A Multi-path Far-Infrared and Sub-millimetre Gas Cell for Spectral Tests of Herschel/HIFI

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Abstract – We present the design and operation of a gas cell developed in the framework of the Herschel/HIFI instrument-level ground-based test campaign. This cell is aimed at acting as a representative spectral source by feeding the system with signal from molecular lines excited by radiometric loads. Its main goal is to measure the sideband ratio of the double-side-band mixers used in the HIFI instrument. The design makes use of multiple reflection optics to increase the total path length through the gas sample while keeping the overall device size into reasonable limits. The system is operated under vacuum to get rid of any water line absorption along the line of sight. It offers a front-to-end 1:1 optical magnification and is designed to keep the beam waists within a $4w$ criterion for the HIFI test setup case. We present the first outcomes of the current test measurements at the SRON premises in Groningen.

I. INTRODUCTION

HIFI (the Heterodyne Instrument for the Far-Infrared) is one of the three instruments to be launched on the Herschel Space Observatory (HSO) and will operate between 160 and 625 microns (480-1910 GHz). The detectors used in this instrument are based on the heterodyne mixer technology (SIS and HEB) and have the particularity to work in Double Side-Band mode (DSB). Each of these side-bands will contribute to the final spectra with a given gain, which may be strongly frequency-dependent along the mixer tuning range. Observational techniques exist to restore the signal detected in each of the bands but they cannot provide estimates of the side-band ratio (ratio between the gains of the two respective bands) to the accuracy required for the HIFI calibration. In the framework of the AIV/ILT (Assembly, Integration and Verification / Instrument Level Tests), dedicated measurements need to be performed on the HIFI development and flight models.

Several options can be considered to measure the side-band ratio. One common practice consists in using absorption cells filled with adequate gases for the frequency range of interest. This system proved to be very efficient during the SWAS [1] and Odin [2] test phase and allowed to check several detector characteristics (e.g. side-band ratio, mixer compression). It has the additional advantage to provide simulation of astrophysical spectra to the integrated instrument and to test many of the observing modes and reduction schemes. In particular it should help to validate dedicated algorithms to deconvolve the signal between the two side-bands. Alternative systems exist, mostly based on Fabry-Perot or Fourier-Transform spectrometers. They have the advantage to provide as many frequency measurement points as required (monochromatic signals), but are more expensive, hard to calibrate and significantly complex and time-consuming to design.

II. THE LESSONS FROM SWAS

Design recommendations can be found in a report by R. Schieder on gas cell measurements for SWAS tests [3]. The cell should be sufficiently long (30-100 cm) and filled with a gas which provides saturated lines. The pressure should be relatively low (undefined but typically a few mbar) but higher pressures might help to saturate lines with blended structures. The measurements are performed against hot and cold loads which look through empty and filled cells for calibration purpose. Glass cells seem more suitable

than metal cells because molecules are expected to stick more in the later case. The cell window, preferably made of Teflon to avoid internal fringes, shall be tilted to reduce standing waves. The absorption by water vapour along the light pass significantly affects the measurements. Vacuum isolation is not mandatory but dry air conditions would be required in the frequency range of interest (480 to 1910 GHz). Fig. 1 illustrates the expected water vapour spectral contamination for a 1 meter path computed with the ATM software [4].
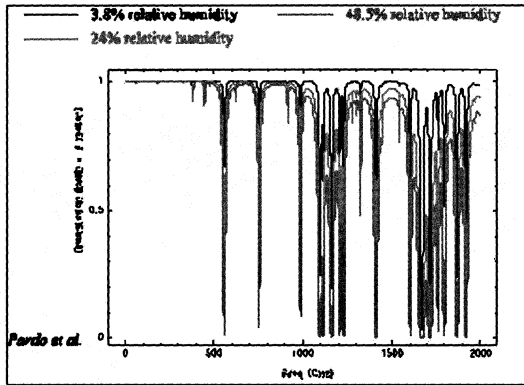

Fig.1: Computed water vapour absorption along a 1 meter path in the 0 to 2000 GHz frequency range (courtesy of Pardo). The transmission is computed for three values of the relative humidity. It shows that spectral measurement above 1 THz requires perfectly dry air conditions.

