CARMA SUMMER SCHOOL - July 2007

Introduction to Millimeter Wavelength Interferometry

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1. OUTLINE

• Day 1: Basic introduction to everything to get you going.

• Day 2-4:

— Radio antennas, arrays, aperture synthesis.

— Receivers and correlators.

— Observing techniques, scheduling

— Calibration, data inspection, imaging.

• Day 5: Data analysis, future developments, VLBI.

2. DAY 1: INTRODUCTION

2.1. Sources of Radio Emission

• Radio astronomy is an observational science. We make images of the radio intensity

$I(\mathbf{s}, \nu, polarization, time)$.

— Must design instruments to measure I with sufficient resolution in $\mathbf{s}, \nu, polarization, time$, and sensitivity to measure the source characteristics.

• What we actually measure is

$I' = I * B + Noise$

where B is the instrumental response, and $Noise$ is additive noise from the radio receivers and the atmosphere.

• Data reduction is the process of obtaining I from our measurements, I'

— Must calibrate, and deconvolve the instrumental response to otain I from I'.

• Data Analysis is interpretting what I means for astronomy.

• We need to know something about the sources of radio emission in order to design our telescopes and observations.

— Some of the 1st observations in a new waveband are usually surveys to find the distribution and nature of the sources.

— Later observations study the details of individual sources, or classes of sources.

• Source characteristics, instrumentation, and observing techniques together define a matched filter to possible observations with millimeter wavelength interferometers.

— Source selection: astronomy, frequency, size, brightness sensitivity

2.2. Millimeter wavelength Radio Sources

• Astronomy from Comets to Cosmology

— Emission mechanisms: thermal and non-thermal

• Thermal emission is in quasi-equilibrium with the physical temperature.

— Black body - planets, asteroids, quiet sun

— Dust - grey body: dust emisivity at millimeter wavelengths

— Molecular lines: rotational-vibrational transitions

—— Star formation regions, molecular clouds, stellar envelopes, YSO, evolved stars

—— Galactic structure: CO and isotopes, CS, HCN, HCO+....

—— Spiral and Dwarf galaxies: stucture, gas content, rotation curves

• Non-Thermal emission is not in equilibrium with the physical temperature.

— relativistic electrons & magnetic fields, synchrotron radiation.

—— SN remnants

—— radio galaxies: hot spots

—— active galaxies: nuclei

—— quasars, blazars, and seyfert galaxies.

—— Active sun: Solar flares.

—— Masers:

2.3. Atmospheric windows

• Atmospheric windows at optical, IR, and radio frequencies

— Earthbound astronomical observations are possible through atmospheric windows at optical, IR, and radio frequencies. (FIGURE 1)

— optical: $0.5 - 0.8\ 10^{-6}m$.

— IR: $1 - 1000\ 10^{-6}m$.

— Radio: $350\ 10^{-6} - 60m$.

— λ mm: $0.3mm - 1cm$. (30 to 1000 GHz)

• λ mm astronomy atmospheric windows are defined by O_2 and H_2O lines into a number of bands bounded by tropospheric absorption at high freq and ionospheric absorption at low freq. (FIGURE 2).

• Away from the strong absorption lines, the atmospheric absorption is strongly dependent on atmospheric water vapor which has a scale height of about 2 km.

— Observations at higher, drier sites have less absorption.

• CARMA site characteristics. (FIGURE 3).

— CARMA altitude 2196 m. Typical "good" conditions $\sim$ 4 mm precipitable water vapo

— best winter weather. $\sim$ 2 mm precipitable water vapor.

— c/f Mauna Kea at 4 km altitude often has less than 1 mm precipitable water vapor.

• CARMA observing bands.

— CARMA currently has receivers for 2 bands.

— 3mm band which can be tuned from $\sim$ 75 – 115 GHz

— 1mm band which can be tuned from $\sim$ 210 – 270 GHz

— In the 1mm band the effects of atmospheric absorption are more serious and the advatages of a high, dry site are more obvious.

