# A Practical Introduction to ALMA Correlator and Spectral Line Observations

Sheng-Yuan Liu

# Receiver Bands

**Table 2** Summary of ALMA receivers

| Band no. | | Frequency range (GHz) | Receiver noise temperature[a] (K) | Mixing scheme | IF Bandwidth |
|---|---|---|---|---|---|
| 3 | NA (HIA) | 84–116 | 37 | 2SB | 4 GHz |
| 4 | EA (NAOJ) | 125–169 | 51 | 2SB | 4 GHz |
| 5[b] | EU (OSO), 6? | 163–211 | 65 | 2SB | 4 GHz |
| 6 | NA (NRAO) | 211–275 | 83 | 2SB | 8 GHz |
| 7 | EU (IRAM) | 275–373 | 147 | 2SB | 4 GHz |
| 8 | EA (NAOJ) | 385–500 | 98 | 2SB | 4 GHz |
| 9 | EU (SRON) | 602–720 | 175 | DSB | 8 GHz |
| 10[b] | EA (NAOJ) | 787–950 | 230 | DSB | 8 GHz |

[a]Over 80% of the band, specification. Preproduction units tested to date have been outperforming their specifications

[b]At first light, these bands will be available on fewer than all of the antennas in the array

Reference : Wootten (2008), ASS, 313, 9

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[b]At first light, these bands will be available on fewer than all of the antennas in the array

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# Correlator

- Two correlators (nearly identical in functionality and parallel in operation)
  - "ALMA (Baseline) Correlator" by NRAO for the 12 m Array (+ ACA antennas)
    - (F)XF
  - "ACA Correlator" by NAOJ for ACA
    - FX
- This introduction mainly talks about ALMA (Baseline) Correlator, but for users, both correlators should behave/interface in the same way.

ALMA

The ALMA Correlator:

- 32 main racks with 3,000 printed circuit cards
  ( 4 identical but independent quadrant; 8 racks per quadrant)
- a total of 135,000 complex integrated circuits
- factor of 15,000 larger than the VLA correlator
- overall system dissipation: 170,000 W
- ~ 70 operation modes (5 modes [#7, 9, 12, 18, & 70 @ ES])

one quadrant (processing per baseband pair)


NRAO

Reference : Presentation by Remijan (2009)

# ALMA Correlator Modes

**Table 1 Mode chart with one baseband channel per quadrant being processed**

| Mode # | Number of sub-channel filters | Total Bandwidth | Number of Spectral Points | Spectral Resolution | Velocity resolution at 230 GHz | Correlation | Sample Factor | Minimum dump time* | Sensitivity** |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 32 | 2 GHz | 8192 | 244 kHz | 0.32 km/s | 2-bit x 2-bit | Nyquist | 512 msec | 0.88 |
| 19 | 32 | 2 GHz | 4096 | 488 kHz | 0.64 km/s | 2-bit x 2-bit | Twice Nyquist | 256 msec | 0.94 |
| 38 | 32 | 2 GHz | 2048 | 976 kHz | 1.28 km/s | 4-bit x 4-bit | Nyquist | 128 msec | 0.99 |
| 2 | 16 | 1 GHz | 8192 | 122 kHz | 0.16 km/s | 2-bit x 2-bit | Nyquist | 512 msec | 0.88 |
| 20 | 16 | 1 GHz | 4096 | 244 kHz | 0.32 km/s | 2-bit x 2-bit | Twice Nyquist | 256 msec | 0.94 |
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| 53 | 16 | 1 GHz | 1024 | 976 kHz | 1.28 km/s | 4-bit x 4-bit | Twice Nyquist | 64 msec | 0.99 |
| 3 | 8 | 500 MHz | 8192 | 61 kHz | 0.08 km/s | 2-bit x 2-bit | Nyquist | 512 msec | 0.88 |
| 21 | 8 | 500 MHz | 4096 | 122 kHz | 0.16 km/s | 2-bit x 2-bit | Twice Nyquist | 256 msec | 0.94 |
| 40 | 8 | 500 MHz | 2048 | 244 kHz | 0.32 km/s | 4-bit x 4-bit | Nyquist | 128 msec | 0.99 |
| 54 | 8 | 500 MHz | 1024 | 488 kHz | 0.64 km/s | 4-bit x 4-bit | Twice Nyquist | 64 msec | 0.99 |
| 4 | 4 | 250 MHz | 8192 | 30 kHz | 0.04 km/s | 2-bit x 2-bit | Nyquist | 512 msec | 0.88 |
| 22 | 4 | 250 MHz | 4096 | 61 kHz | 0.08 km/s | 2-bit x 2-bit | Twice Nyquist | 256 msec | 0.94 |
| 41 | 4 | 250 MHz | 2048 | 122 kHz | 0.16 km/s | 4-bit x 4-bit | Nyquist | 128 msec | 0.99 |
| 55 | 4 | 250 MHz | 1024 | 244 kHz | 0.32 km/s | 4-bit x 4-bit | Twice Nyquist | 64 msec | 0.99 |
| 5 | 2 | 125 MHz | 8192 | 15 kHz | 0.02 km/s | 2-bit x 2-bit | Nyquist | 512 msec | 0.88 |
| 23 | 2 | 125 MHz | 4096 | 30 kHz | 0.04 km/s | 2-bit x 2-bit | Twice Nyquist | 256 msec | 0.94 |
| 42 | 2 | 125 MHz | 2048 | 61 kHz | 0.08 km/s | 4-bit x 4-bit | Nyquist | 128 msec | 0.99 |
| 56 | 2 | 125 MHz | 1024 | 122 kHz | 0.16 km/s | 4-bit x 4-bit | Twice Nyquist | 64 msec | 0.99 |
| 6 | 1 | 62.5 MHz | 8192 | 7.6 kHz | 0.01 km/s | 2-bit x 2-bit | Nyquist | 512 msec | 0.88 |
| 24 | 1 | 62.5 MHz | 4096 | 15 kHz | 0.02 km/s | 2-bit x 2-bit | Twice Nyquist | 256 msec | 0.94 |
| 43 | 1 | 62.5 MHz | 2048 | 30 kHz | 0.04 km/s | 4-bit x 4-bit | Nyquist | 128 msec | 0.99 |
| 57 | 1 | 62.5 MHz | 1024 | 61 kHz | 0.08 km/s | 4-bit x 4-bit | Twice Nyquist | 64 msec | 0.99 |
| 25 | 1 | 31.25 MHz | 8192 | 3.8 kHz | 0.005 km/s | 2-bit x 2-bit | Twice Nyquist | 512 msec | 0.94 |
| 58 | 1 | 31.25 MHz | 2048 | 15 kHz | 0.02 km/s | 4-bit x 4-bit | Twice Nyquist | 128 msec | 0.99 |
| 68 | Time Division Mode | 2 GHz | 64 | 31.25 MHz | 40.8 km/s | 3-bit x 3-bit | Nyquist | 16 msec | 1.00 |
| 71 | Time Division Mode | 2 GHz | 256 | 7.8125 MHz | 10.2 km/s | 2-bit x 2-bit | Nyquist | 16 msec | 0.88 |

* **Assuming all products, all lags, transferred from correlator to Correlator Data Processor computer (in milli-seconds).**

* ***Multiply numbers in this column by the 0.96 sensitivity imposed by the 3-bit input digitizer.**

Reference : ALMA Memo, 556

# ALMA Correlator Modes

**Table 2 Mode chart with two baseband channels per quadrant processed with no polarization cross products.**

| Mode # | Number of sub-channel filters | Total Bandwidth | Number of Spectral Points | Spectral Resolution | Velocity resolution at 230 GHz | Correlation | Sample Factor | Minimum dump time* | Sensitivity** |
|---|---|---|---|---|---|---|---|---|---|
| 7 | 32 | 2 GHz | 4096 | 488 kHz | 0.64 km/s | 2-bit x 2-bit | Nyquist | 512 msec | 0.88 |
| 8 | 16 | 1 GHz | 4096 | 244 kHz | 0.32 km/s | 2-bit x 2-bit | Nyquist | 512 msec | 0.88 |
| 26 | 16 | 1 GHz | 2048 | 488 kHz | 0.64 km/s | 2-bit x 2-bit | Twice Nyquist | 256 msec | 0.94 |
| 44 | 16 | 1 GHz | 1024 | 976 kHz | 1.28 km/s | 4-bit x 4-bit | Nyquist | 128 msec | 0.99 |
| 9 | 8 | 500 MHz | 4096 | 122 kHz | 0.16 km/s | 2-bit x 2-bit | Nyquist | 512 msec | 0.88 |
| 27 | 8 | 500 MHz | 2048 | 244 kHz | 0.32 km/s | 2-bit x 2-bit | Twice Nyquist | 256 msec | 0.94 |
| 45 | 8 | 500 MHz | 1024 | 488 kHz | 0.64 km/s | 4-bit x 4-bit | Nyquist | 128 msec | 0.99 |
| 59 | 8 | 500 MHz | 512 | 976 kHz | 1.28 km/s | 4-bit x 4-bit | Twice Nyquist | 64 msec | 0.99 |
| 10 | 4 | 250 MHz | 4096 | 61 kHz | 0.08 km/s | 2-bit x 2-bit | Nyquist | 512 msec | 0.88 |
| 28 | 4 | 250 MHz | 2048 | 122 kHz | 0.16 km/s | 2-bit x 2-bit | Twice Nyquist | 256 msec | 0.94 |
| 46 | 4 | 250 MHz | 1024 | 244 kHz | 0.32 km/s | 4-bit x 4-bit | Nyquist | 128 msec | 0.99 |
| 60 | 4 | 250 MHz | 512 | 488 kHz | 0.64 km/s | 4-bit x 4-bit | Twice Nyquist | 64 msec | 0.99 |
| 11 | 2 | 125 MHz | 4096 | 30 kHz | 0.04 km/s | 2-bit x 2-bit | Nyquist | 512 msec | 0.88 |
| 29 | 2 | 125 MHz | 2048 | 61 kHz | 0.08 km/s | 2-bit x 2-bit | Twice Nyquist | 256 msec | 0.94 |
| 47 | 2 | 125 MHz | 1024 | 122 kHz | 0.16 km/s | 4-bit x 4-bit | Nyquist | 128 msec | 0.99 |
| 61 | 2 | 125 MHz | 512 | 244 kHz | 0.32 km/s | 4-bit x 4-bit | Twice Nyquist | 64 msec | 0.99 |
| 12 | 1 | 62.5 MHz | 4096 | 15 kHz | 0.02 km/s | 2-bit x 2-bit | Nyquist | 512 msec | 0.88 |
| 30 | 1 | 62.5 MHz | 2048 | 30 kHz | 0.04 km/s | 2-bit x 2-bit | Twice Nyquist | 256 msec | 0.94 |
| 48 | 1 | 62.5 MHz | 1024 | 61 kHz | 0.08 km/s | 4-bit x 4-bit | Nyquist | 128 msec | 0.99 |
| 62 | 1 | 62.5 MHz | 512 | 122 kHz | 0.16 km/s | 4-bit x 4-bit | Twice Nyquist | 64 msec | 0.99 |
| 31 | 1 | 31.25 MHz | 4096 | 7.6 kHz | 0.01 km/s | 2-bit x 2-bit | Twice Nyquist | 512 msec | 0.94 |
| 63 | 1 | 31.25 MHz | 1024 | 30 kHz | 0.04 km/s | 4-bit x 4-bit | Twice Nyquist | 128 msec | 0.99 |
| 69 | Time Division Mode | 2 GHz | 128 | 15.6 MHz | 20.4 km/s | 2-bit x 2-bit | Nyquist | 16 msec | 0.88 |

* **Assuming all products, all lags, transferred from correlator to Correlator Data Processor computer (in milli-seconds).**

* ***Multiply numbers in this column by the 0.96 sensitivity imposed by the 3-bit input digitizer.**

Reference : ALMA Memo, 556

# ALMA Correlator Modes

**Table 3 Mode chart with two baseband channels per quadrant processed with polarization cross products.**

| Mode # | Number of sub-channel filters | Total Bandwidth | Number of Spectral Points | Spectral Resolution | Velocity resolution at 230 GHz | Correlation | Sample Factor | Minimum dump time* | Sensitivity** |
|---|---|---|---|---|---|---|---|---|---|
| 13 | 32 | 2 GHz | 2048 | 976 kHz | 1.28 km/s | 2-bit x 2-bit | Nyquist | 512 msec | 0.88 |
| 14 | 16 | 1 GHz | 2048 | 488 kHz | 0.64 km/s | 2-bit x 2-bit | Nyquist | 512 msec | 0.88 |
| 32 | 16 | 1 GHz | 1024 | 976 kHz | 1.28 km/s | 2-bit x 2-bit | Twice Nyquist | 256 msec | 0.94 |
| 15 | 8 | 500 MHz | 2048 | 244 kHz | 0.32 km/s | 2-bit x 2-bit | Nyquist | 512 msec | 0.88 |
| 33 | 8 | 500 MHz | 1024 | 488 kHz | 0.64 km/s | 2-bit x 2-bit | Twice Nyquist | 256 msec | 0.94 |
| 16 | 4 | 250 MHz | 2048 | 122 kHz | 0.16 km/s | 2-bit x 2-bit | Nyquist | 512 msec | 0.88 |
| 34 | 4 | 250 MHz | 1024 | 244 kHz | 0.32 km/s | 2-bit x 2-bit | Twice Nyquist | 256 msec | 0.94 |
| 17 | 2 | 125 MHz | 2048 | 61 kHz | 0.08 km/s | 2-bit x 2-bit | Nyquist | 512 msec | 0.88 |
| 35 | 2 | 125 MHz | 1024 | 122 kHz | 0.16 km/s | 2-bit x 2-bit | Twice Nyquist | 256 msec | 0.94 |
| 51 | 2 | 125 MHz | 512 | 244 kHz | 0.32 km/s | 4-bit x 4-bit | Nyquist | 128 msec | 0.99 |
| 18 | 1 | 62.5 MHz | 2048 | 30 kHz | 0.04 km/s | 2-bit x 2-bit | Nyquist | 512 msec | 0.88 |
| 36 | 1 | 62.5 MHz | 1024 | 61 kHz | 0.08 km/s | 2-bit x 2-bit | Twice Nyquist | 256 msec | 0.94 |
| 52 | 1 | 62.5 MHz | 512 | 122 kHz | 0.16 km/s | 4-bit x 4-bit | Nyquist | 128 msec | 0.99 |
| 66 | 1 | 62.5 MHz | 256 | 244 kHz | 0.32 km/s | 4-bit x 4-bit | Twice Nyquist | 64 msec | 0.99 |
| 37 | 1 | 31.25 MHz | 2048 | 15 kHz | 0.02 km/s | 2-bit x 2-bit | Twice Nyquist | 512 msec | 0.94 |
| 67 | 1 | 31.25 MHz | 512 | 61 kHz | 0.08 km/s | 4-bit x 4-bit | Twice Nyquist | 128 msec | 0.99 |
| 70 | Time Division Mode | 2 GHz | 64 | 31.25 MHz | 40.8 km/s | 2-bit x 2-bit | Nyquist | 16 msec | 0.88 |

* **Assuming all products, all lags, transferred from correlator to Correlator Data Processor computer (in milli-seconds).**

* ***Multiply numbers in this column by the 0.96 sensitivity imposed by the 3-bit input digitizer.**

Reference : ALMA Memo, 556

# ALMA Correlator Modes

**Table 3 Mode chart with two baseband channels per quadrant processed with polarization cross products.**

Purpose of this presentation :
To go through the basic picture and terminologies

* **Assuming all products, all lags, transferred from correlator to Correlator Data Processor computer (in milli-seconds).**

