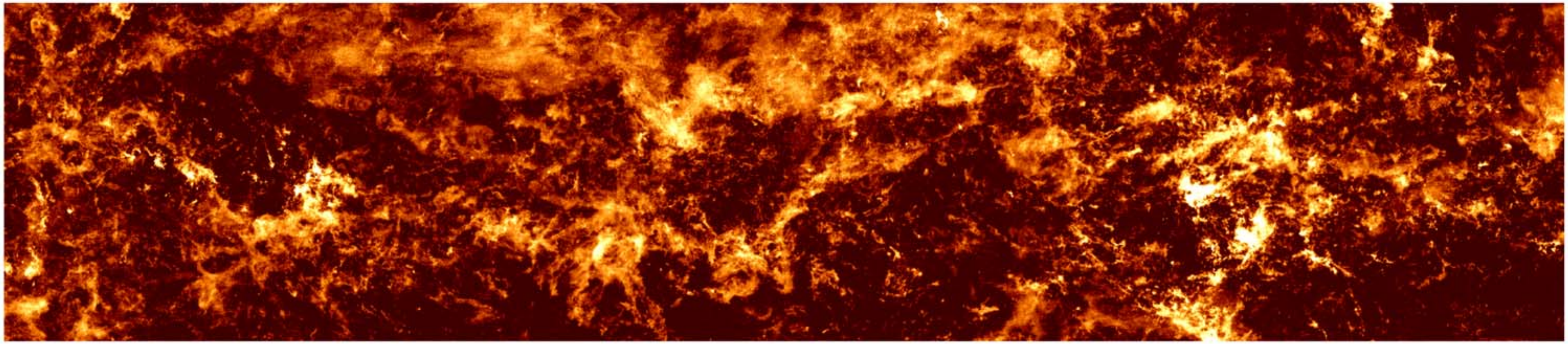
Heterodyne Focal Plane Arrays



Mark Heyer
University of Massachusetts
2^{nd} NAIC-NRAO School on Single Dish Radio Astronomy
15 August 2003

Outline

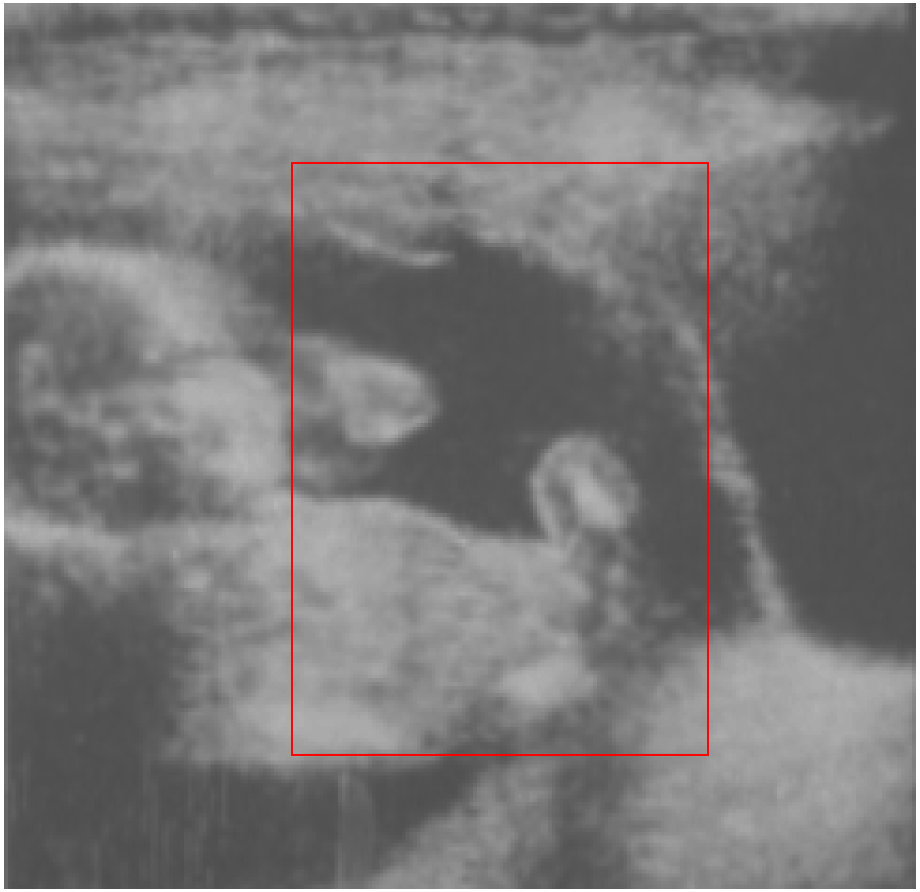
- Motivate the need for heterodyne focal plane arrays
- Summarize current and future instrumentation
- Present observing modes and consequences
- Analysis of Spectroscopic Data cubes

The Value of Focal Plane Arrays

- Improved *relative* pixel registration and calibration
- High Spatial Dynamic Range Imaging
  - Detect small compact objects
  - Place objects into environmental context
  - Detect large scale patterns
  - Gather large ensemble of objects → statistics
- Deeper, more sensitive maps over more limited fields
  - Image weaker but more diagnostic line emission
  - Transitional regions (cloud edges, outflows)

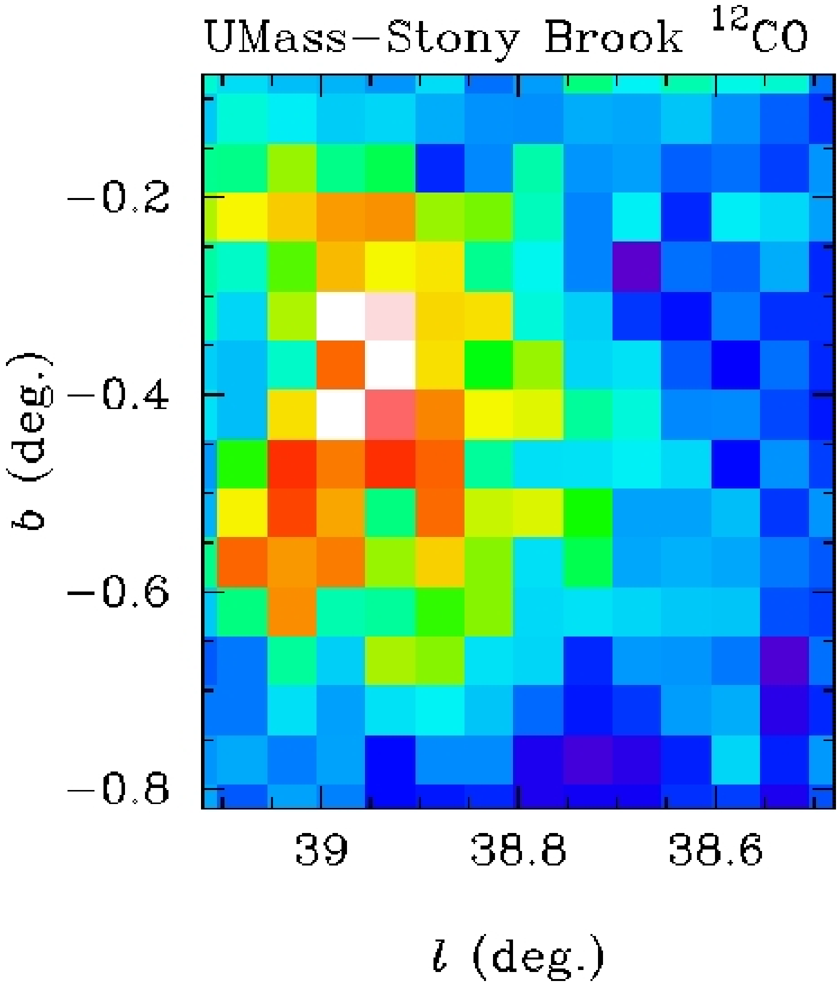
A Unique Region in the Galaxy

Ellis Heyer, Age –0.3

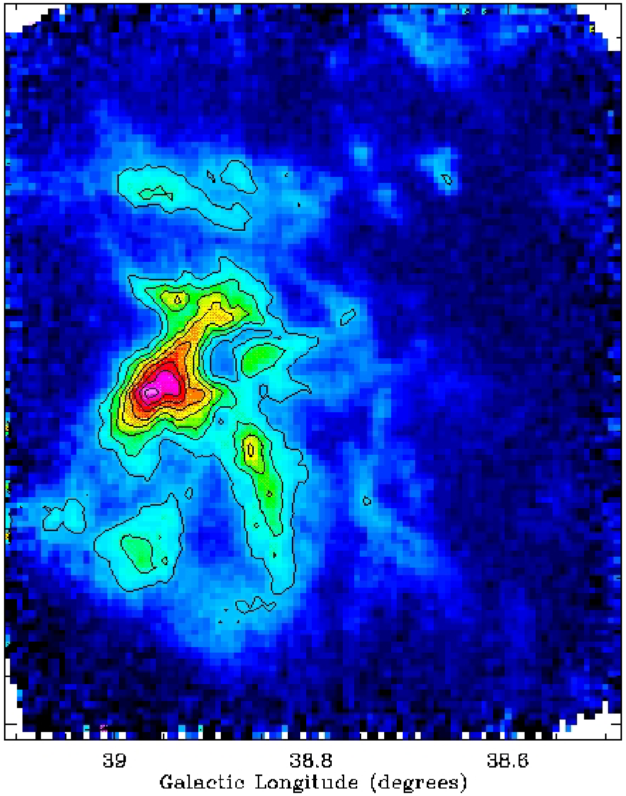


Ellis Heyer, Age 14

High Sensitivity Imaging



BU-FCRAO Gal. Ring Survey



Current Instruments

Instrument	Telescope	Pixels	Band (GHz)	#spectra
SEQUOIA	FCRAO 14m LMT 50m (2005)	32	85-116	64
BEARS	NRO 45m	25	82-116	25
CHAMP	MPI/Bonn	16	460-495	16
HERA	IRAM 30m	9	210-280	18
Pole STAR	ASTRO	4	490,810	8
KOSMA array	KOSMA	4	490,810	8

Future Instruments

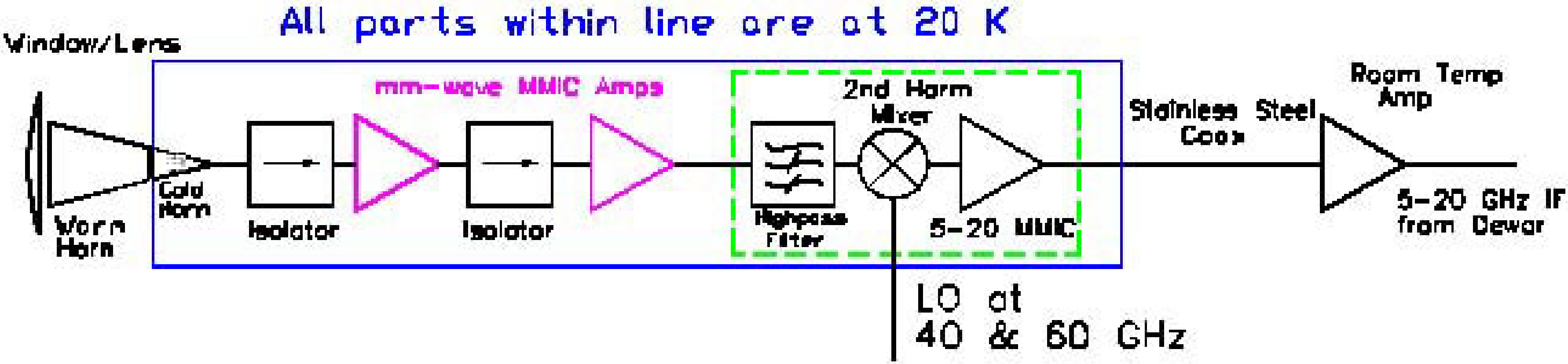
Instrument	Telescope	Pixels	Band (GHz)	#spectra
DesertSTAR	HHT 10m	7	300-380	7
HARP-B	JCMT	16	325-375	16
ALFA	Arecibo	7	1.225-1.525	14

