An Introduction to the IRAM NOEMA interferometer

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This document introduces IRAM's NOEMA to potential users. It contains general information about the capabilities and performance of the interferometer and on related documentation.

Related information is available in:

- GILDAS: Grenoble Image and Line Data Analysis Software
- ASTRO: Astronomical Software To pRepare Observations
- CLIC: Continuum and Line Interferometric Calibration
- NOEMA: Calibration Cookbook
- NOEMA: Mapping Cookbook

Revision 5.0: NOEMA Antenna 7
Revision 4.2: Band 4
Revision 4.1: WideX
Revision 4.0: NGR system and extended array configurations

Contents

1 Description

The NOrthern Extended Millimeter Array (NOEMA) is located in the South of the French Alps, near St Etienne en Dévoluy in the Départment Hautes Alpes. The interferometer's altitude is 2560 m at the intersection of the Azimuth and Elevation axes of the telescopes, and its longitude and latitude are 05:54:28.5 E and 44:38:02.0 N at the array phase center. The interferometer currently comprises

- Seven antennas of 15 m diameter,
- one north-south track 368 m long,
- one east-west track 760 m long,
- a wide-band correlator *WideX* covering a bandwidth of 3.6 GHz in dual polarization with a channel spacing of 1.95 MHz that is able to accommodate up to 8 antennas,
- a flexible spectral narrow-band correlator, consisting of 8 independent units, with resolutions ranging from 0.039 MHz to 2.5 MHz, and with 128 to 512 associated channels per unit and baseline useable for up to 6 antennas,
- dual polarization receivers: a 3 mm receiver band tunable between 80 and 116 GHz, a 2 mm band (129 to 177 GHz), a 1.3 mm receiver band tunable between 201 and 267 GHz, and a 0.8 mm receiver band covering the 277 to 371 GHz frequency range.

The seven antennas of the interferometer can be positioned on 32 stations layed out along a "T" shaped track (see Figure 1).

The north-south arm is 368 m long, and the east-west oriented arm extends 216 m west and 544 m east of the intersection. The angle between the arms is 75°. The station names are taken from the arm orientation and a two digit code indicating the distance from the track intersection (station W00) in 8 m units.

Each antenna is a 15 m diameter Cassegrain telescope constructed largely of carbon fiber. The primary mirrors have a surface accuracy below 50 μm rms. The antenna mounts incorporate self propelled transporters for moving the antennas along the tracks between stations. The antennas are equipped with four receiver bands, observing in dual polarization in the 3 mm, 2 mm, 1.3 mm, and 0.8 mm atmospheric windows, respectively. The 3 mm SIS mixers have typical SSB receiver noise temperature between 40 K and 55 K, the 2 mm mixers have typical noise temperature between 30 K and 60 K, the 1.3 mm SIS mixers have typical receiver noise temperature between 40 K and 60 K, and the noise temperatures at 0.8 mm are typically 30-50 K. More details about the receivers are given in Sect. 2.2, a summary can be found in Table 8.

The two IF-channels (one per polarization), each 3.6 GHz wide, are transmitted by optical fibers to the central building. Details on the IF transport and processing are given in Sect. 2.3.2.

The wide-band correlator WideX with fixed spectral resolution, capable of processing 28 baselines (8 antennas), is available in parallel with a narrow-band correlator, the latter comprising eight correlator units. Each of the eight units is a fully independent, flexible entity, capable of processing 15 baselines (6 antennas). Full 2-bit sampling scheme is used to give 88% efficiency. For details of the unit capabilities, see Sect. 2.3.3.

A 64-bit Linux computer and several embedded processors control the interferometer and acquire the data. The user interface is a variant of PaKo, familiar to most users of the IRAM 30 m telescope.

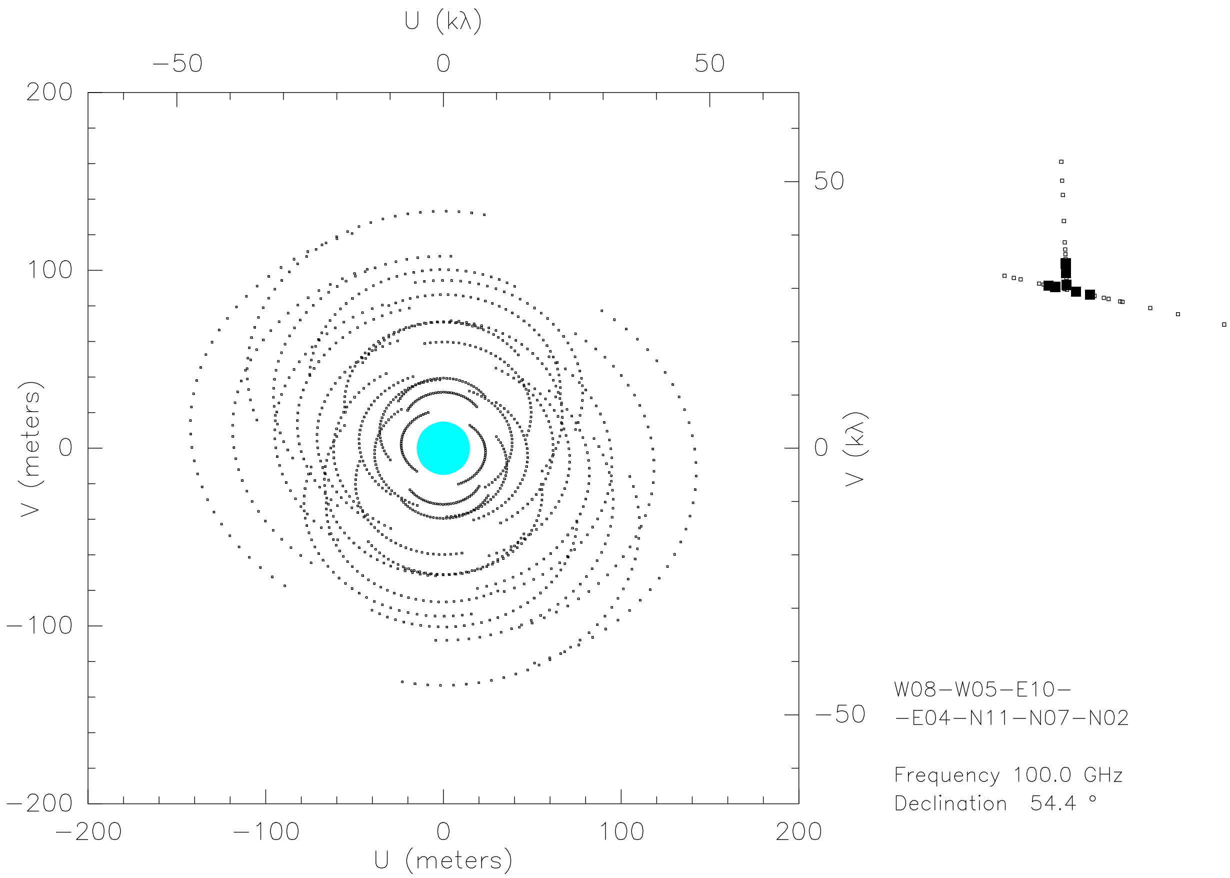

Figure 1: Example of uv-coverage (left) and interferometer station layout (right) for the 7D configuration, as produced by the ASTRO `UV_TRACK` command. The shaded circle at the center of the uv-plane shows the antenna shadowing region.

Each interferometer "configuration", i.e. the placement of the 7 antennas on given stations within the array, simultaneously provides 21 baselines. The interferometer is run with several projects progressing in parallel, allowing for a flexible scheduling of the observations well adapted to the actual meteorological conditions. Depending on the weather and on the season (antenna maintenance period in the summer semester, i.e. the array is observing in its 6 antenna D configuration), configurations are changed every two to six months, so a project that requires two configurations will on average take about four months to be completed.

2 Capabilities

2.1 Spatial Resolution

Four primary 7 antenna configurations (see Table 1) are available that can be combined to produce maps with different angular resolution. All four configurations are usually scheduled during the course of a year. During the summer period (May until September) each antenna undergoes a thorough maintenance and the interferometer is operated in a 6 antenna D configuration, equal to the 7D configuration given in Table 1 but without station E10).

