Heterodyne Receivers

Introduction to heterodyne receivers for mm-wave radio astronomy

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Outline

Introduction to Heterodyne receiver and technologies

Noise temperature

Transmission lines

Feeds and Gaussian beam propagation

Low Noise Amplifiers (LNAs)

SIS mixers

Polarization splitters

Vacuum windows and IR filters

EMIR receiver
   - Cryogenic system
   - Local Oscillator system
   - Cryogenic modules

ALMA receiver

Array receivers

Part 1

Part 2
Geometry of the IRAM 30 m telescope optics

Paraboloidal main reflector:
- diameter: $D = 30$ m
- focal length: $f = 10.5$ m
- focal ratio: $f/D = 0.35$

Hyperboloidal subreflector:
- diameter: $d = 2.0$ m
- eccentricity: $e = 1.0746$

Nasmyth reflectors (flat):
- size: $d_n = 1.0 \times 0.7$ m

Cassegrain magnification factor: $M = 27.8$

Effective focal ratio of Nasmyth: $f_e/D = 9.73$

Distance from prime to secondary focus: $f_c = 19.79$ m
Heterodyne receivers in short

Radiation collected by the telescope is focused onto a ‘feed horn’ that couples it into a waveguide.

The heterodyne receiver amplifies and converts some frequency range of the incoming RF signals to a lower frequency “IF” (Intermediate Frequency) that is sent to the control building.
Heterodyne Receivers → Coherent
- Frequency conversion from RF to IF using a non-linear device (mixer)
- Phase information is preserved – used in single-dish telescopes and interferometers
- Spectral information is preserved: very high spectral resolution
- Used from the cm to the sub-mm region of the spectrum (few GHz to ~THz)
- Operate at ~4K or ~15 K depending on technology (see later)

Bolometers → Incoherent
- Absorbed photon increases temperature, changes resistance
- 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 (~100 GHz to ~THz)
- Operate at ~0.3 K
Heterodyne frequency (down)-conversion by mixing

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

Non-linear device (mixer)

RF signal at frequency $v_{RF}$

LO at frequency $v_{LO}$

IF at frequency $v_{IF} < < v_{RF}, v_{LO}$

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

DSB mixer: Two sidebands, LSB and USB

DSB=Double Side Band
LSB=Lower Side Band
USB=Upper Side Band
Roles of a heterodyne receiver

The main roles of a heterodyne receiver are to collect efficiently the RF astronomical signal 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.

<table>
<thead>
<tr>
<th>Antenna</th>
<th>Heterodyne Receiver</th>
<th>Spectrometer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very weak RF input signals ($\sim 10^{-15}$ W)</td>
<td>Gain $\sim 120$ dB</td>
<td>Power level of order few mW; Freq. $\approx$ few GHz</td>
</tr>
<tr>
<td>Freq. $\approx 10^{11}$ Hz (100 GHz)</td>
<td>Frequency down-conversion</td>
<td>IF signal transport (coaxial cables or fibers)</td>
</tr>
</tbody>
</table>

**Diagram:**
- The Antenna collects a very weak RF signal.
- The Heterodyne Receiver amplifies and down-converts the signal.
- The Spectrometer receives the amplified signal.

**Notes:**
- The frequency is $\approx 10^{11}$ Hz (100 GHz).
- The power level is of order few mW.
- The frequency range for the spectrometer is $\approx$ few GHz.
Active component technologies for heterodyne receivers

HEMT amplifiers (High Electron Mobility Transistors)
- Direct amplification
- From few GHz to 115 GHz on telescopes; beyond 500 GHz in the lab
- Instantaneous bandwidth > 30%
- Cooled at ~15 K

SIS mixers (Superconductor-Insulator-Superconductor)
- Heterodyne mixing
- From ~100 GHz to 700GHz (Nb); >1THz (NbTiN)
- Instantaneous bandwidth 2 x 8 GHz
- Cooled at ~4 K

HEB mixers (Hot Electron Bolometer)
- Heterodyne mixing
- Up to several THz
- Instantaneous bandwidth ~ 4 GHz
- Cooled at ~4 K

