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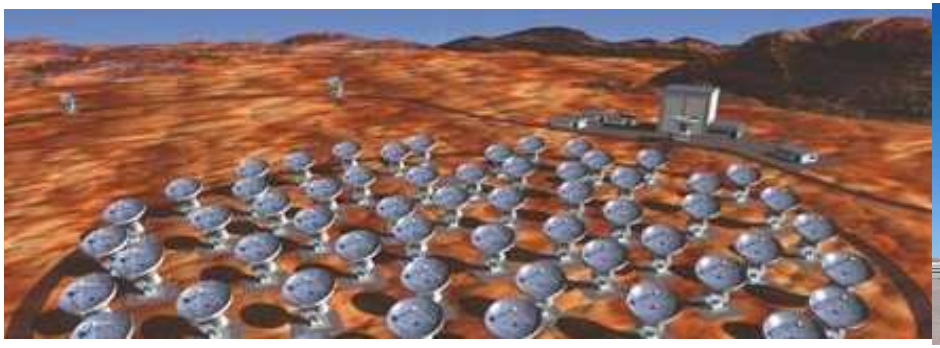
ALMA Correlator Modes

Frédéric Gueth, IRAM Grenoble
with inputs from A.Baudry, R.Hills, R.Lucas, P.Salome



ALMA Memo 556

ALMA Memo 556

Observational Modes Supported by the ALMA Correlator

By
R. Escoffier, G. Comoretto, C. Broadwell, R. Lacasse, J. Webber, A. Baudry

Abstract

Observational modes including multi-resolution operation supported by the ALMA correlator hardware and firmware are presented.

Introduction

A lot of work has recently been done on observational mode support in the ALMA correlator. Mode charts outlining the capacity of the baseline correlator were originally presented in the B version of the correlator specifications and requirements document, ALMA-60.00.00.00-001-B-SPE. In developing the firmware necessary to support the modes in the system, 4 modes defined in this spec were discovered to be impossible because of hardware connectivity limitations in the correlator.

The capacity for multi-resolution operation in the correlator has also recently been defined and will be described below.

Discussion in this memo will be from a hardware and firmware standpoint, giving the capabilities of the system.

ALMA Memo 556

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
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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
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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.

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53	16	250 MHz	4096	61 kHz	0.08 km/s	2-bit x 2-bit	Nyquist	2048 msec	0.94
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54	8	250 MHz	2048	122 kHz	0.16 km/s	3-bit x 3-bit	Nyquist	1024 msec	0.96
4	4	2 GHz	1024	1.95 MHz	2.56 km/s	4-bit x 4-bit	Nyquist	64 msec	0.99
22	4	1 GHz	1024	977 kHz	1.28 km/s	4-bit x 4-bit	Nyquist	128 msec	0.99
41	4	500 MHz	1024	488 kHz	0.64 km/s	4-bit x 4-bit	Nyquist	256 msec	0.99
55	4	250 MHz	1024	244 kHz	0.32 km/s	4-bit x 4-bit	Nyquist	512 msec	0.99
5	2	2 GHz	512	3.9 MHz	5.1 km/s	4-bit x 4-bit	Nyquist	32 msec	0.99
23	2	1 GHz	512	1.95 MHz	2.56 km/s	4-bit x 4-bit	Nyquist	64 msec	0.99
42	2	500 MHz	512	977 kHz	1.28 km/s	4-bit x 4-bit	Nyquist	128 msec	0.99
56	2	250 MHz	512	488 kHz	0.64 km/s	4-bit x 4-bit	Nyquist	256 msec	0.99
6	1	2 GHz	256	7.8 MHz	10.2 km/s	4-bit x 4-bit	Nyquist	16 msec	0.99
24	1	1 GHz	256	3.9 MHz	5.1 km/s	4-bit x 4-bit	Nyquist	32 msec	0.99
43	1	62.5 MHz	2048	30 kHz	0.04 km/s	4-bit x 4-bit	Nyquist	128 msec	0.99
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56	2	125 MHz	1024	
6	1	62.5 MHz	8192	
24	1	62.5 MHz	4096	
43	1	62.5 MHz	2048	
57	1	62.5 MHz	1024	
25	1	31.25 MHz	8192	
58	1	31.25 MHz	2048	
68	Time Division Mode	2 GHz	64	
71	Time Division Mode	2 GHz	256	

* 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.

