Multibeam Heterodyne Receiver
For ALMA

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National Astronomical Observatory of Japan
Advanced Technology Centor
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and Band-
Question discussed in this talk and outline

What challenges and technologies exist to develop multibeam receivers for the future ALMA (this is considered based on “current ALMA receiver technology.”).
× how many pixels is it possible to put on a cartridge

1. Multibeam receivers in the world
2. Technological challenges to develop the multibeam receiver for ALMA
   1. Optics
   2. Local Oscillator system
   3. Intermediate Frequency system
   4. Integration
3. Summary
Current Heterodyne multibeam receivers for radio astronomy

For the purpose of fast mapping and high spectral resolution, multibeam heterodyne receivers have been developed. Most of the receivers has 7-9 pixels. SuperCam is the heterodyne receiver with the largest number of pixels.
Superheterodyne Camera (SuperCam)  
Univ. of Arizona, Arizona State Univ., Caltech

Installed on the Heinrich Hertz Telescope  
Number of Pixels: 8 x 8 pixel  
RF: 320-380 GHz  
IF: 4-6 GHz  
LO: Solid state source

First light On May 2012 with 32 pixels.  
They are also planning on development of Kilopixel Array Pathfinder project (KAPPa)
SIS 25-BEam Array Receiver System (BEARS)
NRO, Japan

Installed on 45-m Telescope

Number of Pixels: 5x5
RF: 82-116 GHz
IF: 2.0-2.6 GHz
LO: Gunn Oscillator

This was built in 2000.
Challenges toward development of multibeam receivers for ALMA

- ALMA has very tight specification and constraints.
- Devices and components have to be improved and system should be optimized.
Optics

There are several constraints for multibeam optics design to keep ALMA specifications.

- **General Issue**
  1. Defocus and distortion on off-axis
     ⇒ Other telescopes optimize using many mirrors and dielectric Lenses

- **Constraints in ALMA** (Next slide in detail)
  2. Cross-polarization $< -23$ dBc
     ⇒ Other telescopes don’t care so much
  3. Small diameter cryostat window
     ⇒ Other telescopes use large or individual windows for each beam and use high power refrigerator

Of course, one of solutions is to use a widow with as large diameter as possible.

Dielectric lens used in BEARS

Optics

Careful design considering ALMA 12-m antenna is required as well as their size reduction.

In terms of cross polarization, very careful design is necessary.

\[ X_{SP} = X_{SP_OMT} + X_{SP_Horn} + X_{SP_Focus} + X_{SP_IRfilter} \]

- \( X_{SP_OMT} \): Small and simple design such as planar type × Wire grid
- \( X_{SP_Horn} \): Accurate fabrication with cheap technology
- \( X_{SP_Focus} \): can be reduced by proper design △ Dielectric lens
- \( X_{SP_IRfilter} \): can’t be controlled

-One possible solution: Use of individually-optimized ellipsoidal mirrors.
  • This could allow making the focal plane small.
  • We can control pitch with orientation of mirrors.

Comment by Alvaro Gonzalez
In the case using all solid-state LO source, limited power has to be efficiently divided and delivered for each device because of difficulty of amplification.

- LO power is not enough for multibeam receiver if the same LO system design as current one is used.
- Balanced mixers (BM) help to reduce the required power. ⇒ Size reduction

<table>
<thead>
<tr>
<th>Element</th>
<th>150 GHz</th>
<th>500 GHz</th>
<th>900 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>2SB Junctions</td>
<td>0.10</td>
<td>0.13</td>
<td>0.3</td>
</tr>
<tr>
<td>Mixer chip (dB)</td>
<td>-0.5</td>
<td>-0.5</td>
<td>-2.0</td>
</tr>
<tr>
<td>3dB coupler (2SB)</td>
<td>-17</td>
<td>-17</td>
<td>-13</td>
</tr>
<tr>
<td>Waveguide</td>
<td>-6</td>
<td>-6</td>
<td>-2</td>
</tr>
<tr>
<td>Subtotal (mW)</td>
<td>44.2</td>
<td>0.9</td>
<td>57.5</td>
</tr>
<tr>
<td>Available LO power P&lt;sub&gt;LO&lt;/sub&gt; (uW)</td>
<td>630</td>
<td>100</td>
<td>30</td>
</tr>
<tr>
<td>Number of elements</td>
<td>14</td>
<td>714</td>
<td>1</td>
</tr>
</tbody>
</table>
Other Local Oscillator Source for multibeam receiver

For more than 500 GHz, there is no high power source. Photomixing and Josephson Oscillator approaches might be promising as LO source for multibeam terahertz receiver.