Schottky diode mixers
- Heterodyne mixing (fundamental or subharmonic mixing)
- From few GHz to few THz
- Broad instantaneous bandwidth (>100 GHz for mixers operating at few THz)
- Can operate at room temperature (space application)
Synoptic diagram of heterodyne receivers (basic building blocks)

cm-wave receiver: first amplify, then down-convert

\[ \nu_{RF} < 115 \text{ GHz} \]

mm and submm-wave receiver: first down-convert, then amplify

\[ 80 \text{ GHz} < \nu_{RF} < 1.2 \text{ THz} \]
SIS mixer requires cooling at $\approx 4$ K; HEMT amplifier can operate at 15 K. The active devices are located inside a cryostat:

LO: 240 GHz

LSB: 228-236 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.
The IRAM 30 m telescope receiver cabin (Pico Veleta, Spain)
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

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
Quantum limit for the noise

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.
• For a cascade of stages with gain $G_i \gg 1$, the noise of the first stage $T_{N_1}$ dominates the overall noise temperature.

• If the first stage has loss ($G_1 = 1/L_1 < 1$) 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.
Transmission lines

Coaxial line

Two-wire line

Microstrip line

Rectangular waveguide

Dielectric waveguide
Waveguides

- A Hollow metallic tube of uniform cross section for transmitting electromagnetic waves by successive reflections from the inner walls of the tube is called **waveguide**.

- Waveguides may be used to carry energy between pieces of equipment or over longer distances to carry transmitter power to an antenna or microwave signals from an antenna to a receiver.

- Waveguides are made from copper, aluminum or brass. These metals are extruded into long rectangular or circular pipes.

- An electromagnetic energy to be carried by a waveguide is injected into one end of the waveguide.

- The electric and magnetic fields associated with the signal bounce off the inside walls back and forth as it progresses down the waveguide.
Rectangular waveguide

Rectangular waveguide

**TE**\(_{mn}\) modes: \(E_z = 0, H_z \neq 0\)

**TM**\(_{mn}\) modes: \(E_z \neq 0, H_z = 0\)

\[
\lambda_{c, mn} = \frac{2}{\sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2}}
\]

**TE**\(_{10}\) is the fundamental mode with cut-off wavelength \(\lambda_{c,10} = 2a\)

Single-mode operation when: \(a < \lambda < 2a \rightarrow c/2a < \nu < c/a\)

---

1. The size of the waveguide determines its operating frequency range.
2. The frequency of operation is determined by the dimension ‘a’.
3. This dimension is usually made equal to one – half the wavelength at the lowest frequency of operation, this frequency is known as the waveguide cutoff frequency.
4. At the cutoff frequency and below, the waveguide will not transmit energy. At frequencies above the cutoff frequency, the waveguide will propagate energy.

**Example:**

WR10 waveguide:
size 2.54x1.27 mm\(^2\)

Single **TE**\(_{10}\) mode operation:
59 GHz < \(\nu\) < 118 GHz

Recommended band:
75 GHz < \(\nu\) < 110 GHz
(\(
\sim\) 40% relative band)
Rectangular waveguide

Magnetic flux lines appear as continuous loops
Electric flux lines appear with beginning and end points
The dominant mode is the TE\textsubscript{11} with cut-off wavelength

\[ \lambda_{c11} = \frac{2\pi a}{1.814} \]

where \( a \) is the circular waveguide radius.

Two independent degenerate TE\textsubscript{11} modes can propagate in circular waveguide, which can be associated to two independent polarization modes.
Electromagnetic modeling softwares

• A number of powerful commercial electromagnetic softwares are available for accurate modelling 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.
Types of feed

• Planar feeds
• Waveguide horns
Planar feeds

- Broadband (not limited by waveguide cut-off)
- Lower illumination efficiency than waveguide horns
Waveguide feeds

- Rectangular
- Conical
- Diagonal
- Potter (dual-mode)
- Dielectric loaded
- Quad-ridge
- Corrugated (‘scalar’)
- Smooth-wall

Potter horn (picture J.F. Johansson)

