# First proof of concept of the Nanocosmos project: a gas chamber at the 40m RT

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# Revision history

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# Contents

# 1 Introduction

We describe a proof of concept of the Nanocosmos project tested at the 40 m radiotelescope in September 2015. Nanocosmos will study the physical and chemical processes that lead to the formation of cosmic dust. Several simulation chambers will be built to study the precursors of the dust grains, gas-grain interactions, processing and spectroscopy. The conditions in these chambers will try to mimic the environment of evolved stars. The proof of concept described in this report consisted in installing a gas chamber in the path of radiation of the 40 m radiotelescope to detect the emission from molecules in the 41-49 GHz band using standard astronomy receivers. Tests were performed between September 21st and October 1st and lasted several days.

The main goal was to detect radiation from a chamber at ambient temperature and a cold background. We also wanted to test all the equipment and its setup, the data aquisition process and reduction software, to find out the problems which arise and how to improve and optimize the whole process.

# 2 The emission of radiation in the chamber

Molecules in the chamber emit spectral radiation from rotational transitions in the millimeter wavelength range. This spectral radiation can be detected if the molecules in the chamber are at physical conditions similar to the interstellar medium. Ideally the background radiation should come from a blackbody with a very low temperature if the lines are to be seen in emission. According to the transport radiation equation the antenna temperature should be given by:

$$T_a(f) = T_{ex}\,(1 - e^{-\tau(f)}) + T_{bg}\,e^{-\tau(f)}$$

$\tau$ is the opacity of the media which depends on the frequency $(f)$, $T_{ex}$ the excitation temperature of the molecule for the transition being observed and $T_{bg}$ the background temperature. In the chamber, the excitation temperature, $T_{ex}$, is approximately the environment temperature because the molecule gets thermalized via collisions due to the large density in the cell.

To mimic the column density from a typical interstellar cloud, the projected density should be approximately $10^{17}$ particles/cm$^{-2}$. This is achieved for pressures close to $10^{-1}$mbar. According to the equation of ideal gases, 1 mol is approximately 22.4 L for 1 atm of pressure and T = 273 K. Although the temperature was approximately 293 K, and the volume was $\sim$ 25 L, we can assume that in the chamber there were approximately $6\,10^{23}$ molecules. The projected column per cm$^{-2}$ is the number of molecules divided by the surface of the windows. If the window diameter was 25 cm then the projected density would be $\sim 10^{21}$ particles/cm$^{-2}$ for 1 atm of pressure. To have $10^{17}$ molecules/cm$^{-2}$, the pressure should be 0.1 mbar approximately.

Initial tests were performed at pressures from $10^{-4}$ to 1 mbar to detect the lines of three different molecules.

The procedure to obtain line emission from molecules consists in performing a scan composed of two phases: ON, with the gascell full, and OFF, with the gascell empty, and substract both voltages. In temperature scale that is:

$$T_l(f) = T_{on} - T_{off} \quad = \quad T_{ex}\,(1 - e^{-\tau(f)}) + T_{bg}\,e^{-\tau(f)} - T_{bg}$$

$$= \quad (T_{ex} - T_{bg})(1 - e^{-\tau(f)})$$

According to the previous equation the line temperature will increase as $T_{bg}$ decreases. Therefore the background load should be chosen to have the lowest possible temperatures.

The acquisition procedure does not measure temperature but voltages. In order to convert from voltage to temperature a calibration scan is required. The calibration scan is composed of two phases: measuring the voltage towards a hot and towards a cold load of known temperature.

$$V_{hot}(f) = kT_{hot}(f) + V_0$$
$$V_{cold}(f) = kT_{cold}(f) + V_0$$

When measuring with the gas cell in each phase the temperature can be obtained using the voltages measured in the calibration scan. For example, the antenna temperature in the ON phase would be:

$$T_{on}(f) = V_{on}(f)\frac{T_{hot} - T_{cold}}{V_{hot}(f) - V_{cold}(f)}$$

The same conversion is used to obtain the temperature in the OFF phase. The calibration and onoff reduction procedures are managed by the software as it will be dicussed in section 5.

