Tenth Synthesis Imaging Summer School, University of New Mexico, June 13-20, 2006

MM Interferometry and ALMA

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Claire Chandler & Todd Hunter

• Why a special lecture on mm interferometry?
  – High frequency interferometry suffers from unique problems
  – We are poised on the brink of a mm/summ revolution with the advent of new telescopes

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Outline

• Summary of existing and future mm/sub-mm arrays
• Unique science at mm & sub-mm wavelengths
• Problems unique to mm/sub-mm observations
  • Atmospheric opacity
  • Absolute gain calibration
  • Tracking atmospheric phase fluctuations
  • Antenna and instrument constraints
• Summary
• Practical aspects of observing at high frequency with the VLA
Summary of existing and future mm/sub-mm arrays

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<thead>
<tr>
<th>Telescope</th>
<th>altitude (feet)</th>
<th>diam. (m)</th>
<th>No. dishes</th>
<th>A (m²)</th>
<th>vmin (GHz)</th>
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<td>NMA</td>
<td>2,000</td>
<td>10</td>
<td>6</td>
<td>470</td>
<td>250</td>
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<td>CARMA¹</td>
<td>7,300</td>
<td>3.5/6/10</td>
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<td>800</td>
<td>250</td>
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<td>6</td>
<td>8</td>
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<td>650</td>
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<td>ALMA²</td>
<td>16,400</td>
<td>12</td>
<td>50</td>
<td>5700</td>
<td>950</td>
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¹ BIMA+OVRO+SZA 3.5 m Array at higher site = CARMA first call for proposals soon
² First call for early science proposals expected in Q2 2009, planned for full operation by 2012
Progress in ALMA construction

Operations Support Facility: Contractors Camp

ALMA Test Facility (VLA)

Array Operations Site

Operations Support Facility

Road

The Tri-Partner ALMA Project

One-stop shopping for NA astronomers
- Proposals
- Observing scripts
- Data archive and reduction

NAASC: North America ALMA Science Center, Charlottesville, VA
Why do we care about mm/submm?

- mm/submm photons are the most abundant photons in the spectrum of most spiral galaxies – 40% of the Milky Way Galaxy
- After the 3K cosmic background radiation, mm/submm photons carry most of the energy in the Universe
- Unique science can be done at mm/sub-mm wavelengths because of the sensitivity to thermal emission from dust and lines
- Probe of cool gas and dust in:
  - Proto-planetary disks
  - Star formation in our Galaxy
  - Star formation at high-redshift

Science at mm/submm wavelengths: dust emission

In the Rayleigh-Jeans regime, \( h\nu \ll kT \),

\[
S_\nu = \frac{2kT \nu^2 \tau_\nu \Omega}{c^2} \quad \text{Wm}^{-2} \text{Hz}^{-1}
\]

and dust opacity, \( \tau_\nu \propto \nu^2 \)

so for optically-thin emission, flux density

\[
S_\nu \propto \nu^4
\]

⇒ emission is brighter at higher frequencies
Dusty Disks in our Galaxy: Physics of Planet Formation

Vega debris disk simulation: PdBI & ALMA

Simulated PdBI image  Simulated ALMA image

Science at mm/sub-mm wavelengths: molecular line emission

- Most of the dense ISM is H₂, but H₂ has no permanent dipole moment ⇒ use trace molecules

<table>
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<tr>
<th>Molecule</th>
<th>J(1-0) GHz</th>
<th>J(2-1) GHz</th>
<th>J(3-2) GHz</th>
<th>(n_{\text{crit}}[J(1-0)]) cm⁻³</th>
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<td>CO</td>
<td>115.271</td>
<td>230.538</td>
<td>345.795</td>
<td>(10^2 - 10^3)</td>
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<td>CS</td>
<td>48.991</td>
<td>97.981</td>
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<td>HCO⁺</td>
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<td>SiO</td>
<td>43.122</td>
<td>86.243</td>
<td>130.268</td>
<td>(10^3 - 10^4)</td>
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</table>

Plus: many more complex molecules (e.g. \(\text{N}_2\text{H}⁺\), \(\text{CH}_3\text{OH}\), \(\text{CH}_3\text{CN}\), etc)
- Probe kinematics, density, temperature
- Abundances, interstellar chemistry, etc...
- For an optically-thin line \(S_ν \propto ν^4\); \(T_B \propto ν^2\) (cf. dust)
Massive stars forming regions are at large distances need high resolution
Clusters of forming protostars and copious hot core line emission
Chemical differentiation gives insight to physical processes
ALMA will routinely achieve resolutions of better than 0.1"  
Brogan et al., in prep.

