The Wide-Band Spectrometer (WBS) for the HIFI instrument of Herschel

O.Siebertz[1], F.Schmülling[1], C.Gal[1], F.Schloeder[1], P.Hartogh[2], V.Natale[3], R.Schieder[1]

[1] KOSMA, I. Physikalisches Institut, Univ. Cologne, Germany
[2] Max Planck Institut für Sonnensystemforschung, Katlenburg-Lindau, Germany
[3] IRA – INAF, Firenze, Italy

Abstract

The Wide Band Spectrometer (WBS) of The HIFI-instrument on Herschel consists of two Array-acousto-otpical spectrometers with 4 GHz total bandwidth each. The full bandwidth is composed of four 1 GHz sub-bands. The spectrometer includes an IF-processor, which splits the input band between 4 and 8 GHz into the AOS bands between 1.6 and 2.6 GHz. The spectrometers are stable with an Allan-variance minimum time of 500 seconds, and the gain linearity has been measured to better than ±0.3% maximum deviation from linear response. The total power consumption is 7 Watts for the AOS and 20 Watts for the IF-section. The spectrometers are fully space qualified and already in permanent use for system tests of the HIFI instrument during integration.

Introduction

The HIFI instrument (Heterodyne Instrument for the Far Infrared) is one of the most complex heterodyne systems built for astronomy. It has 7 mixer bands covering the frequency range between about 490 and 1910 GHz nearly completely. For each band two mixers with crossed polarizations are implemented. The IF-bandwidth of most of the mixers is 4 GHz, which is spectrally analyzed by means of two acousto-optical spectrometers and/or two digital correlators. The WBS (Wide Band Spectrometer) is based on a recent development of an array acousto-otptical spectrometer [1], which provides four identical bands of 1 GHz bandwidth each at a frequency resolution of 1 MHz. Since spectrometers with 4 GHz instantaneous bandwidth at this kind of resolution do not exist, the frequency coverage is provided with a hybrid system, which splits the original band between 4 to 8 GHz into four identical bands between 1.6 and 2.6 GHz. We have built five WBS units: 1 development model (DM), 1 qualification model (QM), 2 Flight models (FM1 and FM2 for horizontal and vertical polarization mixers), and one spare model (SM).

The spectrometer

A scheme of the WBS is shown in Fig.1. The spectrometer consists of two boxes, one optics unit (WBO) and one electronics unit (WBE). The electronics unit includes 4 AD-converters with 14 Bit each. In order to reduce differential non-linearity effects (DNL), a dither voltage is added to the ADC input, which is then digitally subtracted afterwards. This improves the DNL to that of a typical 16-Bit ADC, because the irregularities caused by the DNL are partly averaged out. The data are accumulated into custom designed ASICs, which are commanded via the command interface. In the IF section (WBI) the input band between 4 to 8 GHz is first amplified and then converted into 4 sub-bands between 1.6 and 2.6 GHz, which are then fed to the four transducers of the Bragg-cell in WBO. Variable attenuators are needed to adjust the gain for appropriate signal light levels on the CCD in WBO. A comb generator is built in for good frequency calibration of the spectrometer.

The principle of the optics of the array-AOS is shown in Fig.2. The laser output of approximately 35 mWatt is collimated by a collimation lens with an f-number of 0.5. The resulting parallel beam is then focussed by a cylindrical lens so that the light is well concentrated onto the narrow acoustic zone (~70 µm) in the Bragg-crystal. The beam is then split into four identical beams by a beam splitter. The beam distances match the distance between the four transducers in the Bragg-cell (1.6 mm). Behind the Bragg-cell the cross-polarized deflected light is passing a polarizer in order to avoid instabilities from scattered laser light. The following scan-lens focuses the light onto the CCD. The four signal beams are vertically separated by means of a second cylindrical lens, which is positioned to match the location of the four resulting images with the four linear CCD lines, and to perfectly image the illuminated area in the Bragg-cell onto the CCD lines simultaneously. Since the signal beams cross between lens and CCD, a slit aperture is inserted at this position, which reduces the light scatter seen by each CCD line from the other areas in the Bragg-cell. This is extremely important because of stability problems due to the influence of laser speckles.

