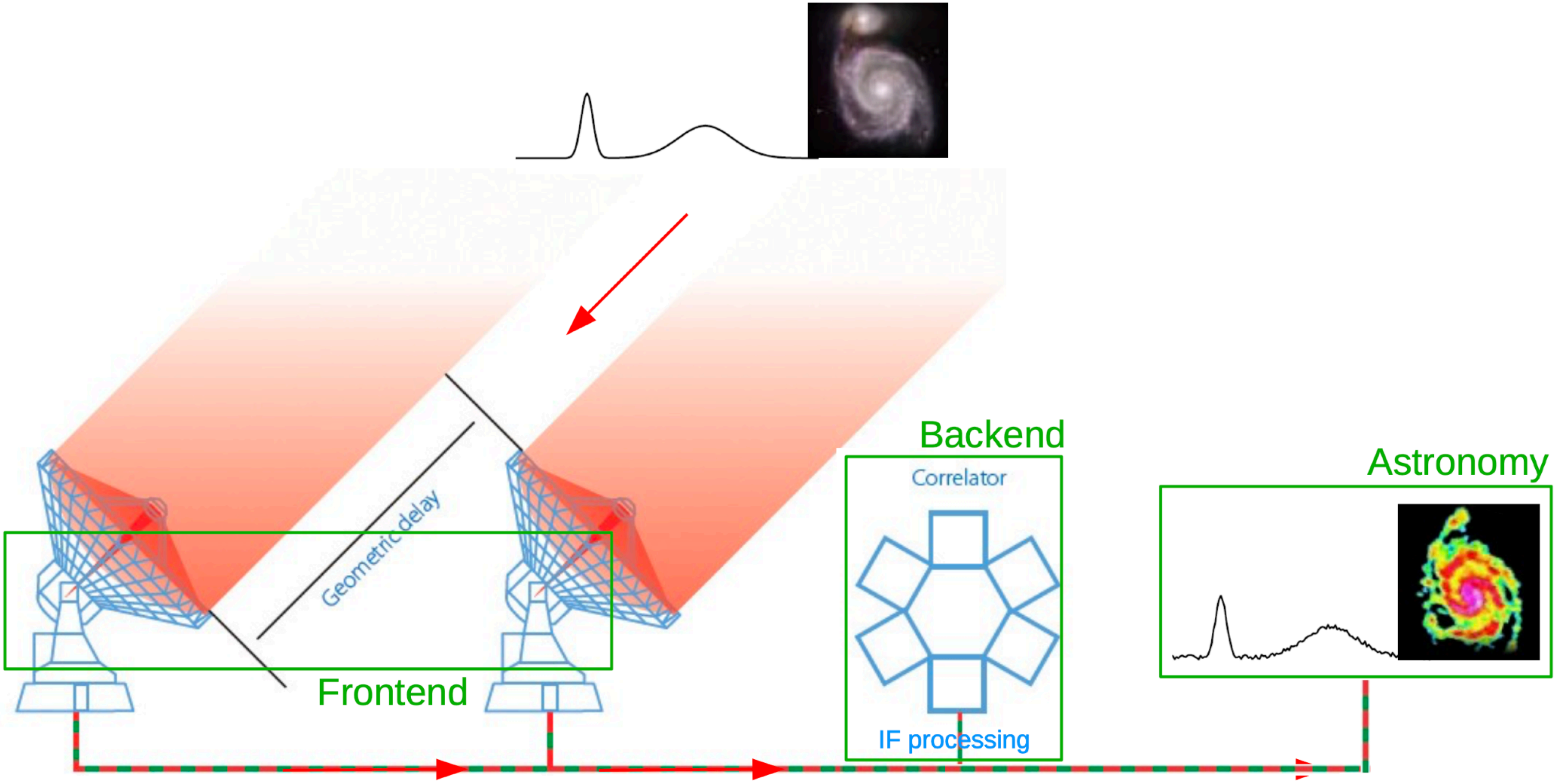
Radio receivers



Geometric delay

Frontend

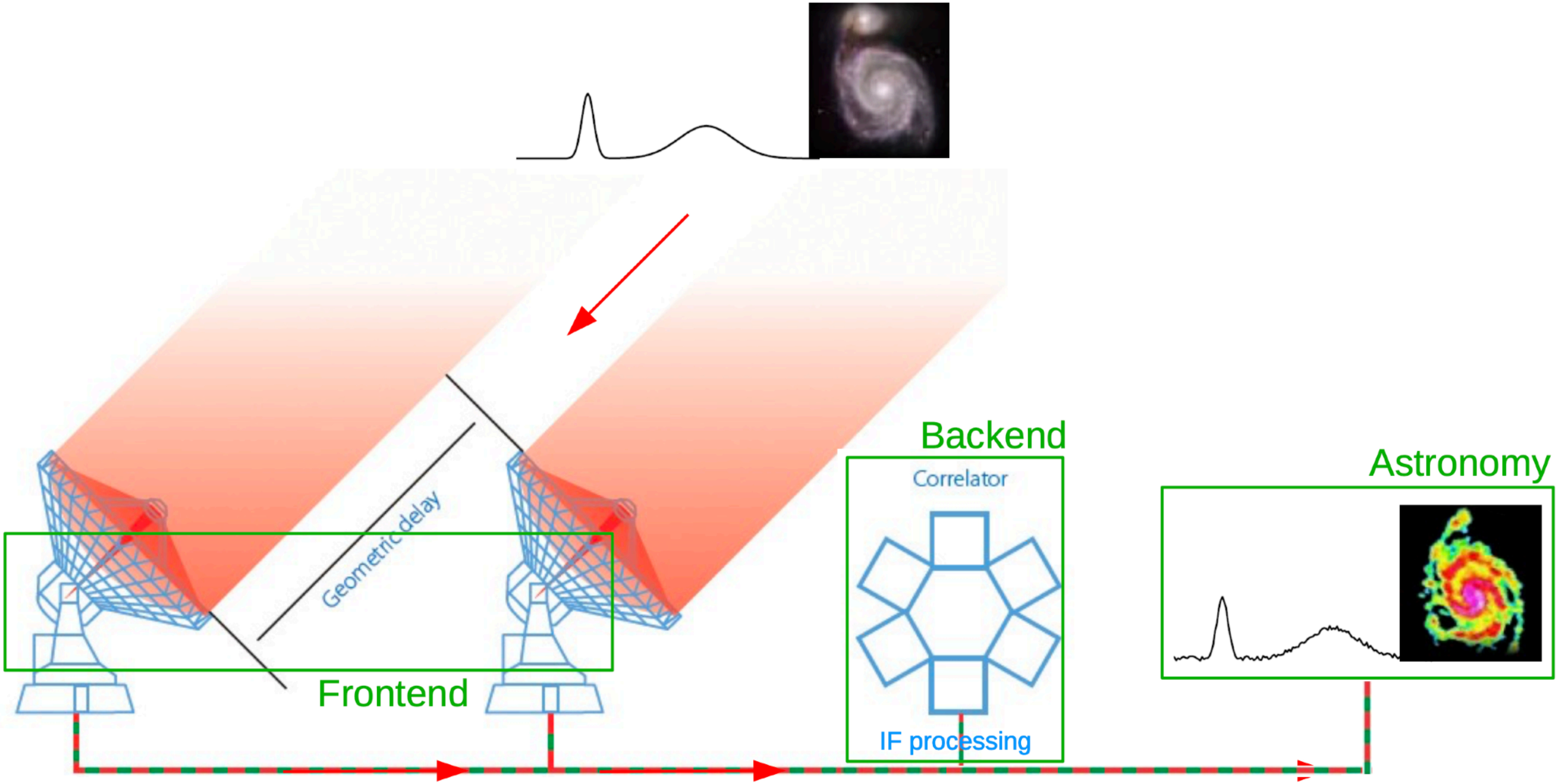
Backend

Correlator

IF processing

Astronomy

Radio receivers



A radio receiver used to measure the average power coming from a radio telescope in a well-defined frequency range is called a radiometer.

Noise of a Radiometer

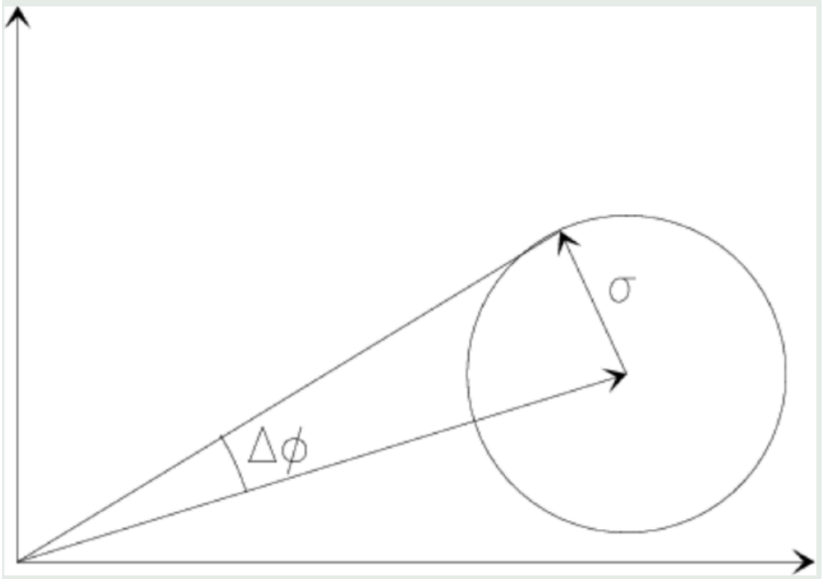
Visibility measurements are limited by several sources of noise: the atmosphere, the antenna itself, the ground and the receivers. The rms noise associated with a given baseline *ij* is given by:

$$\delta S_{ij} = \frac{\sqrt{2}k}{A\eta_{\mathrm{A}}\eta_{\mathrm{Q}}\eta_{\mathrm{P}}} \cdot \frac{T_{\mathrm{SYS}}}{\sqrt{B\,T}}$$

- A antenna physical aperture
- η_{A} antenna aperture efficiency
- η_{Q} efficiency for the correlator
- T_{SYS} system noise temperature (single dish)
- B bandwidth
- T integration time
- η_{P} phase decorrelation factor (LO jitter)

This is the noise on the real and on the imaginary parts of the visibilities (measured independently). This is also the noise on the amplitude *S*.

It is more complex to define the error on the phase, scales as σ/S.



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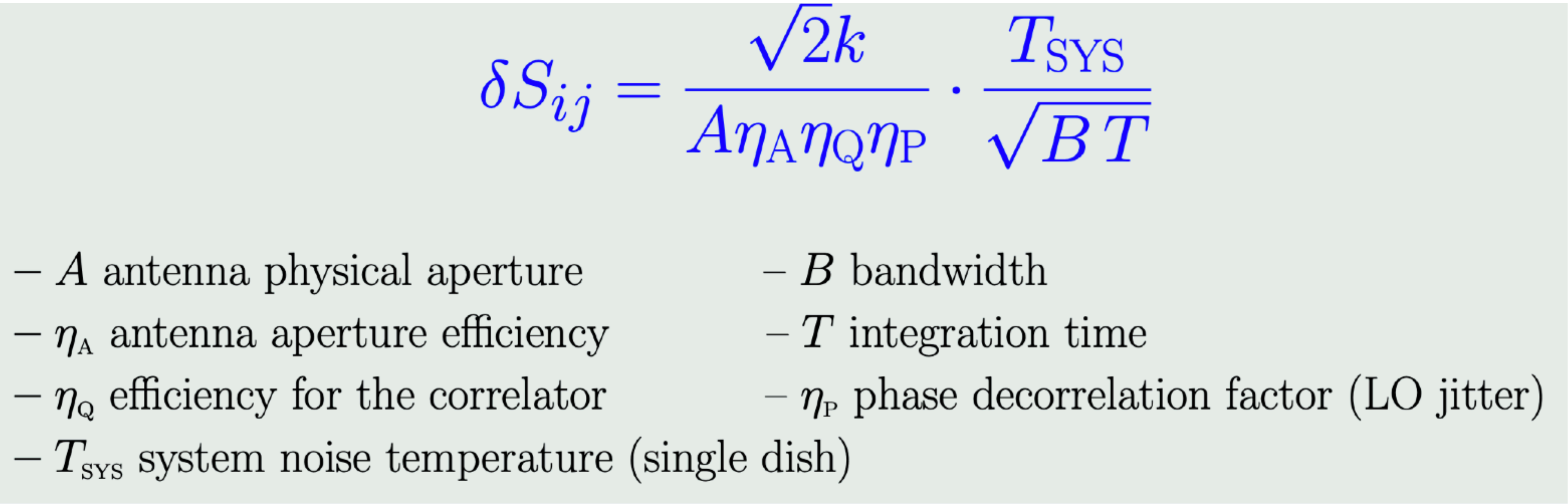

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It is more complex to define the error on the phase, of the order of σ/S.

$$\boxed{T_{\mathrm{sys}} = T_{\mathrm{CMB}} + T_{\mathrm{rsb}} + \Delta T_{\mathrm{source}} + [1 - exp(-\tau_A)]T_{\mathrm{atm}} + T_{\mathrm{spill}} + T_r + \ldots}$$

where

T_{rsb} radio source background

$\Delta T_{\mathrm{source}}$ source brightness temperature

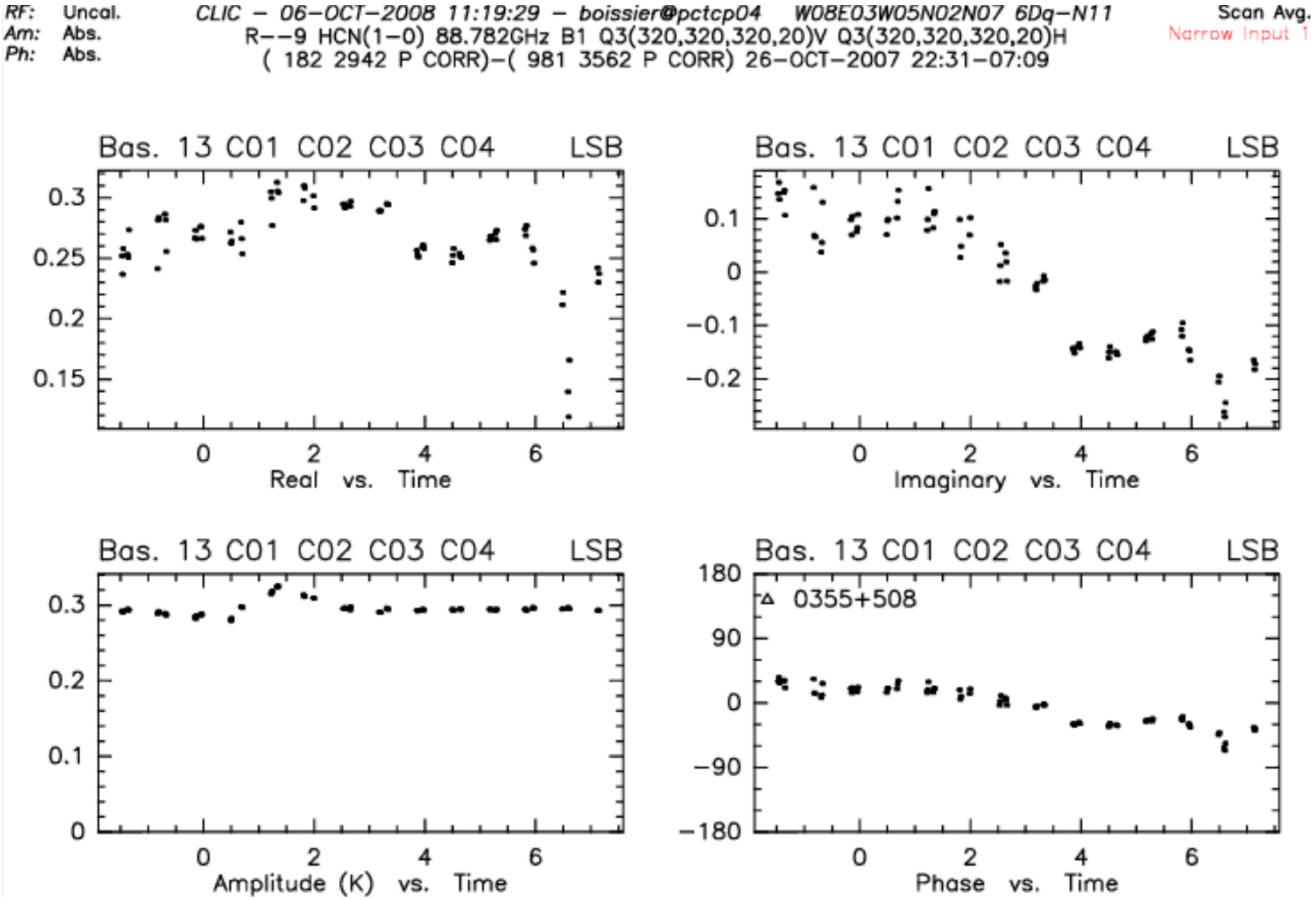
$[1 - exp(-\tau_A)]T_{\mathrm{atm}}$ brightness of atmospheric emission