# 3 Mechanical setup at the telescope

The gas cell was mounted on the 45/22 GHz optical table, which holds the K and Q band receivers, the mirrors and the hot load. The hot load was dismounted to give space for the gas chamber. The gas cell location was chosen to be where the gaussian beam narrows to its minimum width. This allowed to keep the size of the windows to a reasonable size.

Fig. 2 shows a picture of the installation together with a simple sketch of the radiation path from the sky, and from a cold load, towards the 45 GHz receiver.

## 3.1 The mixing chamber

The gas cell is filled with gases from a mixing chamber which contains several input/outputs controlled by manual cut-off valves. The mixing chamber is a horizontal cylinder with an input/output connected to the vacuum pump and a second connection to measure the pressure. It also has an output that connects to the gas chamber. Besides there are more than 4 inputs for gases in liquid state, stored in small metalic cylinders at high pressure and for gases in gas state. The pressure inside the mixing chamber can be controlled manually with the cut-off valves.

## 3.2 The gas cell

The gas cell is a cylinder with two windows in both ends. The windows are not parallel (see Fig. 3 upper view) to avoid standing waves between them. The outer dimensions of the windows was 25 cm and the inner 21 cm. The length of the cell was 42 cm along its shortest distance and 45 cm along its longest one.

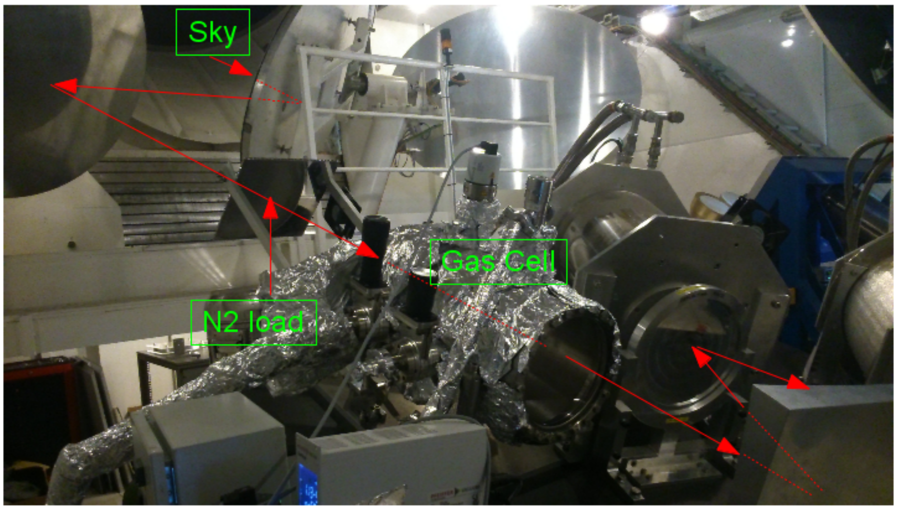


Figure 1: *Gas cell mounted in the optical table of the 40m radiotelescope. The chamber was wrapped with an aluminium foil that later was removed.*

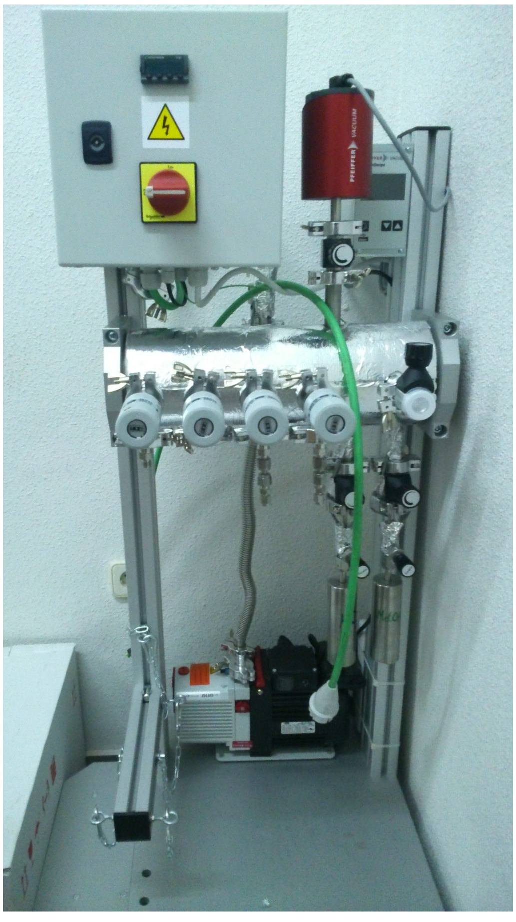

Figure 2: *Gas cell: mixing chamber*

The cell has two input/outputs on top of the cylinder for connecting a pressure meter and a security valve. Two more connections were on one side: the input for injecting gases and an output for extracting them. Gases were expelled in the receiver cabin.