List of Currently Known Interstellar Molecules (DEMIRM)²

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² The list includes numerous organic molecules, radicals, and ions that are known to exist in interstellar space, reflecting the complex chemistry that occurs in these environments. The notation includes ions such as H₂⁺, HD⁺, HD⁺, and HD⁺, as well as molecules like H₂, HD, CH⁻, CH⁺, and C₂H₂, which are fundamental to understanding the chemical processes in star-forming regions.
Galaxy Feeding

CO(1-0) BIMA-SONG

ALMA science goal:
Ability to trace chemical composition of galaxies to redshift of 3 in less than 24 hours

M82 starburst
Red: optical emission
Blue: x-ray emission
Green: OVRO $^{12}$CO(J=1-0)
(Walter, Weiss, Scoville 2003)

Unique mm/submm access to highest z

• Redshifting the steep submm SED counteracts inverse square law dimming

• Detect high-z galaxies as easily as those at z~0.5
• 2mJy at 1mm ~5x10^{12} L_{\odot}
  –Current depth of submm surveys
  –ALMA has no effective limit to depth

Andrew Blain
### Problems unique to the mm/sub-mm

- Atmospheric opacity significant $\lambda<1$cm: raises $T_{\text{sys}}$ and attenuates source
  - Opacity varies with frequency and altitude
  - Gain calibration must correct for opacity variations
- Atmospheric phase fluctuations
  - Cause of the fluctuations: variable H$_2$O
  - Calibration schemes must compensate for induced loss of visibility amplitude (coherence) and spatial resolution (seeing)
- Antennas
  - Pointing accuracy measured as a fraction of the primary beam is more difficult to achieve: $\text{PB} \sim 1.22 \frac{\lambda}{D}$
  - Need more stringent requirements than at cm wavelengths for: surface accuracy & baseline determination

### Problems, continued...

- Instrument stability
  - Must increase linearly with frequency (delay lines, oscillators, etc…)
- Millimeter/sub-mm receivers
  - SIS mixers needed to achieve low noise characteristics
  - Cryogenics cool receivers to a few K
  - IF bandwidth
- Correlators
  - Need high speed (high bandwidth) for spectral lines: $\Delta V = 300$ km s$^{-1} \rightarrow 1.4$ MHz @ 1.4 GHz, 230 MHz @ 230 GHz
  - Broad bandwidth also needed for sensitivity to thermal continuum and phase calibration
- Limitations of existing and future arrays
  - Small FoV $\Rightarrow$ mosaicing: FWHM of 10 m antenna @ 230 GHz is $\sim 30''$
  - Limited uv-coverage, small number of elements (improved with CARMA, remedied with ALMA)
Atmospheric opacity

- Due to the troposphere (lowest layer of atmosphere): \( h < 10 \text{ km} \)
- Temperature decreases with altitude: clouds & convection can be significant
- Dry Constituents of the troposphere: \( \text{N}_2, \text{O}_2, \text{Ar, CO}_2, \text{Ne, He, Kr, CH}_4, \text{H}_2 \)
- \( \text{H}_2\text{O} \): abundance is highly variable but is \(< 1\%\) in mass, mostly in the form of water vapor

Troposphere opacity increases with frequency:

Models of atmospheric transmission from 0 to 1000 GHz for the ALMA site in Chile, and for the VLA site in New Mexico

\( \Rightarrow \) Atmosphere transmission not a problem for \( \lambda > \text{cm} \) (most VLA bands)
**Optical depth of the atmosphere at the VLA site**