3. Mon 10 - 11 am: APERTURE SYNTHESIS BASICS

3.1. Intensity Units.

• Intensity units: $I(\mathbf{s}, \nu, polarization, time)$ watts $m^{-2} str^{-1} Hz^{-1}$

— 1 Jansky = 10 $^{-26}$ watts $m^{-2} str^{-1} Hz^{-1}$

• Brightness Temperature

— for black body radiation

$I = 2\ h\ \nu^3/c^2\ 1/(e^{h\ \nu/kT}\ - 1)$

T is the **brightness temperature** of an equivalent black body radiator.

$h/k = 4.8\ [GHz/100]\ K$

For $h\ \nu/kT << 1$, $I = 2kT/\lambda^2\ [1 - h\ \nu/2kT + ...]$

• Rayleigh Jeans brightness temperature, $I = 2kT_b/\lambda^2$

• Flux density

$S = \Sigma\ I\ \delta\Omega$ integrated over an astronomical source.

3.2. Radio antennas: collecting area and resolution.

• **collecting area** $\sim D^2$

— we must build antennas to collect radio photons from astronomical sources.

— Radio astronomy: antennas are not used to transmit radio waves - as in radar astronomy - but it is often useful to think of antennas as transmitters.

— Amount of power we collect depends on the intensity, or brightness of radiation.

• Antenna has an effective collecting area $A(\mathbf{s})$

— for an elemental flat collector, the effective collecting area = $\delta A \times cos(\theta)$

• Power we collect, $P = \Sigma\ I(s)\ A(s)\ \delta\Omega\ \delta\nu\ \delta A$ watts.

• Aperture efficiency

— $effective\ collecting\ area = aperture\ efficiency \times collecting\ area$

— aperture illumination, the weighted sum of electic fields across the aperture

— feed legs, subreflector blockage,

• Surface accuracy

— E- fields are summed in phase, so aperture efficiency also depends on surface roughness.

— Ruze losses reduce effective collecting area by a factor $exp{-}(4\pi\ \sigma/\lambda)^2$

— Surface accuracy should be better than about $\lambda/16$ for reasonable aperture efficiency.

• **Resolution** $\sim \lambda/D$

• Voltage pattern

— antenna forms a weighted vector average of the E-field across the aperture

$V(\mathbf{s}) = \Sigma\ W(\mathbf{r})\ E(\mathbf{r})\ exp(2\pi\ i\ \mathbf{r}.\mathbf{s}/\lambda)\ \delta\mathbf{A}$

• Forward Gain of antenna add up the E-field across the aperture in phase in direction s_0.

$- > - > - > - > - > - > - > - > - >$ in direction s_0.

• In other directions a phase gradient across the aperture reduces the vector sum of the E-field across the aperture.

— It is this phase gradient which gives an antenna resolution in direction.

— for a uniformly weighted rectangular aperture diameter D,

$V(\theta) = sin(\pi\ D\ \theta/\lambda)/(\pi\ D\ \theta/\lambda)$

— for a uniformly weighted circular aperture diameter D,

$V(\theta) = J_1(\pi\ D\ \theta/\lambda)/(\pi\ D\ \theta/\lambda)$

3.3. Antenna Holography, Primary beam patterns

— The E-field distribution across the aperure is the Fourier transform of the Voltage pattern

$W(\mathbf{r})\ E(\mathbf{r}) = \Sigma\ V(\mathbf{s})\ exp(-2\pi\ i\ \mathbf{r}.\mathbf{s}/\lambda)\ \delta\mathbf{s}$

– we can measure the amplitude and phase of the voltage pattern by scanning one antenna across a strong radio source, or a radio transmitter, while using another antenna as a phase reference.

— The measured aperture distribution gives the illumination - the weighting of the E-field - across the aperture. The phase gives the surface error.

— Can clearly see the shadow of the feed legs and subreflector (FIGURE).

— Phase gradient across the aperture is due to pointing error.

— after removing the phase gradient and a quadratic term due to focus error, we measure a surface RMS $\sim$ 30 microns. These are very good antennas at millimeter wavelengths.

• Antenna power pattern

$P(\mathbf{s}) = V(\mathbf{s}) \times conjgV(\mathbf{s})$

— Primary beamwidth, $FWHM\!\sim 1.2\ \lambda/D$

— 6m antenna primary beam FWHM (arcmin): 2.40 at 80 GHz; 0.83 at 230 GHz.

— 10m antenna primary beam FWHM (arcmin): 1.34 at 80 GHz; 0.47 at 230 GHz.