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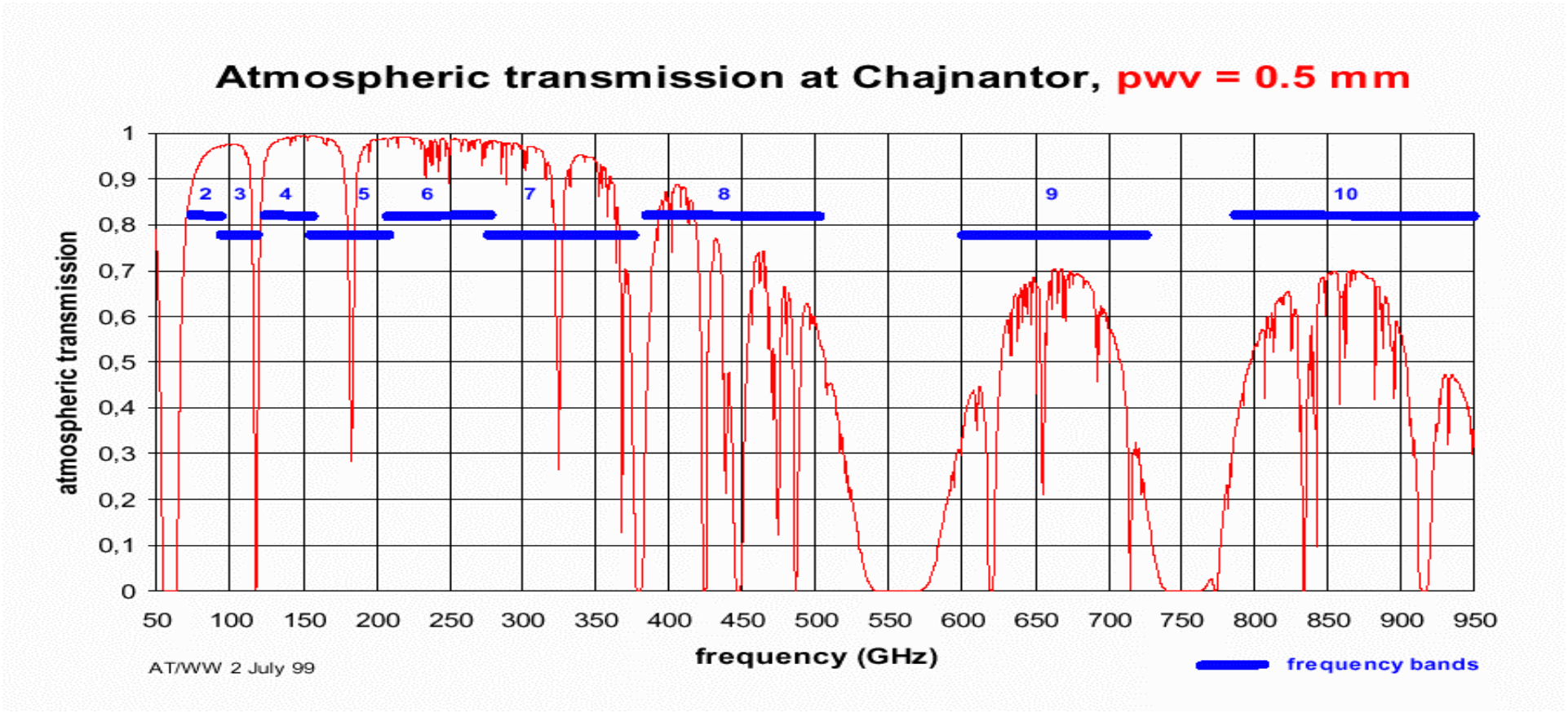
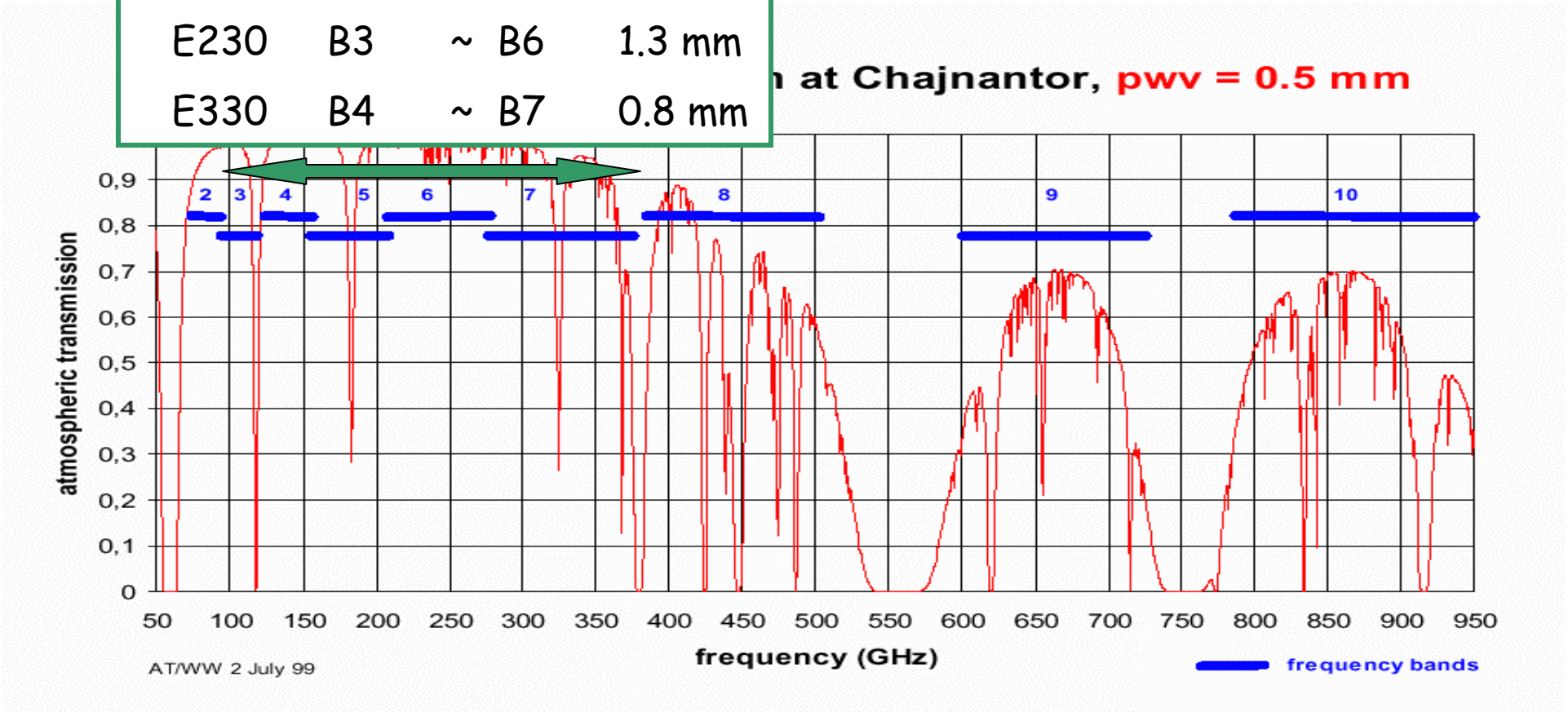
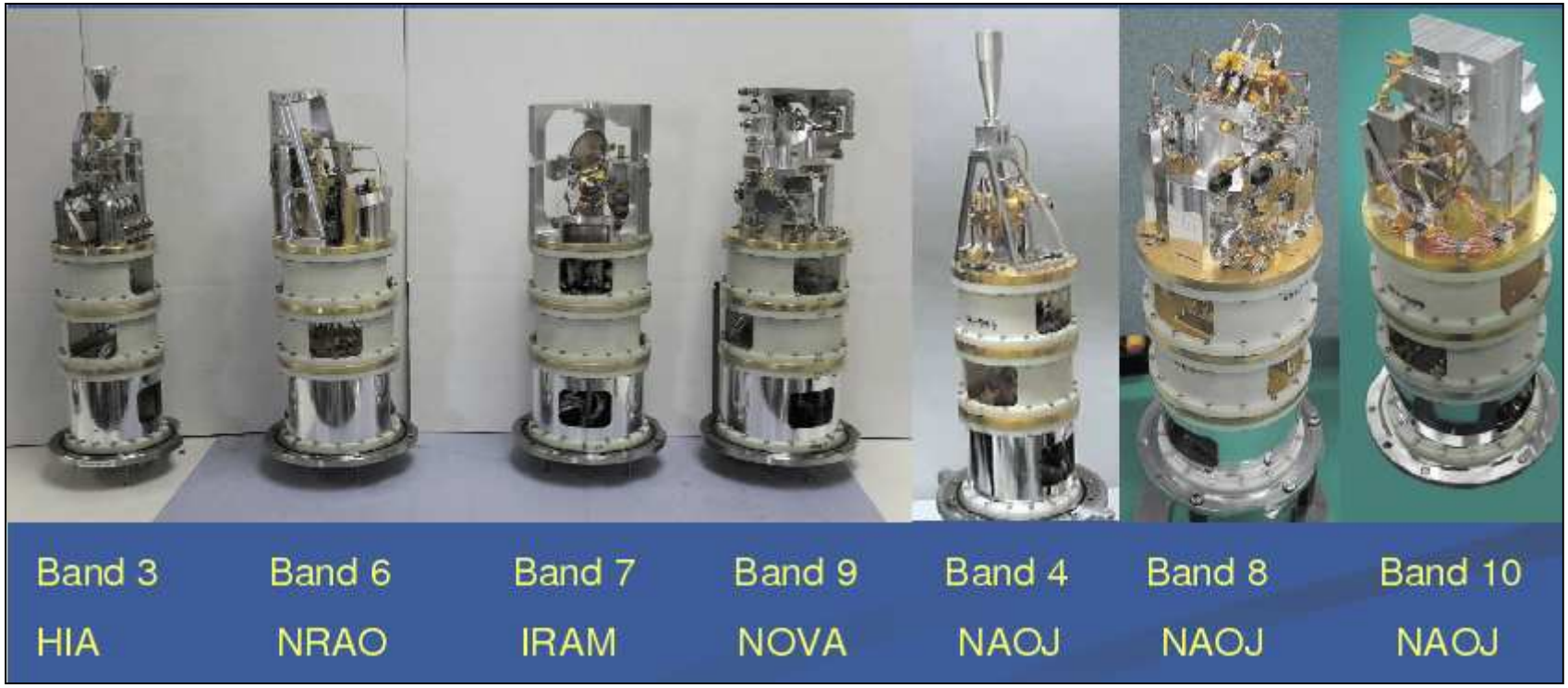
Receiver bands



Receiver bands

30m EMIR	PdBI	ALMA	λ
E090	B1	~ B3	3 mm
E150	B2	~ B4	2 mm
E230	B3	~ B6	1.3 mm
E330	B4	~ B7	0.8 mm





B3	84-116 GHz	HIA	B7	275-373 GHz	IRAM
B4	125-163 GHz	NAOJ	B8	385-500 GHz	NAOJ
B5	163-211 GHz	OSO	B9	602-720 GHz	NOVA
B6	211-275 GHz	NRAO	B10	787-950 GHz	NAOJ

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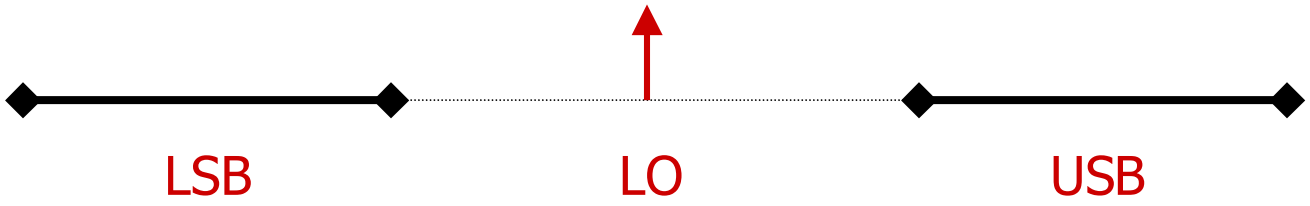
Receiver bandwidth

Heterodyne receivers are sensitive to Lower Side Band and Upper Side Band



Receivers can be

- **DSB** outputs the sum LSB + DSB → separated in the correlator
- **SSB** outputs LSB **or** DSB
- **2SB** outputs LSB and DSB separately