T_{spill} brightness temperature due to antenna spillovers

T_{r} radiometer noise temperature

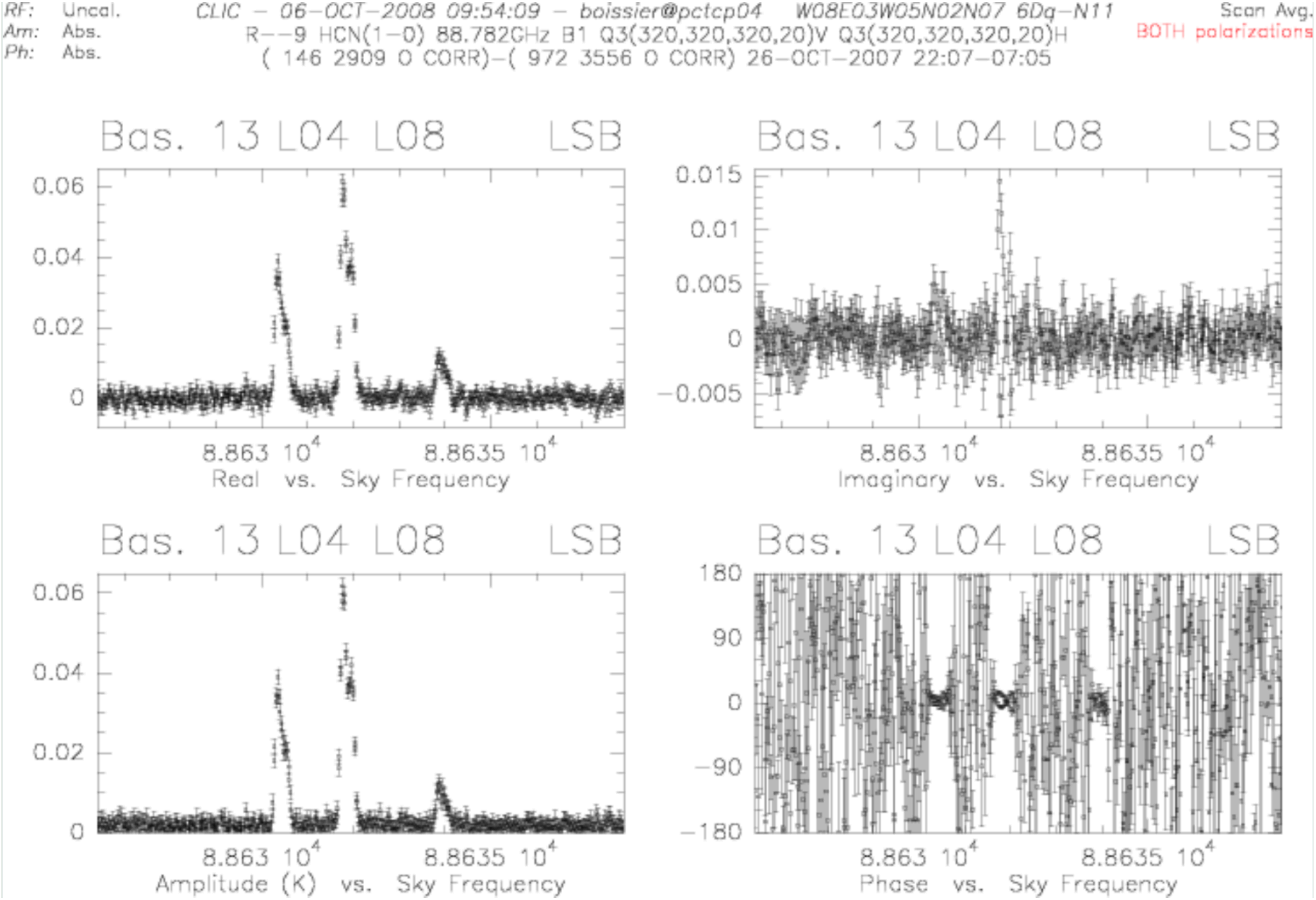
Noise of a Radiometer

Visibility parameters as a function of time



Noise of a Radiometer

Visibility parameters as a function of frequency



Noise of a Radiometer

For N identical antenna/receivers, i.e. N (N − 1)/2 baselines, the point-source sensitivity is

$$\delta S = \frac{2k}{A\eta_{\mathrm{A}}\eta_{\mathrm{Q}}\eta_{\mathrm{P}}} \cdot \frac{T_{\mathrm{SYS}}}{\sqrt{N(N-1)\,B\,T}}$$

For large N, scales as $\sim \frac{1}{N}$

The sensitivity for extended sources depends on the angular resolution

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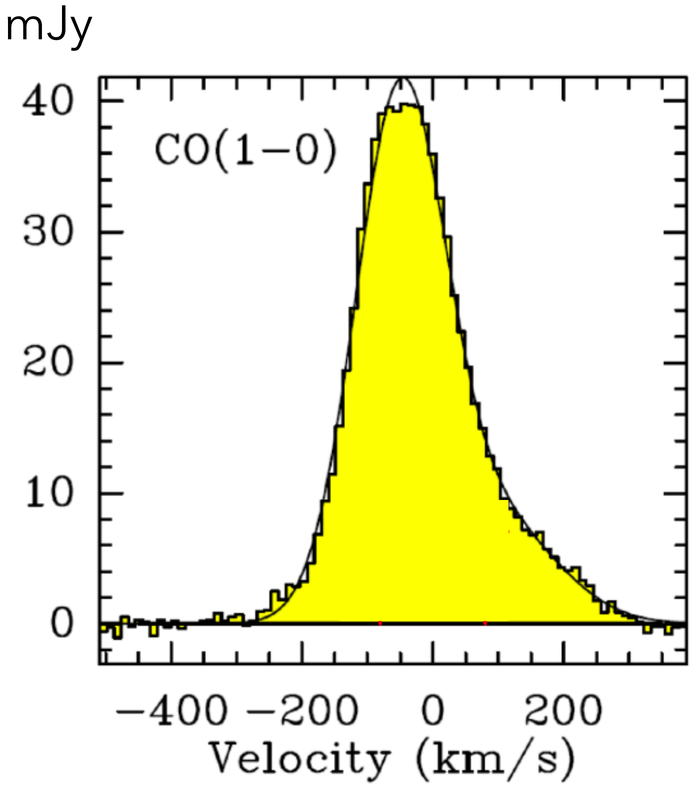
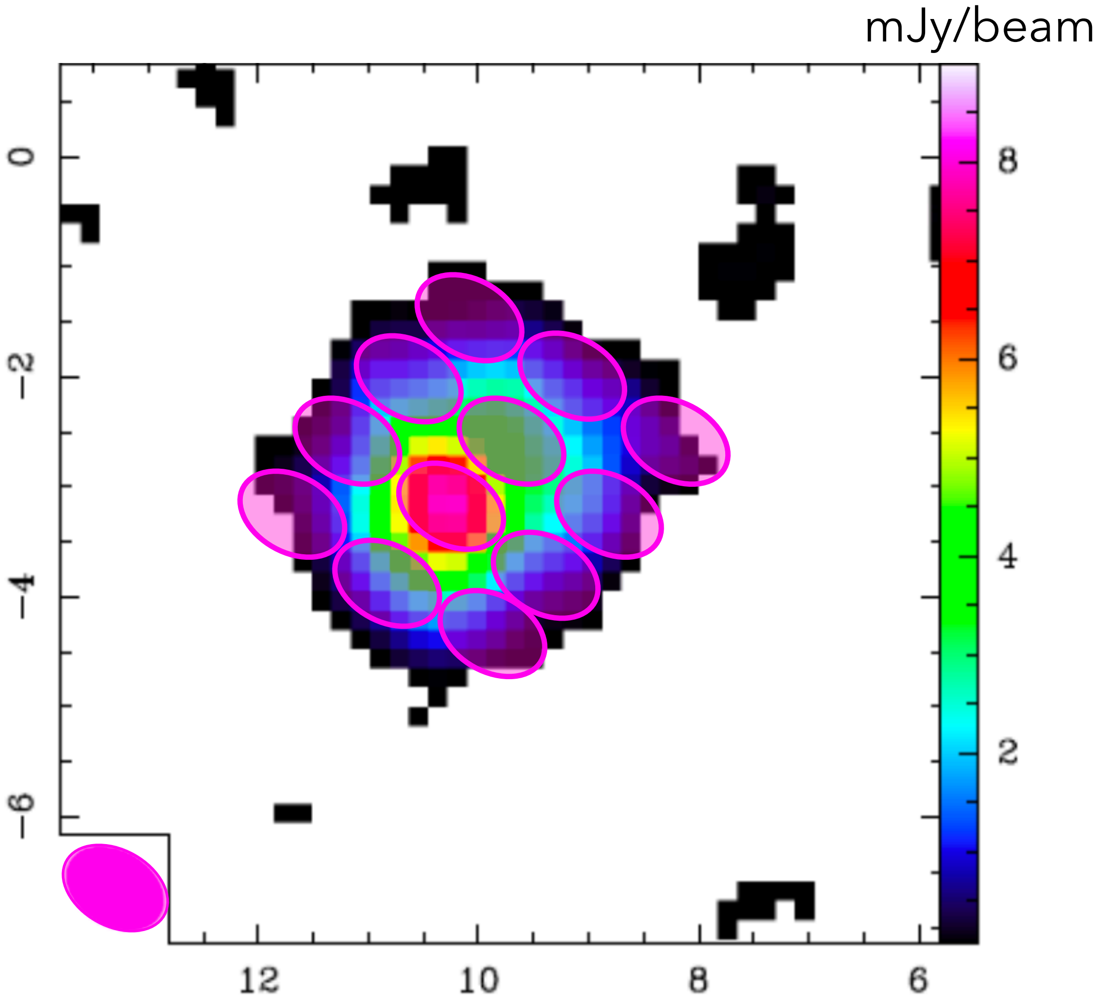
The sensitivity for extended sources depends on the angular resolution

Example:

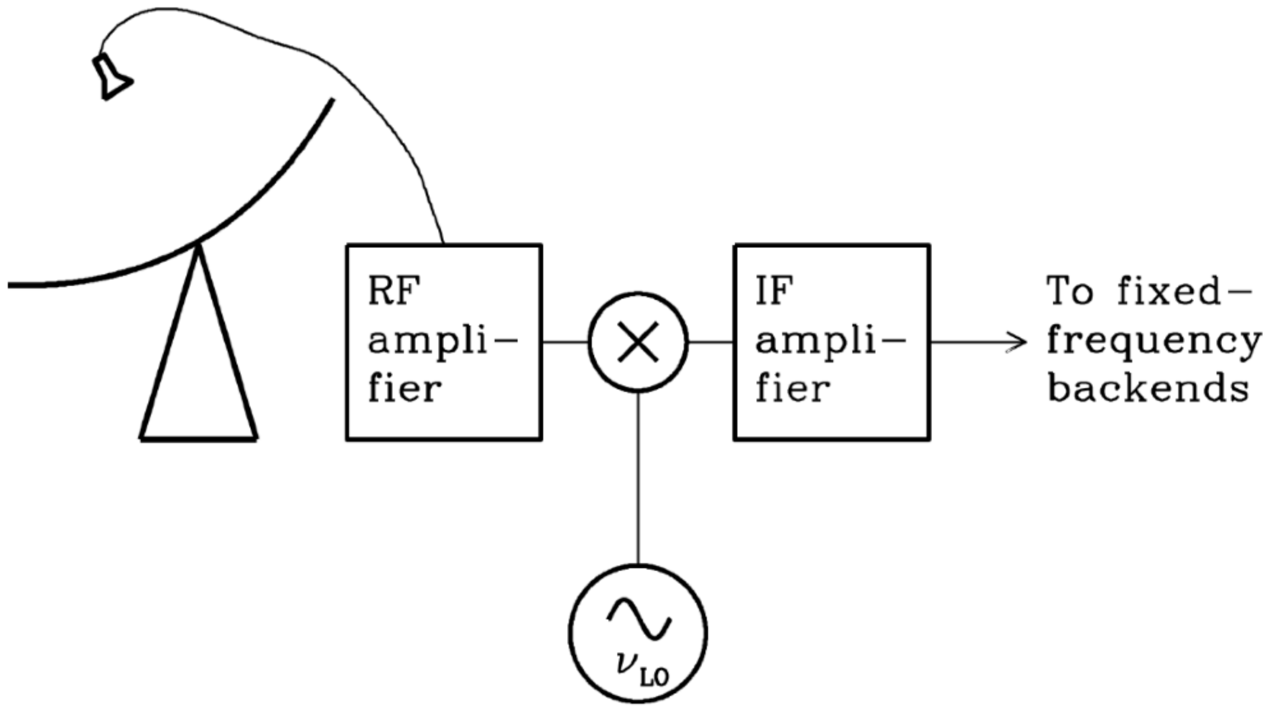
Galaxy at z=0.05 as seen by NOEMA with a beam of 0.97″x0.67″ (Combes+2019). The CO(1-0) emission is resolved in ~12 beams





Heterodyne receivers

Nearly all practical radiometers are heterodyne receivers



The reference frequency (RF) amplifier is followed by a mixer that multiplies the RF signal by a sine(cosine) wave of frequency ν_{LO} generated by a local oscillator (LO). The intermediate frequency (IF) is a result of a phase shift.

$$2\sin(2\pi\nu_{LO}t)\sin(2\pi\nu_{RF}t) = \cos[2\pi(\nu_{LO}-\nu_{RF})t] - \cos[2\pi(\nu_{LO}+\nu_{RF})t],$$

The advantages of heterodyne receivers include

1. shifting the signals to lower frequencies $\nu_{IF} < \nu_{RF}$ which are easier to amplify, transmit over long distances, filter, and digitize;
2. tunability over a wide range of ν_{RF}
3. tuning by adjusting only the local oscillator frequency so that
4. the IF amplifier and back-end devices such as multichannel filter banks or digital spectrometers can all operate over fixed frequency ranges.

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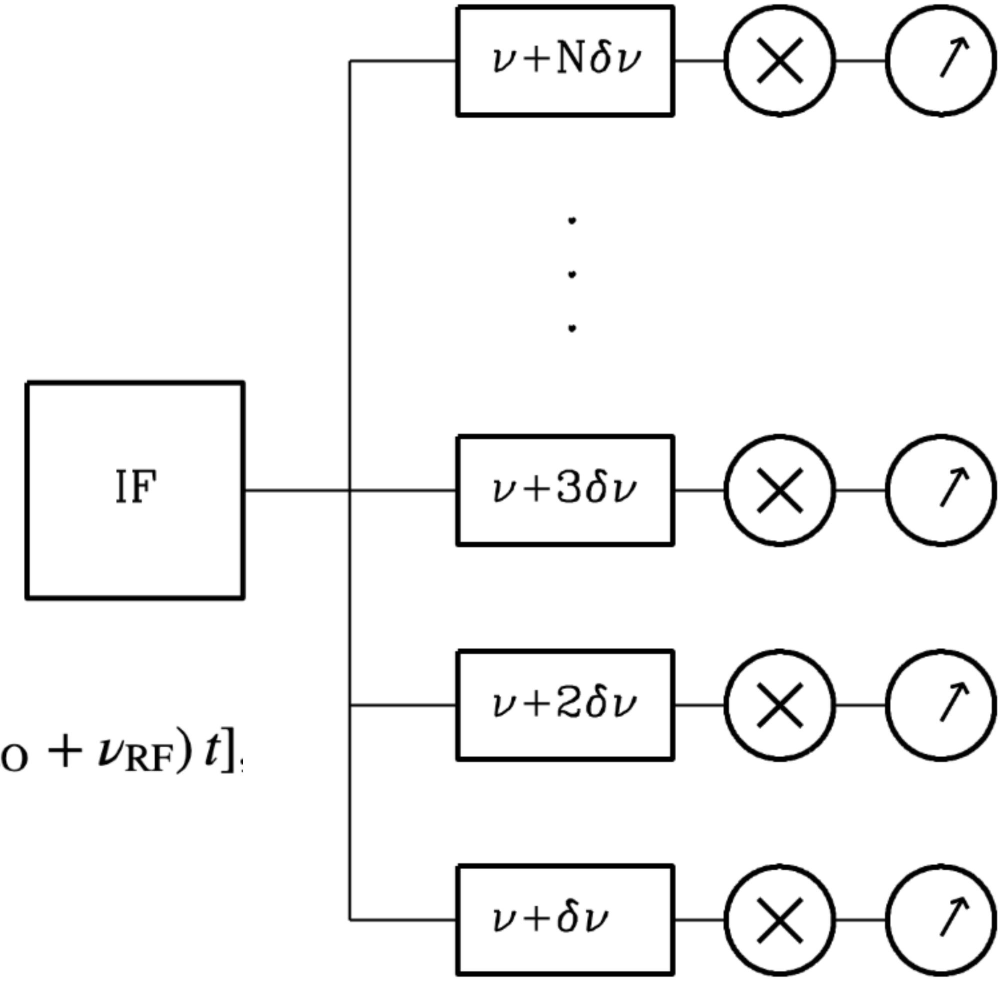

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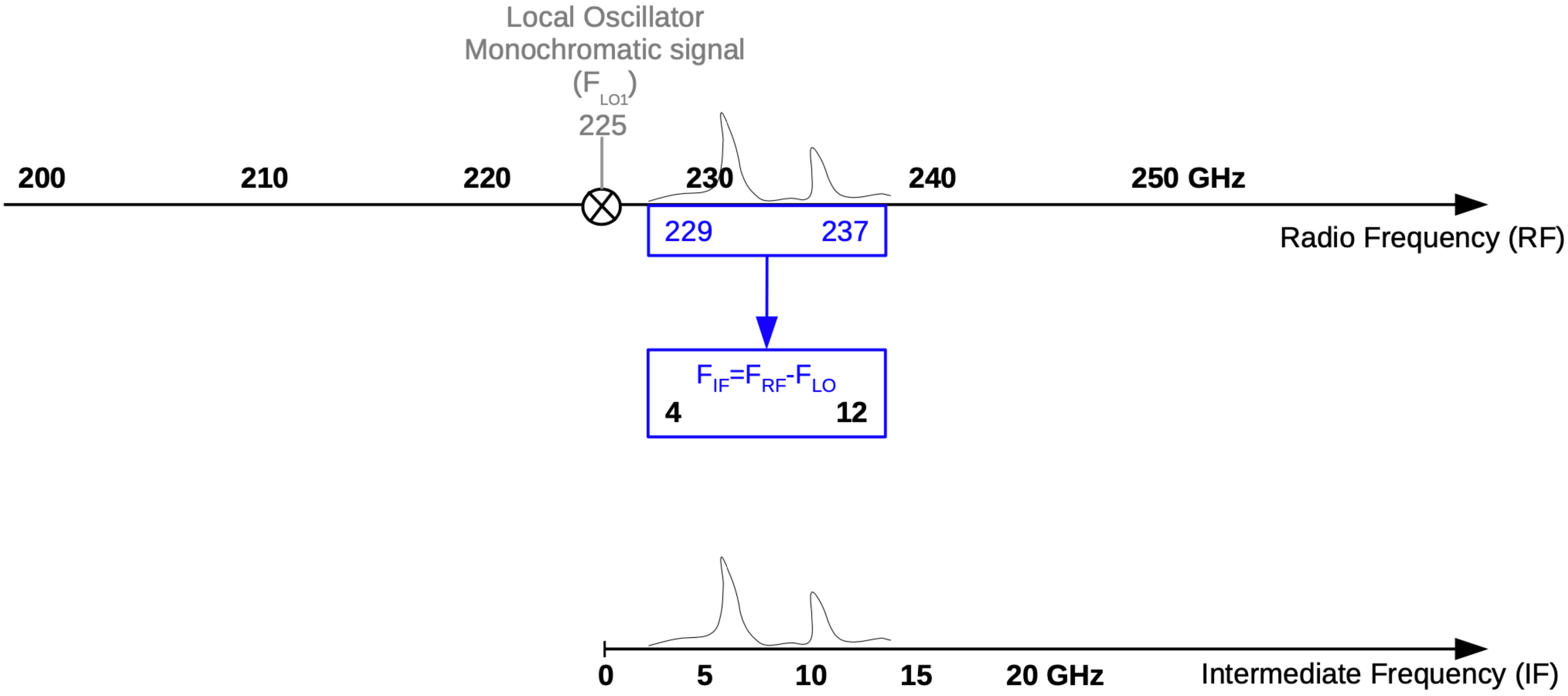
Example of heterodyne receiver: NOEMA

