508
IF 509
IF 510
IF 511
Disk Storage
32 Gbe in
Band 0-3
IF 0-127
4 10-Gbe out
Band 0-3
IF 128-255
Band 0-3
IF 256-383
Band 0-3
IF 384-511
Band 4-7
IF 0-127
Band 12-15
IF 384-511
16 Concentaring Network Switches
Band 0
IF 0-511
Band 1
IF 0-511
Band 2
IF 0-511
Band 3
IF 0-511
Band 4
IF 0-511
Band 15
IF 0-511
16 GPUs

Design:

W

Dipoles: 2 4 6 8 10 12 14 16

S

N

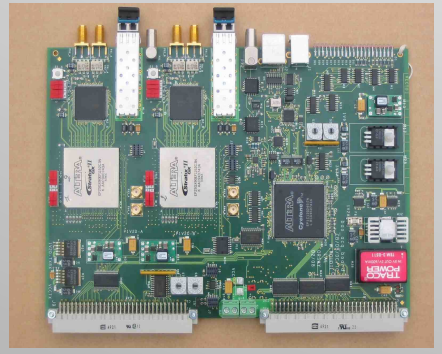
Dipoles: 1 3 5 7 9 11 13 15

X

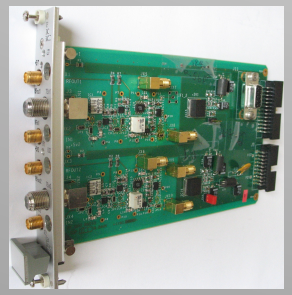
Y

E

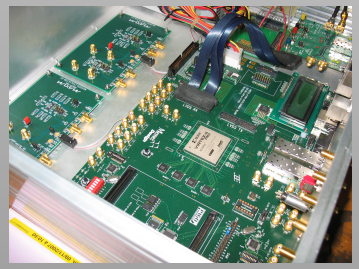
Sampling electronics, LAL, CEA



500MHz ADC board



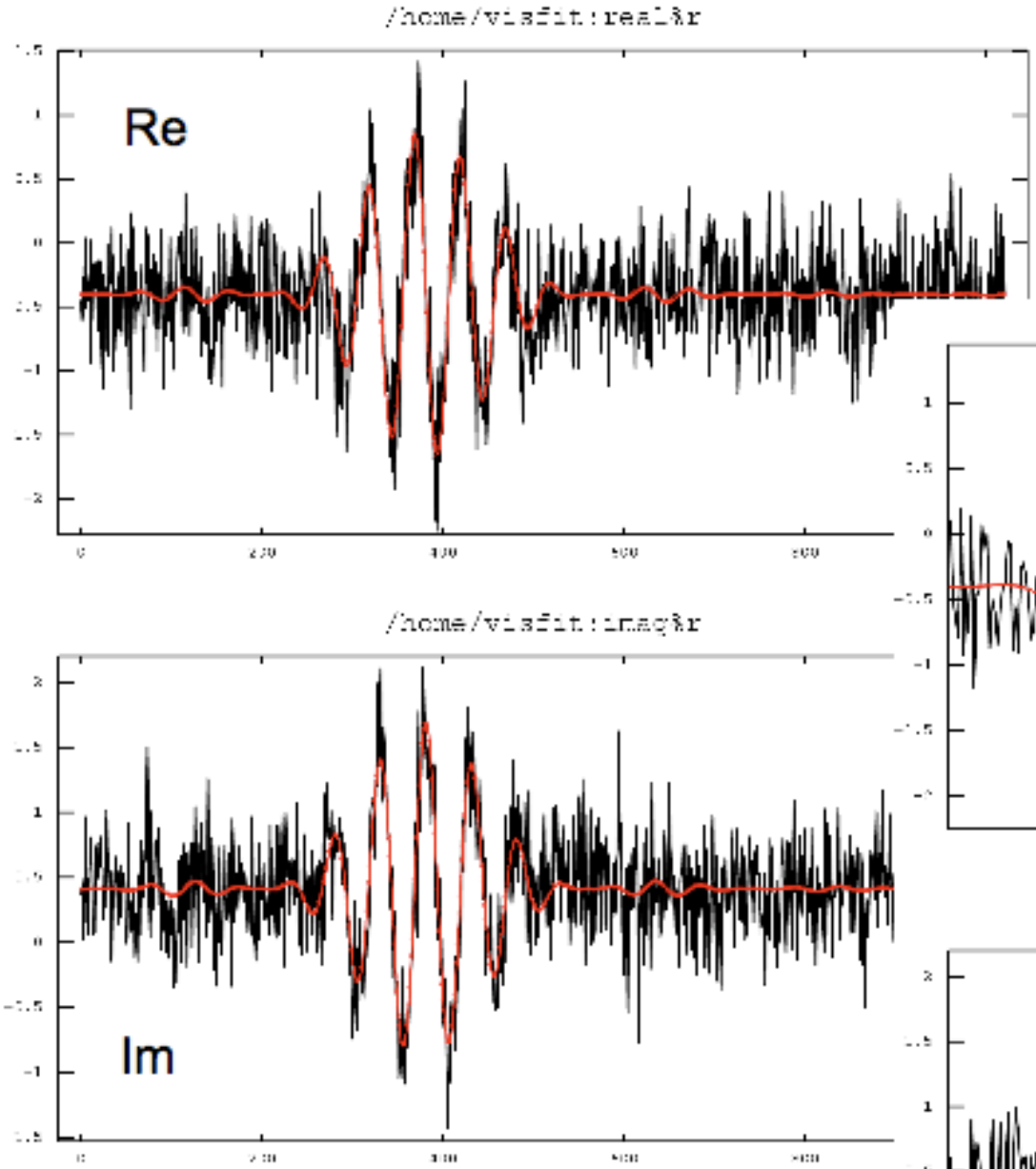
Analog electronics

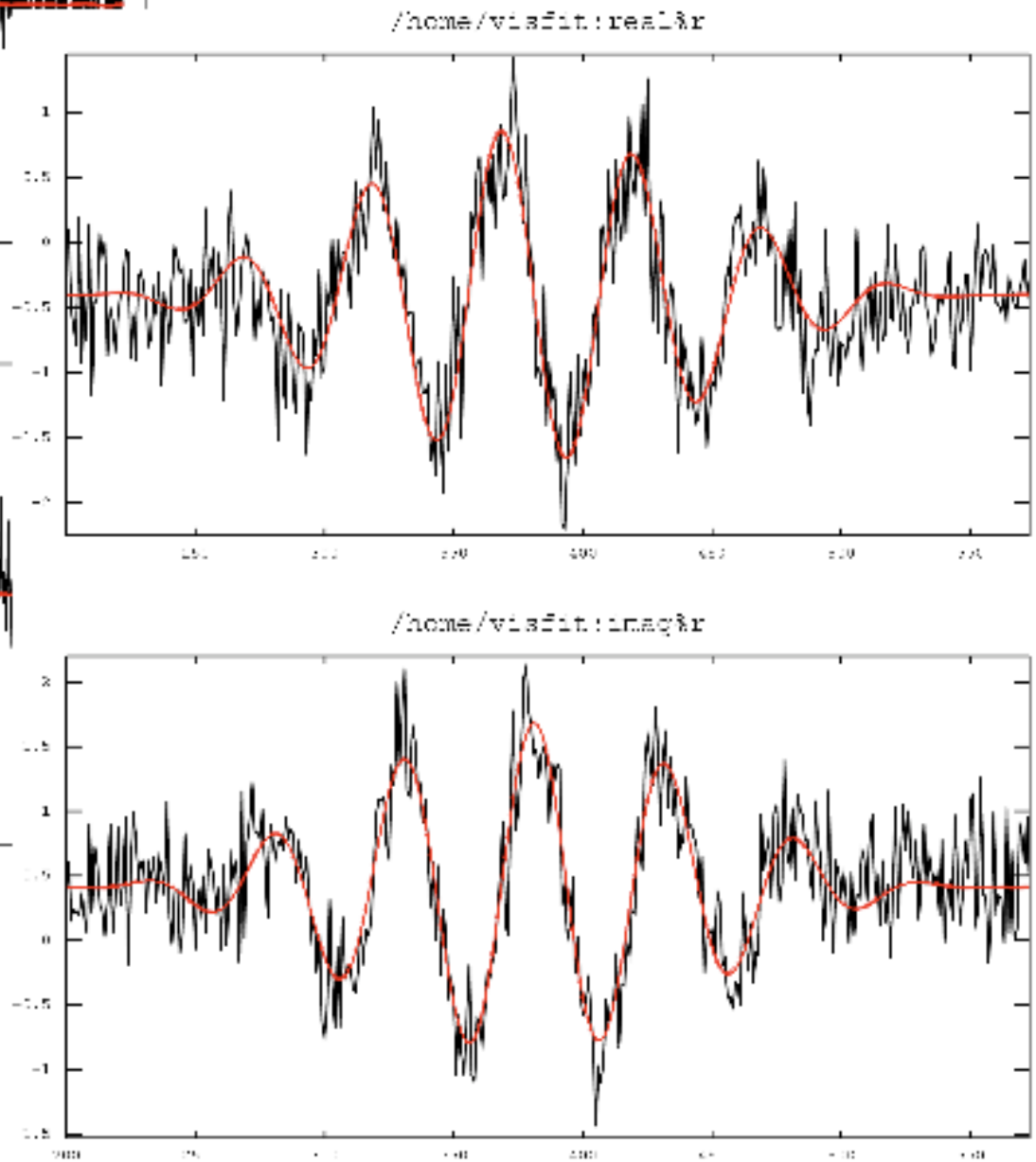


Clock distribution

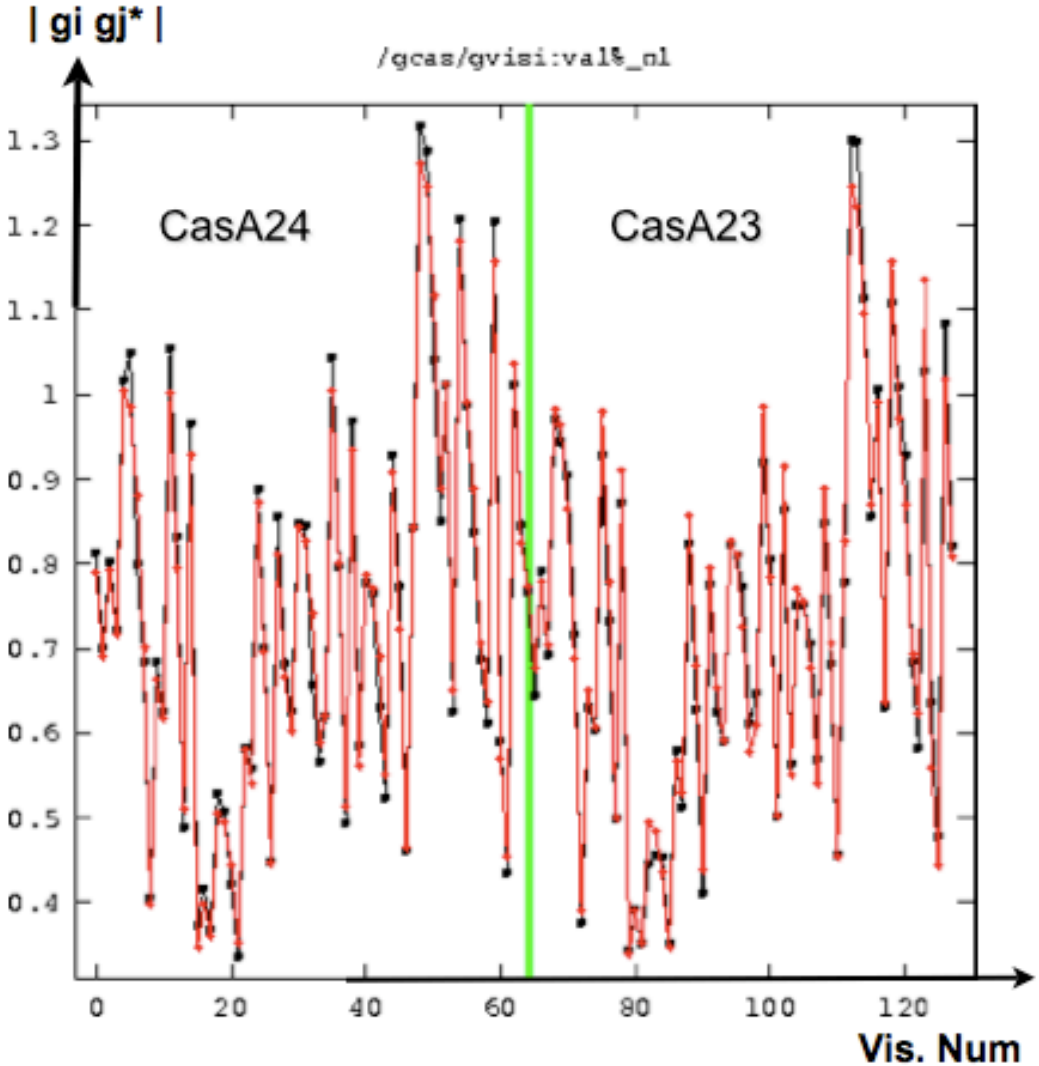
Saclay-Irfu engineers: Ph. Abbon, E. Delagnes, H. Deschamps, P. Kestener
Irfu physicists: J.-M. Le Goff, Ch. Magneville, J. Rich, **Ch.Yeche**
Orsay-LAL engineers: Ch. Beigbeder, D. Breton, T. Caceres, D. Charlet, B. Mansoux, C. Pailler, M. Taurigna
LAL physicists: R. Ansari, M. Moniez