SEQUOIA/FCRAO

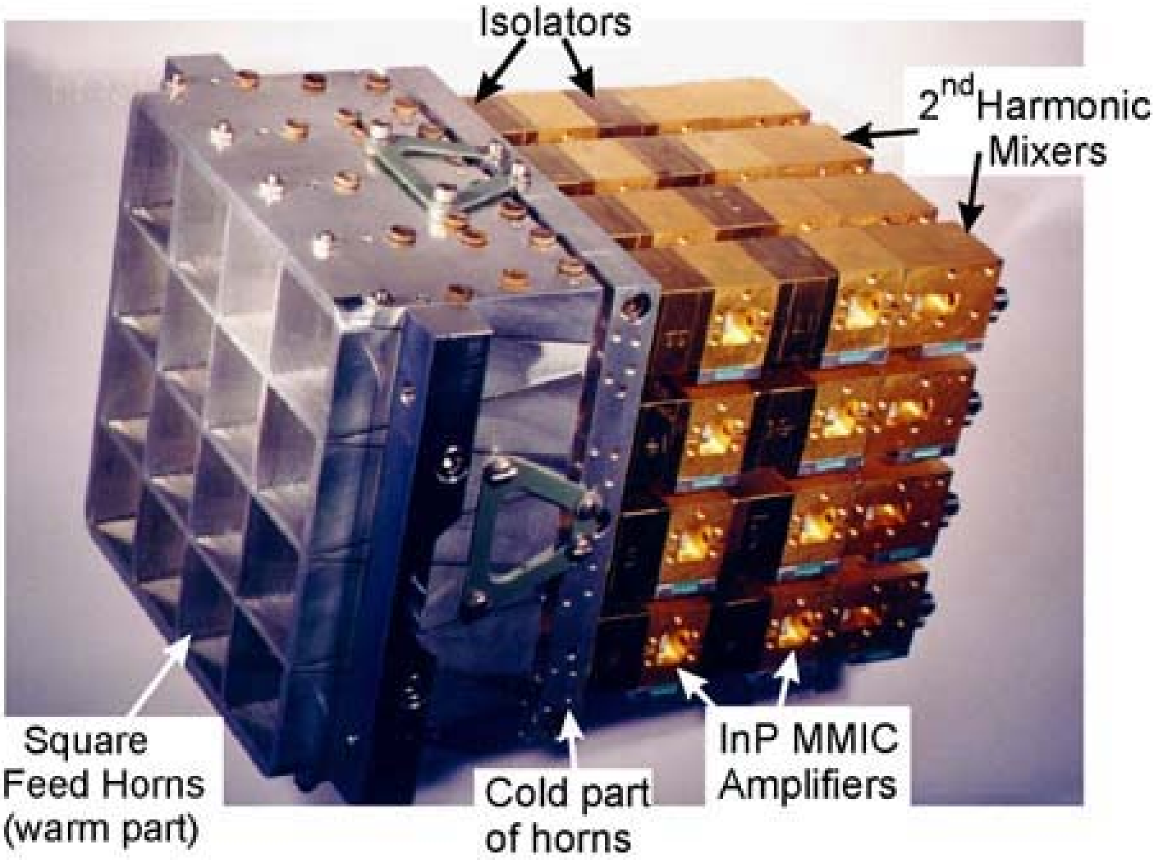
Based on MMIC Pre-Amplifiers

- 35 GHz instantaneous bandwidth – no tuning required
- SSB

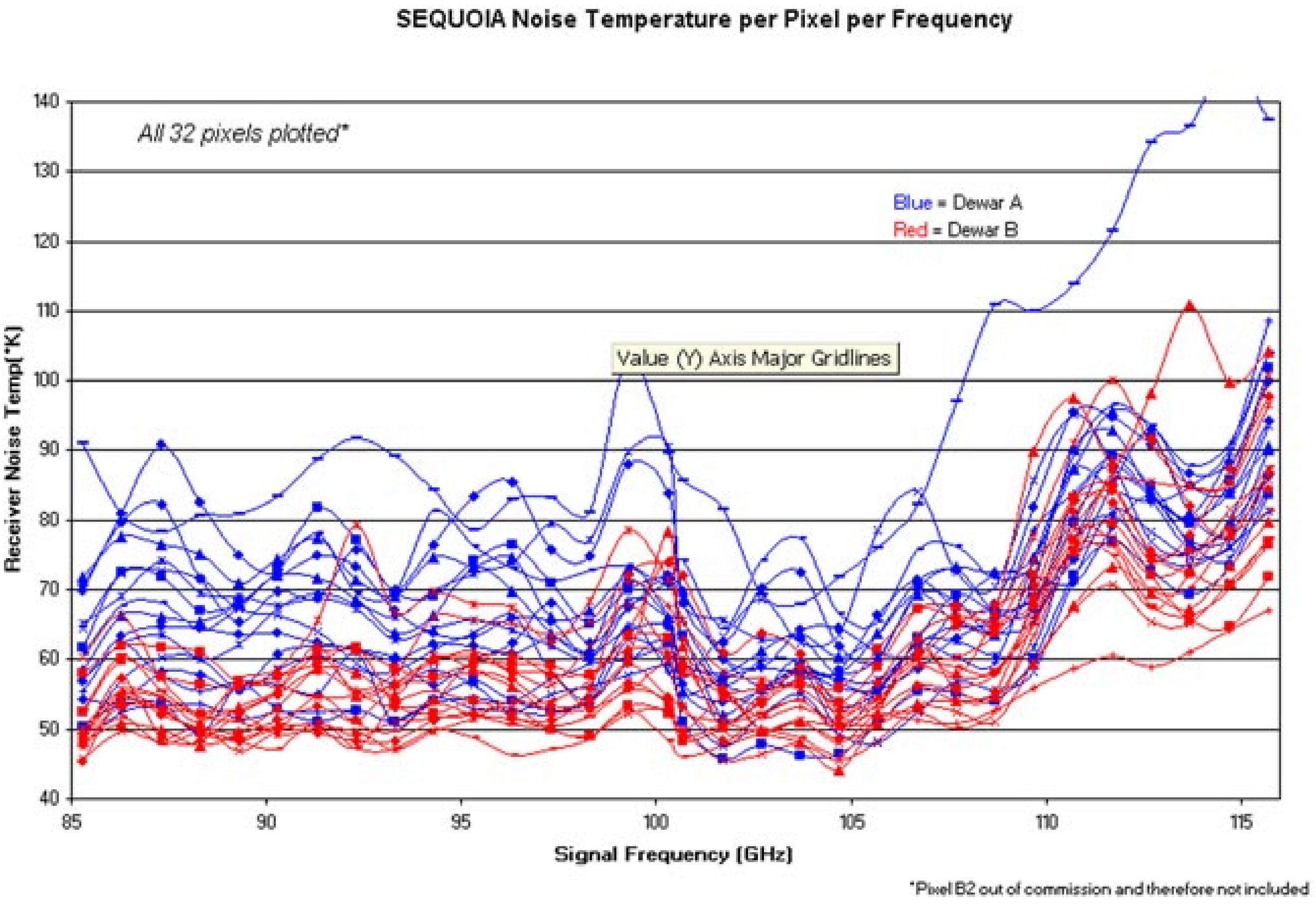
Single pixel block diagram



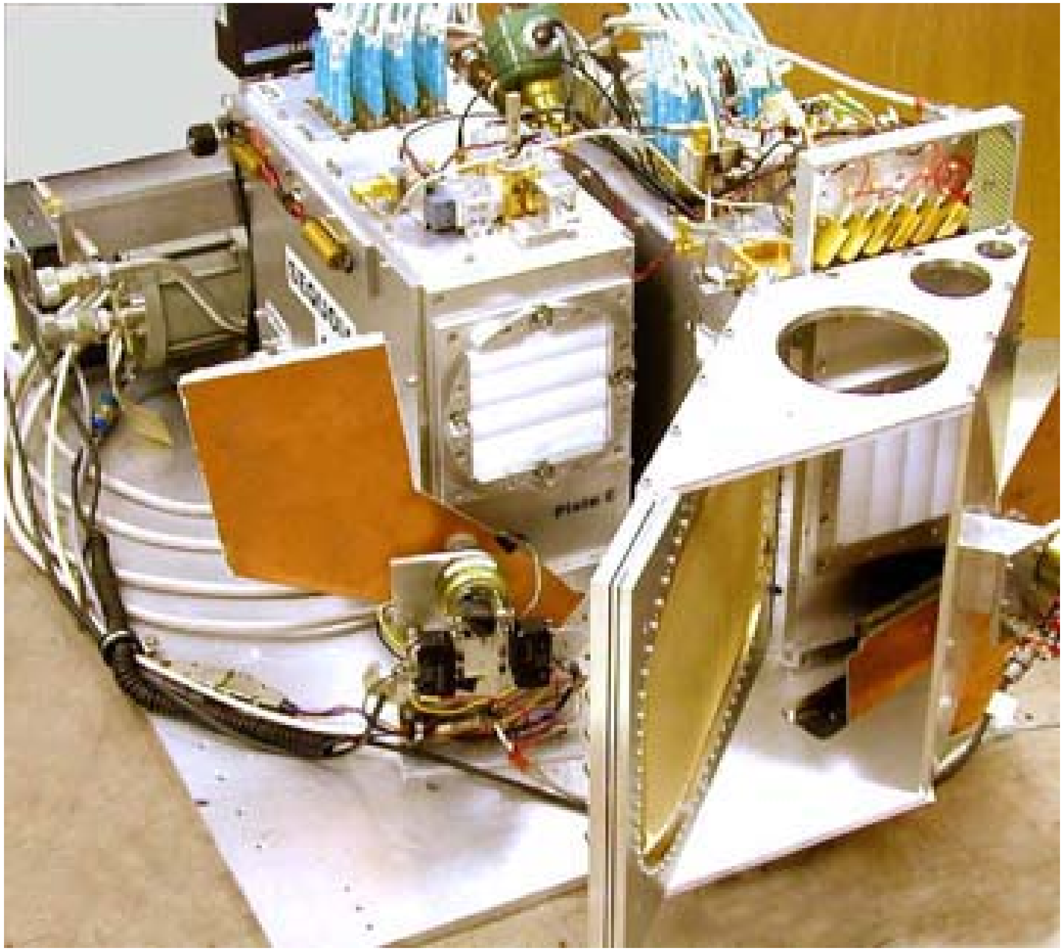
SEQUOIA Horn Block



SEQUOIA/Receiver Noise



SEQUOIA/32 pixels



I.F. Processing/Backends

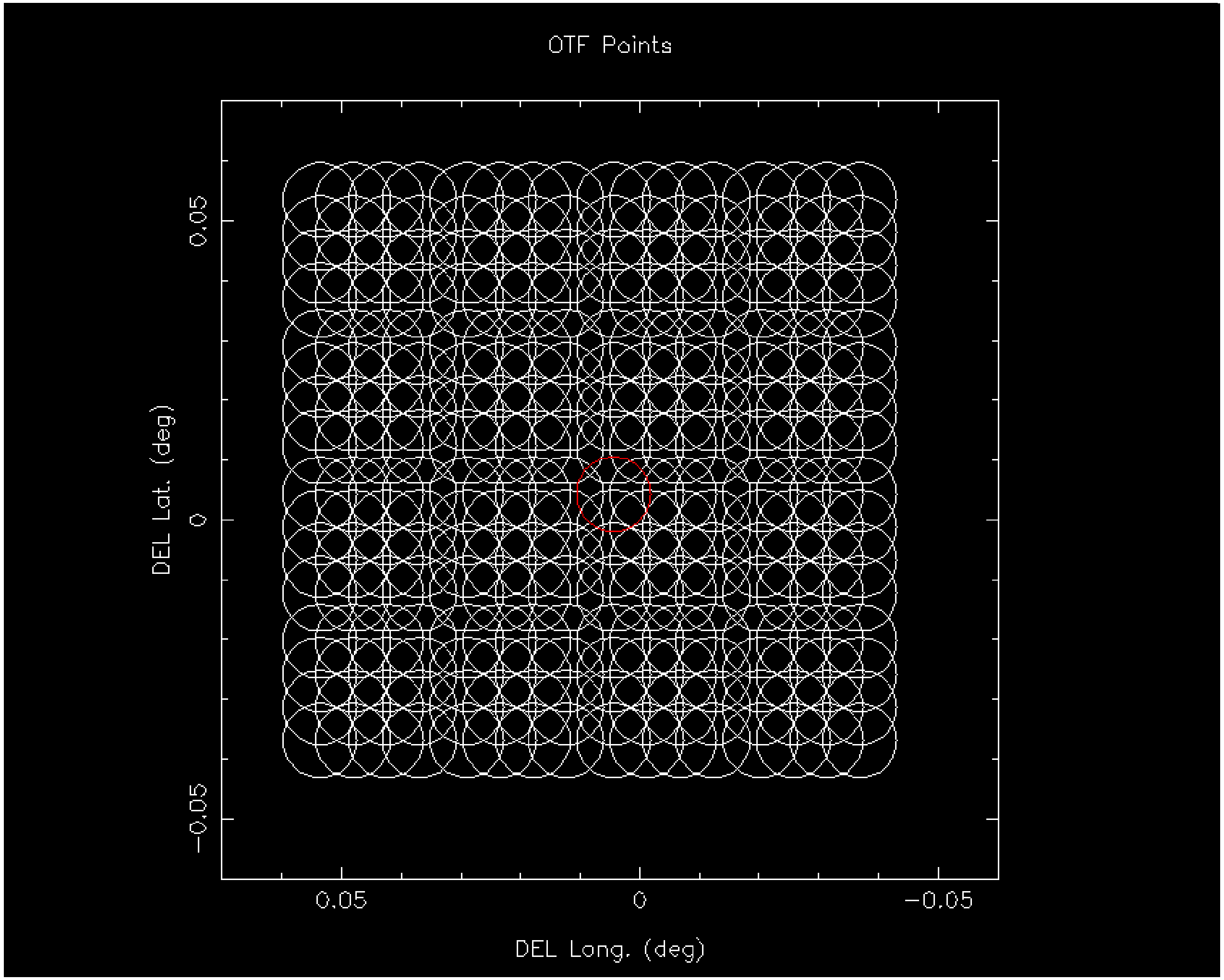
- Take advantage of broad bandwidth, dual polarization output of modern frontends
- Autocorrelation or AOS