Heterodyne systems

LO = local oscillator

- Down-convert the spectrum
  from Radio Frequency (50 < F_{RF} < 500 GHz)
  to Intermediate Frequency (F_{IF} < 20 GHz)
- Tuning the receiver = setting the FLO1 + optimizing some LO and Mixer parameters



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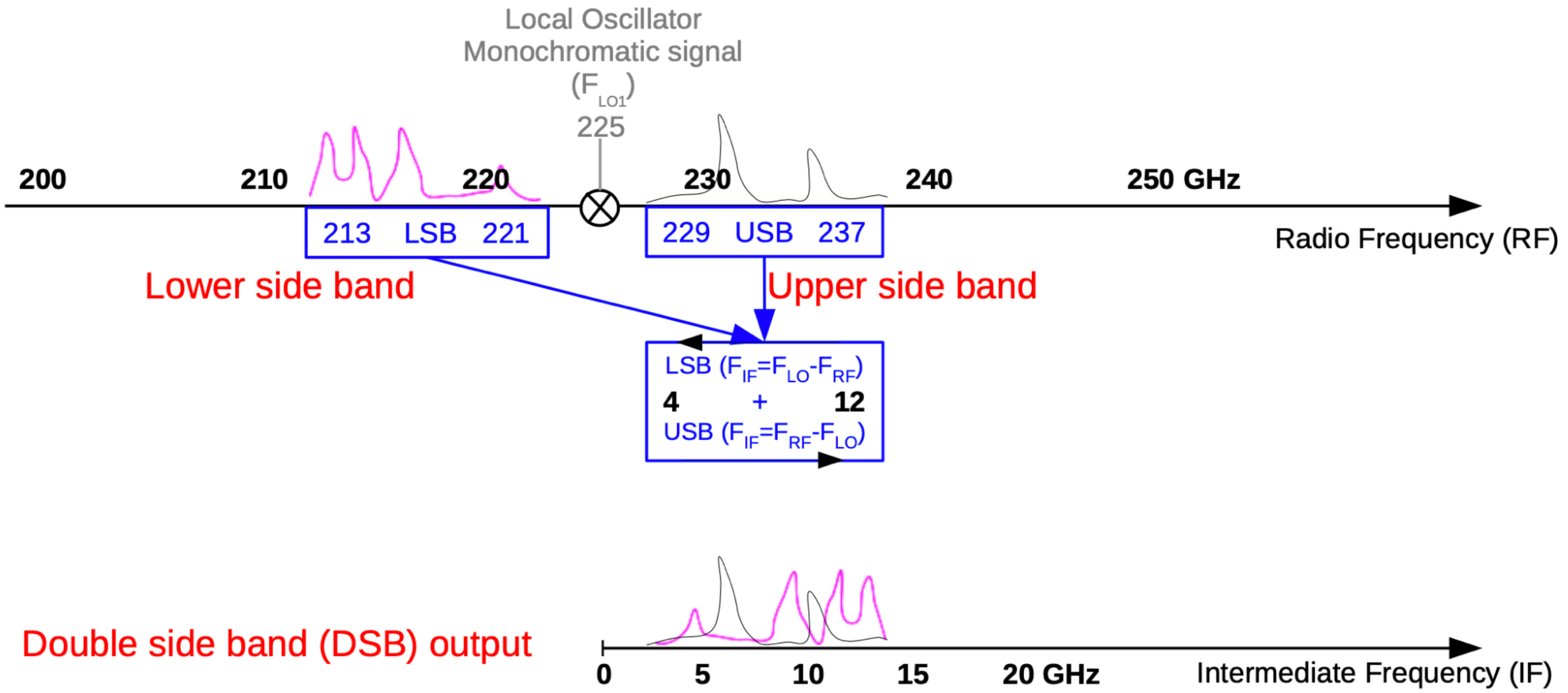

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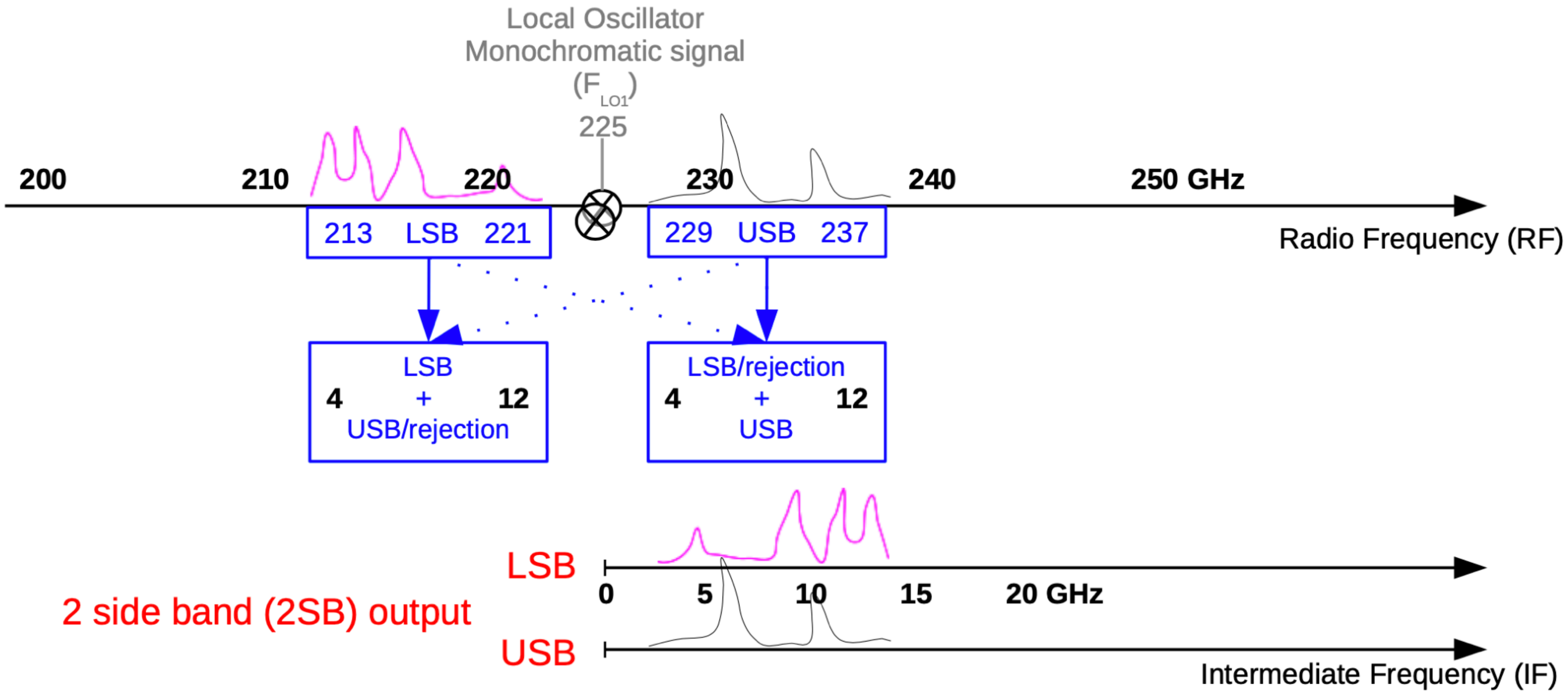

Local Oscillator
Monochromatic signal
(F_{LO1})
225

213 LSB 221

229 USB 237

LSB
4 + 12
USB/rejection

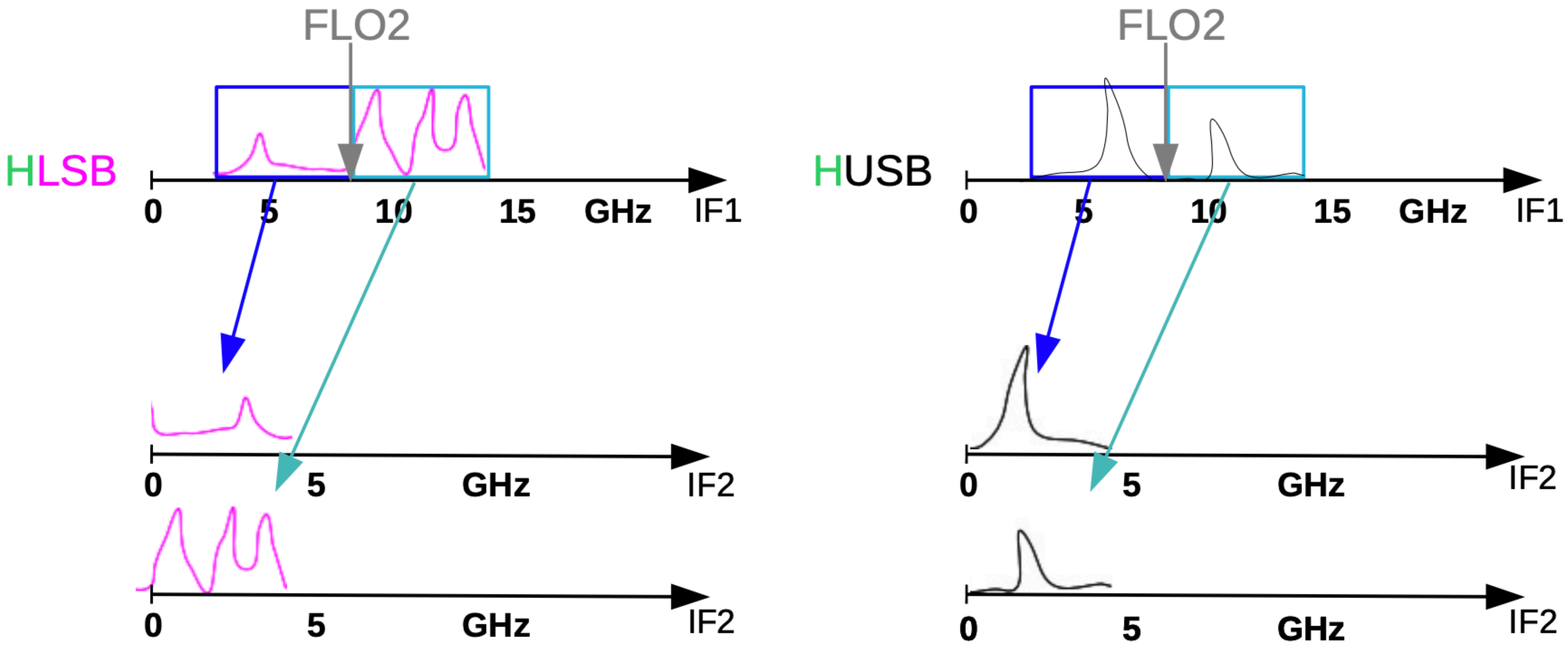
LSB/rejection
4 + 12
USB

2 side band (2SB) output

Example of heterodyne receiver: NOEMA

IF Processing

- Adapt the output of the receiver to the input of the correlator
  - 1 NOEMA receiver band delivers 4 x 8 GHz sidebands [4-12 GHz IF1]
  - 1 NOEMA correlator unit accepts 1 x 4 GHz [0-4 GHz IF2] x 12 antennas
- IF processor splits each sideband into 2 x 4GHz **basebands**
  - Downconvertion to 0-4GHz IF2



(A receiver is sensitive to a single polarization, here example for H polarization)

Example of heterodyne receiver: NOEMA

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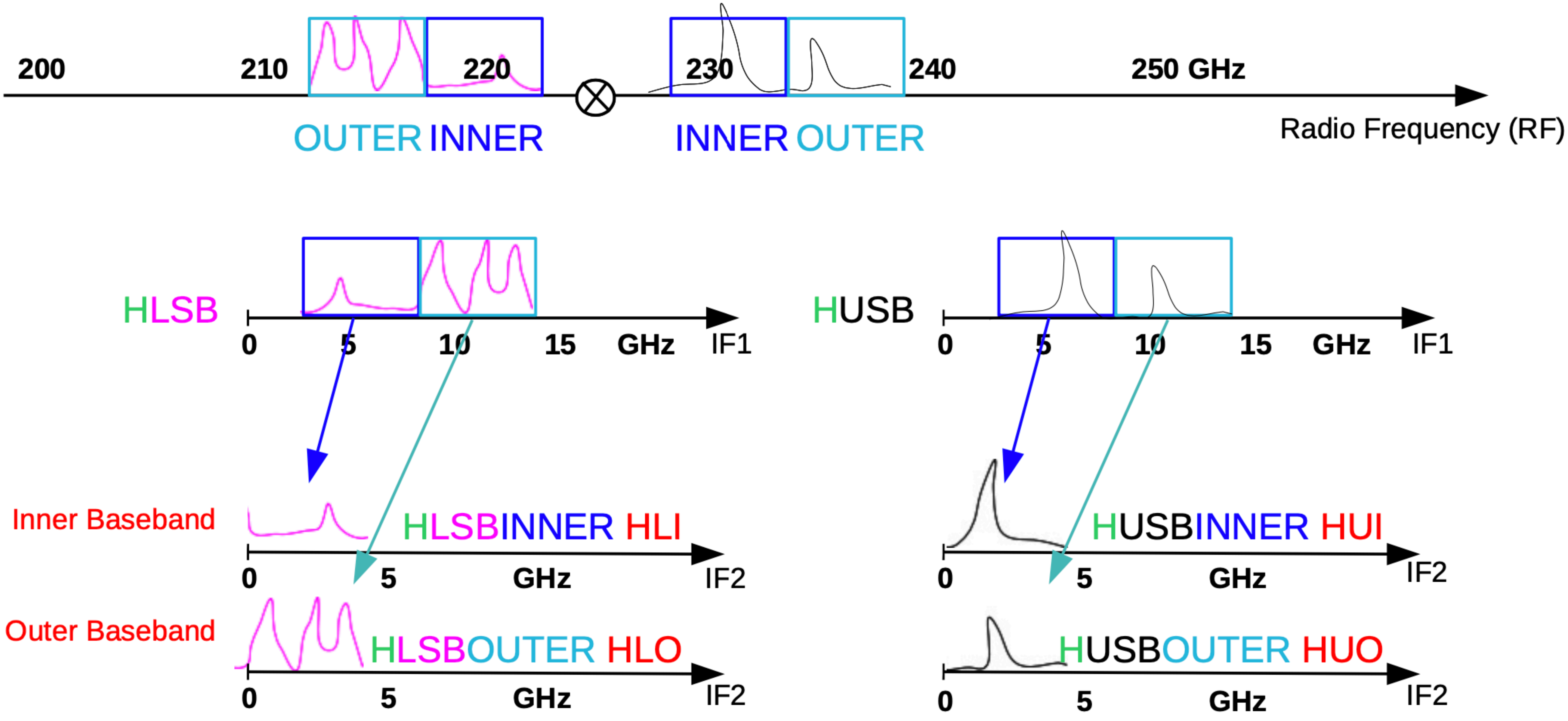
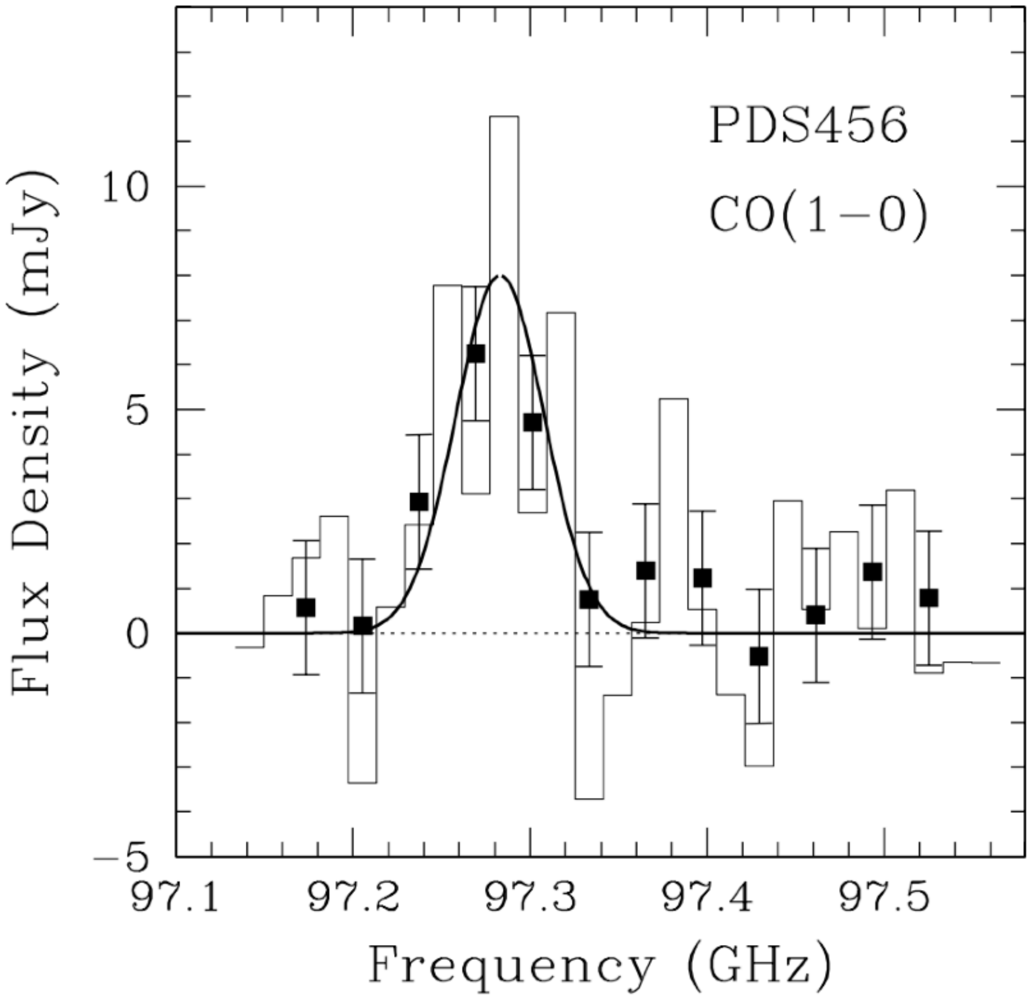


Setting up a radio observation (e.g. PDS456 with ALMA)