III. PRINCIPLES

In a given LO (Local Oscillator)- and mixer bias-setting, the side-band ratio measurement is based on the comparison of two signals taken successively through a filled and an empty cell. The measurements are performed against hot and cold loads, and the differential signal, if done fast enough, should be free from system noise contribution. The frequency range is chosen such that an absorption line affects only one of the side-bands and can be compared to the absolute continuum level. The following equations illustrate the basics for the ratio derivation and allow to assess the accuracy of a measurement. We assume that an absorption line (of opacity τ) is seen in the lower side-band, while the spectra in the upper side-band is not affected by any spectral feature. The differential measurements are then respectively:

$$S_{filled} = G_u(J_{hot} - J_{cold}) + G_l(J_{hot} - J_{cold})e^{-\tau}$$

and

$$S_{empty} = G_u(J_{hot} - J_{cold}) + G_l(J_{hot} - J_{cold})$$

where G_u and G_l stand for the upper and lower side-band gains respectively, including all transmission elements along the optical path, and J_{hot} and J_{cold} are the effective (Rayleigh-Jeans) hot and cold load temperatures of a black body of temperature T and frequency ?.

Using the measurements described above, the side-band ratio is finally given by:

$$R_G = \frac{G_l}{G_u} = \frac{1 - S_{filled}/S_{empty}}{S_{filled}/S_{empty} - e^{-\tau}}$$

The opacity needs to be accurately known, unless the line is saturated (high τ), in which case R_G simply writes $S_{empty}/S_{filled} - 1$. Typically, a side-band ratio of unity would be observed for $S_{empty}/S_{filled} = 0.5$ at the line peak position, i.e. an absorption line of half the continuum level in a normalized spectra.

Based on this simple formalism, the measurement accuracy depends on the accuracy of the opacity knowledge (if lines are not saturated) and on the spectra rms noise. One can prove that a 1% uncertainty on the opacity is small enough to be neglected in the final measurement accuracy. This level is reasonably reached, depending on the species used. In order to reach a goal of 1% accuracy on R_G, the relative error on each individual spectrum has to be smaller than 2.5×10^{-3}. The temperature difference between hot and cold loads has thus a critical impact on the accuracy. Given the pressure conditions envisaged here (some mbar), expected line widths are of the order of 200 MHz, so that a 15 MHz spectral resolution is adequate. With detector operated under vacuum, relatively low DSB system temperatures are reachable, allowing to get the required sensitivity in a couple a seconds, far below the expected system drift time constants.

IV. CALIBRATION GASES

The choice of the gases depends on the type of measurement to be done. For side-band ratio measurements, gases with high line strengths and lines nicely distributed over the instrument frequency range should be considered. For the specific HIFI case, species such as OCS, N_2O, H_2CO or CO are of particular interest. When the gas cell is used as molecular line source aiming at mimicking lines of sight observed towards the cosmos, more complex molecules (symmetric and asymmetric tops) are well suited as they possess much more transitions and multiplet line structures. Typical examples are methanol (CH_3OH) or acetonitril (CH_3CN), which can

be used in order to exercise extensive frequency surveys (see Fig.10) across the instrument bands, and consequently optimise dedicated reduction tools necessary to recover the signals arising from either of the upper and lower side-bands.

V. TECHNICAL DESCRIPTION

In contrast to other similar systems operated in the millimetre and sub-millimetre domain (e.g. at University of Cologne), this cell was built following the multi-path concepts commonly used at visible and Near-Infrared wavelengths (e.g. [5]). The overall device is shown in Figs.2 and 3, and consists mainly of two parts: a lower cavity, that we call *connection chamber*, providing the mechanical interface to the input and output ports, and an upper glass cavity (*the cell*) hosting the gas sample. The interface between these two entities consists of two thin (50 microns) Mylar windows adequately tilted in order to avoid any back reflection along the signal path.

An Offner relay located inside the cell (mirrors M1 and M2 on Fig.2) allows a total path of more than 1 metre in a very compact (less than 30 cm high) configuration, easing thus operations and integration in a variety of measurement setups. In order to reduce the efforts on the glass cavity, the plate holding the M1 mirror, and located above the cell, is sustained by 4 stainless-steel bars directly screwed onto the connection chamber (see Fig.4 for an overview). This rigid interface also allows for a reproducible alignment even when the glass cell needs to be removed for any reason. In particular, it keeps constant the distance between M1 and M2, as well as their relative positions.