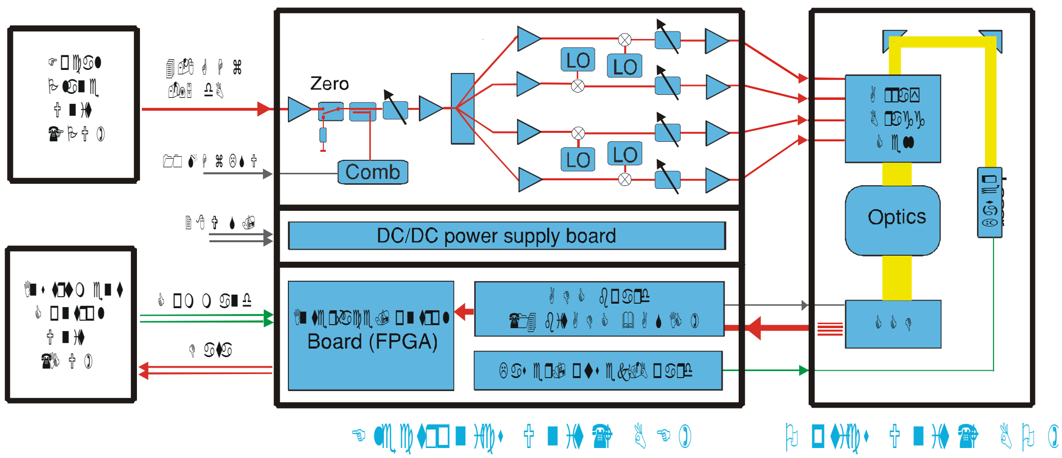

Fig.1: Scheme of the WBS

Since WBS is built for a space program with a lifetime of 4 years, the optics includes a second, redundant laser, which needs to be coupled to the system with low losses as well. Typically, a beam splitter is used for this purpose (see e.g. [2]), but it was important to make the optics as efficient as possible so that the additional 3 dB loss from an ordinary beam splitter was not acceptable. We therefore developed a special prism beam splitter, which accepts two laser beams at different input angles and provides identical output beams. The input and output facets of the prisms are oriented near Brewster angle so that negligible loss is introduced for both lasers at the same time. The accuracy for the prism assembly is very critical and it required several attempts to achieve satisfying results.

The requirements for the quality of the optics in an AOS are rather stringent since one has to deal with fully diffraction limited imaging. In order to avoid massive deterioration of the frequency resolution, the accuracy of all optical components must be better than $\lambda/10$ at a laser wavelength of 785 nm. This is a particular challenge for the collimation optics in front of the laser, which is difficult to fabricate because of the very small f-number. The imaging optics, which is a scan lens design, is also critical in this respect. When talking about imaging errors, it is clear that the orientation of the two cylindrical lenses in the system needs to be accurate within a few arc minutes. This requires very sophisticated alignment procedures, for which we investigated the far field patterns of the laser beams by means of a scanning linear CCD very carefully. At the same time, the accuracy of the position of the input laser beams must be accurate within 10 µm, and the input angle of the beams to the prism beam splitter needs to be within a few arc minutes as well. Again, this alignment is very critical.

Last, but not least, the whole assembly had be space qualified, meaning that it had to survive thermal cycling between –35 and +65 C, vibration test with 12 g rms, and shock test at 2000 g peak. The operating temperature of the mounting platform on the spacecraft was specified to +10 ± 5 C. It was also essential to include corrections for the absence of air, which has significant impact on the imaging in the optics unit. At the same time, degradations because of thermal expansion within a temperature range of 10 C (+10 ± 5 C) should not change the optical alignment within 20 µm or so. This needed a stress-free envelope of WBO, which we tried to ensure by grinding all mating surfaces of the cover and the base plate to an accuracy of a few µm, so that after combining the parts no visible change in performance due to stress deformation could occur.

