ALMA Correlator *tutorial*

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Purpose

- To describe the use of the ALMA correlator and to provide examples of its capabilities. The setting of the correlator using OT is also described along with some scientific cases.

Outline

- Basic description of the correlator
- Antennas (quantization, ...)
- Tunable Filter Cards (filters, re-quantization, ...)
- Correlator Array (correlation, ...)
- Observing modes and Splatalogue
- Observing Tool (spectral lines, bandwidths, resolution, sensitivity, ...)
- Early Sience Phase

Quick description of the correlator

Short overview

- The observatory has a 12 m (64 antennas) and 7 m (12 antennas) arrays. There is a correlator for each of them.
- The main correlator will process the outputs from 64 antennas: either the 64 12m-antennas or a combination with the Compact Array (12 7m-antennas). These accounts for 2016 independent baselines!
- The correlator will process 8 GHz of bandwidth per antenna in both polarizations.
- **At full-capacity, the correlator will perform 1.7X10^{16} multiply-and-add operations per second!**

General specifications

antennas: **64**

Baseband channels input per antenna: **8**

Input sample format: **3 bit, 8 level** at 4 Gsample/s per baseband channel

Correlation sample format: **2 bit, 4 level and 4 bit, 16 level; Niquist and twice Niquist**

Maximum baseline delay range: **30 km**

Hardware cross-correlators per baseline: **32768 leads+32768 lags**

Hardware autocorrelations per antenna: 32768

Product pairs possible for polarization: HH, VV, HV, VH (H and V orthogonal)

ALMA correlator consists of 4 quadrants

Quadrant 1 of the correlator

From left to right: Power supply, station racks, correlator racks, station racks, computer.

Correlator type XF

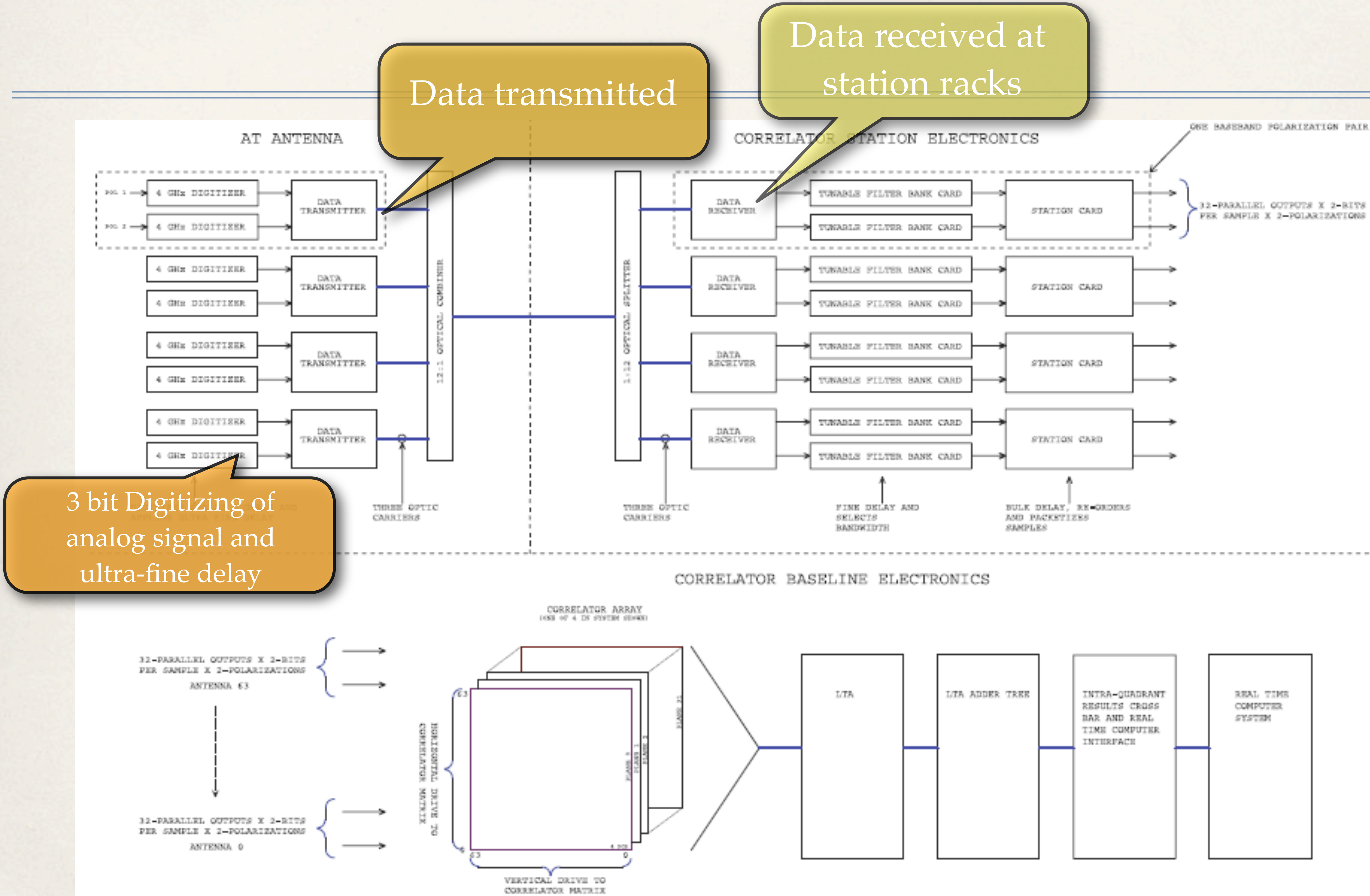
- The correlator will produce the cross-correlated data and then will apply the Fourier transform to obtain the frequency domain.
- A new design for a Tunable Filter Bank (TFB) of cards gives the opportunity to increase the spectral resolution by a factor of 32. The 2 GHz baseband is then split in 32 parts of 62.5 (or 31.25) MHz. The correlator is then called an FXF (hybrid) type.
- The correlator for the Atacama Compact Array will do first the Fourier transform of the data and then the cross correlation (FX type).

Data processing

- Antennas take the data (analogic) -->
- digitized at 3 bits -->
- bandwidth selection (TFC) -->
- to the correlator

Antennas

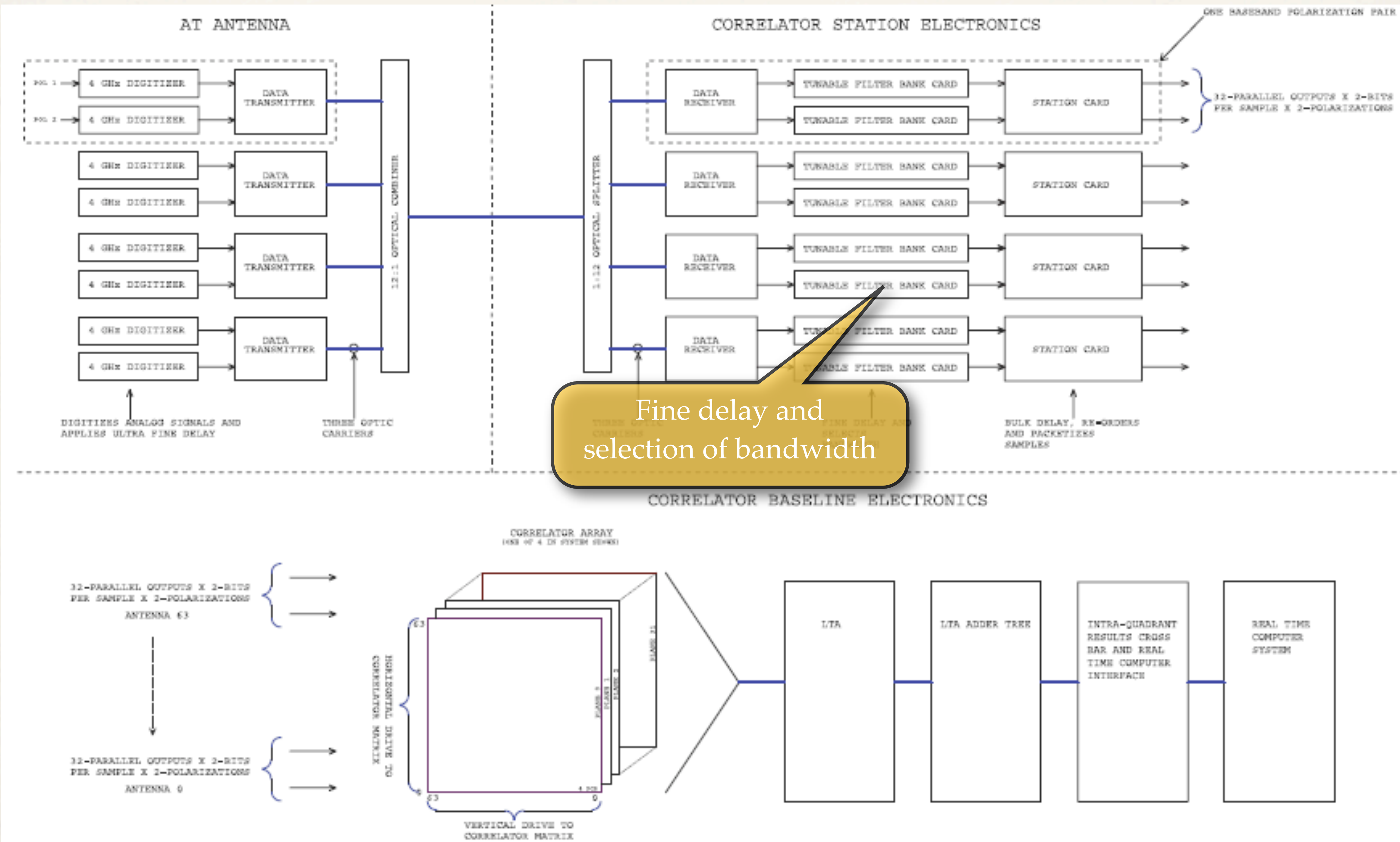
Schematic data flow



Digitizing

- **ALMA digitizers at antennas quantize samples at the 3-bit level ==> sets the system efficiency at 96%.**
- **But the correlator circuits are 2-bit level.**

Schematic data flow



Observing modes

- The telescope can be set in "frequency division mode", which means that high spectral resolution can be reached but with bandwidth, quantization, and Nyquist sampling restrictions.
- In the "time division mode", the entire 2 GHz bandwidth is used at 3 bit level quantization. This mode is used to observe continuum.

Tunable Filter Cards and Correlator “planes”

Tunable Filter Cards (TFC)

- TFC splits a 2 GHz bandwidth of data into 32 parts or filters, each one with 62.5 (or 31.25) MHz.
- **Central frequency of each filter is independently tunable -> each group of filters can have different resolutions and be placed anywhere (30.5 KHz precision) inside the 2GHz bandwidth!**
- Each filter is processed independently in the correlator. Then cross-correlation coefficients for the same bands for all the 64 antennas are calculated. This gives the increment by 32 in the spectral resolution.
- If not all the 32 filters are used, correlator resources can be distributed to get higher spectral resolution.

Re-quantization

- After bandwidth selection:
- In frequency division mode, after going through digital mixers and filters, the samples are re-quantized at 2- or 4-bit level.
  2-bit implies 88% correlator efficiency, while 99% for 4-bit (4 times less frequency resolution available).
- In time division mode, 3-bit samples from the ALMA digitizers go directly to the correlator. To handle this a loss of a factor of 4 in frequency resolution is done, but it allows higher sensitivity.

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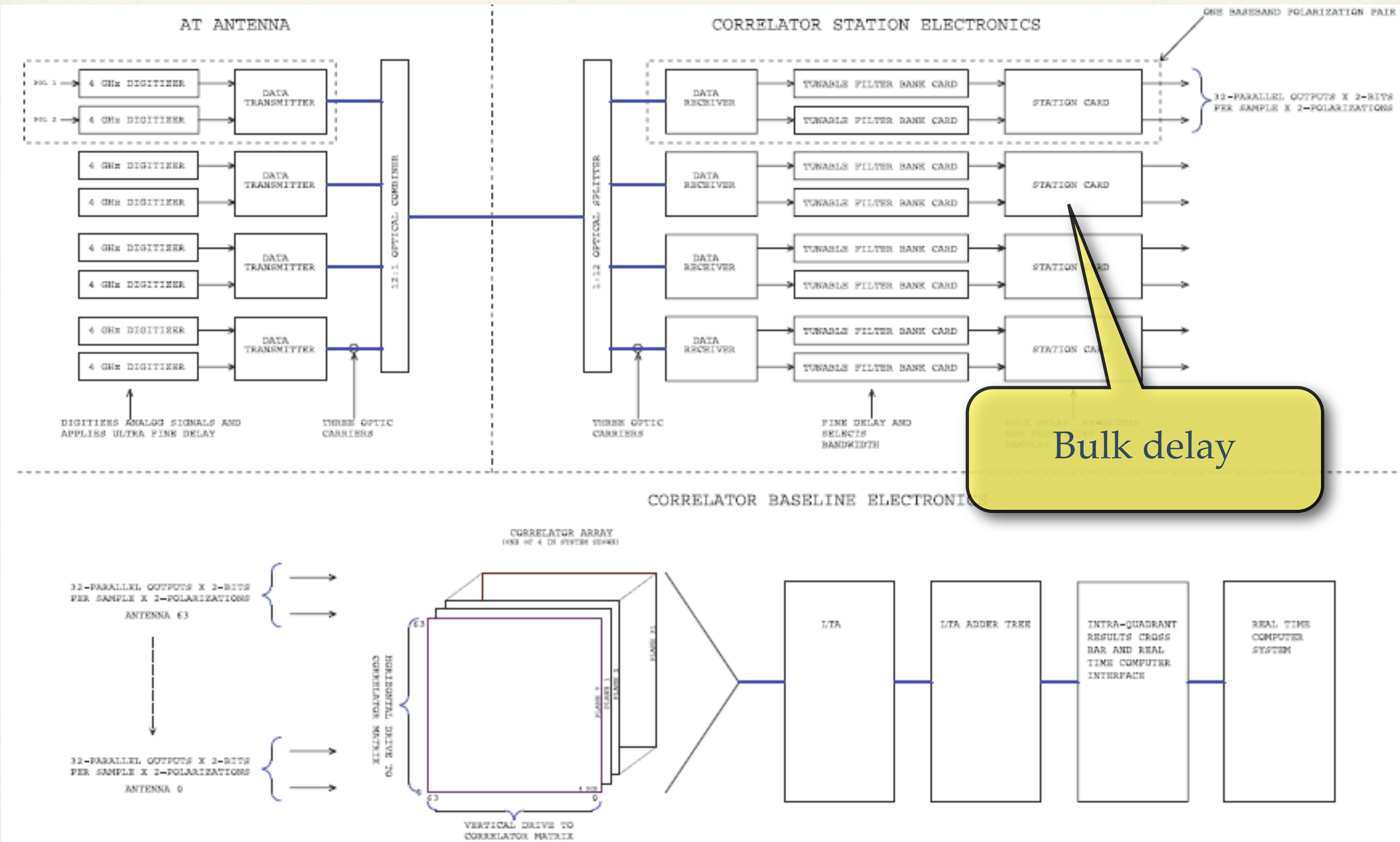
- Each quadrant of the correlator has 128 cards.
- A set of 3 chips implements fine-delay to the 3-bit signal, which is synchronized with the bulk delay of the Station Cards.