3.4. Aperture Arrays

• **Antenna size, Resolution and confusion.**

• An antenna provides collecting area $\eta\ D^2$, and resolution $FWHM \sim 1.2\ \lambda/D$.

• Large antennas with enough sensitivity to detect more than one source within the beam are **confusion limited**.

— often have enough collecting area, but we need more resolution

— can separate the functions of resolution and collecting area by building several smaller antennas.

— Need to add up the E-field across this distributed aperture - preserving the relative phase of the wavefront across the array of antennas.

— This is quite difficult. Not only do the electronics at each antenna need to preserve phase, but also atmospheric phase shifts distort the wavefront and we must compensate for these effects.

— The problem is rather like adaptive optics. We must keep the path lengths within $\sim\ \lambda/16$ to make an accurate telescope.

• **Surface accuracy** (FIGURE)

• **cost of large antennas** $\sim D^2\ \lambda^{-0.7}(FIGURE)$

3.5. Need for high resolution

• Early radio astronomy discovered radiation from the Galaxy, with unresolved maxima.

• Peaks were named Cas A, Cygnus A, Sag A, Taurus A, Virgo A etc. Resolution ~ 7 degrees.

• Small optical telescope resolution, $\lambda/D \sim 5\ 10^{-5}/10cm \sim 1$ arcsec.

• Arecibo, $\lambda/D \sim 6cm/300m \sim 36$ arcsec.

• Bonn, $\lambda/D \sim 1cm/100m \sim 20$ arcsec.

• IRAM 30m, $\lambda/D \sim 3mm/30m \sim 20$ arcsec.

• Small scale structure in radio sources

— hot spots in radio galaxies (0.1 - 1 arcsec)

— filaments in crab nebula (1 arcsec)

— IR sources, OH and masers in star formation regions (1 - 10 arcsec)

— molecular cloud structure (0.1 arcsec - several degrees)

— spiral arm structure in galaxies (1 arcsec - a few degrees)

— quasars components with $\lambda/D \sim 3mm/3000km \sim 0.2$ milliarcsec.

• Conclude that we need to observe structures over a wide range of angular scales.

— single antennas can image structures larger than $\sim 20''$ at 3mm.

— need effective antenna diameters ~ 1 kilometer to image arcsec structures.

• Techniques for high resolution observations

— lunar occultations

— interplanetary scintilations

— Interferometers

3.6. Aperture Synthesis

• Consider aperture as set of sub-apertures each with its own E-field and phase.

Voltage response = $\Sigma\ E_i\ cos(\omega\ t + \phi_i)$

Power = $(\Sigma\ E_i\ cos(\omega\ t + \phi_i))^2 = \Sigma\ E_i^2 + \Sigma\ E_i\ E_j\ cos(\phi_i - \phi_j)$

— 1st term is sum of total powers from all sub-apertures

— 2nd term is cross products of all antenna pairs

– cross corelation and the relative phase contains information about wavefront across the aperture.

• If the source structure does not change, we can sample different pieces of the aperture at different times.

— must preserve the relative phase across the whole aperture to synthesize a large telescope.

• skeleton arrays, T-arrays contains all the relative spacings of square apperture.

— T-array has a different shaped beam because of different weights for each cross product, $E_i\ E_j$

• **Aperture synthesis imaging.**

• response of a 2-element interferometer to point source.

• Earth rotation Aperture synthesis

• coordinate systems: (u,v,w), u,v tracks for different arrays.

— East-west baseline

$u = b/\lambda \ cos \ h; v = b/\lambda \ sin \ h \ cos \ \delta$

• Mapping extended sources.

4. Monday 3-4 pm OBSERVING PROCEDURES

4.1. CARMA array characteristics. Primary beam and Synthesized beam

• Primary beamwidth, $FWHM \sim 1.2\ \lambda/D$

— 6m antenna primary beam FWHM (arcmin): 2.40 at 80 GHz; 0.83 at 230 GHz.

— 10m antenna primary beam FWHM (arcmin): 1.34 at 80 GHz; 0.47 at 230 GHz.

• Primary beam illuminates the sky brightness distribution.

— sources smaller than primary beam can be observed with a single pointing

— sources larger than the primary beam need multiple pointings

— we must allow for the different primary beam patterns of 10 and 6m antennas.