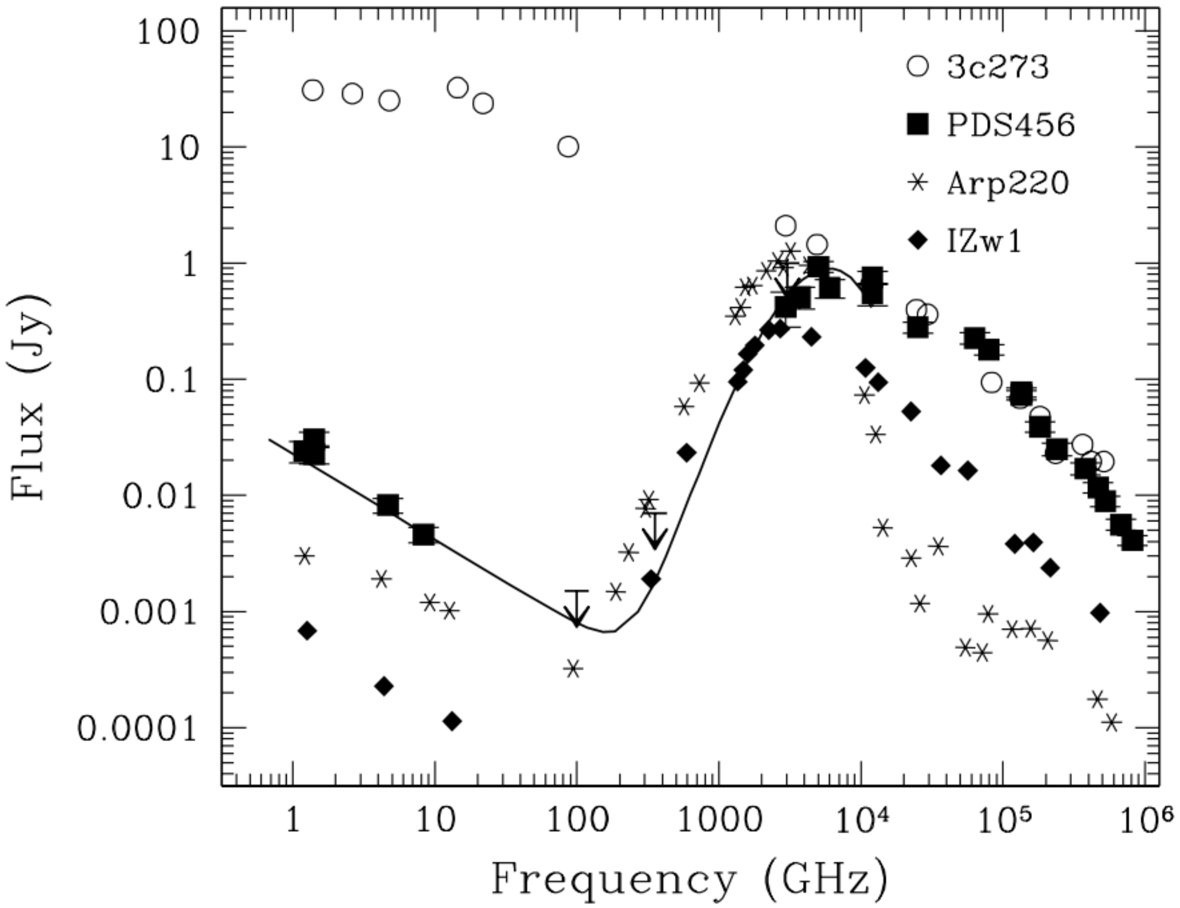
PDS456 z=0.185 (1"~3 kpc)

We aim to map the CO emission in the quasar host galaxy and detect the far-infrared continuum emission, due to dust heated by star formation

Let's start from what we already know…



Yun et al. 2004, Owens Valley Radio Observatory (OVRO) detection of CO(1-0). Source is unresolved, beam ~6"



Yun et al. 2004, known far-infrared/radio continuum SED

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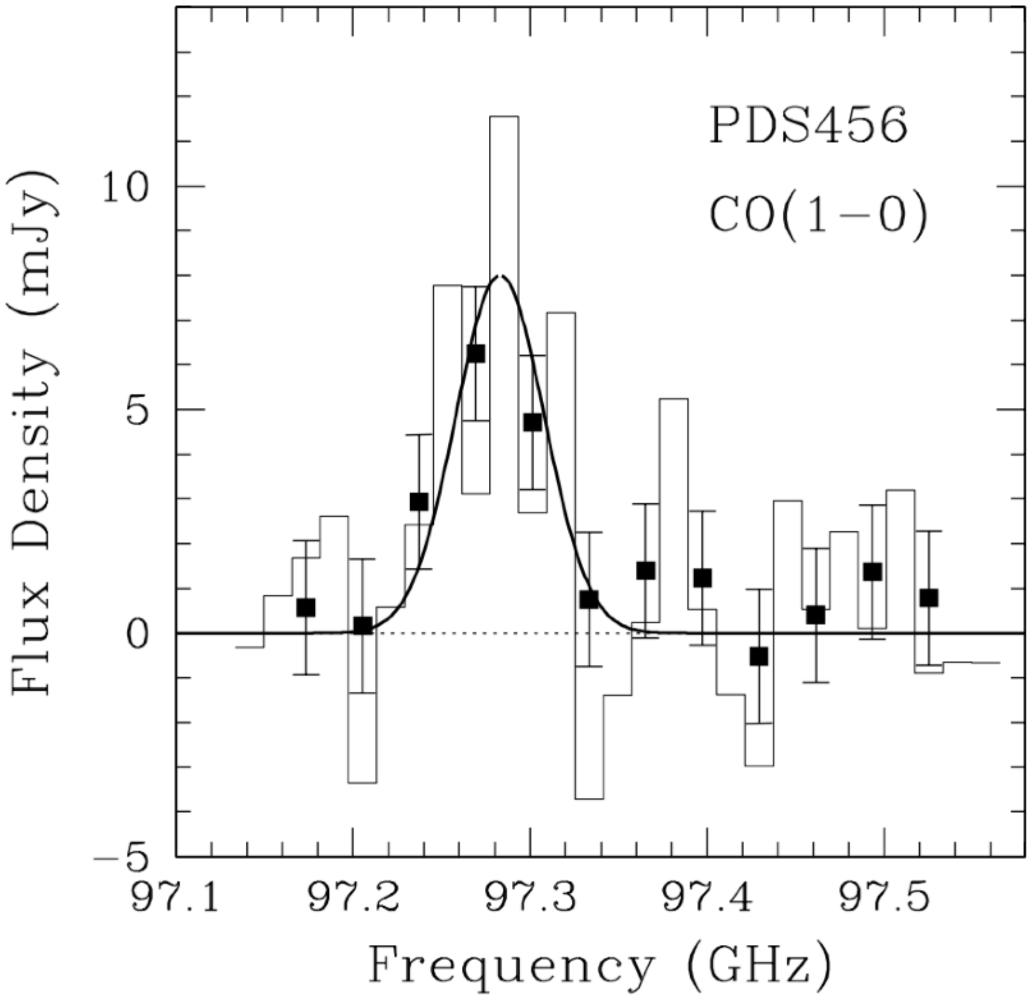

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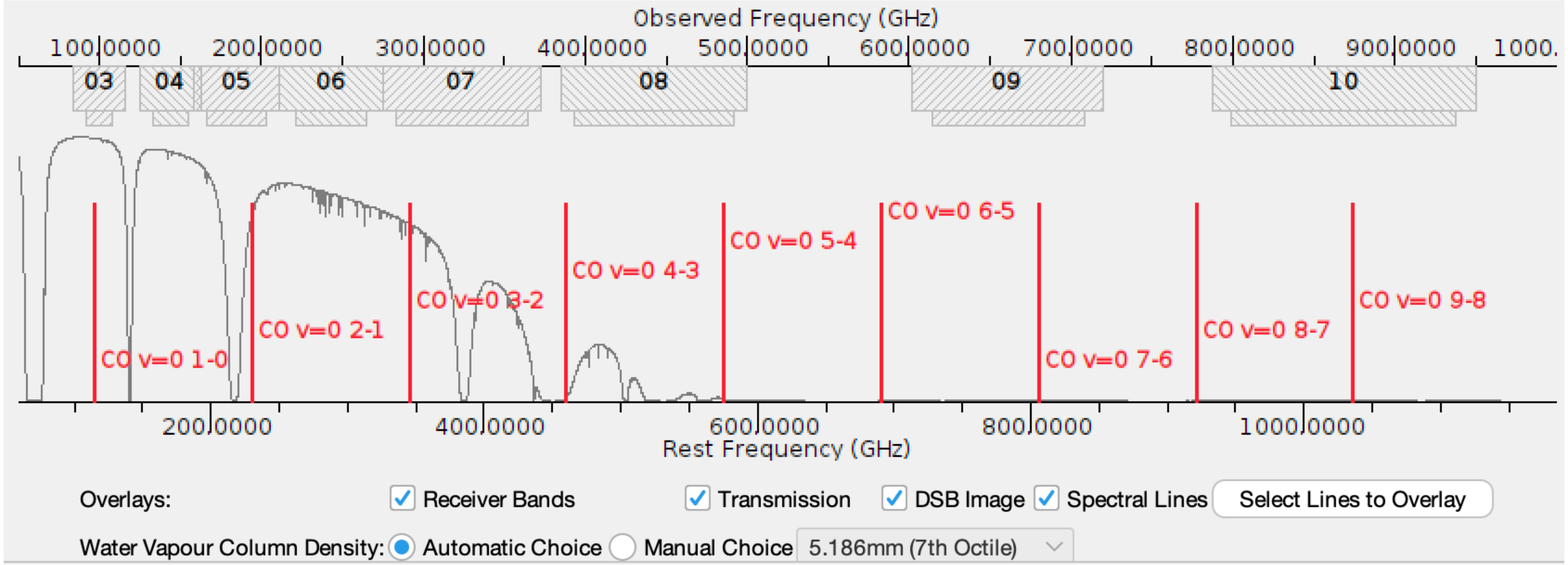
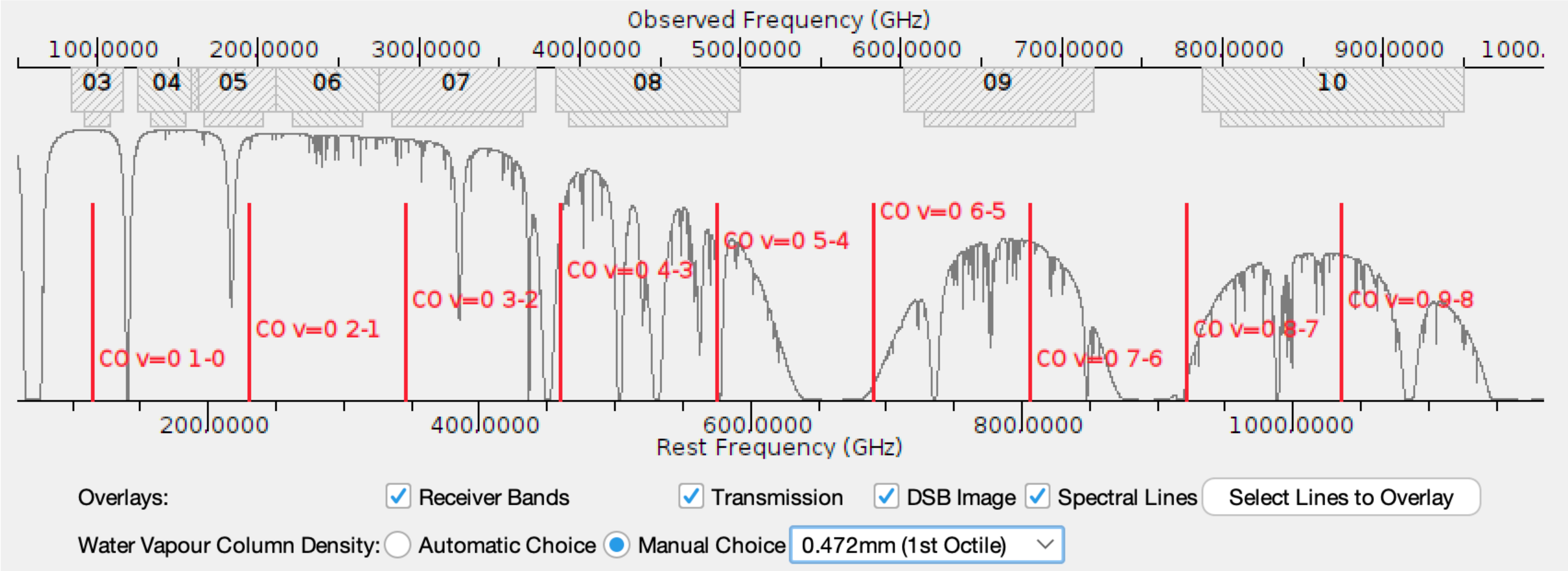


Overlays: ☑ Receiver Bands ☑ Transmission ☑ DSB Image ☑ Spectral Lines

Water Vapour Column Density: ● Automatic Choice ○ Manual Choice 5.186mm (7th Octile)



Overlays: ☑ Receiver Bands ☑ Transmission ☑ DSB Image ☑ Spectral Lines

Water Vapour Column Density: ○ Automatic Choice ● Manual Choice 0.472mm (1st Octile)

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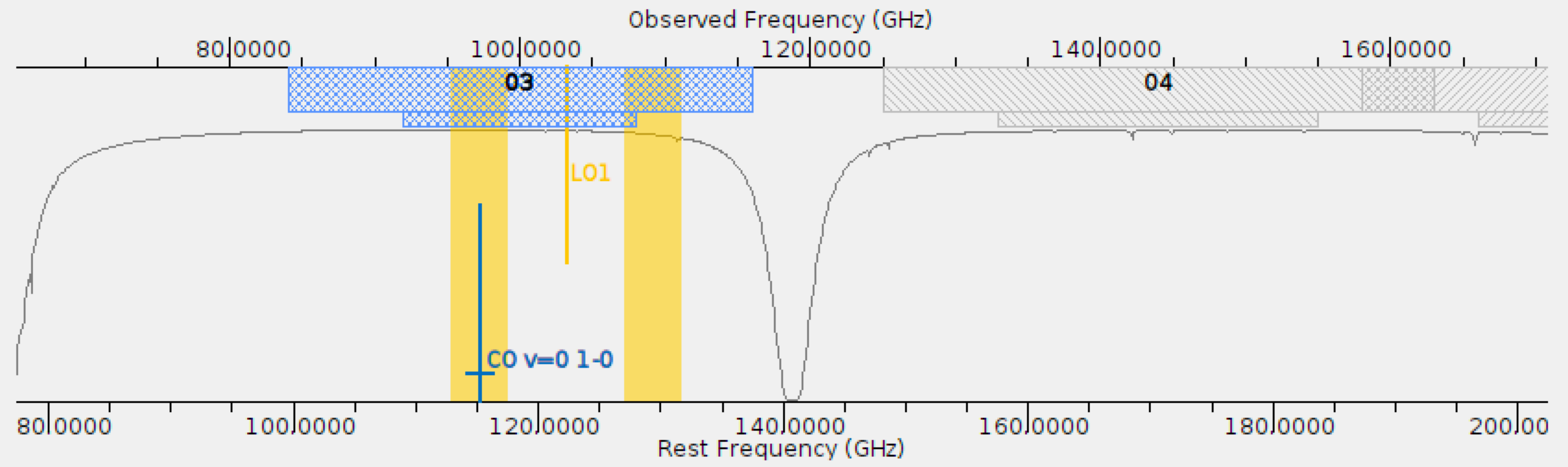
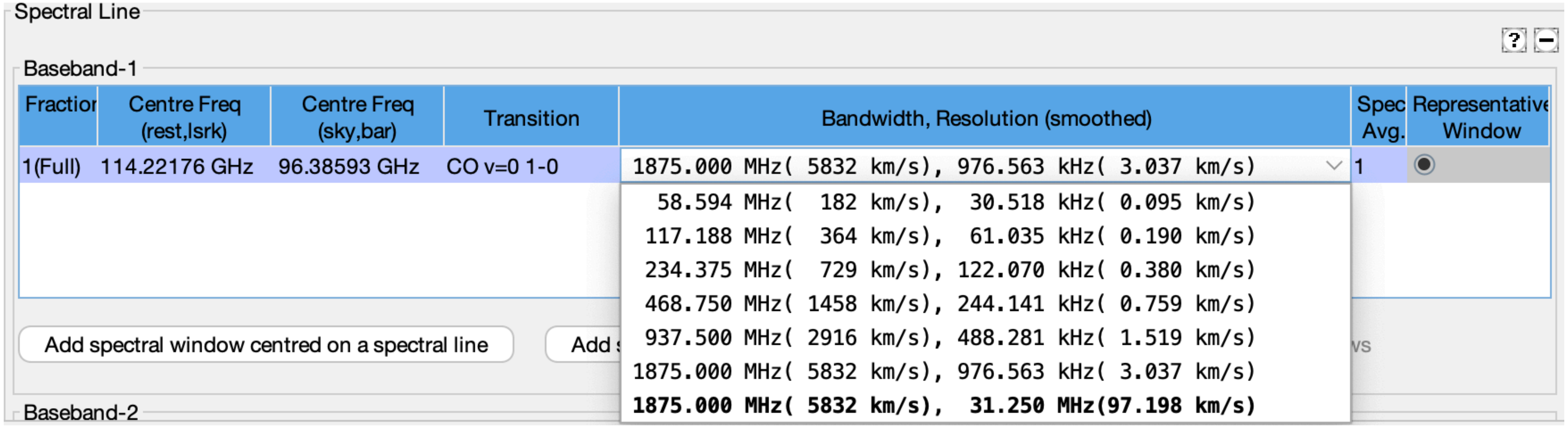