Phasing Section

Mode Converter
$TE_{11} \leftrightarrow TE_{11} + TM_{11}$

Conical Horn

$100\% \ TE_{11}$

$85\% \ TE_{11}$

$15\% \ TM_{11}$

85\%-15\% In phase

$TE_{11}$

$TM_{11}$

$HE_{11}$
Corrugated feeds

Properties:
- Circularly symmetric pattern
- Low sidelobes
- Low cross-pol
- ~40% relative bandwidth
- Low reflection coefficient

Variants:
- Diffraction limited
- Wideband
- Profiled
- Dual-band

Fundamental mode of corrugated waveguide

HE_{11}
**Dual-polarization feed**

E-fieldPol H

E-fieldPol V

Two orthogonal TE_{11} modes in circ. waveguide

**Single-polarization feeds**

E-field

E-field

E-field

Waveguide twist

Single TE_{10} mode in rect. waveguide couples to one TE_{11} mode in circ. waveguide
Corrugated feeds

A scalar, or 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 of passive components scale approximately with operating wavelength:
- High frequency → small size
- Low frequency → big size
Fundamental Gaussian beam propagation

\[ R = z + \frac{1}{z} \left( \frac{\pi w_0^2}{\lambda} \right)^2, \quad \text{Radius of curvature} \]

\[ w = w_0 \left[ 1 + \left( \frac{\lambda z}{\pi w_0^2} \right) \right]^{0.5}, \quad \text{Beam radius (radius at which the fields falls to 1/e relative to its on-axis value)} \]

\[ \frac{P(r)}{P(0)} = \exp \left[ -2 \left( \frac{r}{w} \right)^2 \right], \quad \text{Power density distribution} \]
**Antenna efficiency**

Edge Taper $T_e$: 
relative power density at radius $r_e$

$$T_e = \frac{P(r_e)}{P(0)} = \exp\left(\frac{-2r_e^2}{w^2}\right)$$

$$T_e (dB) = -10 \log_{10}(T_e)$$

---

TABLE 2.1 Fundamental Mode Gaussian Beam and Edge Taper

<table>
<thead>
<tr>
<th>$r_e/w$</th>
<th>$T_e(r_e)$</th>
<th>$F(r_e)$</th>
<th>$T_e$ (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>1.0000</td>
<td>0.0000</td>
<td>0.0</td>
</tr>
<tr>
<td>0.2</td>
<td>0.9231</td>
<td>0.0769</td>
<td>0.4</td>
</tr>
<tr>
<td>0.4</td>
<td>0.7262</td>
<td>0.2739</td>
<td>1.4</td>
</tr>
<tr>
<td>0.6</td>
<td>0.4868</td>
<td>0.5133</td>
<td>3.1</td>
</tr>
<tr>
<td>0.8</td>
<td>0.2780</td>
<td>0.7220</td>
<td>5.6</td>
</tr>
<tr>
<td>1.0</td>
<td>0.1353</td>
<td>0.8647</td>
<td>8.7</td>
</tr>
<tr>
<td>1.2</td>
<td>0.0561</td>
<td>0.9439</td>
<td>12.5</td>
</tr>
<tr>
<td>1.4</td>
<td>0.0198</td>
<td>0.9802</td>
<td>17.0</td>
</tr>
<tr>
<td>1.6</td>
<td>0.0060</td>
<td>0.9940</td>
<td>22.2</td>
</tr>
<tr>
<td>1.8</td>
<td>0.0015</td>
<td>0.9985</td>
<td>28.1</td>
</tr>
<tr>
<td>2.0</td>
<td>0.0003</td>
<td>0.9997</td>
<td>34.7</td>
</tr>
<tr>
<td>2.2</td>
<td>0.0001</td>
<td>0.9999</td>
<td>42.0</td>
</tr>
</tbody>
</table>

$\alpha = (\text{Aperture Radius} / \text{Gaussian Beam Radius})^2$
A relay optics is typically used to image the horn aperture on the telescope’s aperture. This fulfils the condition of frequency-independent illumination of the dish.
Re-imaging the subreflector into the feed-horn aperture with one or two reflective focusing elements (curved mirrors)
Focal plane fields: truncation

- Effect of truncation depends on location
  - effect worst near (image of) focal plane
  - effect least near (image of) aperture plane

- Clear **diameter** of 5 beam **radii** is conservative
HEMT low noise amplifiers (LNA)

In HEMT (but not in FET), current travels through very pure layer.