CygA24 <1-2*> 1D fit <16 MHz>





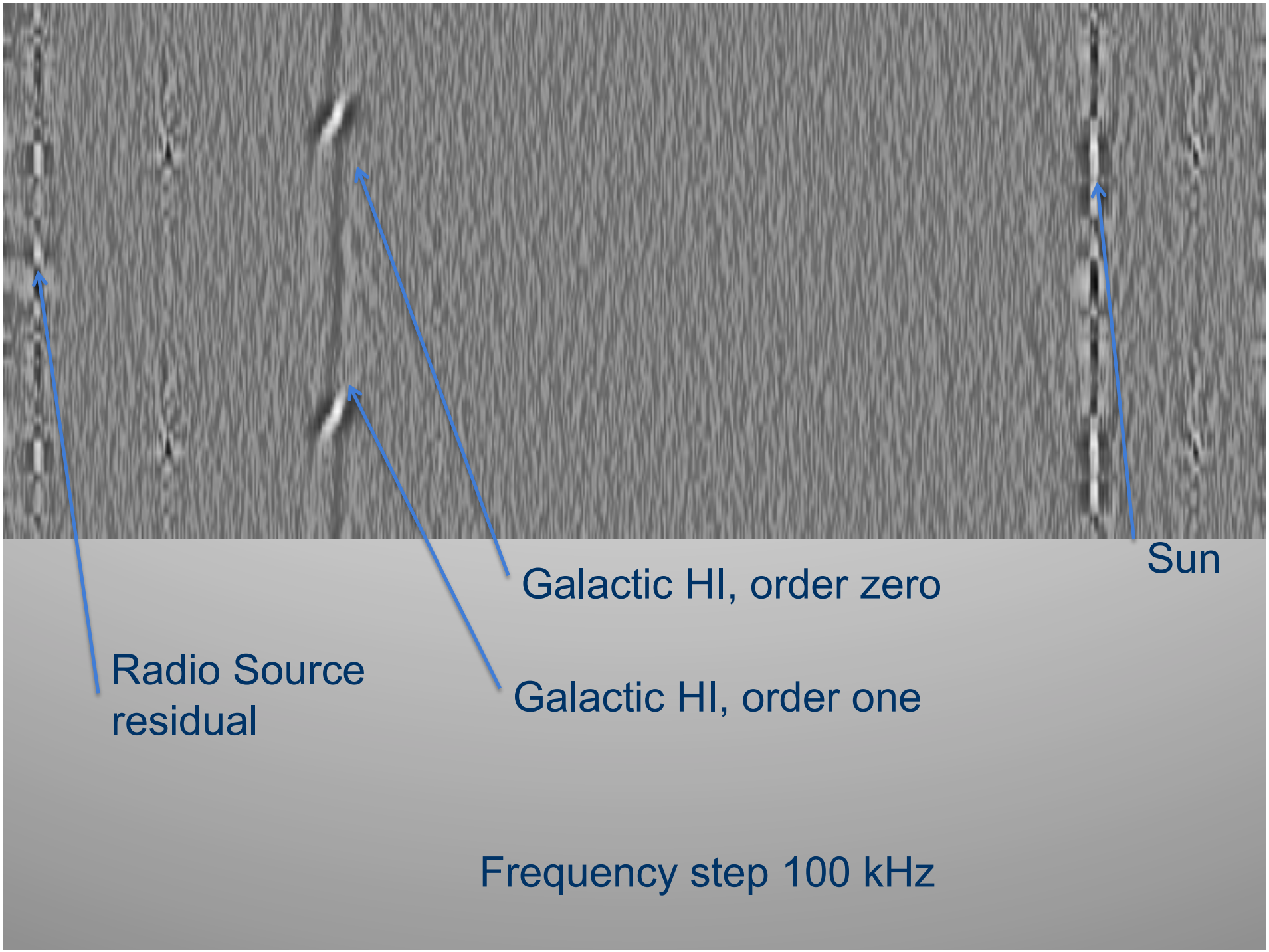
Individual antenna gain - module

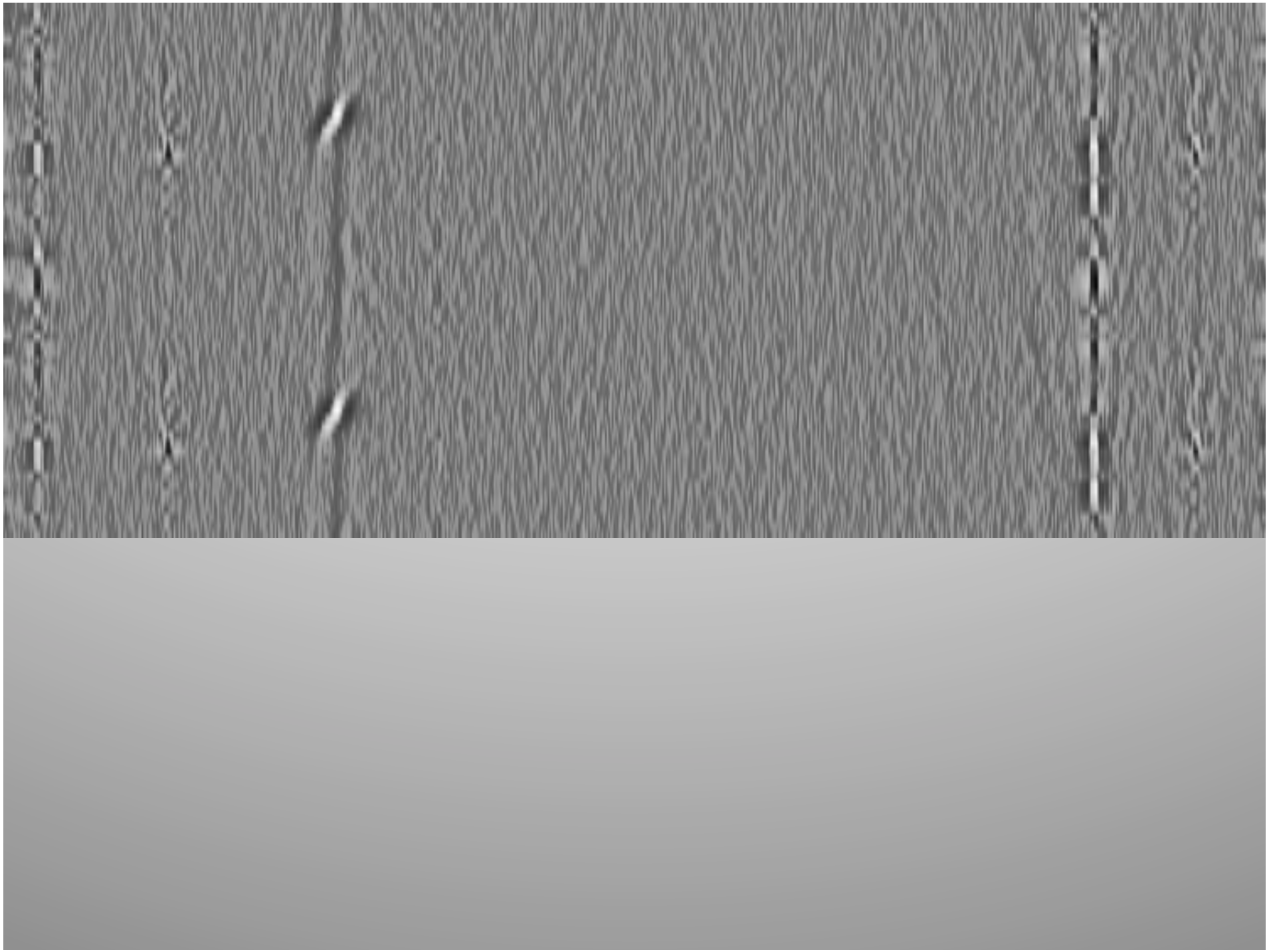