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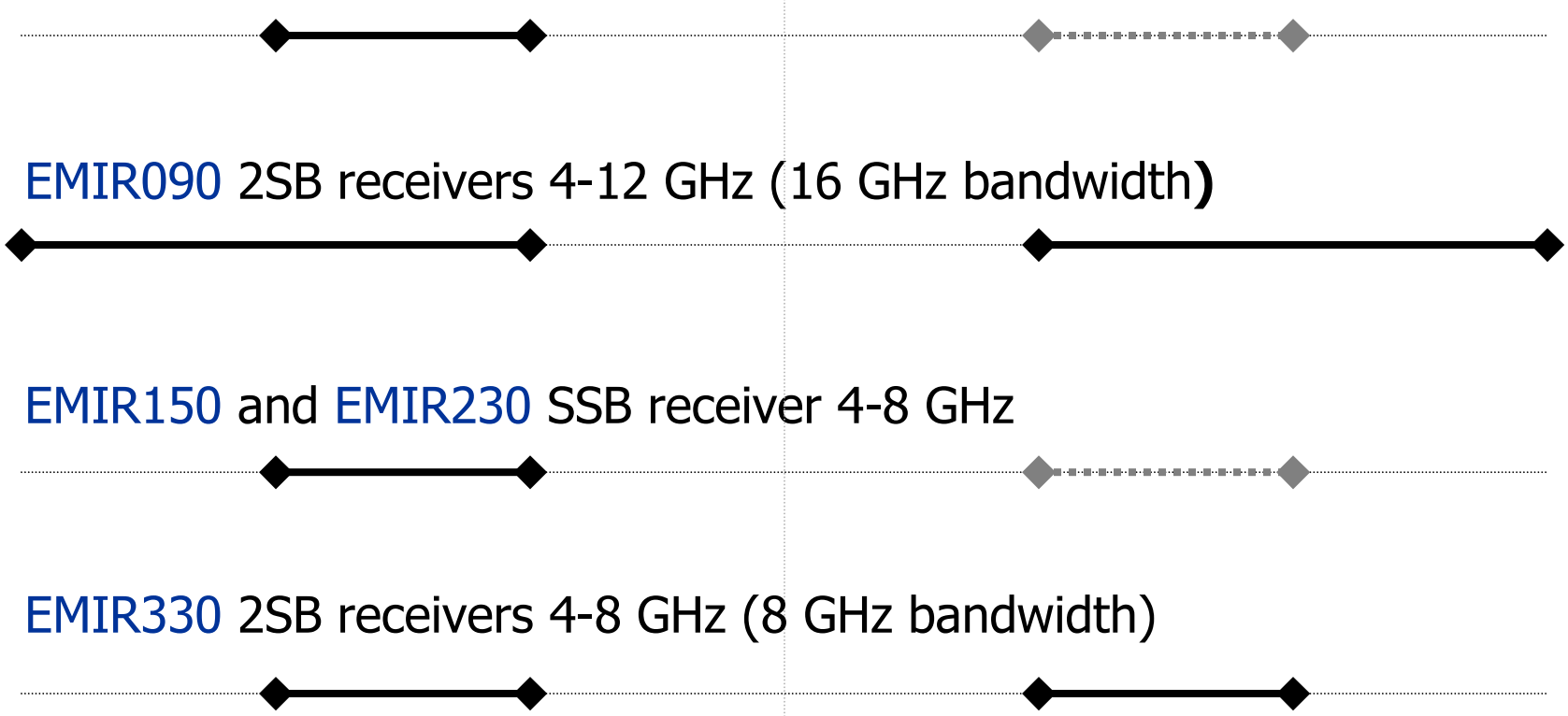
IRAM receivers

PdBI SSB receivers 4-8 GHz (4 GHz bandwidth LSB or USB)

EMIR090 2SB receivers 4-12 GHz (16 GHz bandwidth)

EMIR150 and EMIR230 SSB receiver 4-8 GHz

EMIR330 2SB receivers 4-8 GHz (8 GHz bandwidth)



Receivers have 4 to 16 GHz bandwidth

x 2 polarizations

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ALMA receivers

ALMA B3/B4/B5/B7/B8 2SB receivers 4-8 GHz

ALMA B6 2SB receivers 6-10 GHz

ALMA B9 + B10 DSB receivers 4-12 GHz

All ALMA receivers bands have 8 GHz bandwidth

x 2 polarizations

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ALMA correlator

- ALMA correlator = **4 basebands**
- Each baseband processes
  - 64 antennas (2016 baselines)
  - 2 polarizations
  - **2 GHz input**
- Each baseband can be centered anywhere* in the incoming 8 GHz
- All four basebands can be setup independently

(* Minor limitations because of LOs finite step)

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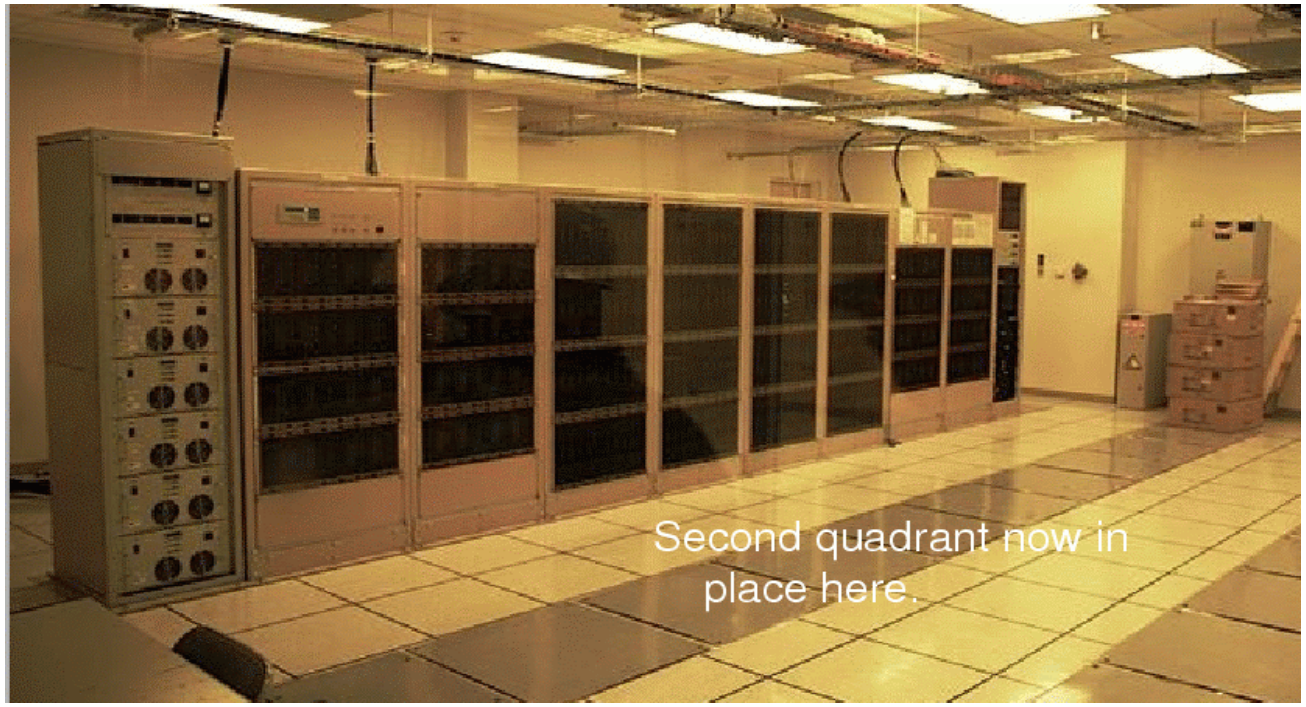
ALMA correlator

- Physically: correlator = 4 quadrants
- **Full ALMA: 1 quadrant = 1 baseband**
- **<16 antennas : 1 quadrant = 4 basebands**



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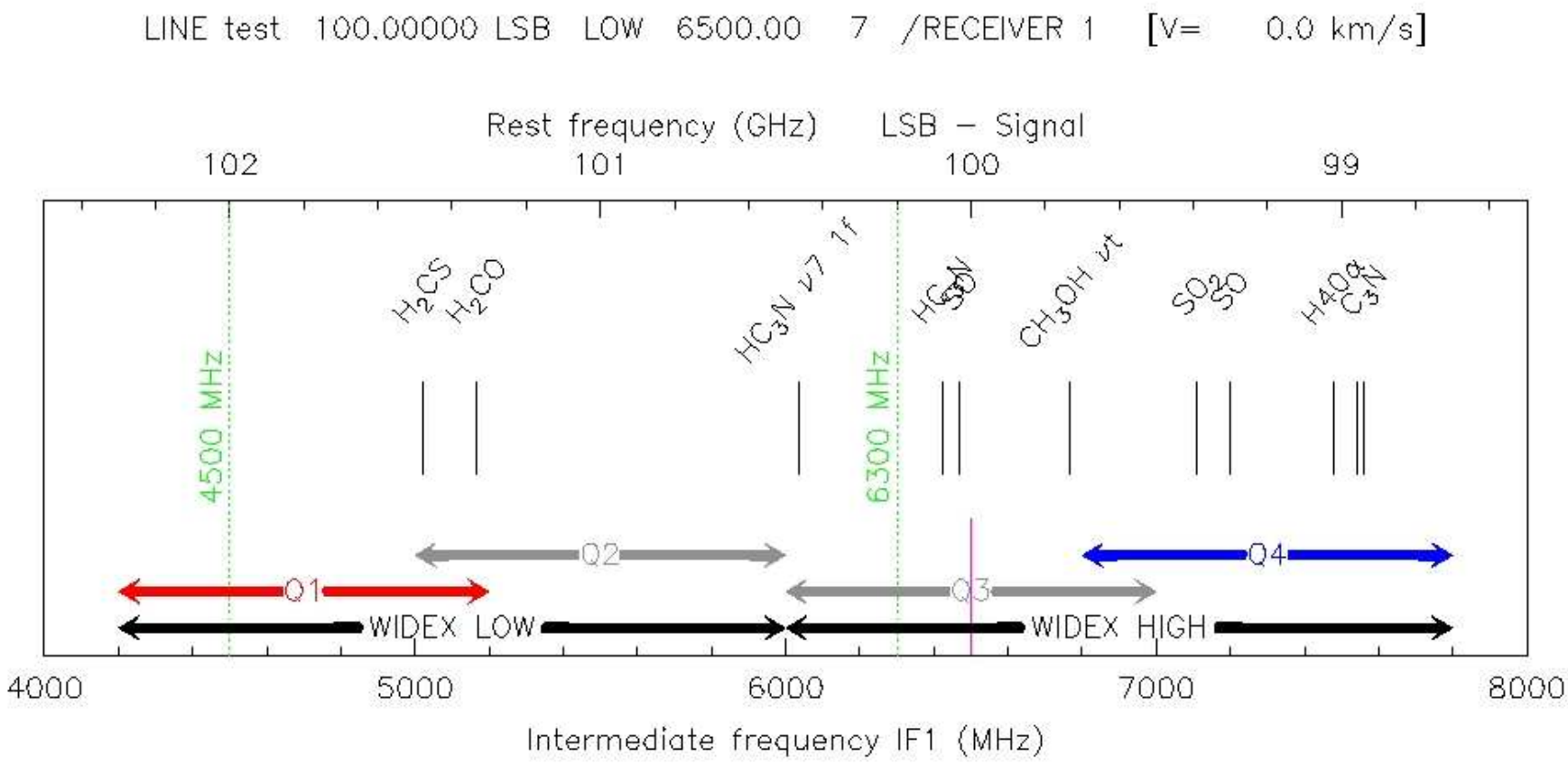
PdBI