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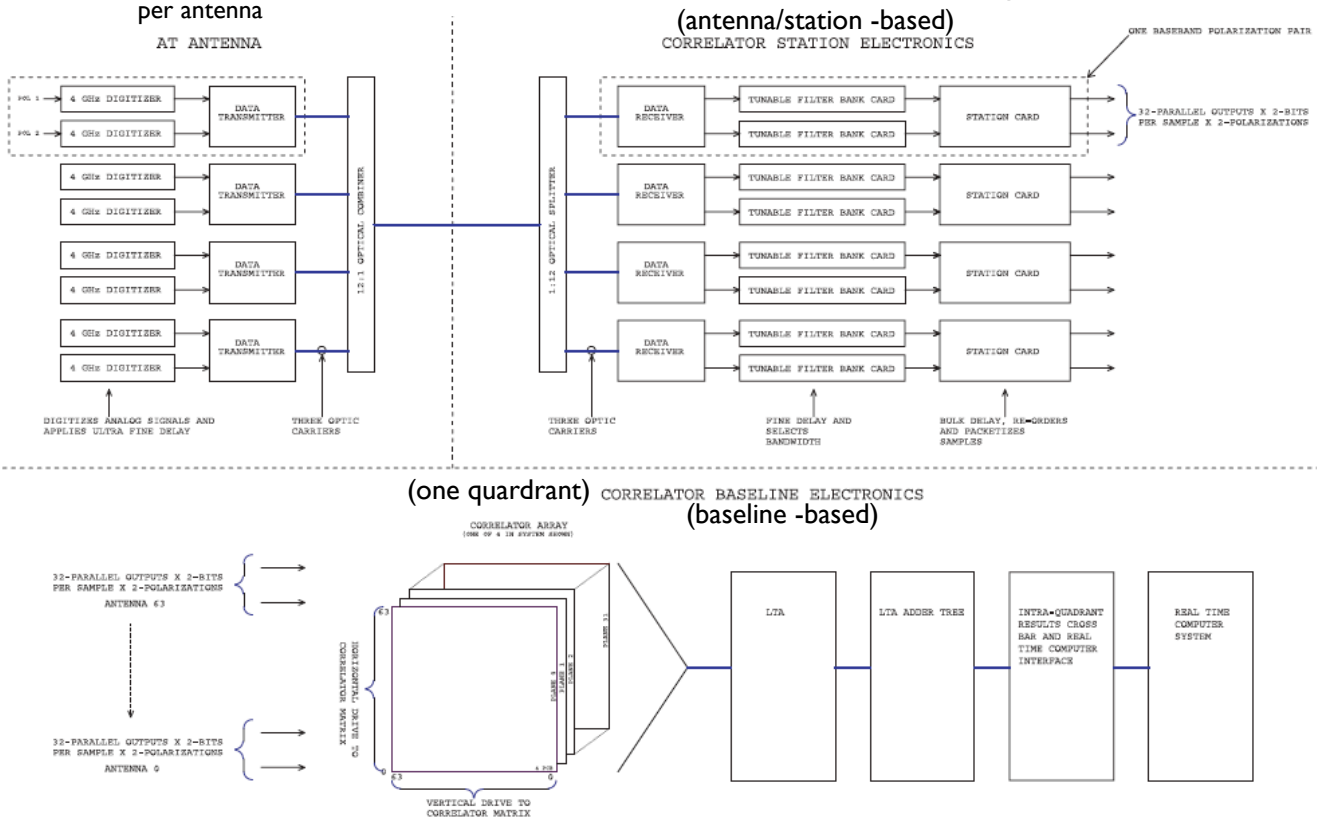
Reference : ALMA Memo, 556

# ALMA Correlator Block Diagram

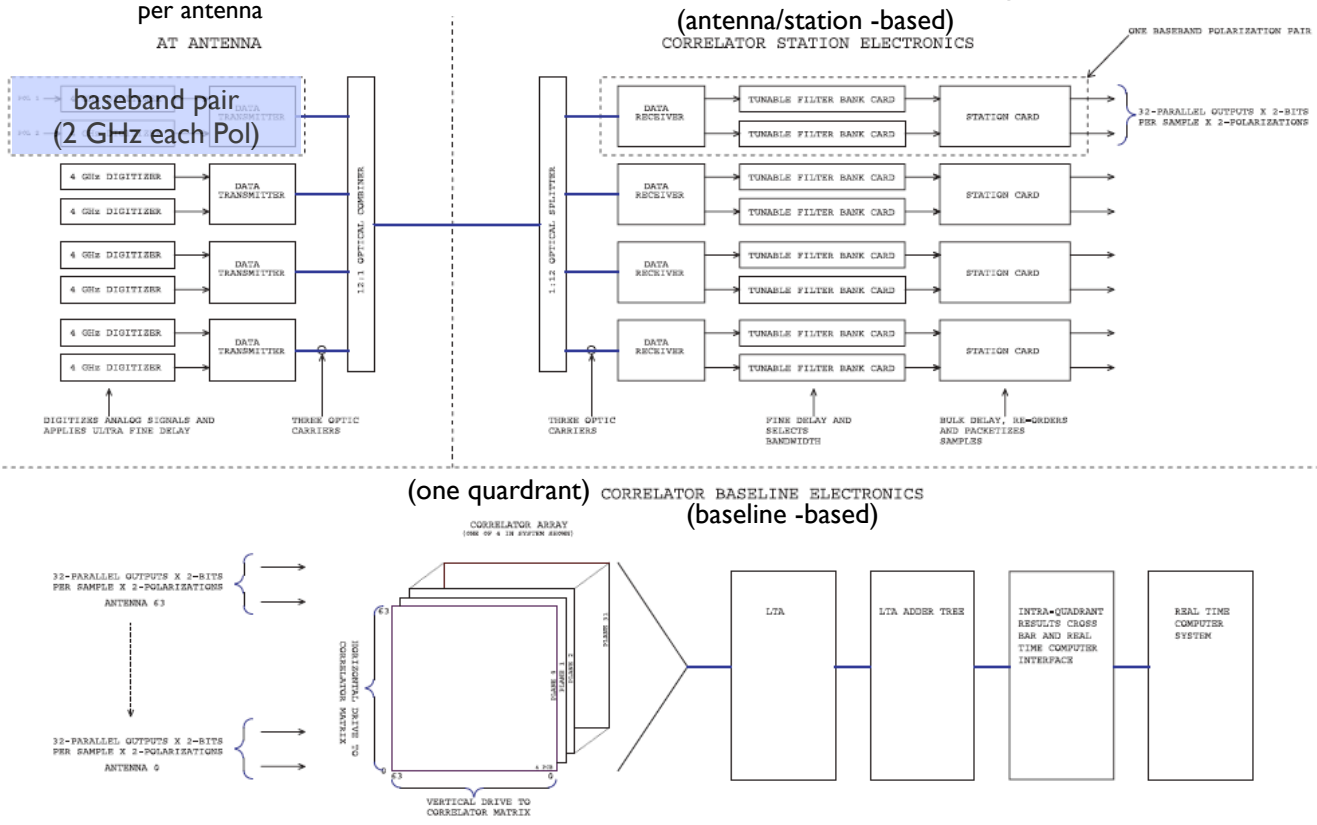
16 GHz bandwidth per antenna




Reference : Escoffier (2007), A&A, 462, 801


# ALMA Correlator Block Diagram

16 GHz bandwidth per antenna



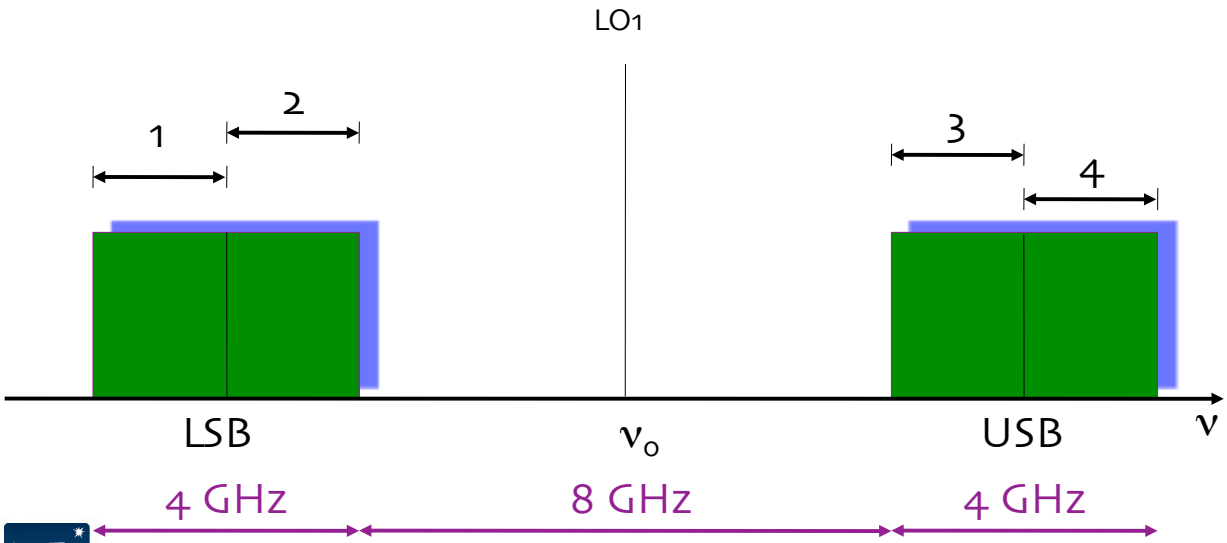
Reference : Escoffier (2007), A&A, 462, 801

# Correlator Modes

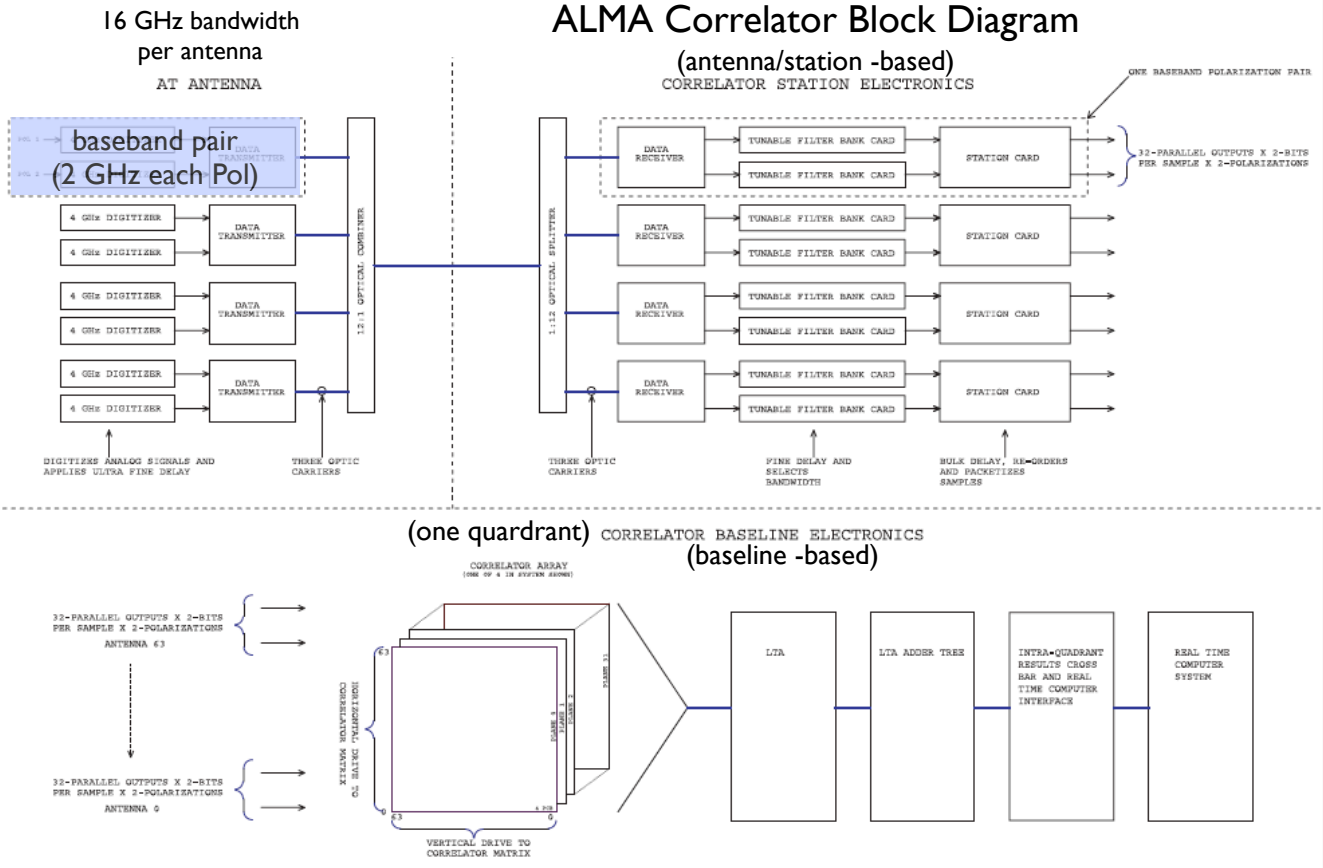
- baseband pairs from antennas are 2 GHz wide
- 4 baseband pairs are independently tunable

"baseband" - a bit similar to "block" in SMA

e.g., Band 3:




Reference : Presentation by Remijan (2009)

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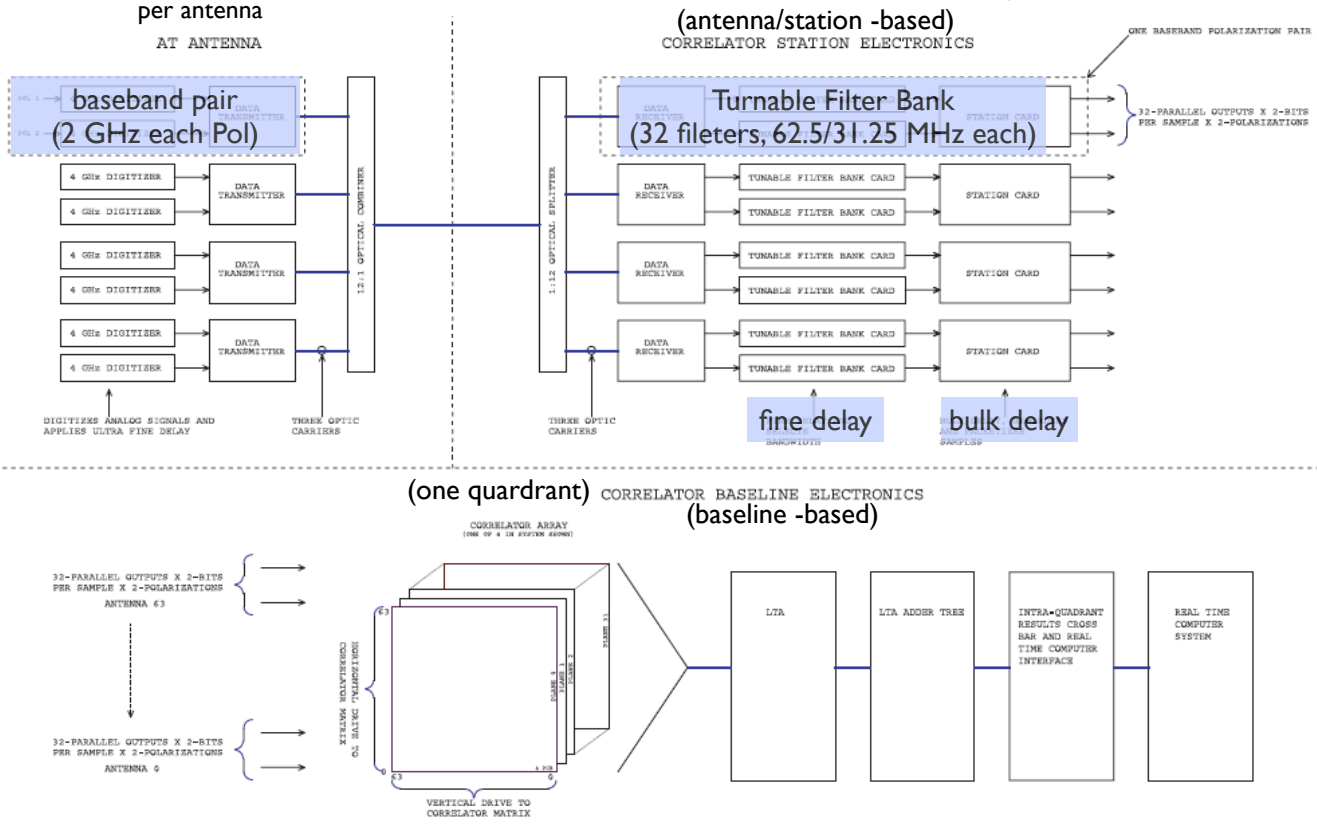
# ALMA Correlator Block Diagram




