Heterodyne Receivers

Introduction to heterodyne receivers for cm and mm-wave radioastronomy

6th 30 m Summer School

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Geometry of the IRAM 30 m telescope optics

Paraboloidal main reflector:
  diameter \( D = 30 \text{ m} \)
  focal length \( f = 10.5 \text{ m} \)
  focal ratio \( f/D = 0.35 \)

Hyperboloidal subreflector:
  diameter \( d = 2.0 \text{ m} \)
  eccentricity \( e = 1.0746 \)

Nasmyth reflectors (flat):
  size \( d_n = 1.0 \times 0.7 \text{ m} \)

Cassegrain magnification factor: \( M = 27.8 \)

Effective focal ratio of Nasmyth: \( f_e/D = 9.73 \)

Distance from prime to secondary focus: \( f_c = 19.79 \text{ m} \)
Types of receivers

Bolometers $\rightarrow$ Incoherent
- Phase information is lost – used on single-dish antennas
- Large bandwidths and high sensitivities
- Total power detection, spectral information is lost
- Used for the mm and sub-mm region of the spectrum

Heterodyne Receivers $\rightarrow$ Coherent
- Frequency conversion using a non-linear device (mixer)
- Phase information is preserved – used in single-dish telescopes and interferometers
- Spectral information is preserved $\rightarrow$ very high spectral resolution
- Used from the cm to the sub-mm region of the spectrum
Heterodyne frequency (down)-conversion by mixing

- Signal (RF), $\nu_{RF}$
- Local Oscillator (LO), $\nu_{LO}$
- Intermediate (beat) frequency (IF), $\nu_{IF}$

Non-linear device (mixer)

RF signal at frequency $\nu_{RF}$

LO at frequency $\nu_{LO}$

IF at frequency $\nu_{IF} \ll \nu_{RF}, \nu_{LO}$

$\nu_{IF} = |\nu_{RF} - \nu_{LO}|$

DSB mixer: Two sidebands, LSB and USB

DSB=Double Side Band
LSB=Lower Side Band
USB=Upper Side Band
The main roles of a receiver are to collect efficiently the astronomical signal (RF) concentrated by the antenna near its focal point and to amplify and convert it, by adding as little noise as possible, to a frequency range (IF) and power level suitable for further processing by spectrometers or continuum detectors.

**Antenna**
- Very weak RF input signals
- Freq. $\approx 10^{11}$ Hz (100 GHz)

**Heterodyne Receiver**
- Frequency down-conversion
- High gain
- Low added noise

**Spectrometer**
- IF signal transport (coaxial cables)
- Power level of order few mW; Freq. $\approx$ few GHz
IRAM 30 m telescope receiver cabin
Active component technologies for heterodyne receivers

HEMT amplifiers
- Direct amplification
- $\rightarrow$ 115 GHz on telescopes; beyond 200 GHz in the lab
- Instantaneous b/w $\sim$ 30%

SIS mixers
- Heterodyne mixing
- $\rightarrow$ 700GHz (Nb); >1THz (NbTiN)
- Instantaneous b/w 2 x 8 GHz

HEB mixers
- Heterodyne mixing
- $\rightarrow$ Several THz
- Instantaneous b/w $\sim$ 4 GHz
Synoptic diagram of heterodyne receivers

cm-wave receiver: first amplify, then down-convert
ν_{RF} < 115 GHz

mm and submm-wave receiver: first down-convert, then amplify
80 GHz < ν_{RF} < 1.2 THz

Noise critical!
SIS mixer requires cooling at $\approx 4$ K; HEMT amplifier can operate at $15$ K.

