Radio Astronomy

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Radio astronomy
Atmospheric Window

Gamma Rays, X-Rays and Ultraviolet Light blocked by the upper atmosphere (best observed from space).

Visible Light observable from Earth, with some atmospheric distortion.

Most of the Infrared spectrum absorbed by atmospheric gasses (best observed from space).

Radio Waves observable from Earth.

Long-wavelength Radio Waves blocked.
Centimeter radio astronomy

Effelsberg 100m telescope (Germany)

Green Bank 100m telescope
(National Radio Astronomy Observatory; West Virginia)
Centimeter radio astronomy

HI 21cm line emission traces the distribution of atomic hydrogen.
Centimeter radio astronomy

Thermal Bremsstrahlung emission from HII regions

Fig. 2.4. Open circles mark observations of the integrated flux from the HII region W3 Main. Solid line: bremsstrahlung emission; dashed line: thermal emission from dust. (Malkamäki et al., 1979.)
Centimeter radio astronomy

Synchrotron radiation

M87 -- galaxy at center of Virgo cluster of galaxies

Optical

Radio (20cm obs. with the Very Large Array)

Formation of extragalactic jets from black hole accretion disk

Radio (20cm obs. with the Very Large Array)
Millimeter radio astronomy

IRAM 30m telescope (Spain)

Millimeter wavelength

Nobeyama 45m telescope (Japan)

Large Millimeter Telescope (Mexico, UMASS)
Millimeter radio astronomy

Molecular line emissions (CO, HCN, CS, NH3, many mores) trace dense molecular gas where stars form.
Submillimeter radio astronomy

James Clerk Maxwell telescope - 15m (Hawaii, UK)

Sub-Millimeter wavelength

Caltech Submillimeter Observatory - 10m (Hawaii)

Atacama Submillimeter Telescope Experiment - 10m (Chile, Japan)

Atacama Pathfinder Experiment - 10m (Chile, Europe)
Submillimeter radio astronomy

**Molecular Evolution: Hot Cores**

Have to be able to separate flowers from the weeds

Formic acid  Formic acid
Methyl      Dimethyl
formate     ether

SGR B2(N), ALMA Band 6 mixer at SMT
Size of telescope

Snow sweep at Nobeyama 45m telescope
Antennas
Antenna response function

- Resolution \( \sim \frac{\lambda}{D} \)
- Main beam & sidelobes
  - depends on surface accuracy -- sidelobes could be very high
Detectors/Receivers
suppose we observed a 10 Jy calibrator with CARMA for 1 year, 24 hrs/day – how much energy would we collect?

\[ E = \frac{1}{2} S \eta A \Delta v \ t \]

- \( S = \) source flux density = 10 Jy = 10 \( \times \) 10\(^{-26}\) watts m\(^{-2}\) Hz\(^{-1}\)
- the factor of \( \frac{1}{2} \) arises because we are sensitive to 1 polarization
- \( \eta = \) aperture efficiency \( \sim \) 0.60
- \( A = \) geometrical collecting area = 6 \( \times \) 85 m\(^2\) + 9 \( \times \) 29 m\(^2\) = 771 m\(^2\)
- \( \Delta v = \) instantaneous bandwidth = 2 \( \times \) 1.5 GHz = 3 \( \times \) 10\(^{9}\) Hz
- \( t = \) 1 year = 3 \( \times \) 10\(^{7}\) sec

Result: \( E = 2.1 \times 10^{-6} \) joules

1 calorie = 4.2 joules heats 1 cm\(^3\) (20 drops?) of water by 1 C

\( \Rightarrow \) must observe for 10\(^5\) years to heat 1 drop of water by 1 C
detectors for radio astronomy

1. bolometers
   • absorbed photon increases temperature, changes resistance
   • phase of incoming signal is lost – unsuitable for aperture synthesis
   • operate at ~0.3 K

2. HEMT (High Electron Mobility Transistor) amplifiers
   • preferred below 50 GHz, good up to 115 GHz
   • operate at ~20 K

3. SIS mixers
   • mixes incoming signal with local oscillator to convert it to a lower frequency where it is amplified (by HEMT)
   • preferred for 100+ GHz
   • operate at ~4 K
Bolometer

Welcome to the SHARC-II Homepage

Bolocam
High Electron Mobility Transistor (HEMT) amplifier

- gate voltage controls width of channel, modulates current from source to drain
- to operate at 100 GHz, charge carriers must transit under the gate in \( \sim \frac{1}{10} \times \frac{1}{100} \) GHz \( \sim 10^{-12} \) sec
- must travel 0.1 um in \( 10^{-12} \) sec \( \sim 100 \) km s\(^{-1}\)

in HEMT (but not in FET), current travels through very pure layer \( \rightarrow \) no scattering by impurities

\[ 0.1 \text{ µm} = 1000 \text{ Å} \]
heterodyne receiver

- converts incoming signal to a lower frequency where it can be amplified

- how? ‘mix’ the incoming signal with a strong ‘local oscillator’ in a nonlinear device to generate an ‘intermediate frequency (IF)’