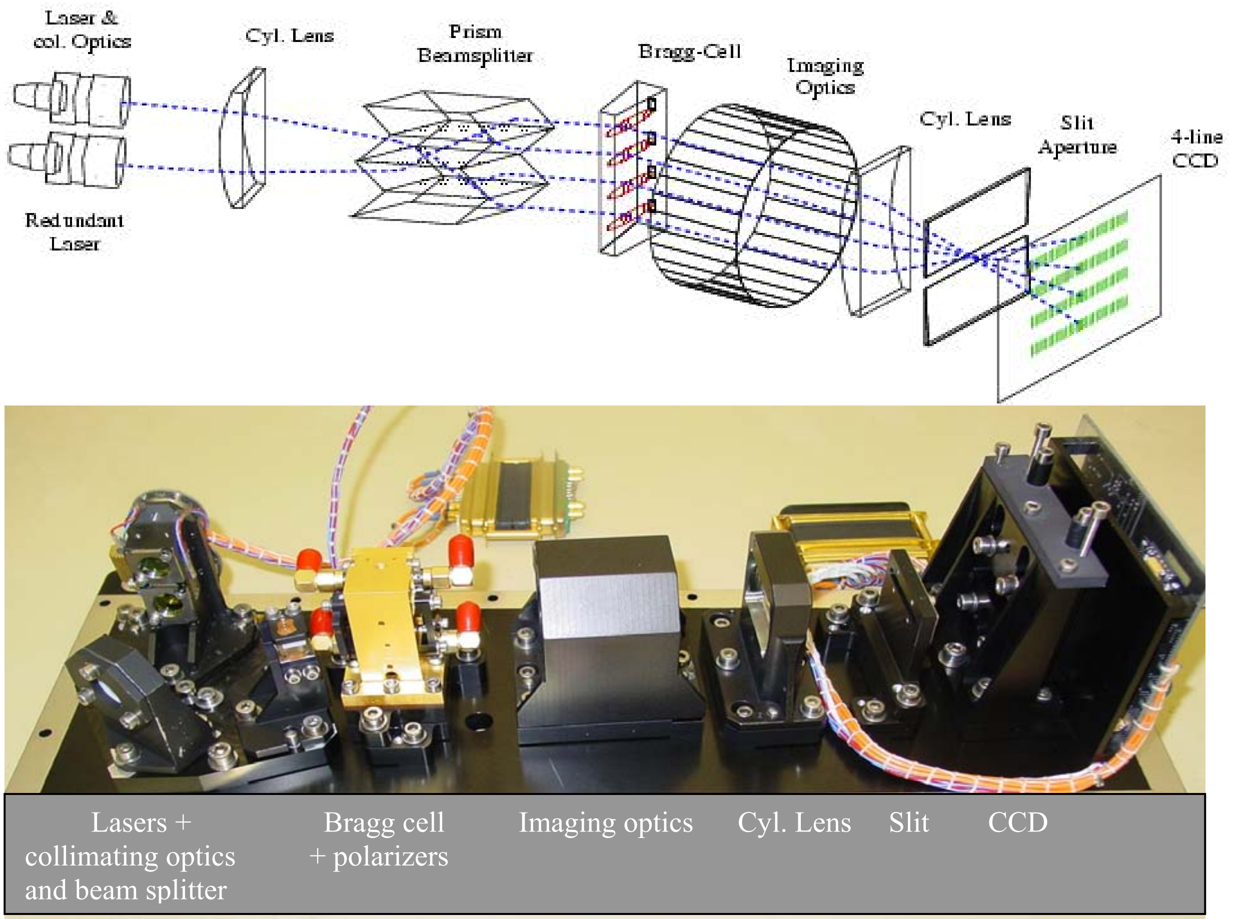

Fig.2: Scheme of the WBS optics and view of the hardware

As was mentioned before, the optical efficiency is rather decisive, because the required RF-power for sufficient illumination of the CCD needs to be as small as possible. This helps to keep the DC power for the final amplifiers in the IF-system at low level reducing the required DC power of the system. The focussing of the laser power onto the acoustic zones in the Bragg-crystal together with the perfect imaging of the illuminated area in the crystal onto the CCD gives an advantage in efficiency of more than one order in magnitude, in comparison to the SWAS AOS for example.

The stability of WBS is one of the most important parameters for WBS, since for a massive spacecraft like Herschel it is inevitable that switching between different positions on sky will cause substantial time delays. Therefore the Allan variance should still show near radiometric performance even at integration times above 100 seconds. This requirement is in conflict with the optical design, which is optimized for maximum efficiency, and is therefore extremely sensitive to alignment changes due to thermal drift for example. Therefore it was one of the most important interface requirements for the WBO to experience very little thermal fluctuations. The specification for the thermal interface to the spacecraft service module is one degree C per hour maximum gradient. Further increase of the thermal stability is achieved by reducing the thermal contact of WBO to the spacecraft base-plate.