Figure 3: *Gas cell with Quartz windows. Left panel: front view. Right panel: upper view.*

### 3.3 The windows

The gas chamber was used with two types of windows: Quartz and Kapton windows. Both windows are attached to both ends of the chamber using a number of screws, with an O-ring that allows to keep the vacuum inside the cell. Quartz windows are 9 mm thick whereas Kapton windows were 70 $\mu$m thick. The latter get deformed towards the inside when the air is pumped out the cell. The vacuum was tested increasing progessively its value when using the Kapton windows since there was a risk that the material broke under the pressure of the atmosphere.

### 3.4 Preparing the cell: heating

Prior to the experiments the gas chamber was wrapped with an aluminium foil and heated to 100 C to evaporate gases sticked on the walls and the windows. The main purpose was to remove water molecules. The chamber once heated required several hours to attain the ambient temperature. Once the temperature stabilized vacuum was applied to remove molecules inside.

## 4 Data acquisition

The 45 GHz receiver has an instantaneous band of 8 GHz between 41 and 49 GHz. The Intermediate Frequency (IF) provides two pairs of signals in right circular polarization (RCP) and left circular polarization (LCP) of 500 MHz and 2000 MHz band. During the tests the LCP showed some problems related to the gain in the IF stage. The 2 GHz band signal was not usable either. Therefore all results described in this report rely only on the 500 MHz wide band in RCP.

The data acquisition was performed with a Fast Fourier Transform Spectrometer (FFTS) with 8 modules. We only used modules 3 and 4, which are configured to deliver 16384 channels and a spectral resolution of 30 KHz. The integration time was set to 5 seconds, which is the highest value available for the FFTS. Module 3 was connected to the RCP IF output of the 45 GHz receiver and module 4 to the LCP IF output.

Integration times higher than 5 seconds were achieved by repeating the basic integration interval up to the desired value. To avoid gain changes from the receiver and the IF chain the maximum integration time was set to 40 seconds. Cycles were typically composed of 4 subscans: OFF, ON, ON, OFF. Each subscan lasted 40 seconds. The OFF subscans were obtained with the cell empty (pressure in this case was approximately $10^{-4}$ mbar). The ON subscans were performed with the gas cell filled with gas at different pressures, some of which are listed in tables 7.1 and 7.2

We used two types of background loads: a liquid nitrogen load and the sky. The latter case was used with good weather conditions: clear blue sky and the antenna pointing towards the zenith. The nitrogen load is approximatey 70 K whereas the sky is approximately 42 K at 44 GHz.

The gain of the IF was modified automatically for every observing frequency to generate an adequate level for an optimum sampling of the data in the FFTS.

Calibration was done with the gas cell empty. The procedure consisted in a scan composed of two subscans: a cold load at the back of the gas cell and a hot load at that same position. In both cases, the loads generate radiation that crosses the chamber and reaches the receiver.

# 5 The gascell line command shell

The control and acquisition of data is managed from an iPython shell called “gascell”. This line interface, developed in house, is an ACS client that is used to set the receivers, the FFTS backends and gets information from the weather station and the atmosphere component which provides the temperature and opacity of the sky. The “gascell” application also generates raw and reduced spectra and can be used to reanalyze old data.

“gascell” uses projects to store and classify the results. Every project is associated to a folder under the *project* directory. In each project there can be several folders tagged with its date. Each directory hosts several kind of files: ASCII files which contain the spectral power distribution for each subscan and RAW data for each of these subscans written as CLASS spectra. These spectra have been neither calibrated nor get the OFF subscan substracted. RAW data can be used to perform operations by hand and check that the automatic reduction process works as expected. The directory also contains a CLASS file with the final product: spectra averaged and calibrated.