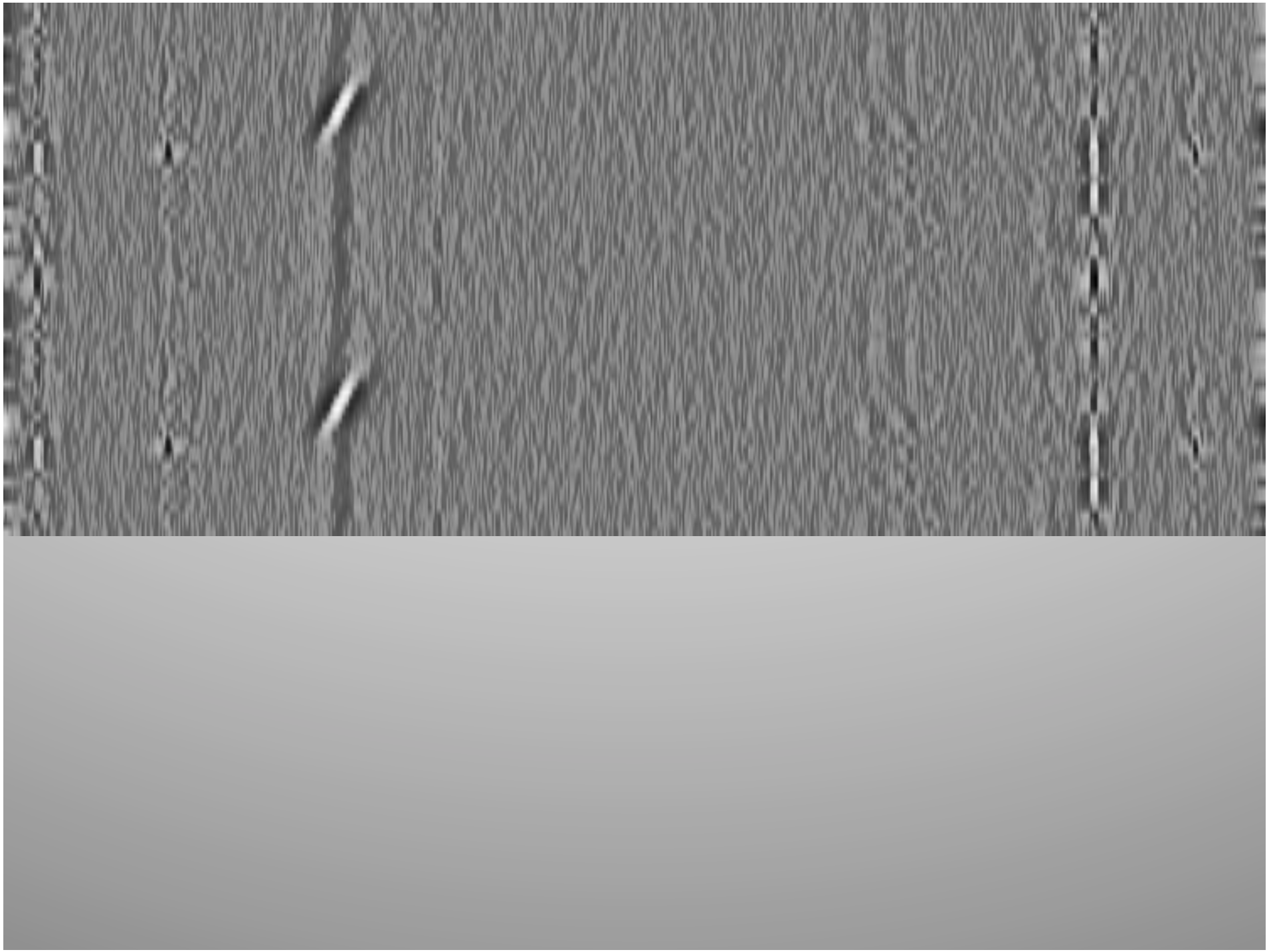
Black = visibility gain datas

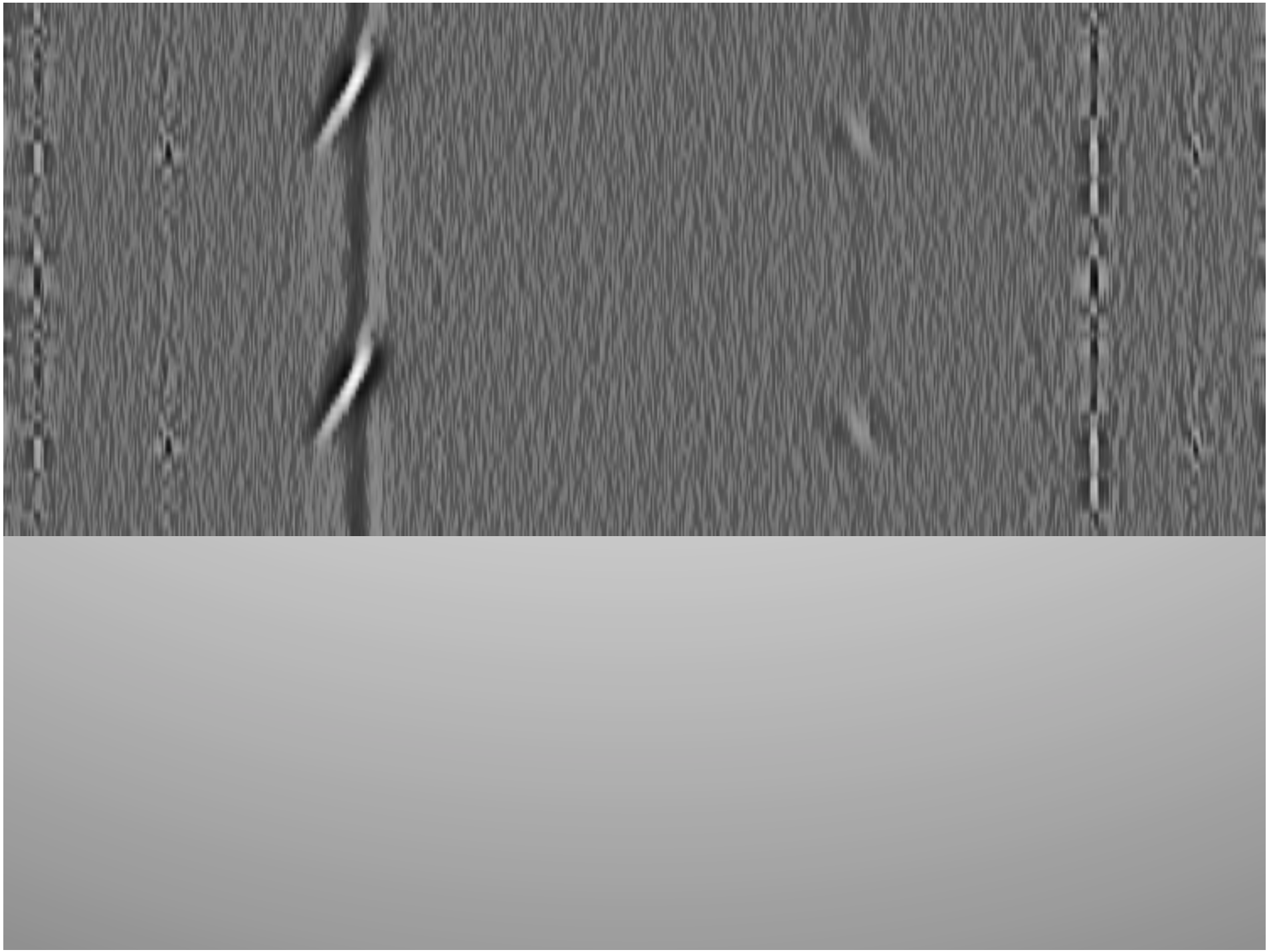
Red = fitted gain model , from individual dipole gains