- VLA K band
- VLA Q band

- 22 GHz
- 43 GHz

**Sensitivity: Receiver noise temperature**

- Good receiver systems have a linear response: $y = m(x + \text{constant})$
- Output power: $P_{\text{out}} = m \times (T_{\text{input}} + T_{\text{receiver}})$

In order to measure $T_{\text{receiver}}$, you need to make measurements of two calibrated 'loads':

- $T_1 = 77$ K liquid nitrogen load
- $T_2 = T_{\text{load}}$ room temperature load

$$T_{\text{receiver}} = \frac{(T_2 - T_1) P_1}{(P_2 - P_1)} - T_1$$

Let $y = \frac{P_2}{P_1}$

$$\left(\frac{T_2 - y T_1}{y - 1}\right)$$
In addition to receiver noise, at millimeter wavelengths the atmosphere has a significant brightness temperature:

\[ T_{B_{\text{atm}}} = T_{\text{atm}} \times (1 - e^{-\tau}) \]

(where \( T_{\text{atm}} \) = temperature of the atmosphere, \( \sim 300 \) K)

\( T_{B_{\text{atm}}} \) represents additional noise at the input of the receiver:

The “system noise temperature” is a measure of the overall sensitivity:

\[ T_{\text{noise}} = T_{\text{atm}}(1-e^{-\tau}) + T_{\text{rec}} \]

Consider the signal to noise ratio for a source outside the atmosphere:

\[ \frac{S}{N} = \left( \frac{T_{\text{source}} e^{-\tau}}{T_{\text{noise}} / (T_{\text{noise}} e^{-\tau})} \right) \]

\[ T_{\text{sys}} = T_{\text{noise}} e^{\tau} = T_{\text{atm}} e^{\tau(1-1)} + T_{\text{rec}} e^{\tau} \]

The system sensitivity drops rapidly (exponentially) as opacity increases.

**Practical measurement of \( T_{\text{sys}} \)**

- So how do we measure \( T_{\text{sys}} \) without constantly measuring \( T_{\text{receiver}} \) and the opacity? \[ T_{\text{sys}} = T_{\text{atm}}(e^{\tau}-1) + T_{\text{rec}} e^{\tau} \]

- At mm \( \lambda \), \( T_{\text{sys}} \) is usually obtained with the absorbing-disc method (Penzias & Burrus 1973) in which an ambient temperature load (\( T_{\text{load}} \)) is occasionally placed in front of the receiver.

- We want to know the overall sensitivity, not how much is due to the receiver vs. how much is due to the sky. Therefore, we can use:

\[ T_{\text{sys}} = T_{\text{load}} * \frac{T_{\text{noise}}}{(T_{\text{cal}} - T_{\text{noise}})} \]

\[ T_{\text{cal}} = T_{\text{load}} + T_{\text{rec}} \]

\[ T_{\text{noise}} = T_{B_{\text{atm}}} + T_{\text{rec}} \]

- As long as \( T_{\text{atm}} \) is similar to \( T_{\text{load}} \), this method automatically compensates for rapid changes in mean atmospheric absorption.

These are really the measured power but is \textit{temperature} in the R-J limit.
Atmospheric opacity, continued

Typical optical depth for 345 GHz observing at the SMA:

at zenith $\tau_{225} = 0.08 = 1.5 \text{ mm PWV}$, at elevation = 30° $\Rightarrow \tau_{225} = 0.16$

Conversion from 225 GHz to 345 GHz $\Rightarrow \tau_{345} \sim 0.05 + 2.25 \tau_{225} \sim 0.41$

$T_{\text{sys (DSB)}} = T_{\text{sys}} e^{\tau} = e^{(T_{\text{atm}}(1-e^{\tau}) + T_{\text{rec})}} = 1.5(101 + 100) \sim 300 \text{ K}$

assuming $T_{\text{atm}} = 300 \text{ K}$

For single sideband, $T_{\text{sys (SSB)}} = 2 T_{\text{sys (DSB)}} \sim 600 \text{ K}$

Atmosphere adds considerably to $T_{\text{sys}}$ and since the opacity can change rapidly, $T_{\text{sys}}$ must be measured often.