The active devices are located inside a cryostat:

- **LSB:** 228-236 GHz
- **LO:** 240 GHz
- **IF:** 4-12 GHz
SIS mixer require cooling at $\approx 4$ K; HEMT amplifier can operate at $15$ K. The active devices are located inside a cryostat.
Noise

- All parts of receiver contribute noise
  - Passive (transmission lines, etc.)
  - Active (Mixers, Amplifiers, etc.)
- Millimeter & Submillimeter wavelengths – Usual to characterize noise of devices by **Noise Temperature**

\[ \text{BB at } 0 \text{ K} \rightarrow \text{Device Noise Temperature } T_N \rightarrow \text{Equivalent} \rightarrow \text{BB at } T_N \text{ K} \rightarrow \text{Noiseless Device} \]

A noisy device acts as if its input is connected to a (virtual) blackbody at a temperature which is the same as the noise temperature of the device – usually shown as in the right figure.
For example, a measure with input blackbody at 290 K (room temperature) and 77K (LN2) gives $Y = 3 \Rightarrow T_N \approx 30$ K

Blackbodies are available (Eccosorb) at mm and sub-mm wavelengths

Advantages of Y-factor method:
• Requires no knowledge of $G$ and bandwidth
• Only linear detectors required
• Fast and reasonably accurate
Irrespective of the technical progress, the system noise temperature has a fundamental quantum limit:

\[ T_Q = \frac{h \nu}{k_B} \approx 5 \text{ K} \left( \nu/100 \text{ GHz} \right) \]

Receivers across the mm-wave domain achieve noise performances of only few times the quantum limit.
Noise temperature of a cascade of stages

For a cascade of stages with gain $G_i \gg 1$, the noise of the first stage $T_{N1}$ dominates the overall noise temperature.

If the first stage has loss ($G_i = 1/L_i < 1$) or little gain, the noise temperature of the subsequent stage can become important. This is the case of SIS mixers, whose gain is of order 1 or lower.

Noise temperature of an attenuator

... with attenuation $L$ and physical temperature $T_{\text{phys}}$:

$$T_N = T_{\text{phys}} (L-1)$$

Cooling the low loss optics and the waveguide components (feed, OMT) in front of the active devices reduces the receiver noise temperature.
Feed Horns

A scalar, or conical corrugated feed-horn, generates an electric field with almost perfect Gaussian distribution at its aperture. 98% of the power radiated (or received) by the conical corrugated feed is in the fundamental Gaussian mode.

Physical dimensions scale $\approx$ with wavelength

A relay optics is typically used to image the horn aperture on the telescope’s aperture. This fulfils the condition of frequency-independent illumination.
HEMT low noise amplifiers (LNA)

Risultati @ 20 K Packaged Cryo cooled

Gain [dB], Te [K.]

Freq. [GHz]

Discrete transistors

MMIC

3.2 mm
Two kinds of particles exist in a superconductor:

- Quasiparticles
- Cooper pairs

The tunneling of quasiparticles through the insulating barrier is responsible of SIS mixer operation. The effect is named photon-assisted tunneling.

The tunneling of Cooper pairs is responsible of Josephson currents and prevents the good functioning of the SIS mixers. Josephson currents are suppressed using a magnetic field.
**SIS mixers**

![Image of SIS mixer micrograph]

- **V_{gap} = 2\Delta/e**
- **\alpha = e v_{LO} / h v_{LO} = 1**
- **v_{LO} = 300 GHz**
- **v_{LO} = h v_{LO} / e = 1.24 mV**

**Graphs:***

- **Current \(I_0\) vs. Voltage \(V_0\) when \(V_{gap} = 2\Delta/e\)**
- **Density of states**

**Notes:**
- **Etched counter electrode**
- **SiO₂ sputtered**
- **Nb ground plane**

**Substrate (fused quartz):**

- **Caesar**
- **Date: 27 Sep 2004**
- **Time: 11:24:51**
- **File Name: RA03_0/1f**
Waveguide SIS mixers

80-116 GHz mixer

- SIS junctions located on a quartz substrate
- Waveguide probe couples the signal into the SIS junction(s), usually through microstrip and/or coplanar waveguides
- Superconducting Nb transmission lines

ALMA Band 7 mixer chip
275-373 GHz
Double Side Band (DSB): Both the USB and the LSB are converted and superimposed on each other at the IF.

Single Side Band (SSB): Either the USB or the LSB is down-converted to IF, i.e. one sideband is rejected. Sideband rejection can be achieved through:
- Sideband Filter
- Mechanically tunable backshort

Sideband Separating (2SB):
Both sidebands converted to two different IF outputs.

SIS mixers installed on IRAM telescopes are SSB and 2SB (no DSB)
2SB SIS Mixer: Principle of Operation
Why image rejection, i.e. SSB or 2SBmixer?