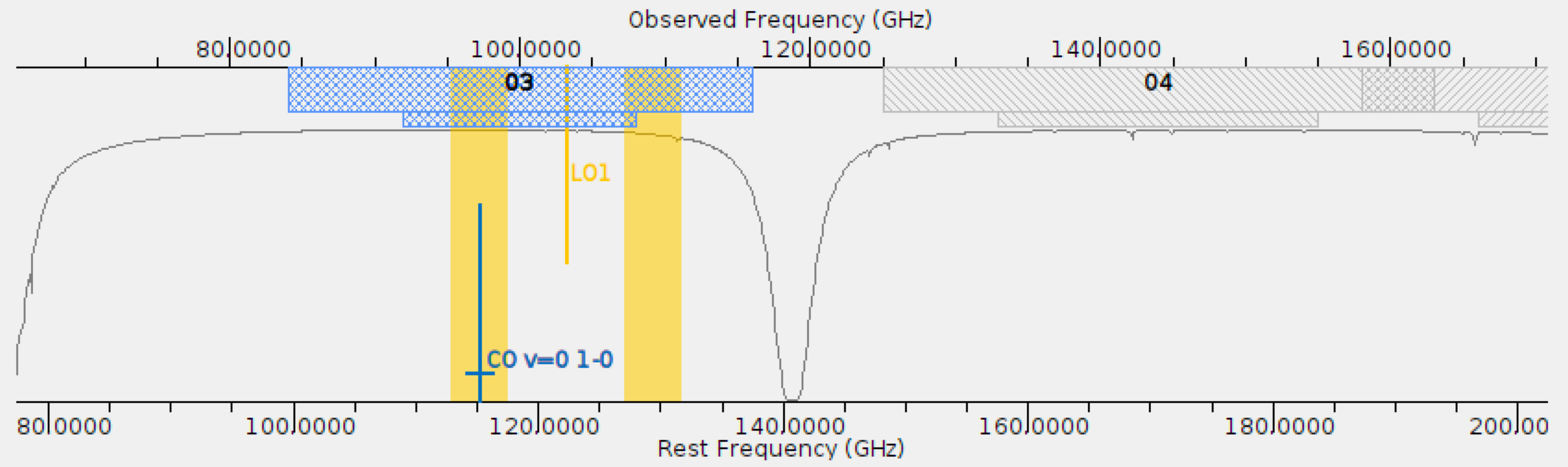


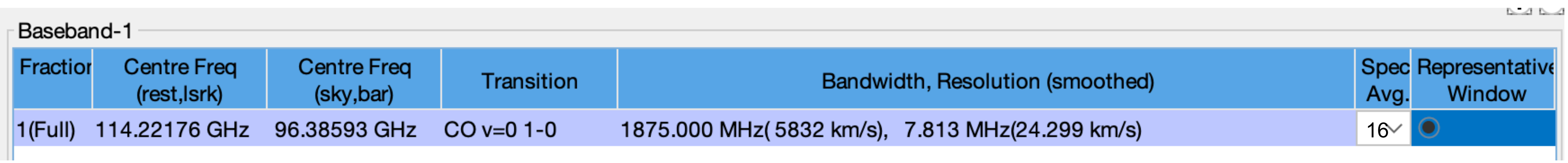
Fraction	Centre Freq (rest,lsrk)	Centre Freq (sky,bar)	Transition	Bandwidth, Resolution (smoothed)	Spec Avg.	Representative Window
1(Full)	114.22176 GHz	96.38593 GHz	CO v=0 1-0	1875.000 MHz(5832 km/s), 976.563 kHz(3.037 km/s)	1	●

```
  58.594 MHz(  182 km/s),  30.518 kHz( 0.095 km/s)
 117.188 MHz(  364 km/s),  61.035 kHz( 0.190 km/s)
 234.375 MHz(  729 km/s), 122.070 kHz( 0.380 km/s)
 468.750 MHz( 1458 km/s), 244.141 kHz( 0.759 km/s)
 937.500 MHz( 2916 km/s), 488.281 kHz( 1.519 km/s)
1875.000 MHz( 5832 km/s), 976.563 kHz( 3.037 km/s)
1875.000 MHz( 5832 km/s),  31.250 MHz(97.198 km/s)
```

Setting up a radio observation (e.g. PDS456 with ALMA)

PDS456 z=0.185 (1″~3 kpc)



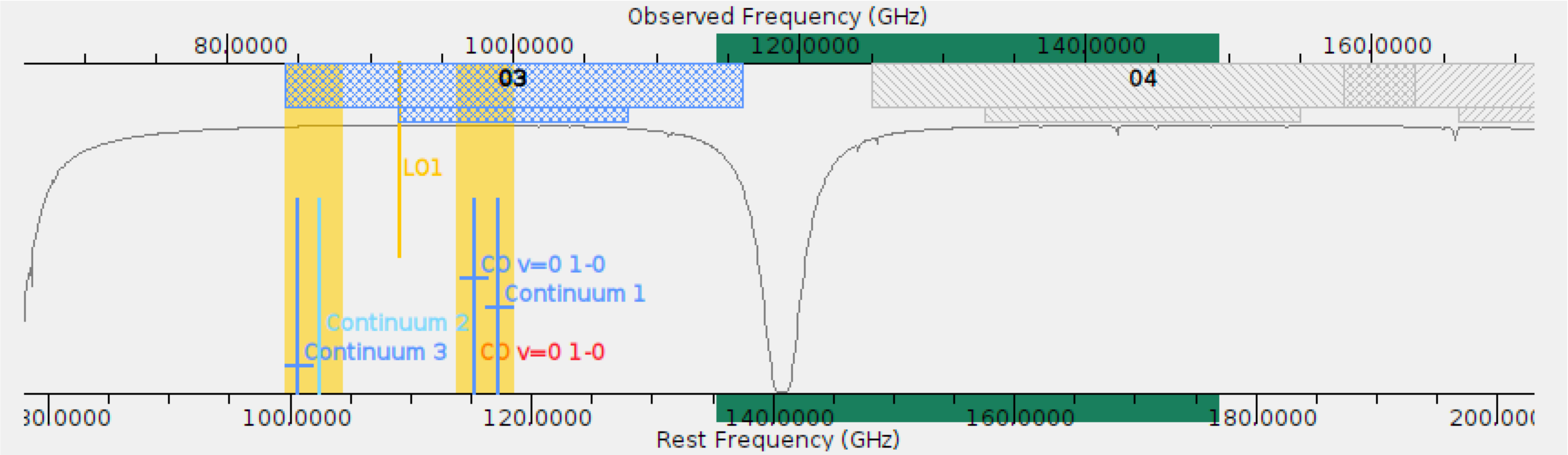


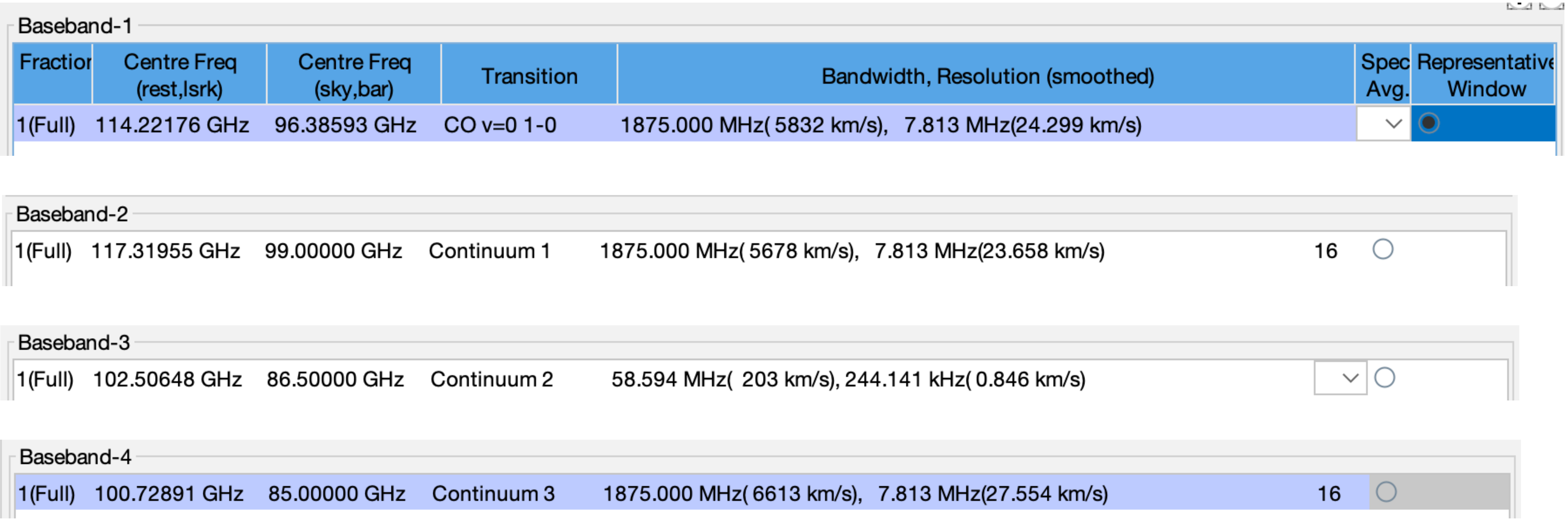
Baseband-1

Fractior	Centre Freq (rest,lsrk)	Centre Freq (sky,bar)	Transition	Bandwidth, Resolution (smoothed)	Spec Avg.	Representative Window
1(Full)	114.22176 GHz	96.38593 GHz	CO v=0 1-0	1875.000 MHz(5832 km/s), 7.813 MHz(24.299 km/s)	16	●

Setting up a radio observation (e.g. PDS456 with ALMA)

PDS456 z=0.185 (1"~3 kpc)





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Baseband-2

1(Full)	117.31955 GHz	99.00000 GHz	Continuum 1	1875.000 MHz(5678 km/s), 7.813 MHz(23.658 km/s)	16	○

Baseband-3

1(Full)	102.50648 GHz	86.50000 GHz	Continuum 2	58.594 MHz(203 km/s), 244.141 kHz(0.846 km/s)		○

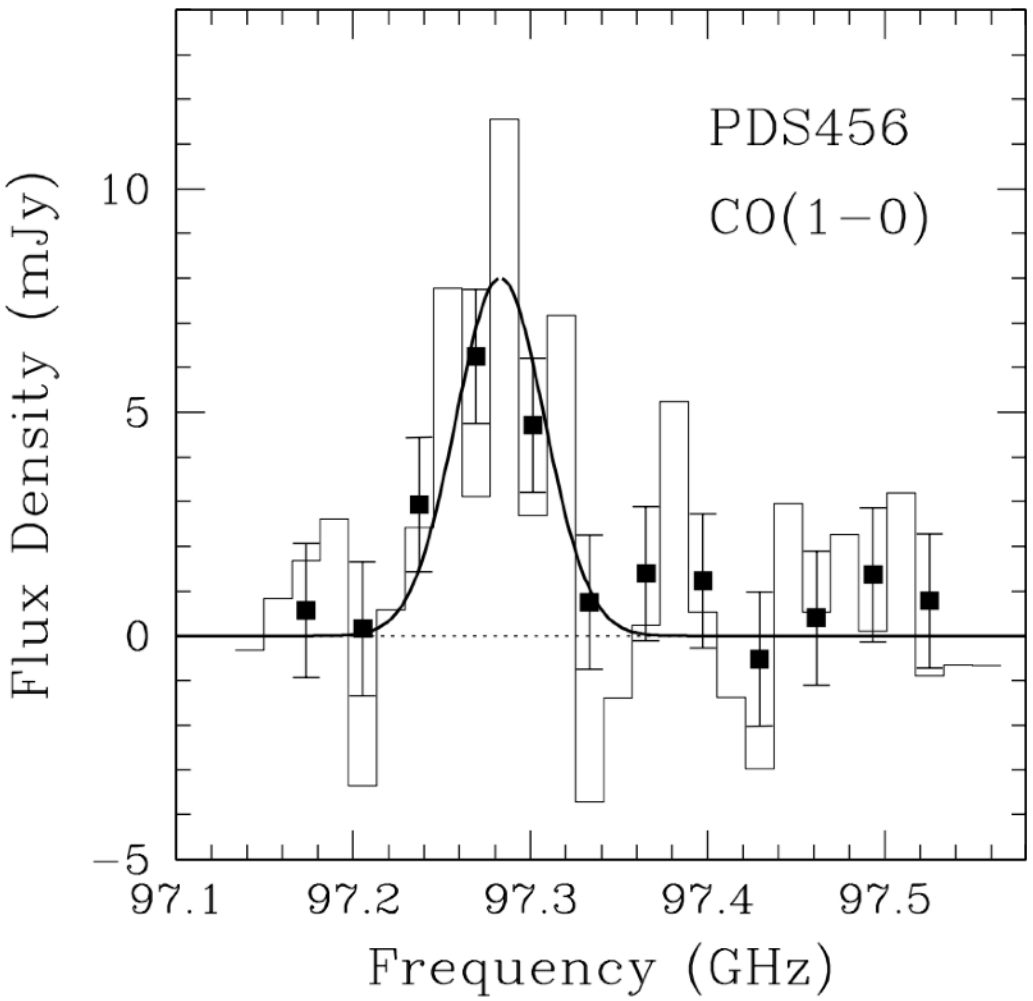
Baseband-4

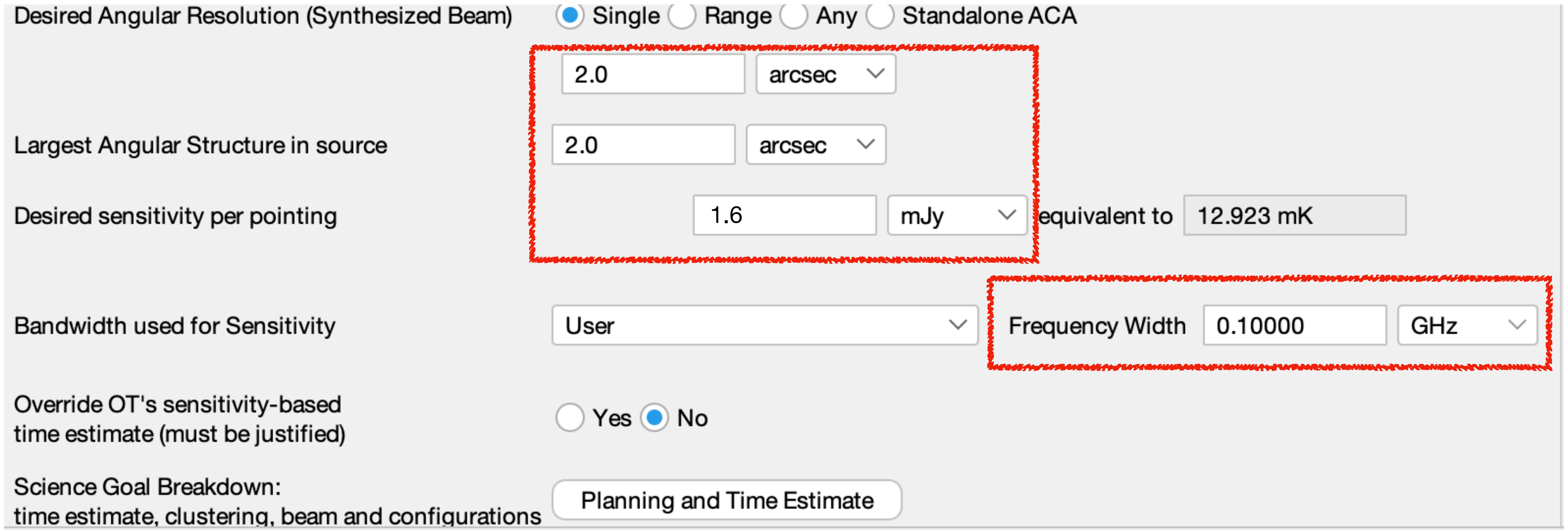
1(Full)	100.72891 GHz	85.00000 GHz	Continuum 3	1875.000 MHz(6613 km/s), 7.813 MHz(27.554 km/s)	16	○

Setting up a radio observation (e.g. PDS456 with ALMA)

PDS456 z=0.185 (1″~3 kpc)

Detection





Desired Angular Resolution (Synthesized Beam) ● Single ○ Range ○ Any ○ Standalone ACA

2.0 arcsec

Largest Angular Structure in source: 2.0 arcsec

Desired sensitivity per pointing: 1.6 mJy equivalent to 12.923 mK

Bandwidth used for Sensitivity: User — Frequency Width 0.10000 GHz

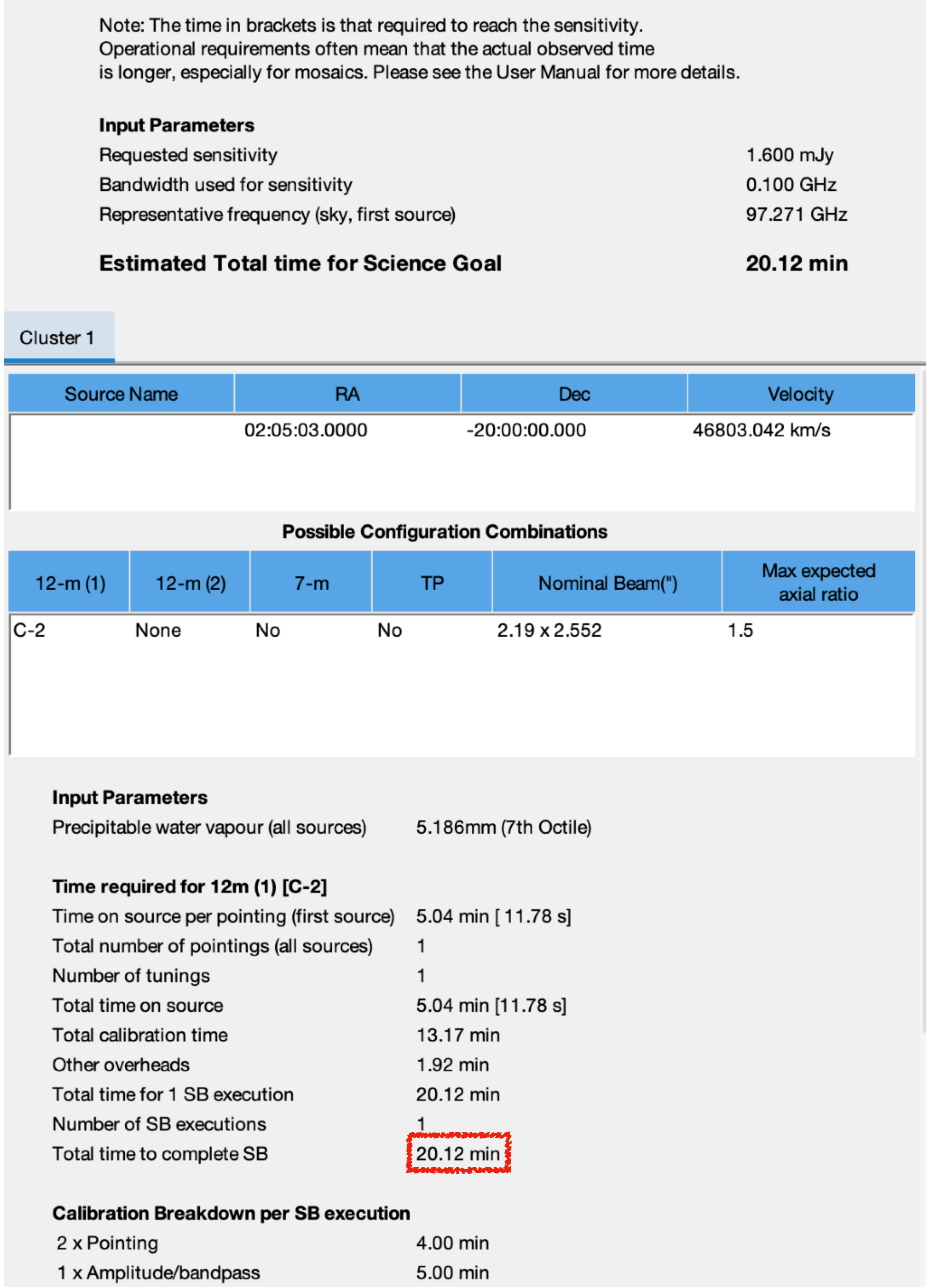
Override OT's sensitivity-based time estimate (must be justified): ○ Yes ● No

Science Goal Breakdown: time estimate, clustering, beam and configurations

Setting up a radio observation (e.g. PDS456 with ALMA)

PDS456 z=0.185 (1″~3 kpc)
Detection SNR~5 of the frequency-integrated CO line

We have assumed a CO FWHM of 0.1 GHz (~300 km/s)



Note: The time in brackets is that required to reach the sensitivity. Operational requirements often mean that the actual observed time is longer, especially for mosaics. Please see the User Manual for more details.