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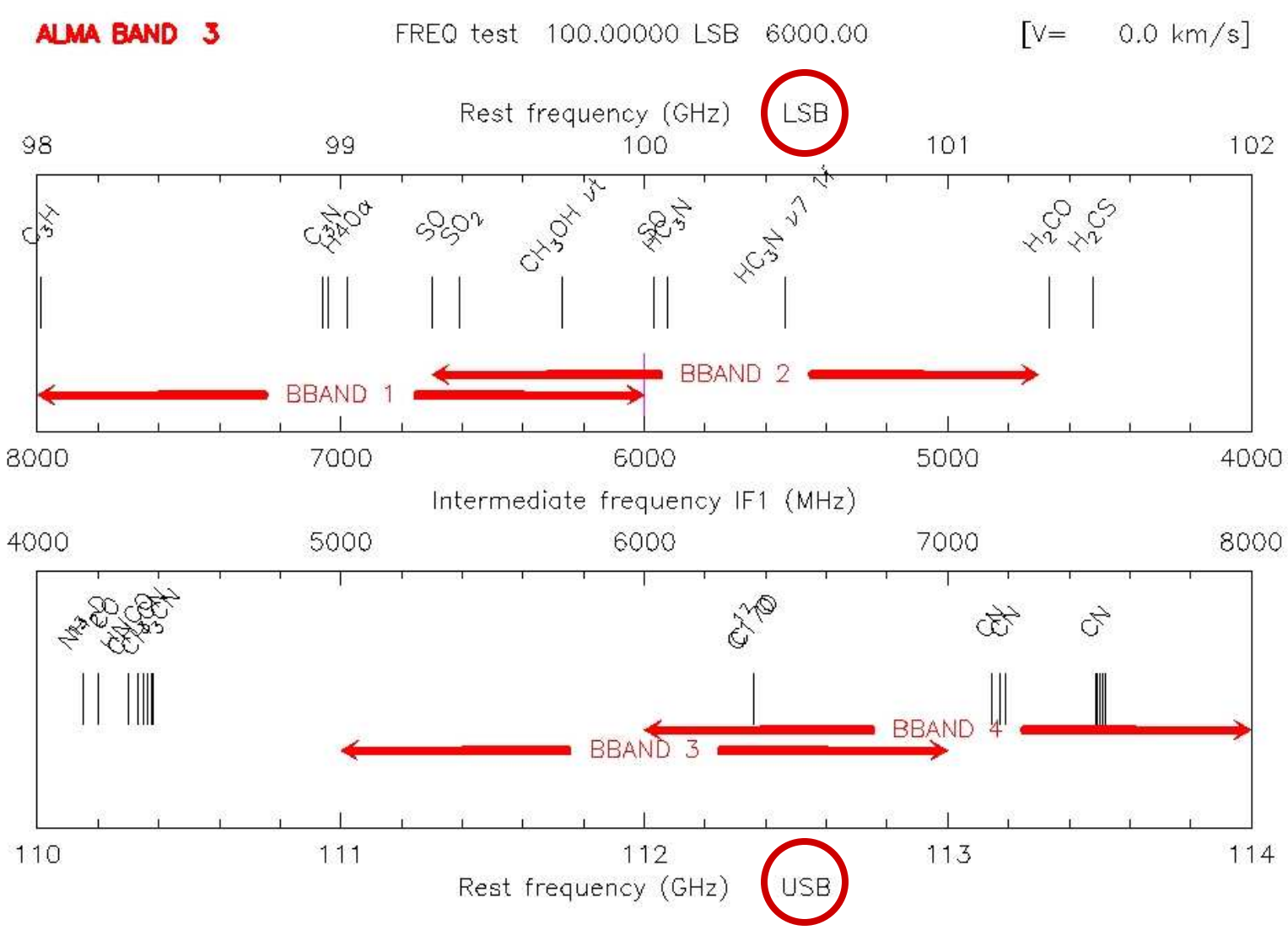
ALMA : basebands



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Basebands modes

1 polarization output (H or V)

- 2 GHz 8192 channels x 1 Pol = 244 kHz resol.
- 1 GHz 8192 channels x 1 Pol = 122 kHz resol.
- 500 MHz 8192 channels x 1 Pol = 61 kHz resol.
- 250 MHz 8192 channels x 1 Pol = 30 kHz resol.
- 125 MHz 8192 channels x 1 Pol = 15 kHz resol.
- 64 MHz 8192 channels x 1 Pol = 7.5 kHz resol.
- 31.25 MHz 8192 channels x 1 Pol = 3.8 kHz resol.
- Continuum mode 256 ch. x 1 Pol = 7.5 MHz resol.

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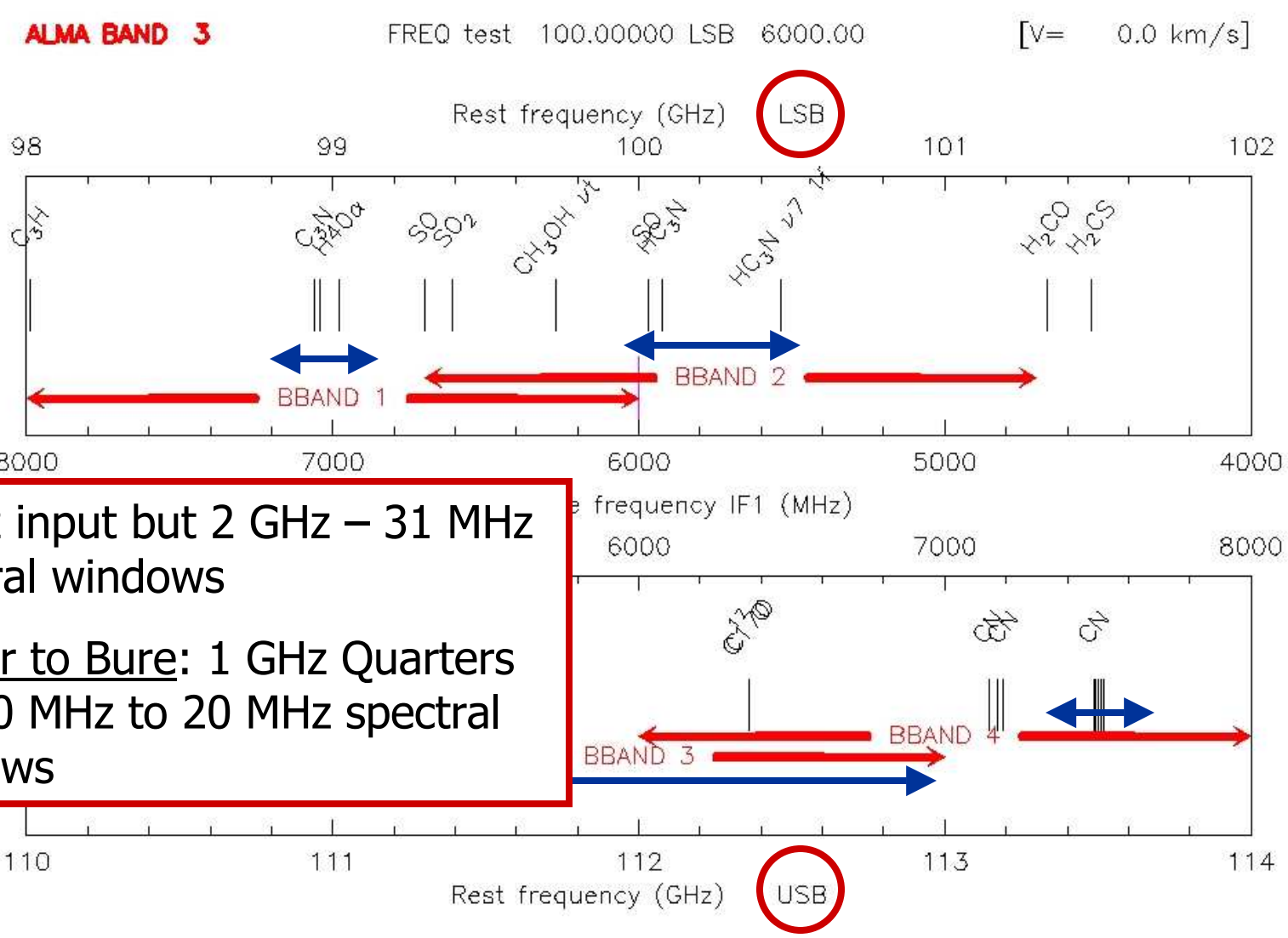
ALMA : basebands