Eliminate this and reduce $T_{SYS, SSB}$

$$T_{SYS, SSB} = \left[ G_S^{-1} \cdot (T_{out} + T_{IF}) + T_{in} + T_{in} \cdot \frac{G_I}{G_S} \right] \cdot \frac{e^{A\cdot\tau}}{F_{eff}}$$

- $G_S, G_I$: Signal and Image Gain;
- $T_{out}$: Mixer noise temperature referred to its output;
- $T_{IF}$: Noise temperature of the IF amplifier;
- $e^{-A\tau}$: Atmospheric transmission factor;
- $F_{eff}$: Forward efficiency.

$T_{out}$ includes contributions from atmosphere, spillover, and optics.
SSB:
- Lower spectral confusion;
- Rejects atmospheric noise in the image sideband;

DSB:
- Twice as much as spectral data (if care is taken);
- Twice as much continuum power;
- Receiver has fewer components - less complexity;

2SB:
- Best of both worlds! Requires twice the processing capabilities of SSB and DSB schemes (two IF bands);
Wire grid

E-field perpendicular to wires so incident field transmitted.

Wire grid polariser

E-field parallel to wires so incident field reflected.

OMT (Orthomode Transducer)

Modified Turnstile junction

E-plane power combiner

180° E-plane bend

Pol 2

Pol 1
Electromagnetic modeling softwares

• A number of powerful commercial electromagnetic softwares are available

• They allow accurate modeling of 2D (planar circuitry) and 3D (waveguide and antenna structures). Fast computers are required to perform optimizations on a large parameter space

• Mechanical modeling CADs have also a primary importance for the receiver designer
**EMIR: Multi-band mm-wave SIS receiver for IRAM 30 m telescope**

<table>
<thead>
<tr>
<th>Band#</th>
<th>RF coverage (GHz)</th>
<th>Mixing scheme</th>
<th>IF config. Pol× Sb× BW(GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>83 – 117</td>
<td>2SB</td>
<td>2 × 2 × 8</td>
</tr>
<tr>
<td>B2</td>
<td>129 – 174</td>
<td>SSB</td>
<td>2 × 1 × 4</td>
</tr>
<tr>
<td>B3</td>
<td>200 – 267</td>
<td>SSB</td>
<td>2 × 1 × 4 &lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>B4</td>
<td>260 – 360</td>
<td>2SB</td>
<td>2 × 2 × 4 &lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

**Diagram:**
- Warm IF amplifiers
- Cryocooler
- Monitor and Bias Modules
- Local Oscillators
EMIR Band 3 (200-267 GHz) cold optics module
Receiver performance in the four EMIR RF bands
Typical receiver requirements

• RF band (typically $\Delta v_{RF}/\nu_{RF} \approx 30\text{-}40\%$)
• IF band: $(\Delta v_{IF}/\nu_{RF} \approx 15\%$ for SIS, $\approx 30\%$ for HEMT)
• LO tuning range (from RF and IF) and LO type (Gunn, YIG+AMC, photonic, or QCL)
• Dual-polarization (linear or circular) with OMTs or quasi-optics wire grids.
• Multiband operation (observe two RF bands simultaneously, frequency diplexing)
• Optimum optical coupling to the antenna
• Sensitivity: receiver and system noise temperatures referred to the input; cal. load
• Receiver technology: HEMT, SIS (DSB, SSB or 2SB)
• Polarization purity
• Stability: total power stability expressed as Allan deviation
• Linearity
• Freedom from spurious response (suppression of image sideband)
• Power level (in dBm/MHz) at the IF receiver output
• IF passband flatness (minimum slope and ripple)
• Full remote control of all functions (bias, temperatures, etc.)
• No cryogenic fluid refills: closed cycle cryocooler
• Screened from external RFI environment and free from self-generating RFI
### ALMA Band 7 receiver cartridge and specifications