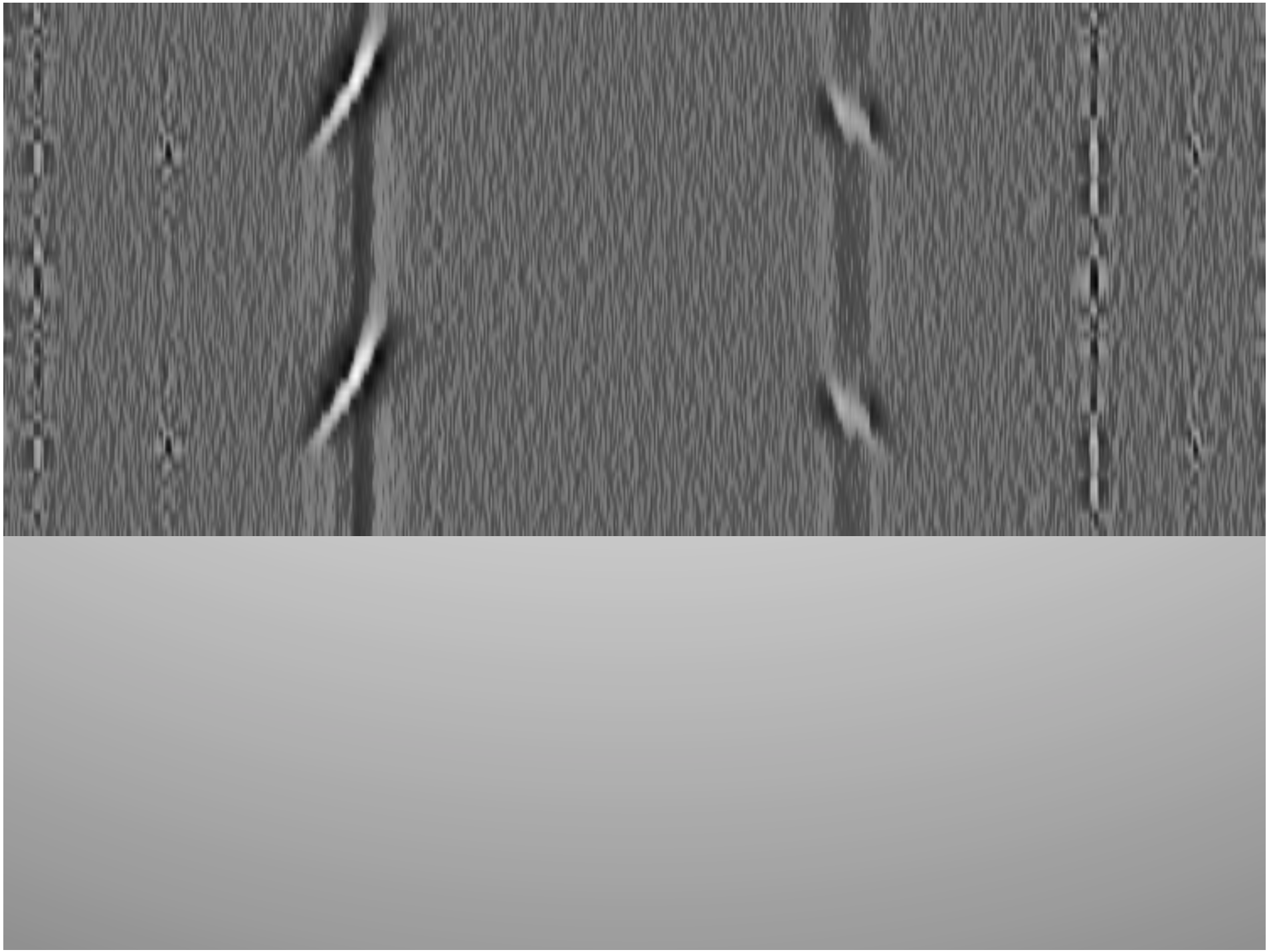
- FFT beam forming requires the knowledge of individual dipole gains
- Determine the 16 dipole complex gains (g_i) using redundancies (64 g_i g_j* visibility gains)
- Gains dispersion about 6dB (factor ~4) for around 90dB gain
- RMS model/gains ~ 1%

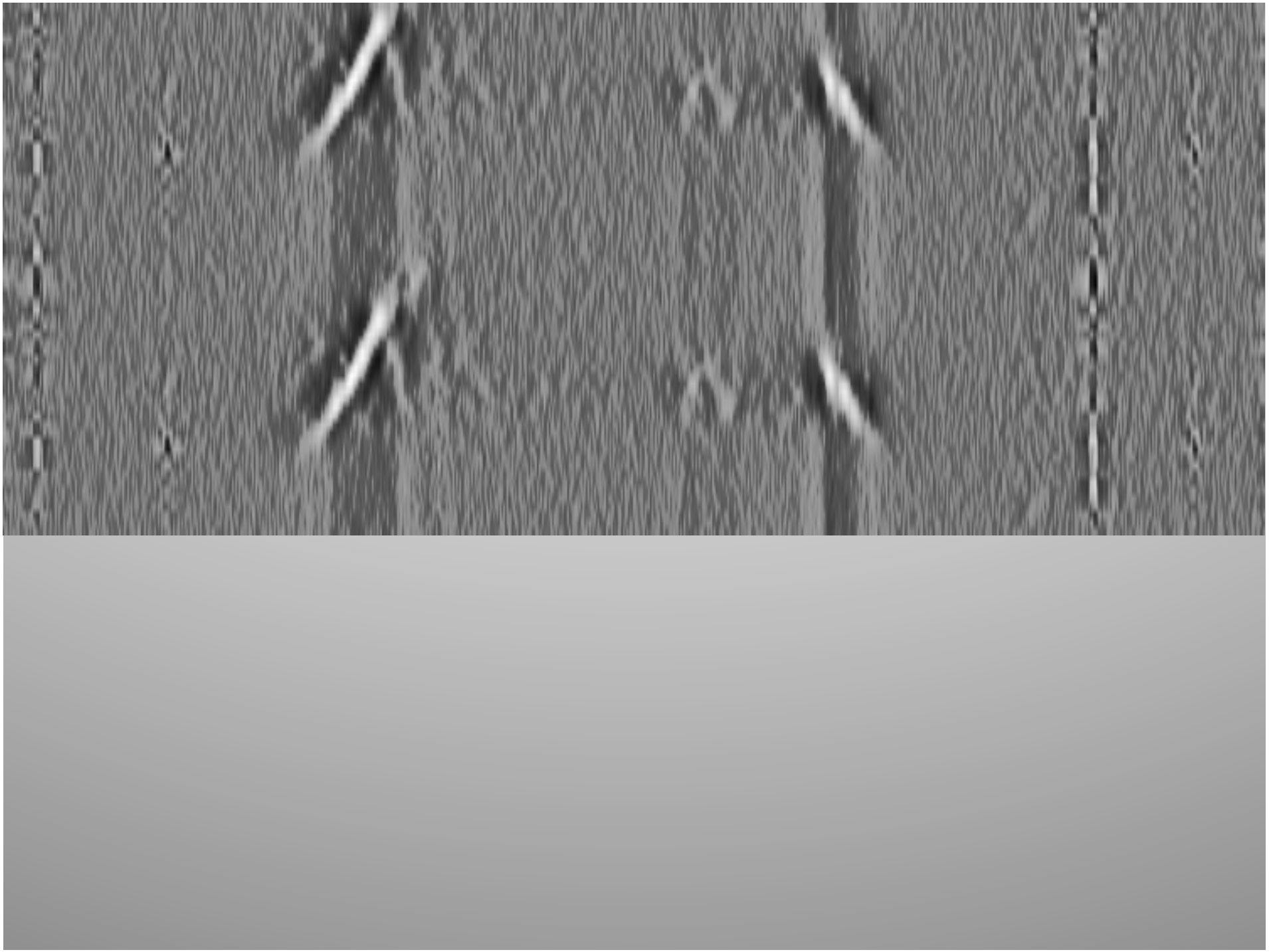

Sun
Galactic HI, order zero
Radio Source residual
Galactic HI, order one
Frequency step 100 kHz