Sampling (performed in the TFC)

- Nyquist: It is the standard option.
- Double Nyquist: Two different filters sample zero and 1/2 bit time-shifted versions of the same 62.5 MHz band. They are processed separately in the correlator and the lags are summed.
- Twice Nyquist is possible for a bandwidth smaller than 2 GHz, and imply a lost of a factor of 2 in frequency resolution, compared to the single Nyquist option.
- For 31.25 MHz a true twice Nyquist is sampled, both at frequency and time division modes.

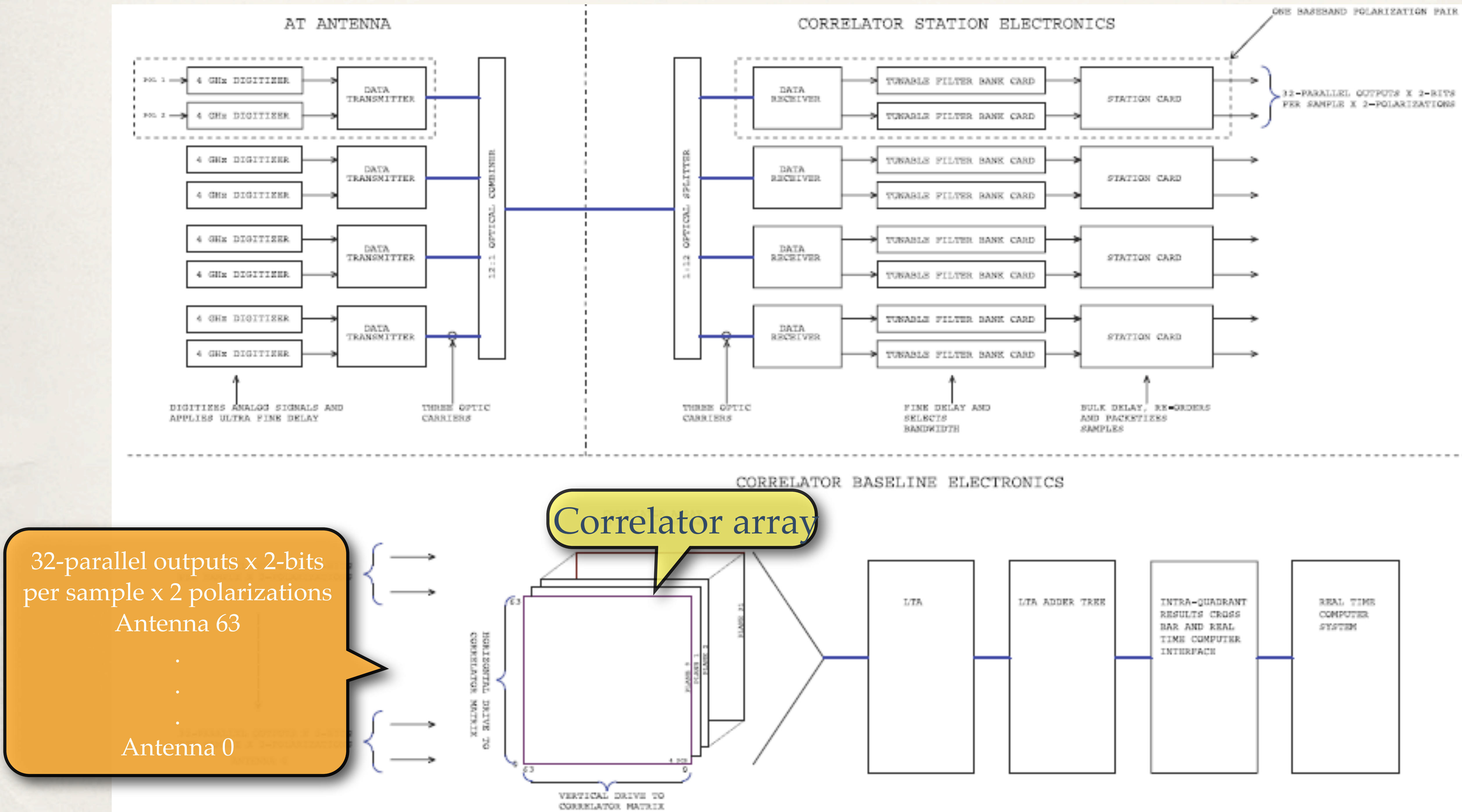
Schematic data flow



Station Cards:

- To implement the geometric (bulk) delay.
- Each station card stores two 4 ms buffers, and each of them holds 4 ms of samples of the 4 GHz sample rate of a baseband.
- Lag generation for high frequency resolution modes *
- 1 ms packets in time division operation at 125 MHz **

Schematic data flow



“Planes” in the correlator

- To process all baselines, the correlator has an array chips to correlate a matrix of 64X64 elements, with a depth of 32 (“planes”).
- At each of the 64X64 intersections of each plane, there is a 256 lag correlator element. These elements work with both polarizations and can deliver one 256-, two 128- or four 64-lag blocks to support polarization schemes.
- The autocorrelation occurs at the diagonal of the matrix (same antenna) and cross-correlation elsewhere (for the rest of antennas).

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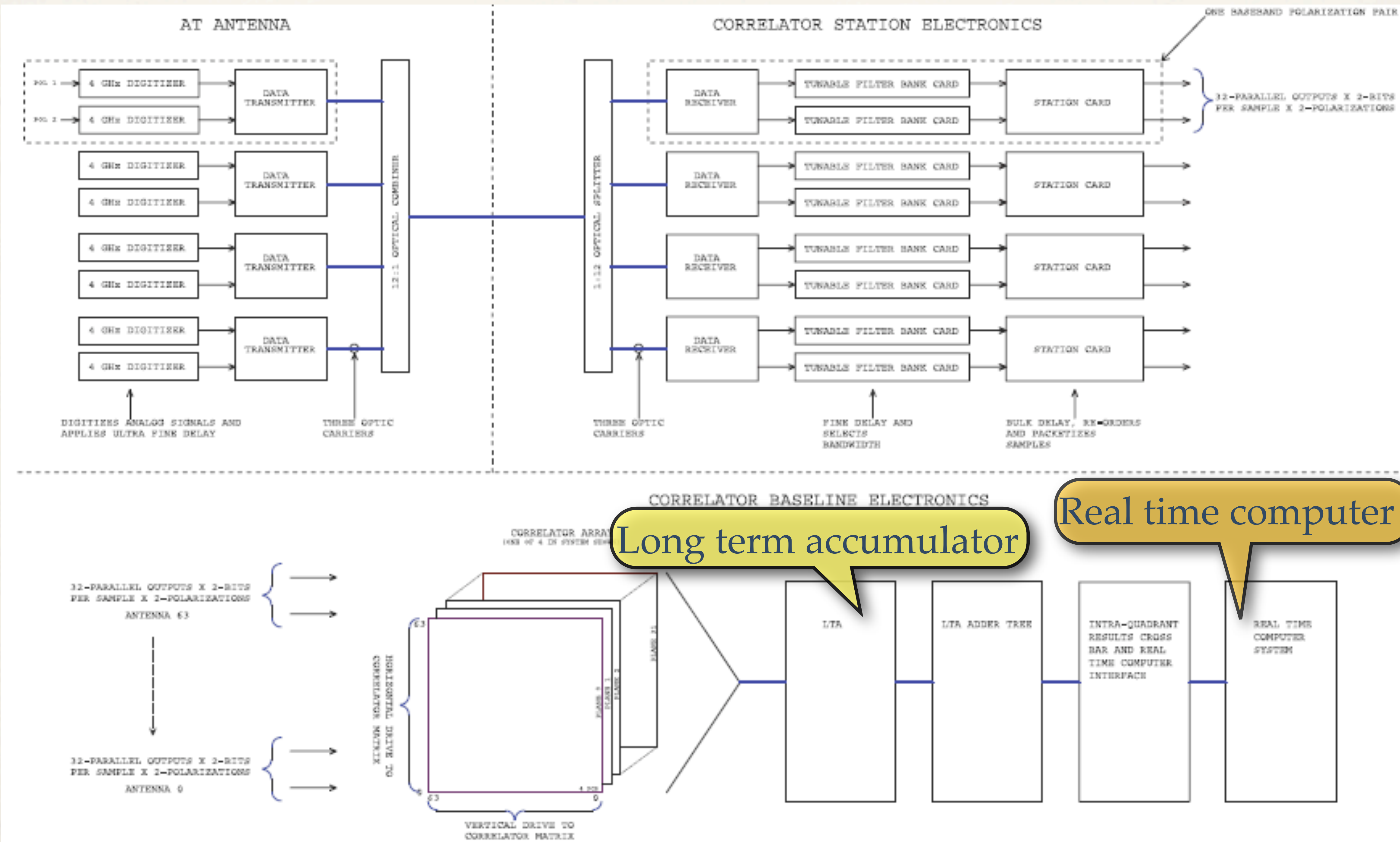
*This mode is for the frequency division mode. The input to the card is from 1 to 32 separate filters at single or double Nyquist sampling. Each plane processes one of the 32 filters coming from the TFC.

**This mode is for the time resolution mode. The card processes the all 4 GHz clock rate of the ALMA digitizers (3 bit). Each ms of data of split into 32 ms block of 125 MHz clock rate. Each ms block is processed in each plane of the correlator.

- **Each quadrant can process 2 X 2 GHz bandwidth from all the array.**

Schematic data flow



Long Term Accumulator (LTA):

- To produce long time-integration options from 1 ms or 16 ms integrations coming from the “planes”.
- To provide an interface with the real-time computer system.
- In time division mode, the LTA performs the adding of the correlator planes.

4 quadrants

- ***The correlator consists of 4 quadrants, each of them has all the specifications mentioned before.***

- Each 8 GHz per polarization per antenna are split in 4 basebands of 2GHz wide per polarization. A total of 16 GHz (8 basebands of 2 GHz) per antenna enters the correlator.

Distribution of resources

- Several spectral resolutions with a different number of filters are available to select, which also implies different bandwidths.
- 3.8 kHz is the maximum spectral resolution.
- Data can be sampled at single- or double-Nyquist. The last one implies half of the spectral resolution, but provides higher signal to noise.
- It is also possible to select 2- or 4-bit correlation.

Observing modes and Splatalogue

Observing modes (1 quadrant)

For one baseband: 3.8 kHz is the highest resolution.

Number of active filters	Total bandwidth	Number of spectral points	Spectral resolution	Velocity resolution at 230 GHz	Correlation*
32	2 GHz	8192/4096/2048	244/488/976 kHz	0.32/0.64/1.28 km s^{-1}	2B-N/2B-2N/4B-N
16	1 GHz	8192/4096/2048/1024	122/244/488/976 kHz	0.16/0.32/0.64/1.28 km s^{-1}	2B-N/2B-2N/4B-N/4B-2N
8	500 MHz	8192/4096/2048/1024	61/122/244/488 kHz	0.08/0.16/0.32/0.64 km s^{-1}	2B-N/2B-2N/4B-N/4B-2N
4	250 MHz	8192/4096/2048/1024	30/61/122/244 kHz	0.04/0.08/0.16/0.32 km s^{-1}	2B-N/2B-2N/4B-N/4B-2N
2	125 MHz	8192/4096/2048/1024	15/30/61/122 kHz	0.02/0.04/0.08/0.16 km s^{-1}	2B-N/2B-2N/4B-N/4B-2N
1	62.5 MHz	8192/4096/2048/1024	7.6/15/30/61 kHz	0.01/0.02/0.04/0.08 km s^{-1}	2B-N/2B-2N/4B-N/4B-2N
1	31.25 MHz	8192/2048	3.8/7.6 kHz	0.005/0.01 km s^{-1}	2B-2N/4B-2N
Time Division Mode	2 GHz	64	31.25 MHz	40.8 km s^{-1}	Full 3-bit x 3-bit, Nyquist sampling

In the highlighted observing mode, 8 filters are selected in the TFCs to get 500 MHz of bandwidth. Using 2-bit quantization and twice Nyquist sampling, we get 4096 spectral points (122 kHz wide), and 0.16 km/s in velocity resolution at a 230 GHz observation.

...

For two basebands with no polarization cross-products:

7.6 kHz is the highest resolution.

Number of active filters	Total bandwidth	Number of spectral points	Spectral resolution	Velocity resolution at 230 GHz	Correlation*
32	2 GHz	4096	488 kHz	0.64 ms	2B-N
16	1 GHz	4096/2048/1024	244/488/976 kHz	0.32/0.64/1.28 km s^{-1}	2B-N/2B-2N/4B-N
8	500 MHz	4096/2048/1024/512	122/244/488/976 kHz	0.16/0.32/0.64/1.28 km s^{-1}	2B-N/2B-2N/4B-N/4B-2N
4	250 MHz	4096/2048/1024/512	61/122/244/488 kHz	0.04/0.08/0.16/0.32 km s^{-1}	2B-N/2B-2N/4B-N/4B-2N
2	125 MHz	4096/2048/1024/512	30/61/122/244 kHz	0.04/0.08/0.16/0.32 km s^{-1}	2B-N/2B-2N/4B-N/4B-2N
1	62.5 MHz	4096/2048/1024/512	15/30/61/122 kHz	0.02/0.04/0.08/0.16 km s^{-1}	2B-N/2B-2N/4B-N/4B-2N
1	31.25 MHz	4096/1024	7.6/30 kHz	0.01/0.04 km s^{-1}	2B-2N/4B-2N
Time Division Mode	2 GHz	128	15.6 MHz	20.4 km s^{-1}	2B-N

In this case, using two polarization products implies we are using DOUBLE of the resources of the correlator. Then, with 8 filters (to get the same 500 MHz of bandwidth) and the same 2-bits quantization and twice Nyquist sampling, we will get 2048 spectral points (244 kHz wide), and 0.32 km/s in velocity resolution at a 230 GHz observation.

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For two basebands with polarization cross-products:

15 kHz is the highest resolution.

Number of active filters	Total bandwidth	Number of spectral points	Spectral resolution	Velocity resolution at 230 GHz	Correlation*
32	2 GHz	2048	976 kHz	1.28 km s^{-1}	2B-N
16	1 GHz	2048/1024	488/976 kHz	0.64/1.28 km s^{-1}	2B-N/2B-2N
8	500 MHz	2048/1024	244/488 kHz	0.32/0.64 km s^{-1}	2B-N/2B-2N
4	250 MHz	2048/1024	122/244 kHz	0.16/0.32 km s^{-1}	2B-N/2B-2N
2	125 MHz	2048/1024/512	61/122/244 kHz	0.08/0.16/0.32 km s^{-1}	2B-N/2B-2N/4B-N
1	62.5 MHz	2048/1024/512/256	30/61/122/244/ kHz	0.04/0.08/0.16/0.32 km s^{-1}	2B-N/2B-2N/4B-N/4B-2N
1	31.25 MHz	2048/512	15/61 kHz	0.02/0.08 km s^{-1}	2B-2N/4B-2N
Time Division Mode	2 GHz	64	31.25 MHz	40.8 km s^{-1}	2B-N

In this case, using cross-products for polarization, we are using DOUBLE of the resources of the previews mode. Then, with 8 filters (to get the same 500 MHz of bandwidth) and the same 2-bits quantization and twice Nyquist sampling, we will get 1024 spectral points (488 kHz wide), and 0.64 km/s in velocity resolution at a 230 GHz observation.