Two types:

- Discrete transistors
- MMIC
Cryogenic IF Low Noise Amplifier used in ALMA Band 7 (CAY, Spain)

**FREQUENCY RANGE**: 4 – 8 GHz

**GAIN**: 33 dB < Gain < 41 dB (all band)

**GAIN RIPPLE**: < ±1.0 dB

**NOISE TEMPERATURE**: < 5 K

**INPUT REFLECTION**: < -4 dB without isolator

**OUTPUT REFLECTION**: < -13 dB without isolator

**GAIN FLUCTUATIONS**: < 8.4×10⁻⁵ (Hz)⁻¹/² @ 1 Hz

**STABILITY**: K > 1 at all frequencies

**POWER CONSUMPTION**: < 9 mW

**MECHANICAL INTERFACES**: Unit envelope: < 50×13×12 mm

**Unit weight**: < 50 g

**ELECTRICAL INTERFACES**: RF connectors: SMA female

**DC connector**: MDM

0.1x150 µm HRL InP transistor
MMIC low noise amplifier for the 3 mm band (80-116 GHz) packaged at IRAM
Metamorphic technology from IAF
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 magnetic fields.

SIS mixing theory by Tucker is the tool to design SIS mixers.
SIS mixers

\[ V_{\text{gap}} = 2\Delta/e \]

\[ \alpha = e \frac{v_{\text{LO}}}{h} \]

\[ v_{\text{LO}} = 300 \text{ GHz} \]

\[ v_{\text{LO}} = h \frac{v_{\text{LO}}}{e} = 1.24 \text{ mV} \]

\[ \alpha = e \frac{v_{\text{LO}}}{h} \frac{v_{\text{LO}}}{e} = 1 \]

\[ I_0 \] [mA]

\[ V_0 \] [mV]
Waveguide SIS mixers

- SIS junctions located on a quartz substrate;
- Waveguide probe couples the signal into the SIS junction(s), usually through supercond. microstrip and/or coplanar waveguides;
- Mixer chip is embedded in a waveguide structure machined in a mechanical block;
- The junction capacitance (Cj~75 fF/um2) is tuned out by on-chip superconducting circuitry.

IRAM mixer chip used in ALMA Band 7, PdBI Band 4, and EMIR Band 4 (275-373 GHz)

Chip size: 0.08x0.25x2 mm³
Main SIS mixer types: DSB, SSB and 2SB

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 and separated to two different IF outputs.
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;
- $e^{-A \cdot \tau}$: Atmospheric transmission factor;
- $F_{eff}$: Forward efficiency;
SSB, DSB or 2SB?

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 per polarization);
SIS mixer types: DSB, SSB and 2SB

**Double Side Band (DSB):** Both the USB and the LSB are downconverted and superimposed on each other at the IF:

**Single Side Band (SSB):** Either the USB or the LSB is downconverted to IF, i.e. one sideband is rejected. Sideband rejection achieved (at Iram) by mechanically tunable backshort:

**Example of LSB tuning (USB is rejected):**
SSB SIS mixer currently installed in EMIR and PdBI Band 2 receivers

RF band: 129-174 GHz (2 mm band);
IF Band: 4-8 GHz

It will be replaced this week in EMIR by a 2SB mixer
**SIS mixer types: DSB, SSB and 2SB**

**Sideband Separating mixer (2SB):** Both sidebands (USB and LSB) downconverted and separated to independent outputs

2SB mixer diagram

ALMA Band 7 2SB mixer (275-373 GHz)

SIS mixers currently installed on IRAM receivers are SSB and 2SB (no DSB).
EMIR Band 3 (200-276 GHz) 2SB SIS mixer

LO input

IF1

IF2

Signal input (from feed)

LO couplers

RF coupler

SIS mixer chips

LO splitter

Signal input
EMIR Band 3 (200-276 GHz) 2SB SIS mixer
**Polarization splitters**

### Wire grid

- **Output**
- **Input**

E-field perpendicular to wires so incident field transmitted.