The optics are designed to control and keep the beam waists in required ranges at the input and output ports (here $4w$ criterion for the HIFI beams). They offer a 1:1 magnification, allowing the system to be operated with any microwave detection system whose beam properties would fit within the constraints of the gas cell optics. This versatile spectral source can be interfaced to the HIFI detection chain in such a way
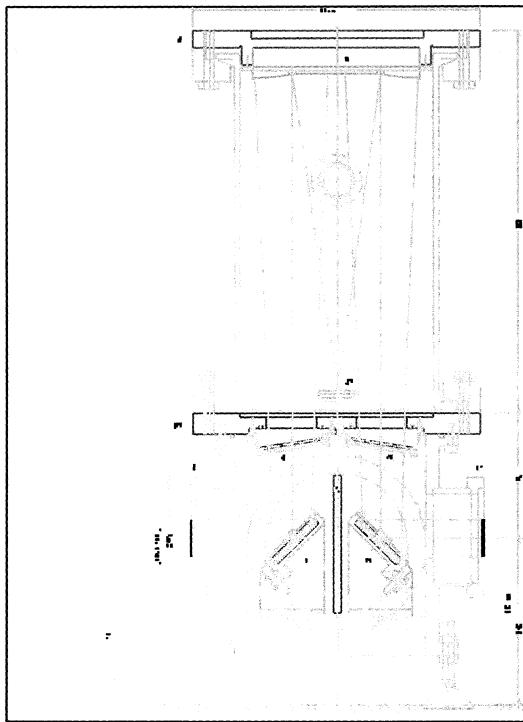

Fig.2: Drawing from the cell as seen laterally. Chief-ray and $4w$ beam envelopes are shown along the entire optical path. Indicated on this figure are the two folding mirrors P1 and P2, as well as the Offner relay consisting of spherical mirrors M1 and M2. Also shown are the tilted Mylar windows (F1 and F2).
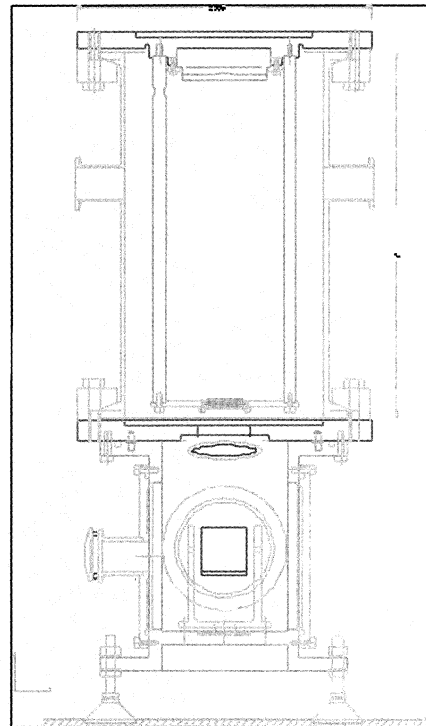

Fig.3: Drawing from the cell as seen from the input (or output) beam. Shown on the cell are two pipes dedicated to the filling and emptying of the gas sample (see next section). Also shown is the pipe at the side of the connection chamber (see text for details).
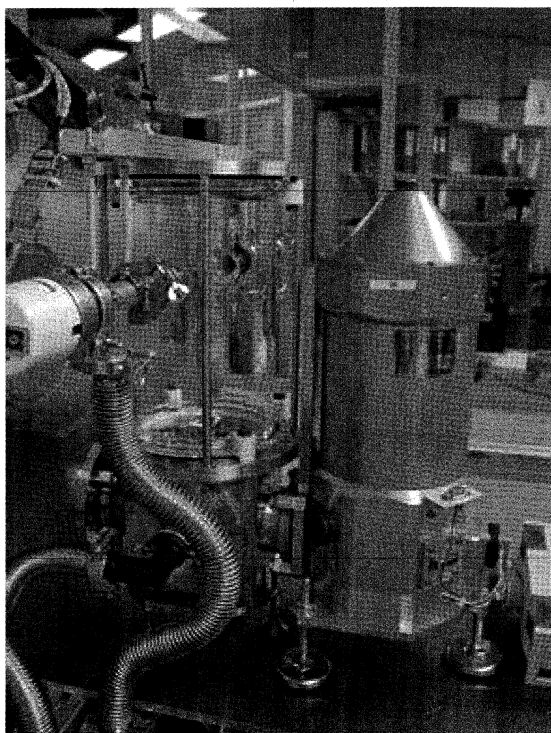
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Fig.4: Picture of the gas cell (left) and of the hot/cold load source (golden cryostat) mounted onto the HIFI test setup.