Data Collection

- Conventional Position Switching
- Frequency Switching
- Beam Switching with Secondary
- Reference Sharing
- On the Fly Mapping (OTF)

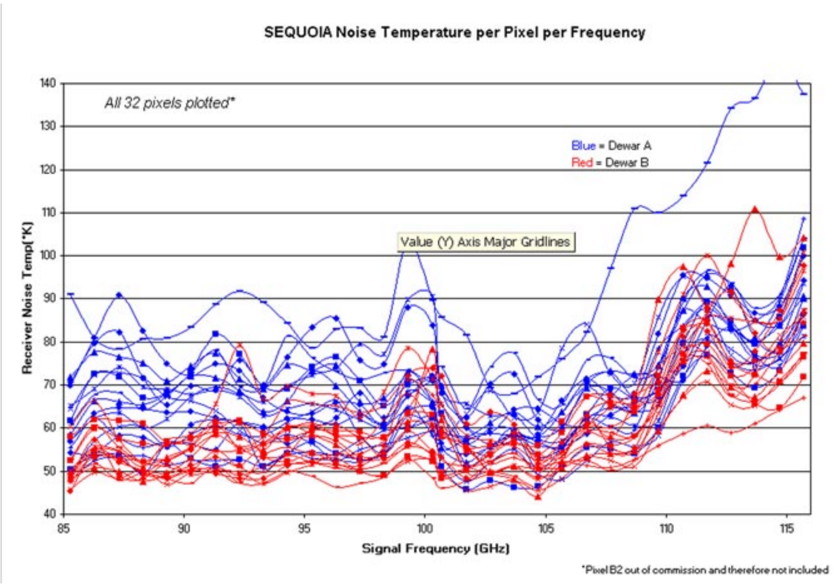
Discrete Steps of antenna

Discrete Steps to “fill in” Grid

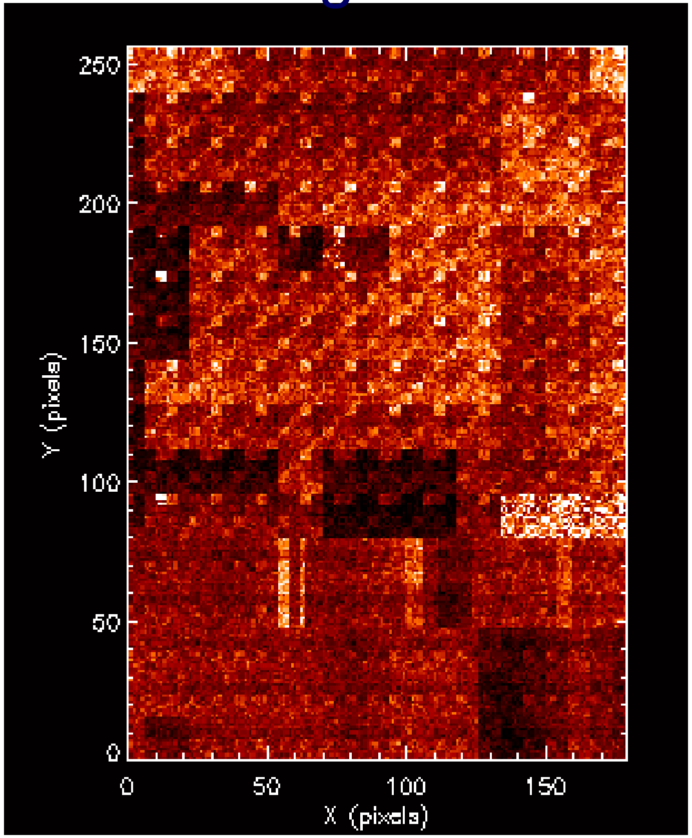


Non-Uniform Noise Distribution

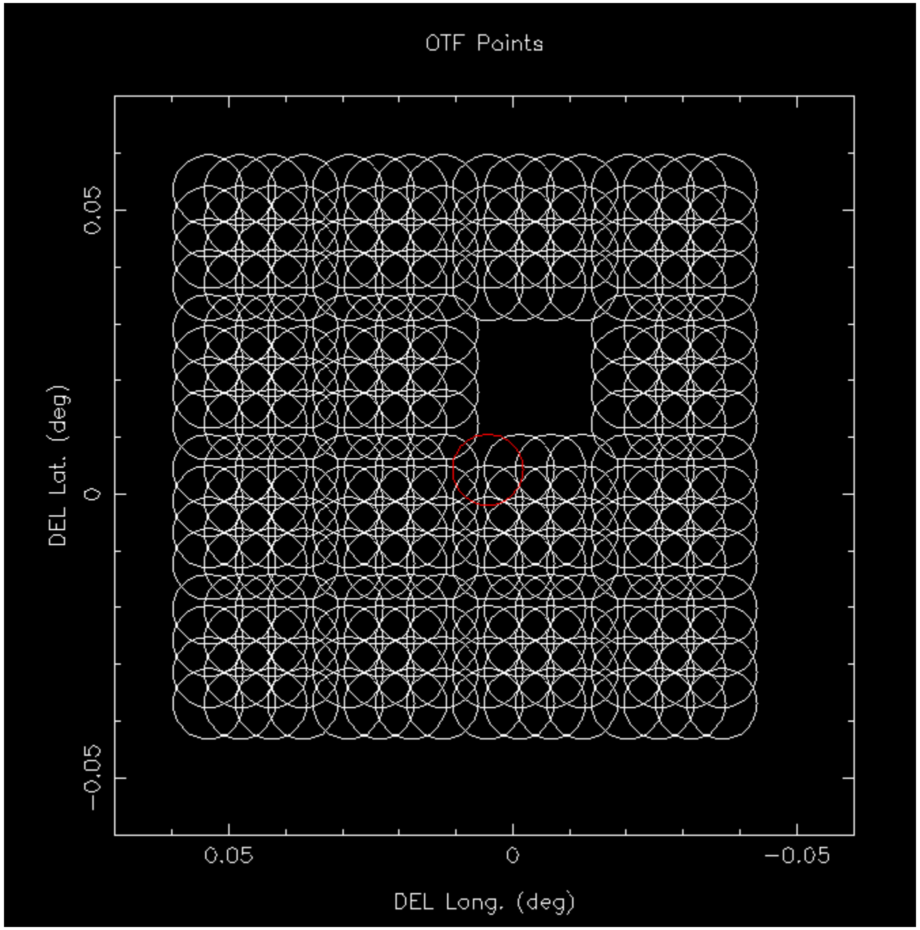
- Inhomogeneity of T_{rec}



RMS image

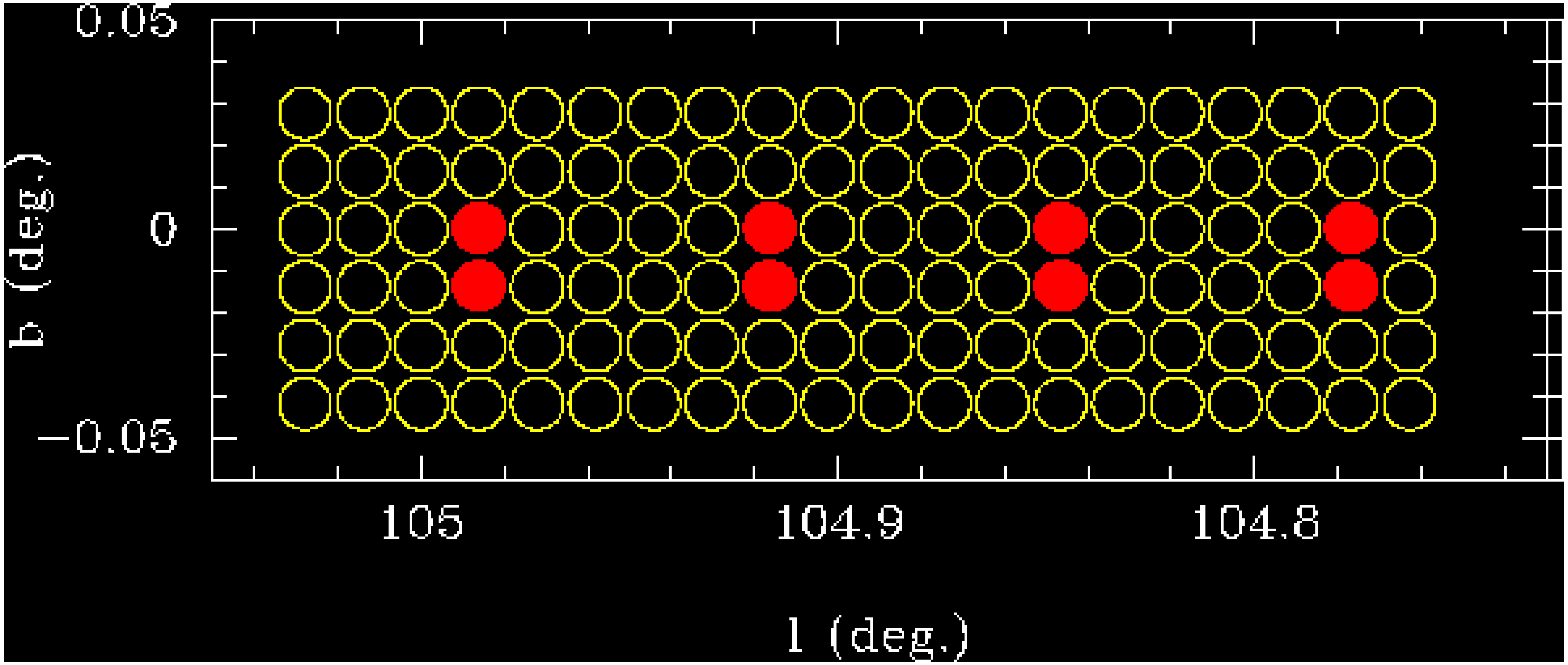


Malfunctioning Pixel – Image holes



Reference Sharing

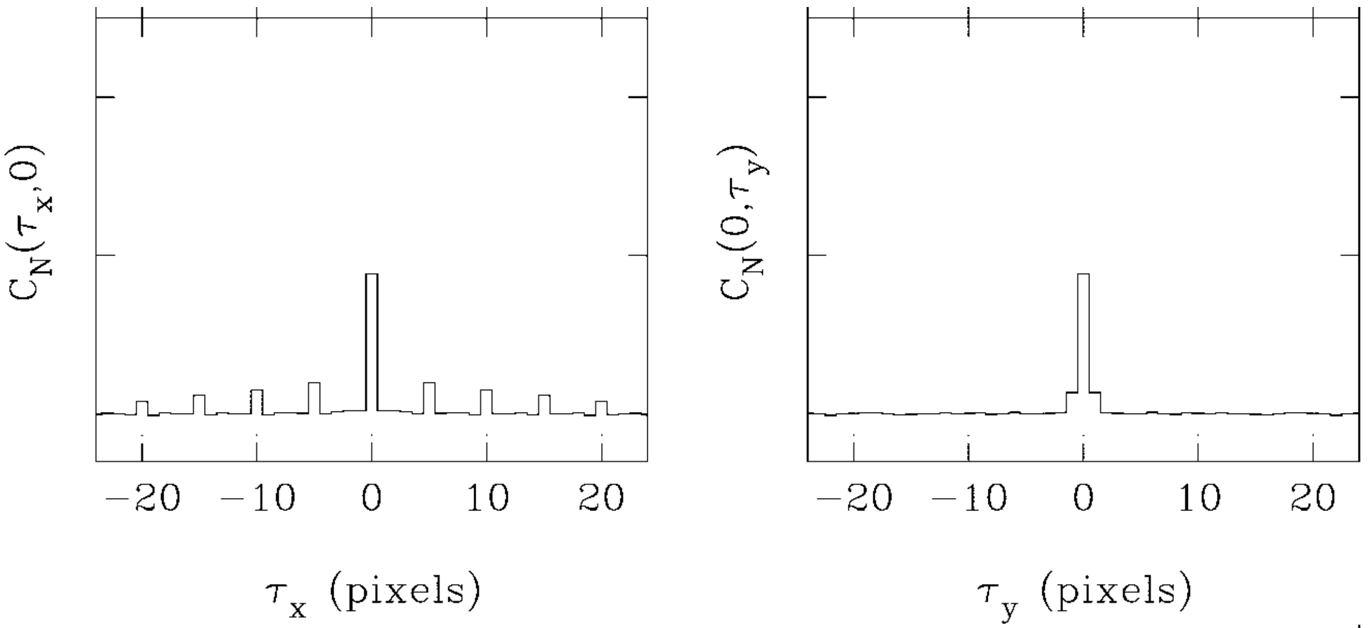
Single reference measurement applied to many source measurements