Group in Max plank succeeded astronomical observation at 1.05 THz for single pixel. (L. Mayorga, 2012)

Two wavelength laser generates terahertz wave
- Possible to be amplified after dividing power.
- Easy to make coupler and divider circuits using photonic crystal.
- Low power consumption
- Task: Development of Stable system for the interferometer.

Applying 1mV produces the 0.4836 THz
- Possible to supply LO power individual SIS junction.
- Easy to integrate Superconducting mixers
- No low frequency source is needed.
- Ultra low power consumption.
- Task: Improvement of Line width.

Valery P. Koshelets, 2010 SPIE
Thermal Load Issues

Thermal loads in the ALMA cartridge on 4, 15, 110-K stages are limited within 41, 162, 850 mW. The largest thermal load is the HEMT amplifier. We need to reduce power consumption of Low noise amplifiers and/or to move to the other stage or to use a high power refrigerator.

<table>
<thead>
<tr>
<th>Source of heat load</th>
<th>Band 4</th>
<th></th>
<th>Band 8</th>
<th></th>
<th>Band 10</th>
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<tbody>
<tr>
<td></td>
<td>4 K</td>
<td>15 K</td>
<td>110 K</td>
<td>4 K</td>
<td>15 K</td>
<td>110 K</td>
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<tr>
<td>Wiring Heat Load</td>
<td>3.1</td>
<td>16.6</td>
<td>32</td>
<td>3.1</td>
<td>10.2</td>
<td>17.3</td>
</tr>
<tr>
<td>LO waveguide</td>
<td>0.2</td>
<td>21</td>
<td>90</td>
<td>0.4</td>
<td>24</td>
<td>94</td>
</tr>
<tr>
<td>IF coax</td>
<td>1.1</td>
<td>44.5</td>
<td>132</td>
<td>1.4</td>
<td>27</td>
<td>102</td>
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<tr>
<td>HEMT amplifiers</td>
<td>8 x 4</td>
<td></td>
<td>8 x 4</td>
<td></td>
<td>17 x 2</td>
<td></td>
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<tr>
<td>Multiplier</td>
<td>20</td>
<td></td>
<td>100</td>
<td></td>
<td>200</td>
<td></td>
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<tr>
<td>Summary (mW)</td>
<td>36.2</td>
<td>82.1</td>
<td>174</td>
<td>36.9</td>
<td>61.2</td>
<td>313.3</td>
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<tr>
<td>Dewar ICD (mW)</td>
<td>41</td>
<td>162</td>
<td>850</td>
<td>41</td>
<td>162</td>
<td>850</td>
</tr>
</tbody>
</table>
The less $P_{\text{amp}}$ is reduced, the larger we achieve $N_{\text{pixel}}$. $P_{\text{amp}} < 1\ \text{mW},\ N_{\text{pixel}} > 10$

But it is difficult to increase $N_{\text{pixel}}$ due to wiring and IF cable.
**Single stage preamplifier**

*for reduction of thermal loads in 4-K stage*

- The use of single stage preamplifier help to reduce the power consumption in the 4-K stage.
- Difficult to control gain flatness, 2-stage LNA to tune gain would be necessary on 110 K.

**Current cartridge design**

- 3-stage Low noise and flat Gain amplifier

**Cartridge design using preamplifier**

- Single stage Low noise preamplifier
- Two-stage Low-Noise and Gain equalizing amp.
What performance is required for the preamplifier?