- essentially the local oscillator is a clock that samples the incoming signal periodically

- example of nonlinear device: a diode
mixer – a nonlinear device

• linear device (superposition principle):
  \[ \omega_1, \omega_2 \rightarrow \text{linear device} \rightarrow \omega_1, \omega_2 \]

• nonlinear device:
  \[ \omega_1, \omega_2 \rightarrow \text{nonlinear device} \rightarrow \omega_1, \omega_2, \omega_1+\omega_2, \omega_1-\omega_2, 2\omega_1+\omega_2, \ldots \]

• diode is an example of a nonlinear device:
  \[ I = I_0(e^{\alpha V} - 1) \sim I_0(\alpha V + \frac{1}{2} \alpha^2 V^2 + \ldots) \]
  \[ V = A \cos \omega_1 t + B \cos \omega_2 t \]
  \[ V^2 = A^2 \cos^2 \omega_1 t + B^2 \cos^2 \omega_2 t + 2AB \cos \omega_1 t \cos \omega_2 t + \ldots \]
  \[ = \ldots + AB \cos(\omega_1 + \omega_2) t + AB \cos(\omega_1 - \omega_2) t + \ldots \]

• note: amplitude at frequency \( \omega_1-\omega_2 \) is linearly related to amplitudes \( A \) and \( B \)
waveforms in a heterodyne receiver

local oscillator (LO)

‘signal’ – just random noise for radio astronomy

LO + signal (voltage in diode)

current through diode

IF after low pass filtering
DSB (double sideband) downconversion

- upper and lower sidebands are folded together in the i.f. – e.g., HCN at 88.6 and CS at 98.0 both appear at 4.7 GHz in the i.f. – but can be separated by phase switching (lecture 3)
- LO tunable from 85-114 GHz (3mm) and 215-270 GHz (1mm)
- SZA 3mm receivers amplify first, then downconvert, hence are sensitive just to the USB
SIS (Superconductor-Insulator-Superconductor) mixers

AIO insulating layer, 10Å thick

Nb

SIS junction cross section

photographs of SIS device with matching circuitry
SIS devices have extremely sharp nonlinearity

normal metal: tunneling barrier looks like a resistor

superconductor; no single particle current until $V >$ energy gap; produces sharp nonlinearity

photon-assisted tunneling across barrier (1 meV = $h\nu$ for $\nu = 242$ GHz)
closed cycle 4 K refrigerators

- similar to Carnot cycle:
  - compress helium to ~280 psi, air-cool to remove heat of compression
  - in the ‘cold head,’ expand to ~60 psi to provide refrigeration

- except: use heat exchangers (bronze screens, Pb spheres, Er$_3$Ni spheres) in the cold head to reduce the pressure difference that is needed

- above the critical pressure of ~30 psi, 4 K helium does not separate into gas and liquid phases – it is a dense fluid
dewar design

to minimize heat load on cryocooler:

- evacuate to minimize gas conduction; pressure $< 10^{-9}$ atm, $\sim$ a few $\times 10^{10}$ cm$^{-3}$

- use low thermal conductivity materials; a copper wire 24” long x .022” diam would conduct 50 mW from room temp to 4 K

- copper shields reduce loading from room temperature radiation (300 mW/sq in for a 300 K black body)
Calibration
receiver calibration

- amplifies signal, preserving its phase
- measures power (no phase)

\[ V_{out} = G (T_{in} + T_{rcvr}) \] (volts or counts)

- black body emitters are the most convenient calibration sources (K instead of ergs cm\(^{-2}\) s\(^{-1}\) Hz\(^{-1}\)); power collected in 1 polarization by horn with aperture \(D\) is:

\[
P_{in} = \frac{1}{2} B A \Delta \Omega \Delta \nu = \frac{1}{2} \frac{2kT}{\lambda^2} D^2 \frac{\lambda^2}{D^2} \Delta \nu = kT\Delta \nu
\]

- \(T_{rcvr}\) is the noise generated by the receiver, referred to the input of the receiver
receiver calibration

- in the lab, use black body emitters at room temperature (295 K) and immersed in LN$_2$ (77K)
- solve for gain G and receiver temperature Trcvr
- $T_{sys} = T_{in} + Trcvr$ is the total noise power from the receiver, calibrated as an input temperature
receiver calibration

- lossy layer (e.g. dewar window) in front of the receiver lowers the gain, increases $T_{rcvr}$
- e.g., if dewar window has transmission $t$, $rcvr$ noise temperature measured outside the dewar is

$$T_{rcvr}' = \frac{T_{rcvr} + T_W (1 - t)}{t}$$

- so if $t = 0.95$, $T_W = 295$ K, $T_{rcvr} = 40$ K, $T_{rcvr}' = 57.6$ K
calibration for astronomical objects