Reference : Escoffier (2007), A&A, 462, 801; Presentation by Di Francesco (2009)


# ALMA Correlator Block Diagram

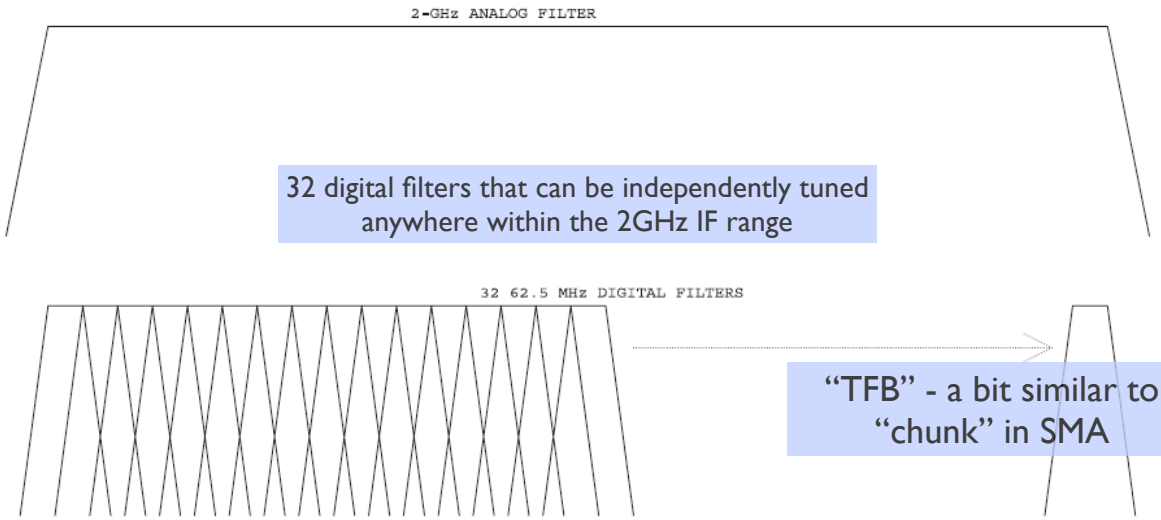
16 GHz bandwidth
per antenna
AT ANTENNA
baseband pair
(2 GHz each Pol)
(antenna/station -based)
CORRELATOR STATION ELECTRONICS
Turnable Filter Bank
(32 fileters, 62.5/31.25 MHz each)


"F": divide incoming signal up to smaller chunks (sub-bands) using a Tunable Filter Bank card

TFB divides up the input 2 GHz baseband into 32 sub-bands, each 62.5 MHz wide

- each sub-band can be tuned independently within the 2 GHz baseband
- allows quadrant to work simultaneously on many pieces of baseband
- no. of filters used determines band width:
  e.g., 32 filters ⇒ 2 GHz
  1 filter ⇒ 62.5 MHz


Reference : Escoffier (2007), A&A, 462, 801; Presentation by Di Francesco (2009)




32 digital filters that can be independently tuned anywhere within the 2GHz IF range

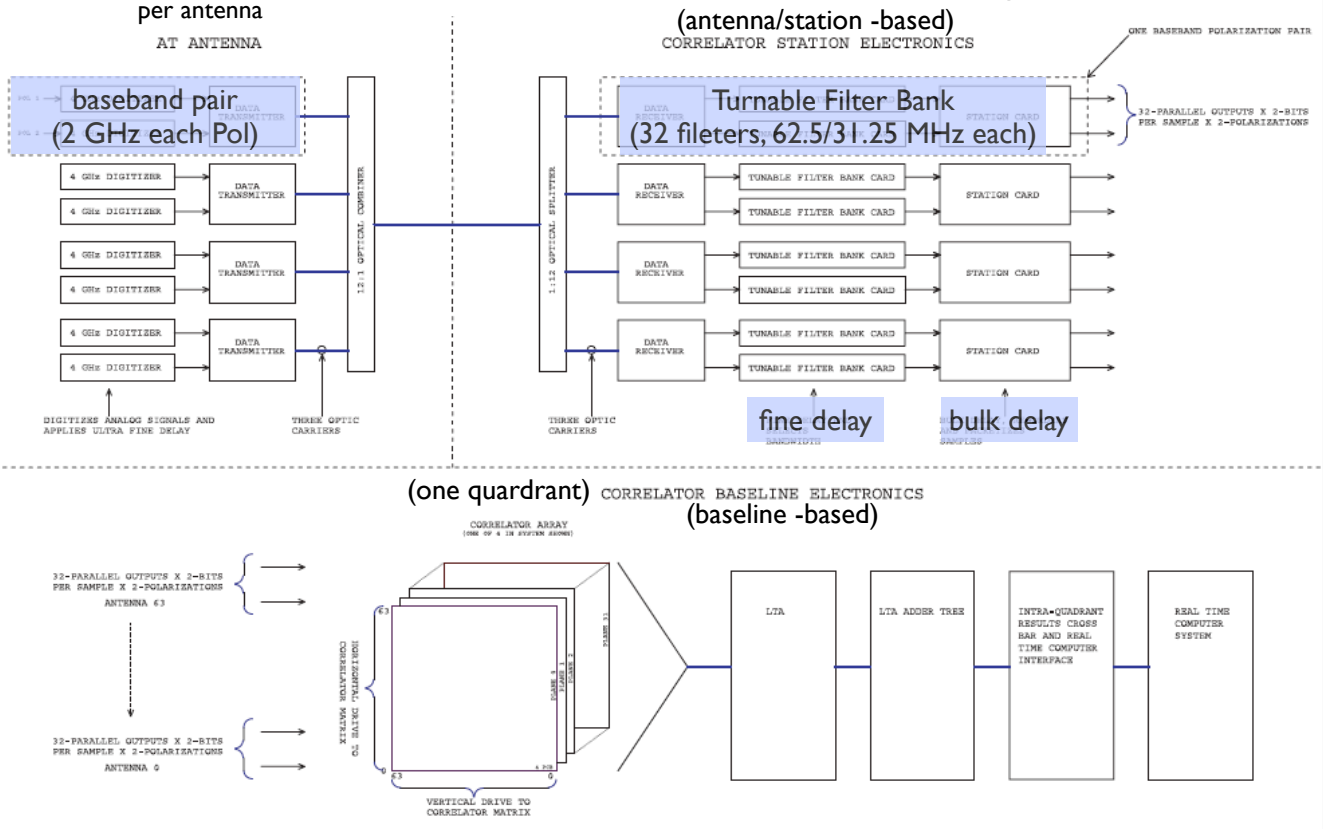
"TFB" - a bit similar to "chunk" in SMA

Bandwidth-for-resolution trade can be made with only a fraction of the 32 filters are active

Reference : Escoffier (2007), A&A, 462, 801

16 GHz bandwidth per antenna

# ALMA Correlator Block Diagram

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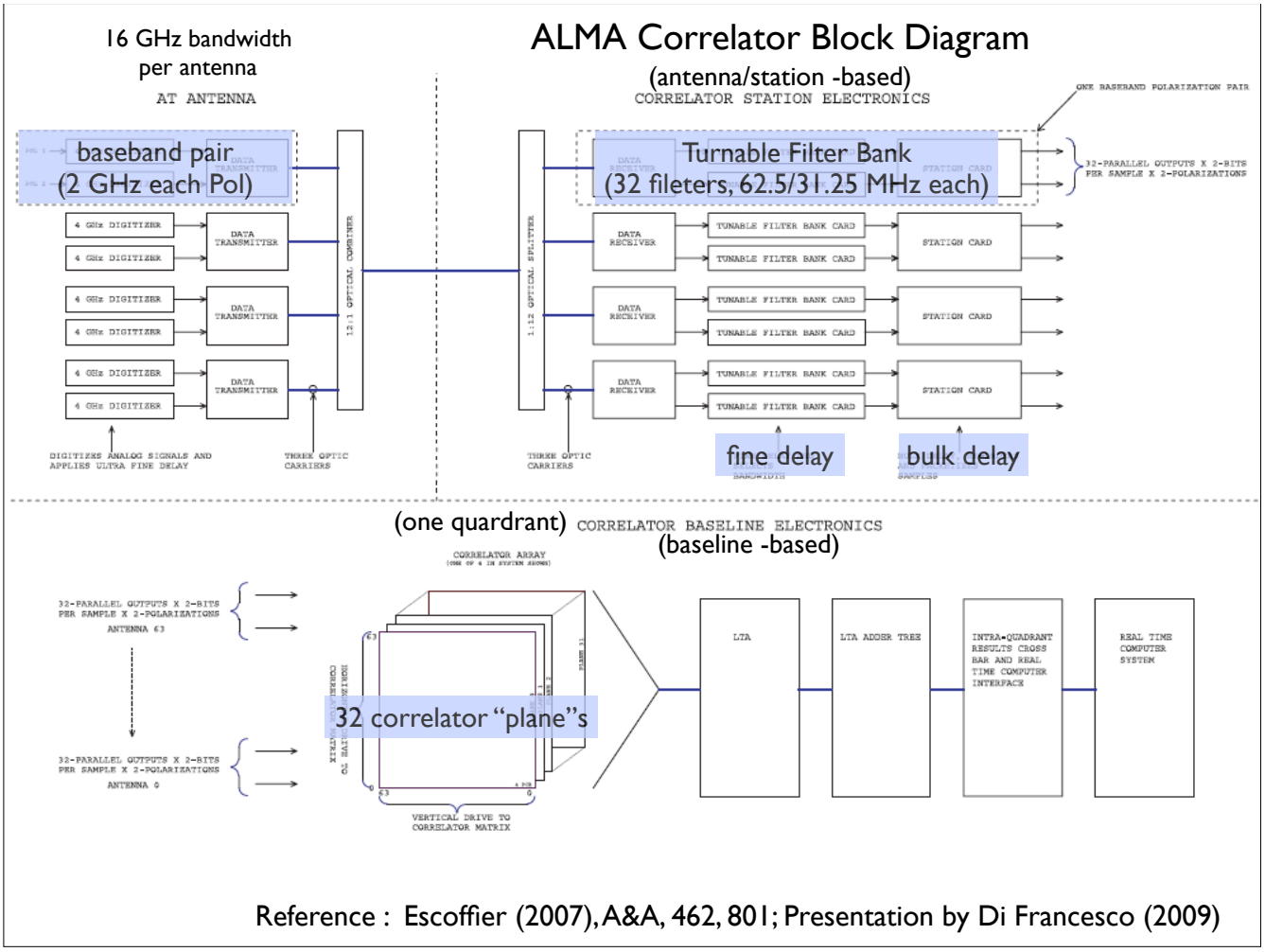


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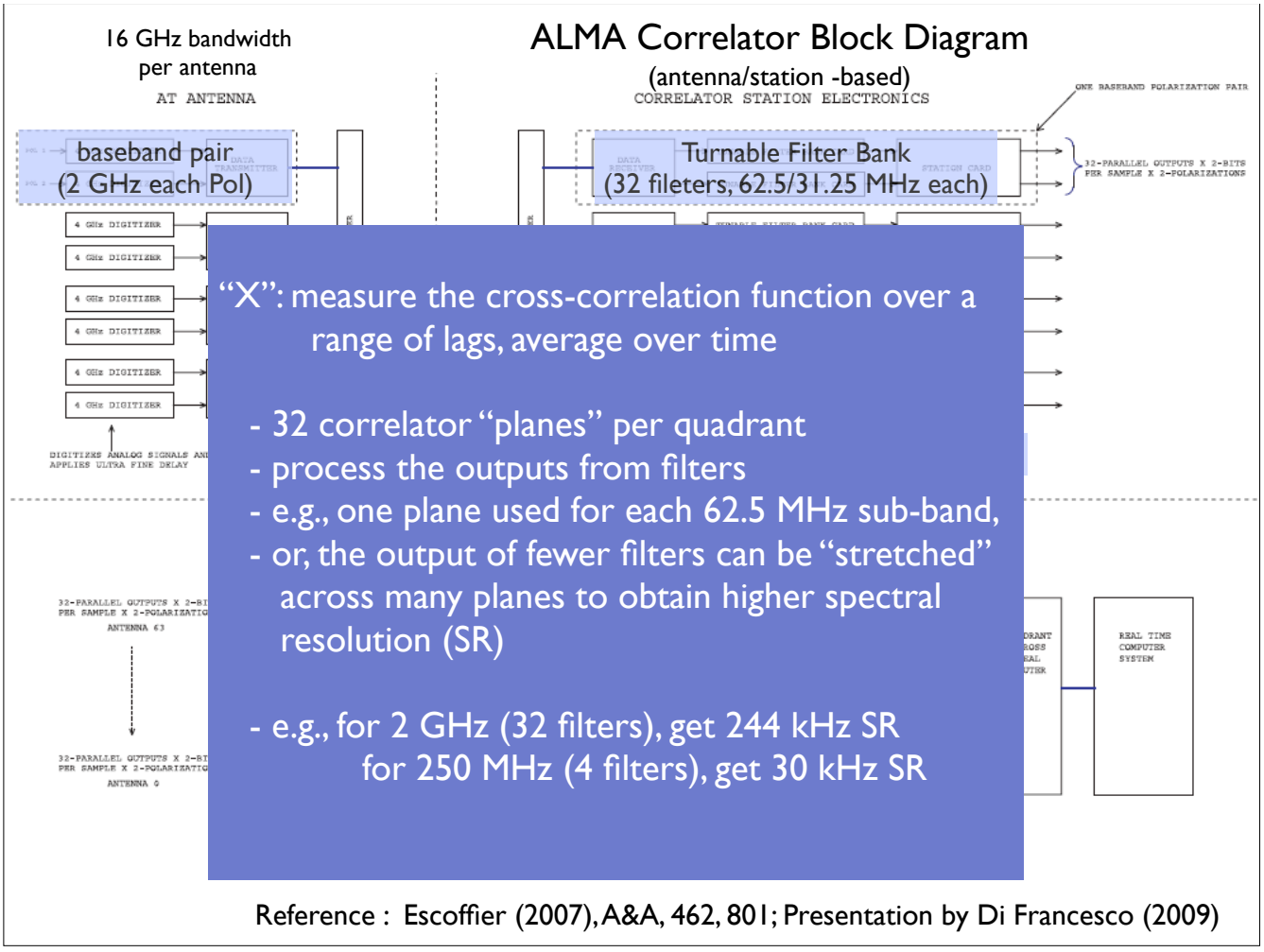