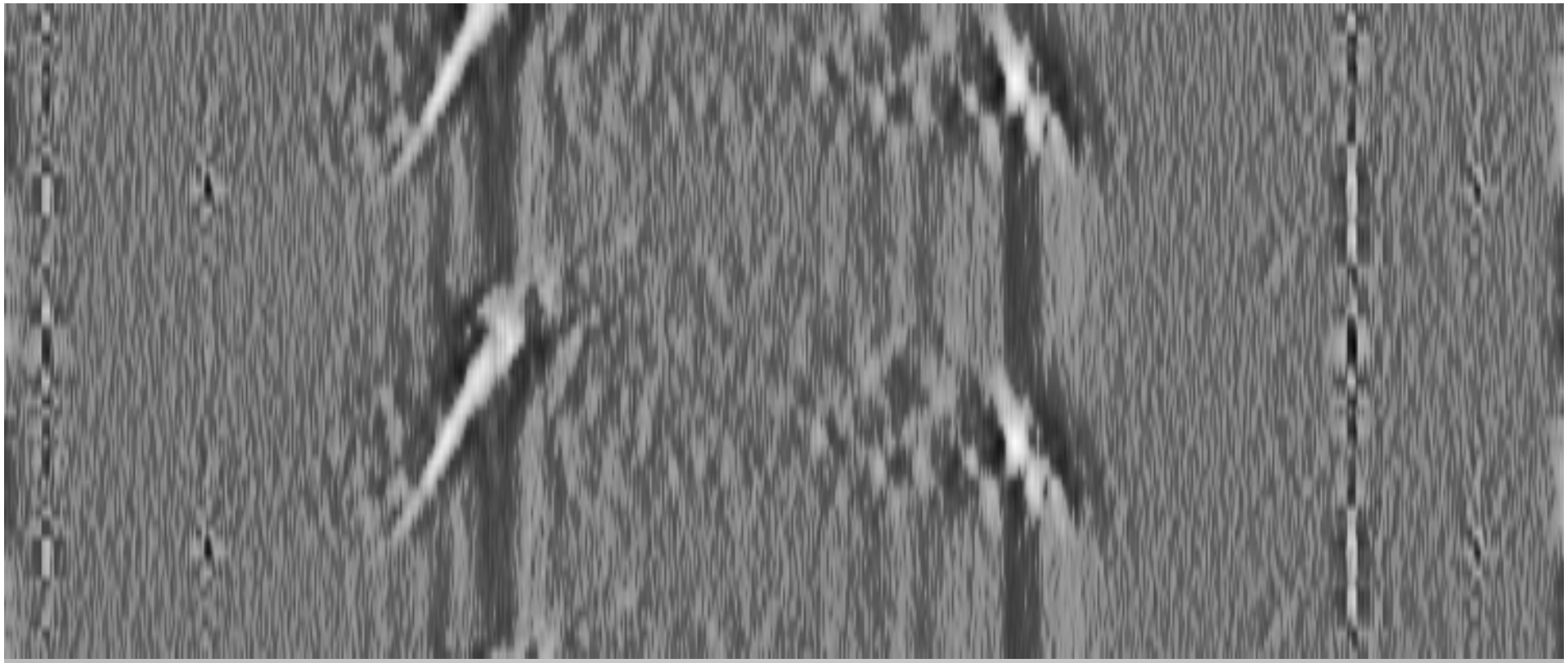


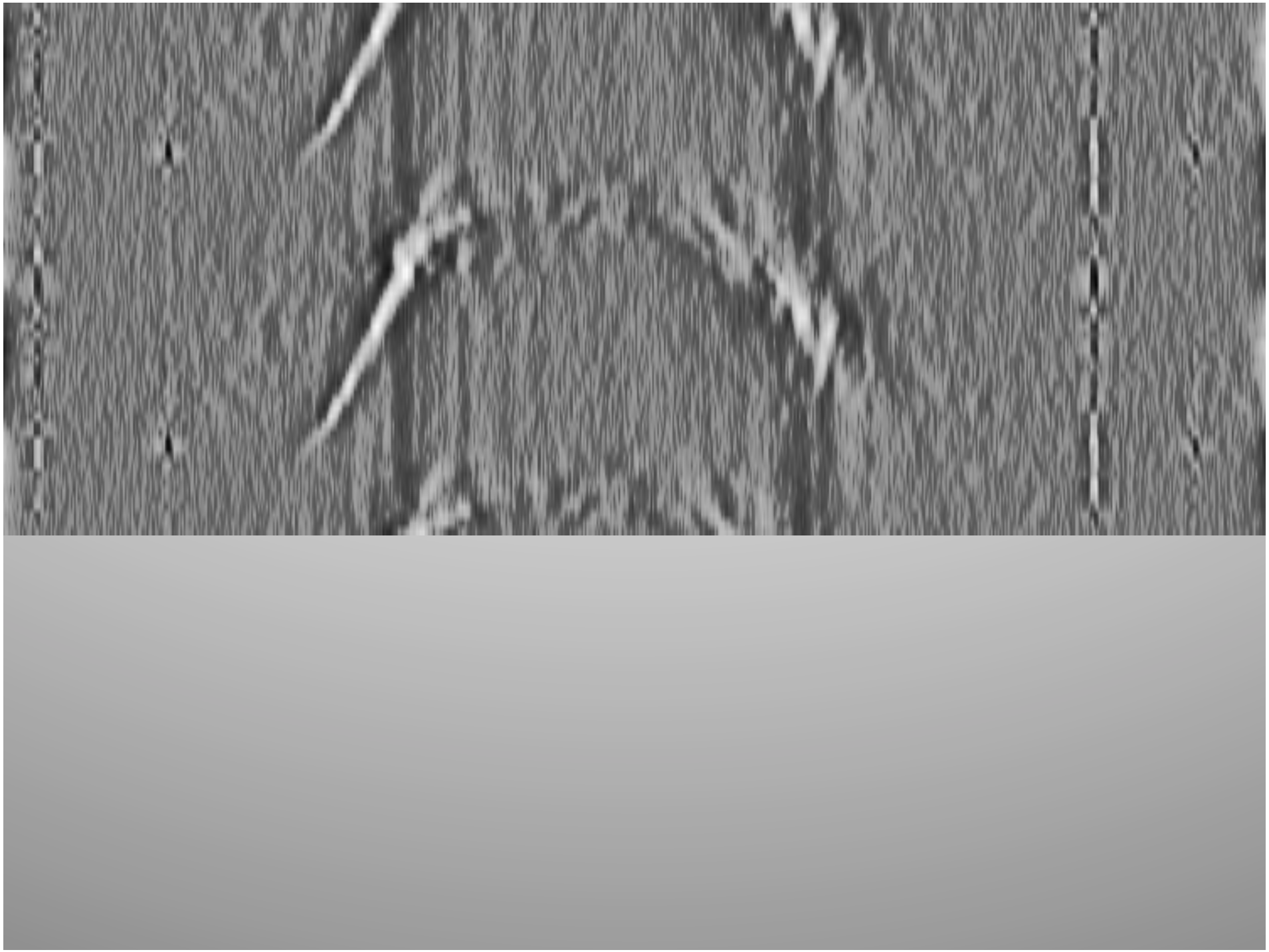


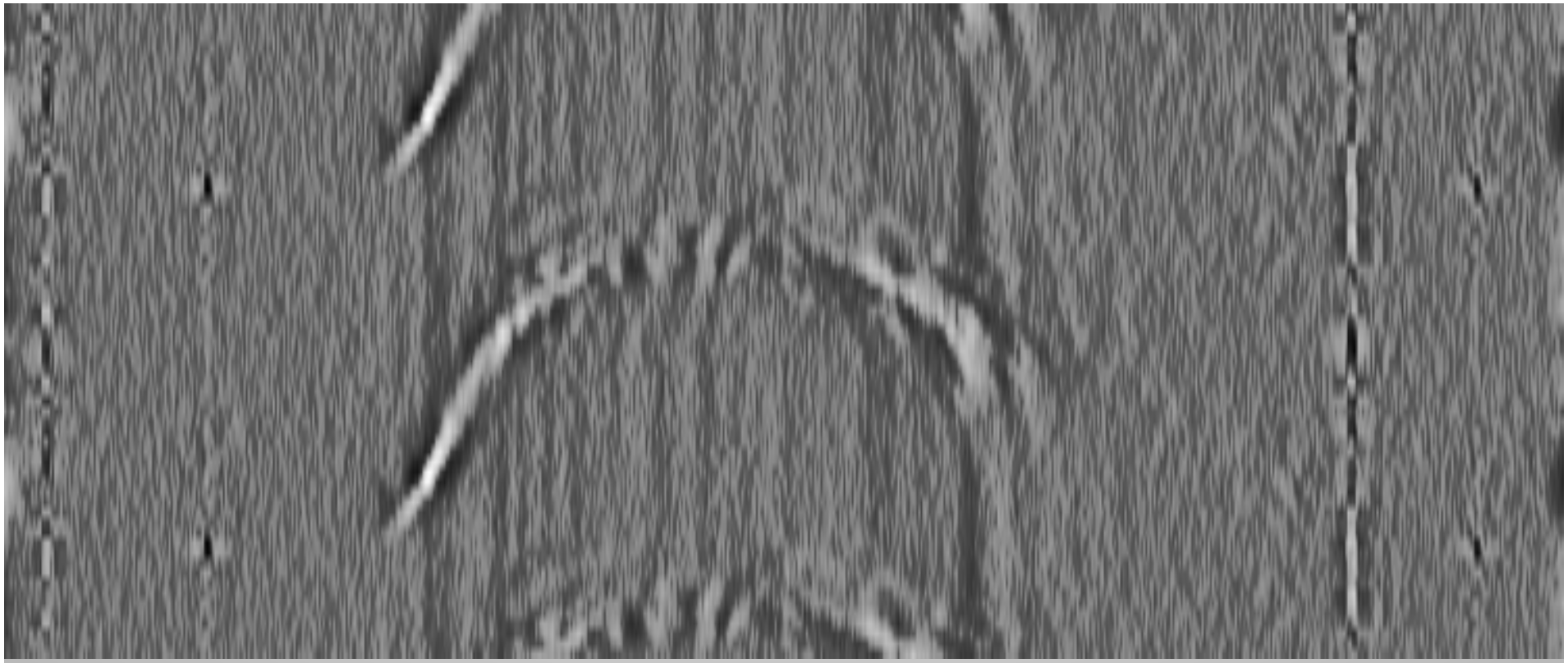


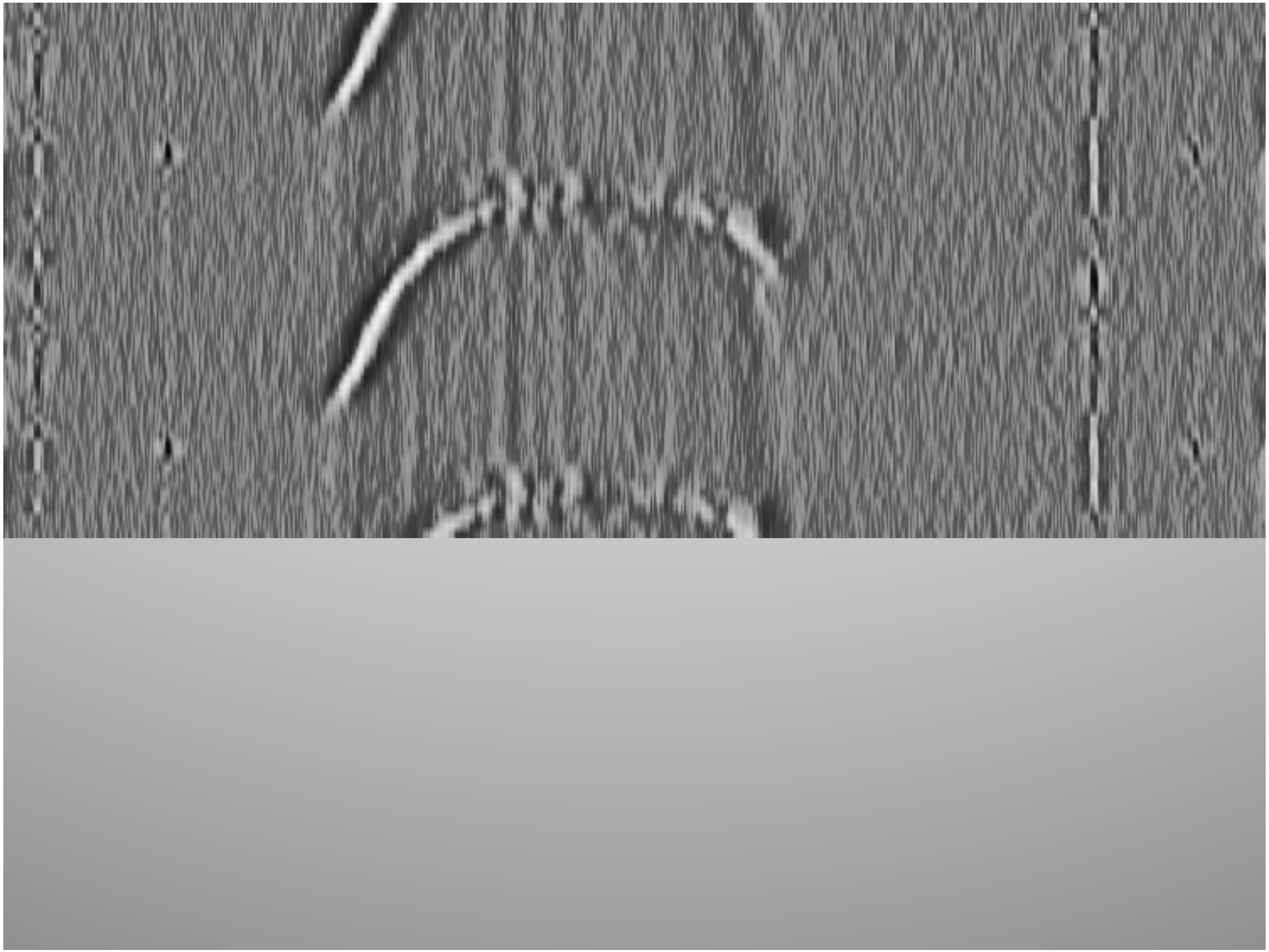


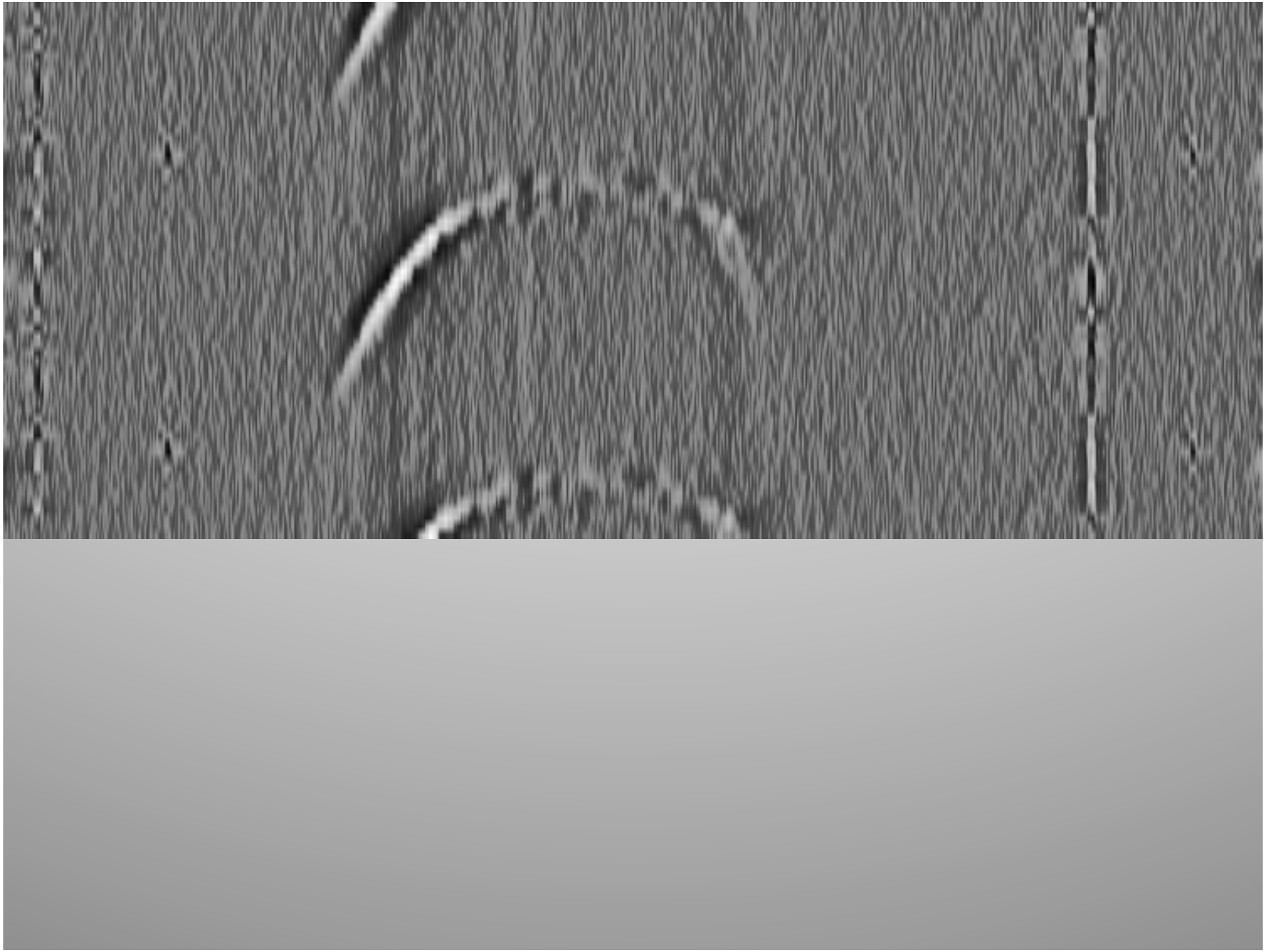


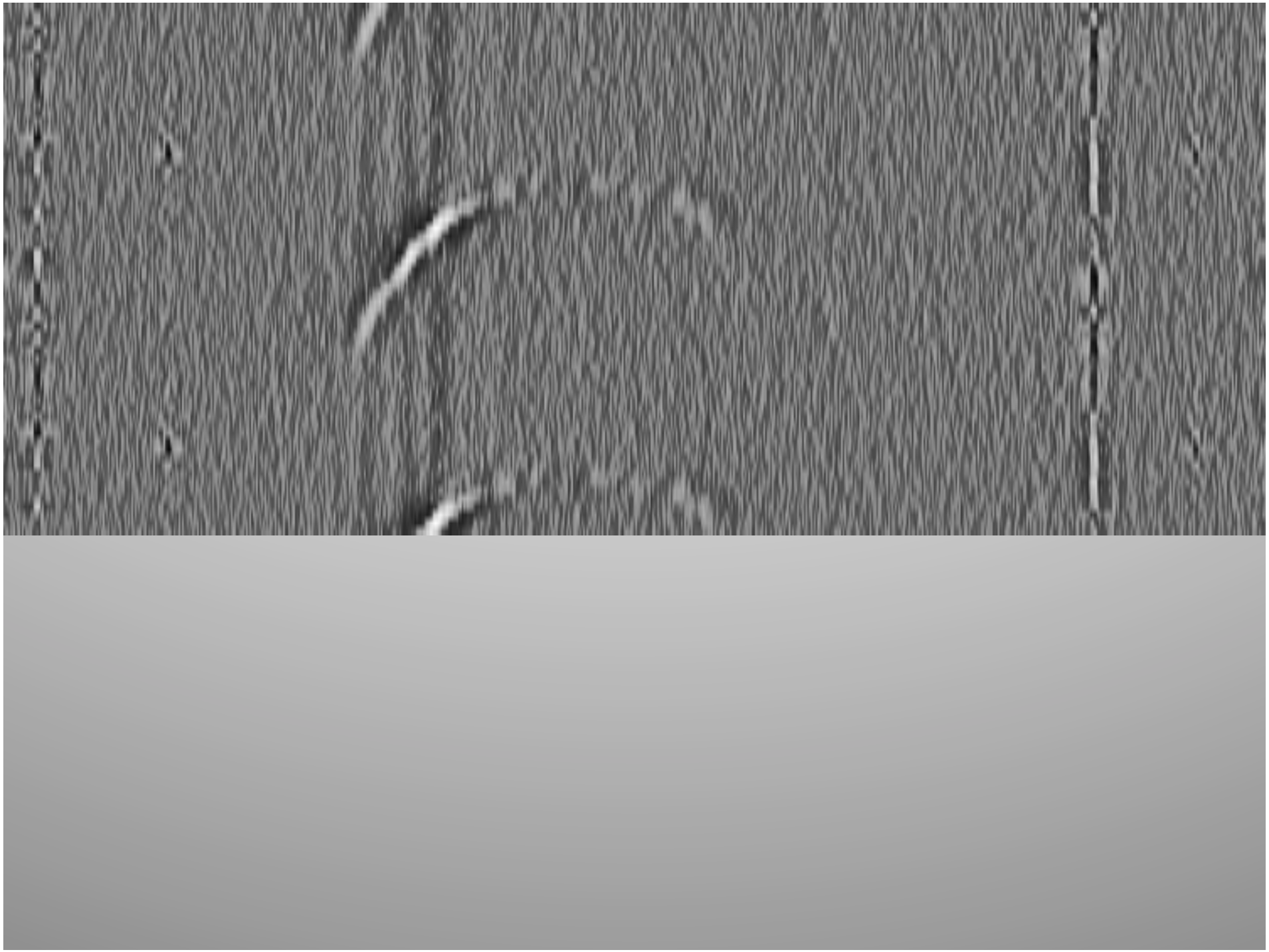


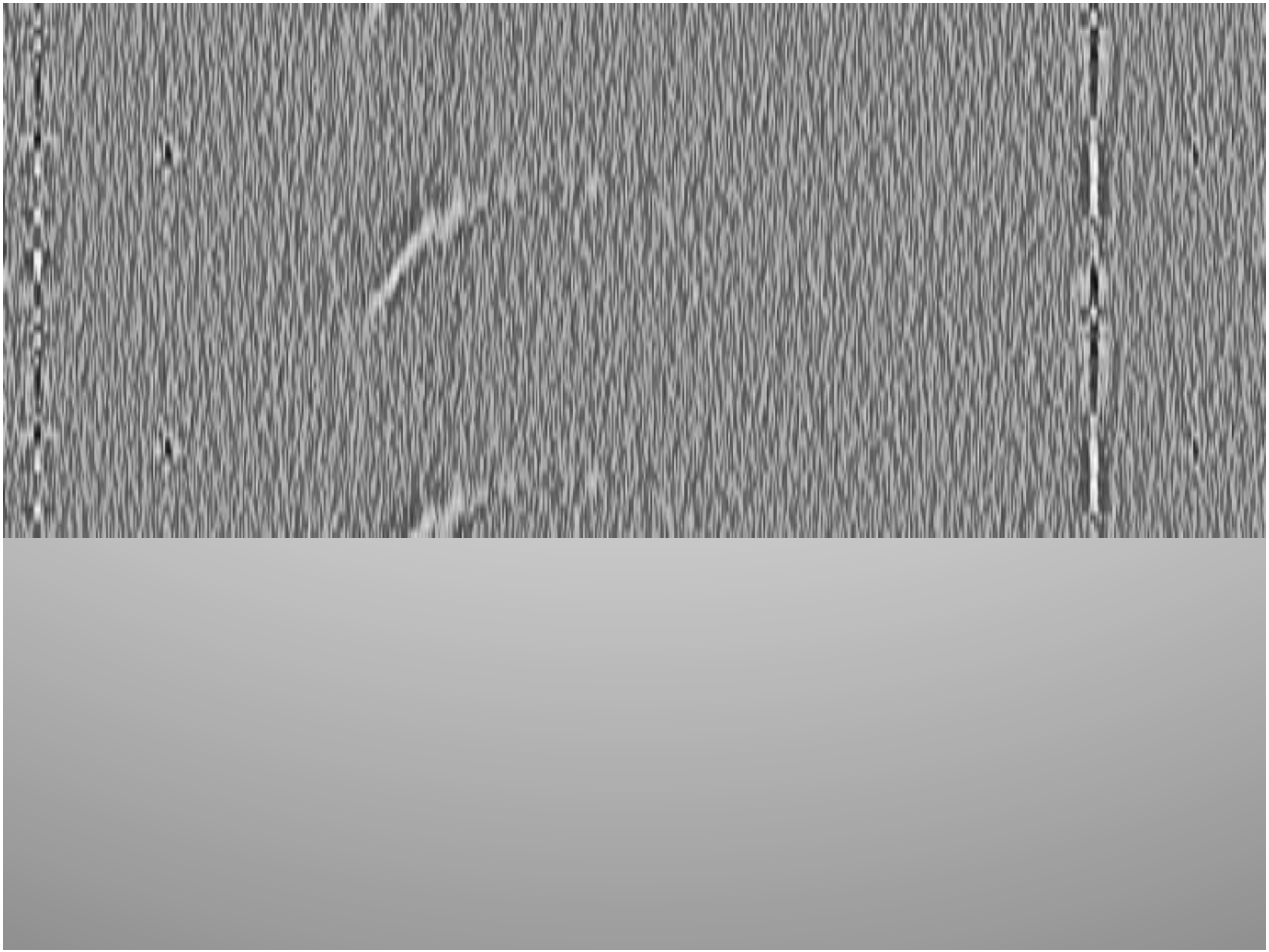


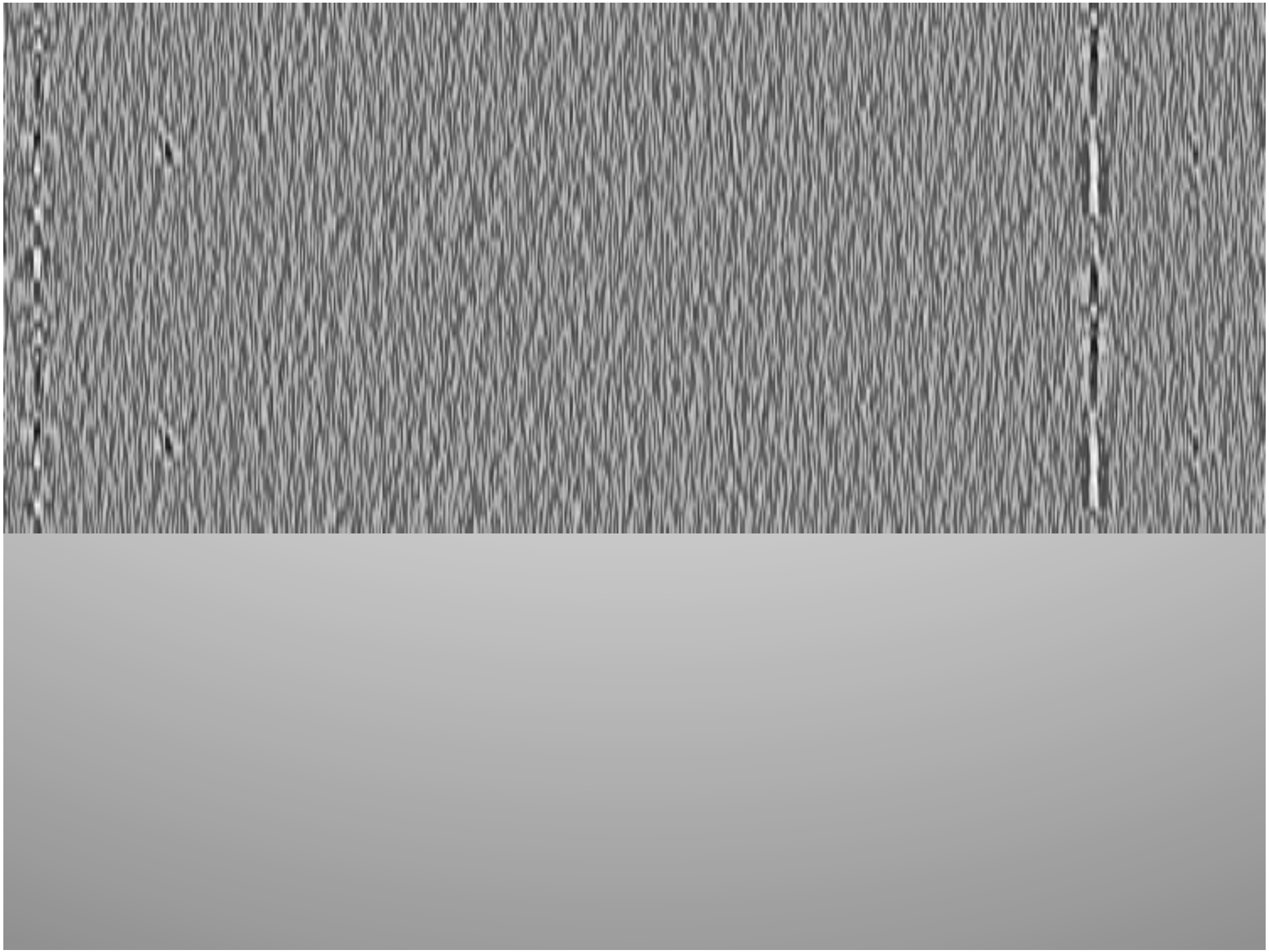


