Heterodyne Focal Plane Arrays

Mark Heyer
University of Massachusetts
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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

UMass–Stony Brook $^{12}$CO

BU-FCRAO Gal. Ring Survey
## Current Instruments

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

<table>
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<tr>
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<th>#spectra</th>
</tr>
</thead>
<tbody>
<tr>
<td>DesertSTAR</td>
<td>HHT 10m</td>
<td>7</td>
<td>300-380</td>
<td>7</td>
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<tr>
<td>HARP-B</td>
<td>JCMT</td>
<td>16</td>
<td>325-375</td>
<td>16</td>
</tr>
<tr>
<td>ALFA</td>
<td>Arecibo</td>
<td>7</td>
<td>1.225-1.525</td>
<td>14</td>
</tr>
</tbody>
</table>
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 Noise Temperature per Pixel per Frequency

All 32 pixels plotted*

Blue = Dewar A
Red = Dewar B

Value (Y) Axis Major Gridlines

*Pixel B2 out of commission and therefore not included
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)

\textit{Discrete} Steps of antenna
Discrete Steps to “fill in” Grid
Non-Uniform Noise Distribution

- Inhomogeneity of $T_{\text{rec}}$
Malfunctioning Pixel – Image holes
Reference Sharing
Single reference measurement applied to many source measurements

FCRAO QUARRY Receiver (1990-1997)
Spatially Correlated Noise

$$ACF$$

$${C_N(\tau_x,0)}_{\text{X}}$$

$${C_N(0,\tau_y)}_{\text{Y}}$$

$${\tau_x} \ (\text{pixels})$$

$${\tau_y} \ (\text{pixels})$$
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
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:
  \[ W = \sum T_a(v) \Delta v \]

- First Moment = Centroid Velocity:
  \[ V_c = \frac{\sum T_a(v_i)v_i}{\sum T(v_i)} \]

- Second Moment = Line Width:
  \[ \delta v = \left[ \frac{\sum T_a(v_i)(v_i - V_c)^2}{\sum T(v_i)} \right]^{1/2} \]
0th Moment
$1^{st}$ Moment
2nd Moment
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 \textit{orthogonal} axes $u$, for which the data, $X$, when projected upon $u$, \textit{maximizes the variance}.

In Practice:

PCA \textit{identifies Line Profile Differences} due to the dynamics \textit{with respect to noise}.
Data Matrix: \[ X_{ij} = T (r_i, v_j) - <T_j> \]

To Project Data: \[ y_i - <y_i^l> = \sum X_{ij} u_j^l \]

\[ \text{var} \ (y^l) = u^l S \ u^l \]

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

Covariance Matrix

\[ \sum_{j=1}^{nc} u_j^l u_j^m = 1 ; \text{if } l = m \]

Orthogonal Condition

\[ \sum_{j=1}^{nc} u_j^l u_j^m = 0 ; \text{if } l \neq m \]
Solve the eigenvalue equation: 

\[ S \mathbf{u}^l = \lambda_l \mathbf{u}^l \]

\( l = 1, n\text{channels} \)

\( \mathbf{u}^l = \text{eigenvector of the } l^{\text{th}} \text{ component} \)

\( \lambda_l = \text{variance projected onto the } l^{\text{th}} \text{ component} \)

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

\[ I_l(x, y) = \sum_{j=1}^{nc} X_{ij} \mathbf{u}^l_j \]

Measurement Error: \( \sigma(r_i) = \sigma(X_{ij}) \)
PCA-01
PCA-03
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.