A typical session with “gascell” would be like below:

```
gascell> project_id('GC-085-2015', True)
```

```
gascell> receiver("het45", freqMHz=48034.412, line='H2O2')
gascell> backend([3,4])
gascell> cal(5.0, pauseNeeded=True, coldSkyOrN2='Sky', press=0.1)
gascell> offonoff(5.0, reps=8, dec=1, pauseNeeded=True, press=0.1,
            coldSkyOrN2='sky')
```

- `project_id()` command sets the name of the project. All data will be stored in a directory with that name until a new project is defined. The directory will be created if it does not exist.
- `receiver()` command sets the observing frequency and the name of a line to be written in the spectrum header. The system also sets the appropiate IF attenuation per frequency setup.
- `backend()` command connects the selected FFTS modules to the receiver.
- `cal()` command sets the integration time for each subscan and specifies that a pause is needed to give time for the operator to change the loads. This command also allows to specify if the cold load is Nitrogen or the sky.
- `offonoff()` command also allows to have a pause between the subscans. The basic integration time is defined as well as the number of repetitions. In this case the FFTS integration time is set to 5 seconds and this is repeated 8 times. It is possible to use decimation to discard integrations. Since the pressure in the chamber cannot be read automatically, this parameter has to be entered using a parameter. As with the previous command it is also necessary to specify the cold load used.

All relevant information required to uniquely identify the observations is stored in a MySQL database. This information is used by "gascell" for some operations. For example, the last calibration scan closest to the spectra is used to calibrate the spectra.

# 6 Estimating the performance of the gas cell windows. System temperature

The gas cell was equipped with two windows, in principle transparent to millimeter radiation, at its both sides. As already mentioned in a previous section, two materials were used: Quartz and Kapton. We checked the performance of the windows across the band for both cases. The results are displayed in Fig. 4. This figure represents the system temperature $T_{sys}$ versus frequency.

Data were obtained by observing every 500 MHz from 41 to 49 GHz and later stitching all bands together. The acquisition cycle consisted in looking towards the sky with the gas cell empty and later to a hot load in front of the receiver. The sky temperature was estimated from a model of the atmosphere, the elevation of the antenna (88 degrees in all cases) and an assumed forward efficiency of 95%. The hot load temperature was the environment temperature at the receiver cabin which is constantly monitored by a probe. To reduce the number of channels,

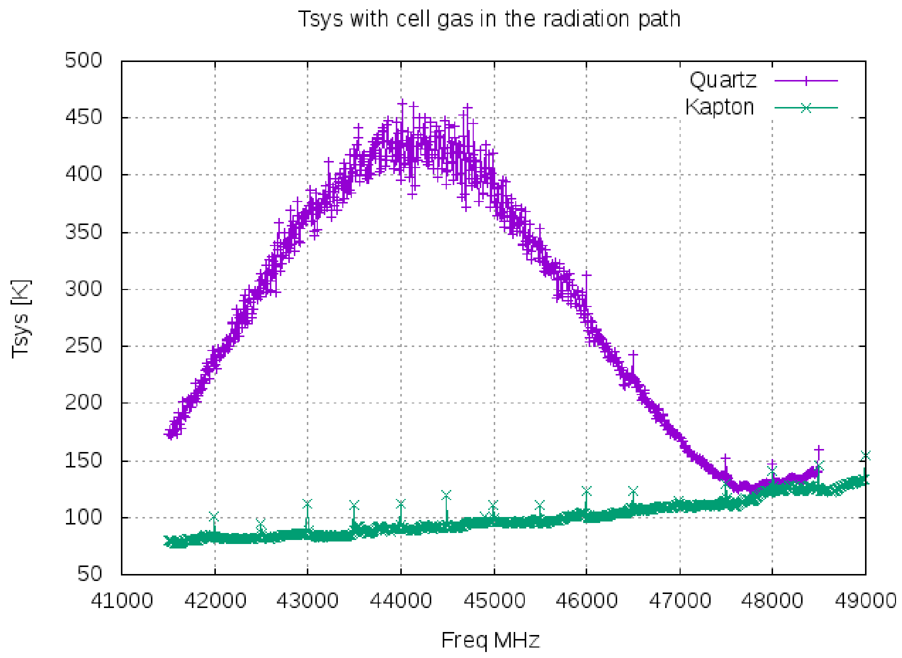


Figure 4: *System temperature across the band with the cell gas empty. Two cases were considered: Quartz windows and Kapton windows. The spikes every 500 MHz are not real and come from the borders of the backend and the concatenation of spectra.*

16384 every 500 MHz, the spectrum was smoothed averaging channels in groups of 256. This allowed to reduce the spikes, still visible in Fig. 4, in between the 500 MHz bands.