Table 1: NOEMA 7 antenna configurations

Configuration	Stations						
7A	W27	W10	E68	E24	E12	N46	N29
7B	W23	W05	E24	E18	E04	N46	N20
7C	W12	W09	E18	E12	E04	N17	N11
7D	W08	W05	E10	E04	N11	N07	N02

- **D** – the compact configuration with just the D array for maximum sensitivity. This configuration is best suited for detection experiments and coarse mapping. It provides the lowest phase noise and highest sensitivity.
- **C** – the next most compact configuration provides a fairly complete coverage of the uv-plane (low sidelobe level) and is well adapted to be combined with D for low angular resolution studies (∼2.6″ at 100 GHz, ∼1.1″ at 230 GHz) and with B for higher resolution (∼1.5″ at 100 GHz, ∼0.7″ at 230 GHz). C alone is also well suited for snapshot and size measurements and for detection experiments at low source declinations.
- **B** – the second most extended configuration yields ∼1.2″ at 100 GHz and, in combination with A provides an angular resolution of ∼0.9″ at 100 GHz. It is mainly used for relatively strong sources.
- **A** – the most extended configuration is well suited for mapping or size measurements of very compact, strong sources. It provides a resolution of 0.7″ at 100 GHz, ∼0.3″ at 230 GHz.

The four configurations can be used in different combinations to achieve complementary sampling of the uv-plane, and to improve on angular resolution and sensitivity. The combinations AB, BC, CD are reasonably suited for all declinations above 0°(see Tables 3 to 6). For lower source declinations, the beam becomes increasingly elliptical. Sources lower than -25°declination cannot reasonably be observed from Plateau de Bure. Mosaicing is usually done with D or CD, but the combination BCD can also be requested for high resolution mosaics.

The antenna half-power beam size is 50″ at 100 GHz and the shortest possible antenna spacing is 24 m to avoid collisions between two antennas. Even taking into account projection effects that shorten the effective baseline, sources larger than about 15″ are already heavily resolved at 100 GHz. In these cases, additional short-spacing observations should be acquired by observing a raster- or OTF- (On-The-Fly) map using the IRAM 30 m telescope[1]. The short-spacing information can then easily be added to the uv-tables obtained from the interferometer by means of the GILDAS MAPPING software.

Tables 2-7 give a summary of possible beam sizes at various observing frequencies in different configurations using natural weighting. The numbers were obtained assuming observations of the target source from 6 hours before to 6 hours after transit down to elevations above 20 degrees. Typical uv-coverages and resulting beam shapes for the seven-element array are shown in Figs. 2 (D and CD), 3 (BCD and BC), and 4 (A and AB).

[1]see also the IRAM memo 2008-2: *Single-dish observation and processing to produce the short-spacing information for a millimeter interferometer* by N.J. Rodríguez-Fernández, J. Pety & F. Gueth

Table 2: Beam sizes for configuration D

Dec.	100 GHz		150 GHz		230 GHz		300 GHz		345 GHz		PA
	Maj.	Min.	Maj.	Min.	Maj.	Min.	Maj.	Min.	Maj.	Min.	°
80	4.54	3.78	3.03	2.52	1.97	1.64	1.51	1.26	1.31	1.09	23
60	4.35	3.61	2.90	2.41	1.89	1.57	1.45	1.20	1.28	1.10	38
40	4.51	3.58	3.00	2.38	1.95	1.60	1.50	1.19	1.30	1.06	36
20	5.07	3.63	3.38	2.42	2.20	1.57	1.69	1.21	1.47	1.05	26
0	6.42	3.69	4.28	2.46	2.79	1.60	2.14	1.23	1.86	1.07	-162
-20	9.80	3.36	6.53	2.24	4.47	1.47	3.26	1.12	2.98	0.98	-173

Table 3: Beam sizes for configuration CD

Dec.	100 GHz		150 GHz		230 GHz		300 GHz		345 GHz		PA
	Maj.	Min.	Maj.	Min.	Maj.	Min.	Maj.	Min.	Maj.	Min.	°
80	3.44	2.72	2.29	1.81	1.49	1.18	1.14	0.90	0.99	0.78	23
60	3.29	2.59	2.19	1.72	1.43	1.12	1.09	0.86	0.95	0.75	34
40	3.45	2.55	2.30	1.70	1.49	1.10	1.15	0.85	0.99	0.73	32
20	3.96	2.56	2.64	1.70	1.72	1.11	1.32	0.85	1.14	0.74	25
0	5.09	2.60	3.39	1.73	2.21	1.13	1.69	0.86	1.47	0.75	-161
-20	7.52	2.40	5.01	1.60	3.27	1.04	2.50	0.80	2.18	0.69	-172

Table 4: Beam sizes for configuration C

Dec.	100 GHz		150 GHz		230 GHz		300 GHz		345 GHz		PA
	Maj.	Min.	Maj.	Min.	Maj.	Min.	Maj.	Min.	Maj.	Min.	°
80	2.61	2.04	1.74	1.36	1.13	0.89	0.87	0.68	0.75	0.59	25
60	2.59	1.96	1.72	1.30	1.12	0.85	0.86	0.65	0.75	0.56	32
40	2.72	1.93	1.81	1.28	1.18	0.83	0.90	0.64	0.78	0.55	32
20	3.15	1.95	2.10	1.30	1.37	0.85	1.05	0.65	0.91	0.56	25
0	4.07	1.98	2.69	1.35	1.75	0.88	1.34	0.67	1.18	0.57	19
-20	6.13	1.88	4.09	1.25	2.66	0.81	2.04	0.62	1.77	0.54	8

Table 5: Beam sizes for configuration BC

Dec.	100 GHz		150 GHz		230 GHz		300 GHz		345 GHz		PA
	Maj.	Min.	Maj.	Min.	Maj.	Min.	Maj.	Min.	Maj.	Min.	°
80	1.91	1.56	1.27	1.04	0.83	0.67	0.63	0.52	0.55	0.45	35
60	1.91	1.48	1.27	0.98	0.83	0.64	0.63	0.49	0.55	0.43	45
40	2.08	1.48	1.39	0.99	0.90	0.64	0.69	0.49	0.60	0.43	40
20	2.60	1.56	1.73	1.04	1.13	0.68	0.86	0.52	0.75	0.45	26
0	3.72	1.64	2.48	1.09	1.61	0.71	1.24	0.54	1.07	0.47	-162
-20	5.02	1.56	3.35	1.04	2.18	0.68	1.67	0.52	1.45	0.45	8