Remember

- The user has to remember and keep in mind that the correlator resources are finite. **Going from Nyquist sampling to twice Nyquist implies 2 times less spectral resolution.**

- **Going from 2-bit quantization to 4-bit implies 4 times less spectral resolution.**

- In general cases, if a high spectral resolution is not needed, 4 bit correlation and twice Nyquist can be set to achieve high correlator sensitivity and require a smaller observing time.

- User has to read carefully the tables for observing modes, and take into consideration which polarization observation scheme is needed.

Efficiency

- 2-bit X 2-bit correlation (Nyquist sampling) provides an efficiency of 0.88.

- 2-bit X 2-bit correlation (double Nyquist sampling) provides an efficiency of 0.94, but allows 14% less integration time.

- 4-bit X 4-bit correlation (Nyquist sampling) provides an efficiency of 0.99; and allows 27% less integration time.

- 4-bit X 4-bit correlation (double Nyquist sampling) provides an efficiency of approx. 0.99 (little usefulness).

ALMA bands

- All the observing modes described can be used in any of the bands that will be available in the ALMA observatory:
- **1**: 31-45 GHz **2**: 67-90 GHz **3**: 84-116 GHz **4**: 125-163 GHz
  5: 163-211 GHz **6**: 211-275 GHz **7**: 275-373 GHz
  8: 385-500 GHz **9:** 602-720 GHz **10:** 787-950 GHz

Splatalogue

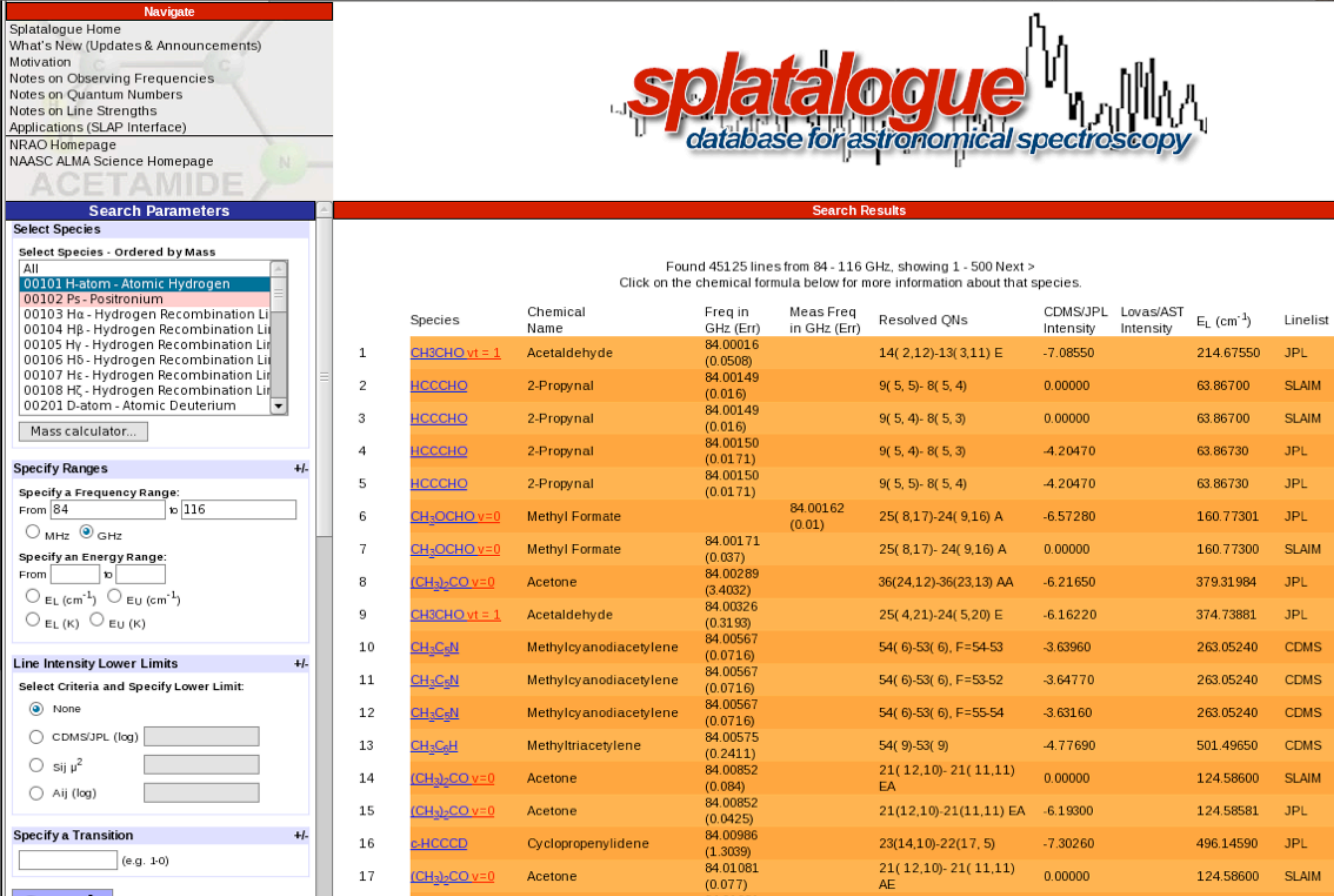
- The splatalogue catalog is maintained by NRAO and is a compilation from several databases for molecular and atomic lines. Many spectral lines are listed in it, so it is a very useful tool in planning observations for ALMA.

- There are several rearch options in splatalogue to narrow down the results obtained. In the next slides we show an example of the use of the database.

- To consult the database, go to http://www.splatalogue.net

Query search

- Looking for spectral lines in the band 3 of ALMA, using the defaults query parameters, the database returns more than 45000 results!
- The information is presented in a table-format way, including species composition, chemical name, frequency, etc.
- By making click in a result, a new window displays more information about the line, including references and the origin of the information.



Navigate

Splatalogue Home
What's New (Updates & Announcements)
Motivation
Notes on Observing Frequencies
Notes on Quantum Numbers
Notes on Line Strengths
Applications (SLAP Interface)
NRAO Homepage
NAASC ALMA Science Homepage

splatalogue
database for astronomical spectroscopy

Search Parameters

Select Species

Select Species - Ordered by Mass

All
00101 H-atom - Atomic Hydrogen
00102 Ps - Positronium
00103 Hα - Hydrogen Recombination Li
00104 Hβ - Hydrogen Recombination Li
00105 Hγ - Hydrogen Recombination Li
00106 Hδ - Hydrogen Recombination Li
00107 Hε - Hydrogen Recombination Li
00108 Hζ - Hydrogen Recombination Li
00201 D-atom - Atomic Deuterium

Mass calculator...

Specify Ranges +/-

Specify a Frequency Range:
From 84 to 116
MHz GHz

Specify an Energy Range:
From to
E_L (cm^{-1}) E_U (cm^{-1})
E_L (K) E_U (K)

Line Intensity Lower Limits +/-

Select Criteria and Specify Lower Limit:
None
CDMS/JPL (log)
Sij μ^2
Aij (log)

Specify a Transition +/-

(e.g. 1-0)

Search

Search Results

Found 45125 lines from 84 - 116 GHz, showing 1 - 500 Next >
Click on the chemical formula below for more information about that species.

	Species	Chemical Name	Freq in GHz (Err)	Meas Freq in GHz (Err)	Resolved QNs	CDMS/JPL Intensity	Lovas/AST Intensity	E_L (cm^{-1})	Linelist
1	CH3CHO vt = 1	Acetaldehyde	84.00016 (0.0508)		14(2,12)-13(3,11) E	-7.08550		214.67550	JPL
2	HCCCHO	2-Propynal	84.00149 (0.016)		9(5, 5)- 8(5, 4)	0.00000		63.86700	SLAIM
3	HCCCHO	2-Propynal	84.00149 (0.016)		9(5, 4)- 8(5, 3)	0.00000		63.86700	SLAIM
4	HCCCHO	2-Propynal	84.00150 (0.0171)		9(5, 4)- 8(5, 3)	-4.20470		63.86730	JPL
5	HCCCHO	2-Propynal	84.00150 (0.0171)		9(5, 5)- 8(5, 4)	-4.20470		63.86730	JPL
6	CH_3OCHO v=0	Methyl Formate		84.00162 (0.01)	25(8,17)-24(9,16) A	-6.57280		160.77301	JPL
7	CH_3OCHO v=0	Methyl Formate	84.00171 (0.037)		25(8,17)- 24(9,16) A	0.00000		160.77300	SLAIM
8	$(CH_3)_2CO$ v=0	Acetone	84.00289 (3.4032)		36(24,12)-36(23,13) AA	-6.21650		379.31984	JPL
9	CH3CHO vt = 1	Acetaldehyde	84.00326 (0.3193)		25(4,21)-24(5,20) E	-6.16220		374.73881	JPL
10	CH_3C_5N	Methylcyanodiacetylene	84.00567 (0.0716)		54(6)-53(6), F=54-53	-3.63960		263.05240	CDMS
11	CH_3C_5N	Methylcyanodiacetylene	84.00567 (0.0716)		54(6)-53(6), F=53-52	-3.64770		263.05240	CDMS
12	CH_3C_5N	Methylcyanodiacetylene	84.00567 (0.0716)		54(6)-53(6), F=55-54	-3.63160		263.05240	CDMS
13	CH_3C_6H	Methyltriacetylene	84.00575 (0.2411)		54(9)-53(9)	-4.77690		501.49650	CDMS
14	$(CH_3)_2CO$ v=0	Acetone	84.00852 (0.084)		21(12,10)- 21(11,11) EA	0.00000		124.58600	SLAIM
15	$(CH_3)_2CO$ v=0	Acetone	84.00852 (0.0425)		21(12,10)-21(11,11) EA	-6.19300		124.58581	JPL
16	c-HCCCD	Cyclopropenylidene	84.00986 (1.3039)		23(14,10)-22(17, 5)	-7.30260		496.14590	JPL
17	$(CH_3)_2CO$ v=0	Acetone	84.01081 (0.077)		21(12,10)- 21(11,11) AE	0.00000		124.58600	SLAIM

Example for the band 3 of ALMA.

Looking for information about carbon monoxide

Search Results

43	$g'Ga\text{-}(CH_2OH)_2$	Ethylene Glycol	115.24661 (0.0016)		12(3,10) v= 1 - 11(3, 8) v= 1	-5.99950		26.12200	CDMS
44	CH_3OCHO v=0	Methyl Formate	115.24722 (0.034)		5(2, 3)- 4(1, 4) A	0.00000		4.25800	SLAIM
45	CH_3OCHO v=0	Methyl Formate	115.24950 (0.112)		27(5,23)- 26(6,20) E	0.00000		163.65600	SLAIM
46	$t\text{-}CH_2CHCHO$	Propenal	115.24983 (0.237)		29(5,25)- 30(4,26)	0.00000		161.21600	SLAIM
47	$^{13}CH_3OH$ $v_t = 0$	Methanol	115.25340 (1.046)		22(5,18)- 23(4,19) ++	0.00000		490.40900	SLAIM
48	H_2NCH_2CN	Aminoacetonitrile	115.26350 (0.233)		31(2,29)-31(2,30)	-5.78400		152.21210	CDMS
49	CH_3CH_2CN v = 0	Ethyl Cyanide		115.26503 (0.05)	7(3, 4)- 7(2, 5)	-4.93500		11.47930	JPL
50	$^{13}CH_3CH_2CN$	Ethyl Cyanide	115.26754 (0.015)		8(3, 6)- 8(2, 7)	0.00000		13.54400	SLAIM
51	$(CH_3)_2CO$ v=0	Acetone	115.26954 (21.4113)		54(33,21)-54(32,22) EE	-6.26950		835.60529	JPL
52	CO v = 0	Carbon Monoxide	115.27120 (0)	115.27120 (0.001)	1- 0	0.00000	60.00000	0.00000	SLAIM
53	CH3CHO vt = 1	Acetaldehyde	115.27182 (0.021)	115.27192 (0.04)	4(2, 2)- 4(1, 3) A+-	0.00000		151.60500	SLAIM
54	Hα	Hydrogen Recombination Line	115.27440 (0)		H (38) α	0.00000		0.00000	Recomb
55	$CH_3{}^{13}CH_2CN$	Ethyl Cyanide	115.28185 (0.137)		35(3,32)- 35(2,33)	0.00000		193.10100	SLAIM
56	$c\text{-}H_2COCH_2$	Ethylene Oxide	115.28201 (0.0172)		10(6,5)-9(9,0)	-7.95620		74.65260	CDMS
57	CH_3OCHO v=1	Methyl Formate		115.28565 (0.01)	39(8,31)-39(8,32) A	-6.43660		481.33151	JPL
58	$CH_3{}^{13}CH_2CN$	Ethyl Cyanide	115.28754 (0.006)		13(2,12)- 12(2,11)	0.00000		26.14200	SLAIM
59	CH_2CHCN v= 0	Vinyl Cyanide		115.28767 (0.005)	20(4,16)-21(3,19)	-5.38680		86.71430	JPL
60	$g'Ga\text{-}(CH_2OH)_2$	Ethylene Glycol		115.29074 (0.01)	12(1,11) v= 0 - 11(1,10) v= 1	-4.42070		23.55610	CDMS

First part of the information for CO v=0 1-0

Carbon Monoxide
CO v = 0
Splat ID: 02812

CDMS

species_id	204
Name	Carbon Monoxide, *v* = 0
Date	Oct. 2000
Contributor	H. S. P. Müller
Q_2000_	726.7430
Q_1000_	362.6910
Q_500_0	181.3025
Q_300_0	108.8651
Q_225_0	81.7184
Q_150_0	54.5814
Q_75_00	27.4545
Q_37_50	13.8965
Q_18_75	7.1223
Q_9_375	3.7435
MU_A	0.11011
B	57635.96
Ref1	The experimental measurements were summarized by G. Winnewisser, S. P. Belov, T. Klaus, and R. Schieder, 1997, *J. Mol. Spectrosc.*, **184**, 468.
Ref20	http://www.astro.uni-koeln.de/cgi-bin/cdmsinfo?file=e028503.cat
planet	1
ism_hotcore	1
comet	1
extragalactic	1
LineList	10
v1_0	1
v2_0	2
linelist	CDMS

Second part of the information for CO v=0 1-0

JPL

species_id	204
Name	CO Carbon monoxide
Date	Aug. 1997
Contributor	H. S. P. M¨ller
Q_300_0	108.865
Q_225_0	81.718
Q_150_0	54.581
Q_75_00	27.455
Q_37_50	13.897
Q_18_75	7.122
Q_9_375	3.744
MU_A	0.11011
B	57635.96
Ref1	The experimental measurements were reported by (1) G. Winnewisser,S. P. Belov, Th. Klaus, and R. Schieder, 1997, J. Mol. Spect. **184**, . The dipole moment and dipole centrifugal corrections are taken from (2) D. Goorvitch, 1994, Astrophys. J. Suppl. **95**, 535.
Ref20	http://spec.jpl.nasa.gov/ftp/pub/catalog/doc/d028001.cat
planet	1
ism_hotcore	1
comet	1
extragalactic	1
LineList	12
v1_0	1
v2_0	2
linelist	JPL

Observing Tool (OT)

purpose

- Here we assume the user has already set all necessary parameters, including the sources to study, calibrators, etc. This part shows how to set the bandwidth to use, spectral lines, spectral resolution, etc.