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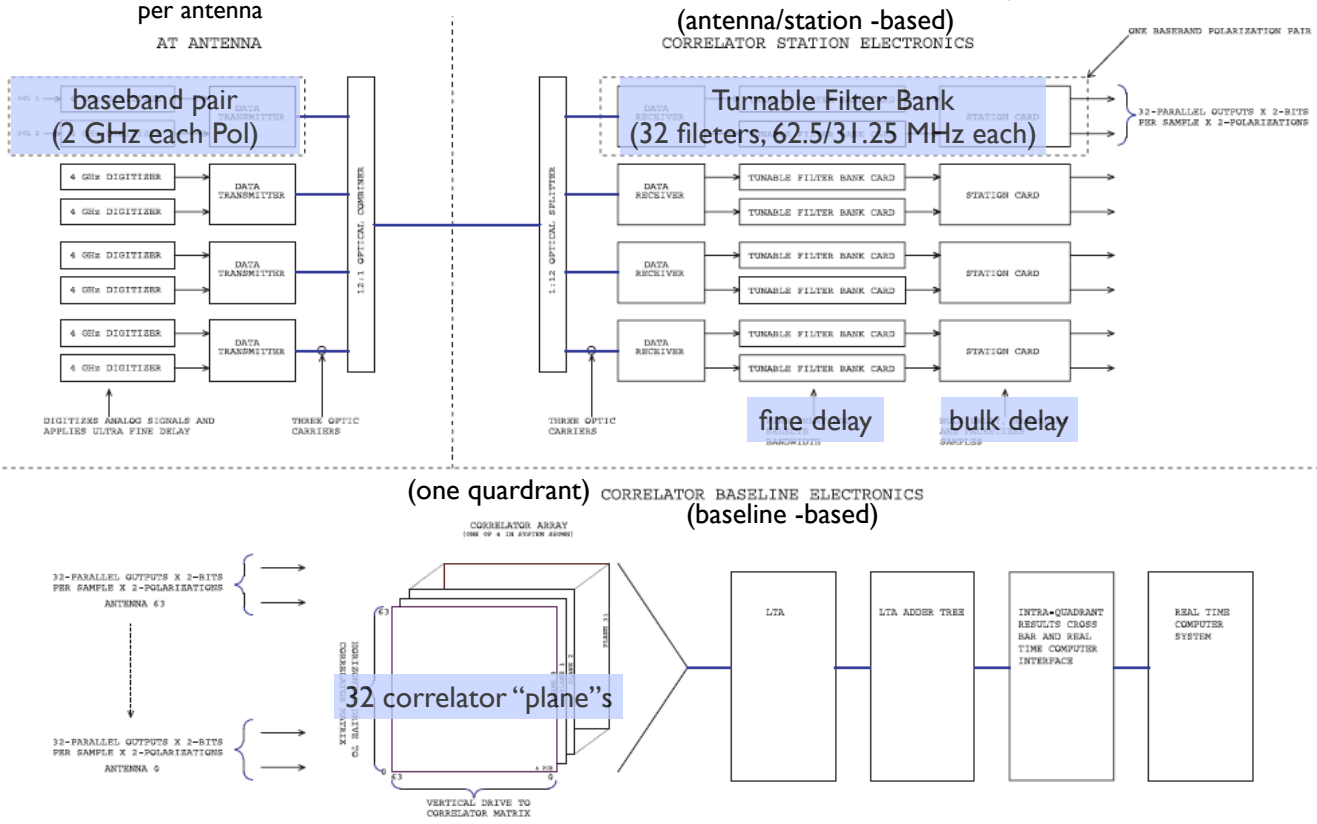


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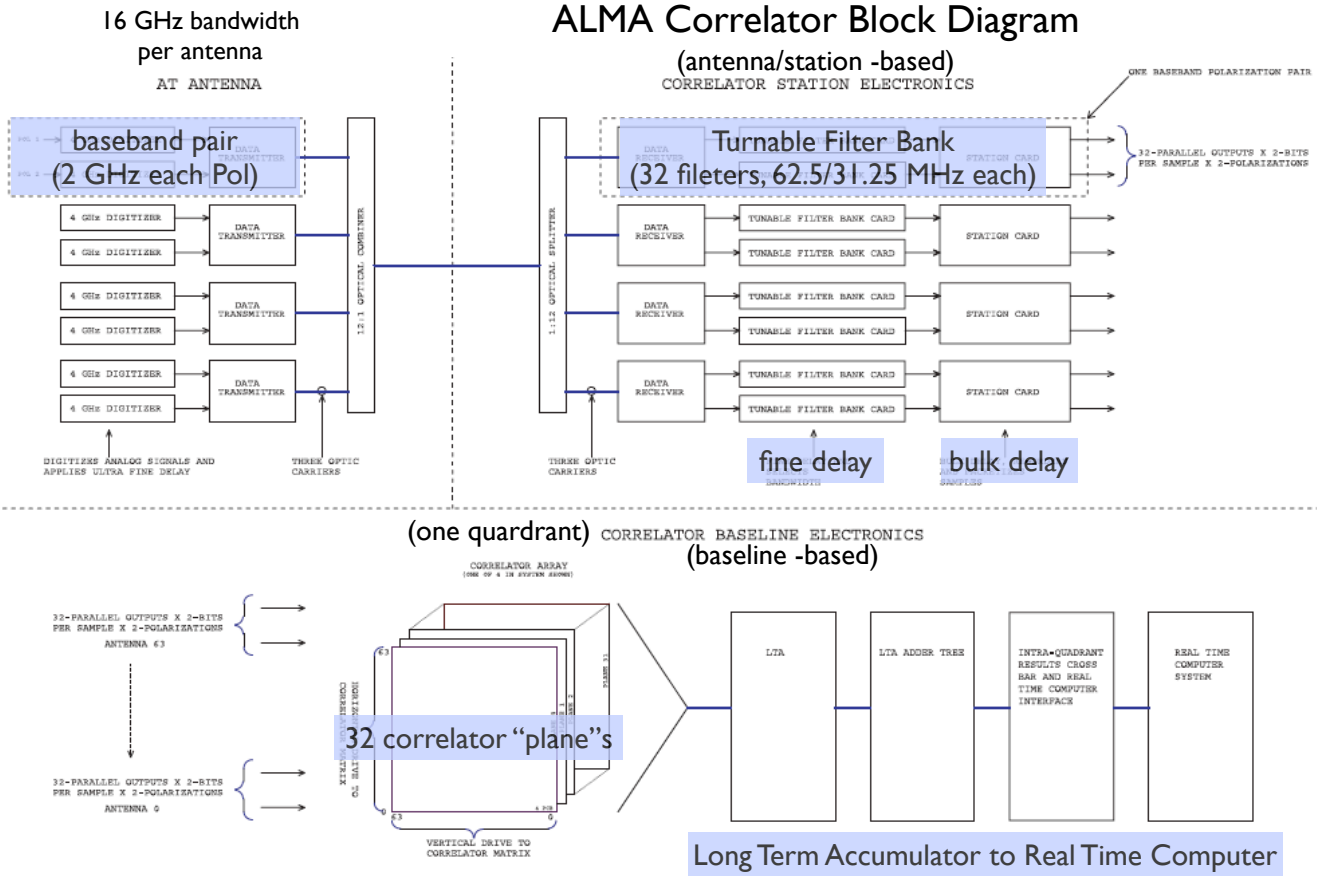
# ALMA Correlator Block Diagram



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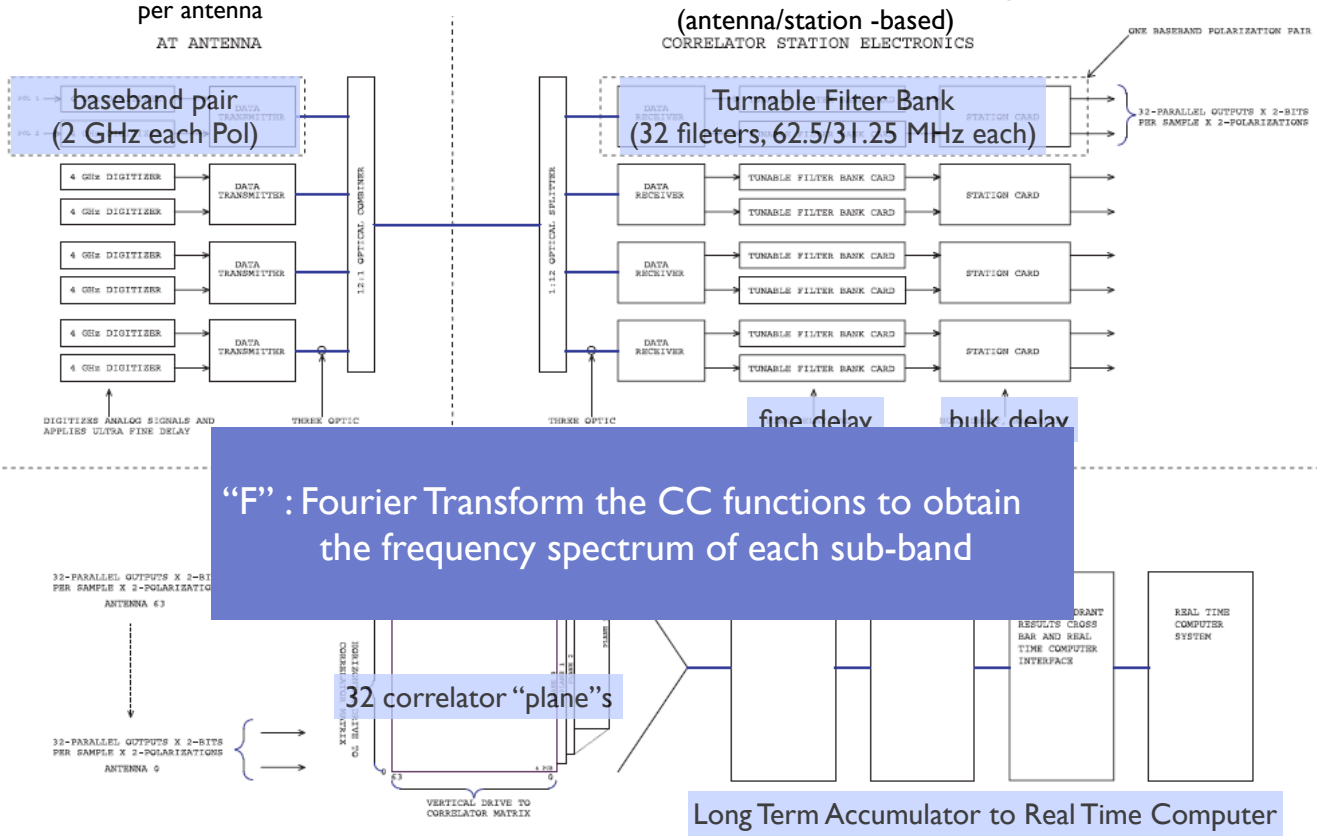


Reference : Escoffier (2007), A&A, 462, 801; Presentation by Di Francesco (2009)

# Correlator Modes

## adapted to any type of line observations

### *Total BW covers all cases*

from

- Pressure broadened lines in planets (>2-3 GHz required)
- Nearby galaxies (say < 200 Mpc) where we need $\Delta v_{Max}$ < or ~ 2000 km/s to map CO, CN, HCN, HNC => BW ~ 0.6 to 6 GHz in 90-950 GHz range

to

- Dark clouds where $\Delta v$ ~ 5 km/s require BW ~ 2-15 MHz only, depending on ALMA band

Spectral line surveys or CO line search in high-z objects … BW as large as possible: max provided 2, 4 or 8 GHz

### *Spectral Resolution covers all cases*

- Narrow features ~ 0.02-0.05 km/s expected for *Wind velocities in Planets, Dark Molecular Clouds, Protostellar Disks* etc. => ~ 6 kHz in Band 3 at 90 GHz
- *Galaxies* or *Energetic Outflows* ~ 1 MHz often sufficient

Reference : Presentation by Baudry (2008)

# Constraint/Consideration over Correlator Modes

- Bandwidth (31.25 MHz to 2 GHz)
- Central (or starting) frequency
- Resolution (or number of spectral points)
- Number of polarization products: 1 (AA or BB), 2 (AA & BB), or 4 (cross polarization products AB and BA also included)
- Improved sensitivity options: 4x4 bit correlation or double Nyquist modes (it is possible to specify both, but with very limited usefulness)

Reference : ALMA Memo, 556

## ALMA Correlator Modes

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| 55 | 4 | 250 MHz | 1024 | 244 kHz | 0.32 km/s | 4-bit x 4-bit | Twice Nyquist | 64 msec | 0.99 |
| 5 | 2 | 125 MHz | 8192 | 15 kHz | 0.02 km/s | 2-bit x 2-bit | Nyquist | 512 msec | 0.88 |
| 23 | 2 | 125 MHz | 4096 | 30 kHz | 0.04 km/s | 2-bit x 2-bit | Twice Nyquist | 256 msec | 0.94 |
| 42 | 2 | 125 MHz | 2048 | 61 kHz | 0.08 km/s | 4-bit x 4-bit | Nyquist | 128 msec | 0.99 |
| 56 | 2 | 125 MHz | 1024 | 122 kHz | 0.16 km/s | 4-bit x 4-bit | Twice Nyquist | 64 msec | 0.99 |
| 6 | 1 | 62.5 MHz | 8192 | 7.6 kHz | 0.01 km/s | 2-bit x 2-bit | Nyquist | 512 msec | 0.88 |
| 24 | 1 | 62.5 MHz | 4096 | 15 kHz | 0.02 km/s | 2-bit x 2-bit | Twice Nyquist | 256 msec | 0.94 |
| 43 | 1 | 62.5 MHz | 2048 | 30 kHz | 0.04 km/s | 4-bit x 4-bit | Nyquist | 128 msec | 0.99 |
| 57 | 1 | 62.5 MHz | 1024 | 61 kHz | 0.08 km/s | 4-bit x 4-bit | Twice Nyquist | 64 msec | 0.99 |
| 25 | 1 | 31.25 MHz | 8192 | 3.8 kHz | 0.005 km/s | 2-bit x 2-bit | Twice Nyquist | 512 msec | 0.94 |
| 58 | 1 | 31.25 MHz | 2048 | 15 kHz | 0.02 km/s | 4-bit x 4-bit | Twice Nyquist | 128 msec | 0.99 |
| 68 | Time Division Mode | 2 GHz | 64 | 31.25 MHz | 40.8 km/s | 3-bit x 3-bit | Nyquist | 16 msec | 1.00 |
| 71 | Time Division Mode | 2 GHz | 256 | 7.8125 MHz | 10.2 km/s | 2-bit x 2-bit | Nyquist | 16 msec | 0.88 |

* **Assuming all products, all lags, transferred from correlator to Correlator Data Processor computer (in milli-seconds).**

* ***Multiply numbers in this column by the 0.96 sensitivity imposed by the 3-bit input digitizer.**

