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SMART: The KOSMA Sub-Millimeter Array Receiver for Two frequencies

U. U. Graf, S. Heyminck, E. A. Michael, S. Stanko, C. E. Honingh, K. Jacobs, R. Schieder and J. Stutzki

KOSMA, I. Physikalisches Institut, Universität zu Köln, Zülpicher Straße 77, 50937 Köln, Germany. E–mail: *lastname*@ph1.uni-koeln.de

Abstract

We present the first results obtained with our new dual frequency SIS array receiver SMART[1]. The instrument is operational since September 2001 at the KOSMA 3m telescope on Gornergrat near Zermatt/Switzerland. The receiver consists of two 2×4 pixel subarrays. One subarray operates at a frequency of 490 GHz, the other one at 810 GHz. Both subarrays are pointed at the same positions on the sky. We can thus observe eight spatial positions in two frequencies simultaneously. For the first year of operation we installed only one half of each subarray, i.e. one row of 4 mixers at each frequency.

The receiver follows a very compact design to fit our small observatory. To achieve this, we placed most of the optics at ambient temperature, accepting the very small sensitivity loss caused by thermal emission from the optical surfaces. The optics setup contains a K–mirror type image rotator, two Martin–Puplett diplexers and two solid state local oscillators, which are multiplexed using collimating Fourier gratings. To reduce the need for optical alignment, we machined large optical subassemblies monolithically, using CNC milling techniques. We use the standard KOSMA fixed tuned waveguide SIS mixers with Nb junctions at 490 GHz, and similar Nb mixers with Al tuning circuits at 810 GHz.

We give a short description of the front end design and present focal plane beam maps, receiver sensitivity measurements, and the first astronomical data obtained with the new instrument.

Introduction

At last year's conference [1], [2] we introduced our design of a dual–frequency eight–pixel SIS–heterodyne receiver SMART[1]. SMART's unique feature is that it simultaneously measures in the 650 μm and the 350 μm atmospheric windows, thus combining and extending the frequency coverage of the other two currently installed submillimeter arrays CHAMP [3] and Pole STAR [4]. SMART is mainly intended for simultaneous mapping of the two fine structure transitions of neutral atomic carbon at 492 GHz and at 809 GHz. The large frequency coverage also allows to measure a variety of other spectral lines in this frequency range, for instance the carbon monoxide (CO) rotational transitions at 460, 807 and 880 GHz. The simultaneous measurements of different spectral lines in several spatial pixels enhances the data quality by eliminating a number of calibration and pointing uncertainties [5].

[1] **S**ub–**M**illimeter **A**rray **R**eceiver for **T**wo frequencies

Opto–mechanical Design

In order to fit into the limited space available at the KOSMA 3m telescope [6], the instrument was designed to be very compact. We therefore decided to place essentially all optical elements at ambient temperature. It is obvious that the thermal emission of these elements will degrade the receiver sensitivity to some extent. However, it turned out that the combined effect from a total of 14 warm surfaces only adds a very small amount to the receiver noise temperature.