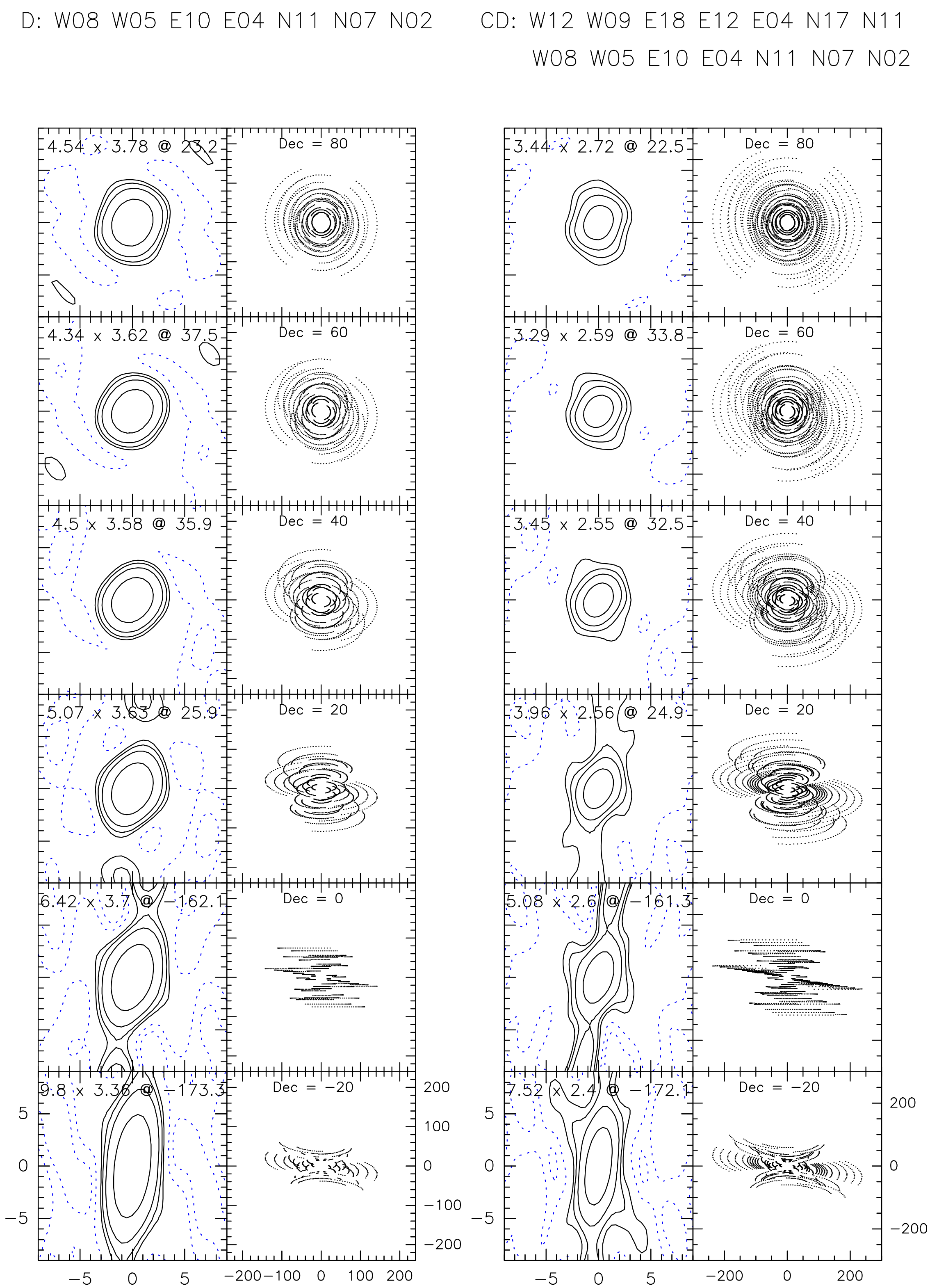

Figure 2: uv-plane coverage and beamshapes for the D and CD (7 antenna) configurations. Contour levels are at 5%, 10%, 20%, and 50%. Frequency is 100 GHz.

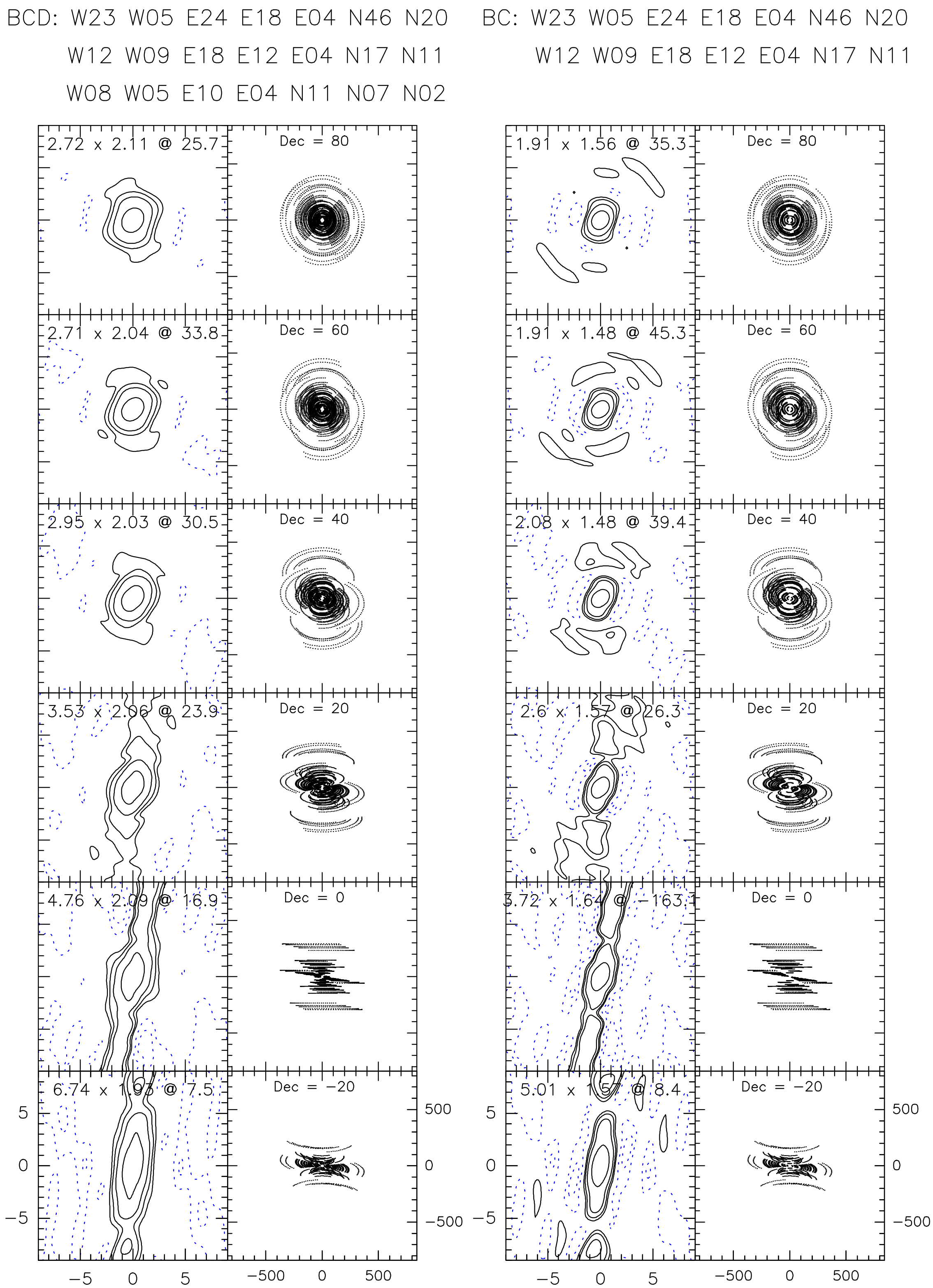

Figure 3: uv-plane coverage and beamshapes for the BCD and BC (7 antenna) configurations. Contour levels are at 5%, 10%, 20%, and 50%. Frequency is 100 GHz. Note the different scaling of the uv-plane with respect to Fig. 2.