Input Parameters

Requested sensitivity	1.600 mJy
Bandwidth used for sensitivity	0.100 GHz
Representative frequency (sky, first source)	97.271 GHz
Estimated Total time for Science Goal	**20.12 min**

Cluster 1

Source Name	RA	Dec	Velocity
	02:05:03.0000	-20:00:00.000	46803.042 km/s

Possible Configuration Combinations

12-m (1)	12-m (2)	7-m	TP	Nominal Beam(")	Max expected axial ratio
C-2	None	No	No	2.19 x 2.552	1.5

Input Parameters

Precipitable water vapour (all sources)	5.186mm (7th Octile)

Time required for 12m (1) [C-2]

Time on source per pointing (first source)	5.04 min [11.78 s]
Total number of pointings (all sources)	1
Number of tunings	1
Total time on source	5.04 min [11.78 s]
Total calibration time	13.17 min
Other overheads	1.92 min
Total time for 1 SB execution	20.12 min
Number of SB executions	1
Total time to complete SB	20.12 min

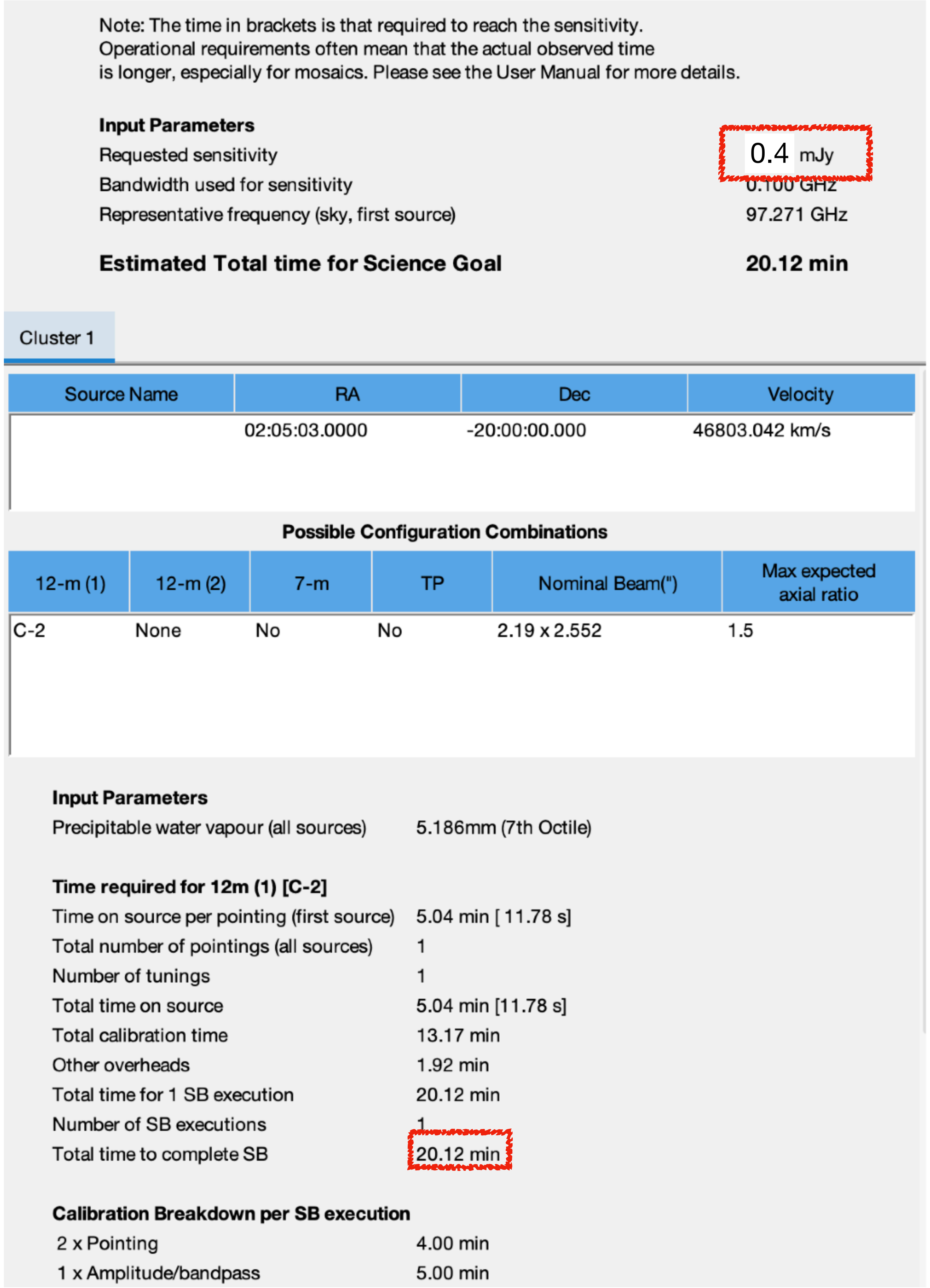
Calibration Breakdown per SB execution

2 x Pointing	4.00 min
1 x Amplitude/bandpass	5.00 min

Setting up a radio observation (e.g. PDS456 with ALMA)

PDS456 z=0.185 (1″~3 kpc)
Detection SNR~20 of the frequency-integrated CO line

We have assumed a CO FWHM of 0.1 GHz (~300 km/s)



Note: The time in brackets is that required to reach the sensitivity. Operational requirements often mean that the actual observed time is longer, especially for mosaics. Please see the User Manual for more details.

Input Parameters

Requested sensitivity	0.4 mJy
Bandwidth used for sensitivity	0.100 GHz
Representative frequency (sky, first source)	97.271 GHz
Estimated Total time for Science Goal	**20.12 min**

Source Name	RA	Dec	Velocity
	02:05:03.0000	-20:00:00.000	46803.042 km/s

Possible Configuration Combinations

12-m (1)	12-m (2)	7-m	TP	Nominal Beam(")	Max expected axial ratio
C-2	None	No	No	2.19 x 2.552	1.5

Input Parameters

Precipitable water vapour (all sources)	5.186mm (7th Octile)

Time required for 12m (1) [C-2]

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Calibration Breakdown per SB execution

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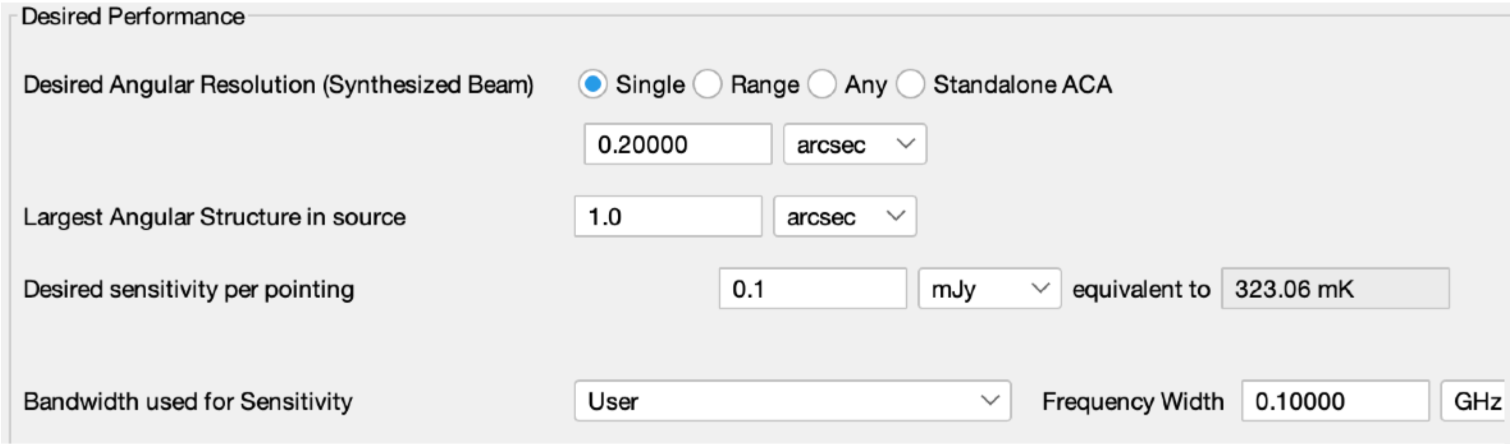
1 x Amplitude/bandpass	5.00 min

Setting up a radio observation (e.g. PDS456 with ALMA)

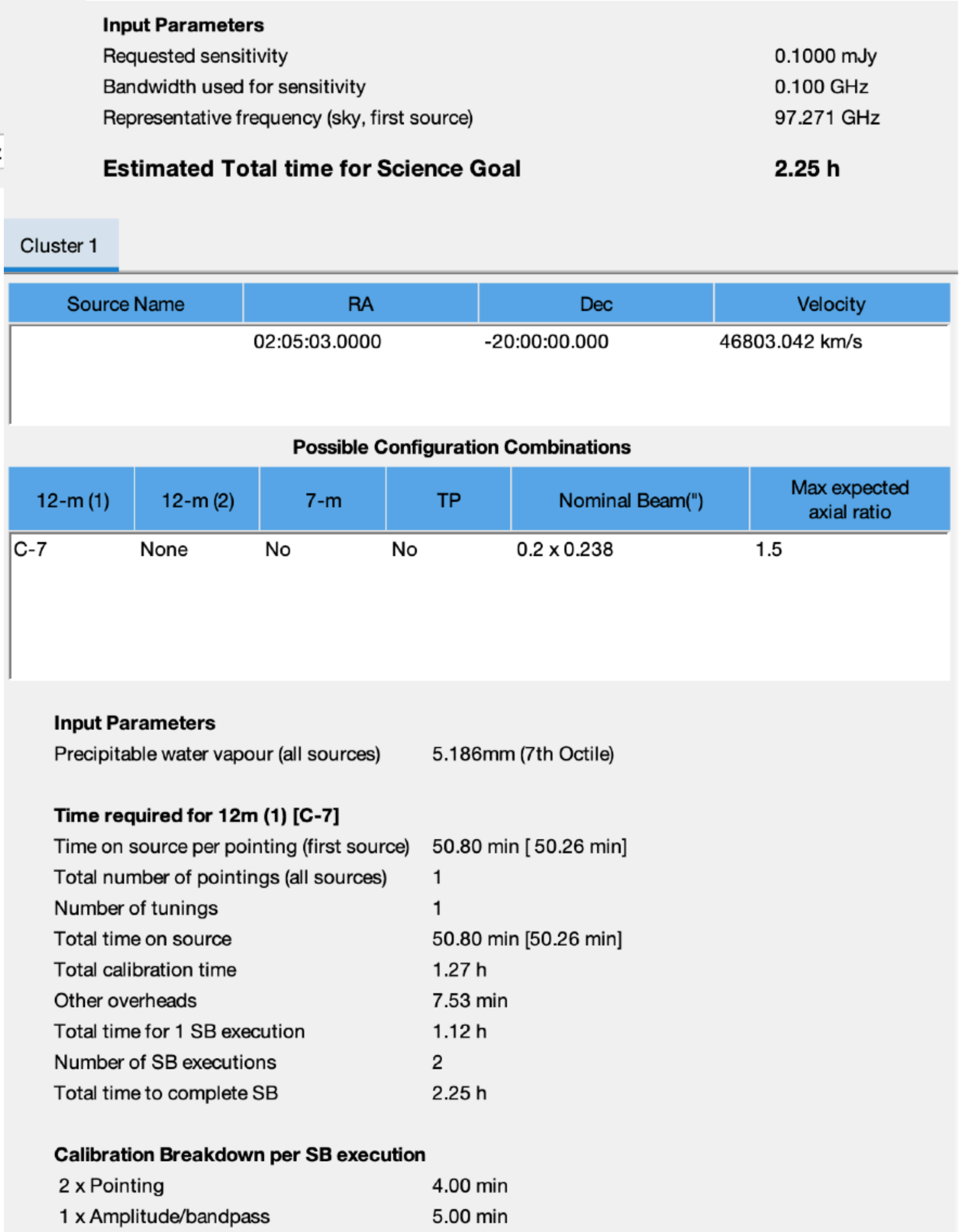
PDS456 z=0.185 (1”~3 kpc)
CO mapping at ~600 pc resolution



Desired Performance

Desired Angular Resolution (Synthesized Beam)	● Single ○ Range ○ Any ○ Standalone ACA 0.20000 arcsec
Largest Angular Structure in source	1.0 arcsec
Desired sensitivity per pointing	0.1 mJy equivalent to 323.06 mK
Bandwidth used for Sensitivity	User · Frequency Width 0.10000 GHz

SNR/beam~5



Input Parameters

Requested sensitivity	0.1000 mJy
Bandwidth used for sensitivity	0.100 GHz
Representative frequency (sky, first source)	97.271 GHz
Estimated Total time for Science Goal	**2.25 h**

Cluster 1

Source Name	RA	Dec	Velocity
	02:05:03.0000	-20:00:00.000	46803.042 km/s

Possible Configuration Combinations

12-m (1)	12-m (2)	7-m	TP	Nominal Beam(")	Max expected axial ratio
C-7	None	No	No	0.2 x 0.238	1.5

Input Parameters

Precipitable water vapour (all sources)	5.186mm (7th Octile)

Time required for 12m (1) [C-7]

Time on source per pointing (first source)	50.80 min [50.26 min]
Total number of pointings (all sources)	1
Number of tunings	1
Total time on source	50.80 min [50.26 min]
Total calibration time	1.27 h
Other overheads	7.53 min
Total time for 1 SB execution	1.12 h
Number of SB executions	2
Total time to complete SB	2.25 h

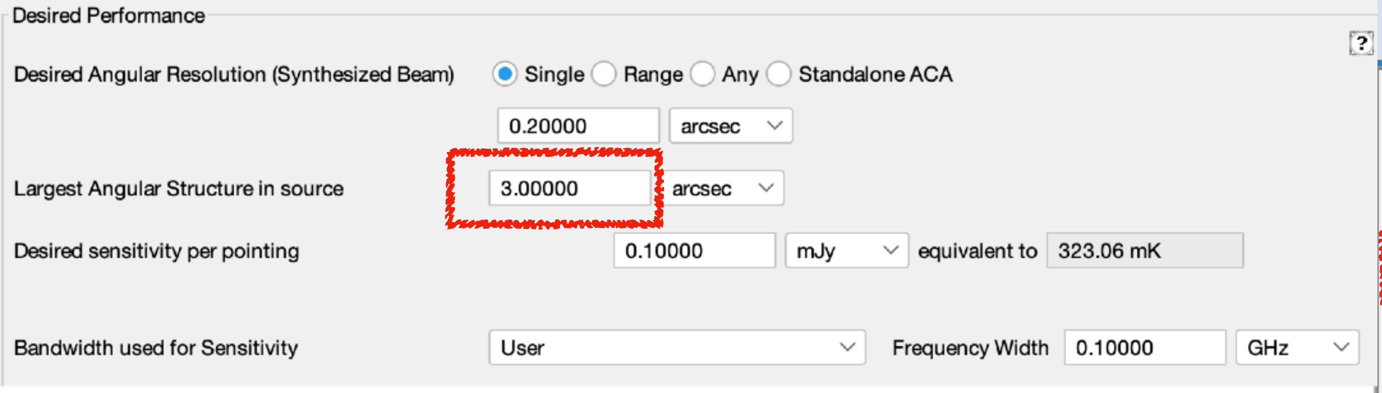
Calibration Breakdown per SB execution

2 x Pointing	4.00 min
1 x Amplitude/bandpass	5.00 min

We have assumed a CO size of ~0.65” (~2kpc)
and a CO FWHM of 0.1 GHz (~300 km/s)

Setting up a radio observation (e.g. PDS456 with ALMA)

PDS456 z=0.185 (1"~3 kpc)
CO mapping at ~600 pc resolution



Desired Performance

Desired Angular Resolution (Synthesized Beam) ● Single ○ Range ○ Any ○ Standalone ACA

0.20000 arcsec

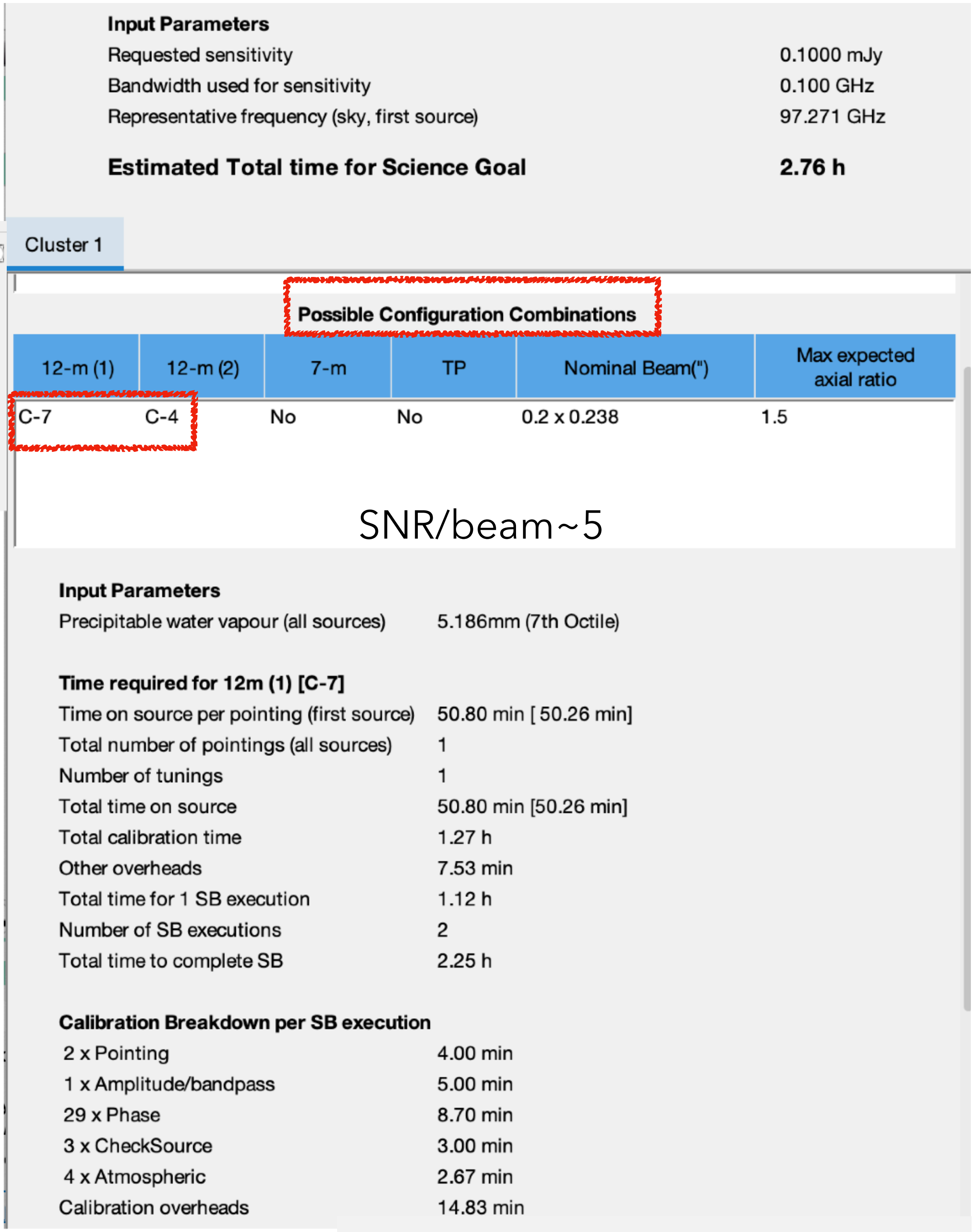
Largest Angular Structure in source 3.00000 arcsec