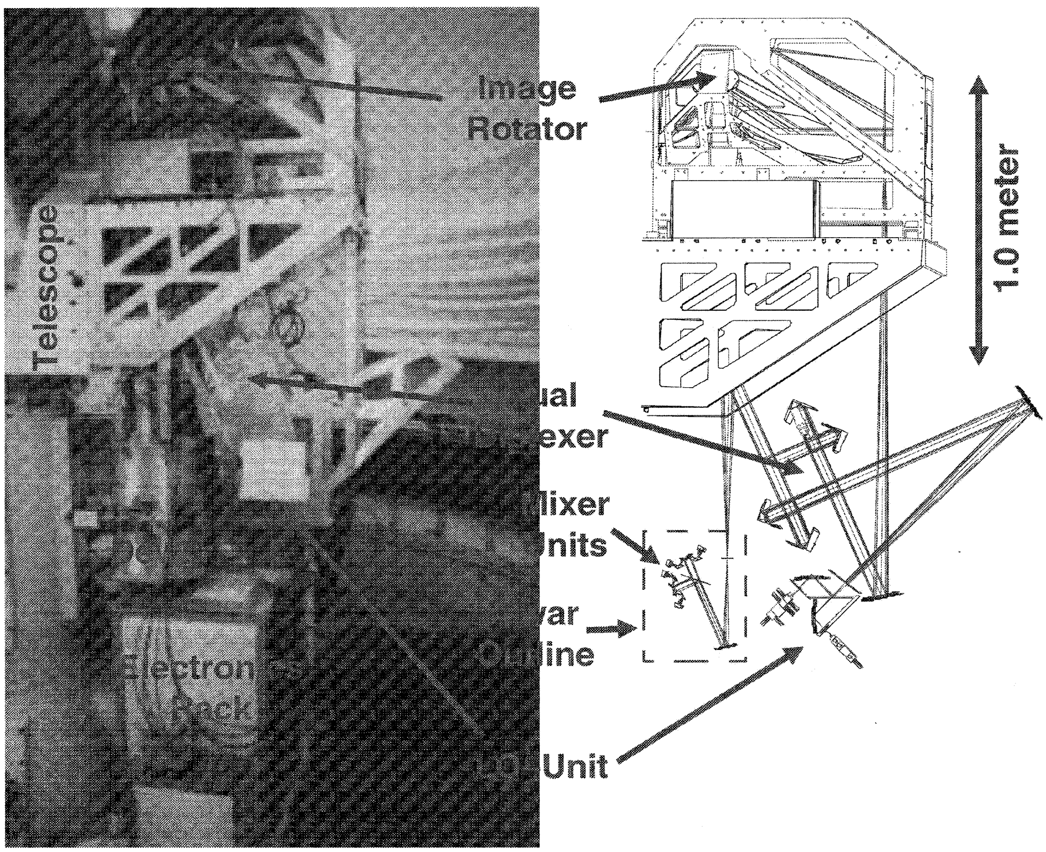

Figure 1: Photograph (left hand panel) and drawing (right hand panel) of SMART mounted at the KOSMA telescope.

Fig. 1 shows a photograph and a schematic drawing of the instrument mounted at the telescope. The main units of the receiver are:

- a K–type image rotator to compensate the image rotation introduced by the alt–az–mounted telescope when tracking an astronomical source,
- the diplexer assembly containing two identical Martin–Puplett–interferometers, which combine the signal beams and the LO–beams,

- the LO–unit, which produces the two LO–signals and splits them into eight beams, each,
- the dewar containing the mixer units, and
- the electronics rack with the instrument control electronics.

The imaging optics consist of two gaussian telescopes made of ellipsoidal and hyperboloidal mirrors. A first set of two mirrors reimages the telescope's focal plane to the optical center of the diplexers to create large beam waists in the diplexer. These waists are reimaged with a second gaussian telescope to the output waists of the mixer units. In order to minimize abberations, all reflection angles are kept small (24° or 32°) and all mirrors have long focal lengths (300 to 1900 mm). The dewar window has been placed between the mirrors of the second gaussian telescope, at the image of the telescope's primary mirror, where the total beam cross section is minimal.