• Synthesized beamwidth, $FWHM \sim\ \lambda/D_{max}$

— Five array configurations giving resolution $\sim 0.1, 0.3, 0.7, 1.8, 3.2''$ at 230 GHz.

— Each antenna configuration is sensitive to a range of angular sizes, $\lambda/D_{max} - \lambda/D_{min}$

— Source structure larger than λ/D_{min} is "resolved out" by the interferometer.

— Source structure larger than λ/D_{min} needs single dish observations.

4.2. Sensitivity

bullet System Temperature

$T_{sys} = [T_{sky}\ (1 - e^{-\tau}) + T_{source} + T_{ant} + T_{Rx}] \times 2\ e^{\tau}$

Noise fluctuations $\Delta\ T = T_{sys}/\sqrt{2\ Bt}$ where B is the bandwidth and t is the integration time.

• Antenna Temperature

• Antenna efficiency = illumination efficiency x surface efficiency

— Jansky/Kelvin

• Flux sensitivity

• Brightness Sensitivity

4.3. Overview of Observation Preparations

4.4. Calibrations

– gain(t,f,p) - gain, bandpass, polarization, pointing.

• calibration intervals.

— interpolate the antenna gain amplitude and phase between observations of a known source.

V' = gain(t,f,p) x V + noise

• Observing scripts

• selecting suitable observations for the target sources.

– sensitivity

– source size; mosaicing.

• CARMA correlator capabilities; selecting a correlator settup.

• choosing calibrators for gain, bandpass, flux and pointing.

4-5 pm group discussion selecting student projects. (Douglas)

5-6 pm Intro to preparing CARMA observing scripts (Marc)

6 pm Dinner at the CARMA site.

Student projects observed on CARMA array overnight.

5. DAY 2: Tues 9-10 am DATA INSPECTION AND CALIBRATION

5.1. Overview of data reduction procedure

• introduction to MIRIAD data reduction package.

• basic Miriad data format: header, history, uvdata, gains, bandpass

• inspecting uvdata: uvindex, uvlist, uvplt, uvspec

• selecting uvdata: keywords select= and line=

• flagging bad data with uvflag

• antenna based calibration; selfcal and mfcal. gpplt. gains bandpass polcal

• rewriting edited data sets with uvaver, uvcat, uvcal

6. Day 2: Tues 10-11am IMAGING

• Review of basic math: brightness distribution is FT of visibility data.

• FFT requires convolving onto a grid; choosing the pixel and image size.

– mosaicing

• invert; choice of natural, uniform, robust weighting, effect on the synthesized beam

• deconvolution algorithms: clean, maxen, mossdi, mosmem, restor

11-12 am Laptop tutorial reduction and analysis of student data (Melvyn)

12 - 1 pm Lunch at the CARMA site

1-2 pm. CARMA hardware - I. Receivers and Calibration (Dick)

- introduce system block diagram; receiver, cal load, local osc, phaselocks, fiber, down-converter, correlator

- compute energy collected if observing 20 Jy source for 1 yr; would need to observe for $10^5 yrstoheat1dropofwaterby1C$

- receiver types:

- bolometers: not suitable for interferometry because they don't preserve phase

- HEMT amplifiers: not yet competitive at 1mm

- heterodyne rcvr: downconvert to lower freq in a nonlinear device

- SIS mixers: photon-assisted tunneling; not a Josephson effect

- cryogenics; closed-cycle refrigerators, compressors

- local oscillator: Gunn oscillator

- must be synchronized between all antennas; discuss in lecture 2

- both USB and LSB are downconverted to IF; can be separated with 90 degree phase switch; also defer to lecture 2

- combining LO and signal: mylar beamsplitter

- receiver and system temperature

- calibration:

- ideally, calibrate on loads outside the earth's atmosphere

- the chopper wheel method

- CARMA sensitivity calculator

2-3 pm. Demos on CARMA system

3-4 pm Planning observations and preparing observing scripts

4-5 pm Source selection and script preparation for student projects

5-6 pm students prepare observing scripts, analyze data.

Dinner at the CARMA site.

Student projects observed on CARMA array overnight.

