SEQUOIA and 1 mm SIS Receiver
WARES Spectrometer

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LMT Community Meeting #3
October 30, 2020
SEQUOIA

16-element Focal Plane Array

- 4 X 4 Array – 27.8” grid spacing
  - Field Rotates with Elevation Angle
- 15 GHz Instantaneous BW
  - 85-100 GHz (TRX ~ 55K)
  - 100-115 GHz (TRX 55-90K)
- Aperture Efficiency 55% at 100 GHz
- HPBW: 15.5”@86 GHz  13”@110 GHz
- Observing Modes:
  - On-the-fly Mapping
  - Position Switched Spectra
- WARES Spectrometer
- Sensitivity calculator verified with commissioning observations.
WARES

Digital Spectrometer

• Based on ROACH 2
• Modes:
  • Wide
  • Intermediate
  • Narrow
• Current Setup
  • 16 Spectrometers
  • 1 line per pixel
• Coming Soon
  • 32 Spectrometers
  • 2 lines in same SEQUOIA band per pixel

<table>
<thead>
<tr>
<th>MODE</th>
<th>W</th>
<th>I</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandwidth (MHz)</td>
<td>800</td>
<td>400</td>
<td>200</td>
</tr>
<tr>
<td>N Channels</td>
<td>2048</td>
<td>4096</td>
<td>8192</td>
</tr>
<tr>
<td>Resolution (kHz)</td>
<td>391</td>
<td>98</td>
<td>24</td>
</tr>
</tbody>
</table>

**SEQUOIA**

CO J=1-0 Line - 115.3 GHz

| Bandwidth (km/s) | 2082 | 1041 | 520 |
| Resolution (km/s) | 1.02 | 0.25 | 0.06 |

**SEQUOIA**

HCN J=1-0 Line - 88.6 GHz

| Bandwidth (km/s) | 2709 | 1354 | 677 |
| Resolution (km/s) | 1.32 | 0.33 | 0.08 |

**1mm SIS Receiver**

CO J=2-1 Line - 230.5 GHz

| Bandwidth (km/s) | 1041 | 521  | 260  |
| Resolution (km/s) | 0.51 | 0.125| 0.03 |
Commissioning Observations

*Orion Molecular Cloud*

OTF Mapping Example: Data Cube

10’ X 10’ Maps required 2200 s *elapsed telescope time* to complete

*65 mK rms in 1.3 km/s channel*
Commissioning Observations

*IRC+10216*

OTF Mapping Example: Data Cube

Average of four 10’x10’ Maps – 7” Nyquist Pixel Cells – 0.08K rms in 1 km/s channel

Each map required 2200s of elapsed telescope time to complete.
Observations from 2018-S1 Program

*GMC’s in M31 – Loinard et al.*

OTF Mapping Example: Data Cube

Each map has about 1 hour of observing time
Observations from 2018-S1

*M51 Maps – Calzetti et al.*

OTF Mapping Example: Data Cube

**Single Map** – 10’ X 10’

*4k seconds integration time*

**Multiple Maps**

*9.2 hours integration time – 4mk rms in 5km/s channel*
1 mm SIS Receiver ("MSIP 1mm Receiver")

- Single Pixel Heterodyne Receiver
  - Dual Polarization
  - Sideband Separation
  - 4 IF’s – IF Band: 4-12 GHz
- Frequency Range: 210-280 GHz
- TRX: 60-75K
- Aperture Efficiency: 26% @ 230 GHz
- 6” HPBW Beam
- WARES Spectrometer
  - Current Setup: 2 spectral lines, with one in each sideband.
- Observing Modes: OTF and PS
Commissioning Test
Observations of Comet 46P/Wirtanen

------ Observed Simultaneously ------

**USB**
- Frequency: 265.9 GHz

**LSB**
- Frequency: 225.7 GHz

**Narrow (200 MHz) Band Mode**
16 minutes of integration time

**Intermediate (400 MHz) Band Mode**
60 minutes of integration time
Redshift Search Receiver (RSR)

- Two receiver pixels with dual-polarization
- 1 kHz beam-switching to reduce 1/f noise
- 72 – 111 GHz instantaneous bandwidth at 31 MHz (~100 km/s) resolution
- Receiver temp ~ 60K; stable baselines
- detect multiple molecular-lines without prior information on galaxy redshift
RSR Study of UGC 5101 by Cruz-Gonzalez et al. (2020)

RSR spectrum from 32m LMT
Planck Selected SMG's
31 Objects detected ... here are 20

Harrington et al. (2016)
Berman et al., in prep

RSR spectra from 32m LMT
RSR: LMT 50-m vs. LMT 32-m

lensed high redshift galaxy
$z = 3.2$

[Credit: D. Sanchez]
Band 4 Receiver (B4R)

B4R Team

PI: Ryohei Kawabe (NAOJ)
Project Scientist: Bunyo Hatsukade (U. Tokyo)
Receiver Leader: Takeshi Sakai (UEC Tokyo)
BE leader: Kunihiko Tanaka (Keio University)
Science Advisors: Yoichi Tamura (Nagoya U.) and Kotaro Kohno (U. Tokyo)
Technical Advisor: Tai Oshima (NAOJ)
Other members: Akio Taniguchi, Masato Hagimoto, Keiichi Matsuda, Yohei Togami (Nagoya University), Yuki Yoshimura (U. Tokyo), Tatsuya Takekoshi (Kitami Tech/U. Tokyo), Teppei Yonetsu, Hiroyuki Maezawa (Osaka Pref. Univ), and Yoshito Shimajiri (NAOJ)
B4R

• Single-beam two-polarization 2mm-band receiver and dedicated digital spectrometer composed of four XFFTS boards