2 GHz input but 2 GHz – 31 MHz spectral windows

Similar to Bure: 1 GHz Quarters → 320 MHz to 20 MHz spectral windows

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FDM

- Continuum mode 256 ch. x 1 Pol = 7.5 MHz resol. **TDM**

Frequency/Time division modes

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Basebands modes

2 polarization outputs (H and V)

- 2 GHz 4096 channels x 2 Pol = 488 kHz resol.
- 1 GHz 4096 channels x 2 Pol = 244 kHz resol.
- 500 MHz 4096 channels x 2 Pol = 122 kHz resol.
- 250 MHz 4096 channels x 2 Pol = 61 kHz resol.
- 125 MHz 4096 channels x 2 Pol = 30 kHz resol.
- 64 MHz 4096 channels x 2 Pol = 15 kHz resol.
- 31.25 MHz 4096 channels x 2 Pol = 7.5 kHz resol.
- Continuum mode 128 ch. x 2 Pol = 15 MHz resol.

Baseband = 8192 channels

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Basebands modes

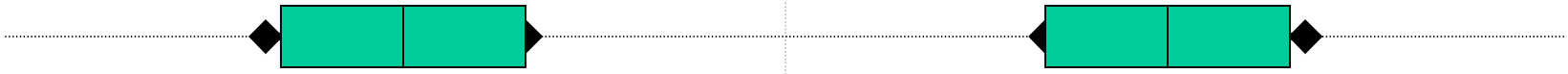
4 polarization outputs (HH, VV, HV, VH)

- 2 GHz 2048 channels x 4 Pol = 976 kHz resol.
- 1 GHz 2048 channels x 4 Pol = 488 kHz resol.
- 500 MHz 2048 channels x 4 Pol = 244 kHz resol.
- 250 MHz 2048 channels x 4 Pol = 122 kHz resol.
- 125 MHz 2048 channels x 4 Pol = 61 kHz resol.
- 64 MHz 2048 channels x 4 Pol = 30 kHz resol.
- 31.25 MHz 2048 channels x 4 Pol = 15 kHz resol.
- Continuum mode 64 ch. x 4 Pol = 31 MHz resol.

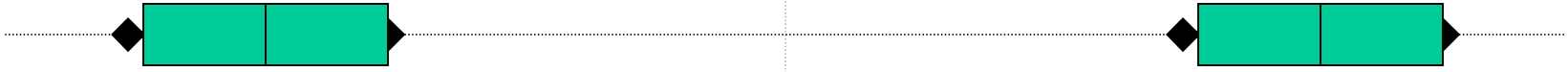
Baseband = 8192 channels

Examples

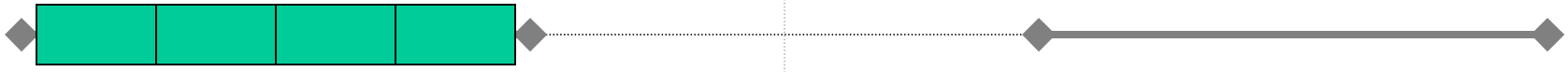
ALMA B3/B4/B5/B7/B8 2SB receivers 4-8 GHz



ALMA B6 2SB receivers 6-10 GHz



ALMA B9 + B10 SSB receivers 4-12 GHz



Four basebands covering 8 GHz

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Examples

ALMA B3/B4/B5/B7/B8 2SB receivers 4-8 GHz

ALMA B6 2SB receivers 6-10 GHz

ALMA B9 + B10 SSB receivers 4-12 GHz

Four basebands with different width/resolution

B9 + B10: choice of LSB vs USB done for each baseband

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Summary

- **4 independent spectral windows**
- **2 GHz to 31.25 MHz bandwidth**
  - **1, 2, or 4 polar. products**
  - **8192 channels**
- ***OR* 2 GHz continuum**

- NB: real bandwidths are smaller:
  - 1800 instead of 2000 MHz
  - 938 instead of 1000 MHz
  - 469 instead of 512 MHz
  - 234 instead of 256 MHz
  - 117 instead of 128 MHz
  - 58.6 instead of 64 MHz

real resolutions are higher:
1.2 to 2 times the channel spacing

Summary

- **4 independent spectral windows**
- **2 GHz to 31.25 MHz bandwidth**
  - **1, 2, or 4 polar. products**
  - **8192 channels**
- ***OR* 2 GHz continuum**

- Anything more?

Each mode comes in 2 to 4 flavors: 2,3, or 4 bits correlation and Nyquist/twice Nyquist sampling → gain in sensitivity but loss in spectral points

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Summary

- **4 independent spectral windows**
- **2 GHz to 31.25 MHz bandwidth**
  - **1, 2, or 4 polar. products**
  - **8192 channels**
- ***OR* 2 GHz continuum**

- The resolution of each mode can be degraded to increase the sensitivity (more bits correlation and/or higher sampling)
- Anything more?

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Multi-regions modes

- Goal = observe **several spectral windows in one baseband**

- Multi-regions: basic mode can be **split** in several windows
- Basic unit = 62.5 MHz regions

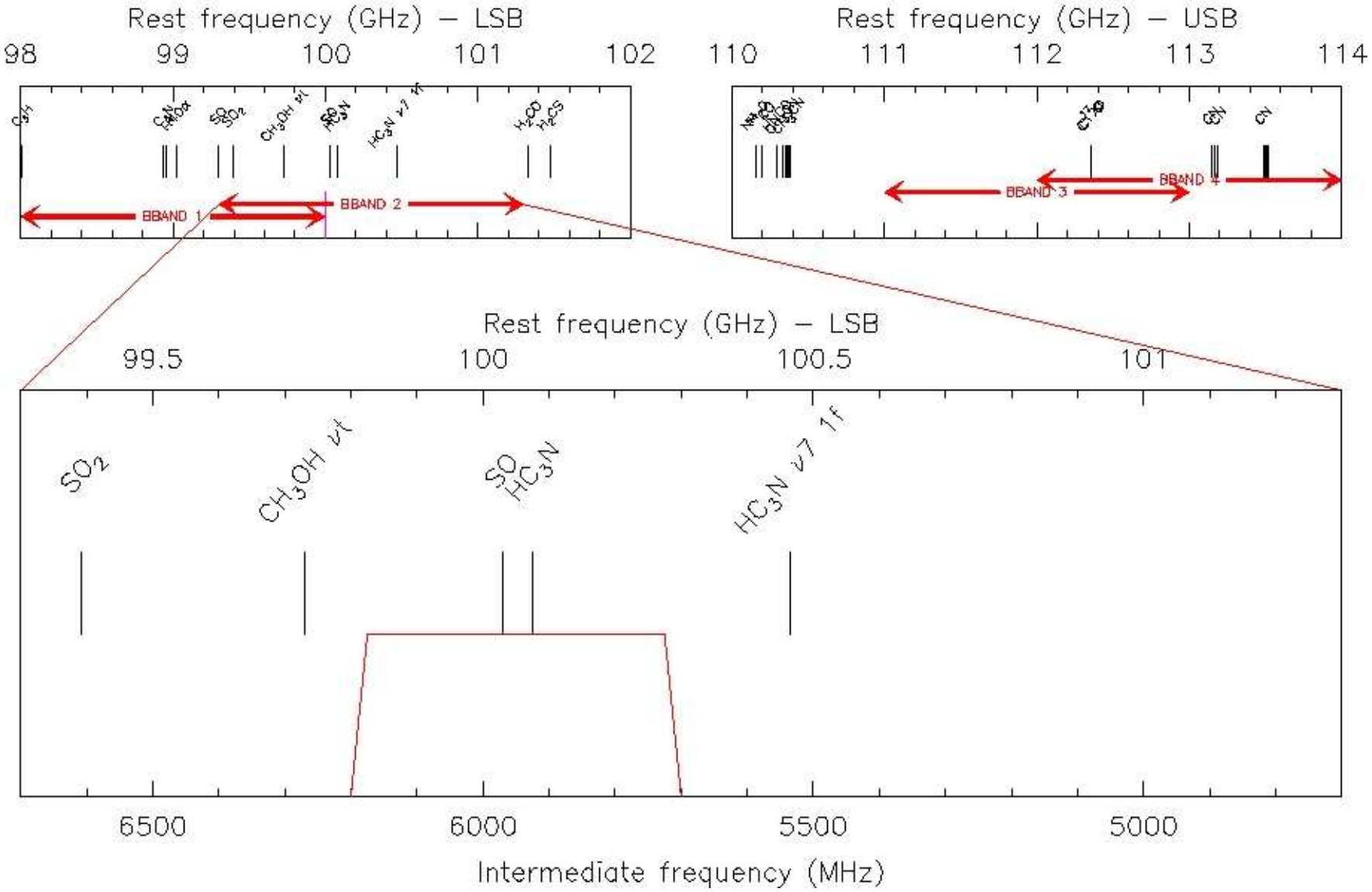
- Spectral windows share the same mode, i.e. the **same resolution, polarization output,** etc