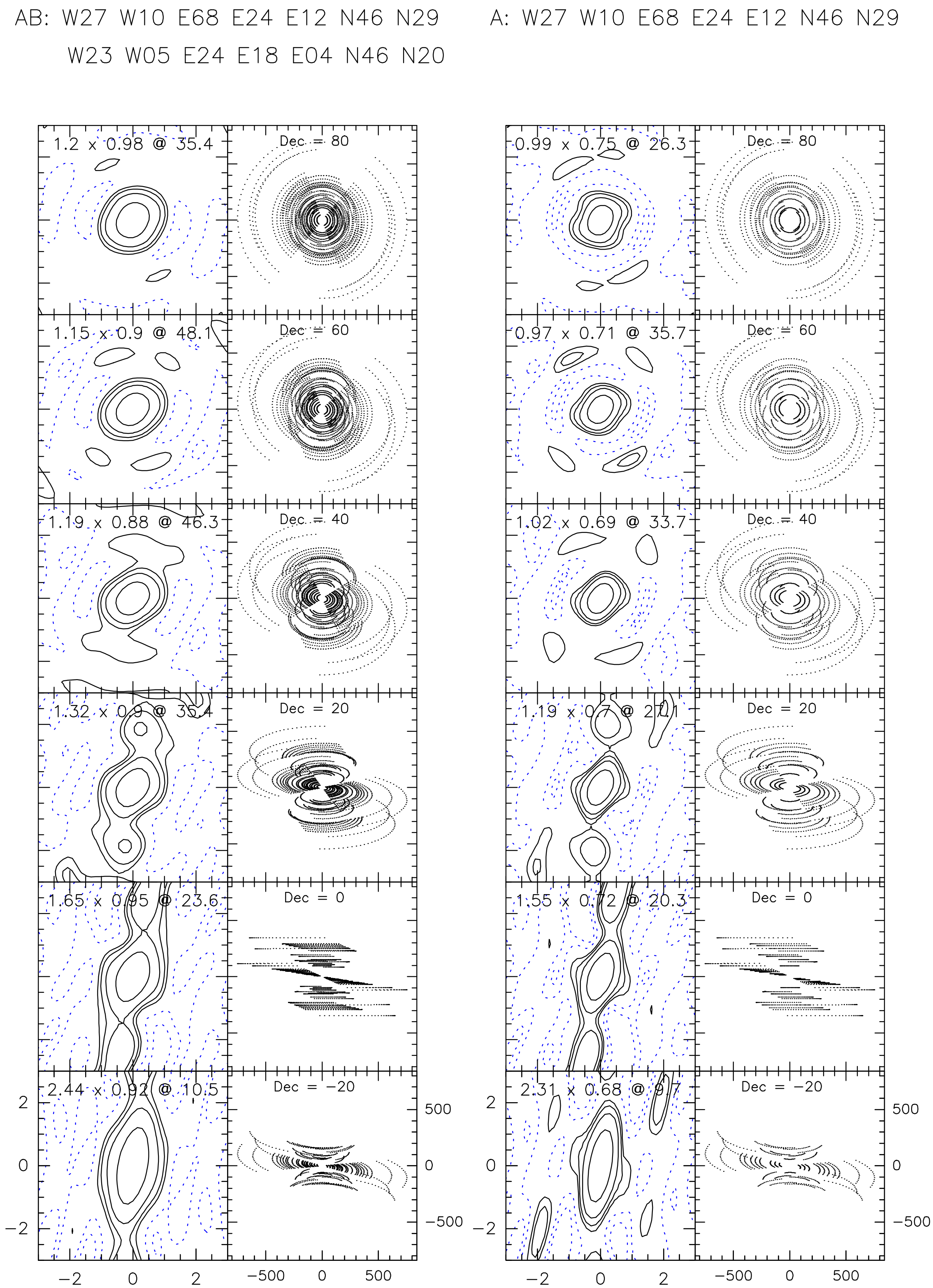

Figure 4: uv-plane coverage and beamshapes for the AB and A (7 antenna) configurations. Contour levels are at 5%, 10%, 20%, and 50%. Frequency is 100 GHz. Note the different scaling of the beam maps with respect to Figs. 2 and 3.

Table 6: Beam sizes for configuration AB

Dec.	100 GHz		150 GHz		230 GHz		300 GHz		345 GHz		PA
	Maj.	Min.	Maj.	Min.	Maj.	Min.	Maj.	Min.	Maj.	Min.	°
80	1.20	0.98	0.80	0.65	0.52	0.42	0.40	0.32	0.34	0.28	35
60	1.15	0.90	0.77	0.60	0.50	0.39	0.38	0.30	0.33	0.26	48
40	1.19	0.88	0.79	0.58	0.51	0.38	0.39	0.29	0.34	0.25	46
20	1.32	0.90	0.88	0.60	0.57	0.39	0.44	0.30	0.38	0.26	35
0	1.65	0.95	1.10	0.63	0.72	0.41	0.55	0.31	0.48	0.27	23
-20	2.44	0.92	1.63	0.61	1.06	0.40	0.81	0.30	0.71	0.26	10

Table 7: Beam sizes for configuration A

Dec.	100 GHz		150 GHz		230 GHz		300 GHz		345 GHz		PA
	Maj.	Min.	Maj.	Min.	Maj.	Min.	Maj.	Min.	Maj.	Min.	°
80	0.99	0.75	0.66	0.50	0.43	0.32	0.33	0.25	0.28	0.21	26
60	0.97	0.71	0.65	0.47	0.42	0.31	0.32	0.23	0.28	0.20	35
40	1.04	0.70	0.69	0.46	0.45	0.30	0.34	0.23	0.30	0.20	33
20	1.19	0.70	0.79	0.47	0.51	0.30	0.39	0.23	0.34	0.20	27
0	1.55	0.72	1.03	0.48	0.67	0.31	0.51	0.24	0.44	0.21	20
-20	2.31	0.68	1.54	0.45	1.00	0.29	0.77	0.22	0.66	0.19	10

2.2 Receivers

All antennas are equipped with dual polarization receivers for the 3 mm, 2 mm, 1.3 mm, and 0.8 mm atmospheric windows. The frequency ranges are 80 GHz to 116 GHz for the 3 mm band, 129 GHz to 177 GHz for the 2 mm band, 201 to 267 GHz for the 1.3 mm band, and 277 to 371 GHz for the 0.8 mm band.

Each receiver band has dual-polarization capabilities with the two RF channels, one per polarization, observing at the same frequency. The four different bands are not co-aligned in the focal plane (and therefore on the sky). Due to the pointing offsets between the different frequency bands, only one band can be observed at any time. One of the three other bands is in stand-by mode (power on and local oscillator phase-locked) and is available, e.g., for pointing. Time-shared observations between different RF bands (e.g., band 1 and band 3) are possible in well justified cases, they are however not very efficient.

The mixers for bands 1, 2, and 3 are single-sideband, backshort-tuned; they will usually be tuned LSB, except for the upper part of the frequency range in all three bands where the mixers will be tuned USB. The band 4 mixers are 2SB receivers, operated in single-sideband mode (SSB). They can be tuned LSB or USB throughout most of the accessible frequency range. The typical image rejection is 10 dB (20 dB for band 4). Each IF channel is 3.6 GHz wide (4.2-7.8 GHz).

The two IF-channels (one per polarization), each 3.6 GHz wide, are transmitted by optical fibers to the central building.

The wide-band correlator WideX is able to process both 3.6 GHz wide IFs simultaneously with a fixed resolution of about 1.95 MHz. The narrow-band correlator can process the two 3.6 GHz wide IF-channels (one per polarization) only partially. A dedicated IF processor converts selected

Table 8: Receiver specifications. The tuning ranges refer to a centering of the respective sky frequency at the center of the IF band at 6 GHz

	Band 1	Band 2	Band 3	Band 4
RF range/[GHz]	80–116	129–177	201–267	277–371
T_{rec}/[K] LSB	40–55	30–50	40–60	30–50
T_{rec}/[K] USB	40–55	40–80	50–70	30–50
G_{im}/[dB]	-10	-12 ... -10	-12 ... -8	-20
RF LSB/[GHz]	80–104	129–165	201–264	277-359
RF USB/[GHz]	104–116	164–177	264–267	289-371

1 GHz wide slices of the 4.2-7.8 GHz first IFs down to 0.1-1.1 GHz, the input range of the narrow-band correlator. Further details are given in Sect. 2.3 describing the correlator setup and the IF processor.

2.3 Correlators

2.3.1 Wideband correlator

The wide-band correlator WideX can accommodate up to 8 antennas. It gives access to the two 3.6 GHz wide IF bands simultaneously. WideX provides a fixed spectral resolution of 1.95 MHz over the full bandwidth and is available in parallel to the narrow-band correlator (see Sect. 2.3.2).

At any given time, only one frequency band can be observed, but with the two polarizations available. Each polarization delivers a 3.6 GHz bandwidth (from IF = 4.2 to 7.8 GHz). The two 3.6 GHz bandwidths coincide in the sky frequency scale.

2.3.2 IF processor and narrow-band correlator

The narrow-band correlator accepts as input two signals of 1 GHz bandwidth, that must be selected within the 3.6 GHz delivered by the receiver. In practice, the IF processor splits the two input 4.2–7.8 GHz bands in four 1 GHz "quarters", labeled *Q1...Q4* (see Fig. 5). Two of these quarters must be selected as narrow-band correlator inputs. The system allows the following choices:

- first correlator entry can only be Q1 HOR, or Q2 HOR, or Q3 VER, or Q4 VER
- second correlator entry can only be Q1 VER, or Q2 VER, or Q3 HOR, or Q4 HOR

where HOR and VER refers to the two polarizations:

Quarter IF1 [GHz]	Q1 4.2 - 5.2	Q2 5.0 - 6.0	Q3 6.0 - 7.0	Q4 6.8 - 7.8
input 1	HOR	HOR	VER	VER
input 2	VER	VER	HOR	HOR

Note, that the combination VER VER is not allowed.