### OMT (OrthoMode Transducer)

- **Pol 2**
- **Pol 1**

Modified Turnstile junction

- 180° E-plane bend

E-plane power combiner

Wire grid polariser

E-field parallel to wires so incident field reflected.
Polarization splitters

Advantages:
- Compact;
- Only one feed-horn required;
- Perfect alignment in the sky for the two polarizations;
Example of specifications of OMT for the 3 mm band (same as ALMA Band 3)

<table>
<thead>
<tr>
<th>Specifications *</th>
<th>ALMA B3 OMT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>84-116GHz</td>
</tr>
<tr>
<td>Input return loss</td>
<td>&gt; 15 dB</td>
</tr>
<tr>
<td>Output return loss</td>
<td>&gt; 15 dB</td>
</tr>
<tr>
<td>Insertion losses</td>
<td>&lt; 0.45 dB</td>
</tr>
<tr>
<td>Output isolation</td>
<td>&gt; 25 dB</td>
</tr>
<tr>
<td>Polarization isolation (≈ Xpol)</td>
<td>&gt; 25 dB</td>
</tr>
</tbody>
</table>
Design and fabrication process of OMT for the 3 mm band recently developed at IRAM

Inner views of turnstile junction waveguide OMT

Wire cut of aluminium mandrel
OMT manufacturing steps

1. Aluminum mandrel machined in one single piece via wire cut process (wire radius = 50μm)

2. Aluminum mandrel + flanges & spacers assembly

3. Electroforming & aluminum etching
IRAM mm-wave Vector Network Analyzer (VNA)
 Allows S-parameter measurements across IRAM receiver bands
 Used for characterization of OMTs, waveguide couplers, feed-horn, etc.
Characterization of OMT with mm-wave VNA

Input reflection @ circular port:
- Transition 2.5mm x 1.2 mm → WR10
- VNA port 1 (WR10)
- Transition WR10 → φ=2.93mm
- WR10 load

Outputs reflection @ rectangular ports:
- VNA port 1 (WR10)
- OMT interfaces

Graphs:
- Input reflection, pol 0
- Input reflection, pol 1
- S11 < -20dB in band 2
- S11 < -17dB in band 2+3

Graphs:
- Output reflection, pol 0
- Output reflection, pol 1
- S11 < -20dB in band 2
- S11 < -16dB in band 2+3
Vacuum windows and IR filters
Vacuum windows and IR filters

Goals:
Windows: ensure good vacuum; Filters: block IR radiations
Windows & Filters: minimize reflection losses, maximize transmission of mm waves

<table>
<thead>
<tr>
<th>Material</th>
<th>HDPE</th>
<th>PTFE</th>
<th>Z-cut quartz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Utilization</td>
<td>Windows</td>
<td>Filters</td>
<td>Windows</td>
</tr>
<tr>
<td>Refraction index (n)</td>
<td>~ 1.52</td>
<td>~ 1.44</td>
<td>~ 2.1</td>
</tr>
<tr>
<td>Tan δ</td>
<td>~ 4E-4</td>
<td>~ 6E-4</td>
<td>~ 1E-4</td>
</tr>
</tbody>
</table>

→ Values from P. Goldsmith: “Quasi-Optical Systems”

Low tan δ → minimize transmission losses
Low n → Minimize reflection losses with anti-reflection coating across a broadband
Small thickness → minimize transmission loss but should be enough to preserve vacuum

→ From ALMA memo 377
Choice of materials and geometry

HDPE & PTFE: matching per triangular grooves:

Matching grooves have orthogonal directions on the two surfaces.

Z-cut quartz: matching per anti-reflection layers:

Anti-reflection coating
quartz

→ Windows: HDPE preferred over z-cut quartz (less expensive, easier manufacturing, lower reflection...
300K HDPE window simulation
(example: 3 mm band)

Corrugation’s geometry:

A (angle) $\rightarrow$ constant (20 degrees)
P (pitch), H (height) $\rightarrow$ vary

$\rightarrow$ Angle of the groove should be compatible with the use of a standard drill ($20^\circ$, $30^\circ$...)