Desired sensitivity per pointing 0.10000 mJy equivalent to 323.06 mK

Bandwidth used for Sensitivity User Frequency Width 0.10000 GHz

We have assumed a CO size of ~0.65" (~2kpc)
and a CO FWHM of 0.1 GHz (~300 km/s)

Plus an extended CO component



Input Parameters

Requested sensitivity	0.1000 mJy
Bandwidth used for sensitivity	0.100 GHz
Representative frequency (sky, first source)	97.271 GHz
Estimated Total time for Science Goal	**2.76 h**

Cluster 1

Possible Configuration Combinations

12-m (1)	12-m (2)	7-m	TP	Nominal Beam(")	Max expected axial ratio
C-7	C-4	No	No	0.2 x 0.238	1.5

SNR/beam~5

Input Parameters

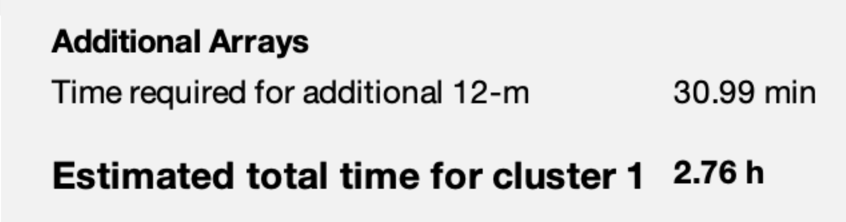
Precipitable water vapour (all sources)	5.186mm (7th Octile)

Time required for 12m (1) [C-7]

Time on source per pointing (first source)	50.80 min [50.26 min]
Total number of pointings (all sources)	1
Number of tunings	1
Total time on source	50.80 min [50.26 min]
Total calibration time	1.27 h
Other overheads	7.53 min
Total time for 1 SB execution	1.12 h
Number of SB executions	2
Total time to complete SB	2.25 h

Calibration Breakdown per SB execution

2 x Pointing	4.00 min
1 x Amplitude/bandpass	5.00 min
29 x Phase	8.70 min
3 x CheckSource	3.00 min
4 x Atmospheric	2.67 min
Calibration overheads	14.83 min

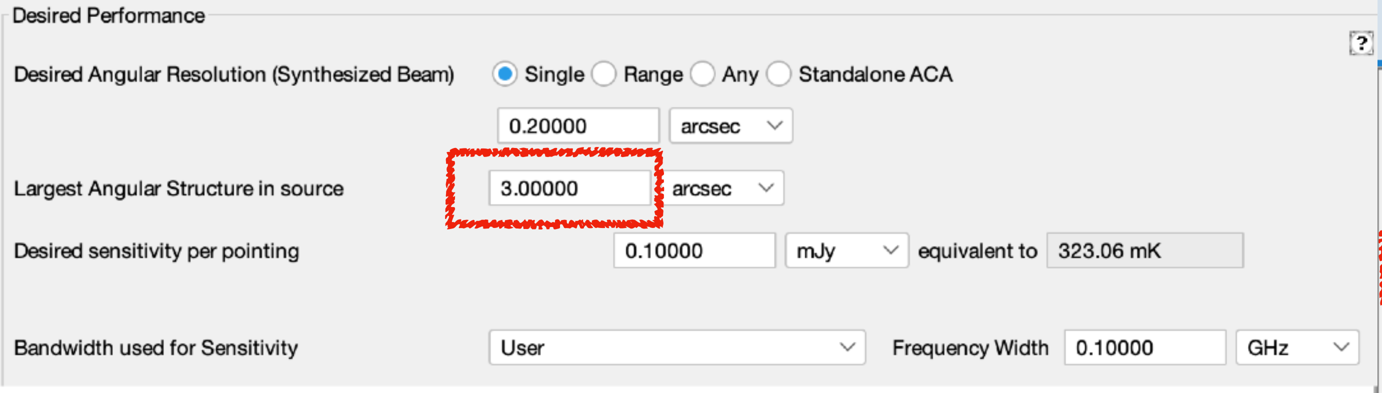


Additional Arrays

Time required for additional 12-m	30.99 min
Estimated total time for cluster 1	**2.76 h**

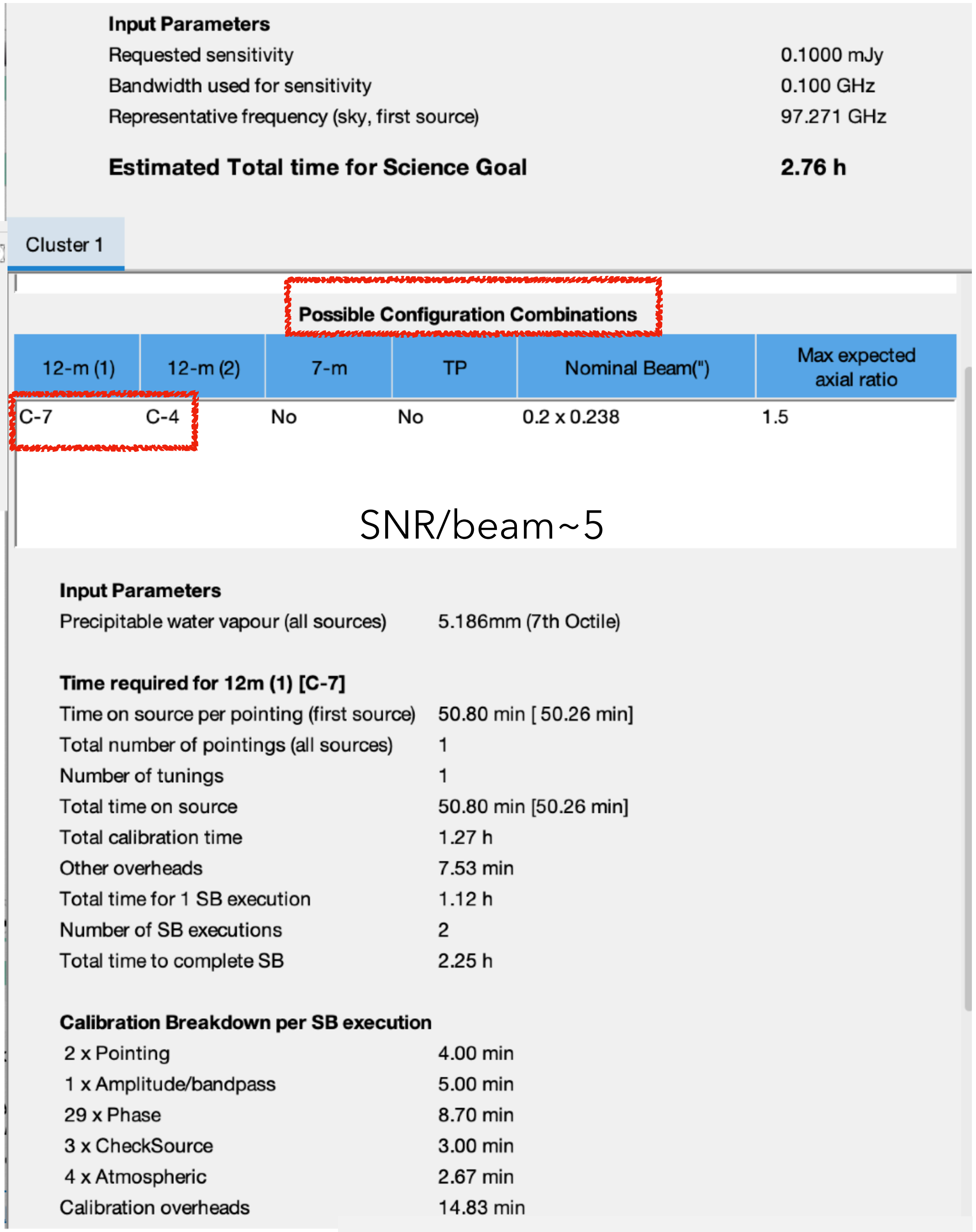
Setting up a radio observation (e.g. PDS456 with ALMA)

PDS456 z=0.185 (1”~3 kpc)
CO mapping at ~600 pc resolution



Desired Performance

Desired Angular Resolution (Synthesized Beam)	● Single ○ Range ○ Any ○ Standalone ACA		
	0.20000	arcsec	
Largest Angular Structure in source	3.00000	arcsec	
Desired sensitivity per pointing	0.10000	mJy	equivalent to 323.06 mK
Bandwidth used for Sensitivity	User	Frequency Width 0.10000	GHz



Input Parameters

Requested sensitivity	0.1000 mJy
Bandwidth used for sensitivity	0.100 GHz
Representative frequency (sky, first source)	97.271 GHz
Estimated Total time for Science Goal	**2.76 h**

Possible Configuration Combinations

12-m (1)	12-m (2)	7-m	TP	Nominal Beam(")	Max expected axial ratio
C-7	C-4	No	No	0.2 x 0.238	1.5

SNR/beam~5

Input Parameters

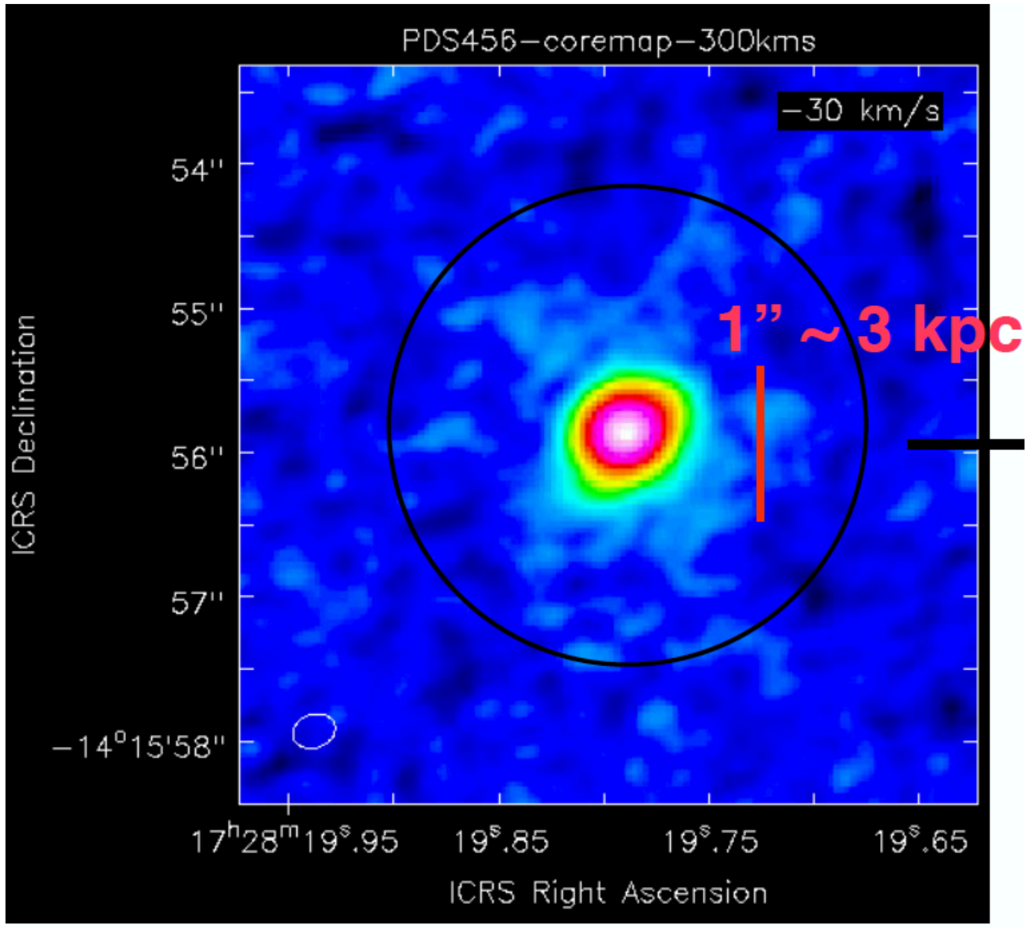
Precipitable water vapour (all sources)	5.186mm (7th Octile)

Time required for 12m (1) [C-7]

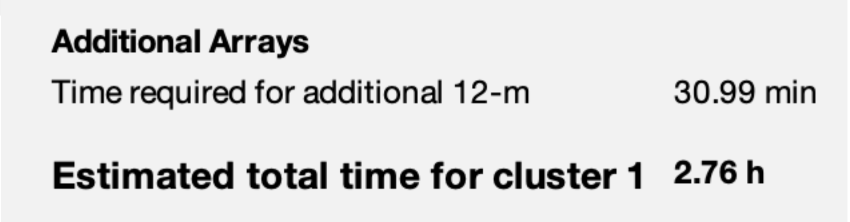
Time on source per pointing (first source)	50.80 min [50.26 min]
Total number of pointings (all sources)	1
Number of tunings	1
Total time on source	50.80 min [50.26 min]
Total calibration time	1.27 h
Other overheads	7.53 min
Total time for 1 SB execution	1.12 h
Number of SB executions	2
Total time to complete SB	2.25 h

Calibration Breakdown per SB execution

2 x Pointing	4.00 min
1 x Amplitude/bandpass	5.00 min
29 x Phase	8.70 min
3 x CheckSource	3.00 min
4 x Atmospheric	2.67 min
Calibration overheads	14.83 min



1” ~ 3 kpc



Additional Arrays

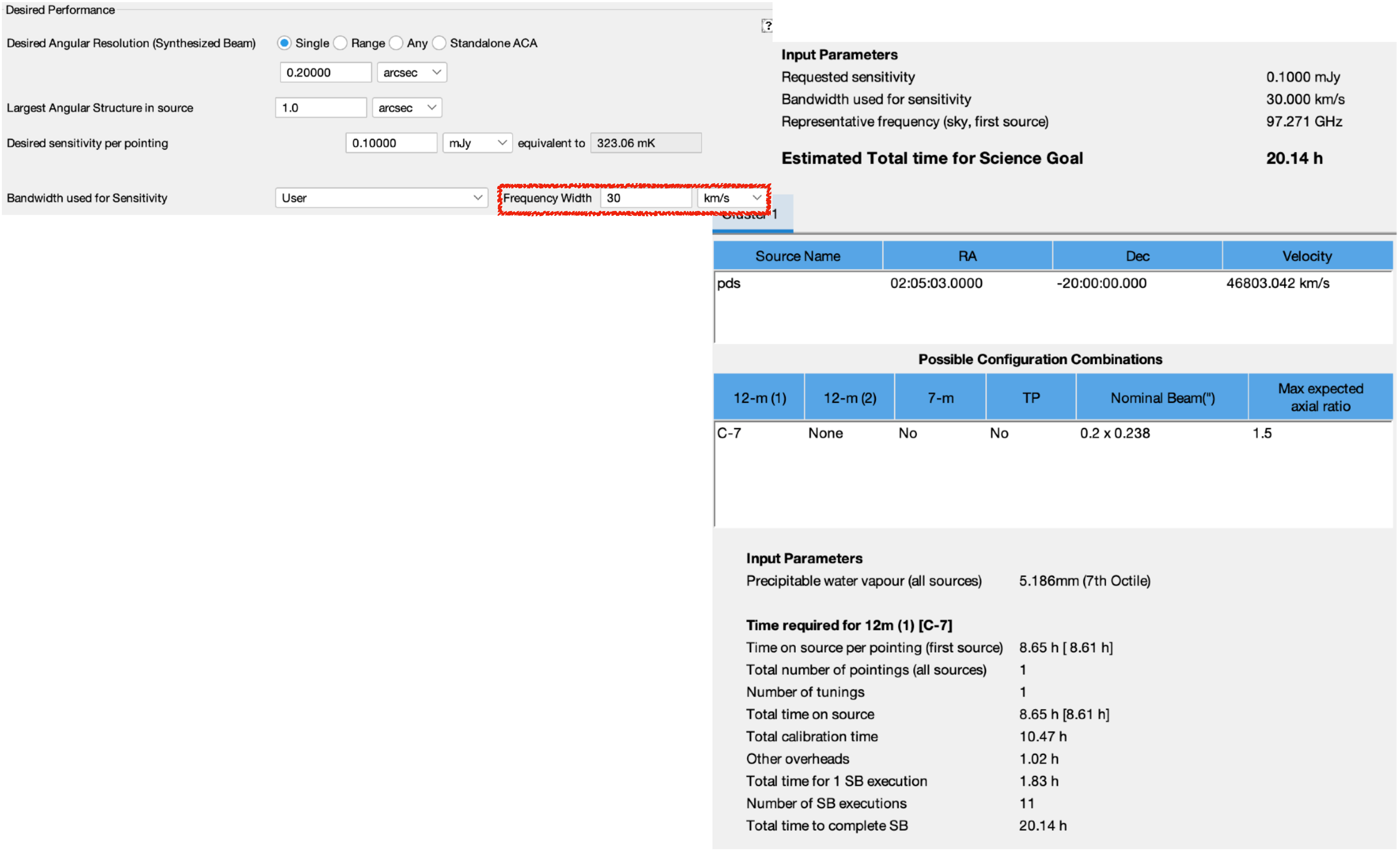
Time required for additional 12-m	30.99 min
Estimated total time for cluster 1	**2.76 h**

Setting up a radio observation (e.g. PDS456 with ALMA)

PDS456 z=0.185 (1″~3 kpc)

CO mapping at ~600 pc resolution

Information about CO kinematics



Desired Performance

Desired Angular Resolution (Synthesized Beam) ● Single ○ Range ○ Any ○ Standalone ACA

0.20000 arcsec

Largest Angular Structure in source: 1.0 arcsec

Desired sensitivity per pointing: 0.10000 mJy equivalent to 323.06 mK

Bandwidth used for Sensitivity: User — Frequency Width 30 km/s

Input Parameters

Requested sensitivity	0.1000 mJy
Bandwidth used for sensitivity	30.000 km/s
Representative frequency (sky, first source)	97.271 GHz
Estimated Total time for Science Goal	**20.14 h**

Source Name	RA	Dec	Velocity
pds	02:05:03.0000	-20:00:00.000	46803.042 km/s

Possible Configuration Combinations

12-m (1)	12-m (2)	7-m	TP	Nominal Beam(")	Max expected axial ratio
C-7	None	No	No	0.2 x 0.238	1.5