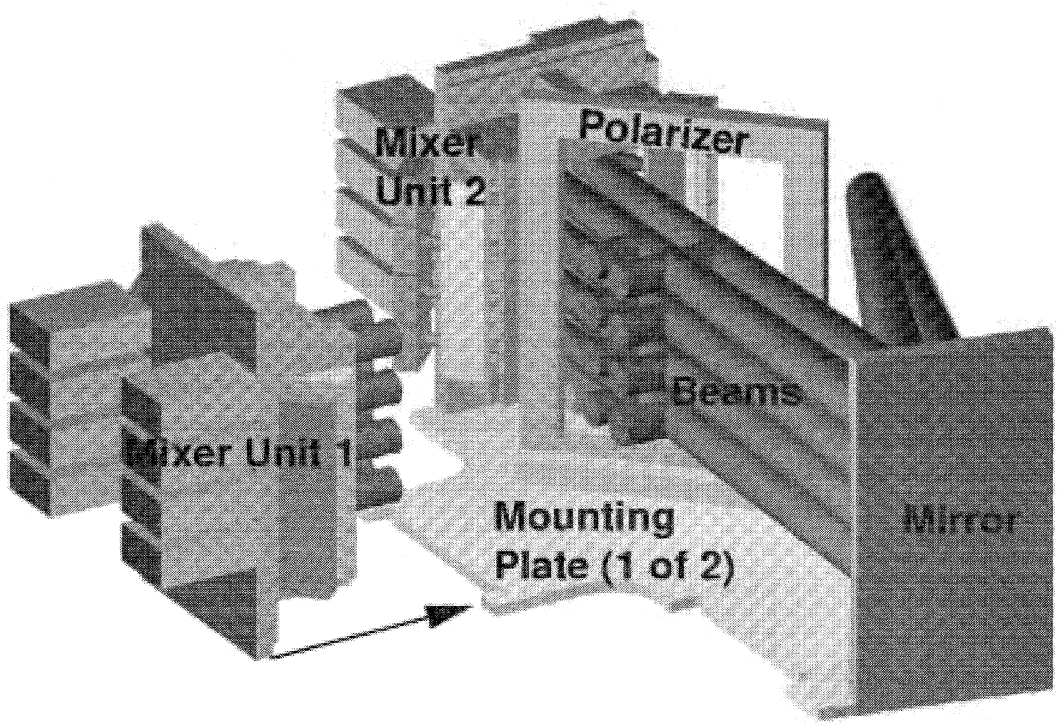

Figure 2: Assembly containing all optical elements inside the dewar. The mixer units (Fig. 3) together with a polarizer grid and a common imaging mirror are sandwiched between two identical CNC–machined plates.

Within the dewar (Fig. 2), the optics consist of the last mirror common to all mixers, a polarizer grid, and two similar mixer units. These mixer units (Fig. 3) are CNC–machined quasi–monolithic integrated optics components, each of which is holding 8 mixers in two rows of four. Within the units, the mounting surfaces for the mixers and their collimating mirrors are machined in a single machining cycle with very high precision, thus eliminating the need for an individual alignment of the mixers. Similarly, all the optical elements inside the dewar are sandwiched between two precision machined plates, which hold them with high enough accuracy that no further alignment is required.

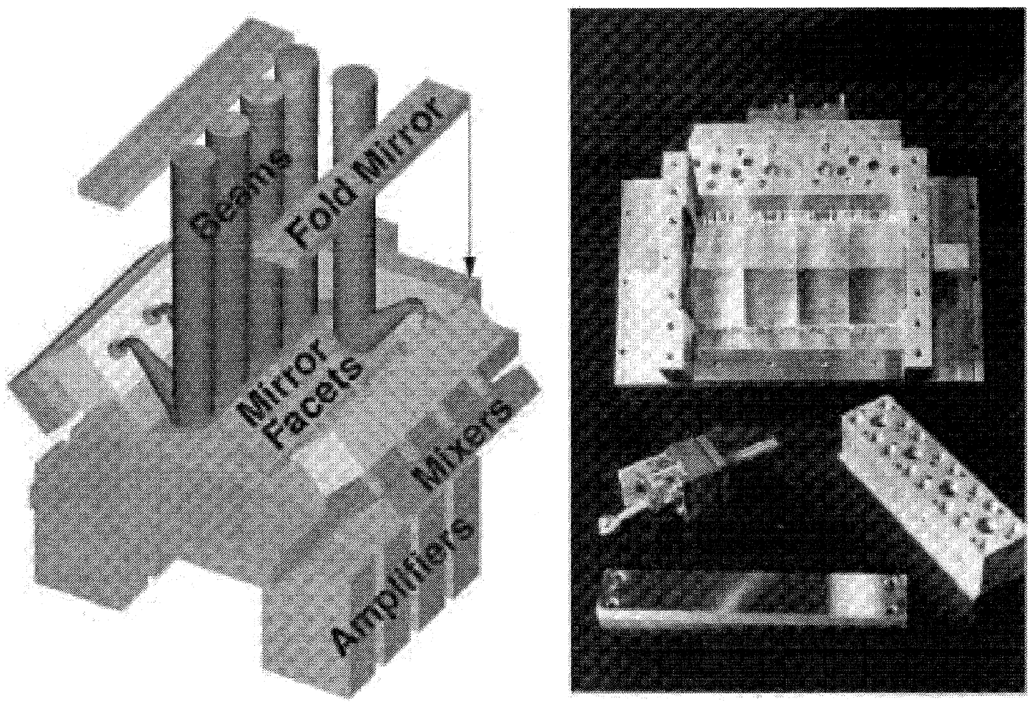

Figure 3: Drawing of the 490 GHz mixer unit (left hand panel) and photograph of the major components (right hand panel). It contains a facetted mirror to collimate the beams from the eight mixer horn antennas. The mixers are held by their feed horns, which are inserted in precision reamed holes in the mixer unit. The eight mirror facets cover an area of 84×42 mm^2.

The first optical element in the diplexer unit (Fig. 1) is a wire grid, which splits the polarization of the incoming signal beams to separate the optical paths for the two frequencies. At the same time, this grid couples the LO–beams onto the signal beams with orthogonal polarizations. The two Martin–Puplett–interferometers match the LO–polarizations to the signal polarizations. A second polarizer grid recombines the beams before they leave the diplexer unit.