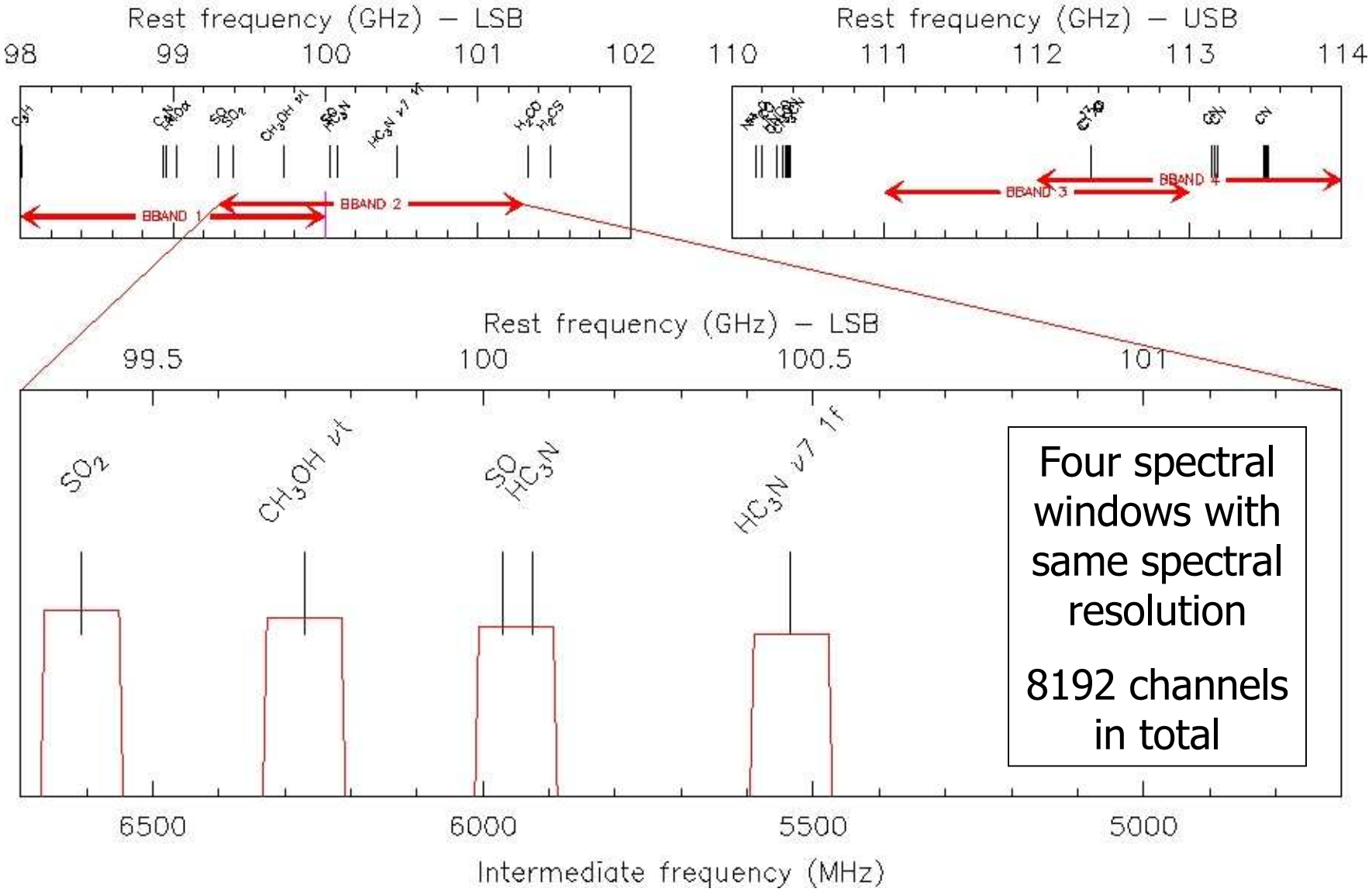
- Example: 500 MHz x 4096 channels x 2 Pol (122 kHz resol.)
  → 8 spectral windows of 62.5 MHz
  x 1024 channels x 2 Pol (122 kHz resol.)

- Only possible with modes 125 MHz – 1 GHz

ALMA BAND 3 FREQ test 100.00000 LSB 6000.00 [V= 0.0 km/s]

BASEBAND 2 is centered at IF1 = 5700.00 MHz (LSB) RF = 100.30000 GHz




ALMA BAND 3
FREQ test 100.00000 LSB 6000.00 [V= 0.0 km/s]
BASEBAND 2 is centered at IF1 = 5700.00 MHz (LSB) RF = 100.30000 GHz
Rest frequency (GHz) – LSB
98
99
100
101
102
Rest frequency (GHz) – USB
110
111
112
113
114
BBAND 1
BBAND 2
BBAND 3
BBAND 4
Rest frequency (GHz) – LSB
99.5
100
100.5
101
SO2
CH3OH νt
SO
HC3N
HC3N ν7 1f
Four spectral windows with same spectral resolution
8192 channels in total
6500
6000
5500
5000
Intermediate frequency (MHz)

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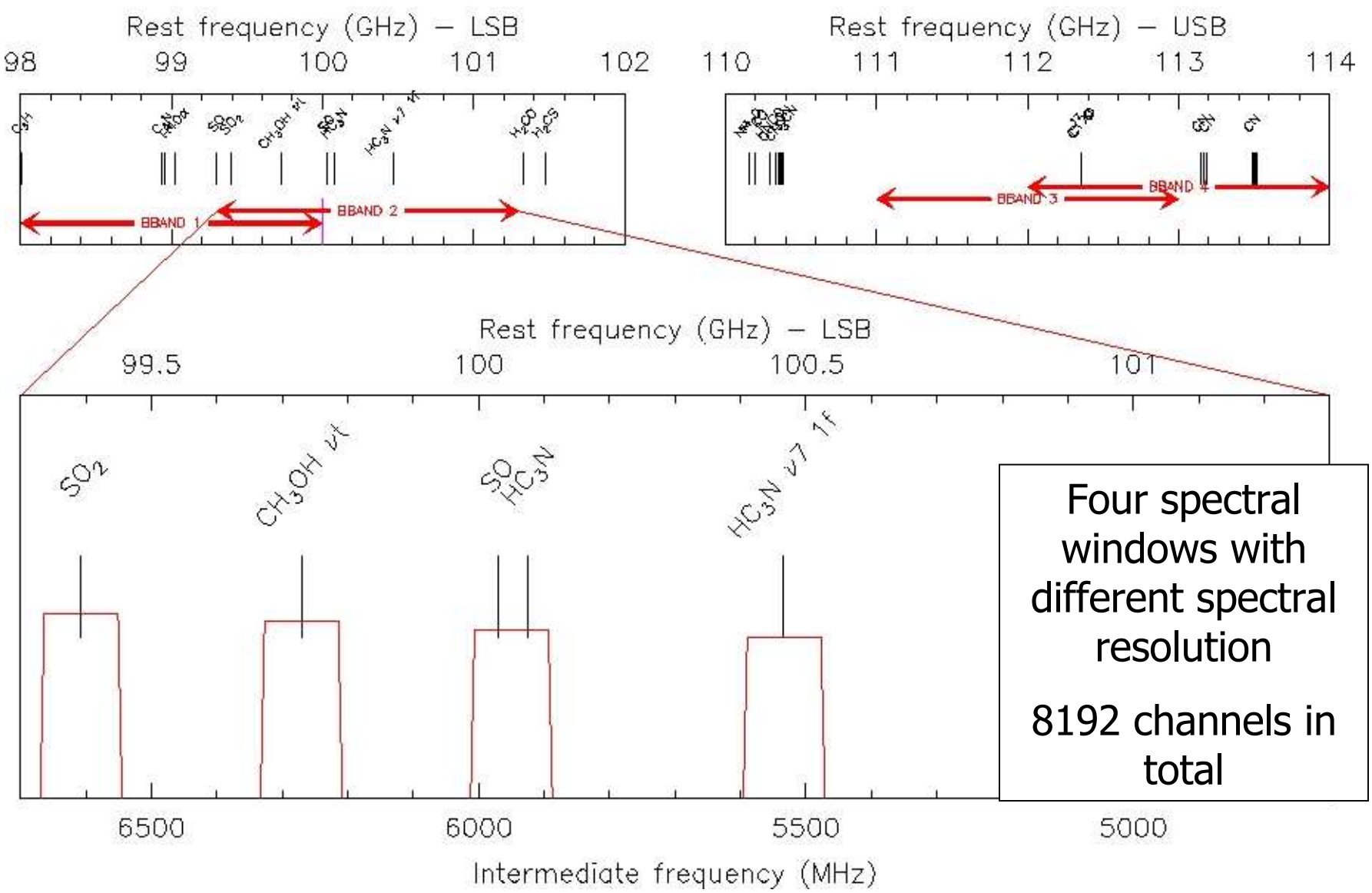
Multi-resolution modes