Reference : ALMA Memo, 556

# ALMA Correlator Modes

**Table 1 Mode chart with one baseband channel per quadrant being processed** (Only AA or BB)

| Mode # | Number of sub-channel filters | Total Bandwidth | Number of Spectral Points | Spectral Resolution | Velocity resolution at 230 GHz | Correlation | Sample Factor | Minimum dump time* | Sensitivity** |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 32 | 2 GHz | 8192 | 244 kHz | 0.32 km/s | 2-bit x 2-bit | Nyquist | 512 msec | 0.88 |
| 19 | 32 | 2 GHz | 4096 | 488 kHz | 0.64 km/s | 2-bit x 2-bit | Twice Nyquist | 256 msec | 0.94 |
| 38 | 32 | 2 GHz | 2048 | 976 kHz | 1.28 km/s | 4-bit x 4-bit | Nyquist | 128 msec | 0.99 |
| 2 | 16 | 1 GHz | 8192 | 122 kHz | 0.16 km/s | 2-bit x 2-bit | Nyquist | 512 msec | 0.88 |
| 20 | 16 | 1 GHz | 4096 | 244 kHz | 0.32 km/s | 2-bit x 2-bit | Twice Nyquist | 256 msec | 0.94 |
| 39 | 16 | 1 GHz | 2048 | 488 kHz | 0.64 km/s | 4-bit x 4-bit | Nyquist | 128 msec | 0.99 |
| 53 | 16 | 1 GHz | 1024 | 976 kHz | 1.28 km/s | 4-bit x 4-bit | Twice Nyquist | 64 msec | 0.99 |
| 3 | 8 | 500 MHz | 8192 | 61 kHz | 0.08 km/s | 2-bit x 2-bit | Nyquist | 512 msec | 0.88 |
| 21 | 8 | 500 MHz | 4096 | 122 kHz | 0.16 km/s | 2-bit x 2-bit | Twice Nyquist | 256 msec | 0.94 |
| 40 | 8 | 500 MHz | 2048 | 244 kHz | 0.32 km/s | 4-bit x 4-bit | Nyquist | 128 msec | 0.99 |
| 54 | 8 | 500 MHz | 1024 | 488 kHz | 0.64 km/s | 4-bit x 4-bit | Twice Nyquist | 64 msec | 0.99 |
| 4 | 4 | 250 MHz | 8192 | 30 kHz | 0.04 km/s | 2-bit x 2-bit | Nyquist | 512 msec | 0.88 |
| 22 | 4 | 250 MHz | 4096 | 61 kHz | 0.08 km/s | 2-bit x 2-bit | Twice Nyquist | 256 msec | 0.94 |
| 41 | 4 | 250 MHz | 2048 | 122 kHz | 0.16 km/s | 4-bit x 4-bit | Nyquist | 128 msec | 0.99 |
| 55 | 4 | 250 MHz | 1024 | 244 kHz | 0.32 km/s | 4-bit x 4-bit | Twice Nyquist | 64 msec | 0.99 |
| 5 | 2 | 125 MHz | 8192 | 15 kHz | 0.02 km/s | 2-bit x 2-bit | Nyquist | 512 msec | 0.88 |
| 23 | 2 | 125 MHz | 4096 | 30 kHz | 0.04 km/s | 2-bit x 2-bit | Twice Nyquist | 256 msec | 0.94 |
| 42 | 2 | 125 MHz | 2048 | 61 kHz | 0.08 km/s | 4-bit x 4-bit | Nyquist | 128 msec | 0.99 |
| 56 | 2 | 125 MHz | 1024 | 122 kHz | 0.16 km/s | 4-bit x 4-bit | Twice Nyquist | 64 msec | 0.99 |
| 6 | 1 | 62.5 MHz | 8192 | 7.6 kHz | 0.01 km/s | 2-bit x 2-bit | Nyquist | 512 msec | 0.88 |
| 24 | 1 | 62.5 MHz | 4096 | 15 kHz | 0.02 km/s | 2-bit x 2-bit | Twice Nyquist | 256 msec | 0.94 |
| 43 | 1 | 62.5 MHz | 2048 | 30 kHz | 0.04 km/s | 4-bit x 4-bit | Nyquist | 128 msec | 0.99 |
| 57 | 1 | 62.5 MHz | 1024 | 61 kHz | 0.08 km/s | 4-bit x 4-bit | Twice Nyquist | 64 msec | 0.99 |
| 25 | 1 | 31.25 MHz | 8192 | 3.8 kHz | 0.005 km/s | 2-bit x 2-bit | Twice Nyquist | 512 msec | 0.94 |
| 58 | 1 | 31.25 MHz | 2048 | 15 kHz | 0.02 km/s | 4-bit x 4-bit | Twice Nyquist | 128 msec | 0.99 |
| 68 | Time Division Mode | 2 GHz | 64 | 31.25 MHz | 40.8 km/s | 3-bit x 3-bit | Nyquist | 16 msec | 1.00 |
| 71 | Time Division Mode | 2 GHz | 256 | 7.8125 MHz | 10.2 km/s | 2-bit x 2-bit | Nyquist | 16 msec | 0.88 |

* **Assuming all products, all lags, transferred from correlator to Correlator Data Processor computer (in milli-seconds).**

* ***Multiply numbers in this column by the 0.96 sensitivity imposed by the 3-bit input digitizer.**

*** dump time 1 msec for auto correlation mode

Reference : ALMA Memo, 556

# ALMA Correlator Modes

(AA & BB)

**Table 2 Mode chart with two baseband channels per quadrant processed with no polarization cross products.**

| Mode # | Number of sub-channel filters | Total Bandwidth | Number of Spectral Points | Spectral Resolution | Velocity resolution at 230 GHz | Correlation | Sample Factor | Minimum dump time* | Sensitivity** |
|---|---|---|---|---|---|---|---|---|---|
| 7 | 32 | 2 GHz | 4096 | 488 kHz | 0.64 km/s | 2-bit x 2-bit | Nyquist | 512 msec | 0.88 |
| 8 | 16 | 1 GHz | 4096 | 244 kHz | 0.32 km/s | 2-bit x 2-bit | Nyquist | 512 msec | 0.88 |
| 26 | 16 | 1 GHz | 2048 | 488 kHz | 0.64 km/s | 2-bit x 2-bit | Twice Nyquist | 256 msec | 0.94 |
| 44 | 16 | 1 GHz | 1024 | 976 kHz | 1.28 km/s | 4-bit x 4-bit | Nyquist | 128 msec | 0.99 |
| 9 | 8 | 500 MHz | 4096 | 122 kHz | 0.16 km/s | 2-bit x 2-bit | Nyquist | 512 msec | 0.88 |
| 27 | 8 | 500 MHz | 2048 | 244 kHz | 0.32 km/s | 2-bit x 2-bit | Twice Nyquist | 256 msec | 0.94 |
| 45 | 8 | 500 MHz | 1024 | 488 kHz | 0.64 km/s | 4-bit x 4-bit | Nyquist | 128 msec | 0.99 |
| 59 | 8 | 500 MHz | 512 | 976 kHz | 1.28 km/s | 4-bit x 4-bit | Twice Nyquist | 64 msec | 0.99 |
| 10 | 4 | 250 MHz | 4096 | 61 kHz | 0.08 km/s | 2-bit x 2-bit | Nyquist | 512 msec | 0.88 |
| 28 | 4 | 250 MHz | 2048 | 122 kHz | 0.16 km/s | 2-bit x 2-bit | Twice Nyquist | 256 msec | 0.94 |
| 46 | 4 | 250 MHz | 1024 | 244 kHz | 0.32 km/s | 4-bit x 4-bit | Nyquist | 128 msec | 0.99 |
| 60 | 4 | 250 MHz | 512 | 488 kHz | 0.64 km/s | 4-bit x 4-bit | Twice Nyquist | 64 msec | 0.99 |
| 11 | 2 | 125 MHz | 4096 | 30 kHz | 0.04 km/s | 2-bit x 2-bit | Nyquist | 512 msec | 0.88 |
| 29 | 2 | 125 MHz | 2048 | 61 kHz | 0.08 km/s | 2-bit x 2-bit | Twice Nyquist | 256 msec | 0.94 |
| 47 | 2 | 125 MHz | 1024 | 122 kHz | 0.16 km/s | 4-bit x 4-bit | Nyquist | 128 msec | 0.99 |
| 61 | 2 | 125 MHz | 512 | 244 kHz | 0.32 km/s | 4-bit x 4-bit | Twice Nyquist | 64 msec | 0.99 |
| 12 | 1 | 62.5 MHz | 4096 | 15 kHz | 0.02 km/s | 2-bit x 2-bit | Nyquist | 512 msec | 0.88 |
| 30 | 1 | 62.5 MHz | 2048 | 30 kHz | 0.04 km/s | 2-bit x 2-bit | Twice Nyquist | 256 msec | 0.94 |
| 48 | 1 | 62.5 MHz | 1024 | 61 kHz | 0.08 km/s | 4-bit x 4-bit | Nyquist | 128 msec | 0.99 |
| 62 | 1 | 62.5 MHz | 512 | 122 kHz | 0.16 km/s | 4-bit x 4-bit | Twice Nyquist | 64 msec | 0.99 |
| 31 | 1 | 31.25 MHz | 4096 | 7.6 kHz | 0.01 km/s | 2-bit x 2-bit | Twice Nyquist | 512 msec | 0.94 |
| 63 | 1 | 31.25 MHz | 1024 | 30 kHz | 0.04 km/s | 4-bit x 4-bit | Twice Nyquist | 128 msec | 0.99 |
| 69 | Time Division Mode | 2 GHz | 128 | 15.6 MHz | 20.4 km/s | 2-bit x 2-bit | Nyquist | 16 msec | 0.88 |

* **Assuming all products, all lags, transferred from correlator to Correlator Data Processor computer (in milli-seconds).**

* ***Multiply numbers in this column by the 0.96 sensitivity imposed by the 3-bit input digitizer.**

Reference : ALMA Memo, 556

# ALMA Correlator Modes

(AA & BB)

**Table 2 Mode chart with two baseband channels per quadrant processed with no polarization cross products.**

| Mode # | Number of sub-channel filters | Total Bandwidth | Number of Spectral Points | Spectral Resolution | Velocity resolution at 230 GHz | Correlation | Sample Factor | Minimum dump time* | Sensitivity** |
|---|---|---|---|---|---|---|---|---|---|
| 7 | 32 | 2 GHz | 4096 | 488 kHz | 0.64 km/s | 2-bit x 2-bit | Nyquist | 512 msec | 0.88 |
| 8 | 16 | 1 GHz | 4096 | 244 kHz | 0.32 km/s | 2-bit x 2-bit | Nyquist | 512 msec | 0.88 |
| 26 | 16 | 1 GHz | 2048 | 488 kHz | 0.64 km/s | 2-bit x 2-bit | Twice Nyquist | 256 msec | 0.94 |
| 44 | 16 | 1 GHz | 1024 | 976 kHz | 1.28 km/s | 4-bit x 4-bit | Nyquist | 128 msec | 0.99 |
| 9 | 8 | 500 MHz | 4096 | 122 kHz | 0.16 km/s | 2-bit x 2-bit | Nyquist | 512 msec | 0.88 |
| 27 | 8 | 500 MHz | 2048 | 244 kHz | 0.32 km/s | 2-bit x 2-bit | Twice Nyquist | 256 msec | 0.94 |
| 45 | 8 | 500 MHz | 1024 | 488 kHz | 0.64 km/s | 4-bit x 4-bit | Nyquist | 128 msec | 0.99 |
| 59 | 8 | 500 MHz | 512 | 976 kHz | 1.28 km/s | 4-bit x 4-bit | Twice Nyquist | 64 msec | 0.99 |
| 10 | 4 | 250 MHz | 4096 | 61 kHz | 0.08 km/s | 2-bit x 2-bit | Nyquist | 512 msec | 0.88 |
| 28 | 4 | 250 MHz | 2048 | 122 kHz | 0.16 km/s | 2-bit x 2-bit | Twice Nyquist | 256 msec | 0.94 |
| 46 | 4 | 250 MHz | 1024 | 244 kHz | 0.32 km/s | 4-bit x 4-bit | Nyquist | 128 msec | 0.99 |
| 60 | 4 | 250 MHz | 512 | 488 kHz | 0.64 km/s | 4-bit x 4-bit | Twice Nyquist | 64 msec | 0.99 |
| 11 | 2 | 125 MHz | 4096 | 30 kHz | 0.04 km/s | 2-bit x 2-bit | Nyquist | 512 msec | 0.88 |
| 29 | 2 | 125 MHz | 2048 | 61 kHz | 0.08 km/s | 2-bit x 2-bit | Twice Nyquist | 256 msec | 0.94 |
| 47 | 2 | 125 MHz | 1024 | 122 kHz | 0.16 km/s | 4-bit x 4-bit | Nyquist | 128 msec | 0.99 |
| 61 | 2 | 125 MHz | 512 | 244 kHz | 0.32 km/s | 4-bit x 4-bit | Twice Nyquist | 64 msec | 0.99 |
| 12 | 1 | 62.5 MHz | 4096 | 15 kHz | 0.02 km/s | 2-bit x 2-bit | Nyquist | 512 msec | 0.88 |
| 30 | 1 | 62.5 MHz | 2048 | 30 kHz | 0.04 km/s | 2-bit x 2-bit | Twice Nyquist | 256 msec | 0.94 |
| 48 | 1 | 62.5 MHz | 1024 | 61 kHz | 0.08 km/s | 4-bit x 4-bit | Nyquist | 128 msec | 0.99 |
| 62 | 1 | 62.5 MHz | 512 | 122 kHz | 0.16 km/s | 4-bit x 4-bit | Twice Nyquist | 64 msec | 0.99 |
| 31 | 1 | 31.25 MHz | 4096 | 7.6 kHz | 0.01 km/s | 2-bit x 2-bit | Twice Nyquist | 512 msec | 0.94 |
| 63 | 1 | 31.25 MHz | 1024 | 30 kHz | 0.04 km/s | 4-bit x 4-bit | Twice Nyquist | 128 msec | 0.99 |
| 69 | Time Division Mode | 2 GHz | 128 | 15.6 MHz | 20.4 km/s | 2-bit x 2-bit | Nyquist | 16 msec | 0.88 |

* Assuming all products, all lags, transferred from correlator to Correlator Data Processor computer (in milli-seconds).

* *Multiply numbers in this column by the 0.96 sensitivity imposed by the 3-bit input digitizer.

Reference : ALMA Memo, 556

# ALMA Correlator Modes

(AA, BB, AB, & BA)

**Table 3 Mode chart with two baseband channels per quadrant processed with polarization cross products.**

| Mode # | Number of sub-channel filters | Total Bandwidth | Number of Spectral Points | Spectral Resolution | Velocity resolution at 230 GHz | Correlation | Sample Factor | Minimum dump time* | Sensitivity** |
|---|---|---|---|---|---|---|---|---|---|
| 13 | 32 | 2 GHz | 2048 | 976 kHz | 1.28 km/s | 2-bit x 2-bit | Nyquist | 512 msec | 0.88 |
| 14 | 16 | 1 GHz | 2048 | 488 kHz | 0.64 km/s | 2-bit x 2-bit | Nyquist | 512 msec | 0.88 |
| 32 | 16 | 1 GHz | 1024 | 976 kHz | 1.28 km/s | 2-bit x 2-bit | Twice Nyquist | 256 msec | 0.94 |
| 15 | 8 | 500 MHz | 2048 | 244 kHz | 0.32 km/s | 2-bit x 2-bit | Nyquist | 512 msec | 0.88 |
| 33 | 8 | 500 MHz | 1024 | 488 kHz | 0.64 km/s | 2-bit x 2-bit | Twice Nyquist | 256 msec | 0.94 |
| 16 | 4 | 250 MHz | 2048 | 122 kHz | 0.16 km/s | 2-bit x 2-bit | Nyquist | 512 msec | 0.88 |
| 34 | 4 | 250 MHz | 1024 | 244 kHz | 0.32 km/s | 2-bit x 2-bit | Twice Nyquist | 256 msec | 0.94 |
| 17 | 2 | 125 MHz | 2048 | 61 kHz | 0.08 km/s | 2-bit x 2-bit | Nyquist | 512 msec | 0.88 |
| 35 | 2 | 125 MHz | 1024 | 122 kHz | 0.16 km/s | 2-bit x 2-bit | Twice Nyquist | 256 msec | 0.94 |
| 51 | 2 | 125 MHz | 512 | 244 kHz | 0.32 km/s | 4-bit x 4-bit | Nyquist | 128 msec | 0.99 |
| 18 | 1 | 62.5 MHz | 2048 | 30 kHz | 0.04 km/s | 2-bit x 2-bit | Nyquist | 512 msec | 0.88 |
| 36 | 1 | 62.5 MHz | 1024 | 61 kHz | 0.08 km/s | 2-bit x 2-bit | Twice Nyquist | 256 msec | 0.94 |
| 52 | 1 | 62.5 MHz | 512 | 122 kHz | 0.16 km/s | 4-bit x 4-bit | Nyquist | 128 msec | 0.99 |
| 66 | 1 | 62.5 MHz | 256 | 244 kHz | 0.32 km/s | 4-bit x 4-bit | Twice Nyquist | 64 msec | 0.99 |
| 37 | 1 | 31.25 MHz | 2048 | 15 kHz | 0.02 km/s | 2-bit x 2-bit | Twice Nyquist | 512 msec | 0.94 |
| 67 | 1 | 31.25 MHz | 512 | 61 kHz | 0.08 km/s | 4-bit x 4-bit | Twice Nyquist | 128 msec | 0.99 |
| 70 | Time Division Mode | 2 GHz | 64 | 31.25 MHz | 40.8 km/s | 2-bit x 2-bit | Nyquist | 16 msec | 0.88 |

* Assuming all products, all lags, transferred from correlator to Correlator Data Processor computer (in milli-seconds).