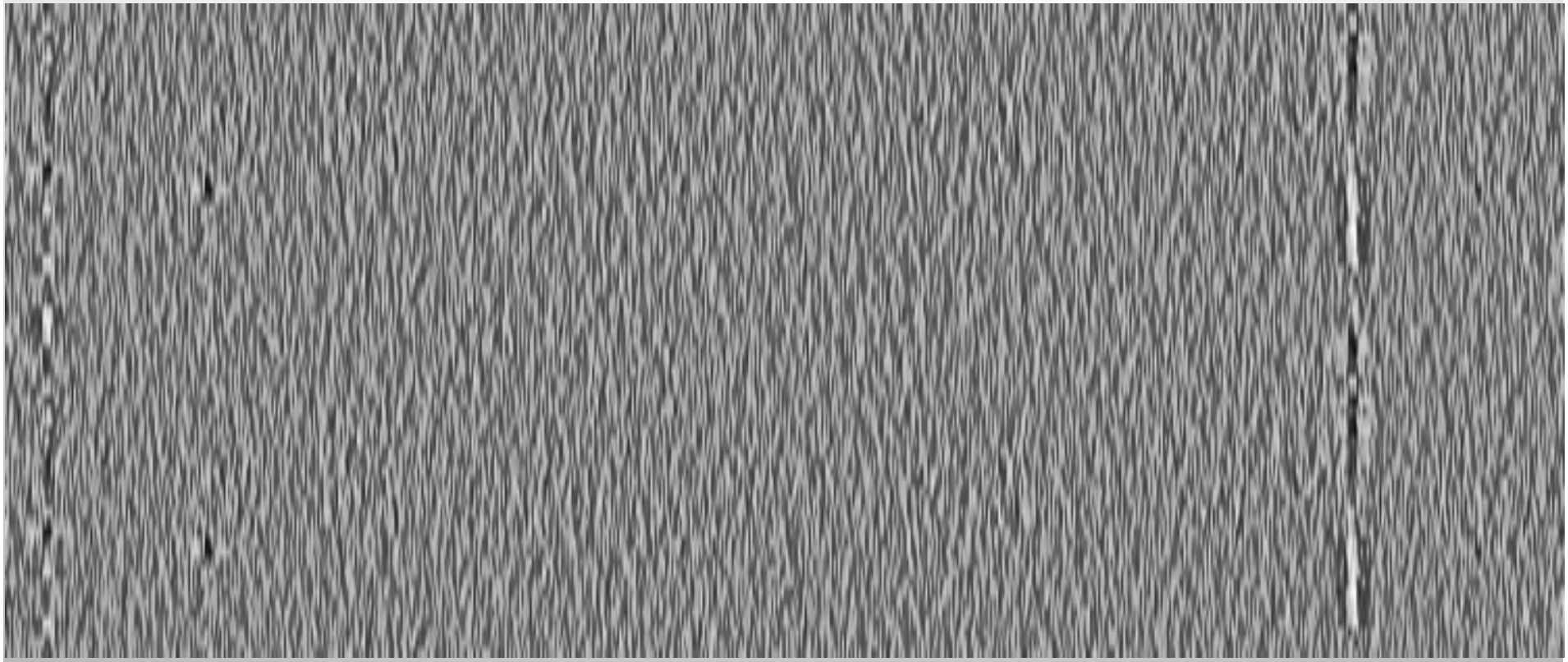


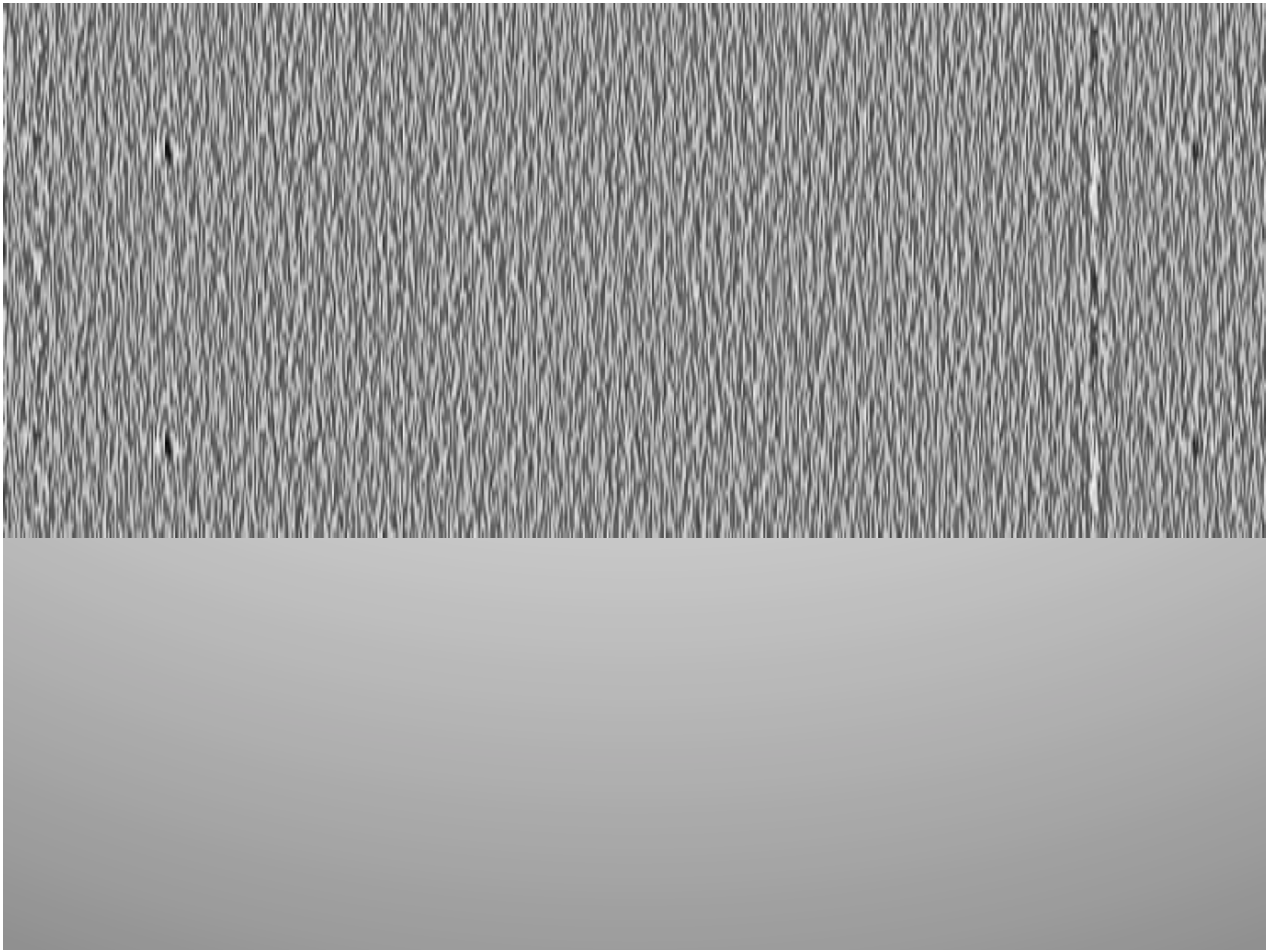








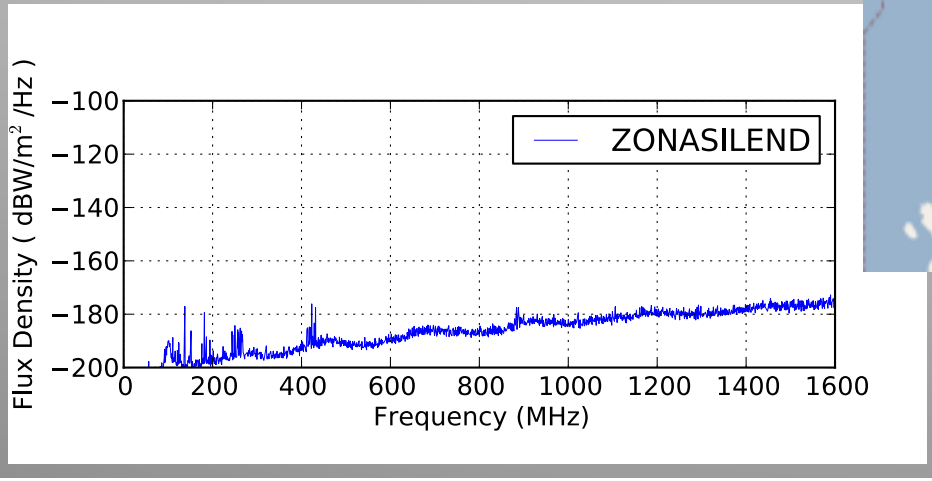




Next steps for CRT

- 3 Cylinders 15x30 m in China
- Use existing 40 chan. Correlator
- 512 chan. Correlator proposed to NSF ($2M)
- Map 21 cm Large Scale structure at z~1, Attempt to measure 21 cm velocity distortions and BAO
- Demonstrate successful foreground subtraction
- Choose a site for full CRT
- Full Funding ($20M)

Possible Sites for CRT



Conclusions.

- 21cm intensity mapping is a very promising tool for 21st century cosmology
- Foregrounds are bright but can be removed.
- Intensity Mapping: without detecting individual galaxies, large structures may be detectable.
- We report detection of HI emission with GBT at z~0.8
- Baryon Acoustic Oscillations – geometric measure of the universe and dark energy
- 21 cm particularly useful in the optical redshift desert z = 1-3.
- Cylinder telescopes are a promising technology.
- Cylinder Prototype built, working, observations beginning.
- Next step in China.