- Goal = observe **several spectral windows in one baseband**
- The modes can be degraded in order to use only a fraction of the correlator → **reduce number of channels, free correlator resources for another window**
- Spectral windows are **independent, can have different resolution, polarization output,** etc
- 1 GHz x 1 pol x **8192** channels **100%** correlator
  1 GHz x 1 pol x **4192** channels **50%** correlator
  125 MHz x 1 pol x 8192 channels 100% correlator
  125 MHz x 1 pol x 4192 channels 50% correlator
- Not all modes/combinations possible (e.g. 2 GHz → 100% only)

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-resolution 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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Four spectral windows with different spectral resolution
8192 channels in total
6500
6000
5500
5000
Intermediate frequency (MHz)

Summary

- **4 independent basebands**
- **Basic modes:**
  - **2 GHz to 31.25 MHz bandwidth / 8192 channels**
  - Each mode have sub-modes [more sensitivity, less resolution]
  - Continuum mode
- **Multi-regions modes:**
  - Several windows per baseband
  - All with the same width/resolution
- **Multi-resolution modes:**
  - Several windows per baseband
  - Different widths/resolutions [less than in basic modes]

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Early science

- **4 independent basebands**
- **Basic modes:**
  - **2 GHz to 31.25 MHz bandwidth / 8192 channels**
  - ~~Each mode have sub modes [more sensitivity, less resolution]~~
  - Continuum mode
- ~~**Multi-regions modes:**~~
  - ~~Several windows per baseband~~
  - ~~All with the same width/resolution~~
- ~~**Multi-resolution modes:**~~
  - ~~Several windows per baseband~~
  - ~~Different widths/resolutions [less than in basic modes]~~

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Early sci

Limitation: the four basebands are not independent: must share the same mode

- **4 independent basebands**
- **Basic modes:**
  - **2 GHz to 31.25 MHz bandwidth / 8192 channels**
  - ~~Each mode have sub modes [more sensitivity, less resolution]~~
  - Continuum mode
- ~~**Multi-regions modes:**~~
  - ~~Several windows per baseband~~
  - ~~All with the same width/resolution~~
- ~~**Multi-resolution modes:**~~
  - ~~Several windows per baseband~~
  - ~~Different widths/resolutions [less than in basic modes]~~

Early Science

TDM modes		Point Spacing (MHz)		
Band-	MHz	7.8	15.6	31.3
width	1800	1	2	4

FDM modes		Spacing of spectral points (kHz)							
Band-	MHz	7.6	15.3	30.5	61	122	244	488	977
width	1800						1	**2**	4
	938					1	2	4	
	469				1	**2**	4		
	234			1	2	4			
	117		1	2	4				
	58.6	1	**2**	4					

Number of cross-products as a function of bandwidth/resolution for one baseband

Highest priority modes (ASAC)

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Early Science

TDM modes		Point Spacing (MHz)		
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width	1800						1	**2**	4
	234			1	2	4			
	117		1	2	4				
	58.6	1	**2**	4					

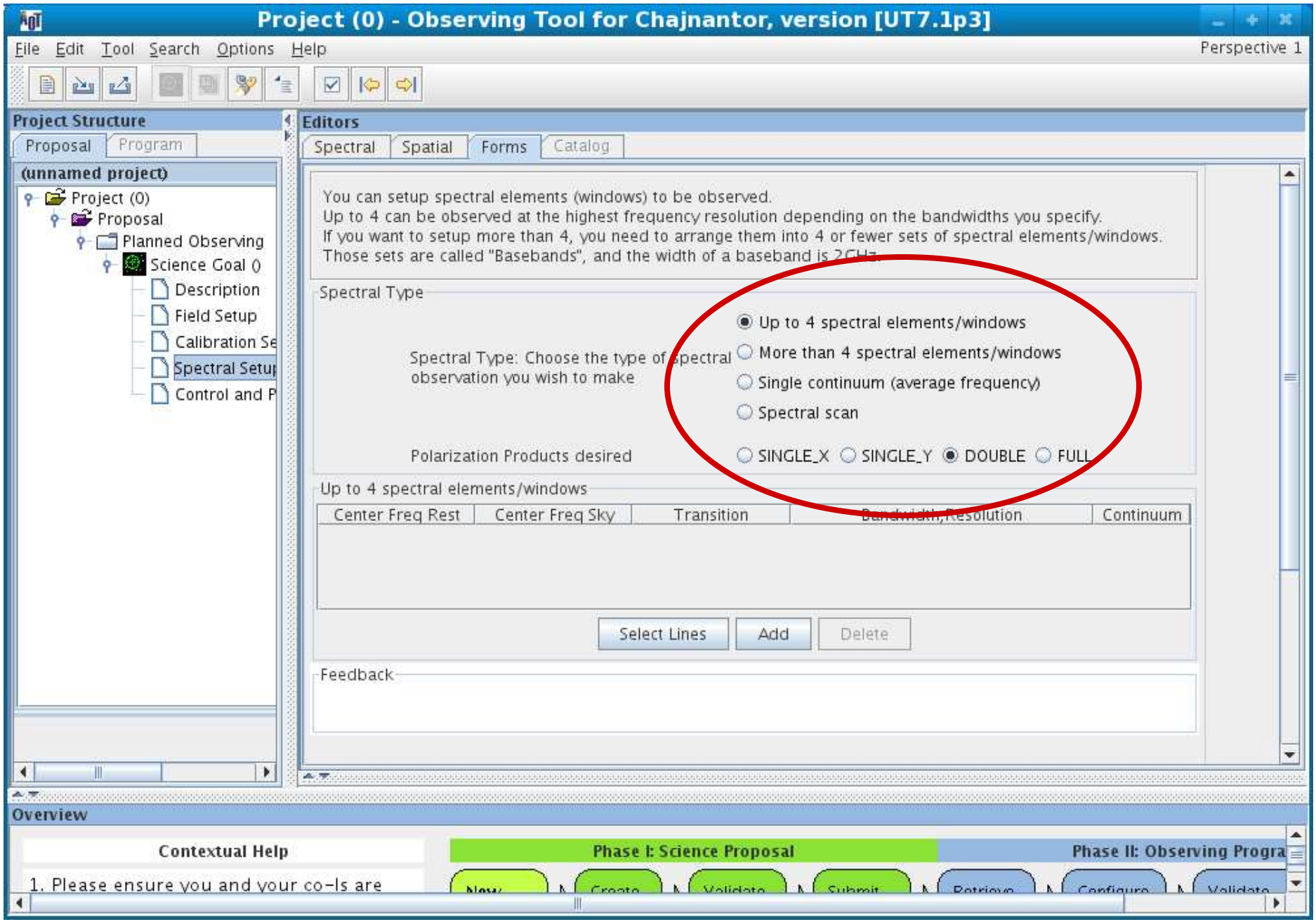
NB: must use 4 cross-products for B7, because polar. not identical on all antennas