Example SMA 345 GHz Tsys Measurements

For calibration and imaging, visibility “sensitivity” weight is $\propto 1/[T_{\text{sys(i)}} * T_{\text{sys(j)}}]$
Correcting for $T_{sys}$ and conversion to a Jy Scale

$$S = S_0 \times [T_{sys}(1) \times T_{sys}(2)]^{0.5} \times 130 \text{ Jy/K} \times 5 \times 10^{-6} \text{ Jy}$$

SMA gain for 6m dish and 75% efficiency

Correlator unit conversion factor

Absolute gain calibration

- No non-variable quasars in the mm/sub-mm for setting the absolute flux scale; instead, have to use:

**Planets and moons:** roughly black bodies of known size and temperature, e.g.,
- Uranus @ 230 GHz: $S_\nu \sim 37 \text{ Jy, } \theta \sim 4''$
- Callisto @ 230 GHz: $S_\nu \sim 7.2 \text{ Jy, } \theta \sim 1.4''$
  - $S_\nu$ is derived from models, can be uncertain by $\sim 10%$
  - If the planet is resolved, you need to use visibility model for each baseline
  - If larger than primary beam, it shouldn’t be used (can be used for bandpass)
Mean Effect of Atmosphere on Phase

• Since the refractive index of the atmosphere $\neq 1$, an electromagnetic wave propagating through it will experience a phase change (i.e. Snell's law).

• The phase change is related to the refractive index of the air, $n$, and the distance traveled, $D$, by

$$\phi_e = \left(\frac{2\pi}{\lambda}\right) \times n \times D$$

For water vapor $n \propto \frac{w}{DT_{atm}}$, $w=$precipitable water vapor (PWV) column

so

$$\phi_e = \frac{12.6\pi}{\lambda} \times w \quad \text{for} \quad T_{atm} = 270 \text{ K}$$

This refraction causes:
- Pointing off-sets, $\Delta \theta \approx 2.5 \times 10^{-4} \times \tan(i)$ (radians)
  @ elevation $45^o$ typical offset~1'
- Delay (time of arrival) off-sets

⇒ These “mean” errors are generally removed by the online system

Atmospheric phase fluctuations

• Variations in the amount of precipitable water vapor cause phase fluctuations, which are worse at shorter wavelengths, and result in
  – Low coherence (loss of sensitivity)
  – Radio “seeing”, typically 1-3" at 1 mm
  – Anomalous pointing offsets
  – Anomalous delay offsets

Simplifying assumption:
The timescale for changes in the water vapor distribution is long compared to time for wind to carry features over the array

$V_w \approx 10 \text{ m/s}$
Atmospheric phase fluctuations, continued…

Phase noise as function of baseline length

![Graph showing phase noise as a function of baseline length.](image)

“Root phase structure function”
(Butler & Desai 1999)

- **Break related to width of turbulent layer**

- **Rms phase of fluctuations given by Kolmogorov turbulence theory**
  \[ \phi_{\text{rms}} = \frac{K b^\alpha}{\lambda} \, \text{[deg]} \]

  Where \( b \) = baseline length (km); \( \alpha \) ranges from 1/3 to 5/6; \( \lambda \) = wavelength (mm); and \( K \) = constant (~100 for ALMA, 300 for VLA)

- The position of the break and the maximum noise are weather and wavelength dependent

Atmospheric phase fluctuations, continued…

22 GHz VLA observations of 2 sources observed simultaneously (paired array)

- **Antennas 2 & 5 are adjacent, phases track each other closely**
- **Antennas 13 & 12 are adjacent, phases track each other closely**

Self-cal applied using a reference antenna within 200 m of W4 and W6, but 1000 m from W16 and W18:
- Long baselines have large amplitude, short baselines smaller amplitude
- Nearby antennas show correlated fluctuations, distant ones do not
VLA observations of the calibrator 2007+404 at 22 GHz with a resolution of 0.1" (Max baseline 30 km):