Results show that Tsys is much higher when using Quartz windows than Kapton windows. There is a maximum at 44 GHz and two minima: at 47.5 GHz and another one which is guessed, at 41 GHz. The maximum, 450 K, shows an RMS much larger than the minimum, a consequence of that high system temperature. It is obvious that the best conditions to observe lines are close to the minima. The Kapton windows show a much better behaviour: a slow drift in which Tsys goes from 80 to 130 K in 8 GHz. Higher Tsys at high frequencies come from the sky temperature and the receiver being noisier at the higher end.

We believe that the previous behaviour is caused by standing waves ....

Discussion here................

# 7 Results

Tests were performed filling the gas cell with methanol ($CH_3OH$), ethanol ($C_2H_5OH$) and acetone ($CH_3COCH_3$) under different conditions. The first two molecules were detected. Acetone was not detected for the pressure conditions we used: 10 mbar, 1 mbar and $10^{-4}$ mbar. In the next subsections we discuss the results for methanol and ethanol

## 7.1 Methanol

Fig. 5 shows $CH_3OH$ line profiles at 44069.15 MHz for different pressures in the gas chamber. All spectra, except the one for 0.01 mbar, were obtained after an integration time of 80 seconds. The two ON subscans were 40 seconds each and were performed after 8 repetitions of 5 seconds FFTS periods. The two OFF subscans were also 40 seconds each. The spectra for 0.01 mbar were obtained after an integration time of 880 seconds.

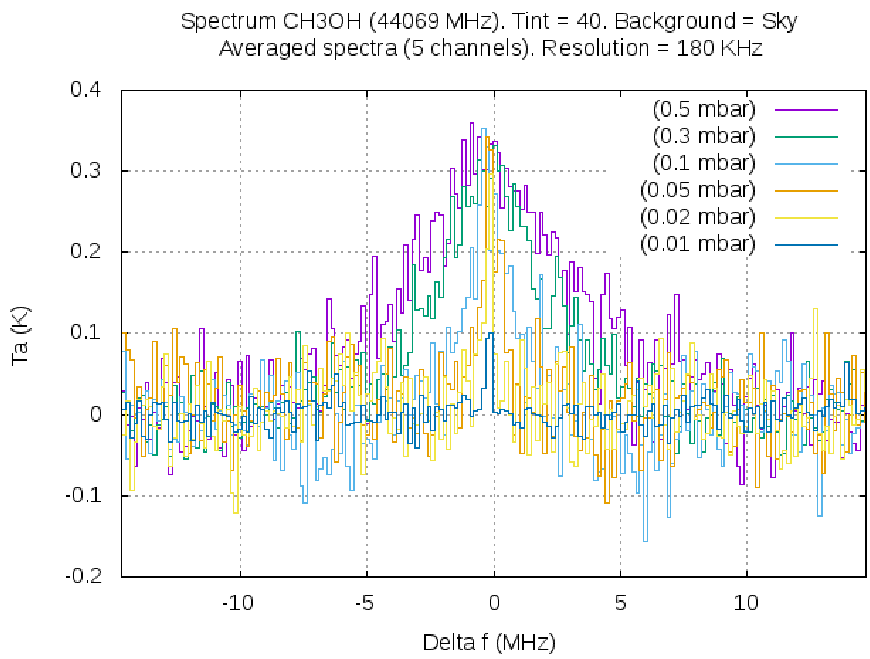


Figure 5: *$CH_3OH$ line profiles for different pressures in the gas cell. The spectra have been smoothed by a factor 5 and the final frequency resolution is 150 KHz*

Spectra were clearly visible between 0.5 mbar and 0.01 mbar. The intensity and width of the lines drop dramatically for pressures below 0.01 mbar. On the other end, lines for pressures larger than 0.5 mbar are very wide and hard to identify if the baseline is not flat. Table 7.1 summarizes the basic parameters obtained from gaussian fits for different gas cell pressures. Figs. 6 show the same results graphically.