Need to a Preamplifier with a gain of more than 10 dB and a noise temperature of less than 5 K at an operating temperature 4 K

<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td></td>
<td>300</td>
<td>-0.06</td>
<td>4</td>
<td>4</td>
<td>-0.10</td>
<td>7</td>
<td>7</td>
<td>-0.09</td>
<td>6</td>
<td>6</td>
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<tr>
<td>IR filter</td>
<td>110</td>
<td>-0.03</td>
<td>1</td>
<td>1</td>
<td>-0.13</td>
<td>3</td>
<td>3.4</td>
<td>-0.19</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>IR filter</td>
<td>12</td>
<td>-0.03</td>
<td>0</td>
<td>0</td>
<td>-0.09</td>
<td>0</td>
<td>0.3</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Cold optics</td>
<td>4</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-0.1</td>
<td>1</td>
<td>1.1</td>
<td>-0.2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Waveguide (hybrid and OMT)</td>
<td>4</td>
<td>-1</td>
<td>1</td>
<td>1</td>
<td>-1.5</td>
<td>6</td>
<td>6.2</td>
<td>-0.5</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>LO Coupler</td>
<td>4</td>
<td>-0.09</td>
<td>2</td>
<td>3</td>
<td>-0.1</td>
<td>5</td>
<td>7.8</td>
<td>-0.5</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>Tuning circuit</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.0</td>
<td>0</td>
<td>0.0</td>
<td>-1.5</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Mixer</td>
<td>4</td>
<td>0</td>
<td>20</td>
<td>26</td>
<td>-3.0</td>
<td>25</td>
<td>40</td>
<td>-4</td>
<td>83</td>
<td>165</td>
</tr>
<tr>
<td>Isolator+hybrid+cable</td>
<td>4</td>
<td>-1</td>
<td>1</td>
<td>1</td>
<td>-1.0</td>
<td>8.0</td>
<td>25.3</td>
<td>-0.6</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>1st amplifier</td>
<td>4</td>
<td>30</td>
<td>8</td>
<td>13</td>
<td>31</td>
<td>8</td>
<td>32</td>
<td>34</td>
<td>5</td>
<td>29</td>
</tr>
<tr>
<td>Cable</td>
<td>150</td>
<td>-0.3</td>
<td>11</td>
<td>0</td>
<td>-1.2</td>
<td>48</td>
<td>0.2</td>
<td>-3</td>
<td>149</td>
<td>0</td>
</tr>
<tr>
<td>2nd amplifier</td>
<td>300</td>
<td>40</td>
<td>100</td>
<td>0</td>
<td>36</td>
<td>92</td>
<td>0</td>
<td>30</td>
<td>120</td>
<td>1</td>
</tr>
<tr>
<td>Attenuator+Cable</td>
<td>300</td>
<td>-10</td>
<td>2700</td>
<td>0</td>
<td>10</td>
<td>2700</td>
<td>0</td>
<td>10</td>
<td>2700</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>57</td>
<td>50</td>
<td>50</td>
<td>123</td>
<td>43</td>
<td>219</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Mixer 4 0 20 27 -3 25 40 -4 83 165
hybrid 4 -0.3 0 0 -0.3 0 1 - - -
Preamplifier 4 10 5 7 10 5 17 10 5 25
Cable 12 -0.5 1 0 -0.5 1 0 -0.5 1 1
Isolator 12 -0.5 1 0 -0.5 1 1 -0.6 2 1
2nd amplifier 110 20 20 4 20 20 9 20 20 13
Cable 150 -0.5 18 0 -0.5 18 0 -0.5 18 0
3rd amplifier 300 40 100 0 36 92 0 30 120 1
Attenuator+Cable 300 -10 2700 0 -10 2700 0 -10 2700 0
|                   |           | 53       | 48    | 49    | 93    | 47    | 227    |           |       |          |

Current cartridge design

Cartridge design using preamplifier
Semiconductor-based LNA with ultra-low power consumption

- Not impossible to develop IF amplifier with a noise temperature below 5 K under 1-mW power consumption.
- Difficult to achieve broad bandwidth due to decrease of GB product under low power condition

- 4-8 GHz 3-stage amplifier
  Total power consumption
  \[ P_{\text{amp}} = 4.2 \text{mW} \left( V_{\text{DD}} = 0.45 \text{ V}, I_{\text{DD}} = 9.3 \text{ mA} \right) \] Black
  \[ P_{\text{amp}} = 0.3 \text{mW} \left( V_{\text{DD}} = 0.10 \text{ V}, I_{\text{DD}} = 3.3 \text{ mA} \right) \] Green
  J. Schleeh, IEEE, 2012
  Chalmers Univ. of Tech.