DAY 3: Wed 11 July

9-10 am CALIBRATION (Melvyn)

- Calibrations - gain, bandpass, polarization, pointing.
- Antenna based calibrations: amplitude and phase closure
- Atmospheric and instrumental phase characteristics
- Tsys and Jy/K
- Pointing
- correlator calibration techniques.

10-12 am calibration and analysis of student projects (all)

12 - 1 pm Lunch at the CARMA site

1-2 pm special topics in mapping (Melvyn)

- the missing short spacing problem; importance for getting correct answers for spectral index, etc; negative sidelobes due to extended structure; filling in missing spacings with larger single dish or Ekers-Rots scheme

- mosaicing: setting up grid files, linear and nonlinear mosaicing schemes

- heterogeneous array imaging

2-3 pm Laptop tutorial data reduction and analysis of student data

3-4 pm CARMA software system (Marc)

– monitor system

– computers

– data flow

– archiving

4-6 pm students prepare observing scripts, and analyze data.

Dinner at the CARMA site.

Student projects observed on CARMA array overnight.

DAY 4: Thurs 12 July

9-12 am Student demos operating the telescope for Barvanis visit

12 - 1 pm Lunch at the CARMA site

1-2 pm CARMA hardware lecture 2 - local oscillators, phaselocks (Dick)

- review system block diagram, heterodyne system, local oscillator

- independent oscillators, 100 GHz, synchronized to fraction of one cycle over periods of hours (sounds hard)

- basic phaselock: mix with reference, low pass filter, generate correction voltage; keeps phase relationship fixed

- CARMA phaselock chain; synth, YIG, Gunn, 10 MHz, 50 MHz

- numerical example: synth = xxx, YIG = yyy, LO = zzz

- fiber system; linelength correction

- lobe rotation

- compute differential doppler shift due to earth's rotation for 100 GHz signal incident on 2 antennas 10-m apart: 0.24 Hz

- lobe rotators

- interferometer response for a double sideband conversion system

- need to offset freq of 1st LO as well as insert delays; can be understood as removing differential doppler shift due to earth's rotation

- phaselocks; the LO system

- cable length measurement system

- phase switching; Walsh functions

- sideband separation by phase switching; note that only signals common to an antenna pair can be separated; noise appears in both sidebands

- fiber optic hardware

- converting to flux density; aperture efficiency; source flux table

2-3 pm calibration and analysis of student projects (all)

. analysis of student data

. students prepare scripts, analyze data.

Dinner at the CARMA site.

. Student projects observed on CARMA array overnight.

DAY 5: Fri 13 July

9-10 am CARMA hardware lecture 3 - correlator; software control (James, DaveW)

- review system block diagram

. Antennas, beam patterns, etc. (James)

. Correlator (DaveW)

- correlator is detector and spectrometer for the array

- XF vs FX

- delays, 2nd LO lobe rotation, sideband separation

- correlator modes

- FPGA's

- noise source

- basic architecture of computer control system, CAN nodes

• Observer's everyday responsibilities (Douglas)

- creating and running the master observing script

- data quality reports

- data archiving and disk management

• polarization measurements (Melvyn)

- interferometer response LR, RL, etc in terms of Stokes parameters

- Walsh function polarization switching schemes

- instrumental leakage terms and how to solve for them

- mapping procedures

• troubleshooting (Dick, Marc)

- generator, air conditioning

- the anticollision system

- cryogenics

- rcvr tuning

- computer hangups

- clocks; resetting the time

- rebooting procedure:

• moving the antennas and calibrating a new array configuration (DaveW, Marc)

- changing IFLO connections in the pits

- running tilt, shimming the antennas

- entering new station coordinates

- finding pointing offsets.

- finding the delay centers

- TV and radio pointing

- finding a baseline

- entering new pointing offsets or baselines

12 - 1 pm Lunch at the CARMA site

• atmospheric phase fluctuations and what we plan to do about them

- like floppy backup structure on a big telescope; causes decorrelation, ruins aperture efficiency

- show results at long and short baselines

- phase structure function

- calibrating by rapid switching; put calibrator in grid file; observe weak nearby calibrator often, strong faraway calibrator less often

- calibrating by observing the total power; need for extreme gain stability; typical results

CARMA future plans (Douglas)

- A-configuration

- Carlstrom's 1 cm system

- wideband receivers

- 23-antenna CARMA array

. analysis of student data