## 7.2 Ethanol

Ethanol was observed with a liquid nitrogen load as background and the baselines of the spectra are worse than in the case in which the sky was used as background (see next section).

Fig. 7 shows spectra from $C_2H_5OH$ for 3 different gas cell pressures: 0.01 mbar, 0.1 mbar and 0.3 mbar. The integration time was 11 minutes for 0.01 mbar, 160 seconds for 0.1 mbar and 320 seconds for 0.3 mbar. The line is detected in the first and in the latter case. The lack of detection for 0.1 mbar might be caused by a wrong operation when filling or emptying the gas cell or to an unknown cause.

| **Pressure mbar** | **Width MHz** | **Intensity (K)** |
|---|---|---|
| 0.5 | 8.7 | 0.30 |
| 0.3 | 6.2 | 0.28 |
| 0.1 | 2.5 | 0.26 |
| 0.05 | 0.9 | 0.27 |
| 0.02 | 0.4 | 0.27 |
| 0.01 | 0.2 | 0.13 |

Table 1: *Intensity and width of the $CH_3OH$ line at 44069.15 MHz for different pressures of the gas cell. Fits were obtained within CLASS and without smoothing the spectra*

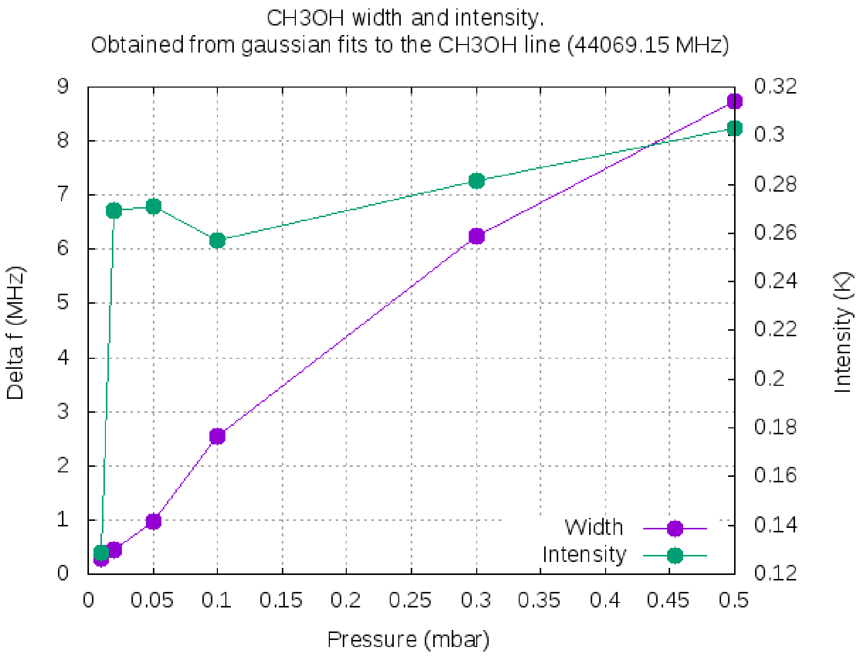


Figure 6: *Width of the $CH_3OH$ line versus pressure in the gas cell (purple line) and intensity versus pressure (green line). The green line is referred to the right Y axis.*