Position offsets due to large scale structures that are correlated ⇒ phase gradient across array

Reduction in peak flux (decorrelation) and smearing due to phase fluctuations over 60 min

Sidetone pattern shows signature of antenna based phase errors ⇒ small scale variations that are not correlated

Phase fluctuations with timescale ~ 30 s

Uncorrelated phase variations degrades and decorrelates image; Correlated phase offsets = position shift

Phase fluctuations: loss of coherence

Coherence = (vector average/true visibility amplitude) = \( \langle V \rangle / V_0 \)

Where, \( V = V_0 e^{i\phi} \)

The effect of phase noise, \( \phi_{rms} \), on the measured visibility amplitude in a given averaging time:

\( \langle V \rangle = V_0 \times \langle e^{i\phi} \rangle = V_0 \times e^{-\phi_{rms}^2/2} \) (Gaussian phase fluctuations)

Example: if \( \phi_{rms} = 1 \) radian (~60 deg), coherence = \( \langle V \rangle = 0.60 \)

\( \frac{V_0}{V_0} \)
Phase fluctuations: radio “seeing”

\[ \frac{\langle V \rangle}{V_0} = \exp(-\phi_{\text{rms}}^2/2) = \exp(-\frac{[K' b^\alpha / \lambda]^2}{2}) \quad \text{[Kolmogorov with } K' = K \cdot \pi/180] \]

- Measured visibility decreases with baseline length, \( b \), (until break in root phase structure function)
- Source appears resolved, convolved with “seeing” function

\[ \Rightarrow \text{Diffraction limited seeing is precluded for baselines longer than 1 km at ALMA site!} \]

\[ \Rightarrow \text{Phase fluctuations severe at mm/submm wavelengths, correction methods are needed} \]

- Self-calibration: OK for bright sources that can be detected in a few seconds.

- Fast switching: used at the VLA for high frequencies and will be used at CARMA and ALMA. Choose fast switching cycle time, \( t_{\text{cyc}} \), short enough to reduce \( \phi_{\text{rms}} \) to an acceptable level. Calibrate in the normal way.

- Paired array calibration: divide array into two separate arrays, one for observing the source, and another for observing a nearby calibrator.
  - Will not remove fluctuations caused by electronic phase noise
  - Only works for arrays with large numbers of antennas (e.g., VLA, ALMA)
Phase correction methods (continued):

- Radiometry: measure fluctuations in $T_{\text{B}}^{\text{atm}}$ with a radiometer, use these to derive changes in water vapor column ($w$) and convert this into a phase correction using

$$\phi_w = \frac{12.6\pi \times w}{\lambda}$$

Monitor: 22 GHz H$_2$O line (CARMA, VLA)
183 GHz H$_2$O line (CSO-JCMT, SMA, ALMA)
total power (IRAM, BIMA)

Results from VLA 22 GHz Water Vapor Radiometry

Baseline length = 2.5 km, sky cover 50-75%, forming cumulus, $n=22$ GHz
Baseline length = 6 km, sky clear, $n=43$ GHz
Examples of WVR phase correction:

22 GHz Water Line Monitor at OVRO, continued…

“Before” and “after” images from Woody, Carpenter, & Scoville 2000

Examples of WVR phase correction:

183 GHz Water Vapor Monitors at the CSO-JCMT and for ALMA

CSO-JCMT Phase fluctuations are reduced from 60° to 26° rms (Wiedner et al. 2001).

Pre-production ALMA Water Vapor Radiometer Operating in an SMA Antenna on Mauna Kea (January 19, 2006)
Antenna requirements

• **Pointing:** for a 10 m antenna operating at 350 GHz the primary beam is ~ 20″.
  
  a 3″ error ⇒ Δ(Gain) at pointing center = 5%
  
  Δ(Gain) at half power point = 22%
  
  ⇒ need pointing accurate to ~1″

• **Aperture efficiency, \( \eta \):** Ruze formula gives
  
  \[
  \eta = \exp(-[4\pi \sigma_{\text{rms}}/\lambda]^2)
  \]
  
  ⇒ for \( \eta = 80\% \) at 350 GHz, need a surface accuracy, \( \sigma_{\text{rms}} \), of 30\( \mu \text{m} \)

Antenna requirements, continued...