- 4-12 GHz 3-stage amplifier
  Total power consumption (Typical)
  \[ P_{\text{amp}} = 15 \text{mW} \left( V_{\text{DD}} = 1.0 \text{ V}, I_{\text{DD}} = 15 \text{ mA} \right) \] S. Weinreb, Caltech
**Superconducting IF amplifier**

- Superconducting Travelling wave parametric amplifier has characteristics of Ultra low power consumption, low noise, wideband and high dynamic range.
- W. Shan in PMO started to design it for multipixel receivers (ISSTT, 2013)

<table>
<thead>
<tr>
<th></th>
<th>Noise</th>
<th>Bandwidth</th>
<th>Power consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>SQUID amp.</td>
<td>A few photon (~mK)</td>
<td>Narrow (MHz)</td>
<td>Ultra low (negligible)</td>
</tr>
<tr>
<td>Josephson junction parametric amp.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Superconducting Travelling wave parametric amp.</td>
<td></td>
<td>Wide (GHz)</td>
<td></td>
</tr>
</tbody>
</table>

Technical challenges
- Higher Operating temperature
- Filtering Pump and Idler power

Integration for larger number of pixels

- Mixer block occupies a large part of 4-K stage. ⇒ Integration
- Integration of devices, systems, and pixels not only reduce the volume but also optimize the system performance.
- For these technologies, integration of technologies and collaboration would be needed.

First generation
For ALMA

Second generation

Possible to develop but...
• Bulky...
• Complex...

Future generation

On-chip antenna
On-chip or hybrid MIC
SIS Mixer+IF amp.

Integration of pixels on-chip
toward larger-pixel Receivers

For ALMA
Possible to develop but...
• Bulky...
• Complex...
### On chip and waveguide technologies

Proper choice of transmission line and packaging technologies will be needed.

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#### Single chip balanced mixer, M P Westig, 2011

![Single chip balanced mixer](image1.png)

#### Waveguide-based 2SB mixer, W. Shan, 2012

![Waveguide-based 2SB mixer](image2.png)

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<table>
<thead>
<tr>
<th></th>
<th>On chip</th>
<th>Off chip/hybrid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>○</td>
<td>×</td>
</tr>
<tr>
<td>Interconnection/transition loss</td>
<td>○</td>
<td>△</td>
</tr>
<tr>
<td>Transmission loss</td>
<td>△</td>
<td>○</td>
</tr>
<tr>
<td>Higher mode</td>
<td>△</td>
<td>○</td>
</tr>
<tr>
<td>Optimal material</td>
<td>△</td>
<td>○</td>
</tr>
<tr>
<td>Packaging</td>
<td>○</td>
<td>△</td>
</tr>
<tr>
<td>Handling</td>
<td>○</td>
<td>△</td>
</tr>
<tr>
<td>Cost</td>
<td>Initial</td>
<td>Individual</td>
</tr>
</tbody>
</table>
On-chip antenna and waveguide technology for integration

Horn fabricated on Low Temperature Co-fired Ceramic (LTCC) or Silicon Study on waveguide technology based on Microwave or Light wave circuits and the application for submillimeter wave has been increasing.

LTCC antenna

- Metal rings
- Microstrip antenna

M. Kawashima 2011

Corrugated Silicon Platelet Feed Horn

- 5 mm
- Si feed array
- OMT-coupled detectors

J. W. Brittona, 2010

Substrate Integrated Waveguide (SIW)

- Same propagation mode as rectangular WG
- High compatibility with planar circuit
- Use of MEMS process or machining

M. BOZZI, 2009

Photonic crystal waveguide

- No metallic loss
- Use of MEMS process or machining

A. L. Bingham, 2008
Summary

• It is not easy to develop multibeam receivers by small modification of current cartridges.

• We have to consider in not only engineering but also research layer.
  – In terms of thermal loads, size and LO power, improvements of component and device are needed.

• New technologies or ones in other fields will help to develop and improve the performance of multibeam receiver.
  – We have to discuss many people in other fields, e.g. other superconductor, semiconductor, MEMS, terahertz, telecommunication and photonics.