We use two local oscillator chains with orthogonal polarizations. Each LO is split by a collimating Fourier grating (Fig. 4 [2]) into eight identical beams, matching the mixer arrangement. A polarizer grid combines the LO beams before injecting them into the diplexer unit.

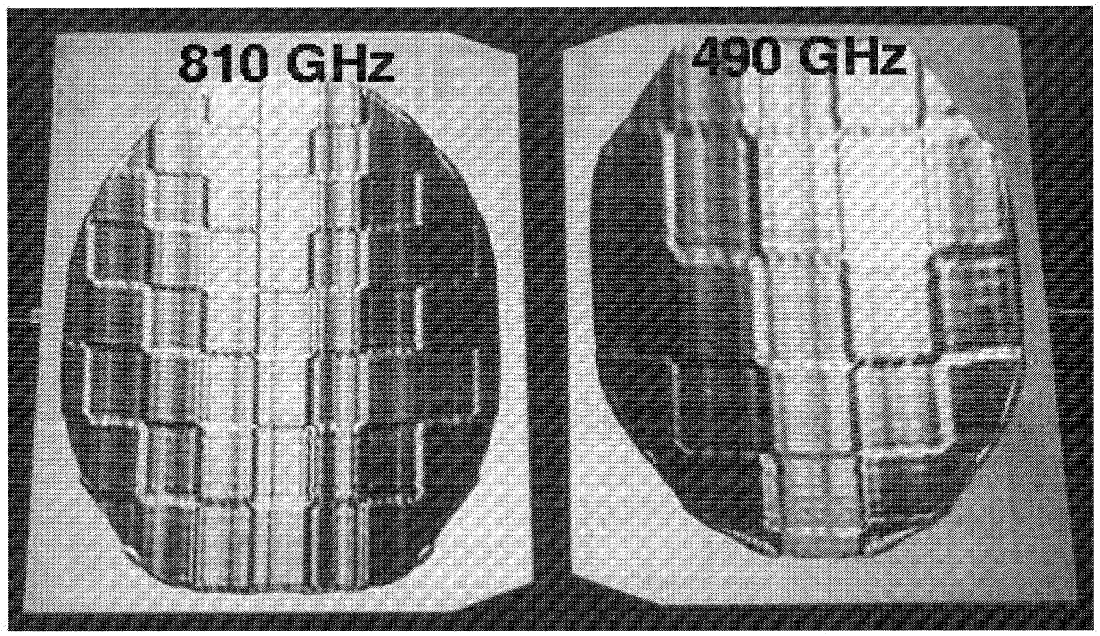

Figure 4: Photograph of the two collimating Fourier gratings used with SMART. Each grating collimates an incoming diverging LO beam and splits it into eight identical beams in a 2×4 arrangement. The grating on the left hand side with the smaller structure is for the 810 GHz frequency band, the one on the right hand side is for the 490 GHz band.

The image rotator is a computer controlled rotating arrangement of three mirrors in an asymmetric K–configuration. It allows to keep the receiver pixels aligned with respect to the astronomical source, while the image of the source is rotating in the telescope focal plane during long term measurements.

Cooling of the instrument dewar is provided by a closed cycle refrigerator [7], which keeps the SIS–mixers at a temperature of 4 K.

Mixers and Backends

In the 490 GHz frequency band we use the standard KOSMA Niobium SIS mixers with fixed tuned backshorts [8]. The mixer block design for the 810 GHz mixers is similar. The SIS devices, however, use a Nb–Al bilayer for the RF tuning circuit, in order to reduce the losses at frequencies beyond the niobium gap frequency.

The spectrometer backends used with SMART are the KOSMA array AOSs [9]. Each of the units combines four 1 GHz wide AOS channels in one opto–mechanical setup. The spectral resolution is approximately 1 MHz. Four array AOSs are required for the complete receiver.

Electronics

The instrument control electronics is described in more detail in Stanko et al. in this volume [10]. There we also present the control software and the automated receiver tuning procedure, which we developed to facilitate the operation of the instrument.