• **Baseline determination:** phase errors due to errors in the positions of the telescopes are given by
  
  \[
  \Delta \phi = \frac{2\pi \times \Delta b \times \Delta \theta}{\lambda}
  \]

  \( \Delta \theta = \) angular separation between source & calibrator

  \( \Delta b = \) baseline error

  \( \Delta \phi = \) angular separation between source and calibrator, can be > 20° in mm/sub-mm

  ⇒ to keep \( \Delta \phi < \Delta \theta \) need \( \Delta b < \lambda/2\pi \)

  e.g., for \( \lambda = 1.3 \text{ mm} \) need \( \Delta b < 0.2 \text{ mm} \)
Observing Practicalities

Do:
• Use shortest possible integration times given strength of calibrators
• Point often
• Use closest calibrator possible
• Include several amplitude check sources
• Bandpass calibrate often on strong source
• Always correct bandpass before gain calibration (phase slopes across wide band)
• Always correct phases before amplitude (prevent decorrelation)

Summary
• Atmospheric emission can dominate the system temperature
  – Calibration of $T_{\text{sys}}$ is different from that at cm wavelengths
• Tropospheric water vapor causes significant phase fluctuations
  – Need to calibrate more often than at cm wavelengths
  – Phase correction techniques are under development at all mm/sub-mm observatories around the world
  – Observing strategies should include measurements to quantify the effect of the phase fluctuations
• Instrumentation is more difficult at mm/sub-mm wavelengths
  – Observing strategies must include pointing measurements to avoid loss of sensitivity
  – Need to calibrate instrumental effects on timescales of 10s of mins, or more often when the temperature is changing rapidly

Recent advances in overcoming these challenges is what is making the next generation of mm/sub-mm arrays possible ⇒ the future is very bright
Practical aspects of observing at high frequencies with the VLA

Note: details may be found at http://www.aoc.nrao.edu/vla/html/highfreq/

• Observing strategy: depends on the strength of your source
  – Strong (≥ 0.1 Jy on the longest baseline for continuum observations, stronger for spectral line): can apply self-calibration, use short integration times; no need for fast switching
  – Weak: external phase calibrator needed, use short integration times and fast switching, especially in A & B configurations
  – If strong maser in bandpass: monitor the atmospheric phase fluctuations using the maser, and apply the derived phase corrections; use short integration times, calibrate the instrumental phase offsets between IFs every 30 mins or so

Practical aspects, continued…

• Referenced pointing: pointing errors can be a significant fraction of a beam at 43 GHz
  – Point on a nearby source at 8 GHz every 45-60 mins, more often when the az/el is changing rapidly. Pointing sources should be compact with $F_{8\text{GHz}} \geq 0.5$ Jy

• Calibrators at 22 and 43 GHz
  – Phase calibration: the spatial structure of water vapor in the troposphere requires that you find a phase calibrator < 3° from your source, if at all possible; for phase calibrators weaker than 0.5 Jy you will need a separate, stronger source to track amplitude variations
  – Absolute Flux calibrators: 3C48/3C138/3C147/3C286. All are extended, but there are good models available for 22 and 43 GHz
Practical aspects, continued…

• If you have to use fast switching
  – Quantify the effects of atmospheric phase fluctuations (both temporal and spatial) on the resolution and sensitivity of your observations by including measurements of a nearby point source with the same fast-switching settings: cycle time, distance to calibrator, strength of calibrator (weak/strong)
  – If you do not include such a “check source” the temporal (but not spatial) effects can be estimated by imaging your phase calibrator using a long averaging time in the calibration

• During the data reduction
  – Apply phase-only gain corrections first, to avoid de-correlation of amplitudes by the atmospheric phase fluctuations

The Atmospheric Phase Interferometer at the VLA

Accessible from http://www.vla.nrao.edu/astro/guides/api