* *Multiply numbers in this column by the 0.96 sensitivity imposed by the 3-bit input digitizer.

Reference : ALMA Memo, 556

## ALMA Correlator Modes

(AA, BB, AB, & BA)

**Table 3 Mode chart with two baseband channels per quadrant processed with polarization cross products.**

| Mode # | Number of sub-channel filters | Total Bandwidth | Number of Spectral Points | Spectral Resolution | Velocity resolution at 230 GHz | Correlation | Sample Factor | Minimum dump time* | Sensitivity** |
|---|---|---|---|---|---|---|---|---|---|
| 13 | 32 | 2 GHz | 2048 | 976 kHz | 1.28 km/s | 2-bit x 2-bit | Nyquist | 512 msec | 0.88 |
| 14 | 16 | 1 GHz | 2048 | 488 kHz | 0.64 km/s | 2-bit x 2-bit | Nyquist | 512 msec | 0.88 |
| 32 | 16 | 1 GHz | 1024 | 976 kHz | 1.28 km/s | 2-bit x 2-bit | Twice Nyquist | 256 msec | 0.94 |
| 15 | 8 | 500 MHz | 2048 | 244 kHz | 0.32 km/s | 2-bit x 2-bit | Nyquist | 512 msec | 0.88 |
| 33 | 8 | 500 MHz | 1024 | 488 kHz | 0.64 km/s | 2-bit x 2-bit | Twice Nyquist | 256 msec | 0.94 |
| 16 | 4 | 250 MHz | 2048 | 122 kHz | 0.16 km/s | 2-bit x 2-bit | Nyquist | 512 msec | 0.88 |
| 34 | 4 | 250 MHz | 1024 | 244 kHz | 0.32 km/s | 2-bit x 2-bit | Twice Nyquist | 256 msec | 0.94 |
| 17 | 2 | 125 MHz | 2048 | 61 kHz | 0.08 km/s | 2-bit x 2-bit | Nyquist | 512 msec | 0.88 |
| 35 | 2 | 125 MHz | 1024 | 122 kHz | 0.16 km/s | 2-bit x 2-bit | Twice Nyquist | 256 msec | 0.94 |
| 51 | 2 | 125 MHz | 512 | 244 kHz | 0.32 km/s | 4-bit x 4-bit | Nyquist | 128 msec | 0.99 |
| 18 | 1 | 62.5 MHz | 2048 | 30 kHz | 0.04 km/s | 2-bit x 2-bit | Nyquist | 512 msec | 0.88 |
| 36 | 1 | 62.5 MHz | 1024 | 61 kHz | 0.08 km/s | 2-bit x 2-bit | Twice Nyquist | 256 msec | 0.94 |
| 52 | 1 | 62.5 MHz | 512 | 122 kHz | 0.16 km/s | 4-bit x 4-bit | Nyquist | 128 msec | 0.99 |
| 66 | 1 | 62.5 MHz | 256 | 244 kHz | 0.32 km/s | 4-bit x 4-bit | Twice Nyquist | 64 msec | 0.99 |
| 37 | 1 | 31.25 MHz | 2048 | 15 kHz | 0.02 km/s | 2-bit x 2-bit | Twice Nyquist | 512 msec | 0.94 |
| 67 | 1 | 31.25 MHz | 512 | 61 kHz | 0.08 km/s | 4-bit x 4-bit | Twice Nyquist | 128 msec | 0.99 |
| 70 | Time Division Mode | 2 GHz | 64 | 31.25 MHz | 40.8 km/s | 2-bit x 2-bit | Nyquist | 16 msec | 0.88 |

* **Assuming all products, all lags, transferred from correlator to Correlator Data Processor computer (in milli-seconds).**

* ***Multiply numbers in this column by the 0.96 sensitivity imposed by the 3-bit input digitizer.**

Reference : ALMA Memo, 556

# Correlator Modes

1. Time Division Modes

(the correlator quadrant analyzes the entire 2GHz IF bandwidth with limited frequency resolution. This mode is well suited for continuum observation and is mandatory for fast dumping rates)

- total band width of 2 GHz (continuum only)
- filters divide up 1 ms of integration into 32 smaller time blocks
- planes process each time block, allows faster integration times of 16 ms
- only Nyquist sampling possible
- SR depends on no. of polzns (1, 2 or 4) and quantization level (2-bit or 3-bit)
- e.g., 128 x 15.6 MHz SR for 2 polzns

Reference : Presentation by Di Francesco (2009); ALMA Memo 556

# Correlator Modes

1. Time Division Modes
(the correlator quadrant analyzes the entire 2GHz IF bandwidth with limited frequency resolution. This mode is well suited for continuum observation and is mandatory for fast dumping rates)
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- filters divide up 1 ms of integration into 32 smaller t
- planes pr integrat
- only Nyq
- SR depends on no. of polzns (1, 2 or 4) and quantization level (2-bit or 3-bit)
- e.g., 128 x 15.6 MHz SR for 2 polzns

Key consideration:
large/max continuum bandwidth
and/or fast time sample

Reference : Presentation by Di Francesco (2009); ALMA Memo 556

ALMA

# Correlator Modes (Examples)

Example of Time Division Modes (Band 6):

- 1 quadrant observes 2 GHz of LSB (230-232 GHz), 2 polzns, 2-bit, Nyq., get 128 spectral points each 15.6 MHz wide

- 1 quadrant observes 2 GHz of LSB (232-234 GHz), 4 polzns, 2-bit, Nyq., get 64 spectral points each 31.25 MHz wide

- 1 quadrant observes 2 GHz of USB (246-248 GHz), 2 polzns, 2-bit, Nyq., get 128 spectral points each 15.6 MHz wide

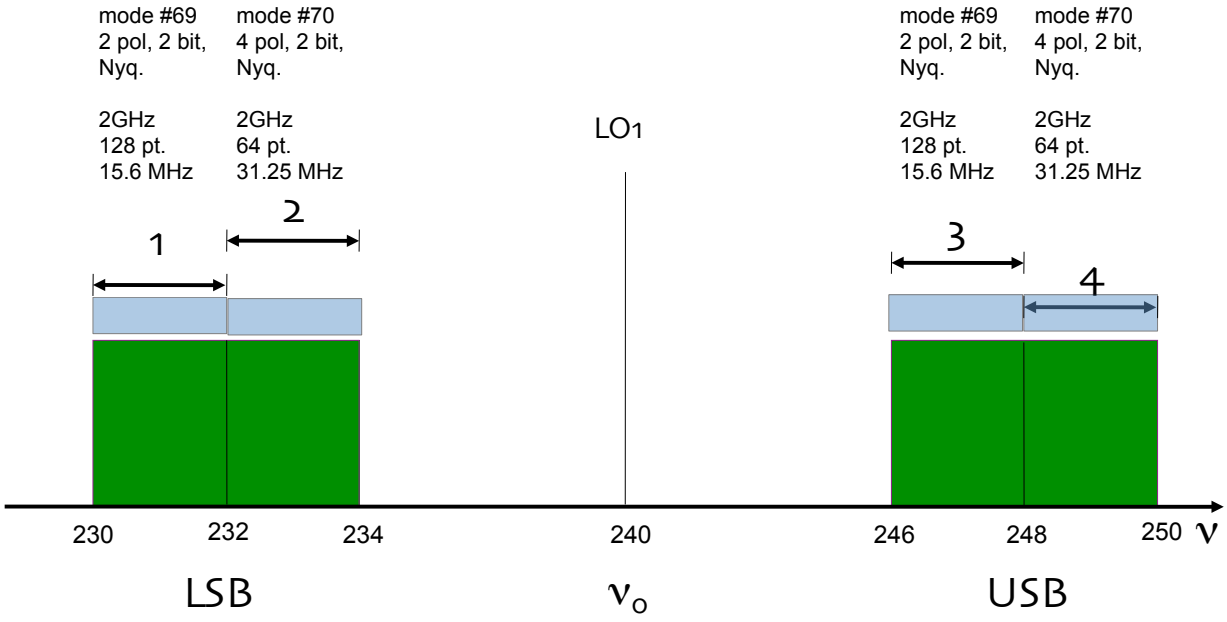
- 1 quadrant observes 2 GHz of USB (248-250 GHz), 4 polzns, 2-bit, Nyq., get 64 spectral points each 31.25 MHz wide

NRAO

Reference : Presentation by Remijan (2009)

# Correlator Modes

e.g., Band 6:



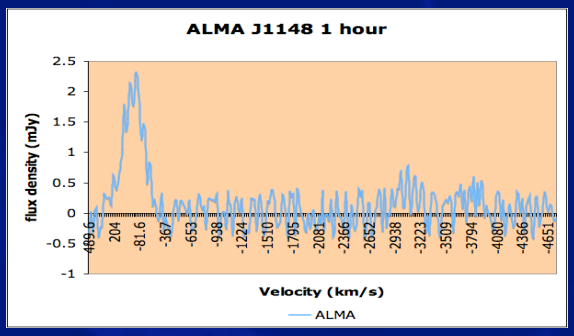

# J1148+5251: an EoR paradigm with ALMA

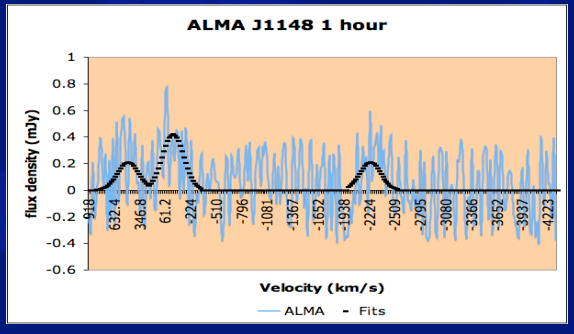
CO J=6-5

Wrong declination (though ideal for Madrid)!
But…
High sensitivity
- 12hr 1σ 0.2mJy

Wide bandwidth
- 3mm, 2 x 4 GHz IF
- Default 'continuum' mode
- Top: USB, 94.8 GHz
  - CO 6-5
  - HCN 8-7
  - HCO+ 8-7
  - H2CO lines
- Lower: LSB, 86.8 GHz
  - HNC 7-6
  - H2CO lines
  - $C^{18}O$ 6-5
  - $H_2O$ 658GHz maser?

Secure redshifts
Molecular astrophysics
ALMA could observe CO-luminous galaxies (e.g. M51) at z~6.




Reference : Presentation by Wootten (2009)

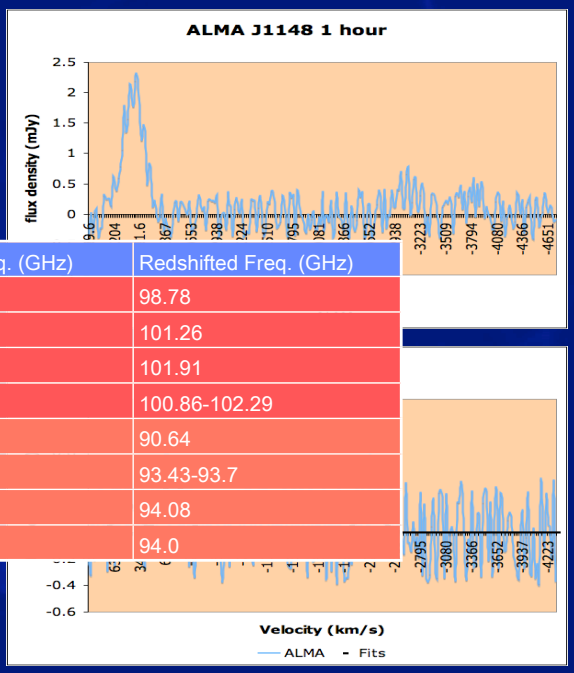
# J1148+5251: an EoR paradigm with ALMA

CO J=6-5

Wrong declination (though ideal for Madrid)!
But…
High sensitivity
- 12hr 1σ 0.2mJy

Wide bandwidth
- 3mm, 2 x 4 GHz IF
- Default 'continuum' mode
- Top: USB, 94.8 GHz
  - CO 6-5
  - HCN 8-7
  - HCO+ 8-7
  - H2CO lines
- Lower: LSB, 86.8 GHz
  - HNC 7-6
  - H2CO lines
  - $C^{18}O$ 6-5
  - $H_2O$ 658GHz maser?

Secure redshifts
Molecular astrophysics
ALMA could observe CO-luminous galaxies (e.g. M51) at z~6.




| Molecule | Rest Freq. (GHz) | Redshifted Freq. (GHz) |
|---|---|---|
| CO 6-5 | 691.47 | 98.78 |
| HCN 8-7 | 708.88 | 101.26 |
| $HCO^+$ 8-7 | 713.34 | 101.91 |
| $H_2CO$ | 706-716 | 100.86-102.29 |
| HNC 7-6 | 634.51 | 90.64 |
| $H_2CO$ | 654-656 | 93.43-93.7 |
| $C^{18}O$ 6-5 | 658.55 | 94.08 |
| $H_2O$ | 658.00 | 94.0 |

Reference : Presentation by Wootten (2009)

# Correlator Modes

2. Frequency Division Modes

(the correlator quadrant analyzes a portion (from 31.25 MHz to the entire 2GHz) of the IF bandwidth with high spectral resolution (up to 8192 spectral points.) Options to limit the sensitivity loss due to multiple quantization levels are available)

- filters used to obtain 31.25 MHz - 2 GHz BWs, all planes work on filtered BW to improve SR
- spectral resolution (SR) depends on:
  - no of polarizations (1, 2, or 4)
  - quantization level (2-bit or 4-bit)*
  - sampling rate (1 Nyq. or 2 Nyq.)
- 1 spectral "window"/"region" per quadrant
- slower integration times: 64-512 ms

* Correlation efficiency is 0.88 for 2-bit x 2-bit, increases to 0.94 (2N) or 0.99 (4-bit), yielding respectively 14% and 27% reductions in observing time.

Reference : Presentation by Di Francesco (2009); ALMA Memo 556

# Correlator Modes

2. Frequency Division Modes
(the correlator quadrant analyzes a portion (from 31.25 MHz to the entire 2GHz) of the IF bandwidth with high spectral resolution (up to 8192 spectral points.) Options to limit the sensitivity loss due to multiple quantization levels are available)

- filters used to obtain 31.25 MHz - 2 GHz BWs,
- sl
  - sampling rate (1 Nyq. or 2 Nyq.)
- 1 spectral "window"/"region" per quadrant
- slower integration times: 64-512 ms

Key consideration:
uniform and continuous spectral coverage of a limited bandwidth within the 2GHz IF range

* Correlation efficiency is 0.88 for 2-bit x 2-bit, increases to 0.94 (2N) or 0.99 (4-bit), yielding respectively 14% and 27% reductions in observing time.