$|S_{1,1}|$ in dB

Frequency / GHz

Perturbation due to appearance of spurious modes (when pitch becomes too big)
EMIR: Multi-band mm-wave SIS receiver for IRAM 30 m telescope

<table>
<thead>
<tr>
<th>Band</th>
<th>RF coverage [GHz]</th>
<th>IF Config</th>
<th>Trx</th>
<th>Gim</th>
</tr>
</thead>
<tbody>
<tr>
<td>E090</td>
<td>83-117</td>
<td>2SB</td>
<td>50</td>
<td>13</td>
</tr>
<tr>
<td>E150</td>
<td>129-174</td>
<td>2SB</td>
<td>50</td>
<td>13</td>
</tr>
<tr>
<td>E230</td>
<td>202-274</td>
<td>2SB</td>
<td>80</td>
<td>13</td>
</tr>
<tr>
<td>E330</td>
<td>277-358</td>
<td>2SB</td>
<td>80</td>
<td>13</td>
</tr>
</tbody>
</table>
Cryogenic system of EMIR receiver and of PdBI (and future NOEMA) receivers

- Sumitomo cryocooler SRDK3ST- Closed cycle system
  - Air cooled Compressor CSA71A
  - 3 stages coldhead 77K, 15K & 4K
  - Cooling powers: 33W@77K, 2W@15K, 1W@4.2K
Dewars of EMIR and PdBI receivers

- Dewar and shields: supplied by SNLS, France;
- Flexible thermal links at each stage to prevent vibration;
- IF LNA amplifiers and optics modules in thermal contact with 15 K plate;
- OFHC copper straps at 4K for couplers, SIS mixers and isolators;
- Cool down time: around 30 hours;
New EMIR Band 2 (129-174 GHz) cold optics module
(to be installed this week)

View 1

- Fiberglass tab (G11) for thermal split
- Feeds and wire grid @ 4 K
- Ellipsoidal mirrors @ 15 K
- Polarization splitting wire-grid

View 2

- @ 15 K
- Fiberglass tab (G11) - thermal split
New EMIR Band 2 (129-174 GHz) cold optics module including the two 2SB SIS mixers and the waveguide LO splitter.
Local Oscillator (LO) types

Based on fundamental source (up to ~150 GHz) cascaded by frequency multipliers to generate the final frequency (from ~150 GHz to up to beyond few THz)

**Fundamental sources:**

1) **Gunn:** Solid state oscillator (InP or GaAs), negative resistance coupled to a resonant cavity.
   
   Operate in second harmonic mode. Frequencies up to ~150 GHz. Output power >10 dBm (>10 mW). Mechanically tuned.

2) **YIG+AMC:**
   
   - **YIG (Yittrium Iron Garnet oscillator):** a ferrite material that resonates at microwave frequencies when immersed in a DC magnetic field B. The resonance is proportional to the strength of B (provided by electromagnet). It has linear tuning over multi-octave frequencies. Operate from few GHz to ~20 GHz. Typical output power is 15 dBm (~30 mW).
   
   - **AMC (Active Multiplier Chain):** The YIG signal at ~15 GHz is multiplied up by a multiplier chain based on active MMIC doubler and tripler to provide LO ~100 GHz. A Power Amplifier (PA) cascaded with coupler can be used to further amplify recombine the signals.

**Other types of LO sources:**

- **Photonic:** based on waveguide photomixers pumped by two lasers at λ~1.55 μm. The laser beams propagate along the same optical fiber and beat in the photodiode to generate their difference frequency (used for ALMA phase reference to v~100 GHz).

- **QCL (Quantum Cascaded Laser):** laser emission through intersubbands transitions in a repeated stack of quantum well heterostructures. Used to generate frequencies v> 1 THz.

- **Vacuum state oscillators (klystron, backward-wave oscillator).**
Local Oscillator system for EMIR and PdBI Band 1, 2 and 3 based on mechanically tuned Gunn oscillators

LO Band 1: 86 - 110 GHz;
LO Band 2: 67.5 – 87 GHz x 2 (frequency doubler);
LO Band 3: 69 – 91.3 GHz x 3 (frequency tripler);
Local Oscillator system for EMIR and PdBI Band 4 based on electronically tuned YIG

- 13-16 GHz YIG oscillator followed by an Active Multiplier Chain (AMC) and Power Amplifiers (PA) that delivers 94.3-121.7 GHz output;
- Fully electronically tuned (no more DC motors and mechanical parts – fast tuning);
- Cascaded tripler + filter-attenuator at ambient temperature delivers $\nu_{\text{LO}}$: 283-365 GHz;
Looking inside the 94.3-121.6 GHz Local Oscillator modules