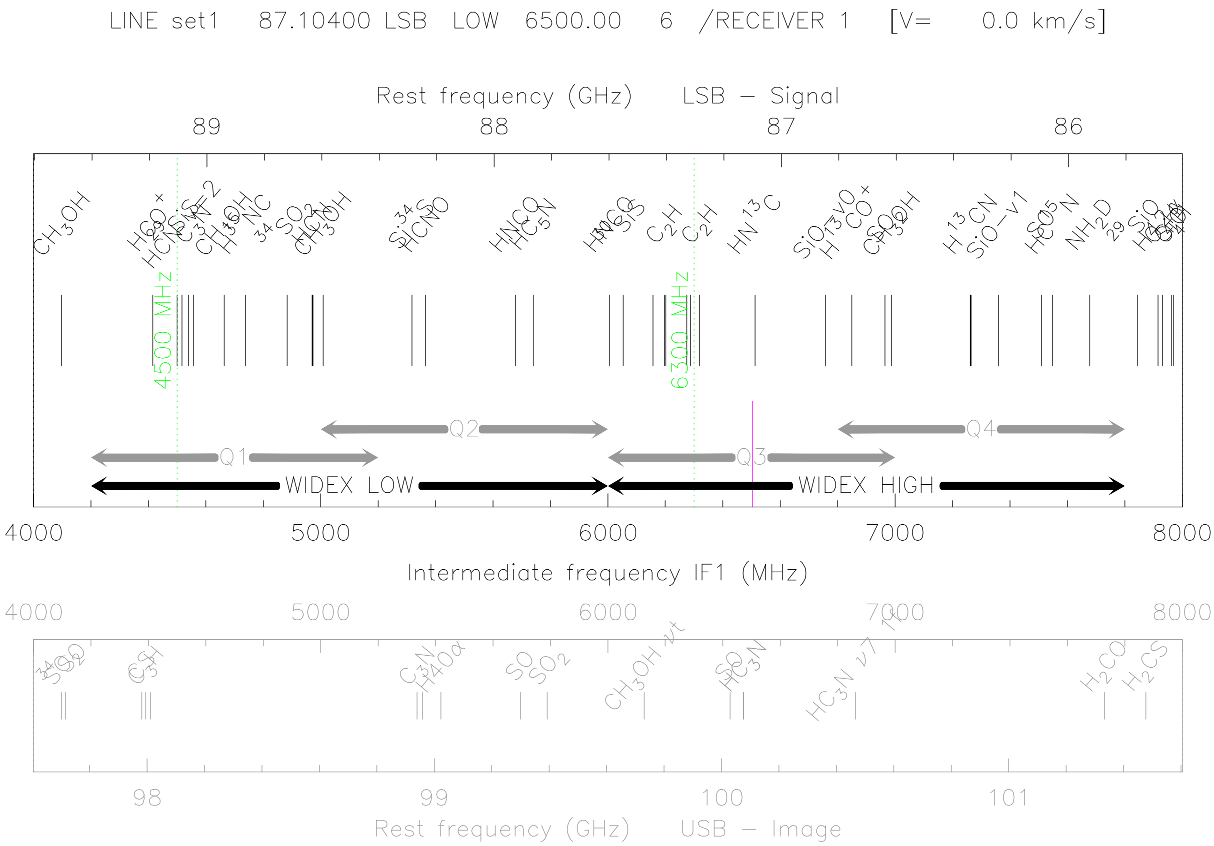

Figure 5: Example of spectral coverage, as produced by the ASTRO `LINE` command. The image band is plotted for information only, the receivers are **single side band**. Possible contamination by instrumental interferences in the signal band are indicated.

How to observe two polarizations? To observe simultaneously two polarizations at the same sky frequency, one must select the same quarter (Q1 or Q2 or Q3 or Q4) for the two narrow-band correlator entries. This will necessarily result in each entry seeing a different polarization. The system thus gives access to 1 GHz $\times$ 2 polarizations.

How to use the full 2 GHz bandwidth of the narrow-band correlator? If two different quarters are selected (any combination except VER VER is possible), a bandwidth of 2 GHz can be analyzed by the narrow-band correlator. Only one polarization per quarter is available in that case; this may or may not be the same polarization for the two chunks of 1 GHz.

Is there any overlap between the four quarters? In fact, the four available quarters are 1 GHz wide each, but with a small overlap between some of them: Q1 is 4.2 to 5.2 GHz, Q2 is 5.0 to 6.0 GHz, Q3 is 6.0 to 7.0 GHz, and Q4 is 6.8 to 7.8 GHz. This results from the combination of filters and LOs used in the IF processor.

Is the 2 GHz bandwidth necessarily contiguous? No. Any combination (except VER VER) of two quarters can be selected. Adjacent quarters will result in a (quasi) continuous 1.8-2 GHz band. Non-adjacent quarters will result in two separate 1 GHz bands.

Table 9: Configurations of the narrow-band correlator units

Spacing (MHz)	Channels	Bandwidth[1] (MHz)	Mode[2]
0.039	1 x 512	20	SSB
0.078	1 x 512	40	SSB
0.156	2 x 256	80	DSB
0.312	1 x 256	80	SSB
0.625	2 x 128	160	DSB
1.250	1 x 128	160	SSB
2.500	2 x 64	320	DSB

[1]: Note that 5% of the passband are lost at both ends of each subband.

[2]: Default mode is `LSB`. There is no practical difference between an `LSB` or a `USB` setting. `DSB Mode` provides twice as many channels as each of the `SSB` modes for the same bandwidth but the central channels suffer from the Gibbs effect. Note, that in this context, "LSB", "USB" and "DSB" have *nothing* to do with the tuning of the receivers; it is just an unfortunate coincidence of the same terms.

Where is the selected sky frequency in the IF band? It would be natural to tune the receivers such that the selected sky frequency corresponds to the middle of the IF bandwidth, i.e. 6.0 GHz. However, this corresponds to the limit between Q2 and Q3. If your project depends on the narrow-band correlator, it is therefore highly recommended to center a line at the center of a quarter (see Section "ASTRO" below). In all bands, the receivers offer best performance in terms of receiver noise and sideband rejection in Q3 (i.e. the line should be centered at an IF1 frequency of 6500 MHz).

2.3.3 Spectral units of the narrow-band correlator

The narrow-band correlator can process the signals from up to 6 antennas. It has 8 independent units which can be placed anywhere in the 100–1100 MHz band (1 GHz bandwidth), by steps of 0.25 MHz. Each unit can be operated in seven modes, as shown in Table 9. Each mode is characterized in the following by couples of total bandwidth/number of channels. In the 3 double-sideband modes (DSB, 320 MHz/128 channels, 160 MHz/256 channels, 80 MHz/512 channels – see Table 9) the two central channels may be perturbed by the Gibbs phenomenon if the observed source has a strong continuum. When using these modes, it is recommended to avoid centering the most important part of the lines in the middle of the band of the correlator unit. In the remaining SSB modes (160 MHz/128 channels, 80 MHz/256 channels, 40 MHz/512 channels, 20 MHz/512 channels) the two central channels are not affected by the Gibbs phenomenon and, therefore, these modes may be preferable for some spectroscopic studies. Because of signal apodization, the effective spectral resolution is slightly broader than the channel spacing (by about a factor 1.6 in the standard case for NOEMA, that uses a Welch time-lag window).

In addition to the spectra produced every integration time (`subscan` in the OBS terminology), the correlator units output every second the visibility for a pseudo-continuum channel created by averaging data from several spectral channels.

The 8 units can be independently connected to the first or the second correlator entry, as selected by the IF processor (see above). Please note that the center frequency is expressed in the frequency range seen by the narrow-band correlator, i.e. 100 to 1100 MHz. The correspondence to the sky frequency depends on the parts of the 3.6 GHz IF1 bandwidth which have been selected as correlator inputs and on the selected receiver side band (LSB or USB): Use the ASTRO software (see Sect. 2.3.4) to display the relation between sky- and IF1 frequencies.

2.3.4 ASTRO

The software ASTRO can be used to simulate these OBS commands. Astronomers are urged to download the most recent version of GILDAS at `../IRAMFR/GILDAS` to prepare their proposals.

- `LINE`: receiver tuning
- `NARROW`: selection of the narrow-band correlator inputs
- `SPECTRAL`: spectral correlator unit tuning
- `PLOT`: control of the plot parameters.

```
ASTRO\LINE name frequency band
```

where

- `name` is a line name to label the plot.
- `frequency` is the rest frequency in GHz.
- `band` is the sideband: LSB or USB.

The setup of the spectral units and the IF processor for the narrow-band correlator is selected by the two commands

```
ASTRO\NARROW Qi Qj /RECEIVER Band_Number
ASTRO\SPECTRAL iunit bandwidth fcent /NARROW Narrow_input -
                                          [/BAND Mode] -
                                          /RECEIVER Band_Number
```

where

- `Qi Qj` are the two 1 GHz wide "quarters" to be analyzed by the narrow-band correlator (see Sect. 2.3.2 for more details).
- `Band_Number` is the receiver band to which the unit should be connected (1 = 3 mm, 2 = 2 mm, 3 = 1 mm, 4 = 0.8 mm).
- `iunit` is the correlator unit number (1 to 8).
- `bandwidth` is the bandwidth of the corresponding correlator unit in MHz (20, 40, 80, 160 or 320).
- `fcent` is the center frequency (in MHz) of the correlator unit in the third IF (100-1100 MHz).
- `Narrow_input` is the IF output (1 or 2).
- `Mode` is used to indicate the sideband code: `LSB`, `USB` (SSB modes), or `DSB`. The DSB mode provides twice as many channels as the LSB or USB modes for the same bandwidth.