Input Parameters

Precipitable water vapour (all sources)	5.186mm (7th Octile)

Time required for 12m (1) [C-7]

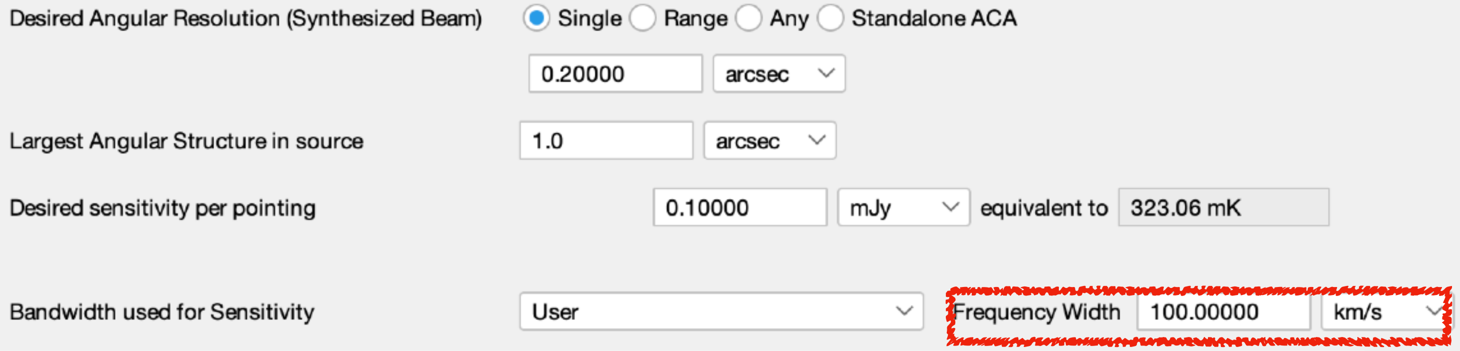
Time on source per pointing (first source)	8.65 h [8.61 h]
Total number of pointings (all sources)	1
Number of tunings	1
Total time on source	8.65 h [8.61 h]
Total calibration time	10.47 h
Other overheads	1.02 h
Total time for 1 SB execution	1.83 h
Number of SB executions	11
Total time to complete SB	20.14 h

Setting up a radio observation (e.g. PDS456 with ALMA)

PDS456 z=0.185 (1″~3 kpc)

CO mapping at ~600 pc resolution

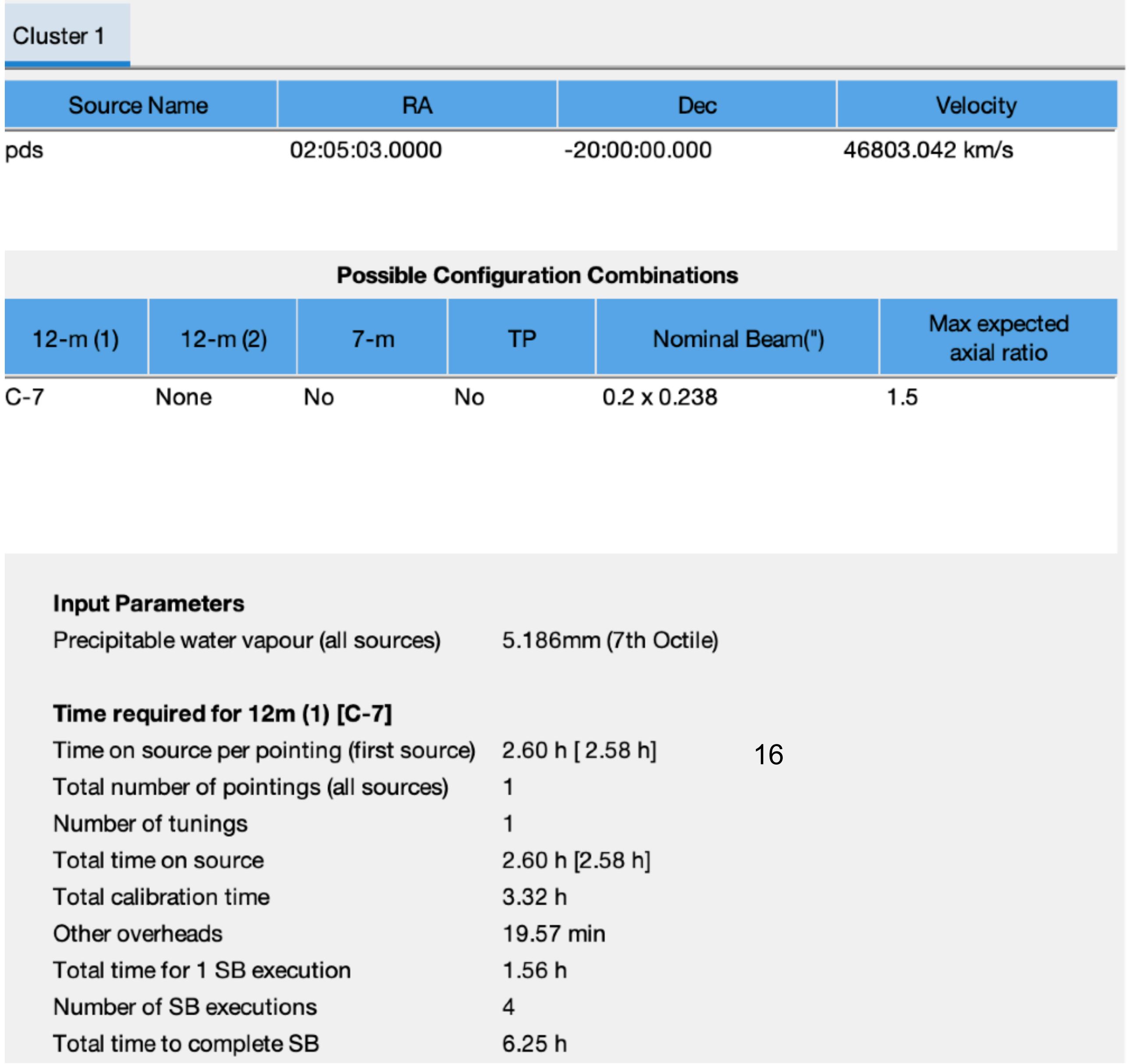
Information about CO kinematics



Desired Angular Resolution (Synthesized Beam)	● Single ○ Range ○ Any ○ Standalone ACA		
	0.20000 arcsec		
Largest Angular Structure in source	1.0 arcsec		
Desired sensitivity per pointing	0.10000 mJy	equivalent to	323.06 mK
Bandwidth used for Sensitivity	User	Frequency Width	100.00000 km/s

Input Parameters

Requested sensitivity	0.1000 mJy
Bandwidth used for sensitivity	100.000 km/s
Representative frequency (sky, first source)	97.271 GHz
Estimated Total time for Science Goal	**6.25 h**



Cluster 1

Source Name	RA	Dec	Velocity
pds	02:05:03.0000	-20:00:00.000	46803.042 km/s

Possible Configuration Combinations

12-m (1)	12-m (2)	7-m	TP	Nominal Beam(")	Max expected axial ratio
C-7	None	No	No	0.2 x 0.238	1.5

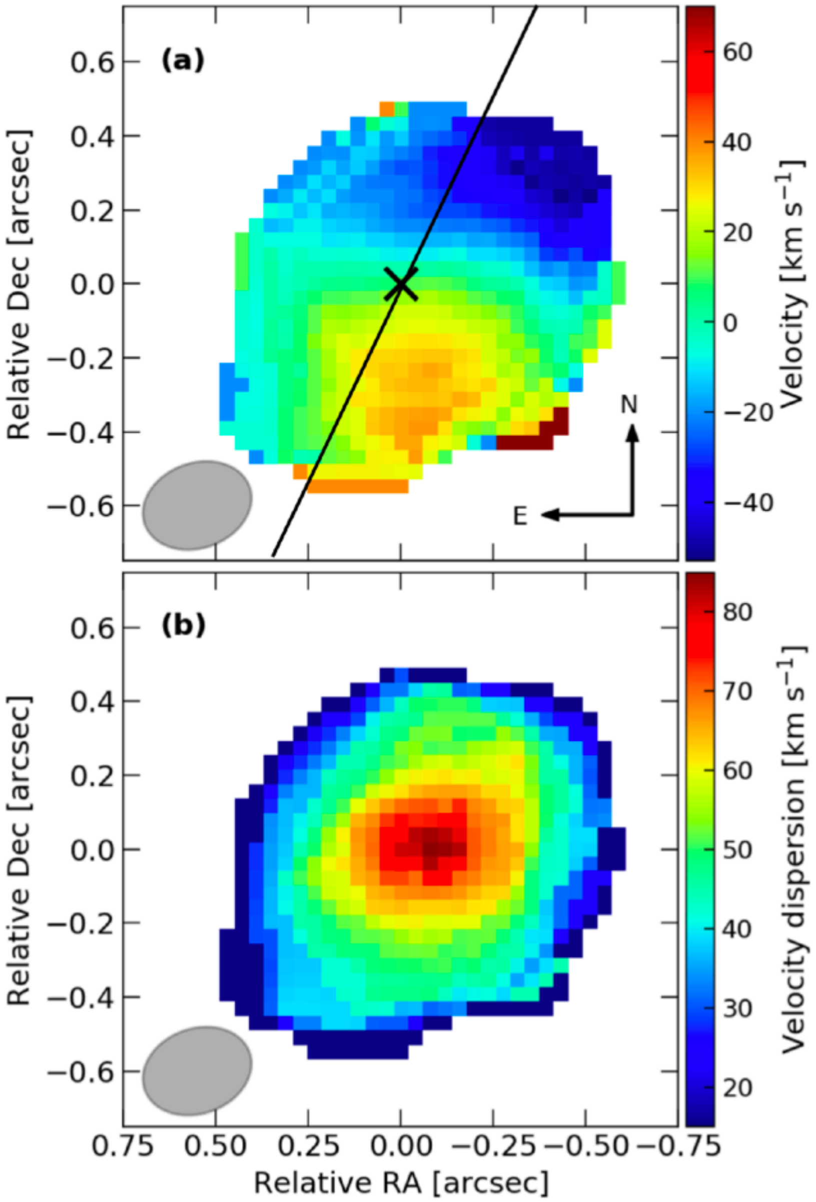
Input Parameters

Precipitable water vapour (all sources)	5.186mm (7th Octile)

Time required for 12m (1) [C-7]

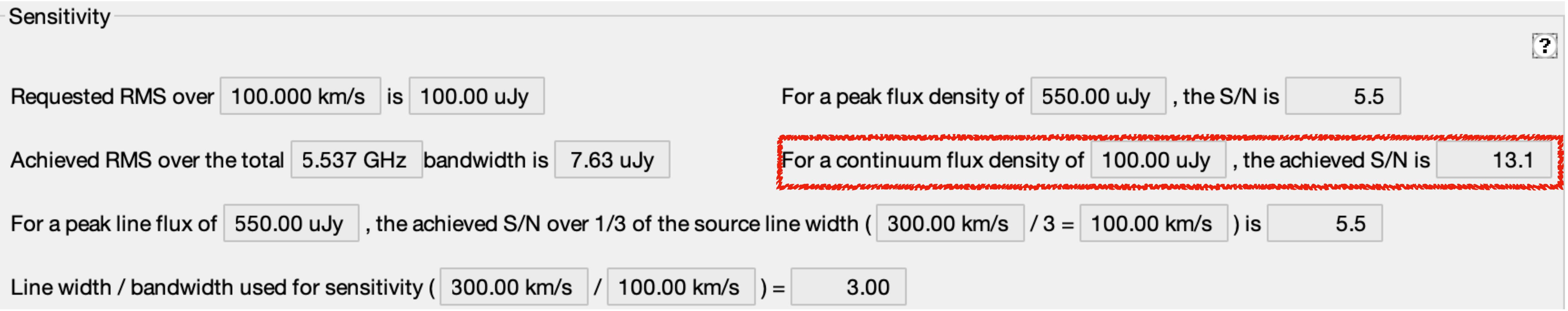
Time on source per pointing (first source)	2.60 h [2.58 h]
Total number of pointings (all sources)	1
Number of tunings	1
Total time on source	2.60 h [2.58 h]
Total calibration time	3.32 h
Other overheads	19.57 min
Total time for 1 SB execution	1.56 h
Number of SB executions	4
Total time to complete SB	6.25 h

16



Setting up a radio observation (e.g. PDS456 with ALMA)

PDS456 z=0.185 (1″~3 kpc)
Continuum detection



Sensitivity

Requested RMS over 100.000 km/s is 100.00 uJy

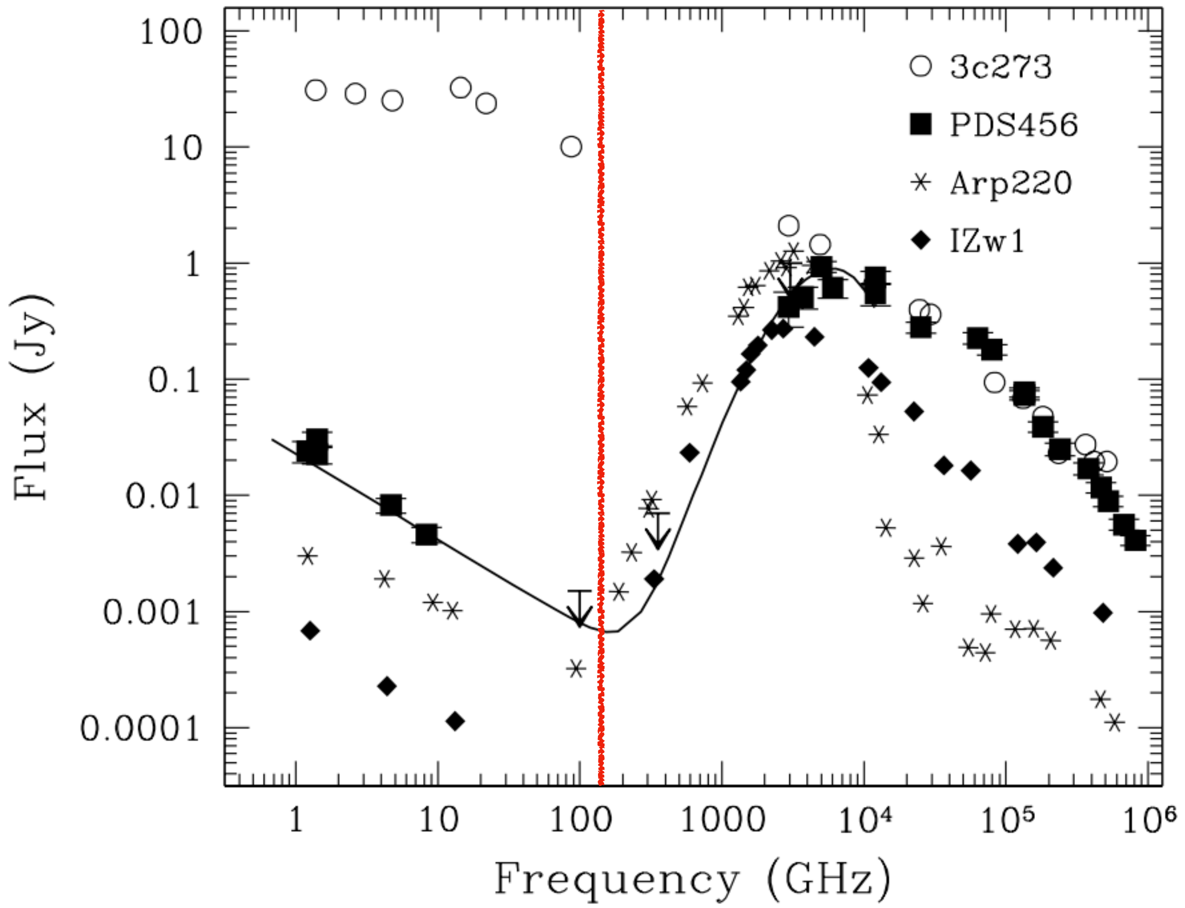
For a peak flux density of 550.00 uJy , the S/N is 5.5

Achieved RMS over the total 5.537 GHz bandwidth is 7.63 uJy

For a continuum flux density of 100.00 uJy , the achieved S/N is 13.1

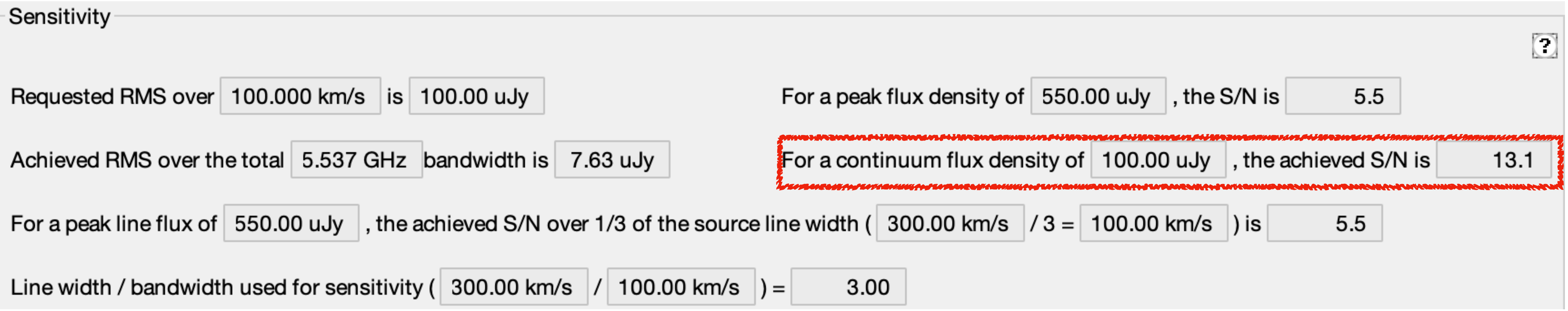
For a peak line flux of 550.00 uJy , the achieved S/N over 1/3 of the source line width (300.00 km/s / 3 = 100.00 km/s) is 5.5

Line width / bandwidth used for sensitivity (300.00 km/s / 100.00 km/s) = 3.00



Setting up a radio observation (e.g. PDS456 with ALMA)

PDS456 z=0.185 (1″~3 kpc)
Continuum detection



Sensitivity

Requested RMS over 100.000 km/s is 100.00 uJy

For a peak flux density of 550.00 uJy , the S/N is 5.5

Achieved RMS over the total 5.537 GHz bandwidth is 7.63 uJy

For a continuum flux density of 100.00 uJy , the achieved S/N is 13.1

For a peak line flux of 550.00 uJy , the achieved S/N over 1/3 of the source line width (300.00 km/s / 3 = 100.00 km/s) is 5.5

Line width / bandwidth used for sensitivity (300.00 km/s / 100.00 km/s) = 3.00