Basic settings

- Inside an ALMA proposal in OT, the Spectral Setup tab can be found inside every Science Goal tab.
- At the Spectral Setup window in OT, the user can choose from: "Up to 4 spectral elements", "More than 4 spectral elements", "Single continuum (average frequency)", and "Spectral scan".
- Also, the user can choose the polarization products: "single_x", "single_y", "double" (default), and "full" (with cross-products).

...

- The "Select Lines" button takes directly to the list of spectral lines, and it is of easy use. Another way is to type the frequency for the spectral element (and identifier) by hand.

- Once the lines are selected, by doing double-click in a line, the spectral resolution can be chosen.

- The time division mode can be accessed directly by marking the dedicated box for continuum in each spectral element.

Restrictions on spectral elements

- Each spectral element can be up to 2 GHz wide, and as small as 62.5 (or 31.25) MHz, and be placed anywhere inside an ALMA Band. In the option of up to 4 spectral elements, the user will define each of them in the 4-element list provided.

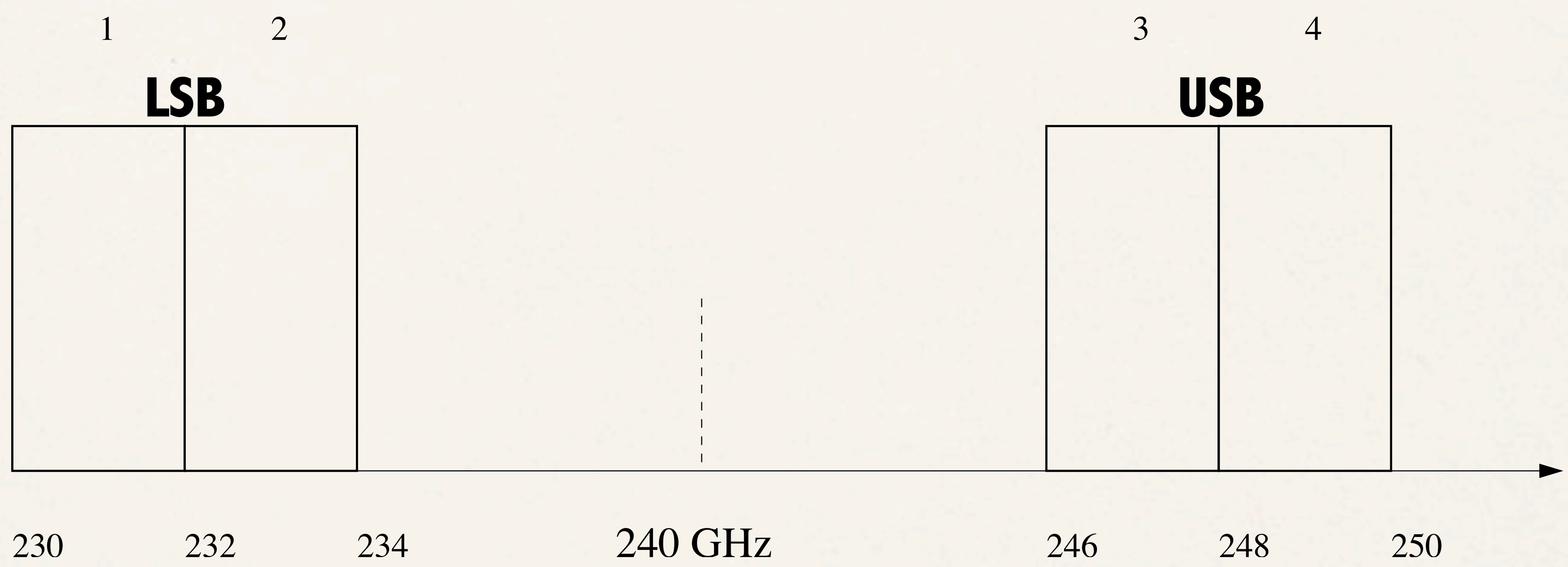
- **For the option of using more than 4 spectral elements, the user has to group them in the 4 set tabs**. In each tab, correlator resources (for 1 quadrant) can be divided in 1, 1/2, 1/4 or 1/8. Then, up to 8 spectral elements can be defined in each set tab.

- **All the spectral elements inside a set tab must be inside the baseband!, i.e. inside a band of 2 GHz wide.**

Restrictions on polarization choices

- Each Science Goal can be defined for ONLY one of the polarization choices. If needed, spectral windows with different polarizations can be set, using several Science Goal sets.
- The polarization choice applies to all the spectral windows in the Science Goal set. This is clearly seen in the next examples.

OT example I: Time division mode only with different polarizations.

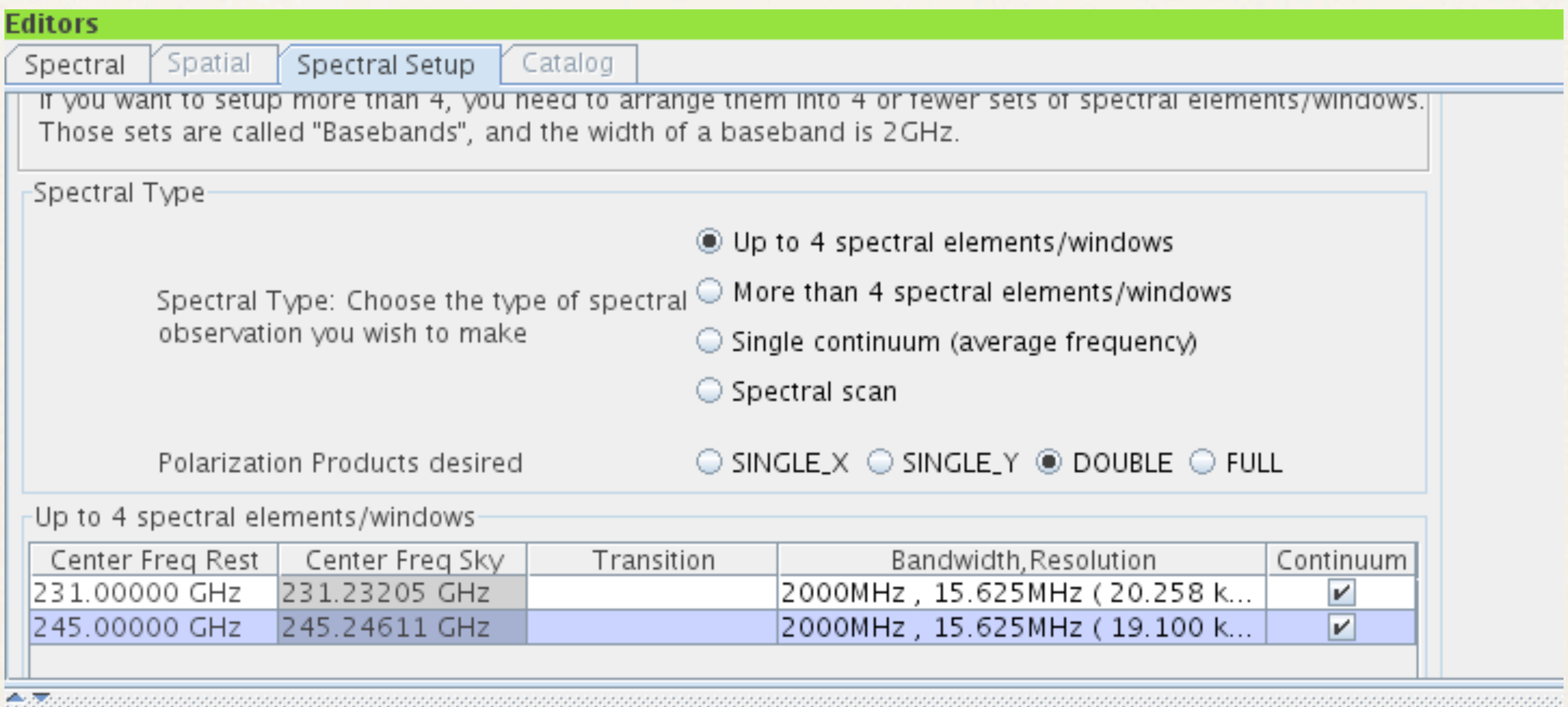


1 & 3: 2 GHz with 128 spectral points (15.6 MHz wide). 2 pol, 2-bit, Nyquist.

2 & 4: 2 GHz with 64 spectral points (31.25 MHz wide). 4 pol, 2-bit, Nyquist

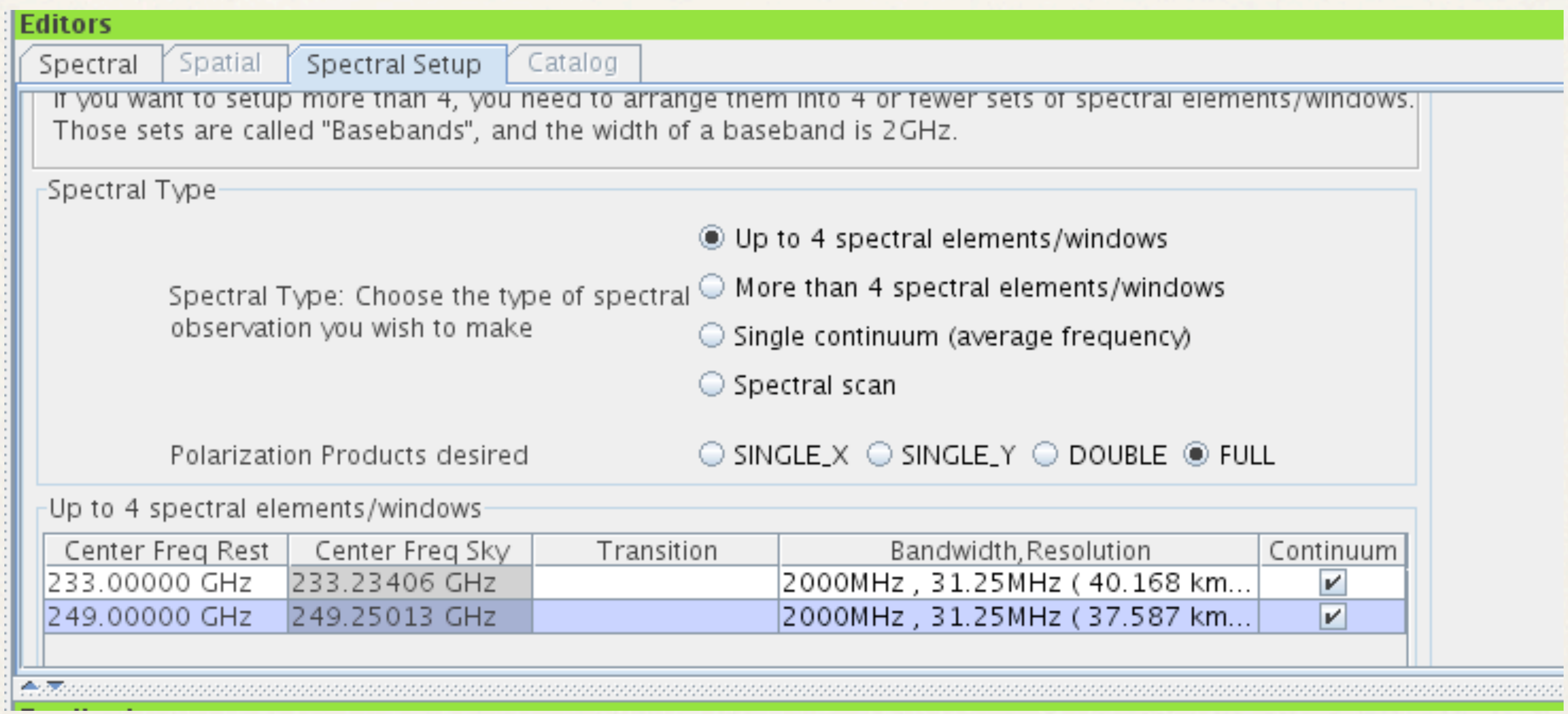
Up to 4 spectral windows

In one Science Goal tab we set the 2 spectral windows with the DOUBLE polarization option.

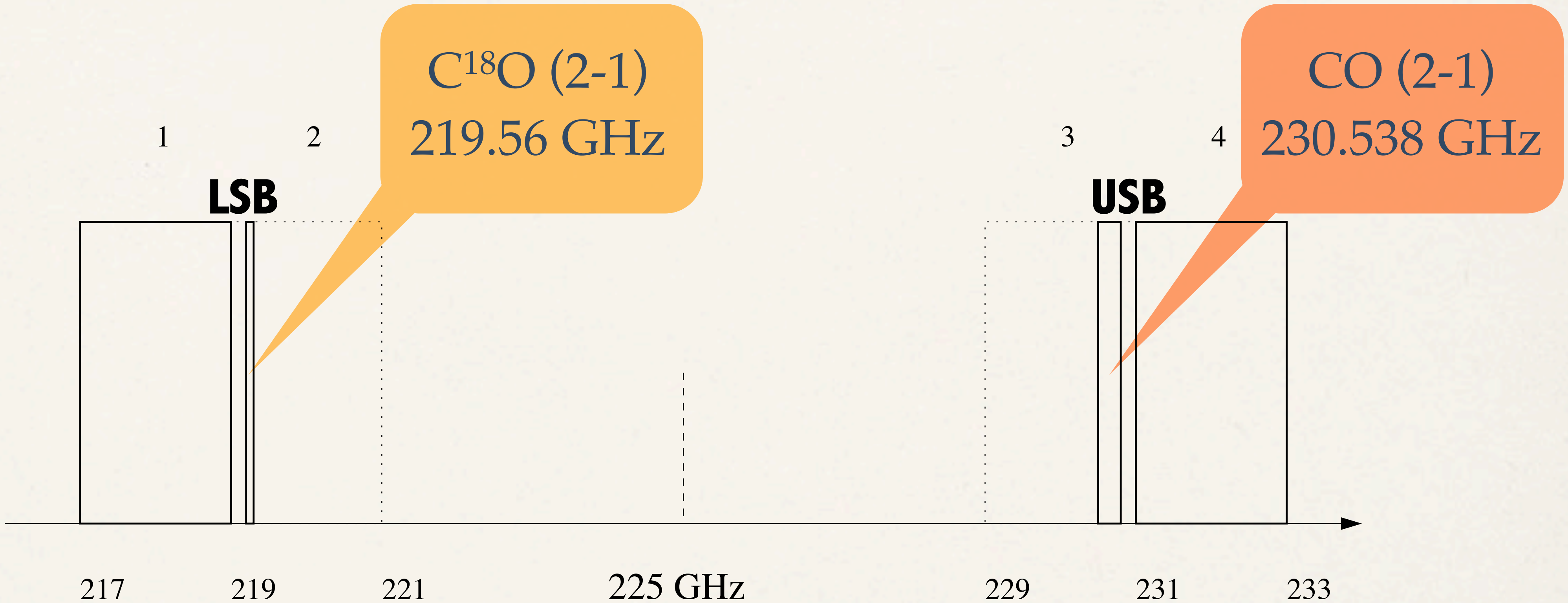


…

In another Science Goal tab we set the 2 spectral windows with the FULL polarization option.