Test results

The specifications of WBS, as measured, are given in the table below. We consider the stability and the gain linearity as most important for the mission, but other parameters are important as well. In Fig.3 an Allan variance plot is depicted. Under best thermal conditions we have achieved an Allan variance minimum time near 500 seconds. This is calculated from the rms of the full 4 GHz spectrum and not from the spectroscopic Allan-variance using two pixels only (see e.g. [3]). Under normal laboratory conditions it reduces to about 100 seconds. WBO is aligned for an operating temperature of the interface plate of about 10 C. Due to the additional thermal insulation the WBO operating temperature is raised from +10 C interface temperature to about +15 C. This was therefore the ambient temperature, at which the alignment procedures had to be done. Due to the very critical optical accuracy we had also to correct for the operating conditions under vacuum in orbit. This correction is achieved by means of an additional plane-parallel glass plate of 2 mm thickness in front of the CCD, which compensates for the shift of focus position between air and vacuum. This was finally verified during the thermal vacuum tests. The full 4 GHz baseline seen after 64 hours of integration at an On/Off switch cycle of 60 seconds is shown in Fig.4. The rms is very close to that predicted by the radiometer equation ($3.2 \cdot 10^{-6}$), when using a fluctuation bandwidth of 1.7 MHz (see Table).

Total bandwidth	4000 MHz in four sub-bands of 1000 MHz
Number of valid frequency pixels	6910
Resolution/fluctuation bandwidth	1.1/1.7 MHz
Allan variance minimum time	> 200 sec
Frequency non-linearity	±0.7 MHz
Power non-linearity	< 0.3 %
Noise dynamic range	13 dB
Internal band-pass ripple	< 3 dB
Dimensions	290x240x176 WBE, 400x170x130 WBO
Mass incl. harness	12 kg (5.5 kg WBO 6.5 kg WBE)
Power consumption	AOS 7 Watt, IF-processor 20 Watt
Operating temperature	10 ± 5 C at the interface (WBO)

The noise dynamic range (NDR) of a spectrometer, which we specify as the input power range, within which the instrumental noise stays at less than 1 dB of the radiometric noise, is a serious concern for low noise mixer receivers with large IF-bandwidth. WBS has a specified NDR of about 10 dB, and we found a NDR up to 13 dB maximum. The main cause of spectrometer noise is shot noise of detected photo-electrons and read-out noise in the CCD. Significant parts of the NDR are already consumed by the gain ripple of the input and of the spectrometer and the power variations due to calibration load or signal power. The alignment of WBO as well as some equalization in WBI helped to reduce the instrumental gain ripple to better than 3 dB. One additional dB is already lost due to the necessity to stay safely below the saturation level of CCD and/or the AD-converter. Gain differences between the four sub-bands of WBO are taken care of by individual adjustable attenuators (±4 dB) in the IF. Therefore, only few dB are left as maximum

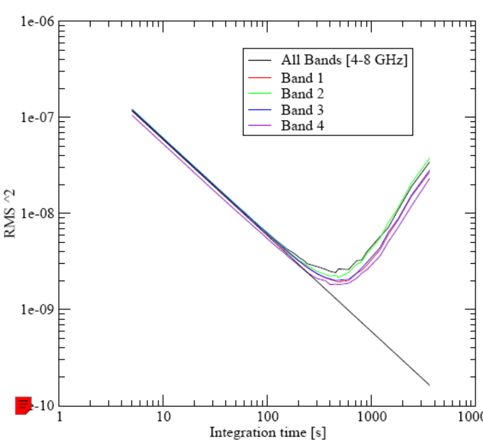

Fig.3:
Allan variance plot of WBS. Plotted are the rms-values of each of the 4 sub-bands and of the full 4 GHz band. They all are practically identical.