<table>
<thead>
<tr>
<th>Property</th>
<th>Required Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mixing scheme</strong></td>
<td>Linearly polarized Sideband Separating Mixer</td>
</tr>
<tr>
<td><strong>RF port frequency range</strong></td>
<td>275-373 GHz</td>
</tr>
<tr>
<td><strong>LO port frequency range</strong></td>
<td>283-365 GHz</td>
</tr>
<tr>
<td><strong>IF bandwidth</strong></td>
<td>4-8 GHz 2SB</td>
</tr>
<tr>
<td><strong>SSB receiver noise</strong></td>
<td>&lt;147K over 80% of the RF frequency band</td>
</tr>
<tr>
<td></td>
<td>&lt;221K at any RF frequency</td>
</tr>
<tr>
<td></td>
<td>&lt;300K in 370-373GHz extended band</td>
</tr>
<tr>
<td><strong>Image band suppression</strong></td>
<td>&gt;10dB, with allowance: no more than 10% &lt;10dB</td>
</tr>
<tr>
<td></td>
<td>no more than 1% &lt;7dB</td>
</tr>
<tr>
<td></td>
<td>Globally over all LO settings</td>
</tr>
<tr>
<td><strong>Total IF output power integrated over 4-8GHz</strong></td>
<td>-32dBm...-22dBm</td>
</tr>
<tr>
<td><strong>IF power variations across 4-8GHz</strong></td>
<td>5dB p-p over any 2GHz window</td>
</tr>
<tr>
<td></td>
<td>7dB p-p full band</td>
</tr>
<tr>
<td><strong>Large signal gain compression @ 300K input</strong></td>
<td>&lt;5%</td>
</tr>
<tr>
<td><strong>Amplitude stability: Allan variance 0.05s...100...300s</strong></td>
<td>4.0E-7, 3.0E-6, respectively</td>
</tr>
<tr>
<td><strong>Signal path phase stability</strong></td>
<td>7.1fs over 300s</td>
</tr>
<tr>
<td><strong>Aperture efficiency</strong></td>
<td>&gt;80%</td>
</tr>
<tr>
<td><strong>Polarization efficiency</strong></td>
<td>99.5% polarization coupling, (equiv&lt;–23dB)</td>
</tr>
<tr>
<td><strong>Focus efficiency</strong></td>
<td>&gt;98%</td>
</tr>
<tr>
<td><strong>Polarization alignment accuracy</strong></td>
<td>&lt; 2°</td>
</tr>
<tr>
<td><strong>Beam squint</strong></td>
<td>1/10 FWHM</td>
</tr>
<tr>
<td><strong>Stabilization time from non-operational</strong></td>
<td>&lt; 15 min</td>
</tr>
<tr>
<td><strong>Stabilization time from stand by mode</strong></td>
<td>&lt; 1.5 s</td>
</tr>
<tr>
<td><strong>Added cartridge mass</strong></td>
<td>&lt; 2.38kg on cold stages</td>
</tr>
</tbody>
</table>
Summary of HEMT, SIS, HEB performance

$T_Q = 4h
\nu/k_B$
Array Receivers

Why heterodyne array receivers?

- Single pixel SIS receivers are approaching quantum limit (esp. at lower frequencies). Remaining limit is atmospheric
- Mapping Speed substantially increased with arrays
- N fold increase in time for an N-element array, also telescope motion is reduced
- Best use of good weather conditions
- Mapping consistency – reduced systematic effects due to pointing offsets, relative calibration

Cons & Challenges

- Complicated
- Expensive
- Tight packing
- Cryogenic cooling capacity
- Delivery of LO Power
Heterodyne Array Receivers for the 30 m telescope

HERA: 3x3 dual-pol. SIS heterodyne receiver array for 1.3 mm band
In operation

230 GHz Continuum on URANUS

Future 5x5 dual-pol SIS heterodyne receiver arrays for the 3mm band

FOV ~5.7’’

2 x HPBW = 48” at 100GHz
64 m diameter SRT (Sardinia Radio Telescope) to be inaugurated very soon
K-band (18-26 GHz) Multibeam Rx for the Gregorian SRT Focus

- 7 feeds in hexagonal configuration with a central feed;
- 14 x 2 GHz IF outputs right and left polarization;
- Feeds and LNAs cooled at 20 K;
- Mechanical de-rotator to track the parallactic angle;

Multibeam installed at the secondary focus of the 32 m Medicina antenna for test
Thanks for your attention