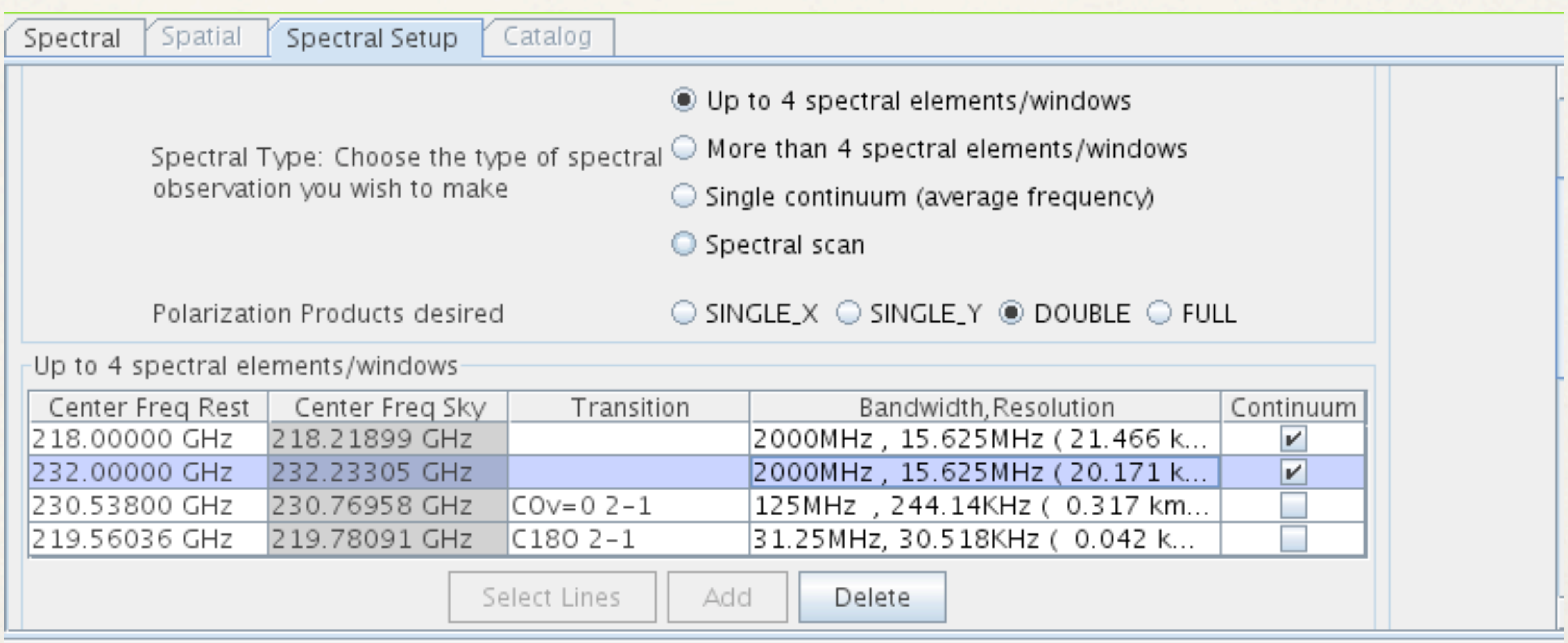
OT example II: Time division mode and frequency division mode together with the same polarization



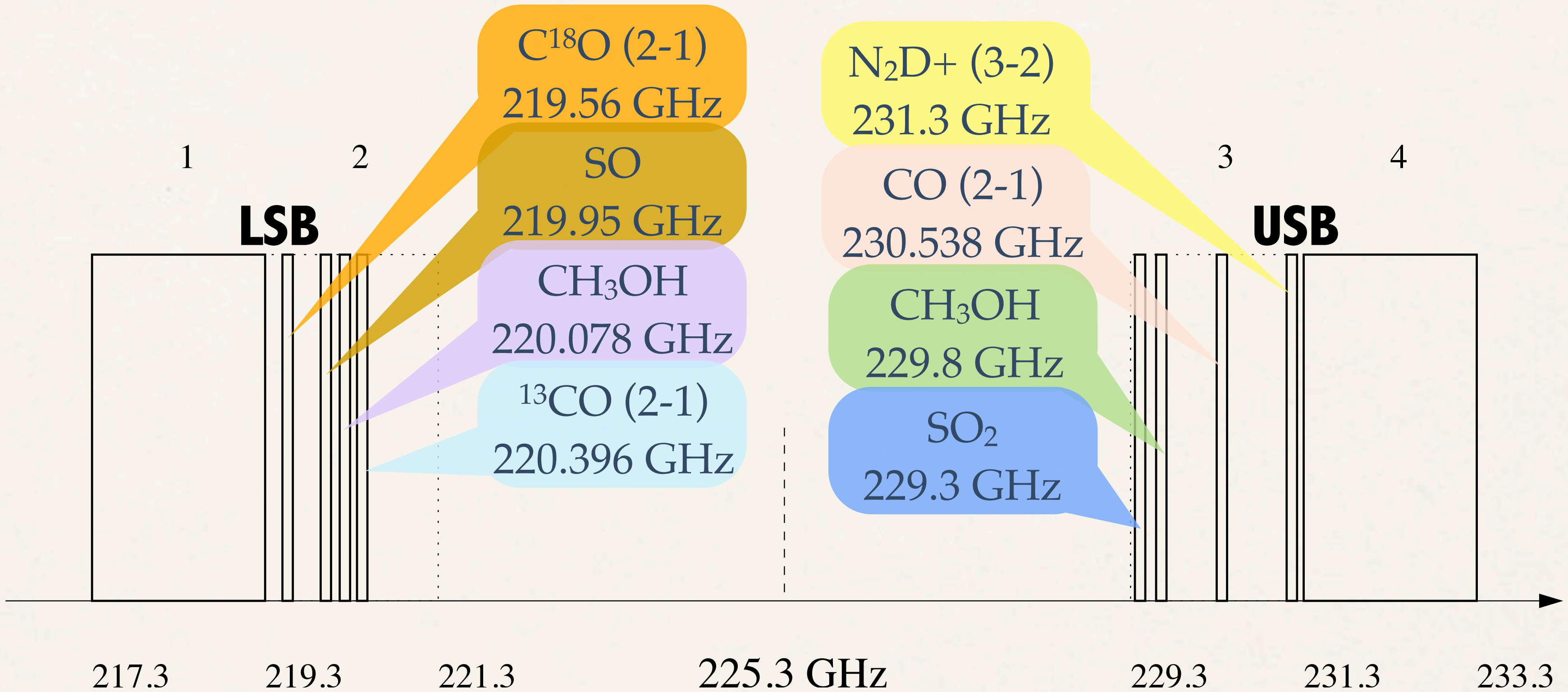
1 & 4: 2 GHz with 128 spectral points (15.6 MHz wide). 2 pol, 2-bit, Nyquist
2: 31.25 MHz with 1024 spectral points (30 kHz wide). 2 pol, 4-bit, 2-Nyquist
3: 125 MHz with 512 spectral points (244 kHz wide). 2 pol, 4-bit, 2-Nyquist

Up to 4 spectral bands

- This example uses double polarization products for 4 spectral windows. The continuum box is chosen to select the time division mode.



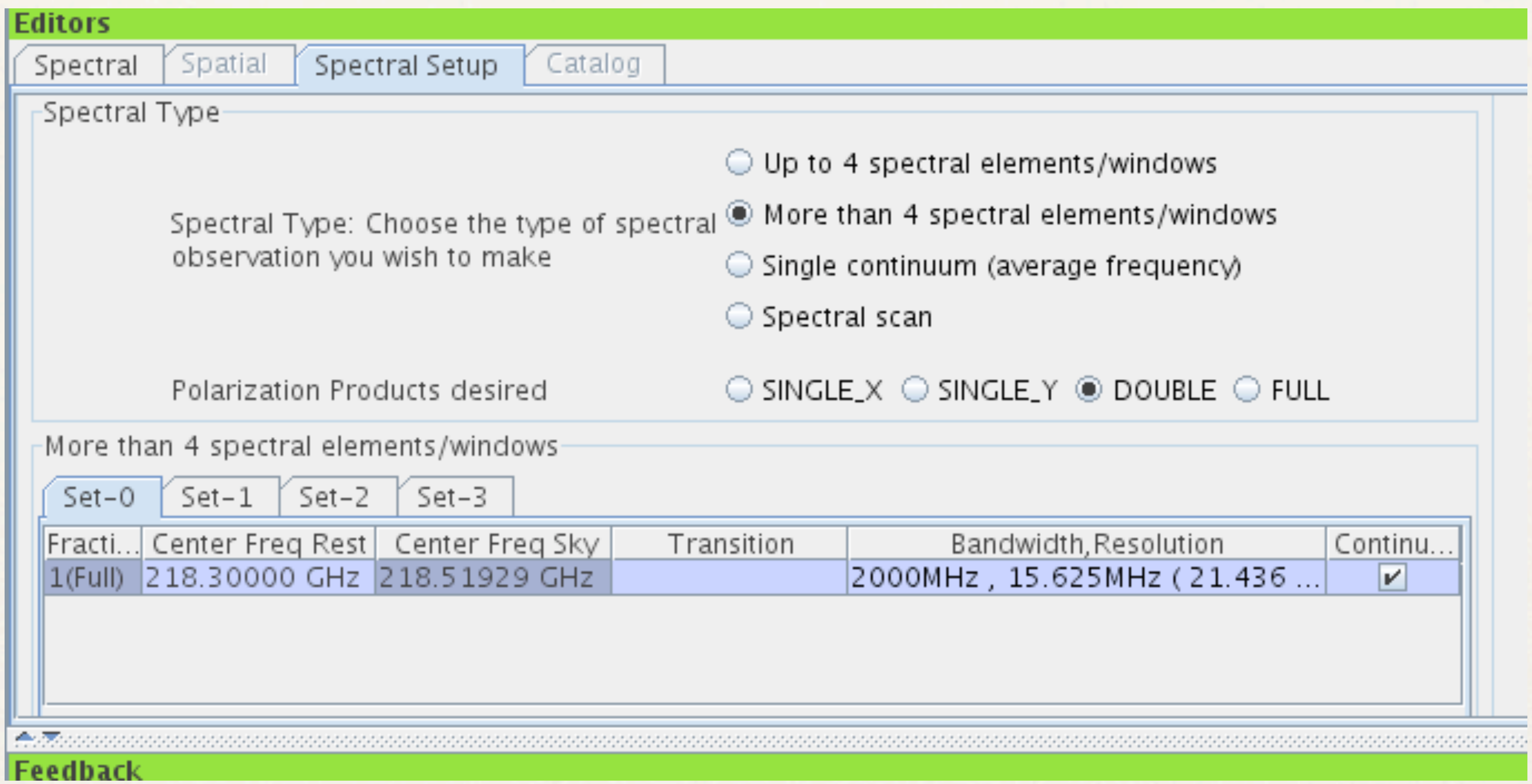
OT example III: Time division mode and frequency division mode together with the same polarization



1 & 4: 2 GHz with 128 spectral points (15.6 MHz wide). 2 pol, 2-bit, Nyquist.

2 y 3: All spectral windows here have 125 MHz of bandwidth with 1024 spectral points (122 kHz wide). 2 pol, 4-bit, Nyquist.