that measurements can be performed under vacuum conditions, cancelling thus the contribution from the line-of-sight water lines over the whole operating frequency range, and reaching low noise temperatures compared to open-air systems.

A dedicated pipe was added on one side of the connection chamber in order to allow balancing of the pressure between the two cavities during the initial pumping out, permitting to protect the thin Mylar windows from too strong pressure difference on either side.

VI. OPERATIONS

The gas cell setup (partially shown on Fig.4) makes use of a dedicated gas handling rack allowing to perform the gas transfers and evacuation in a reproducible manner (see Fig.5). To that purpose, we designed a circuit making use of electronically controlled valves to be commanded automatically from the test control environment. Since the gas cavity and the chamber hosting the folding mirrors P1 and P2 (Fig.2) are separated by thin windows, the two volumes need to be connected during the initial pumping out. Once under vacuum, a by-pass valve is
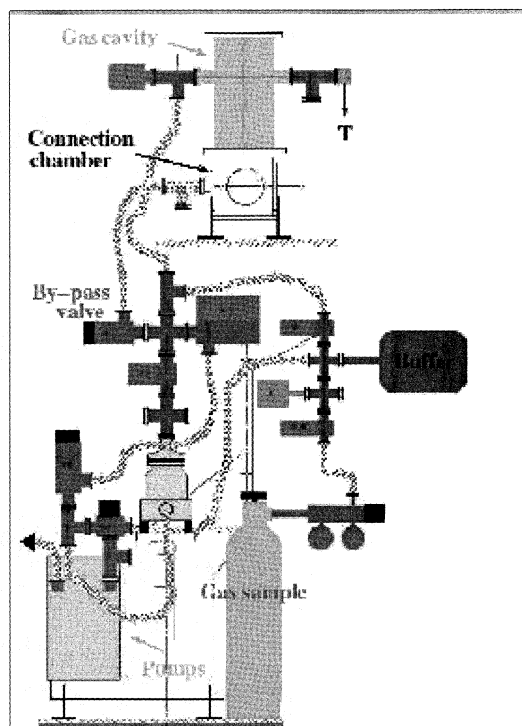

Fig.5: Scheme of the gas handling rack. Valves 1 to 4 are automated devices, while valve 5 serves as a by-pass between the cell and the connection chamber cavities.

closed to isolate the gas sample from the rest of the test setup. As gases are planned to be used in the pressure range 0.1 mbar to 100 mbar, a buffer is necessary in order to thermalize the gas (initially at very high pressure) prior to injection into the gas cavity. Using the combination of primary and secondary pumps, the typical time for a complete measurement cycle is of the order to 10-20 sec., while the evacuation of the gas cavity takes 2-3 min. depending on the pressure contrast required between filled and empty cell spectra.

The system also allows for using species under liquid form, such as methanol or acetonitril. The gas pressure in the cell is then controlled by adapting the ratio between the volumes in the buffer and in the cell cavity respectively, the pressure in the buffer being constant and driven by the vapour pressure of the considered molecule.