In addition to the control electronics, the receiver electronics also comprises the processing of the intermediate frequency mixer output signals, which requires the following functional units:

- amplifiers and filters for the receiver output
- frequency converters to shift the IF to match the AOS's input frequency
- variable attenuators to match the IF power level to the input level required by the AOS
- IF power monitors for receiver tuning and continuum observations
- switches to suppress the receiver output for AOS dark current measurements
- a frequency comb signal for the frequency calibration of the AOSs

We developed a compact IF processor for eight receiver channels, a photograph of which is shown in [10].

Receiver Performance

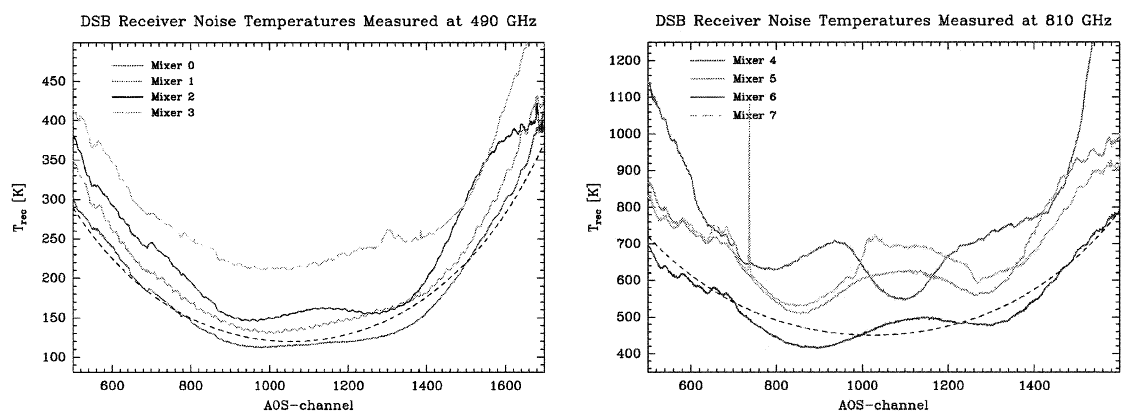

Figure 5: Receiver noise temperatures measured at the telescope. The dashed lines visualize the sensitivity loss caused by a room temperature diplexer calculated for intrinsic receiver temperatures of 120 K (at 490 GHz) and 450 K (at 810 GHz).

In Fig. 5 we show the receiver noise temperature at the telescope, simultaneously measured with all eight currently installed receiver channels. The figure shows the noise temperature variation over the 1 GHz wide IF band plotted against AOS channels. Each backend channel is approximately 1 MHz wide. At 490 GHz the typical minimum noise temperature is around 150 K, at 810 GHz it is approximately 500 to 600 K. The most prominent feature in the plot is a curvature in the band. This loss in sensitivity toward the edges of the IF band reflects the transmission of the diplexer. The dashed lines in the noise temperature plots indicate the noise temperature functions one would get with an intrinsic receiver temperature of 120 K (at 490 GHz) or 450 K (at 810 GHz) looking through a room temperature Martin–Puplett interferometer. These curves represent well the measured values. At 490 GHz, where the effect is more prominent, we plan to increase the noise bandwidth by changing the IF center frequency to 4 GHz.

The most remarkable point in the noise temperature measurement is that, at 810 GHz, we do not see a difference between the receiver temperature measured at the telescope with the array and the noise temperatures measured with the same mixers in a single channel test dewar in the laboratory. Thus, SMART at least partly fulfills the most stringent request imposed on any array receiver: *"The noise performance of the arrays needs to be very close to that of single–pixel receivers if they are to compete"* (cited from [11]).