• Based on ALMA band-4 “2SB”, re-designed to fully use the 50m diameter of the LMT

• Installed and commissioned in 2018, science demonstration observations during fall 2019
Specifications

Commissioning results:

Aperture Efficiency

- $48 \pm 6\%$ (133 GHz)
- $46 \pm 6\%$ (147 GHz)

$T_{sys} = 90 - 120\ K$

for $\tau_{225\text{GHz}} \sim 0.2$

(toward targets)

Beam size~ $10''$ at 150 GHz

$1^{st}$ sidelobe < 3\% of peak

<table>
<thead>
<tr>
<th>Items</th>
<th>Specification</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF Frequency</td>
<td>125 – 163 GHz</td>
<td>ALMA Band-4 spec</td>
</tr>
<tr>
<td># of Beam and Polarization</td>
<td>Single and Two pols</td>
<td>ALMA Band-4 spec</td>
</tr>
<tr>
<td>Sidebands</td>
<td>Two single sidebands</td>
<td>ALMA Band-4 spec</td>
</tr>
<tr>
<td>Image Rejection Ratio</td>
<td>&gt; 13 dB</td>
<td></td>
</tr>
<tr>
<td>Trx (receiver noise)</td>
<td>&lt; 60 K</td>
<td>ALMA Band-4 spec</td>
</tr>
<tr>
<td>IF Frequency</td>
<td>4-8 GHz</td>
<td>ALMA Band-4 spec</td>
</tr>
<tr>
<td>Spectrometer (XFFTS)</td>
<td>4 XFFTS boards</td>
<td>expandable to 8 boards</td>
</tr>
<tr>
<td>Bandwidth/board</td>
<td>2.5 GHz/board</td>
<td>(20 GHz in total)</td>
</tr>
<tr>
<td># of freq channels/board</td>
<td>32,768 channels/board</td>
<td>(131,072 channels)</td>
</tr>
<tr>
<td>freq. resolution</td>
<td>76.3 kHz/channel</td>
<td>~ 0.18 km/s in velocity</td>
</tr>
</tbody>
</table>

Table 1. Specifications of the B4R system.

Beam Map at 129 GHz
Demo Science:
OTF images: OMC-1 5’x5’

Two Freq. Settings
Nov., 2019 40 min x 2
Spectral line survey

Δν = 1.7 km/s
rms ~ 0.038K

CH₂DOH
Vinyl Cyanide

SiS +

Methyl Cyanide

O¹³CS

CH₃OCH₃

HC₅N

H₂O

CH₃¹⁸OH

CH₃OCH₃

Acetone?

CH₃OH

C₃OH

S¹⁸O

CH₃N v=1

OCS

CH₃OCHO

C₃H₅CN

H²¹⁸O

CH₃N v=1

CH₃OCH₃

SO₂

H¹³CO

CH₃OCH₃

CH₂DOH

? CH₃OCHO v¹₈=1

(K)

CH₃OCH₃

C₂H₅CN

CS

CH₃OCHO

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(K)

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CH₃N v=1

OCS

CH₃OCHO

C₃H₅CN

H²¹⁸O

CH₃N v=1

CH₃OCH₃

SO₂

H¹³CO

CH₃OCH₃

CH₂DOH

? CH₃OCHO v¹₈=1
Demo Science:
CO Detections for high-z bright SMGs

On-source ~ 5-10 min.

Ta* (mK)

CO J=4-3  
z = 2.554

CO J=5-4  
z = 2.554

CO J=5-4  
z = 3.549

CO J=5-4  
z = 3.007

CO J=4-3  
z = 2.125

CO J=5-4  
z = 3.12

Nov., 2019

Frequency (GHz)
B4R

The 1st IF is 4 to 8 GHz, and the 1st LO composed of a synthesizer and multiplier chain. The first IF is down-converted using the 2nd LO (or 2nd IF reference) signal from other synthesizers to the final IF signal DC-2.5 GHz. The four sets of the IF signals are fed to the spectrometer via bandpass filters. The observing frequencies at the USB ($f_{USB}$) and the LSB ($f_{LSB}$) are calculated as follows:

$$f_{USB} = f_{LO} + f_{IFref} - f_{USB,XFFTS},$$
$$f_{LSB} = f_{LO} - f_{IFref} + f_{LSB,XFFTS},$$

where $f_{LO}$ is the 1st LO frequency, $f_{IFref}$ is the 2nd IF frequency (8.1 GHz for the default frequency setting), and $f_{USB,XFFTS}$ or $f_{LSB,XFFTS}$ are the XFFTS frequencies.

For example, if we select $f_{LO} = 140$ GHz, the observing frequencies are $f_{USB} = 145.6-148.1$ GHz and $f_{LSB} = 131.9-134.4$ GHz. Note that both band edges at the final IF at the spectrometer (i.e. 0.0 – 2.5 GHz), 0.0 – 0.1 MHz and 2.4 – 2.5 GHz are contaminated by out-band spectral signals due to aliasing of AD converter in the XFFTS board and the 2nd down conversion, respectively.

The 2mm B4R installed in the instruments room of the LMT.
Spectrometer: “XFFTS”

Basic Specifications for single XFFTS board
- Bandwidth: 2.5 GHz/each board
- Total Number of frequency channels: 32,768 ch./each board
- Freq Resolution: 1.16 ch x 76.3 kHz/ch = 88.5 kHz
- Velocity Resolution/Coverage: 0.177 km/s & ~ 5,800 km/s at 150 GHz

Frequency Configuration for B4R
- Four XFFTS boards for two pols & two sidebands (one each IF output)
- => upgrade to 8 XFFTS boards to cover full IF=4-8 GHz
  (currently additional two XFFTS boards purchased)