More than 4 spectral windows



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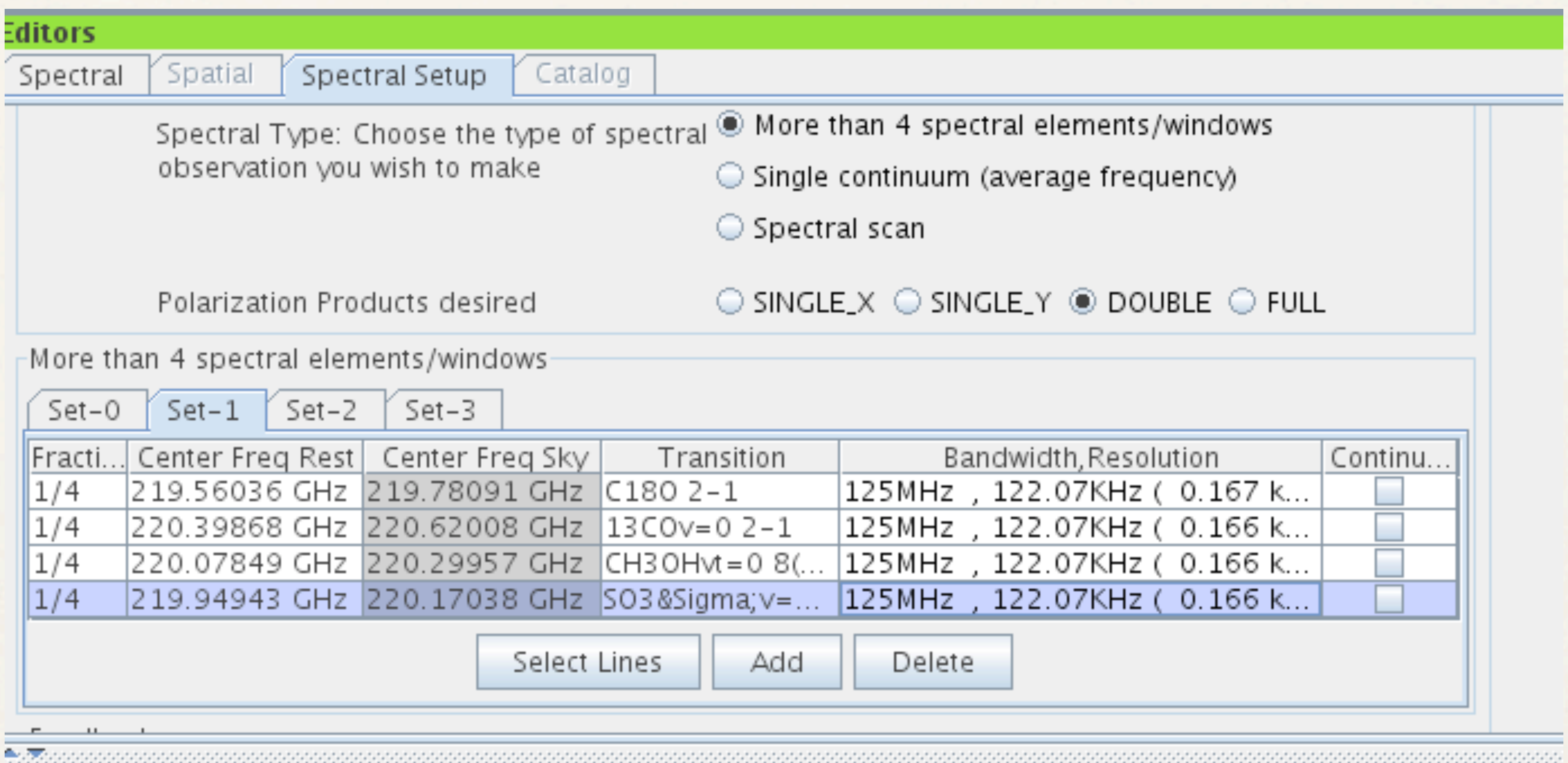
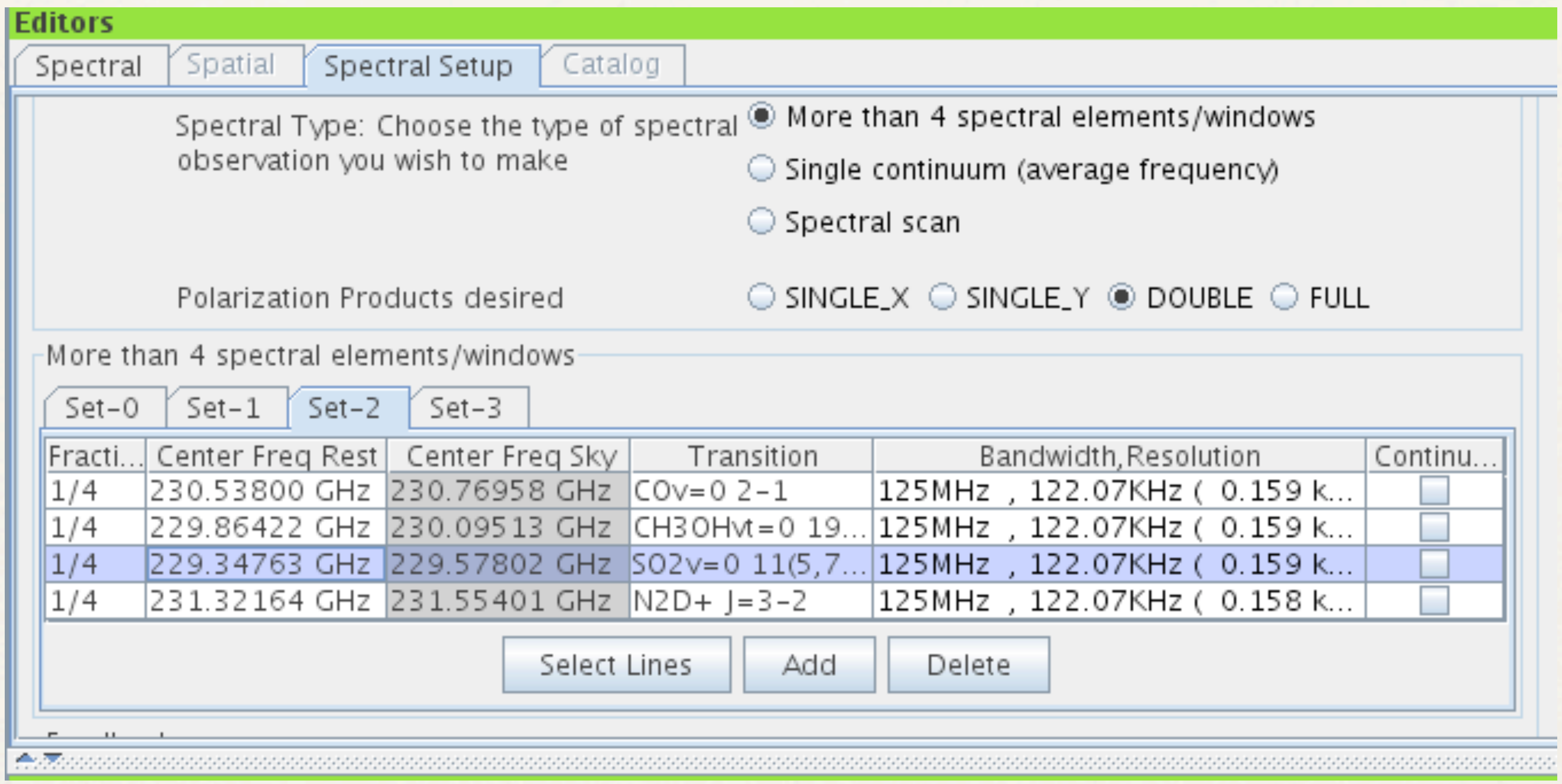


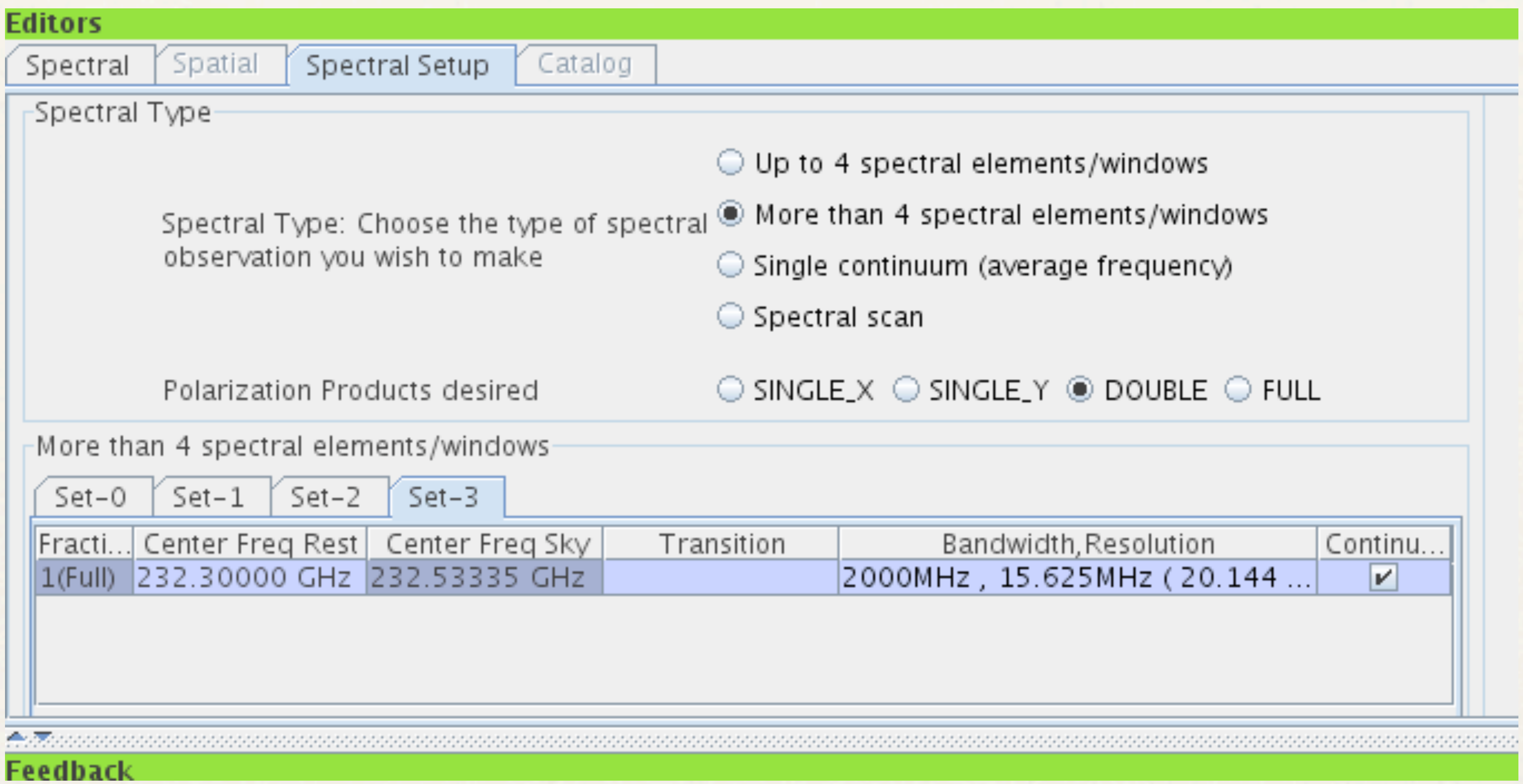
Editors
Spectral
Spatial
Spectral Setup
Catalog
Spectral Type: Choose the type of spectral observation you wish to make
More than 4 spectral elements/windows
Single continuum (average frequency)
Spectral scan
Polarization Products desired
SINGLE_X
SINGLE_Y
DOUBLE
FULL
More than 4 spectral elements/windows
Set-0
Set-1
Set-2
Set-3
Fracti... | Center Freq Rest | Center Freq Sky | Transition | Bandwidth,Resolution | Continu...
1/4 | 219.56036 GHz | 219.78091 GHz | C18O 2-1 | 125MHz , 122.07KHz (0.167 k...
1/4 | 220.39868 GHz | 220.62008 GHz | 13COv=0 2-1 | 125MHz , 122.07KHz (0.166 k...
1/4 | 220.07849 GHz | 220.29957 GHz | CH3OHvt=0 8(... | 125MHz , 122.07KHz (0.166 k...
1/4 | 219.94943 GHz | 220.17038 GHz | SO3Σv=... | 125MHz , 122.07KHz (0.166 k...
Select Lines
Add
Delete

...



Editors
Spectral
Spatial
Spectral Setup
Catalog
Spectral Type: Choose the type of spectral observation you wish to make
More than 4 spectral elements/windows
Single continuum (average frequency)
Spectral scan
Polarization Products desired
SINGLE_X
SINGLE_Y
DOUBLE
FULL
More than 4 spectral elements/windows
Set-0
Set-1
Set-2
Set-3
Fracti... | Center Freq Rest | Center Freq Sky | Transition | Bandwidth,Resolution | Continu...
1/4 | 230.53800 GHz | 230.76958 GHz | COv=0 2-1 | 125MHz , 122.07KHz (0.159 k...
1/4 | 229.86422 GHz | 230.09513 GHz | CH3OHvt=0 19... | 125MHz , 122.07KHz (0.159 k...
1/4 | 229.34763 GHz | 229.57802 GHz | SO2v=0 11(5,7... | 125MHz , 122.07KHz (0.159 k...
1/4 | 231.32164 GHz | 231.55401 GHz | N2D+ J=3-2 | 125MHz , 122.07KHz (0.158 k...
Select Lines
Add
Delete

...


Editors
Spectral
Spatial
Spectral Setup
Catalog
Spectral Type
Up to 4 spectral elements/windows
Spectral Type: Choose the type of spectral observation you wish to make
More than 4 spectral elements/windows
Single continuum (average frequency)
Spectral scan
Polarization Products desired
SINGLE_X
SINGLE_Y
DOUBLE
FULL
More than 4 spectral elements/windows
Set-0
Set-1
Set-2
Set-3
Fracti...
Center Freq Rest
Center Freq Sky
Transition
Bandwidth,Resolution
Continu...
1(Full)
232.30000 GHz
232.53335 GHz
2000MHz , 15.625MHz (20.144 ...
Feedback

After this...

- Further steps are required to set the Scheduling Blocks (SBs), which are required to fully submit an observation program to the observatory.

Early Science Phase of ALMA

Early Science (ES)

- Only one part of the resources described before will be available for the ES phase of the ALMA observatory. With the time, more antennas and receivers will be available for users.

resources for ES

- **16 antennas** will be available.
- **Bands 3, 6, 7, 9.**
- One quadrant of the correlator will process all 4 baseband pairs for the 16 antennas.
- Only 2-bit requantization and simple Nyquist available.
- **NO multiple spectral windows per baseband!**
- **Each baseband's spectral window must have identical characteristics.**

BANDS 3, 6, 7, 9

These 5 highest-priority observing modes will be available for ES

Mode	Filters	width	Spectral points	Spectral resolution	Polarization products	B3 84-116 (km/s)	B6 211-275 (km/s)	B7 275-373 (km/s)	B9 602-720 (km/s)
70	TimeDiv Mode	2 GHz	64	31.25 MHz	4	~ 94	~ 39	~ 29	~ 14
7	32	2 GHz	4096	488 kHz	2	~ 1.5	~ 0.6	~ 0.5	~ 0.2
9	8	500 MHz	4096	122 kHz	2	~ 0.4	~ 0.15	~ 0.1	~ 0.05
12	1	62.5 MHz	4096	15 kHz	2	~ 0.05	~ 0.02	~ 0.015	~ 0.007
18	1	62.5 MHz	2048	30 kHz	4	~ 0.09	~ 0.04	~ 0.03	~ 0.014

The column “B3 84-116” shows the velocity resolution at the center of the band 3. Similar for the other columns/bands.