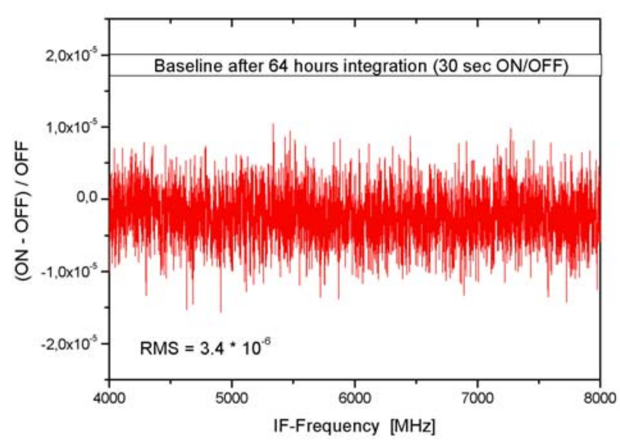

Fig.4:
Full 4 GHz baseline after long integration with WBS and a noise source. The rms matches the theoretical level of $3.2 \cdot 10^{-6}$ very closely (B_{Fl} = 1.7 MHz).

gain variations for all observations within each of the sub-bands. 3 dB power variations are expected as maximum signal variations on planets for example. This means that the maximum gain ripple from the mixer, cryogenic amplifiers is about 3 dB per 1 GHz when following the specification. This is a fairly tight requirement, which is not so easily met, but the increased NDR of WBS of 13 dB helps here a lot.

Gain linearity is an important property of any spectrometer. Non-linearity has consequences for the calibration accuracy, but is even more important for baseline ripple problems. In an AOS the major contributor to non-linearity is the CCD. Although photo effect should be precisely linear, it is very common that non-linearities of photo diodes, particularly in CCDs are problematic. The overall linearitiy of a CCD is strongly influenced by the amplitude and shape of the controlling pulses, and the applied voltages. In case of WBS, the situation became more complex, since it uses four linear CCD lines all operated in parallel on a single chip. The chip was cut out of a wafer taken from a normal linear CCD production line. After bonding and packaging we carefully investigated the properties of the chips. Since now four lines had to be driven in parallel instead of one only, we observed significant changes of the performance in comparison to single line chips. We therefore had to find out by experiment how the applied pulses and voltages had to be tuned. As a result, we have been able to verify a linearity of better than ±0.3% over the full NDR.

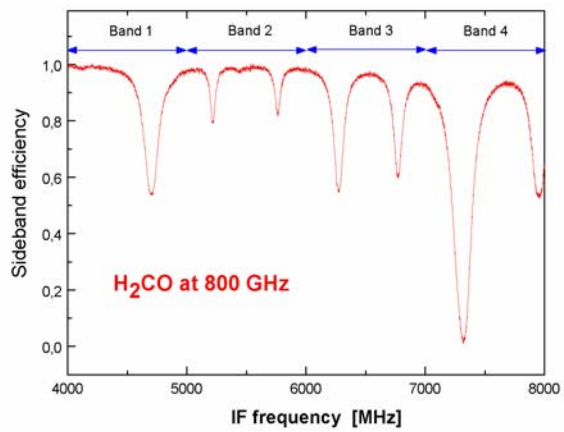

Fig.5:

Molecular line spectrum seen with WBS-QM through a gas-cell together with the Band 2 QM mixer of HIFI. The strong line to the right is the superposition of two saturated lines in both sidebands.

As an example, Fig.5 shows a 4 GHz spectrum of Formaldehyde at a frequency near 800 GHz, taken with the development model of WBS through a 35 cm long gas-cell. The mixer is a Band 2 mixer of HIFI, which was also developed at KOSMA. The lines are from both sidebands, and the strongest line at 7300 IF-frequency is a superposition of two saturated lines in both sidebands. Therefore, the response is 100% instead of only 50% for a line from one sideband only (see Poster P10 at this conference). The measurement took about 4 minutes and the signal to noise is nearly ideal. Note that there is practically zero baseline distortion. This is very satisfying when considering that the spectrum is the result of four independent measurements, HOT- and COLD-load seen through filled cell and HOT- and COLD-load seen through empty gas cell. The spectrum is the ratio of the differences of the two pairs of data. Very good power stability is demonstrated by the value of unity at absorption free frequencies. In particular, platforming is not visible, which confirms the excellent stability of the system.

References

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