- 3 dB Coupler
- Power Amplifier
- Active Multiplier Chain

MMIC Power Amplifier from NRAO
EMIR receiver noise performance across the four RF bands
Typical requirements of a receiver

• RF band: $\Delta v_{RF}/v_{RF} \approx 30\text{-}40\%$

• IF band: $\Delta v_{IF}/v_{RF} \approx 15\%$ for SIS receivers, $\Delta v_{IF}/v_{RF} \approx 30\%$ for HEMT receivers

• LO tuning range (derives from RF and IF) and LO type (Gunn, YIG+AMC, photonic, QCL)

• Dual-polarization (linear or circular) with OMTs or quasi-optics wire grids.

• Multiband operation (observe in 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
## Key specifications of ALMA (heterodyne) receivers

<table>
<thead>
<tr>
<th>Band</th>
<th>Manufacturer</th>
<th>Frequency</th>
<th>Mixing Scheme</th>
<th>Noise Temperature</th>
<th>Cryo LNA</th>
<th>Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>ASIAA</td>
<td>33-52 GHz</td>
<td>USB</td>
<td>26 K (SSB)</td>
<td>2</td>
<td>HEMT</td>
</tr>
<tr>
<td>2</td>
<td>-</td>
<td>67-90 GHz</td>
<td>LSB</td>
<td>47 K (SSB)</td>
<td>2</td>
<td>HEMT</td>
</tr>
<tr>
<td>3</td>
<td>HIA</td>
<td>84-116 GHz</td>
<td>2SB</td>
<td>60 K (SSB)</td>
<td>4</td>
<td>SIS</td>
</tr>
<tr>
<td>4</td>
<td>NAOJ</td>
<td>125-163 GHz</td>
<td>2SB</td>
<td>82 K (SSB)</td>
<td>4</td>
<td>SIS</td>
</tr>
<tr>
<td>5</td>
<td>Chalmers /SRON</td>
<td>163-211 GHz</td>
<td>2SB</td>
<td>105 K (SSB)</td>
<td>4</td>
<td>SIS</td>
</tr>
<tr>
<td>6</td>
<td>NRAO</td>
<td>211-275 GHz</td>
<td>2SB</td>
<td>136 K (SSB)</td>
<td>4</td>
<td>SIS</td>
</tr>
<tr>
<td>7</td>
<td>IRAM</td>
<td>275-373 GHz</td>
<td>2SB</td>
<td>147 K (SSB)</td>
<td>4</td>
<td>SIS</td>
</tr>
<tr>
<td>8</td>
<td>NAOJ</td>
<td>385-500 GHz</td>
<td>2SB</td>
<td>292 K (SSB)</td>
<td>4</td>
<td>SIS</td>
</tr>
<tr>
<td>9</td>
<td>SRON/NOVA</td>
<td>602-720 GHz</td>
<td>DSB</td>
<td>261 K (DSB)</td>
<td>2</td>
<td>SIS</td>
</tr>
<tr>
<td>10</td>
<td>NAOJ</td>
<td>787-950 GHz</td>
<td>DSB</td>
<td>344 K (DSB)</td>
<td>2</td>
<td>SIS</td>
</tr>
</tbody>
</table>

For 66 receivers 1848

- Two main technologies: SIS mixers and HEMT amplifiers;
- Noise specs few times the quantum limit $T_Q = \frac{h \nu}{k_B}$ (~5 K at 100 GHz);
- Dual linear polarization;
- Each receiver delivers 8 GHz of IF band per polarization channel;
In each antenna, one cryostat accommodates 10 receiver cartridges

- Necessary for operating mm and sub-mm high sensitivity SIS mixers and cooling of other electronic components;
- Close cycle cryocooler allows for long term (> 1 year) unattended operation;
- IR filters are mounted on the inner shields to prevent IR radiation from entering and warming up the 4K stage;
## ALMA Band 7 receiver cartridge and specifications
(developed and produced at IRAM – 73 units delivered)