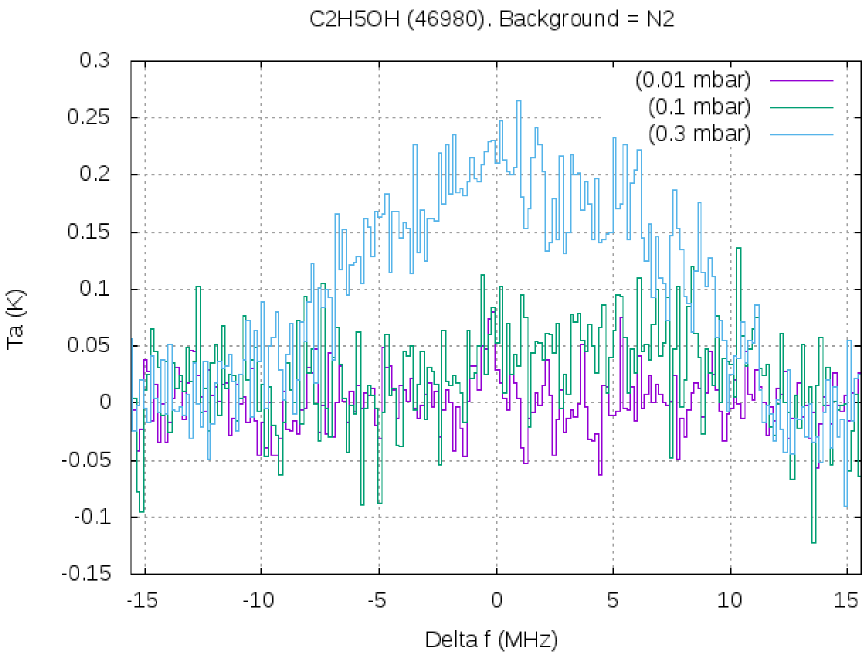


Figure 7: *$C_2H_5OH$ line profiles for different three pressures in the gas cell. The spectra have been smoothed by a factor 5 and the final frequency resolution is 150 KHz*

Fig. 8 shows the spectra of $CH_3OH$ and $C_2H_5OH$ together for two different pressures. The spectra obtained for 0.01 mbar have not been smoothed and we show the original frequency resolution. The line width for $C_2H_5OH$ is larger than for $CH_3OH$ in both cases. In the lower pressure regime the width is mainly due to thermal broadening and at high pressure the width is dominated by pressure broadening.

| **Pressure mbar** | **Width MHz** | **Intensity (K)** |
|---|---|---|
| 0.3 | 13.2 | 0.52 |
| 0.1 | — | —- |
| 0.01 | 0.8 | 0.07 |

Table 2: *Intensity and width of the $C_2H_5OH$ line at 44698 MHz for different pressures of the gas cell. Fits were obtained within CLASS and without smoothing the spectra*

## 7.3 Background loads

To compare the quality of the background we tested both the sky, while the antenna was stopped at 88 degrees elevation and excellent weather conditions, and a load of liquid $N_2$. The load consisted in a big cylindric container, approximately 80 cm diameter, with liquid nitrogen, on top of a support on the receiver cabin floor. Radiation was directed to the load using a mirror.

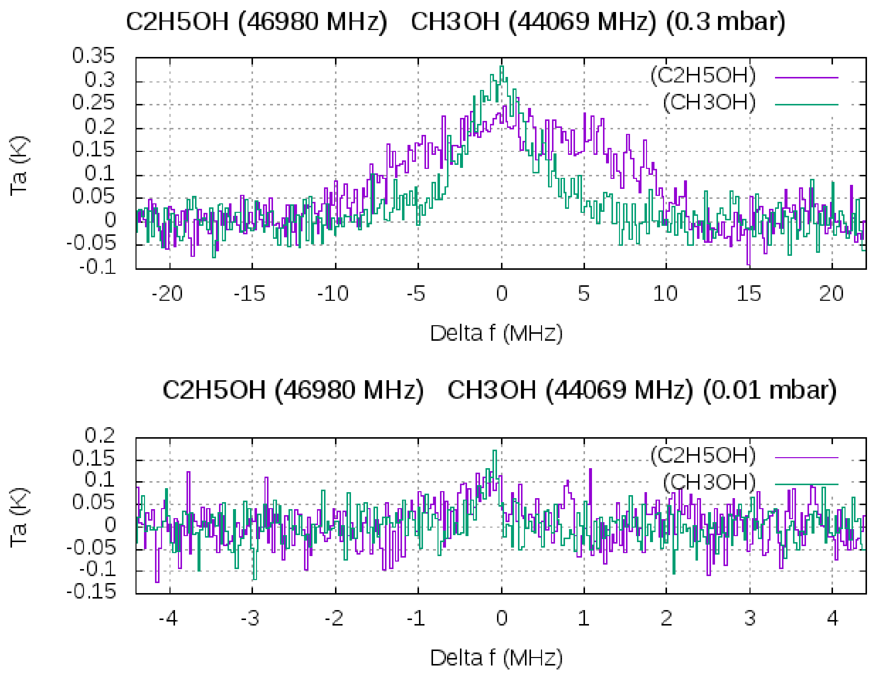


Figure 8: *$C_2H_5OH$ and $CH_3OH$ line profiles for two different pressures in the gas cell. The spectra at 0.01 mbar have not been smoothed in frequency*

The mirror had a fan that blowed the mirror from one side to avoid condensation of water vapour from the environment.