FCRAO QUARRY Receiver (1990-1997)

Spatially Correlated Noise

ACF

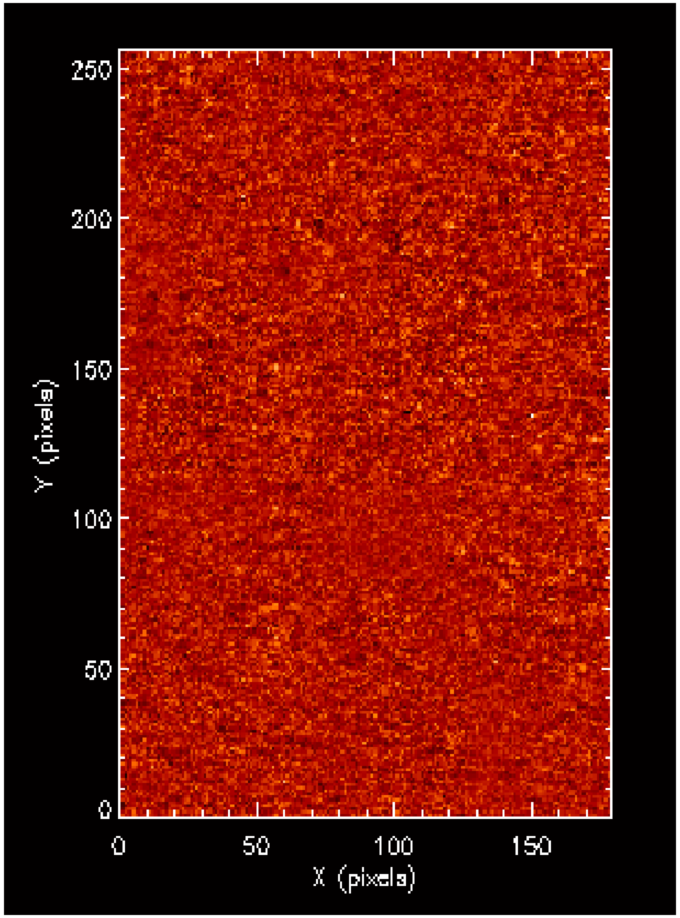


X

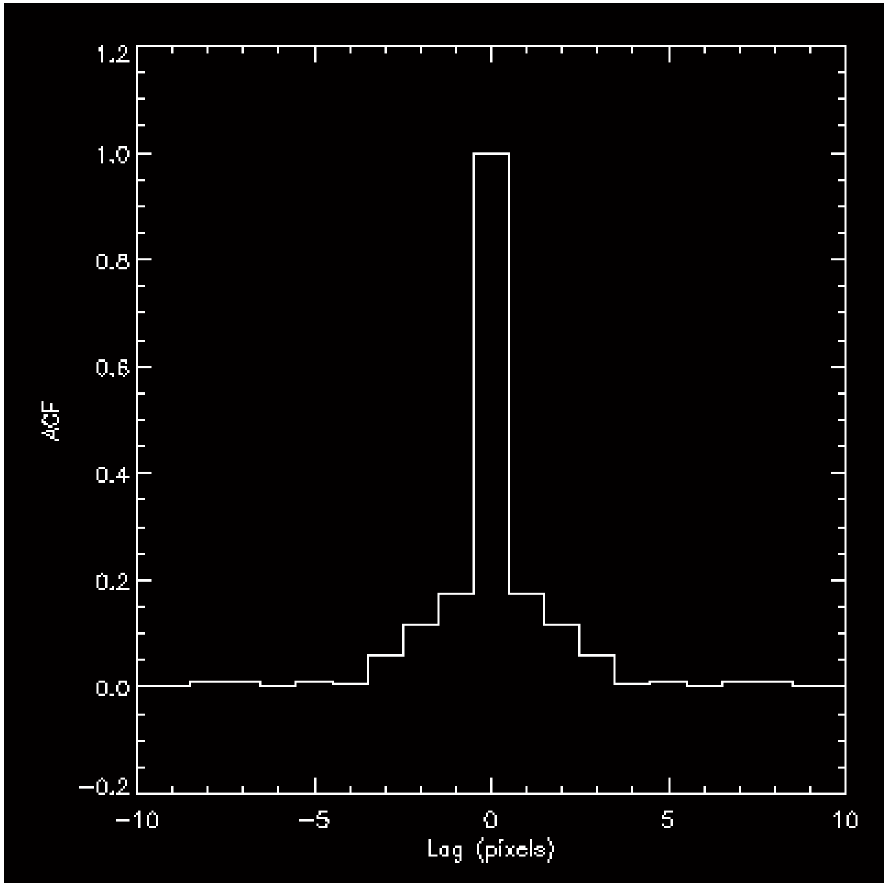
Y

More Correlated Noise

Channel image



ACF

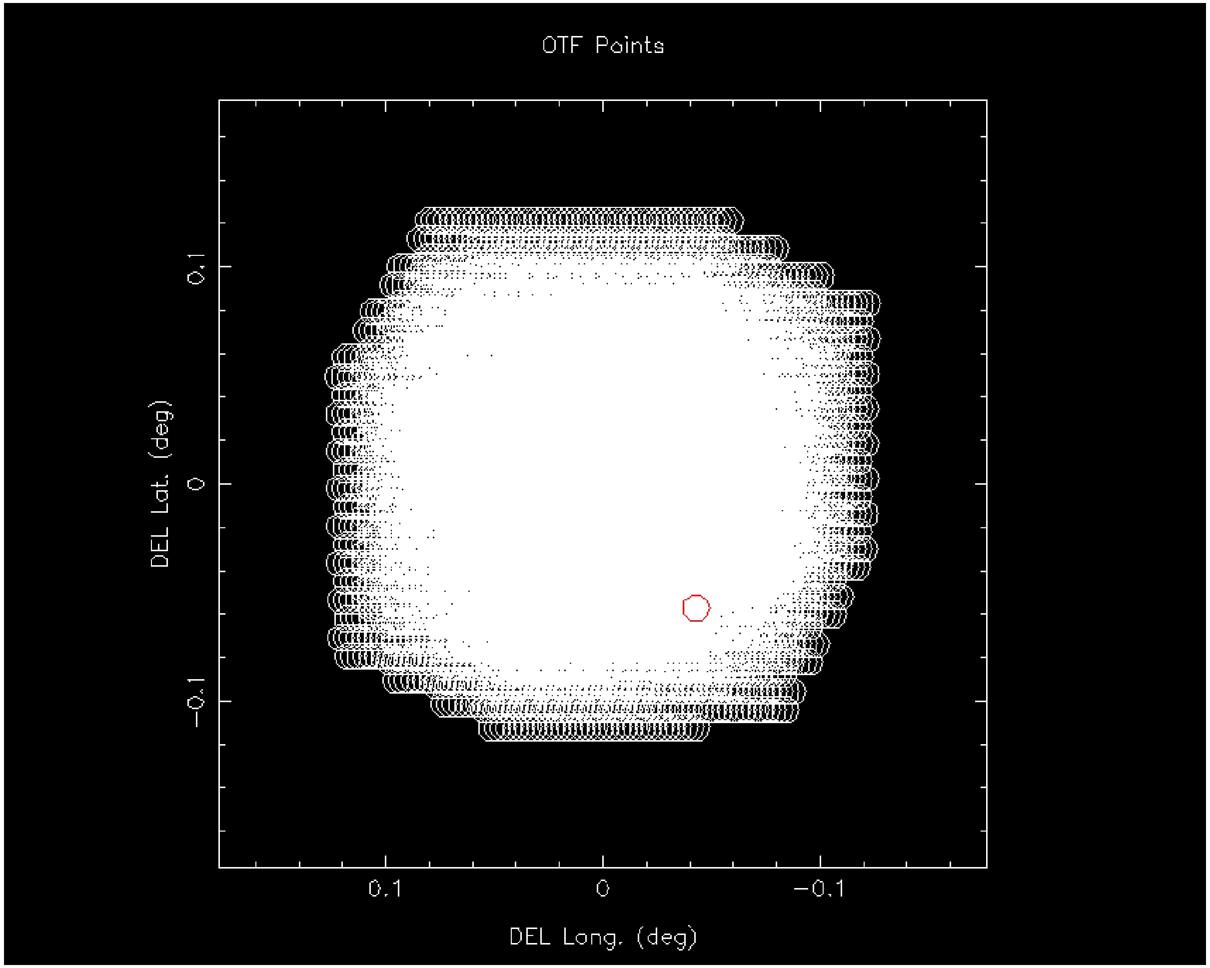


OTF Mapping

continuous readout of backends while antenna slews across the source

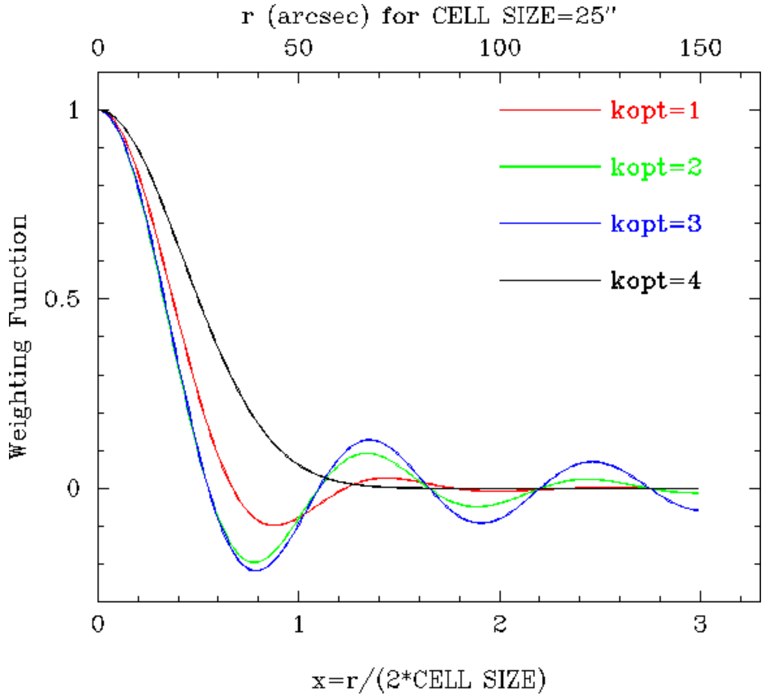
- Increase mapping efficiency - reduced overheads
- More readily account for malfunctioning pixels
- Increased image fidelity
  - Nyquist sampled
  - Uniform sensitivity over observed field
  - Reduced correlated noise