<table>
<thead>
<tr>
<th>Property</th>
<th>Required Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixing scheme</td>
<td>Linearly polarized Sideband Separating Mixer</td>
</tr>
<tr>
<td>RF port frequency range</td>
<td>275-373 GHz</td>
</tr>
<tr>
<td>LO port frequency range</td>
<td>283-365 GHz</td>
</tr>
<tr>
<td>IF bandwidth</td>
<td>4-8 GHz 2SB</td>
</tr>
<tr>
<td>SSB receiver noise</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>Image band suppression</td>
<td>&gt;10dB, with allowance:</td>
</tr>
<tr>
<td></td>
<td>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>Total IF output power integrated over</td>
<td>-32dBm…-22dBm</td>
</tr>
<tr>
<td>4-8GHz</td>
<td>5dB p-p over any 2GHz window</td>
</tr>
<tr>
<td></td>
<td>7dB p-p full band</td>
</tr>
<tr>
<td>IF power variations across 4-8GHz</td>
<td>&lt;5%</td>
</tr>
<tr>
<td>Large signal gain compression @ 300K</td>
<td>&lt;5%</td>
</tr>
<tr>
<td>input</td>
<td>4.0E-7, 3.0E-6, respectively</td>
</tr>
<tr>
<td>Amplitude stability: Allan variance</td>
<td>7.1fs over 300s</td>
</tr>
<tr>
<td>0.05s…100…300s</td>
<td>&gt;80%</td>
</tr>
<tr>
<td>Signal path phase stability</td>
<td>99.5% polarization coupling, (equiv&lt;–23dB)</td>
</tr>
<tr>
<td>Aperture efficiency</td>
<td>&lt;2°</td>
</tr>
<tr>
<td>Polarization efficiency</td>
<td>&lt;2°</td>
</tr>
<tr>
<td>Focus efficiency</td>
<td>1/10 FWHM</td>
</tr>
<tr>
<td>Polarization alignment accuracy</td>
<td>&lt; 15 min</td>
</tr>
<tr>
<td>Stabilization time from non-operational</td>
<td>&lt; 1.5 s</td>
</tr>
<tr>
<td>Stabilization time from stand by mode</td>
<td>&lt; 2.38kg on cold stages</td>
</tr>
</tbody>
</table>

### Addendum

- **Stabilization time from non-operational**: < 15 min
- **Stabilization time from stand by mode**: < 1.5 s
- **Added cartridge mass**: < 2.38kg on cold stages
ALMA Band 7 cartridge validation (using Cartridge Test Set)
Integrated noise temperature over 4-8 GHz for 65 ALMA Band 7 production cartridges
ALMA cold cartridges
73 for each band (including spares)

Production recently started

Production underway

Production completed

Band 3
HIA

Band 6
NRAO

Band 7
IRAM

Band 9
NOVA

Band 4
NAOJ

Band 8
NAOJ

Band 10
NAOJ

Band 5
Chalmers/SRON
First ALMA Front-End with 8 cartridges (Band 3 to Band 10)
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 IRAM 30 m telescope

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

In operation

230 GHz Continuum on URANUS
Proposed implantation of future 3 mm multibeam receiver inside the IRAM 30 m telescope cabin
5 x 5 pixels dual polarization RF module

Local Oscillator (LO) pol 0

Local Oscillator (LO) pol 1

IF outputs

1 → 5 LO power divider

~ 210mm

FOV ~5.7'

2 x HPBW = 48” at 100GHz
5 pixels dual polarization linear array

- LO pol 0
- Ortho Mode Transducer (OMT)
- Corrugated feed horn
- LO pol 1
- Combined LO & RF hybrid coupler, pol 0
- 2 x DSB SIS mixers + IF hybrid + bias T
- LSB & USB IF outputs
70-116GHz single pixel dual polarization 2SB prototype

OMT

Feed Horn

Combined LO + RF hybrid coupler

LO in, pol 0

IF outputs

44mm

Full 2 polarization 2SB unit

44mm
Integrated DSB SIS mixers + IF circuit + bias T assembly
Technical constraints: multibeam vs. single pixel Rx

- Local oscillator (LO):
  - Total LO power required
  - Homogeneity of pixels pumping

These two pixels need to receive the same LO power