The source feeding the cell consists of a cryostat hosting two identical trapping cavities at ambient and liquid nitrogen temperatures respectively (see Fig. 6). These cavities are coated by a mix of SiC grains and Stycast shown to offer specular reflection of 10^{-4} over a wide range of incidence angles, and an emissivity of
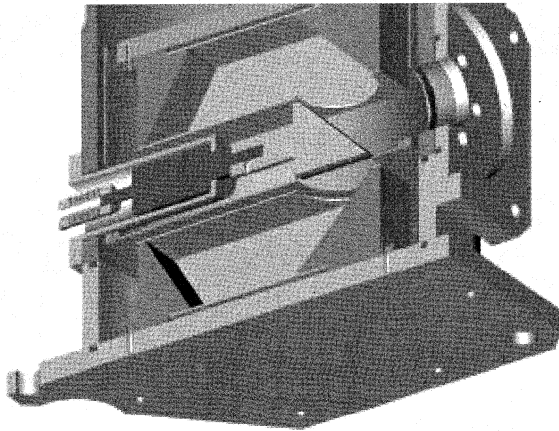
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Fig.6: Partial drawing of the hot/cold source connected to the gas cell. Shown are the two identical trapping cavities serving as hot and cold loads, located above and below a switching mirror controlled by a stepping motor

0.93 [6]. Its dimensions are also chosen to respect the 4w beam truncation criterion.

VII. MEASURED SPECTRA

We present here some representative spectra obtained during the first measurement campaign conducted with the gas cell integrated onto the HIFI test setup. Details about these tests can be found somewhere else in these proceedings [7]. Fig.7 shows a sketch of the gas cell connected to the hot/cold switch and the some other equipment interfaced to the instrument prototype. The instrument was hosting the so-called band 1 mixer, working in the range 480-640 GHz [8], but the operating range was limited to 460-490 GHz by the LO Gunn actually available at that time. The spectra were sampled by an Acousto-Optical Spectrometer (AOS) developed at the University of Cologne [9], providing a instantaneous sampling of the 4 GHz IF band with 1 MHz resolution channels.

We show in Fig. 8 to 10 examples of the spectra measured during this first campaign. Fig. 8 illustrates the case of a side-band ratio measurement using acetonitril at a LO frequency of 484 GHz. In this case, the pressure was increased on purpose in order to broaden lines and achieve high optical depth through line blending. The dip of the absorption is here measured to be 0.497, translating into a side-band ratio of 1.01. However, another absorbed line measured in the same band indicates a ratio of 0.95. Unless rapid side-band ratio variations occur on GHz-scale, which is unlikely, we are probably witnessing side-band ratio
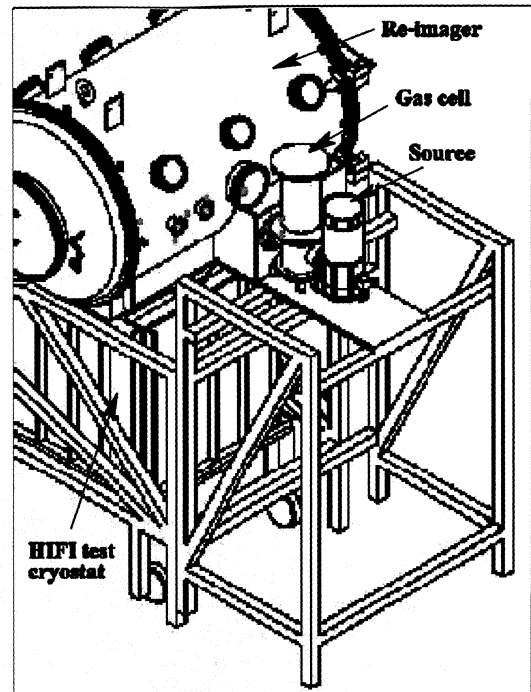

Fig.7: Sketch from the test setup used during the gas cell measurement of the HIFI test campaign. Shown are the re-imager used to focus all HIFI beam at a common position and waist at the cell entrance, as well as the cell itself and the source. The cryostat hosting the HIFI prototype stands below the re-imager.

modulation arising from standing waves generated between the mixer and the LO horns. This phenomenon has been extensively described by [10] and severely limits the accuracy of such measurements if precise knowledge of the shape of this modulation is unknown. Still, the value of the measured ratio is remarkably good considering the fact that we sit at the edge of the mixer working domain, where sideband imbalance is expected to be the worst.