OTF Simulation



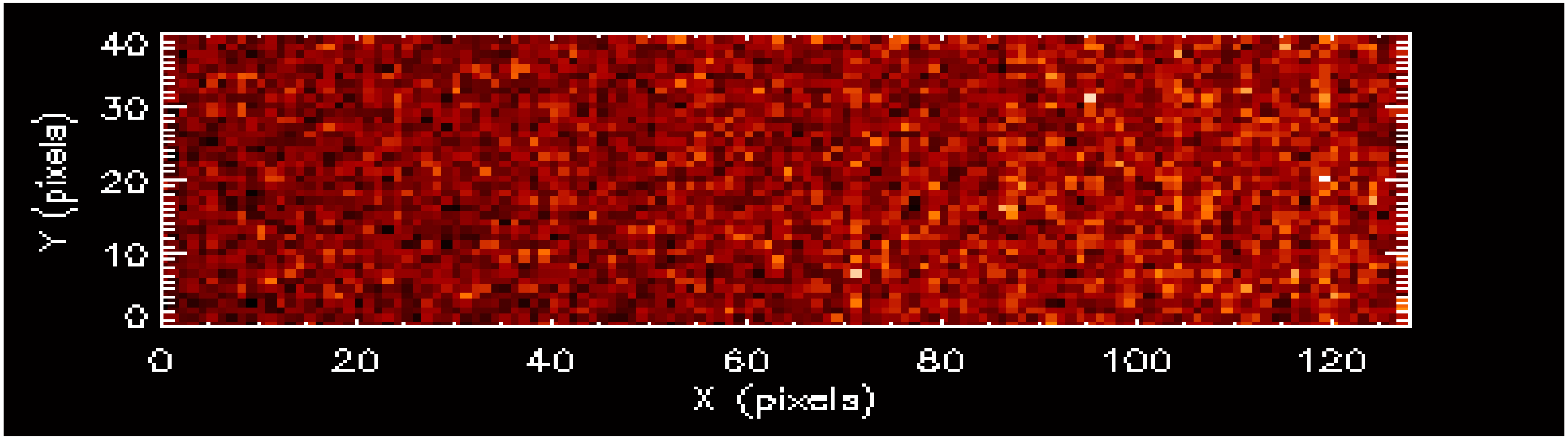
Co-Add/Regridding of Data

- Truncated smoothing kernel
- Spatial Weighting: Jinc*Gaussian
  - minimize aliased noise
  - preserve resolution
- Noise Weighting: $1/\sigma^2$



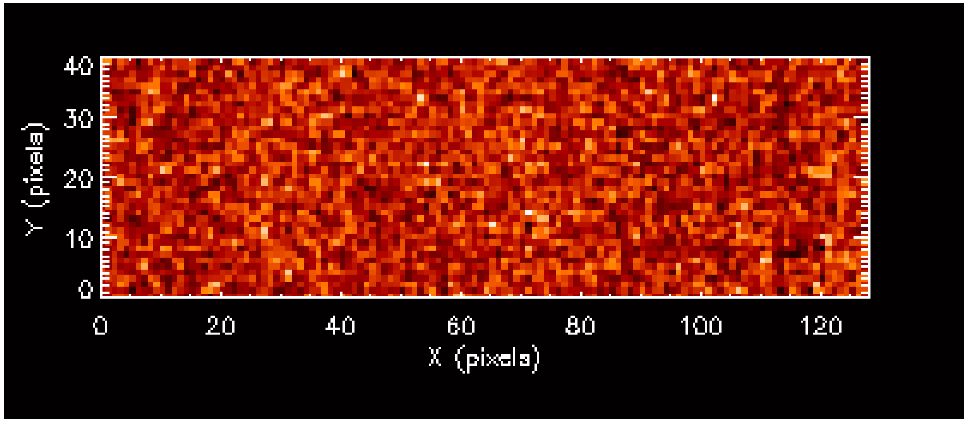
OTF Noise Distribution

RMS Image

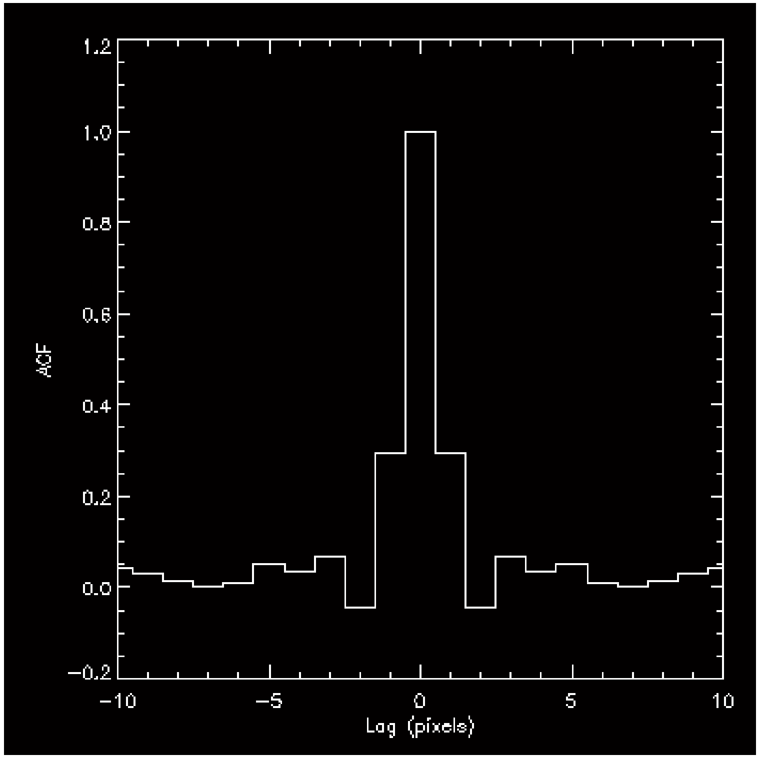


OTF Less Correlated Noise

Channel image



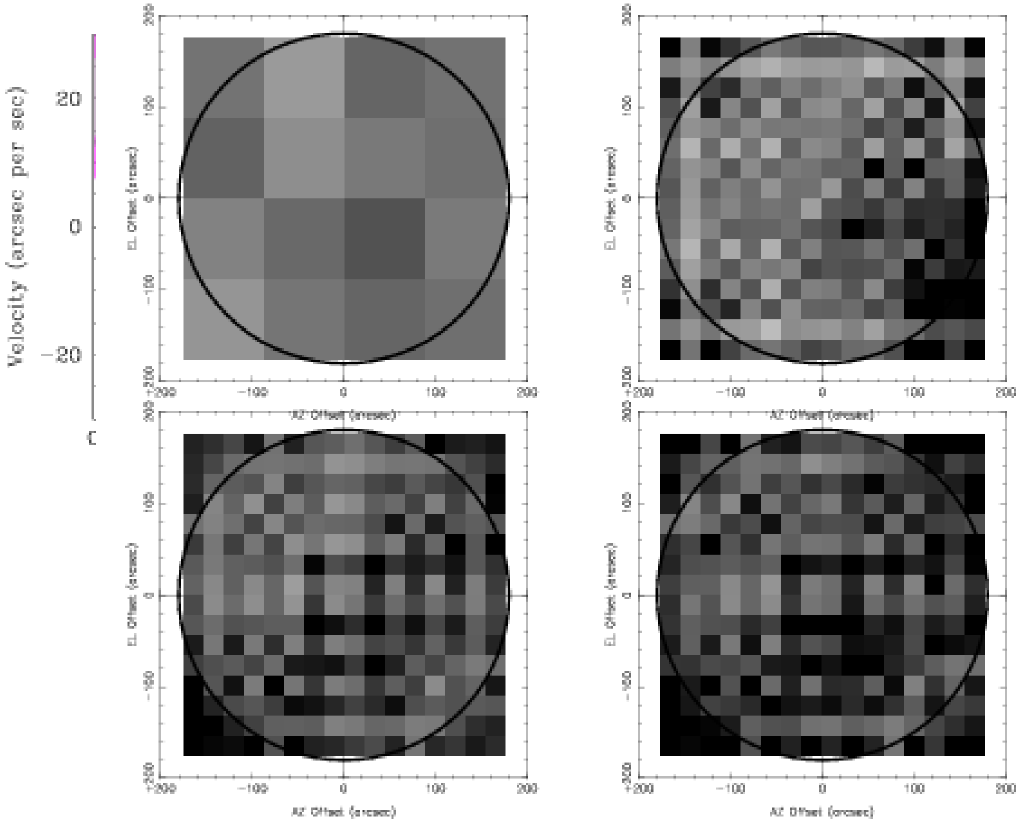
ACF



Compact Fields

- Dynamic OFF position
- Loops are more difficult to implement in antenna servo systems

RMS Images



Analysis of Spectroscopic Data Cubes

- Spectroscopy: chemistry or kinematics
- Imaging: projected 2D distributions
- Exploit all of the available information

Moment Maps

- Zero Moment = Integrated Intensity:

$$W = \Sigma\ T_a(v)\Delta v$$

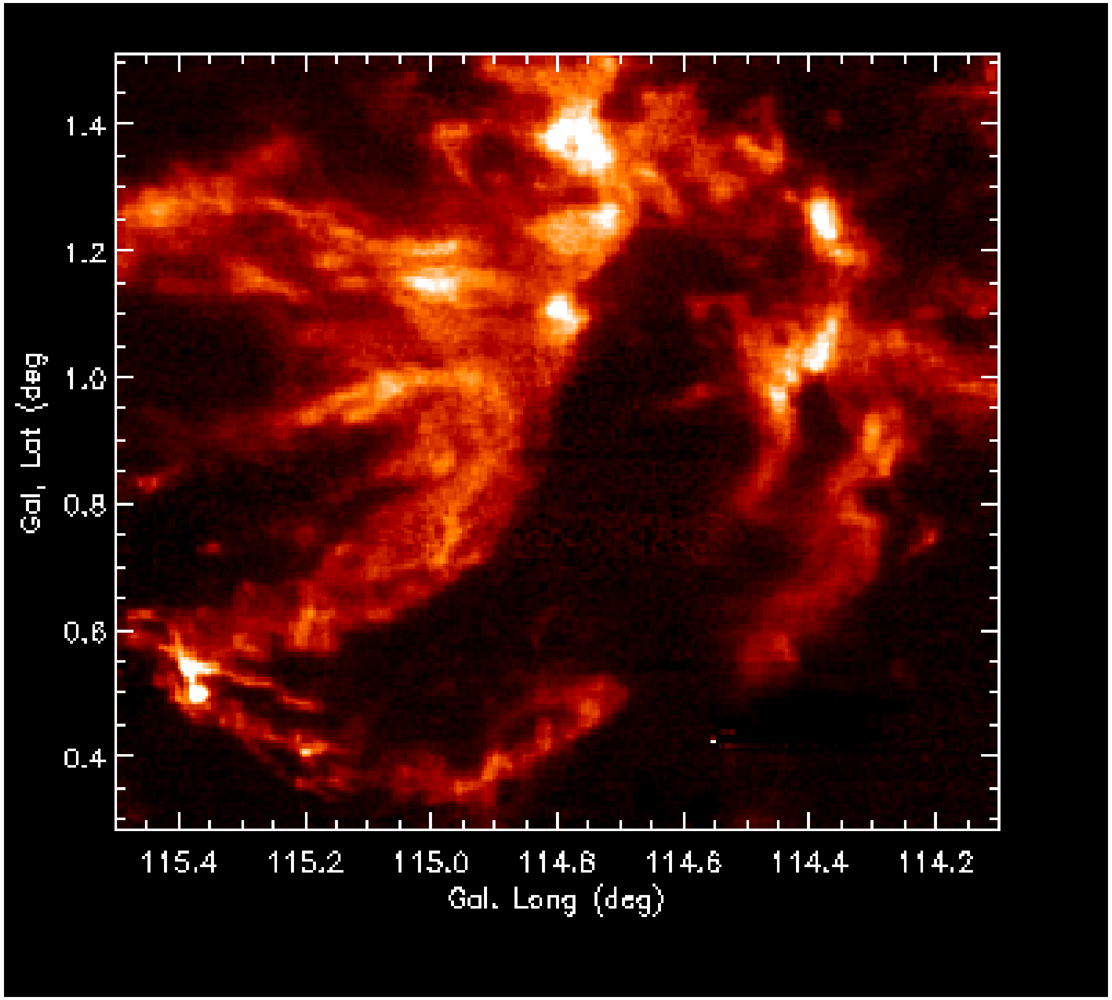
- First Moment = Centroid Velocity:

$$V_c = \Sigma\ T_a(v_i)v_i / \Sigma\ T(v_i)$$

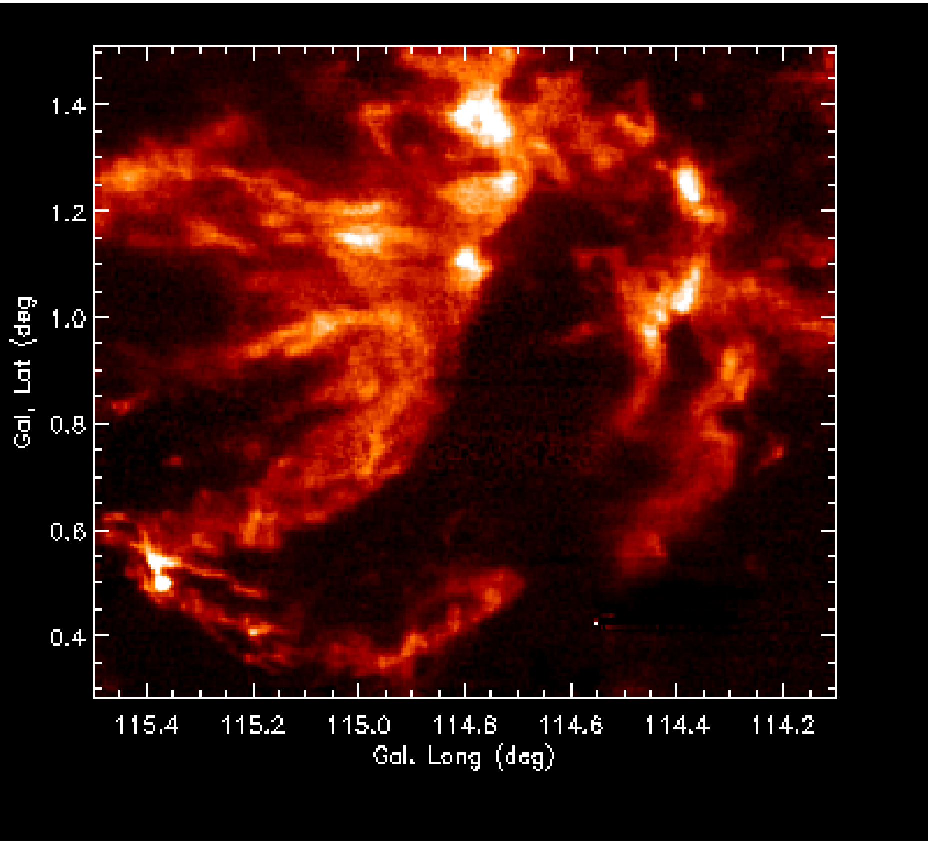
- Second Moment = Line Width:

$$\delta v = [\ \Sigma\ T_a(v_i)(v_i - V_c)^2 / \Sigma\ T(v_i)]^{1/2}$$

0^{th} Moment


1.4
1.2
1.0
0.8
0.6
0.4
Gal. Lat (deg
115.4
115.2
115.0
114.8
114.6
114.4
114.2
Gal. Long (deg)

1st Moment


1.4
1.2
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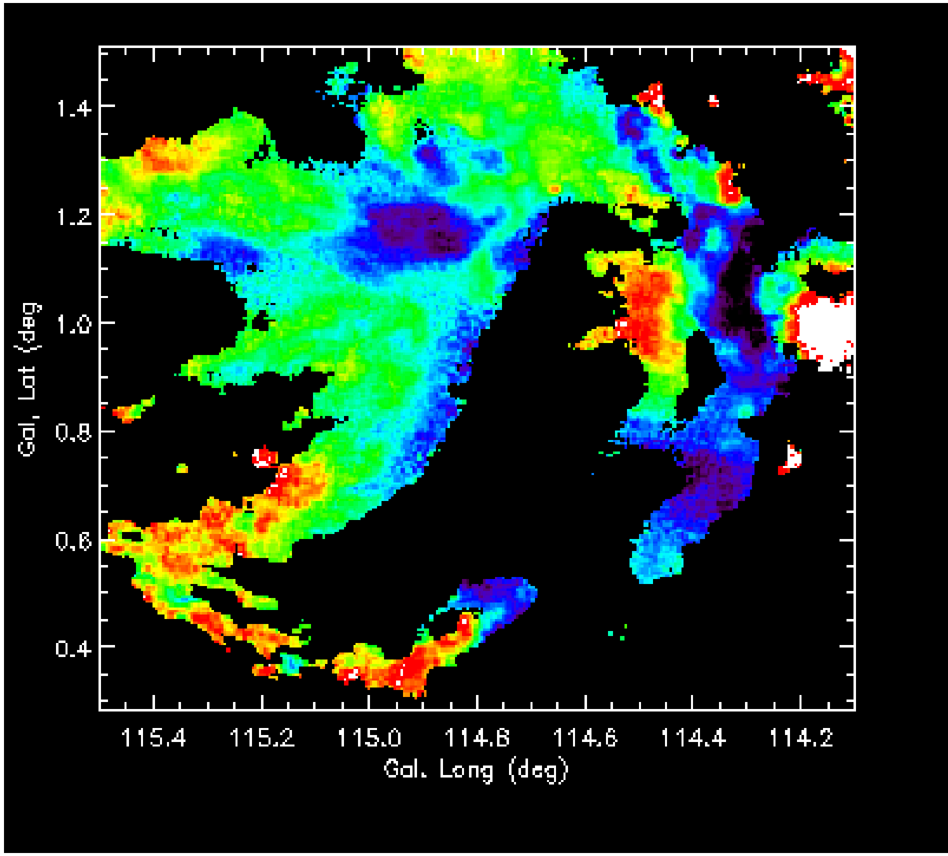
0.8
0.6
0.4
Gal. Lat (deg
115.4
115.2
115.0
114.8
114.6
114.4
114.2
Gal. Long (deg)


1.4
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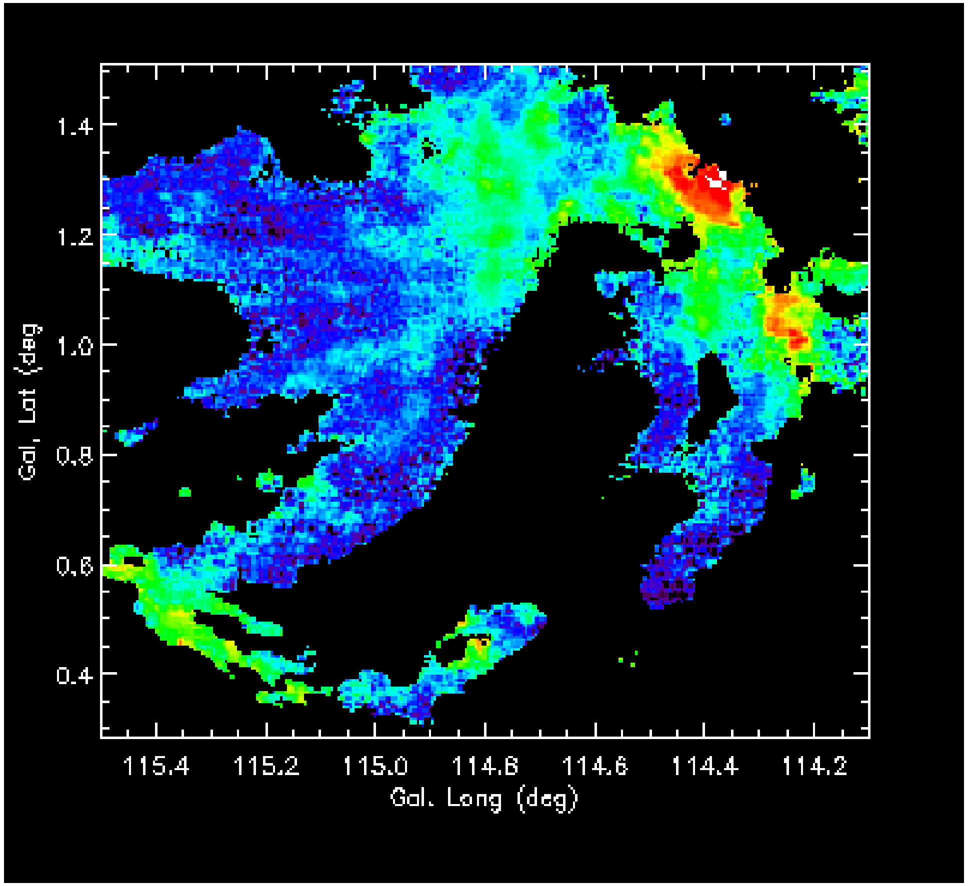
0.8
0.6
0.4
Gal. Lat (deg
115.4
115.2
115.0
114.8
114.6
114.4
114.2
Gal. Long (deg)

2^{nd} Moment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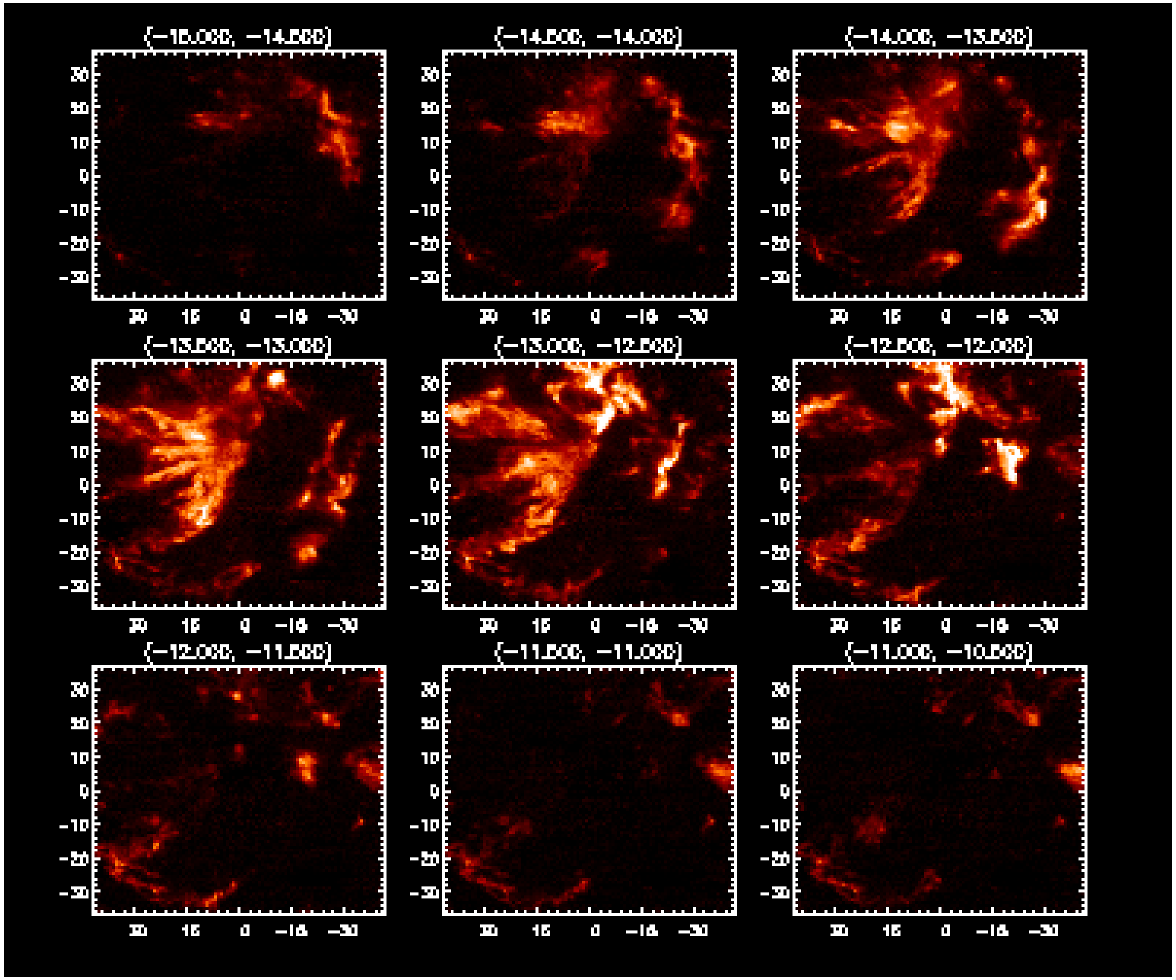
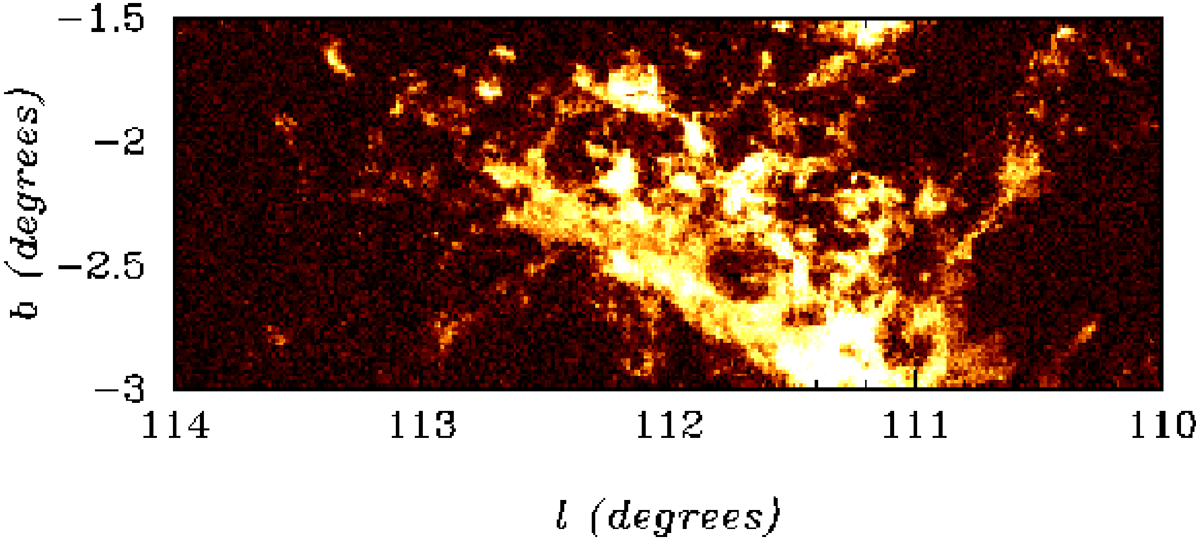
1.2
1.0
0.8
0.6
0.4
Gal. Lat (deg
115.4
115.2
115.0
114.8
114.6
114.4
114.2
Gal. Long (deg)