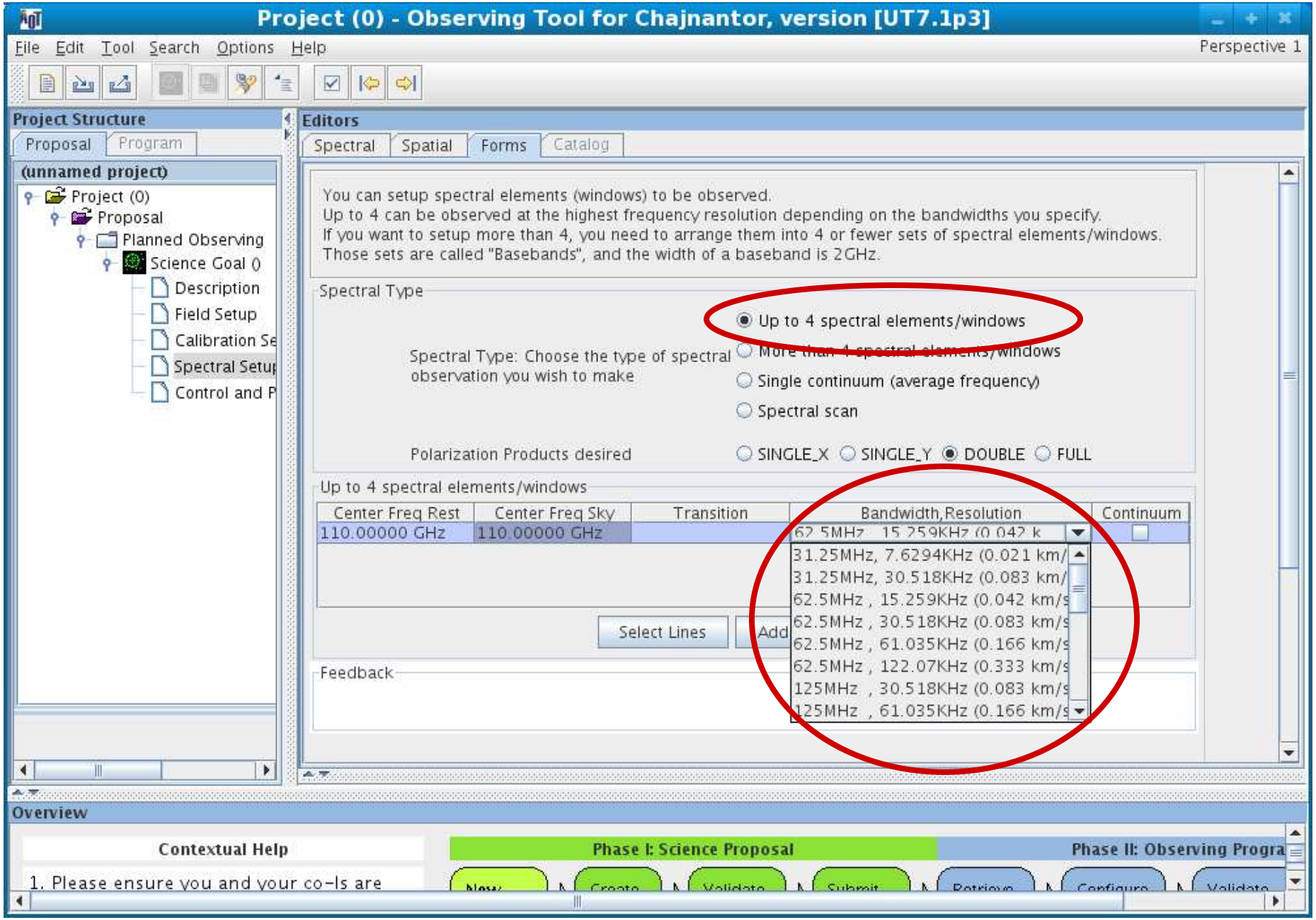
Number of cross-products as a function of bandwidth/resolution for one baseband

Highest priority modes (ASAC)

Observing Tool

- In the **Observing Tool** (demo on Wednesday)
  - Choose 4 or more spectral windows
  - Choose lines
    - The OT finds receiver tuning
  - Choose a correlator mode = resolution/width
    - The OT proposes the list of modes available


Project (0) - Observing Tool for Chajnantor, version [UT7.1p3]
File Edit Tool Search Options Help
Perspective 1
Project Structure
Proposal Program
(unnamed project)
Project (0)
Proposal
Planned Observing
Science Goal ()
Description
Field Setup
Calibration Se
Spectral Setup
Control and P
Editors
Spectral Spatial Forms Catalog
You can setup spectral elements (windows) to be observed.
Up to 4 can be observed at the highest frequency resolution depending on the bandwidths you specify.
If you want to setup more than 4, you need to arrange them into 4 or fewer sets of spectral elements/windows.
Those sets are called "Basebands", and the width of a baseband is 2GHz
Spectral Type
Spectral Type: Choose the type of spectral observation you wish to make
Up to 4 spectral elements/windows
More than 4 spectral elements/windows
Single continuum (average frequency)
Spectral scan
Polarization Products desired
SINGLE_X SINGLE_Y DOUBLE FULL
Up to 4 spectral elements/windows
Center Freq Rest
Center Freq Sky
Transition
Continuum
Select Lines
Add
Delete
Feedback
Overview
Contextual Help
1. Please ensure you and your co-Is are
Phase I: Science Proposal
Phase II: Observing Progra
New
Create
Validate
Submit
Retrieve
Configure
Validate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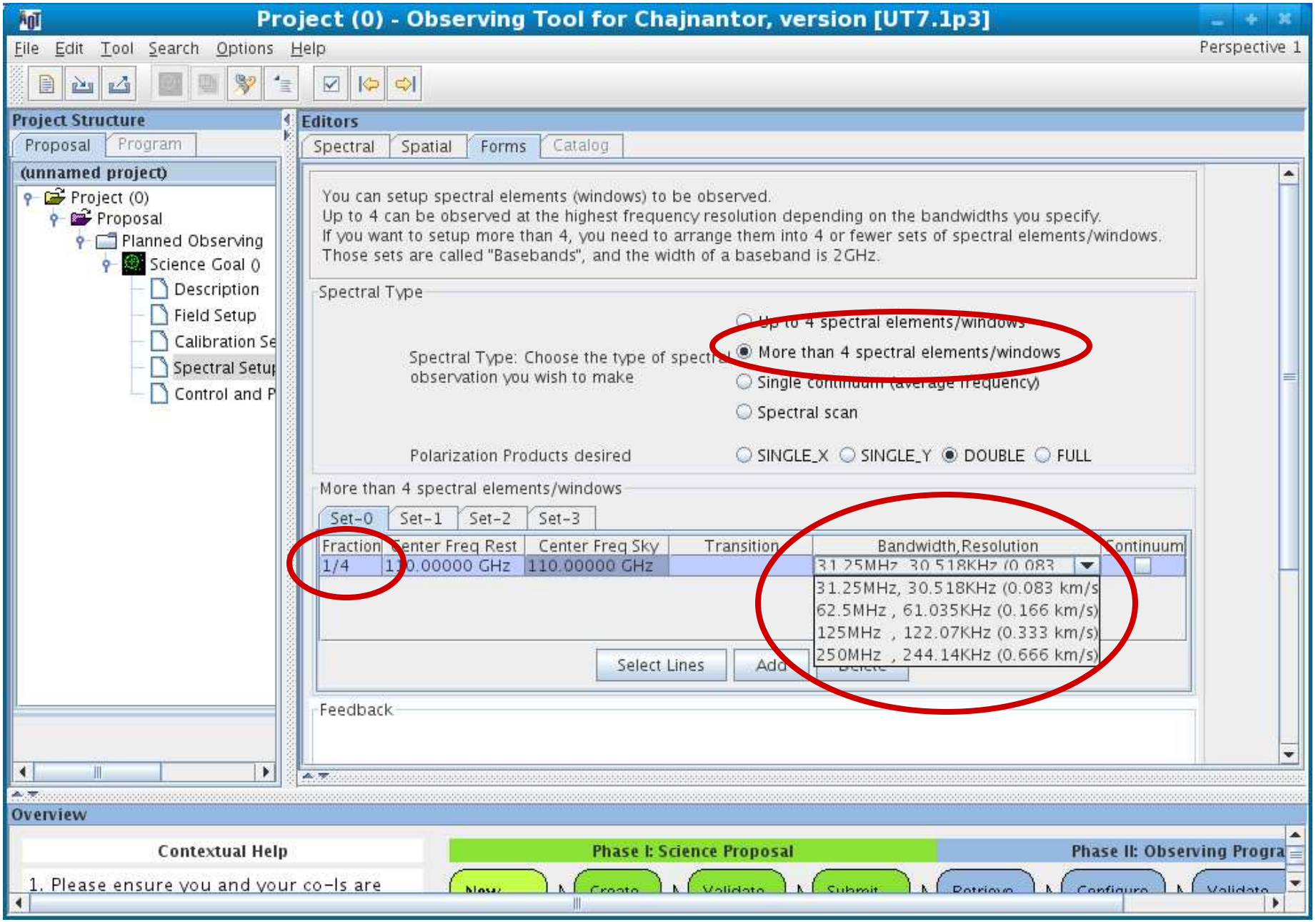
Up to 4 spectral elements/windows
Center Freq Rest
Center Freq Sky
Transition
Bandwidth,Resolution
Continuum
110.00000 GHz
110.00000 GHz
31.25MHz, 7.6294KHz (0.021 km/
31.25MHz, 30.518KHz (0.083 km/
62.5MHz , 15.259KHz (0.042 km/s
62.5MHz , 30.518KHz (0.083 km/s
62.5MHz , 61.035KHz (0.166 km/s
62.5MHz , 122.07KHz (0.333 km/s
125MHz , 30.518KHz (0.083 km/s
125MHz , 61.035KHz (0.166 km/s
Select Lines
Feedback
Overview
Contextual Help
1. Please ensure you and your co-Is are
Phase I: Science Proposal
Phase II: Observing Progra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1/4
110.00000 GHz
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250MHz , 244.14KHz (0.666 km/s)
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Conclusion

- **Early Science**: 4 spectral windows + restrictions
- **Full ALMA**: a very flexible system
  - Easy to define simple settings
  - Much more difficult to *optimize* complex settings

- Bure-like scripts available in ASTRO
- **Exercise with the OT as soon as it is available**

ACA?

- ACA (12 x 7m antennas) has its own correlator
- Very different design (XF vs FX)
- But will provide the **very same modes (bandwidth/resolution) than the main correlator**

  →Needed to merge the data into one single set