Spectral lines for band 3 (84-116 GHz)

Representative transitions

85162.223 (5) $HC^{18}O^+$ 1-0
85338.906* (7) c-C_3H_2 2(1,2)-1(0,1)
86340.1764 (2) $H^{13}CN$ 1-0 F=2-1
85347.869* (5) HCS^+ 2-1
85457.299* (1) CH_3CCH 5(K)-4(K)
85672.57 * (1) C_4H 9-8 J=17/2-15/2
86054.967 (1) $HC^{15}N$ 1-0
86754.288* (1) $H^{13}CO^+$ 1-0
86846.995* (6) SiO 2-1 v=0
87090.859 (46) $HN^{13}C$ 1-0 F=2-1
87316.925 (4) C_2H 1-0 3/2-1/2 F=2-1
88631.8473 (10) HCN 1-0 F=2-1 17.2
89188.526* (21) HCO^+ 1-0
90663.574 (10) HNC 1-0 F=2-1
90978.989* (3) HCCCN 10-9
91987.086* (1) CH_3CN 5(K)-4(K)
93176.265 (7) N_2H^+ 1-0 F_1=0-1 F=1-2
93870.098* (12) CCS N,J=7,8-6,7
96412.950 (1) $C^{34}S$ 2-1
96741.377* (3) CH_3OH 2(0,2)_1(0,1) A++
97980.953 (2) CS 2-1
99299.905* (14) SO N,J=2,3-1,2
100076.386* (3) HCCCN 11-10
102547.983* (1) CH_3CCH 6(K)-5(K)
109173.638* (3) HCCCN 12-11
109782.176 (1) $C^{18}O$ 1-0
110201.354 (1) ^{13}CO 1-0
110383.522* (1) CH_3CN 6(K)-5(K) F=7-6
112358.988 (8) $C^{17}O$ 1-0 F=7/2-5/2
113144.192 (9) CN 1-0 J=1/2-1/2 F=1/2-3/2
115271.202* (1) CO 1-0

Spectral lines for band 6 (211-275 GHz)

Representative transitions

211211.455* (10) H_2CO 3(1,3)-2(1,2)
213360.641* (11) HCS^+ 5-4
213427.118* (7) CH_3OH 1(1,0)-0(0,0) E
214385.741* (17) ^{29}SiO 5-4 v=0
216112.580* (1) DCO^+ 3-2
216278.749* (9) c-C_3H_2 3(3,0)-2(2,1)
217104.984* (14) SiO 5-4 v=0
217238.530* (1) DCN 3-2
218222.195* (10) H_2CO 3(0,3)-2(0,2)
218475.642* (10) H_2CO 3(2,2)-2(2,1)
218760.071* (10) H_2CO 3(2,1)-2(2,0)
219560.358 (1) $C^{18}O$ 2-1
219949.433* (17) SO N,J=5,6-4,5
220398.684 (1) ^{13}CO 2-1
220747.259* (2) CH_3CN 12(K)-11(K)
222166.969* (2) CH_3CCH 13(K)-12(K)
224714.385* (3) $C^{17}O$ 2-1
225697.781* (10) H_2CO 3(1,2)-2(1,1)
225896.720 (38) HDO 3(1,2)-2(2,1) 2.3
226874.764* (20) CN 2-1 J=5/2-3/2 F=7/2-5/2
228910.471* (15) DNC 3-2
230538.000 (1) CO 2-1
231321.635 (50) N_2D^+ 3-2
239137.914* (2) CH_3CN 13(K)-12(K)
239252.292* (2) CH_3CCH 14(K)-13(K)
241016.088 (1) $C^{34}S$ 5-4
241561.550 (37) HDO 2(1,1)-2(1,2)
241791.367* (6) CH_3OH 5(0,5)-4(0,4) A+
244222.170* (11) c-C_3H_2 3(2,1)-2(1,2)
244935.556 (3) CS 5-4
249054.409* (5) c-C_3H_2 5(2,3)-4(3,2)
255050.260 (59) HDO 5(2,3)-4(3,2)
255479.389 (10) $HC^{18}O^+$ 3-2
256027.093* (12) HCS^+ 6-5
256336.627* (3) CH_3CCH 15(K)-14(K)
257255.202* (29) ^{29}SiO 6-5 v=0
257527.381* (2) CH_3CN 14(K)-13(K)
258156.996 (1) $HC^{15}N$ 3-2
259011.787* (1) $H^{13}CN$ 3-2
260255.342* (5) $H^{13}CO^+$ 3-2
260518.122* (17) SiO 6-5 v=0
261263.39 * (10) $HN^{13}C$ 3-2
261843.756* (18) SO N,J=6,7-5,6
262004.26 (5) C_2H 3-2 J=7/2-5/2 F=4-3
265759.484* (6) c-C_3H_2 4(4,1)-3(3,0)
265886.431* (1) HCN 3-2
266161.070 (25) HDO 2(2,0)-3(1,3)
267557.633* (60) HCO^+ 3-2
271981.111* (7) HNC 3-2

Spectral lines for band 7 (275-373 GHz)

Representative transitions

275915.569* (2) CH_3CN 15(K)-14(K)
279511.760* (16) N_2H^+ 3-2
281526.927* (13) H_2CO 4(1,4)-3(1,3)
288143.858* (1) DCO^+ 4-3
289209.068 (1) $C^{34}S$ 6-5
289644.907* (1) DCN 4-3
290110.655* (7) CH_3OH 6(0,6)-5(0,5) A
290623.422* (13) H_2CO 4(0,4)-3(0,3)
291948.077* (13) H_2CO 4(2,2)-3(2,1)
293912.091* (2) CS 6-5
300836.642* (13) H_2CO 4(1,3)-3(1,2)
303926.974* (20) SiO 7-6 v=0
304077.914* (19) SO N,J=7,8-6,7
321225.676* (6) H_2O 10(2,9)-9(3,6)
325152.899 (1) H_2O 5(1,5)-4(2,2)
329330.552 (2) $C^{18}O$ 3-2
330587.965 (1) ^{13}CO 3-2
331071.541* (2) CH_3CN 18(K)-17(K)
335395.50 (3) HDO 3(3,1)-4(2,2)
337061.104* (12) $C^{17}O$ 3-2
337396.459 (1) $C^{34}S$ 7-6
338204.003* (7) c-C_3H_2 5(5,1)-4(4,0)
338408.718* (7) CH_3OH 7(0,7)-6(0,6) A++
339516.690* (30) CN 3-2 J=5/2-5/2 F=7/2-7/2
340630.70 * (16) $HC^{18}O^+$ 4-3
342882.857* (2) CS 7-6
342980.848* (70) ^{29}SiO 8-7 v=0
344200.109 (1) $HC^{15}N$ 4-3
345339.756* (2) $H^{13}CN$ 4-3
345795.990* (1) CO 3-2
346528.587* (20) SO N,J=8,9-7,8
346998.347* (13) $H^{13}CO^+$ 4-3
347330.824* (23) SiO 8-7 v=0
348340.49 * (10) $HN^{13}C$ 4-3
349453.698* (2) CH_3CN 19(K)-18(K)
351768.648* (15) H_2CO 5(1,5)-4(1,4)
354505.473* (1) HCN 4-3
356734.242* (75) HCO^+ 4-3
360169.780* (1) DCO^+ 5-4
362045.742* (1) DCN 5-4
362630.304* (8) HNC 4-3
362736.024* (15) H_2CO 5(0,5)-4(0,4)
363945.876* (15) H_2CO 5(2,4)-4(2,3)
372421.34 (20) H_2D^+ 1(1,0)-1(1,1)

Spectral lines for band 9 (602-720 GHz)

Representative transitions

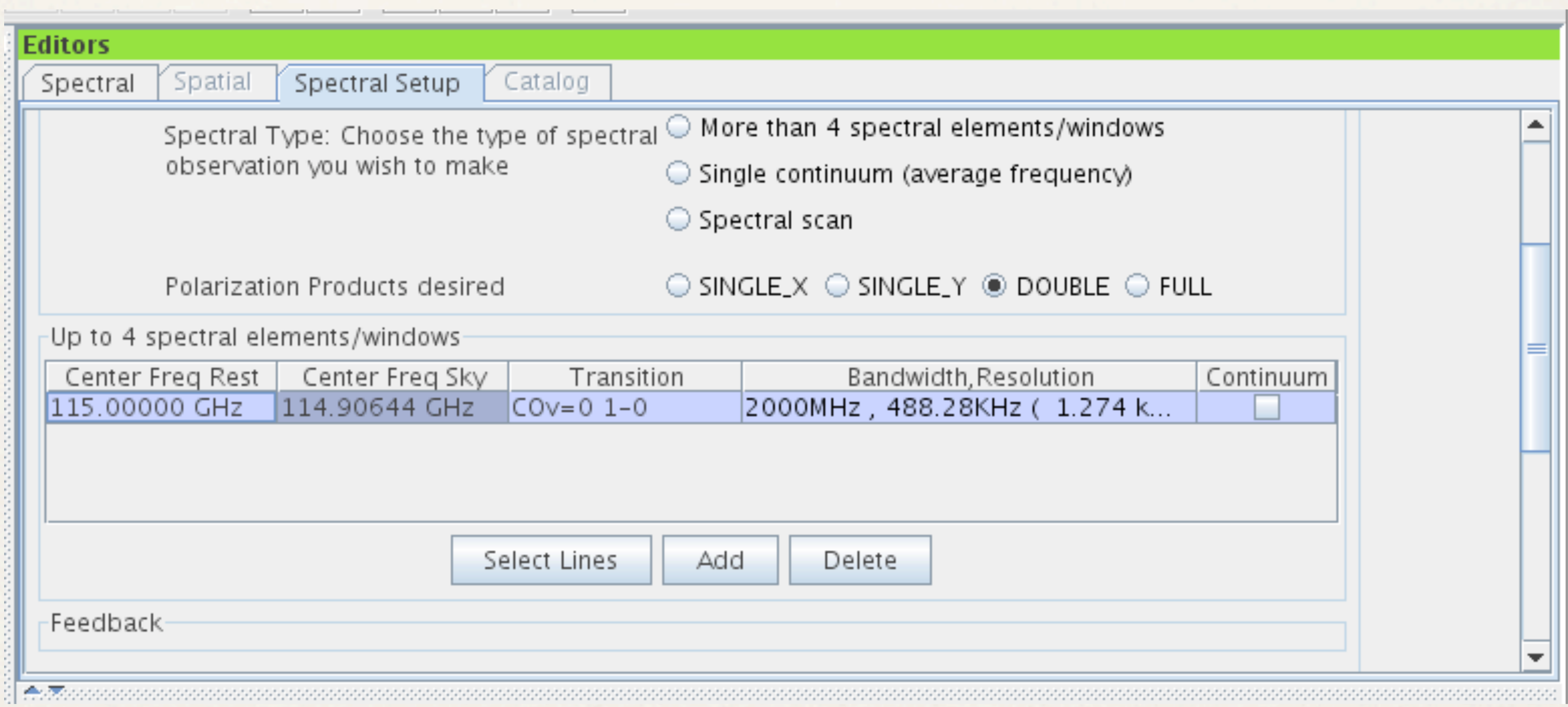
607174.701* (78) $H^{13}CO^+$ 7-6
607608.899* (57) SiO 14-13 v=0
609507.66 * (20) $HN^{13}C$ 7-6
611329.71 (8) C_2H 7-6 13/2,13/2-11/2,11/2
624208.46 * (13) HCO^+ 7-6
624926.466* (2) CH_3CN 34(K)-33(K)
626351.394* (5) $C^{34}S$ 13-12
627558.440* (9) CH_3OH 13(0,13)-12(0,12) A++
634510.820* (8) HNC 7-6
636532.466* (6) CS 13-12
643269.867* (2) CH_3CN 35(K)-34(K)
645875.924 (30) SO N,J=15,16-14,15
647081.760* (19) H_2CO 9(0,9)-8(0,8)
650957.739* (67) SiO 15-14 v=0
651565.964* (4) DCN 9-8
653970.172* (18) H_2CO 9(2,9)-8(2,8)
658553.278 (1) $C^{18}O$ 6-5
661067.276 (2) ^{13}CO 6-5
661610.068* (2) CH_3CN 36(K)-35(K)
662209.169* (18) H_2CO 9(2,7)-8(2,6)
674009.286* (19) $C^{17}O$ 6-5
674473.625* (6) $C^{34}S$ 14-13
674809.798* (19) H_2CO 9(1,8)-8(1,7)
675612.646* (10) CH_3OH 14(0,14)-13(0,13) A++
679946.978* (2) CH_3CN 37(K)-36(K)
680026.757* (38) CN 6-5 J,F=11/2,11/2-9/2,11/2
685435.929* (7) CS 14-13
688273.790 (2) $HC^{15}N$ 8-7
688735.700 (30) SO N,J=16,17-15,16
690552.068* (4) $H^{13}CN$ 8-7
691473.076* (1) CO 6-5
693876.33 * (12) $H^{13}CO^+$ 8-7
694295.863* (78) SiO 16-15 v=0
696534.36 * (25) $HN^{13}C$ 8-7
698280.505* (3) CH_3CN 38(K)-37(K)
698607.46 (10) C_2H 8-7 15/2,13/2-13/2,11/2
701370.493* (18) H_2CO 10(1,10)-9(1,9)
708877.001* (3) HCN 8-7
713341.37 * (16) HCO^+ 8-7
716596.959* (3) CH_3CN 39(K)-38(K)
716938.389* (19) H_2CO 10(0,10)-9(0,9)
718158.806* (15) CH_3OH 15(1,15)-14(1,14) A++

OT example IV: CO

- One spectral line of interest in extragalactic astronomy is CO, with several of its transitions. For example, the rotational transitions **J=1-0** (115.271 GHz, *i. e.* band 3), **2-1** (230.538 GHz, band 6), **3-2** (345.796 GHz, band 7), **6-5** (691.4731 GHz, band 9).
- Using the observing mode 7 for each one of the lines, we can have (in a 2 GHz wide bandwidth) a velocity resolution of 1.27, 0.63, 0.42, and 0.21 km/s, respectively.
- As we noted before, each line must be set up in a different science goal, since they belong to different bands.