Figs.9 and 10 illustrate another powerful use of the gas cell in order to simulate representative spectra of molecular lines. Both of them correspond to line survey, where the LO frequency is changed by small to larger steps in order to get sufficient spectral redundancy at the time of recovering the Single Side-Band (SSB) spectra from the DSB measurements [11]. The survey of Fig,9 is performed without LO retuning as such since only the synthesizers frequency was changed in a range keeping the phase locked. It shows very well the lines in upper and lower side-bands respectively moving in opposite direction as the LO frequency is changed. Fig.10 is obtained with larger LO frequency steps of order 1.5 GHz.
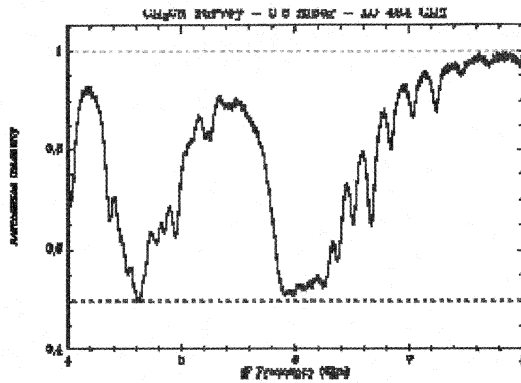
Fig.8: Example of side-band measurement at LO frequency 484 GHz, using acetonitril (CH_3CN). See text for details. Dashed lines indicate the respective 1 and 0.5 levels of the normalized spectrum.
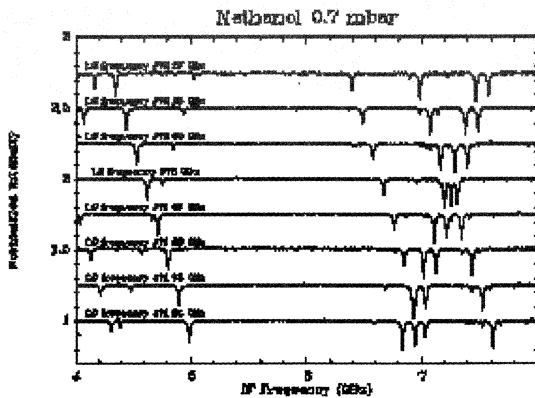

Fig.9: Example of small spectral survey in a LO range of about 600 MHz using methanol (CH_3OH). See text for further details.
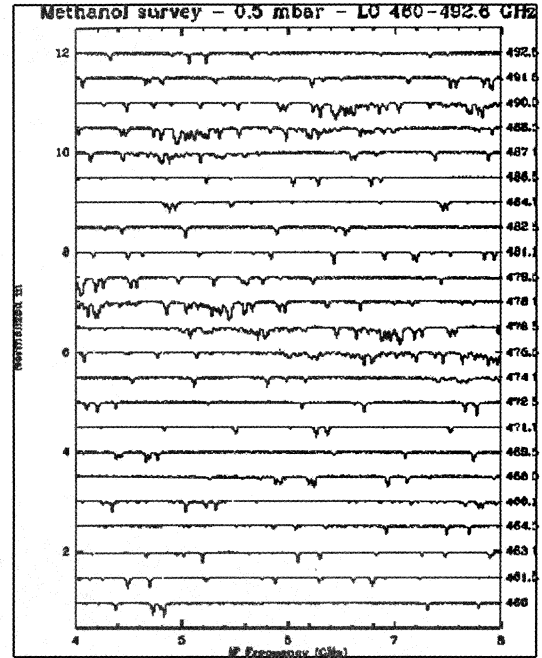

Fig.10: Same as Fig.9 on a larger LO frequency range (460-492 GHz) with tuning steps of order 1.5 GHz. The LO frequency is indicated on the rightmost column.

VIII. CONCLUS IONS

In the framework of the Herchel/HIFI AIV/ILT campaign, we have developed an absorption gas cell aiming at providing representative spectral lines to the detector, as well as at measuring the side-band ratio along the HIFI frequency range using saturated lines. The system consists of multi-reflection optics, allowing long optical path through the gas sample while keeping the instrument compact. It is operated under vacuum and is thus insensitive to water vapour absorption. By acting as a 1:1 optical system, it can in principle be used with any system meeting the beam waist requirement at input and output ports ($4w$ waists of 30 mm in that precise case, located at the gas cell port). More outcomes of this device are expected in the course of the HIFI qualification campaigns over the coming years.

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