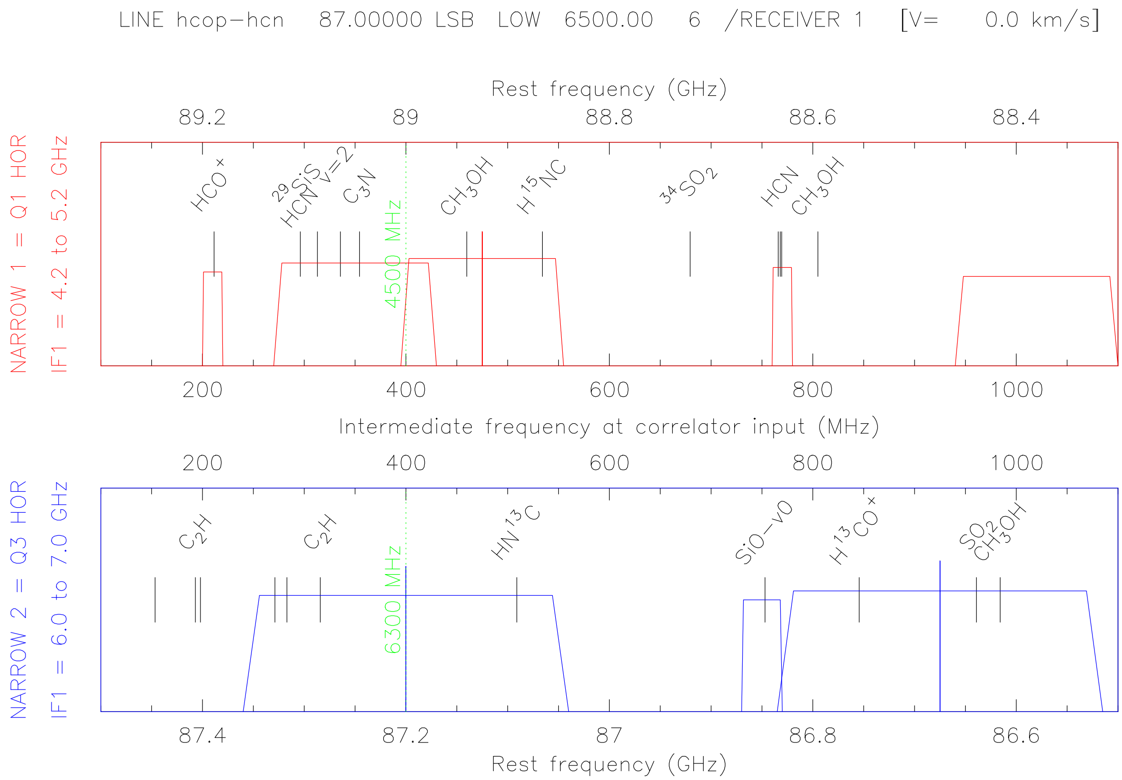

Figure 6: Example of spectral coverage by the narrow-band correlator, as produced by the ASTRO `LINE` command. Possible contamination by instrumental interferences are indicated.

A session to design the above correlator setup could be:

```
LINE HCOP-HCN 87.00 LSB 6500        ! Define the receiver tuning. ASTRO displays
                                    ! the full 3.6 GHz frequency coverage by WideX.
NARROW Q1 Q3                        ! Selects the 4.2GHz - 5.2GHz and 6GHz - 7GHz windows
                                    ! of the 4-8GHz IF1 band. Polarization is HOR HOR.
SPECTRAL 1 160 1020 /NARROW 1       ! Correlator unit #1 covers the [940,1100] IF3 band
                                    ! on the first IF input (4.2GHz - 5.2GHz).
SPECTRAL 2  20  210 /NARROW 1       ! Correlator unit #2 samples a narrow line centered at
                                    ! 210MHz in the IF3 band of the first correlator input.
SPECTRAL 3  20  770 /NARROW 1
SPECTRAL 4 160  350 /NARROW 1
SPECTRAL 5 160  475 /NARROW 1
SPECTRAL 6  40  750 /NARROW 2       ! Correlator unit #6 covers the [730,770] IF3 band on
                                    ! the second IF input (6GHz - 7GHz).
SPECTRAL 7 320  400 /NARROW 2
SPECTRAL 8 320  925 /NARROW 2
```

Fig. 6 displays this example of frequency coverage.

2.4 Sensitivity

2.4.1 Detection experiments

The point source sensitivity (one σ level) for an N_a antenna array, over a bandwidth B in a time T_{ON} is given by

$$\sigma = \frac{J_{\mathrm{pK}} T_{\mathrm{sys}}}{\eta \sqrt{N_a (N_a - 1) N_c T_{\mathrm{ON}} B}} \frac{1}{\sqrt{N_{\mathrm{pol}}}} \tag{1}$$

where

- J_{pK} is the antenna efficiency (Jy K^{-1}) i.e. $2k/(\eta_a A)$ with η_a the aperture efficiency, A the antenna collecting area, and k the Boltzmann constant (22 Jy K^{-1} at 85 GHz, 29 Jy K^{-1} at 150 GHz, 35 Jy K^{-1} at 230 GHz and 45 Jy K^{-1} at 350 GHz). These factors were determined for stable atmospheric conditions.

- T_{sys} is the system temperature outside the atmosphere, i.e. corrected for atmospheric transmission (typically 100 K below 110 GHz, but 180 K (170 K) at 115 GHz, 150 K (130 K) below 150 GHz, 200 K (170 K) above 150 GHz, 250 K (200 K) at 230 GHz, and 500 K (370 K) at 350 GHz in summer (values in brackets are for typical winter conditions)).

- η is a measure of the instrumental and atmospheric decorrelation coefficient, related to the oscillator phase jitter and the atmospheric phase noise, respectively. The instrumental phase jitter increases linearly with frequency. The short and long term atmospheric phase fluctuations depend on the baseline length and water vapor content of the atmosphere. Typical summer (winter) values for η are 0.9 (0.9) in band 1, 0.8 (0.85) in band 2, 0.6 (0.8) in band 3, and 0.5 (0.7) in band 4.

- B is the noise equivalent bandwidth of the correlator in Hz, equal to 1.88 times the channel separation; the effective channel width for standard apodization (using a Welch time-lag window) is 1.60 times the channel separation,

- T_{ON} is the on-source integration time per configuration in seconds (2 to 8 hours, depending on source declination). Because of various calibration observations, the total observing time is typically 1.6 T_{ON}, and

- N_{pol} is the number of polarizations: 1 for single polarization and 2 for dual polarization (see Sect. 2.3.2 for details).

Assuming typical summer conditions at the NOEMA site, 6 antennas, an integration time of one hour in a 3.6 GHz bandwidth and using both polarizations, we find point source sensitivities σ of 0.09 mJy at 90 GHz, 0.19 mJy at 150 GHz, 0.52 mJy at 230 GHz, and 1.61 mJy at 300 GHz. For a full synthesis (e.g., 2 configurations or 10 hours on source), this goes down to about 0.03 mJy, 0.06 mJy, 0.18 mJy, and 0.51 mJy, respectively.

2.4.2 Mapping

The rms brightness temperature is related to the point source sensitivity by

$$\delta T_m = \frac{\rho \lambda^2}{\theta_1 \theta_2} \sigma \tag{2}$$

where λ is the wavelength in millimeters, θ_1 and θ_2 are the beam major and minor axis in arcseconds, σ is the point source sensitivity in Jy, and $\rho \simeq 15$ for untapered maps with natural weighting.

For a typical experiment with configuration BC or CD, tracking the source for 8 hours (but spending 2 hours on calibration) on each configuration, we obtain $\delta T_{BC} = 0.11$ K and $\delta T_{CD} = 0.03$ K, for 0.625 MHz channel spacing with the spectral correlator, with the same assumptions as above at 90 GHz. The factor ρ is increased by uniform weighting and tapering: the amount depends on the uv-coverage and on the phase noise as a function of baseline lengths, but tapering also increases the synthesized beam size.

An equivalent way to look at noise in a map is by comparison to the single-dish sensitivity (given here for position switching)

$$\delta T_s = \frac{2T_{sys}}{\sqrt{BT_{ON}}} \cdot \frac{1}{\sqrt{N_{\rm pol}}} \tag{3}$$

which is typically $\delta T_s = 4.5$ mK in one hour (for a channel spacing of 0.625 MHz and a frequency below 110 GHz).