Fig. 9 shows the spectra obtained in both cases. The scan consisted of 4 subscans: OFF, ON, ON, OFF, each of them lasting 40 seconds. Conditions were the same in all subscans and therefore the spectra should show a line centered in 0 with its typical noise. The result from the case in which the sky was used as background is as expected. A small absorption is seen, probably due to RFI. The result from using $N_2$ is worse than expected, showing ripples in the baseline, probably caused by standing waves in between the load and the horn. The standing waves are variable with time and may come from vibrations on the surface of the nitrogen, perhaps transmited from the floor.

Ripples in the baseline are a nasty effect which may hamper the detection of wide line profiles. Ideally the baseline should be totally flat.

# 8 Conclusions

Tests performed at the 40m radiotelescope were successful and unveiled a number of problems that need to be addressed in the future.

- The usage of a background load in the lab has to be carefuly studied and implemented to avoid bad spectral baselines with ripples. Wide lines require flat baselines..
- It is highly desirable to automate the data acquisition process. Human intervention should

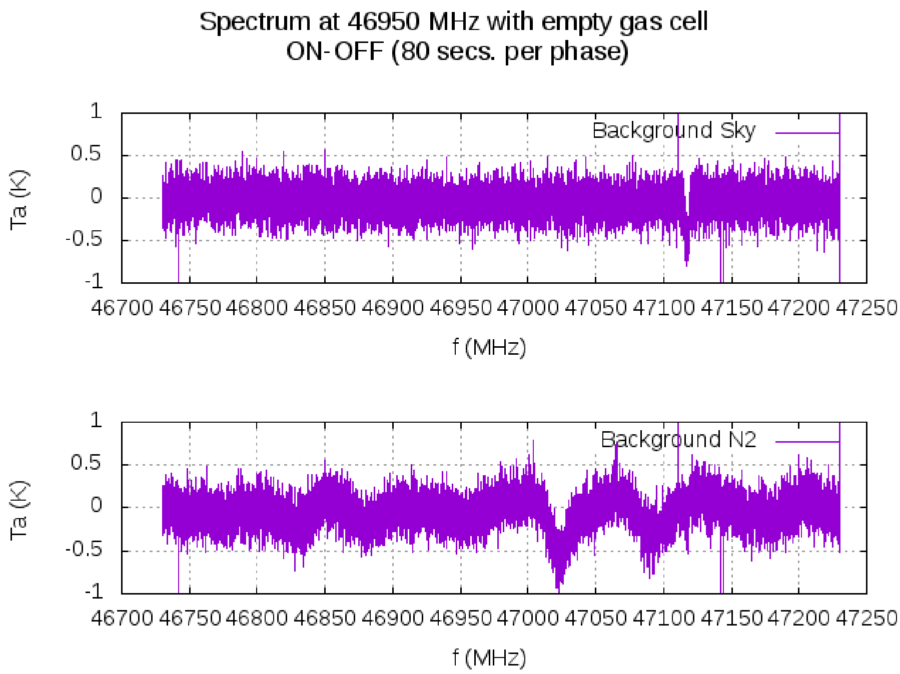


Figure 9: *Spectra after an OFF-ON-ON-OFF scan. Each phase lasted 40 seconds. The background was the sky (upper panel) and a load of liquid $N_2$ (lower panel)*

be avoided in the calibration and onoff procedures. That will require a remotely controlled hot load. It will also require a solution for switching between the off and the on phases.

- Pressure broadening should be taken into account for choosing the optimum pressure in the chamber.
- Pressures in the gas cell should be read automatically. This will require some software development.
- Other molecules with higher intensities in the observing range should be tested. Linear molecules are good candidates but they should be carefully handled if they are toxic.
- Tests with FFTS equipped with several modules to obtain a large instantaneous bandwidth should be performed. New software development is required in this case.