in OT

first science goal



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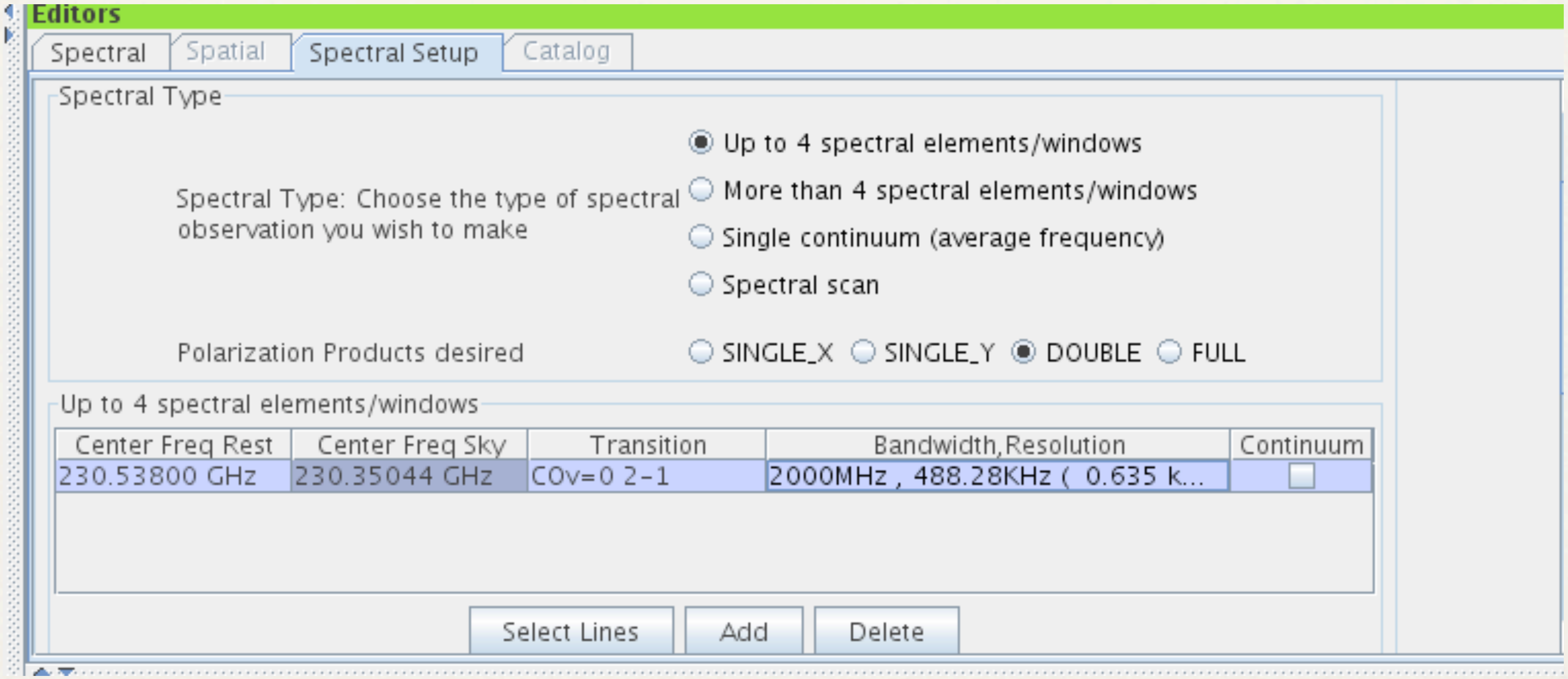
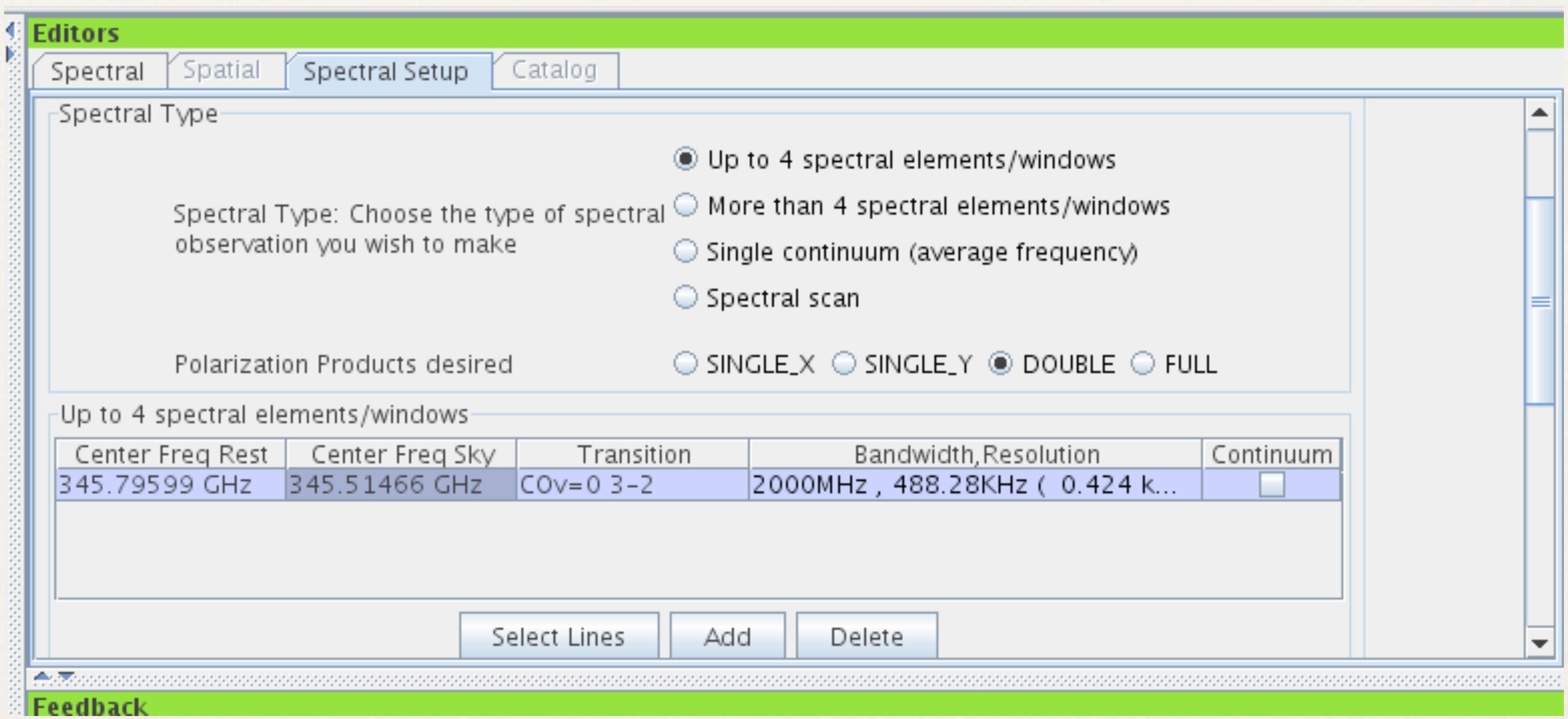
second science goal



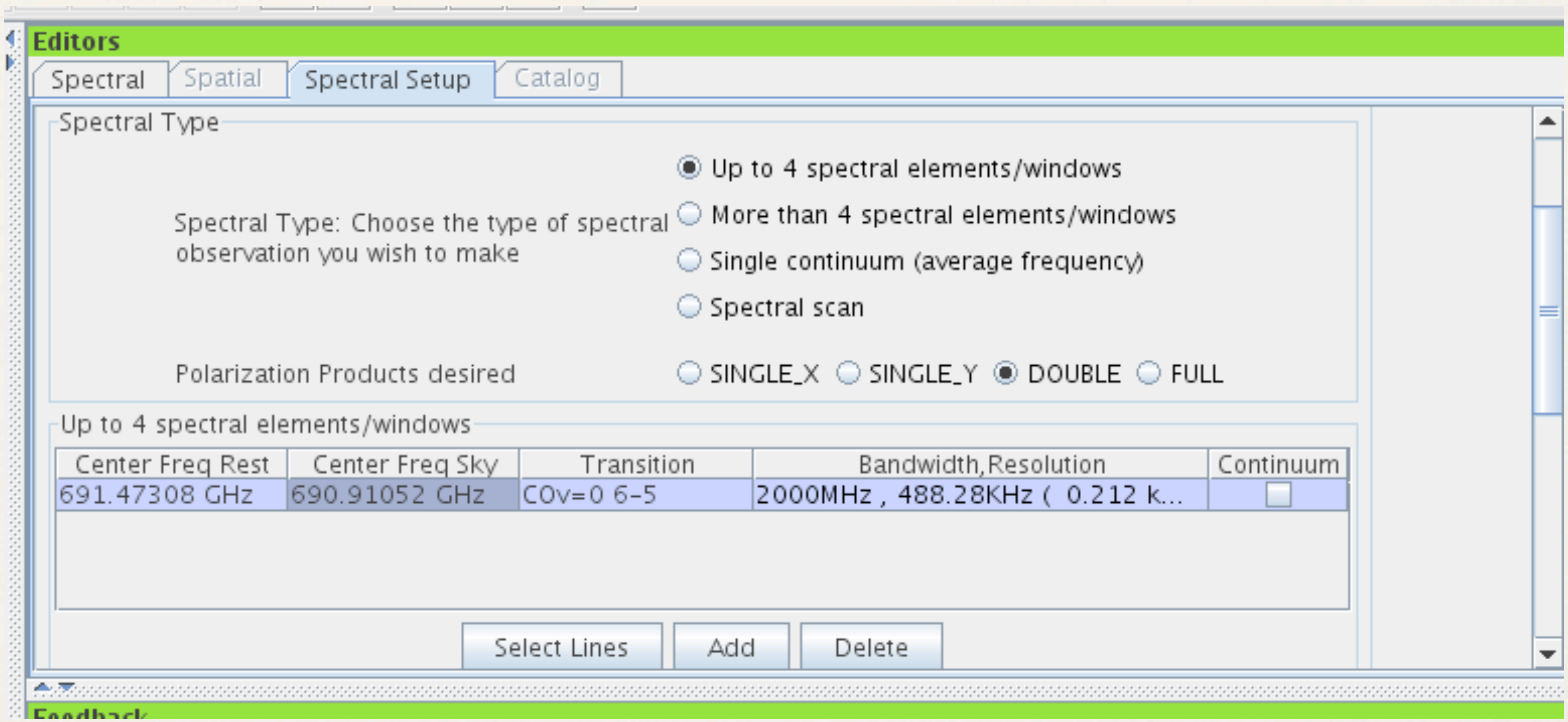
...

third science goal



• • •

fourth science goal

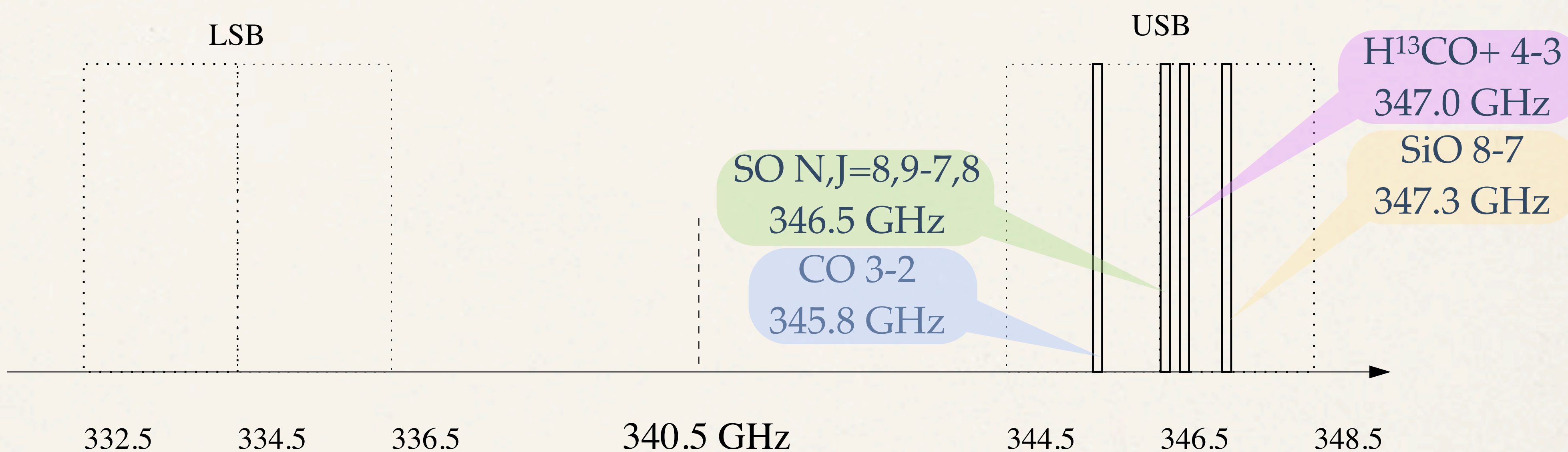


OT example V: lines in band 7

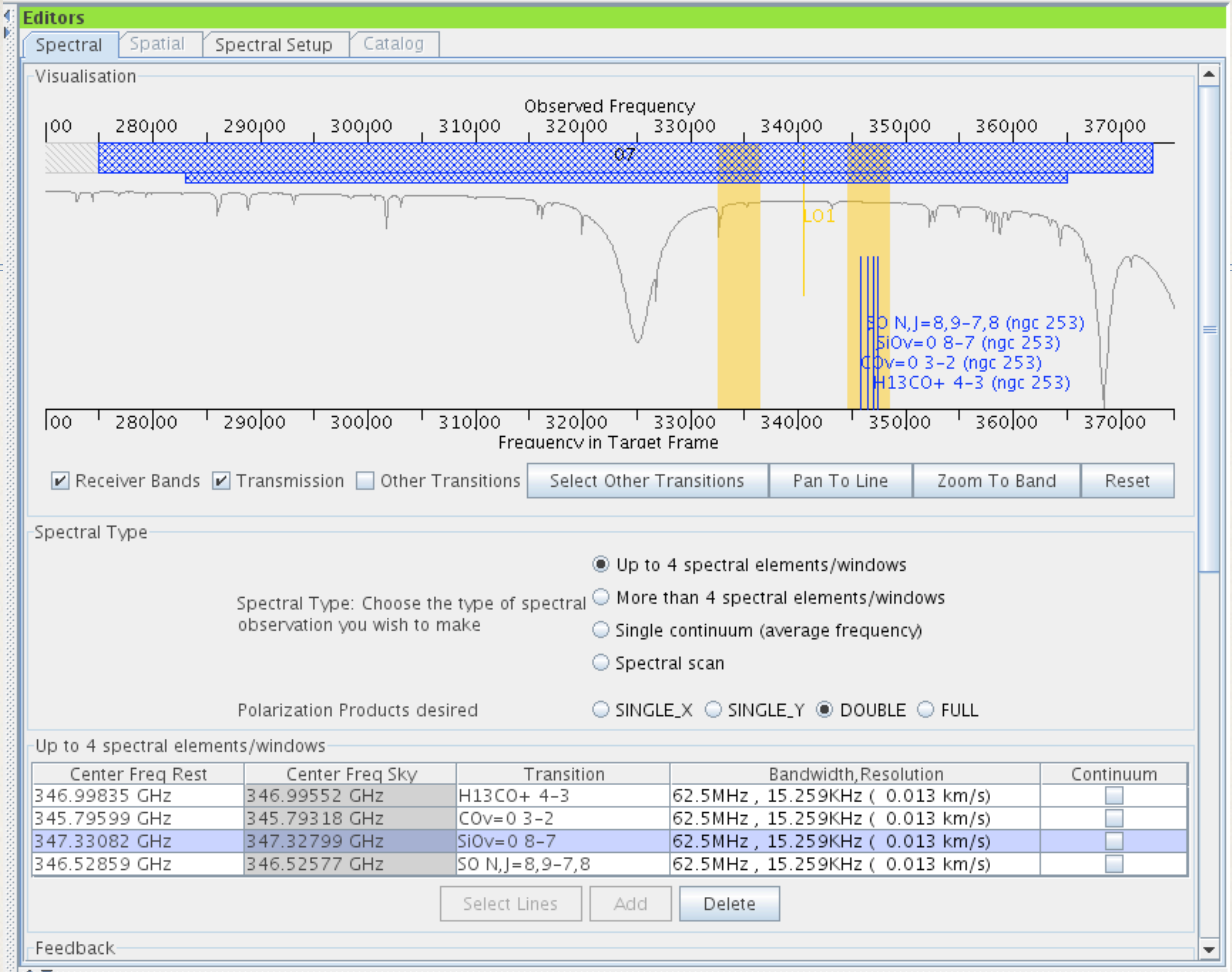
- In this example the next lines are observed:
SiO J=8-7 (347.33... GHz), CO J=3-2 (345.79... GHz), SO N,J=8,9-7,8 (346.52... GHz), and H13CO+ J=4-3 (346.99... GHz). These are some of the lines used in the star formation field.

- We can observe these lines simultaneously, puting each one in a baseband. In star formation, high resolution in velocity is needed most of the times. We then use the mode 12 to achieve it. We will have 62.5 MHz of bandwidth for each line, at Nyquist sampling, 2-bit requantization and two polarizations.

using the Upper Sideband (USB)



Inside ALMA band 7



The four spectral lines observed in one science goal, using the USB.

...

- Using mode 12, we get 0.01 km/s in resolution. If mode 9 is used, the resolution would be about 0.1 km/s, but with a bandwidth of 500 MHz, and may be useful to observe more than one line in each spectral window, and put other basebands at other frequencies.
- Only the USB is used in this example, as can be seen in the graphical representation for the band (the transmission of the atmosphere is also showed).

Further reading

- For a more complete description of the correlator:
- Escoffier *et al*. 2007, A&A, 462, 801.
- Escoffier *et al*., ALMA memo 556.
- Wootten 2008, ASS, 313, 9.