The mapping sensitivity is roughly related to δT_s by

$$\delta T_m = \frac{\Omega^2}{(\theta_1 \theta_2)} \frac{\delta T_s}{\eta \sqrt{N(N-1)}} \tag{4}$$

where Ω is the size of the antenna primary beam in seconds of arc. Then $\delta T_{CD} = 40 \delta T_s$, $\delta T_{BC} = 190 \delta T_s$, and $\delta T_{AB} = 590 \delta T_s$. In practice, a source that is well detected but unresolved at the 30 m telescope can easily be imaged at NOEMA.

3 Array Operation

Since projects are spread over typically four months, the presence of visiting astronomers when their observations are scheduled is practically impossible to guarantee. In the course of observations and data processing, four "people" will play a role: the `proposal PI (PI)`, i.e. any member of the team that proposed the observations, the `local contact`, the `on-duty astronomer`, an IRAM staff member present on the site, and the array `operator`. The `local contact` is an IRAM astronomer assigned to each project that does not have an in-house collaborator. His/her role is to help the `PI` in preparing the observations and in properly calibrating the data. In case of any problem, question, or doubt, the `PI` should contact his `local contact`. The `PI` can monitor the progress of his project on the web: `http://www.iram.fr/IRAMFR/PDB/ongoing-last.html`; this page is updated three times per day. Note that checking results obtained in a given configuration, making intermediate data reductions, etc. is not the responsibility of the `local contact`. In certain cases, and upon request, remote login to a VISITORS account on the Grenoble computers can be granted to the `PI` to help him in this task.

The array is regularly operated by one `operator` and one `on-duty astronomer`. The `operator` has responsibility for conducting all observations, following pre-established observing procedures or under the supervision of the `on-duty astronomer` in case of unanticipated events. `Operators` have also full authority for all safety measures. Receiver tuning is done by the `operator`. The `on-duty astronomer` must assess the data quality during the observations by monitoring the array performance on standard calibrators. The `PI` usually will not be present on the site, but is expected to come to Grenoble for data calibration, once the project is finished.

3.1 Observations

The PI must specify all aspects of his program in an observing procedure. Standard observations can be made using the general, parametric procedures. An example is given in Sect. 6.

The operator will execute the observing procedure, and the on-duty astronomer will monitor the data quality by examining the observations of phase calibration sources. In the case of peculiar observing conditions (high or exceptionally low phase drifts, calibrators too weak, etc.), the on-duty astronomer has full authority to modify the parameters of the observing procedures. He/She will, of course, try to consult with the `PI` or `local contact`.

Non-standard observations may require a specific arrangement with the `local contact` or `on-duty astronomer`.

3.2 Data Handling

Raw data, corresponding to individual dumps of the correlator buffers are not stored. Instead, a real-time job applies automatic calibrations (clipping corrections, atmospheric model, etc.) before writing on disk. This pre-calibrated data is archived daily, and sorted on a project by project basis.

Except for specific experiments, `PIs` will only have access to the sorted data, which contains the source data and all the calibration measurements acquired by the observing procedure. `PIs` will have exclusive access to their data, but no exclusive rights over the calibration data, which are duplicated in special data files to monitor a posteriori the performance of the interferometer.

Off-line calibration (RF bandpass, phase, flux, and secondary amplitude calibration) is the `PI`'s responsibility. It is possible to recalibrate the data for atmospheric transmission and receiver temperature. Recalibrating the IF bandpass is not possible.

4 Documentation and Help

NOEMA is a complex instrument. Previous knowledge of interferometry is necessary to use it correctly, and reading a standard textbook for this field is highly recommended (e.g., Thompson A.R., Moran J.M., and Swenson G.W., 1986 *Interferometry and Synthesis in Radio Astronomy*, John Wiley & Sons, Eds.). Information specific to the IRAM Northern Extended Millimeter Array (NOEMA) is available on the NOEMA documentation web pages and in the following documents:

- NOEMA ASTRO Users Guide:
  ASTRO is a graphic program to help planning observations. It is quite useful for complex observing programs such as series of snapshots on many sources.

- NOEMA Calibration Cookbook:
  A hitch-hiker's guide to calibrating NOEMA data with CLIC .

- NOEMA CLIC Users Manual:
  Detailed documentation of the off-line calibration program. It assumes the user has previous knowledge of interferometry.

- NOEMA Mapping Cookbook:
  A hitch-hiker's guide to produce and analyze images from NOEMA with the GILDAS software.

- GILDAS Users Manual:
  Documentation of the mapping and display software. GILDAS is an image processing system with many capabilities, and the documentation assumes the user has a basic knowledge of image processing.

Although these manuals are updated relatively frequently, only the on-line help within the programs has the latest revisions.

5 Proposal Preparation

To exploit the full capabilities of NOEMA, proposals must be written with special care. It is of the utmost importance to provide the following parameters:

- A source list with accurate coordinates.
- A source list with velocities and line width for spectral line observations.
- Observing frequencies.
- Required spatial and spectral resolution, and estimate of required sensitivity.
- For special cases: Required accuracy of the bandpass calibration (e.g., a weak line on a strong continuum, high precision relative astrometry).
- Dates to be avoided during scheduling, because of sun avoidance (a circle of 32 degree radius), phase stability requirements (daytime is often difficult in summer), or other reasons (specify).
- Any other stringent constraint (e.g. coordinated observations).

This information is absolutely required to decide about the feasibility of the program, a prerequisite before the program committee can consider the proposal.

5.1 The Proposal Management System (PMS)

Proposals should be submitted through the Proposal Management System (PMS) at URL: http://pms.iram.fr/pms/

The editor of the proposal will have to create a PMS account to be able to login and prepare/submit their proposals. To do so, it is sufficient to click on the URL above and to follow the instructions on-screen that guide the proposal editor through the submission process. The submission procedure consists in filling in an on-line form with the details of the requested observations (source coordinates, receiver setups, array configuration, etc.), and to upload a single file in pdf format containing the scientific and technical justification. A LATEX template is provided from the PMS submission page. This file may be customized, but proposers should respect the following requirements: (1) a normal proposal may contain up to two pages of text describing the scientific aims and technical description (4 pages for a Large Program, see below) (2) you may add up to two pages of figures, tables, and references, and (3) the font size must be 11 pt or larger.

For a proposal to be complete, PMS requires that all authors validate their identity (e-mail and affiliation) and their participation to the proposal before the deadline. PMS will be opened for submission of new proposals about three weeks before the deadline. Proposers may modify their proposals in PMS until the deadline, in which case the proposal has to be resubmitted after its modification. Please avoid last minute submissions when the network could be congested.

6 Observing Procedures

After a proposal has been accepted, observing procedures will have to be prepared. All choices have to be finalized. This implies some additional work with your `local contact`. Non standard observations may require an in-house collaborator.

The following procedure is a standard one, which can be used for "normal" projects (full scale mapping on one object).