Reference : Presentation by Di Francesco (2009); ALMA Memo 556

# Correlator Modes

- a quick side-discussion on digitization:

  - Sampling: signals ($v(t)$, $0 \leq \nu \leq \Delta\nu$) are lossless if sampled at the Nyquist rate, $\Delta t < 1/2(\Delta\nu)$

  - Quantization: chosen level (2-bit, 4-bit) can induce offsets (noise), $v(t) \Rightarrow v(t) + \delta$

- higher sampling rate and quantization level better reproduce input signal, improves S/N, at a cost to SR (correlator resources)

- can choose sampling rate (1N or 2N, for factor 2 SR) and quantization level (2-, (3-), 4-bit, for factor 4 SR)

Reference : Presentation by Di Francesco (2009); ALMA Memo 556

- a quick side-dis

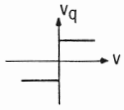
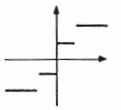
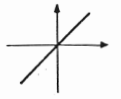
  - Sampling: sig … if sampled at the Nyqui…

  - Quantization … nduce offsets (noise…

  - higher sampli… …etter reproduce inp… …t to SR (correlato…

  - can choose sa… …2 SR) and quantization l… …SR)

Table 4–1.
Signal-to-Noise Ratio vs. Quantization and Sampling Rate

| Quantization | | Sampling Rate | $\frac{S/N\ (digital)}{S/N\ (continuous)}$ |
|---|---|---|---|
|  | 2-level (1 bit) | $2\Delta\nu$ | .64 |
| | | $4\Delta\nu$ | .74 |
|  | 3-level | $2\Delta\nu$ | .81* |
| | | $4\Delta\nu$ | .89 |
|  | 4-level | $2\Delta\nu$ | .88 |
| | | $4\Delta\nu$ | .94 |
|  | ∞-level (continuous) | $2\Delta\nu$ | 1.00 |
| | | $4\Delta\nu$ | 1.00 |

*VLA Case.
All cases assume rectangular bandpasses of width $\Delta\nu$, signal levels adjusted to maximize the signal-to-noise ratio, and small correlation coefficients.

See also TMS 8.4

Reference : Presentation by Di Francesco (2009); ALMA Memo 556

ALMA

# Correlator Modes

Example of Frequency Division Modes (Band 6):

- 1 quadrant observes (in USB) CO 2-1 at 230.538 GHz over 125 MHz; mode 61 yields 512 spectral points with 0.32 km $s^{-1}$ resolution, 2 polzns, 4-bit, 2 x Nyq.

- 1 quadrant observes (in LSB) $C^{18}O$ 2-1 at 219.560 GHz over 31.25 MHz; mode 63 yields 1024 spectral points with 0.04 km $s^{-1}$ resolution, 2 polzns, 4-bit, 2 x Nyq.

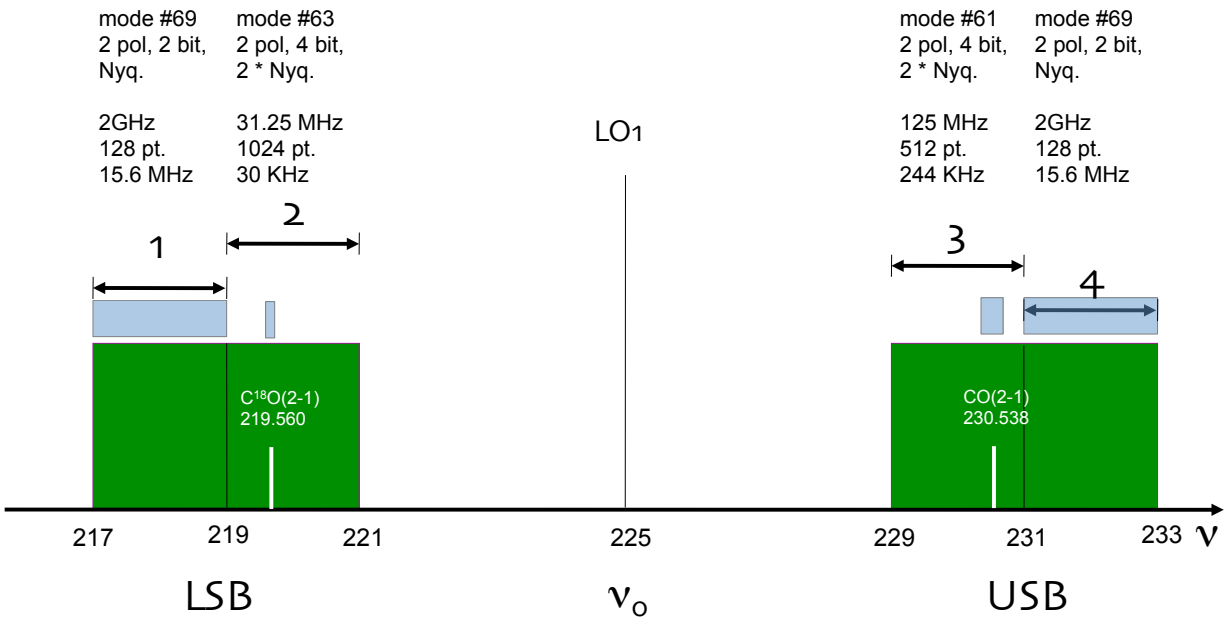
- 2 quadrants observe continuum over 2 GHz each (one in USB, one in LSB) in time division mode; mode 69 yields 128 spectral points, 20.4 km $s^{-1}$ resolution, 2 polzns, 2-bit, Nyq.

NRAO

Reference : Presentation by Remijan (2009)

## Correlator Modes

e.g., Band 6:




# Correlator Modes

3. Multiple Region Modes

(One of the modes in the previous group is split into multiple disjoint spectra regions. Spectral resolution, polarization and sensitivity enhancement options must be the same for all regions.)

- for frequency division modes with BWs of 125 MHz - 1 GHz, can divide up BW…
- allows multiple lines within BW to be observed simultaneously within the 2 GHz baseband, if:
  - region BW must be a multiple of 62.5 MHz
  - other parameters (SR, no. of polzns, quant. level and sampling rate) must be the same for all regions
- trade-off between no. of regions and SR!

Reference : Presentation by Di Francesco (2009); ALMA Memo 556

# Correlator Modes

3. Multiple Region Modes

(One of the modes in the previous group is split into multiple disjoint spectra regions. Spectral resolution, polarization and sensitivity enhancement options must be the same for all regions.)

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  125 M
- allow
  simul
  - regi
  - other parameters (SR, no. of polzns, quant. level and sampling rate) must be the same for all regions
- trade-off between no. of regions and SR!

**Key consideration:**
**bandwidth-for resolution trade-off**
**high and uniform resolution over disjoint spectra regions within 2GHz IF**

Reference : Presentation by Di Francesco (2009); ALMA Memo 556

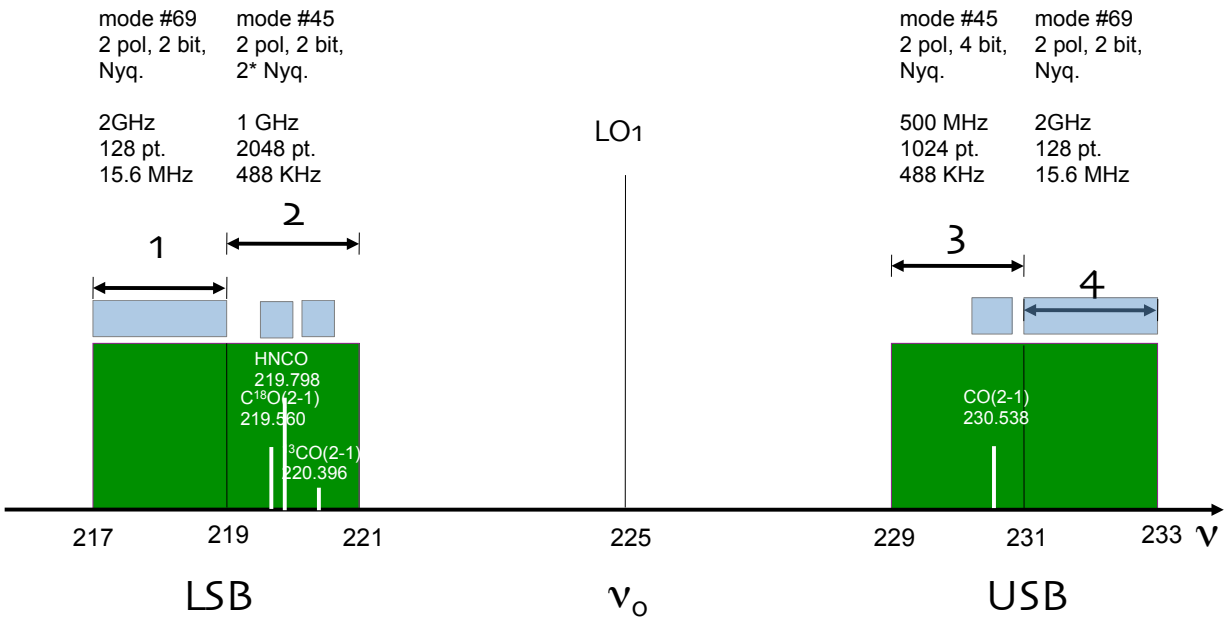
# Extragalactic CO Setup

| Line | CO | 13CO | C18O | HNCO | Cont |
|---|---|---|---|---|---|
| Frequency | 230.538 USB | 220.398 LSB | 219.580 LSB | 219.798 LSB | 4 GHz USB&LSB |
| Resolution* | 0.64 km/s | 0.64 km/s | 0.64 km/s | 0.64 km/s | 21 km/s |
| Window | Q1: 500 MHz | Q2: 500 MHz | Q2: 500 MHz | Q2: 500 MHz | Q3&4: 2 GHz |
| Channel decimation | To ~5 km/s | To ~5 km/s | To ~5 km/s | To ~5 km/s | Excise lines |
| Spatial resolution | 1" (300m) | 1" | 1" | 1" | 1" |

Reference : Presentation by Wootten (2009)

# Correlator Modes

e.g., Band 6:





# Correlator Modes


Example of Multiple Region Modes (Band 6):

- 1 quadrant observes (in USB) uses mode 47, 125 GHz BW, 1024 spectral points at 0.16 km $s^{-1}$ SR, 2 polzns, 4-bit, Nyq.:
  - 1/4 for CO 2-1 at 230.5 GHz,
  - 1/4 for $N_2D+$ 3-2 at 231.3 GHz,
  - 1/4 for $CH_3OH$ $8_{-1}$-$7_0$ E at 229.8 GHz,
  - 1/4 for $SO_2$ 11(5,7) - 12(4,8) at 229.3 GHz,

  for 4 windows each with 256 spectral points (BW: 164 km $s^{-1}$)

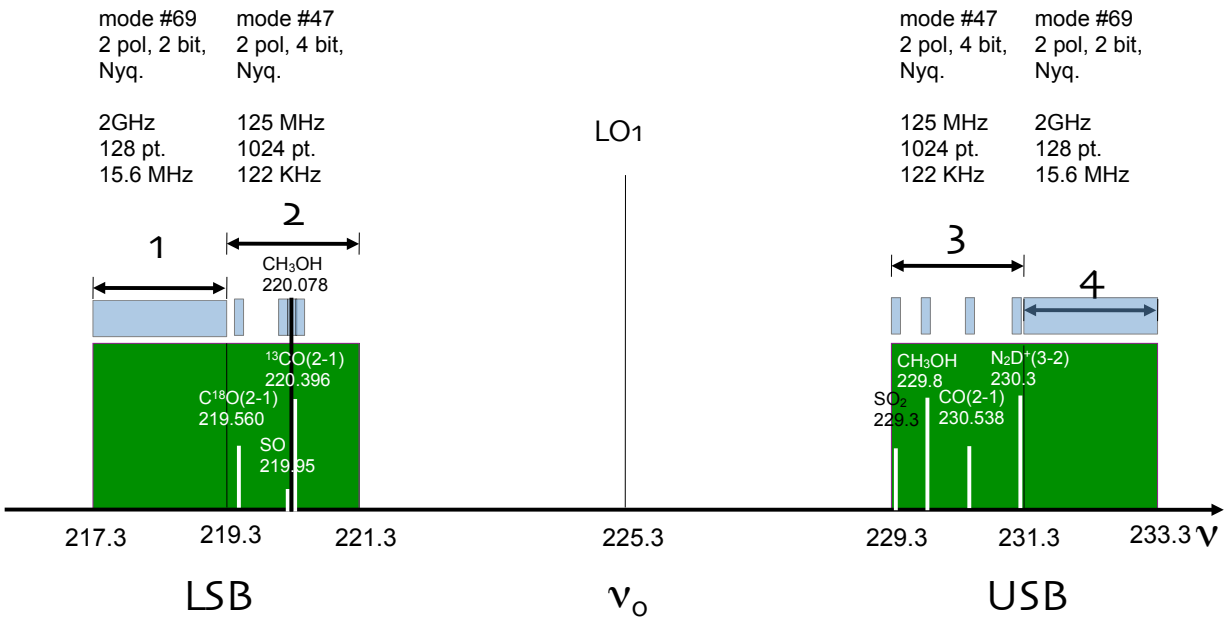
- 1 quadrant observes (in LSB) $C^{18}O$ 2-1, $^{13}CO$ 2-1, SO $5_6$-$4_5$ and $CH_3OH$ $8_0$-$7_1$ E also in mode 47, as above

- 2 quadrants: LSB/USB continuum in time division mode (69)

Reference : Presentation by Remijan (2009)

## Correlator Modes

e.g., Band 6:




# Correlator Modes

4. Multi-resolution Modes

(The correlator quadrant is split into independent subunits, each observing a specific spectral region. Different resolutions, bandwidths and polarization modes can be specified for each region. No sensitivity enhancement options are available.)

- implement frequency division modes over fewer than 32 correlator planes
- correlator resources can be fully divided up for multiple windows with different SR
- allows zoom in into features seen in wide band
- lower SR for a given BW
- only 2-bit quantization available, mostly 1 Nyq. available (three 2 Nyq. Modes)
- no more than 16 filters can be used!