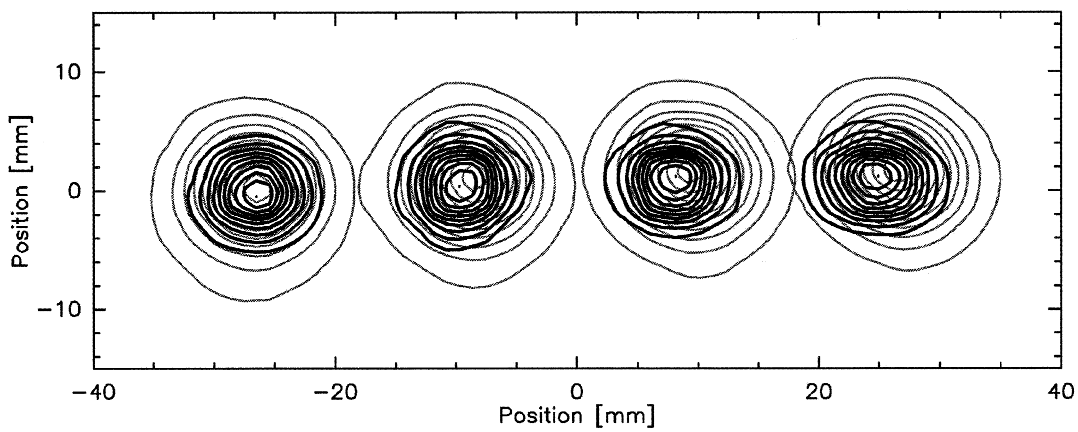

Figure 6: Receiver beam pattern measured at the location of the telescope's focal plane. The red contours are the 490 GHz beams, the black contours are the 810 GHz beams. Contour levels range from 5% to 95% of the peak intensities. The beam sizes and spacing fits well with the design values. The slight offset of the 810 GHz beams with respect to the 490 GHz beams results from a residual misalignment of the diplexer unit.

We measured the beam pattern by scanning the receiver beam in the focal plane using a chopped cold load (Fig. 6). The beams of the 8 mixers currently mounted are very clean and have the correct size and spacing. There is a slight offset between some of the 810 GHz beams and the corresponding 490 GHz beams, which is most likely due to a slight misalignment in the diplexer unit. However, the overlap between the beams is still very good.

First Astronomical Measurements

The power of the array receiver approach becomes evident with the astronomical data gathered. Even with only half of the mixers installed, SMART is a very fast instrument and allows to map extended sources in a short time. In Fig. 7 we show sample spectra obtained during a single integration of 160 seconds duration. With our IF frequency of 1.5 GHz we can measure the [CI] $^3P_2 \rightarrow ^3P_1$ line and the CO J=7→6 line simultaneously in opposite sidebands of the 810 GHz receiver branch. Thus the data contain a total of 12 spectral lines, 3 lines from each of 4 spatial positions.

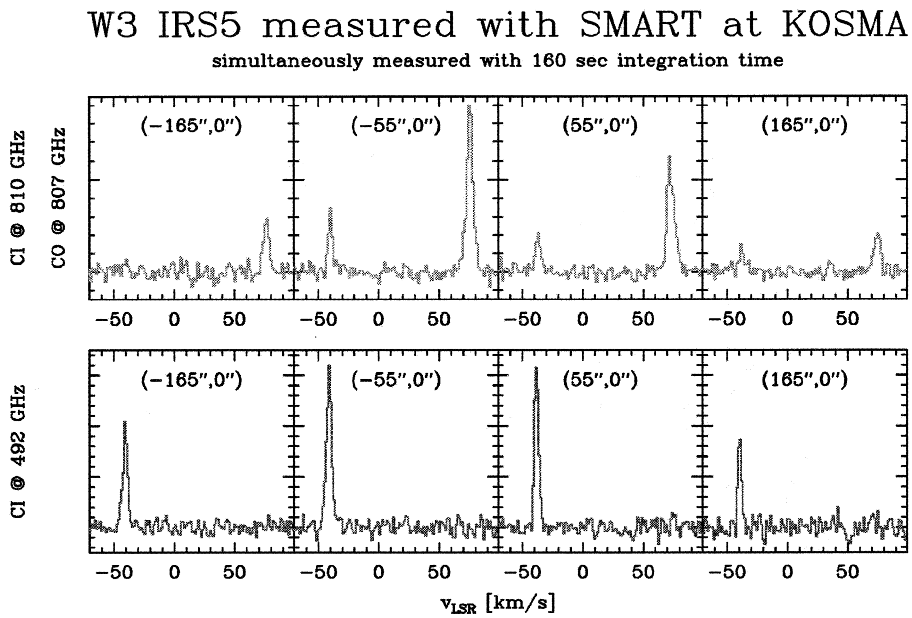

Figure 7: Sample spectra obtained simultaneously toward W3 IRS5 during a single 160 sec integration with SMART at the KOSMA telescope. The lower row of panels shows the 492 GHz fine structure transition of neutral atomic carbon (CI), the upper row shows the 810 GHz fine structure line of CI and the 807 GHz J=7→6 transition of CO. Pixel offsets are indicated in each panel.

Conclusions

We have built and installed the world's first dual frequency submillimeter heterodyne array receiver SMART. The optical alignment of the instrument is very simple because of the innovative integrated optics approach taken in the design. With its low receiver temperature and its good optical performance, SMART is a very powerful instrument for astronomical submillimeter spectroscopy.

Acknowledgments

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