- ideally, calibrate with loads outside the atmosphere
- unfurl a 200 x 200 m load from the space station?
- nature provides $T_1 = \text{CMB}$
- effective temperature of $T_2$ at the input to the receiver:

$$T'_2 = T_2 e^{-\tau} + T_{\text{atm}} (1 - e^{-\tau})$$

so if $T_2 = T_{\text{amb}}$, it doesn’t matter where we position the load along the line of sight – it can be right in front of the receiver!
ideal calibration

\[
\text{gain} = \frac{(V_2-V_1)}{(T_2-T_1)}
\]

chipper wheel calibration

\[
\text{gain} = \frac{(V_{amb}-V_{sky})}{(T_{cal}-T_{cmb})}
\]
**typical system temperatures at CARMA**

<table>
<thead>
<tr>
<th>freq</th>
<th>mmH2O</th>
<th>tau</th>
<th>Trcvr</th>
<th>Ttel</th>
<th>Tsky</th>
<th>Tsyst SSB</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
<td>2</td>
<td>.06</td>
<td>30</td>
<td>10</td>
<td>14</td>
<td>114</td>
</tr>
<tr>
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<td>.13</td>
<td>30</td>
<td>10</td>
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<td>.14</td>
<td>40</td>
<td>10</td>
<td>34</td>
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</tr>
<tr>
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<td>10</td>
<td>.66</td>
<td>40</td>
<td>10</td>
<td>129</td>
<td>808</td>
</tr>
</tbody>
</table>

\[ T_{sys \ (SSB)} = 2 \times (Trcvr + T_{tel} + T_{sky}) \exp(tau), \] where \( Trcvr \) is the DSB receiver temperature measured in the lab, \( T_{tel} \) is emission from the telescope, and \( T_{sky} \) is the effective temperature of the atmosphere at zenith

computed with program obstau
fluctuations in $T_{\text{sys}}$

- remember that $T_{\text{sys}}$ is the AVERAGE noise power
- fluctuations in $T_{\text{sys}}$:
  \[
  \Delta T = \frac{T_{\text{sys}}}{\sqrt{\Delta \nu \tau}}
  \]
- so fluctuations are greater on ambient load or the Sun than on cold sky
Interferometer
Old Green Bank 100m telescope

Angular resolution: $\lambda/D \sim 60''$ in 3cm
Arecibo 300m telescope
Radio interferometer
Radio interferometer

Very Large Array (VLA) (New Mexico)

Centimeter wavelength

Westerbork Synthesis Radio telescope (Netherlands)
Radio interferometer

CARMA Interferometer (California)
Angular resolution: $\lambda/B$
$\sim 1''$ for 1km baseline in 3mm

Sub-Millimeter wavelength

Submillimeter Array (Hawaii)

Millimeter wavelength

Plateau de Bure interferometer (France)
Radio interferometer

Case of 2 elements
Interferometer

\[ F = \sin(2\pi vt) \sin(2\pi v(t - \tau)) \]
\[ \approx \cos(2\pi v\tau) = \cos\left(\frac{2\pi Dl}{\lambda}\right) \]
Interferometer

\[ F = \sin(2\pi vt) \sin(2\pi v(t - \tau)) \]
\[ \approx \cos(2\pi v\tau) = \cos\left(\frac{2\pi DL}{\lambda}\right) \]

Image = \( \sum_{D} A_{D} \cos\left(\frac{2\pi DL}{\lambda}\right) \)
$F = \sin(2\pi vt) \sin(2\pi v(t - \tau))$

$\approx \cos(2\pi v\tau) = \cos\left(\frac{2\pi Dl}{\lambda}\right)$

$\text{Image} = \sum_D A_D \cos\left(\frac{2\pi Dl}{\lambda}\right)$
Synthesis imaging (2 antennas)

Earth (rotating)

Look down the earth from your favorite target

Data coverage in Fourier space
Synthesis imaging (6 antennas)

Earth (rotating)

Data coverage in Fourier space

# of ant pairs = $N(N+1)/2$

N=6 → 15 pairs
Synthesis imaging (15 antennas)

Earth (rotating)

Data coverage in Fourier space

CARMA array

\# of ant pairs = \frac{N(N+1)}{2}

\[ N=15 \quad \rightarrow \quad 105 \text{ pairs!} \]
Configuration Change
B-configuration
E-configuration
Fourier Coverage

Data coverage in Fourier space

CARMA array

Hole!
Synthesis imaging + Single Dish

Data coverage in Fourier space

CARMA array

CARMA + Nobeyama
Single Dish Map of Molecular Gas

Nobeyama 45m telescope

resolution ~20"
Interferometer + Single-Dish Combined

resolution ~4"

resolution ~20"
Non-redundant masking in optical
Near Future
Stony Brook radio interferometer

- Satellite dish antenna
- Receiver
- Flat mirrors
- Elevation drive
- Slidable
- Azimuthal drive

Solar radiation

- Satellite dish antenna
- Flat mirrors
- Flat mirror

Baseline
Future: Space VLBI
Future: ALMA

Altitude ~5000m
Early operation 2011