Channel Maps



Statistical Descriptions

- Complex distributions defy simple geometric descriptions
- Analyzing a single object has limited utility
- Statistical metrics are more useful to constrain physical models



Multivariate Statistics

Data: Ensemble of spectra, $T(v_i)$ i=1,nchannels

Homogenous variates:

- noise is constant for all variates

Determine:

- relationship between variates
- degree of similarity or dis-similarity

Principal Component Analysis

Formally:

The goal of PCA is to determine the set of *orthogonal* axes u, for which the data, X, when projected upon u, *maximizes the variance*.

In Practice:

PCA *identifies Line Profile Differences* due to the dynamics *with respect to noise.*

Data Matrix: $X_{ij} = T(r_i, v_j) - \langle T_j \rangle$

To Project Data:

$$y_i - \langle y^l \rangle = \sum X_{ij} u_j^l$$

$$\mathrm{var}(y^l) = u^l S u^l$$

$$S_{jk} = \frac{1}{n} \sum X_{ij} X_{ik}$$

Covariance Matrix

$$\left. \begin{array}{l} \displaystyle\sum_{j=1}^{nc} u_j^l u_j^m = 1 \,;\, \text{if } 1 = \text{m} \\ \displaystyle\sum_{j=1}^{nc} u_j^l u_j^m = 0 \,;\, \text{if } 1 \neq \text{m} \end{array} \right\}$$

Orthogonal Condition

Solve the eigenvalue equation:

$$\boxed{S\,u^{l} = \lambda_{l} u^{l}}$$

***l*=1,nchannels**

u^l=eigenvector of the l^{th} component

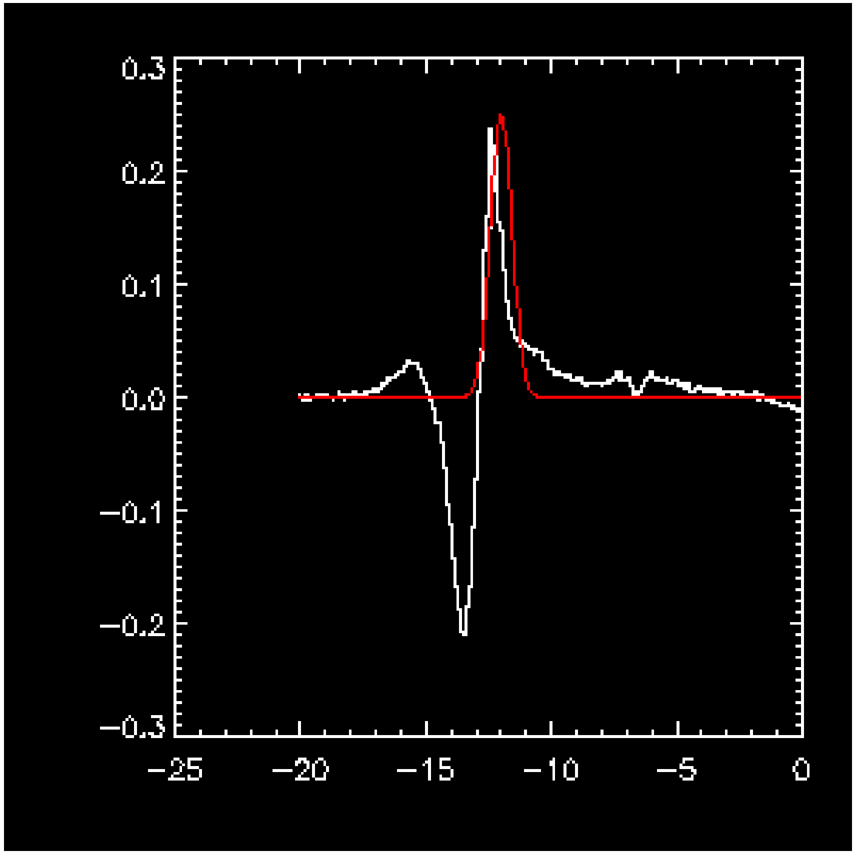
λ_l=variance projected onto the l^{th} component

Eigenimages: To locate the variance in the x,y plane

$$\boxed{I_l(x,y) = \sum_{j=1}^{nc} X_{ij} u_j^l}$$

Measurement Error: $\sigma(r_i) = \sigma(X_{ij})$

PCA-01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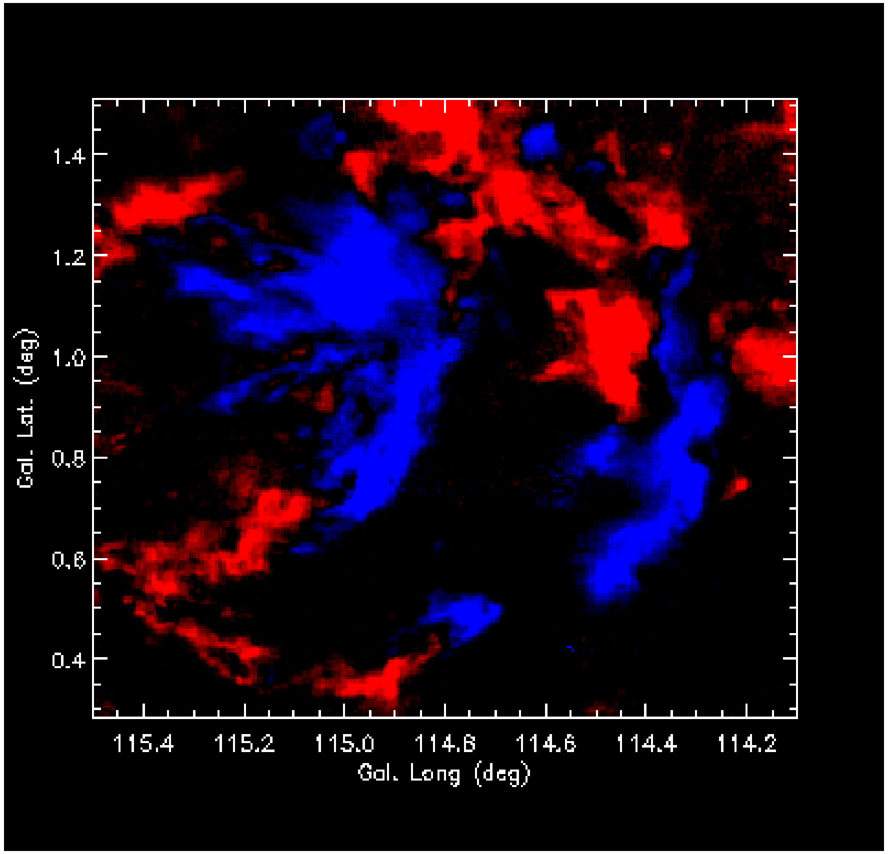
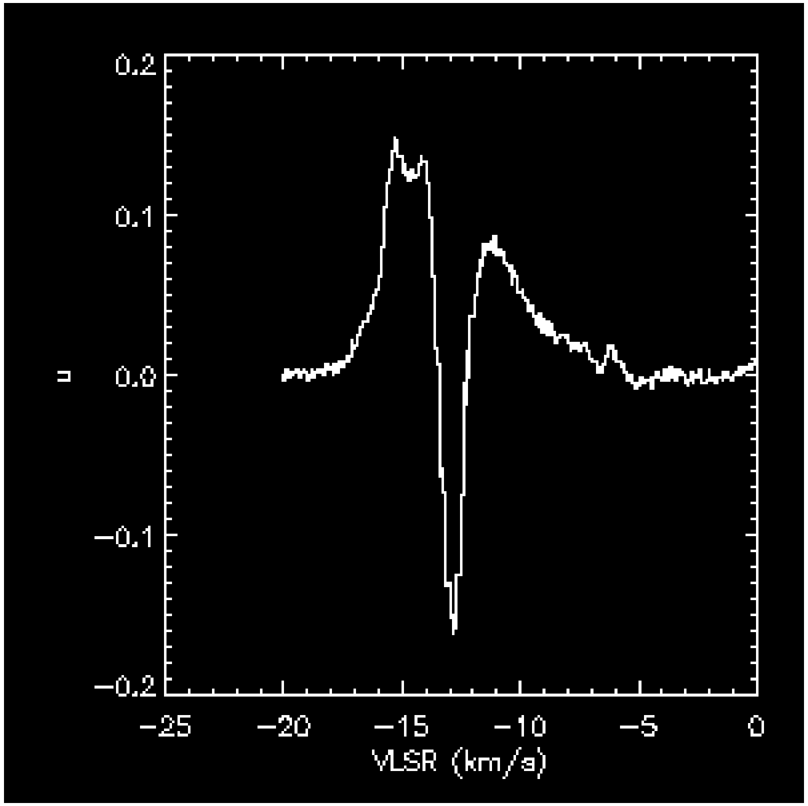
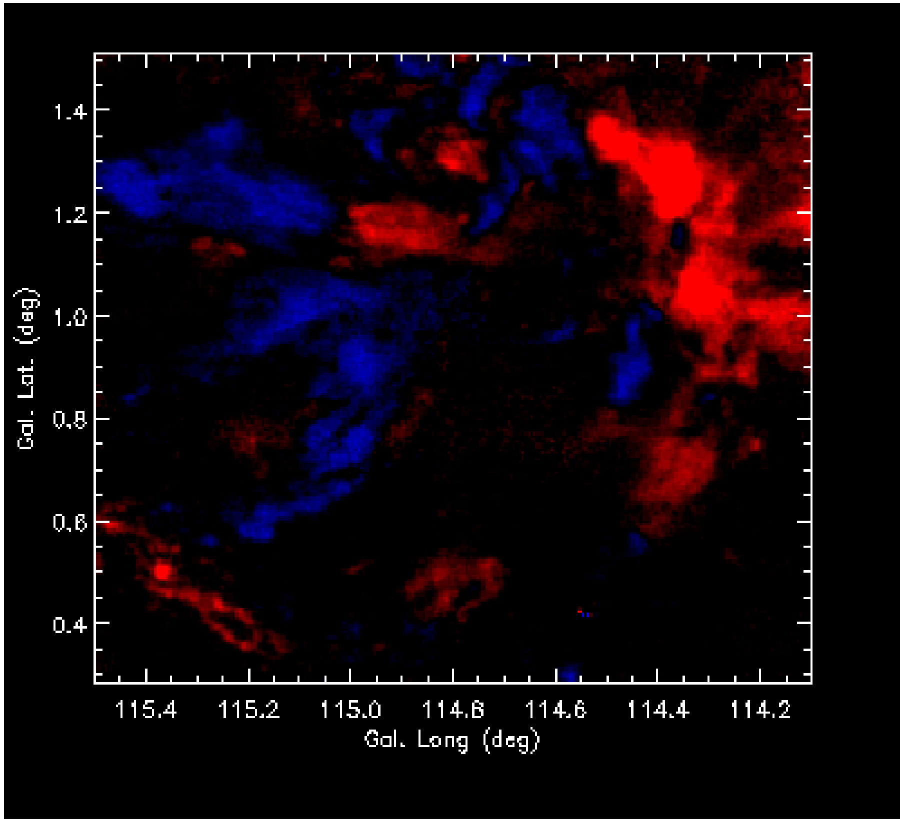
0.1
0.0
−0.1
−0.2
−0.3
−25
−20
−15
−10
−5
0