6.1 Setup Procedure

The standard setup defines the target source(s), configures the spectral correlator, selects the observing frequency, and leaves the system ready for receiver tuning. WideX is always activated by default, no further settings are required in the observing procedure.

```
!----------------------------------------------------------------------
!
! PR:SETUP-zzzzzzzz.OBS ! Setup procedure for project "zzzzzzzz"
!
!    - Date:          03-feb-2015
!    - Author:
!    - PI:
!    - Local contact:
!    - Project ID:    zzzzzzzz
!    - Verified by:   person (date)
!
!    - Rating:                        A / B
!    - Number of telescopes assumed: 7
!    - Observing mode:                mapping/detection/moving body,track-sharing/mosaic
!    - Observing goal:                'm' lines, 'n' continuum
!    - Time:                          [A,B,C,D,any] Any = CD (specify what 'Any' is)
!
!    - Requested on-source time (h): sum(time)
!
! if 1 source & 1 field, or(!) equal for all fields/sources
!    - Requested sensitivity:         20mJy/80kHz
! if rms different for all fields/sources (i.e. 4 sources)
! order should be same as 'Let name_source' below!!!!
!    - Requested sensitivity:         [20mJy/80kHz,15mJy/80kHz,20mJy/160kHz,10mJy/40kHz]
! or(!) e.g. source 1,3,4 ask same rms
!    - Requested sensitivity:         [(1,3-4) 20mJy/80kHz,(2) 10mJy/40kHz]
!^^ Leave only line that is relevant for this setup. ^^
!
!    - Requested minimum S/N:      (will be filled by IRAM staff)
!
```

```
!    - Water limit:                  (will be filled by IRAM staff)
!    - Obs date constraint:      [dd-Mon-yyyy, dd-Mon-yyyy to dd-Mon-yyyy]
! ^^ enter begin and end date for each observable(!!) time span, or single day
!
!    - Sun avoidance:                dd-Mon-yyyy to dd-Mon-yyyy
!    - Other comments:
!
!-------------------------------------------------------------------------
! Do not edit directly, but copy first then
!
!       1: replace "zzzzzzzz" by the project number
!       2: enter the respective information in the preamble
!       3: for summer projects, replace 'number of telescopes assumed: '7' by '6'
!
!        All lines marked !**! must be customized.
!            lines marked !* ! can be modified.
!
!-------------------------------------------------------------------------
SET\END                           ! Finish previous observation
@ PR:defaults                     ! Restore defaults parameters
!
SET\PROJECT zzzzzzzz              !**! Specify project number for further
!
SYMBOL GO "@ PR:observe-all zzzzzzzz" !* ! data processing
CATA SOU INTER_BASE:iram.sou      !* !
CATA PHA INTER_BASE:phase-pdb.sou !* !
LET RECEIVER 1                    !**! Choose observing receiver: receiver 1 @ 3mm
!                                                                 receiver 2 @ 2mm
!                                                                 receiver 3 @ 1mm
!                                                                 receiver 4 @ 0.8mm
!
LET LOW_LIMIT 15.                 !* ! Low elevation limit 15 degrees
SAY "Project 'PROJECT' starting"  !
!
SYMBOL NAME "NNNN EQ 2000 00:00:00.00 00:00:00.00 LSR 0.0"   !**! Source
!
LET N_SUBSCANS 45                 !* ! Scan length (in seconds)
LET N_SCANS 30                    !* ! Number of scans on SOURCE (22.5 minutes = 30*45sec)
LET N_SOURCES 1                   !* ! use SYMBOL NAME if N_SOURCES.EQ.1
IF (N_SOURCES.GT.1) THEN                    !
  LET NAME_SOURCE[1:N_SOURCES]   ".." ".." !* Enter list of sources (maximum 30)
  LET N_SCANS_SOURCE[1:N_SOURCES] .. ..    !* Enter time per source (in scans)
ENDIF
!
LET CALIBRATOR_1 "......."        !**! 1st phase calibrator
LET CALIBRATOR_2 "......."        !**! 2nd phase calibrator
LET CALIBRATOR_3 "......."        !* ! 3rd phase calibrator (if necessary)
```

```
LET N_CALIBRATORS 2              !* ! Use 2 phase calibrators every N_SCANS
LET N_SUBS_CAL  45               !* ! Scan length on calibrator (in seconds)
LET N_SCANS_CAL  3               !* ! Nb scans on each calibrator (3 scans)

LET FSWI_CAL  .FALSE.            !* ! No fast-switching by default

LET N_MOSAIC 0                   !* ! No mosaic mode
IF (N_MOSAIC.NE.0) THEN
   DEFINE REAL X_MOSAIC[N_MOSAIC] Y_MOSAIC[N_MOSAIC] T_MOSAIC[N_MOSAIC] /GLOBAL
   LET X_MOSAIC .. ..            !* ! offsets in arcsec
   LET Y_MOSAIC .. ..            !* ! offsets in arcsec
   LET T_MOSAIC .. ..            !* ! in units of N_SUBSCANS
ENDIF
!
LET SOLVE_POINT YES
LET SOLVE_FOCUS YES
!
LET FOCUS_RECEIVER 'RECEIVER'    !* ! Focusing on observing receiver
LET POINT_RECEIVER 'RECEIVER'    !* ! Pointing on observing receiver
!
LET SOLVE_POLAR "B"              !* ! Solve point on Polar: B=both, V, or H
!
IF (RECEIVER.EQ.4) THEN
  LET T_POINT 0.33
ENDIF
!
LET POINT_SOURCE_1 "......."     !**! 1st pointing source
LET POINT_SOURCE_2 "......."     !* ! 2nd pointing source
LET FOCUS_SOURCE_1 "......."     !**! 1st focusing source
LET FOCUS_SOURCE_2 "......."     !* ! 2nd focusing source
!
SET\UNLOCK
!
@ PR:spec-defaults               ! define standard correlator setup
!
NARROW Q3 Q3 /REC 'RECEIVER'     !**! Define quarters to be connected to
!                                     the two correlator inputs of the NARROW BAND
!                                     CORRELATOR @ the chosen receiver band
!
SPECTRAL 1 320  260 /NARROW 1 /REC 'RECEIVER' !**! Define correlator configuration
SPECTRAL 2 320  480 /NARROW 1 /REC 'RECEIVER' !**! Define correlator configuration
SPECTRAL 3 320  710 /NARROW 1 /REC 'RECEIVER' !**! Define correlator configuration
SPECTRAL 4 320  940 /NARROW 1 /REC 'RECEIVER' !**! Define correlator configuration
SPECTRAL 5 320  260 /NARROW 2 /REC 'RECEIVER' !**! Define correlator configuration
SPECTRAL 6 320  480 /NARROW 2 /REC 'RECEIVER' !**! Define correlator configuration
SPECTRAL 7 320  710 /NARROW 2 /REC 'RECEIVER' !**! Define correlator configuration
SPECTRAL 8 320  940 /NARROW 2 /REC 'RECEIVER' !**! Define correlator configuration
```

```
!
LINE xxxx yyyy LSB 6500 /REC 'RECEIVER'    !**! Define observing frequency
!
IF (N_SOURCES.GT.1) THEN
  SOURCE 'NAME_SOURCE[1]' /TYPE OBJ
 ELSE
  SOURCE 'NAME' /TYPE OBJ
ENDIF
!
SET\RECE 'RECEIVER' /POLAR 'SOLVE_POLAR' ! Choose receiver band for the observation
!
SET\OBS
!
LOAD /FREQUENCY                          ! Load frequency, but don't move antenna now
!
! Make sure any changes in the spectral configuration will be detected:
SET\LOCK
!
LET CHANGE_SPECTRAL .FALSE.       !* ! .TRUE. if need to switch to broad_band
!
IF (CHANGE_SPECTRAL) THEN
   SPECTRAL /BROAD
ENDIF
!
SET SHOW OFF
!
TYPE PR:clean.obs
SAY "Project zzzzzzzz   Type: Detection  /  Category: 3mm, dual polarization" !**!
SAY " "
SAY "        Tuning Receiver "'RECEIVER'":             LSB           " !**!
SAY " "
!
! Insert here any other instructions to the operator/astronomer
!
SAY "Frequency sent, receivers may be tuned"
SAY "Execute all observations by typing GO"
SAY " "
SAY "Type END when project is finished"
SAY " "
SYMBOL PROCEED /INQUIRE "Type RETURN to remove this page: "
SET SHOW ON
SET SHOW ON
```

All information appearing on lines marked `!**!` must have been supplied in the observing proposal, lines marked `!* !` will use default values if not specified. The remaining part of the procedure will be defined by IRAM personal (your `local contact`, usually). The project number (zzzzzzzz in this example) is assigned by IRAM when observing proposals are received.

After final checking by IRAM staff, this file will be given to the `operators`, together with a copy of the proposal and any accompanying information the `PI` may find useful. This small "dossier" will be updated by the `operator` and `on-duty astronomer` during observations, and a copy of it will be given to the `PI` when he/she visits Grenoble for data reduction after the project is completed. In particular, the `on-duty astronomer` will fill in a `NOTE file` that summarizes the individual conditions and particular problems encountered during each track observed. The `NOTE file` will provide some suggestions in cases where the data calibration is not straight-forward.

6.2 Phase Calibrator List

The current list of phase calibrators used at NOEMA includes over 3000 objects. Flux densities at 85 GHz are indicated in Jy. The flux density is followed by the spectral index, by the flux at 230 GHz if measured, or 0 if no measurement is available. The last column gives the date, at which the flux has been measured. Be careful: most if not all sources are variable (both flux and spectral index vary). All coordinates are equatorial J2000.0. Bandpass calibrators should be selected among the strongest phase calibrators, 4 Jy or more if possible, but even 0.3 Jy (at the designated observing frequency) sources are sufficiently strong as phase calibrators.

The planets are not sufficiently point-like to be used as bandpass calibrators in any configuration.

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