Reference : Presentation by Di Francesco (2009); ALMA Memo 556

# Correlator Modes

4. Multi-resolution
(The correlator qu ent subunits, each
observing a specif esolutions,
bandwidths and p cified for each
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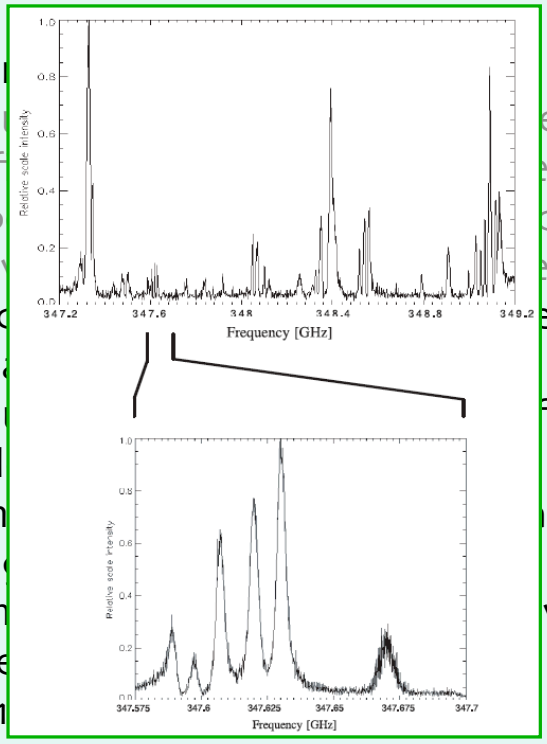
- allows zoom in nd
- lower SR for a
- only 2-bit quan yq.
available (thre
- no more than 1




Reference : Presentation by Di Francesco (2009); ALMA Memo 556


# Correlator Modes

4. Multi-resolution
(The correlator qu ent subunits, each
observing a specif esolutions,
bandwidths and p cified for each
region
- imp
th
- cor
mu
- allows zoom in nd
- lower SR for a
- only 2-bit quan yq.
available (thre
- no more than 1


Key consideration:
high spectral resolution in limited bandwidth for specific target lines, simultaneously with broad spectral coverage at low resolution


Reference : Presentation by Di Francesco (2009); ALMA Memo 556

**Table 5 Multi-resolution modes with one baseband channel per quadrant being processed.**

| Mode # | Minimum size of correlator* | Number of sub-channel filters | Total Bandwidth | Number of Spectral Points** | Correlation | Sample Factor |
|---|---|---|---|---|---|---|
| 2 | 1/2 | 16 | 1 GHz | 8192 | 2-bit x 2-bit | Nyquist |
| 3 | 1/4 | 8 | 500 MHz | 8192 | 2-bit x 2-bit | Nyquist |
| 4 | 1/8 | 4 | 250 MHz | 8192 | 2-bit x 2-bit | Nyquist |
| 5 | 1/16 | 2 | 125 MHz | 8192 | 2-bit x 2-bit | Nyquist |
| 6 | 1/32 | 1 | 62.5 MHz | 8192 | 2-bit x 2-bit | Nyquist |
| 25 | 1/32 | 1 | 31.25 MHz | 8192 | 2-bit x 2-bit | Twice Nyquist |

**Table 6 Multi-resolution modes with two baseband channels per quadrant with no polarization cross products.**

| Mode # | Minimum size of correlator* | Number of sub-channel filters | Total Bandwidth | Number of Spectral Points** | Correlation | Sample Factor |
|---|---|---|---|---|---|---|
| 9 | 1/2 | 8 | 500 MHz | 4096 | 2-bit x 2-bit | Nyquist |
| 10 | 1/4 | 4 | 250 MHz | 4096 | 2-bit x 2-bit | Nyquist |
| 11 | 1/8 | 2 | 125 MHz | 4096 | 2-bit x 2-bit | Nyquist |
| 12 | 1/16 | 1 | 62.5 MHz | 4096 | 2-bit x 2-bit | Nyquist |
| 31 | 1/16 | 1 | 31.25 MHz | 4096 | 2-bit x 2-bit | Twice Nyquist |

**Table 7 Multi-resolution modes with two baseband channels per quadrant with polarization cross products.**

| Mode # | Minimum size of correlator* | Number of sub-channel filters | Total Bandwidth | Number of Spectral Points** | Correlation | Sample Factor |
|---|---|---|---|---|---|---|
| 16 | 1/2 | 4 | 250 MHz | 2048 | 2-bit x 2-bit | Nyquist |
| 17 | 1/4 | 2 | 125 MHz | 2048 | 2-bit x 2-bit | Nyquist |
| 18 | 1/8 | 1 | 62.5 MHz | 2048 | 2-bit x 2-bit | Nyquist |
| 37 | 1/8 | 1 | 31.25 MHz | 2048 | 2-bit x 2-bit | Twice Nyquist |

* **Fraction of the correlator required to maintain the specified bandwidth with the minimum feasible resolution**

** **Utilizing 100% of the correlator**

Reference : ALMA Memo, 556

**Table 5 Multi-resolution modes with one baseband channel per quadrant being processed.**

| Mode # | Minimum size of correlator* | Number of sub-channel filters | Total Bandwidth | Number of Spectral Points** | Correlation | Sample Factor |
|---|---|---|---|---|---|---|
| 2 | 1/2 | 16 | 1 GHz | 8192 | 2-bit x 2-bit | Nyquist |
| 3 | 1/4 | 8 | 500 MHz | 8192 | 2-bit x 2-bit | Nyquist |
| 4 | 1/8 | 4 | 250 MHz | 8192 | 2-bit x 2-bit | Nyquist |
| 5 | 1/16 | 2 | 125 MHz | 8192 | 2-bit x 2-bit | Nyquist |
| 6 | 1/32 | 1 | 62.5 MHz | 8192 | 2-bit x 2-bit | Nyquist |
| 25 | 1/32 | 1 | 31.25 MHz | 8192 | 2-bit x 2-bit | Twice Nyquist |

**Table 6 Multi-resolution modes with two baseband channels per quadrant with no polarization cross products.**

| Mode # | Minimum size of correlator* | Number of sub-channel filters | Total Bandwidth | Number of Spectral Points** | Correlation | Sample Factor |
|---|---|---|---|---|---|---|
| 9 | 1/2 | 8 | 500 MHz | 4096 | 2-bit x 2-bit | Nyquist |
| 10 | 1/4 | 4 | 250 MHz | 4096 | 2-bit x 2-bit | Nyquist |
| 11 | 1/8 | 2 | 125 MHz | 4096 | 2-bit x 2-bit | Nyquist |
| 12 | 1/16 | 1 | 62.5 MHz | 4096 | 2-bit x 2-bit | Nyquist |
| 31 | 1/16 | 1 | 31.25 MHz | 4096 | 2-bit x 2-bit | Twice Nyquist |

**Table 7 Multi-resolution modes with two baseband channels per quadrant with polarization cross products.**

| Mode # | Minimum size of correlator* | Number of sub-channel filters | Total Bandwidth | Number of Spectral Points** | Correlation | Sample Factor |
|---|---|---|---|---|---|---|
| 16 | 1/2 | 4 | 250 MHz | 2048 | 2-bit x 2-bit | Nyquist |
| 17 | 1/4 | 2 | 125 MHz | 2048 | 2-bit x 2-bit | Nyquist |
| 18 | 1/8 | 1 | 62.5 MHz | 2048 | 2-bit x 2-bit | Nyquist |
| 37 | 1/8 | 1 | 31.25 MHz | 2048 | 2-bit x 2-bit | Twice Nyquist |

* **Fraction of the correlator required to maintain the specified bandwidth with the minimum feasible resolution**

** **Utilizing 100% of the correlator**

Reference : ALMA Memo, 556

**Table 8 Multi-resolution mode possibilities**

| Corr Mode Number | Mode Identifier BW | BITS | NYQUIST | POLZ | Spectral Channel Resolution for each polarization data set as a function of the fraction of correlator resources assigned in Multi-reslution Mode (Total #spectral channels per polarization data set in parenthesis) Full | 1/2 | 1/4 | 1/8 | 1/16 | 1/32 |
|---|---|---|---|---|---|---|---|---|---|---|
| 2 | 1GHz | 2x2 | 1N | 1BB | 122 KHz (8192) | 244 KHz (4096) | na | na | na | na |
| 3 | 500MHz | 2x2 | 1N | 1BB | 61 KHz (8192) | 122 KHz (4096) | 244 KHz (2048) | na | na | na |
| 4 | 250MHz | 2x2 | 1N | 1BB | 30.5 KHz (8192) | 61 KHz (4096) | 122 KHz (2048) | 244 KHz (1024) | na | na |
| 5 | 125MHz | 2x2 | 1N | 1BB | 15.3 KHz (8192) | 30.5 KHz (4096) | 61 KHz (2048) | 122 KHz (1024) | 244 KHz (512) | na |
| 6 | 62.5MHz | 2x2 | 1N | 1BB | 7.63 KHz (8192) | 15.3 KHz (4096) | 30.5 KHz (2048) | 61 KHz (1024) | 122 KHz (512) | 244 KHz (256) |
| 9 | 500MHz | 2x2 | 1N | 2BB | 122 KHz (4096) | 244 KHz (2048) | na | na | na | na |
| 10 | 250MHz | 2x2 | 1N | 2BB | 61 KHz (4096) | 122 KHz (2048) | 244 KHz (1024) | na | na | na |
| 11 | 125MHz | 2x2 | 1N | 2BB | 30.5 KHz (4096) | 61 KHz (2048) | 122 KHz (1024) | 244 KHz (512) | na | na |
| 12 | 62.5MHz | 2x2 | 1N | 2BB | 15.3 KHz (4096) | 30.5 KHz (2048) | 61 KHz (1024) | 122 KHz (512) | 244 KHz (256) | na |
| 16 | 250MHz | 2x2 | 1N | 2BB-P | 122 KHz (2048) | 244 KHz (1024) | na | na | na | na |
| 17 | 125MHz | 2x2 | 1N | 2BB-P | 61 KHz (2048) | 122 KHz (1024) | 244 KHz (512) | na | na | na |
| 18 | 62.5MHz | 2x2 | 1N | 2BB-P | 30.5 KHz (2048) | 61 KHz (1024) | 122 KHz (512) | 244 KHz (256) | na | na |
| 25 | 31.25MHz | 2x2 | 2N | 1BB | 3.82 KHz (8192) | 7.63 KHz (4096) | 15.3 KHz (2048) | 30.5 KHz (1024) | 61 KHz (512) | 122 KHz (256) |
| 31 | 31.25MHz | 2x2 | 2N | 2BB | 7.63 KHz (4096) | 15.3 KHz (2048) | 30.5 KHz (1024) | 61 KHz (512) | 122 KHz (256) | na |
| 37 | 31.25MHz | 2x2 | 2N | 2BB-P | 15.3 KHz (2048) | 30.5 KHz (1024) | 61 KHz (512) | 122 KHz (256) | na | na |



Reference : ALMA Memo, 556

**Table 8 Multi-resolution mode possibilities**

| Corr Mode Number | Mode Identifier BW | BITS | NYQUIST | POLZ | Spectral Channel Resolution for each polarization data set as a function of the fraction of correlator resources assigned in Multi-reslution Mode (Total #spectral channels per polarization data set in parenthesis) Full | 1/2 | 1/4 | 1/8 | 1/16 | 1/32 |
|---|---|---|---|---|---|---|---|---|---|---|
| 2 | 1GHz | 2x2 | 1N | 1BB | 122 KHz (8192) | 244 KHz (4096) | na | na | na | na |
| 3 | 500MHz | 2x2 | 1N | 1BB | 61 KHz (8192) | 122 KHz (4096) | 244 KHz (2048) | na | na | na |
| 4 | 250MHz | 2x2 | 1N | 1BB | 30.5 KHz (8192) | 61 KHz (4096) | 122 KHz (2048) | 244 KHz (1024) | na | na |
| 5 | 125MHz | 2x2 | 1N | 1BB | 15.3 KHz (8192) | 30.5 KHz (4096) | 61 KHz (2048) | 122 KHz (1024) | 244 KHz (512) | na |
| 6 | 62.5MHz | 2x2 | 1N | 1BB | 7.63 KHz (8192) | 15.3 KHz (4096) | 30.5 KHz (2048) | 61 KHz (1024) | 122 KHz (512) | 244 KHz (256) |
| 9 | 500MHz | 2x2 | 1N | 2BB | 122 KHz (4096) | 244 KHz (2048) | na | na | na | na |
| 10 | 250MHz | 2x2 | 1N | 2BB | 61 KHz (4096) | 122 KHz (2048) | 244 KHz (1024) | na | na | na |
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| 16 | 250MHz | 2x2 | 1N | 2BB-P | 122 KHz (2048) | 244 KHz (1024) | na | na | na | na |
| 17 | 125MHz | 2x2 | 1N | 2BB-P | 61 KHz (2048) | 122 KHz (1024) | 244 KHz (512) | na | na | na |
| 18 | 62.5MHz | 2x2 | 1N | 2BB-P | 30.5 KHz (2048) | 61 KHz (1024) | 122 KHz (512) | 244 KHz (256) | na | na |
| 25 | 31.25MHz | 2x2 | 2N | 1BB | 3.82 KHz (8192) | 7.63 KHz (4096) | 15.3 KHz (2048) | 30.5 KHz (1024) | 61 KHz (512) | 122 KHz (256) |
| 31 | 31.25MHz | 2x2 | 2N | 2BB | 7.63 KHz (4096) | 15.3 KHz (2048) | 30.5 KHz (1024) | 61 KHz (512) | 122 KHz (256) | na |
| 37 | 3 | | | | | | | | | |

For example, the three modes highlighted above have the same combination of bandwidth and spectral resolution, but provide different polarization products (AA v.s. AA+BB v.s. AA+BB+AB+BA) using different fraction of correlator resources.

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Reference : ALMA Memo, 556

# Correlator Modes

Example of Multi-Resolution Modes (Band 6):

- 1 quadrant observes (in USB) uses:
  - mode 3, 500 GHz BW with 8 planes, gets 2048 spectral points, 1 polzn, 2-bit, Nyq. (wide-band?)
  - mode 6, 62.5 MHz BW with 8 planes, gets 2048 spectral points, 1 polzn, 2-bit, Nyq. (CO 2-1)
  - mode 25, 31.25 MHz BW with 16 planes, gets 4096 spec. points, 1 polzn, 2-bit, 2 x Nyq. ($N_2D^+$ 3-2)
  - windows put anywhere in the 2 GHz input baseband
  - total BW used < 1 GHz (16 filters; NB: if mode 2 is included, filters are shared; BW of m2 window < 1 GHz)

each of other 3 quadrants are set up independently!

Reference : Presentation by Di Francesco (2009); ALMA Memo 556

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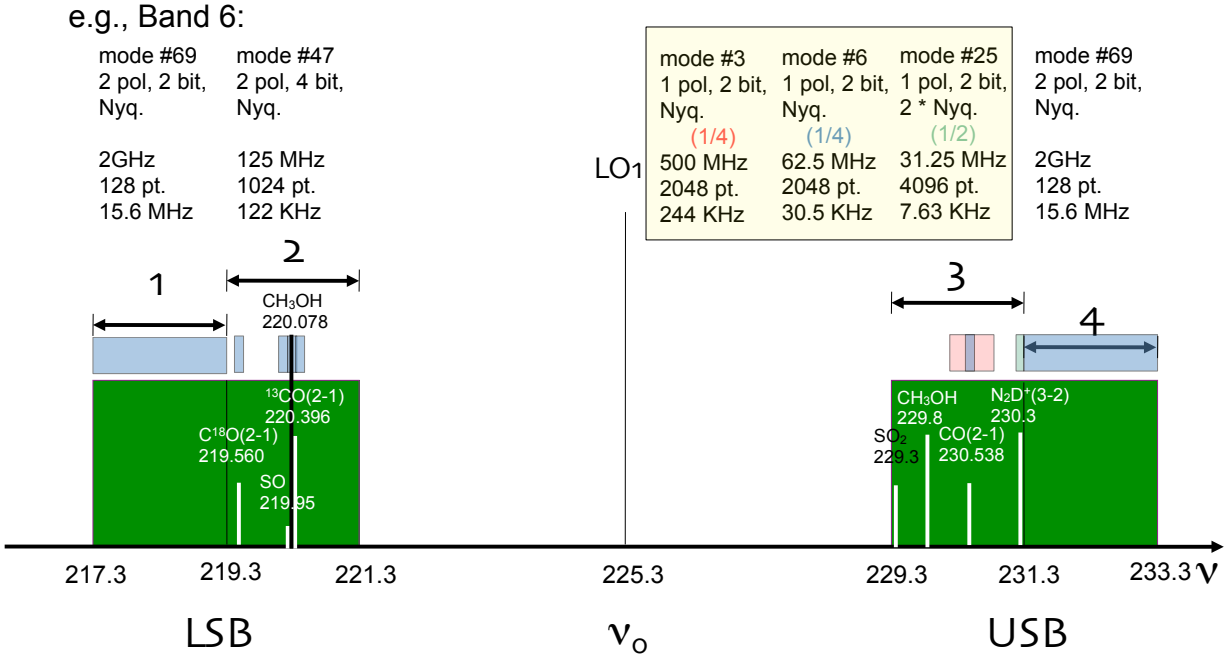
## Correlator Modes

e.g., Band 6:



# Remark

- ALMA correlator is a very powerful and flexible part of the whole instrument
- Its operation modes sound a bit frightening at the beginning, but may not be too complicated after all
- To fully utilize/mater its power, however, it will require well practice and wise planning
  - OT presumably will help to guide users through

# Remark

- ALMA correlator is a very powerful and flexible part of the whole instrument
- Its operation modes sound a bit frightening at the beginning, but may not be too complicated after all
- To fully utilize/mater its power, however, it will require well practice and wise planning
  - OT presumably will help to guide users through

- Some issues:
  - baseband/IF placement for band 6?
  - DSB v.s. 2SB
  - supported modes and multi-resolution OK at ES(?)