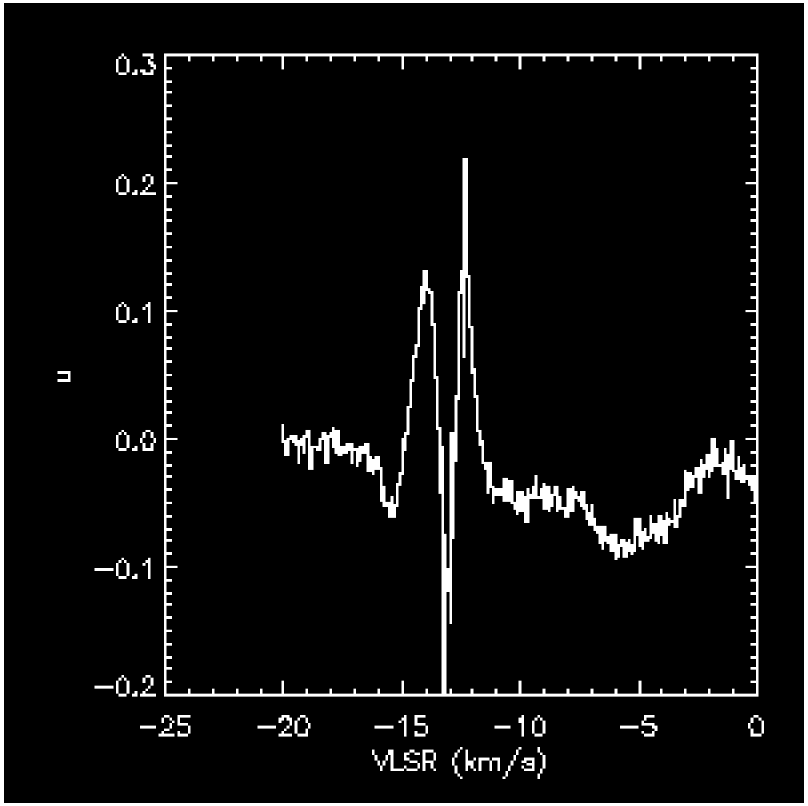

1.4
1.2
1.0
0.8
0.6
0.4
Gal. Lat. (deg)
115.4
115.2
115.0
114.8
114.6
114.4
114.2
Gal. Long (deg)

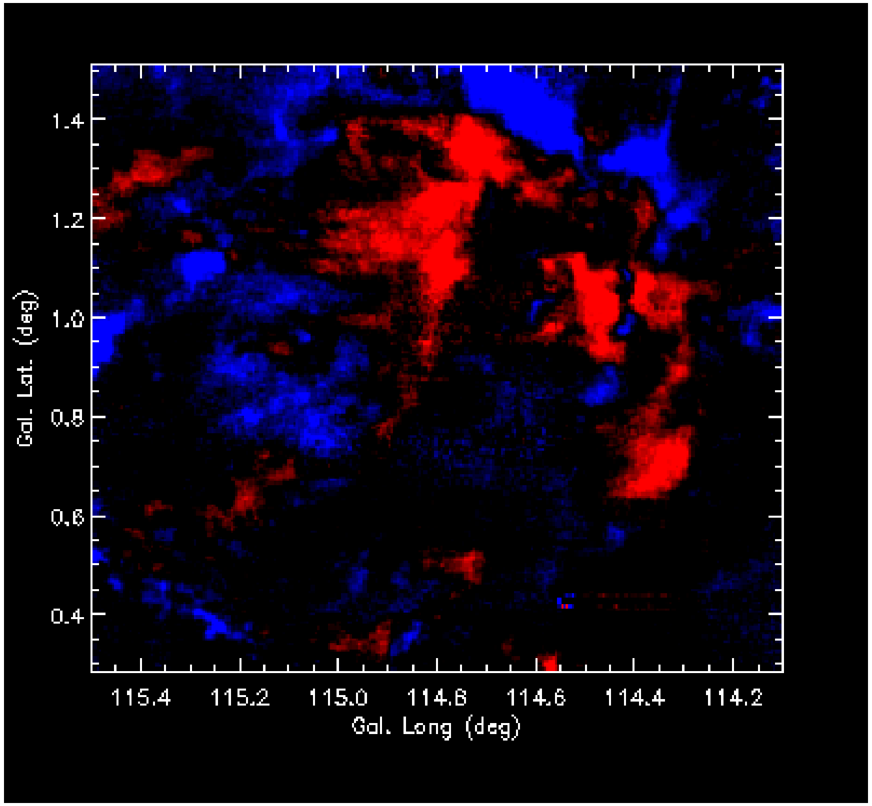
PCA-02


0.2
0.1
0.0
−0.1
−0.2
u
−25
−20
−15
−10
−5
0
VLSR (km/s)


1.4
1.2
1.0
0.8
0.6
0.4
Gal. Lat. (deg)
115.4
115.2
115.0
114.8
114.6
114.4
114.2
Gal. Long (deg)

PCA-03


0.3
0.2
0.1
0.0
−0.1
−0.2
u
−25
−20
−15
−10
−5
0
VLSR (km/s)


1.4
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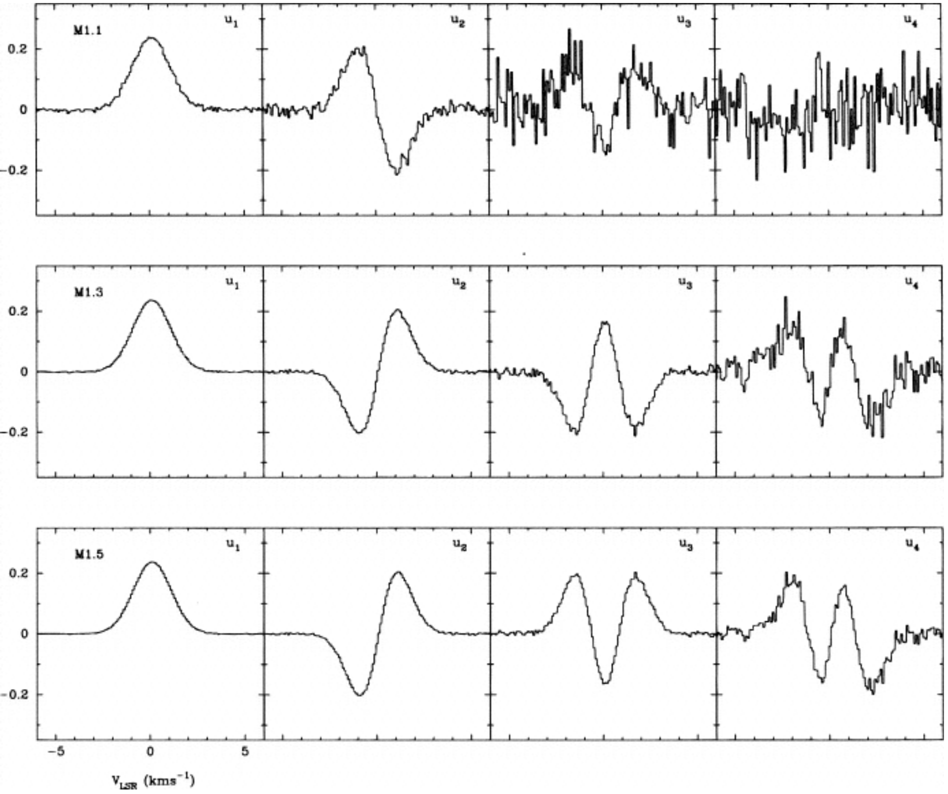
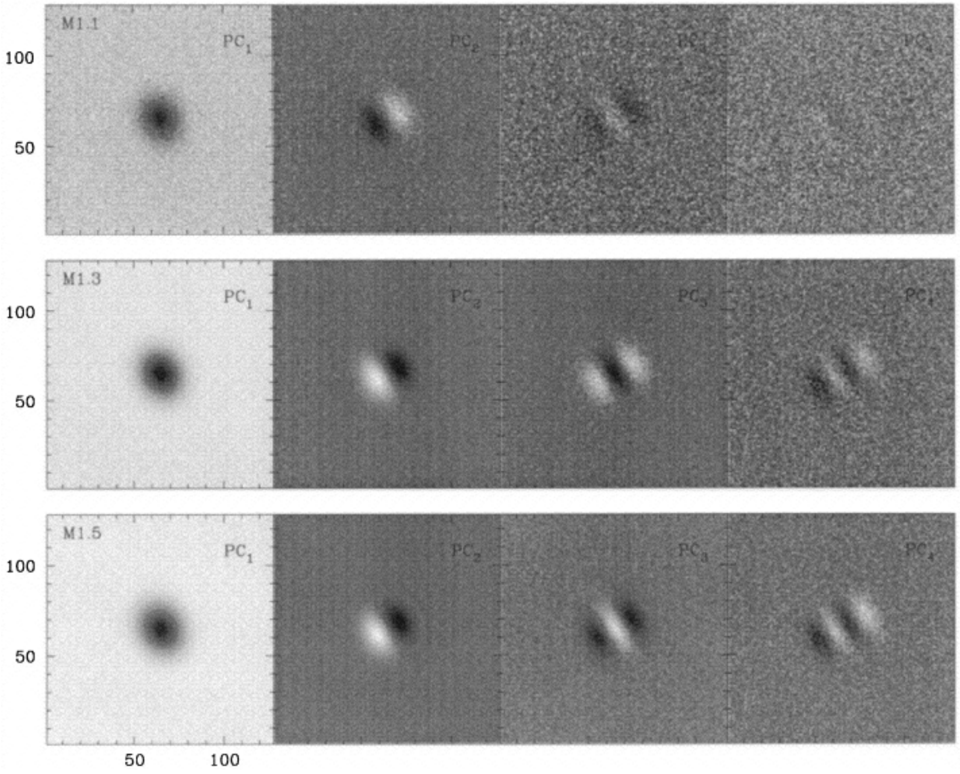
0.8
0.6
0.4
Gal. Lat. (deg)
115.4
115.2
115.0
114.8
114.6
114.4
114.2
Gal. Long (deg)

Rotating Cloud Toy Model

Eigenvectors



Eigenimages



Radio Astronomy Applications

- Interstellar turbulence – constrain velocity structure function
- Non-circular (streaming) motions in galaxies
- Chemical variations in GMC cores
- Polarization
- Spectral index images

Summary

- Focal plane arrays are essential instruments on single dish telescopes!
- OTF mapping provides best imaging fidelity.
- Statistics provide concise descriptions of complex distributions of line emission.