THE HIGH RESOLUTION SPECTROMETER OF HIFI ONBOARD HSO

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ABSTRACT

We present a versatile digital autocorrelation spectrometer designed to suit the needs of HIFI, the sub-millimeter heterodyne instrument of the ESA's Herschel Space Observatory (HSO). This spectrometer will offer a set of four observation modes with different "channel spacing / total bandwidth" combinations. Each subband can be set anywhere in the 4-8 GHz input bandwidth. An original architecture made of an hybride Gallium Arsenide and Silicon technology allowed us to realize a 512 channel, low power consumption and high speed correlation module.

INTRODUCTION

HSO, the *Herschel Space Observatory* is the fourth corner stone of the European Space Agency Horizon 2000 program. It will be the first observatory studying the sub-millimeter domain from space in the range 100 µm to 600 µm. Herschel will be launched with an Ariane 5 rocket in the year 2007; it will be placed at the Lagrange point L2 at about 1.5 million kilometers from the Earth. Three instruments will be placed at the focus of its 3.5 meter antenna: the Spectral and Photometric Imaging Receiver (SPIRE), the Photoconductor Array Camera & Spectrometer (PACS) and the Heterodyne Instrument (HIFI).

Herschel will be a powerful instrument to address very numerous scientific objectives as galaxy formation in the early universe, the physics and chemistry of the interstellar medium and of cometary and planetary atmospheres [6]. Because of its wide frequency coverage, Herschel will allow the discovery of new molecules observable at sub-millimeter wavelengths only. As the submillimeter wavelength range offers unique transitions from light hydrides or highly excited heavier molecules, Herschel-HIFI will help the understanding of star formation and stellar evolution processes. It will also allow observations of key molecules like water which cannot be observed neither with ground-based telescopes, nor with airborne telescopes because they are very abundant in the Earth atmosphere. Water has been shown to be a common constituent of the interstellar gas (ISO results). It is thought to be the species of prime importance to trace the physical conditions of both the interstellar and circumstellar materials.

HIFI will have five channels using superconductor-insulator-superconductor (SIS) detectors to analyze the full 480-1250 GHz frequency domain and 2 more channels with hot electron bolometers (HEB) detectors for the 1410-1910 GHz domain. The astrophysical signal is initialy down converted to the 4-8 GHz frequency range and then analysed by two identical sets of spectrometers (one per polarization). For the both polarizations, each set of spectrometer is made of one Acousto Optic Spectrometer (AOS), providing a medium resolution of 1 MHz over a wide bandwidth of 4 GHz and one Auto Correlation Spectrometer (ACS), providing four observing modes with different channel spacing and bandwidth values which are listed in table 1.

Table 1. The ACS observing modes for one polarization.

Mode	Channel spacing	Bandwidth
High resolution	61 kHz	1×250 MHz
Medium resolution	122 kHz	2×250 MHz
Low resolution	244 kHz	4×250 MHz
Wide band	488 kHz	4×500 MHz

ARCHITECTURE OF THE HSO-HIFI AUTOCORRELATION SPECTROMETER

For each polarization, a filter bank splits the input bandwidth by means of four image rejection mixers (IRM) to produce eight 250 MHz sub-bands (Fig.1). Each sub-band is digitized by a 550 MHz clocked A/D converter.

Respectively 1, 2, 4 or 8 correlation modules with 512 channels each can be used on the same sub-band to obtain the different observing modes: wide band, low resolution, medium resolution or high resolution. A correlation module is made of two GaAs ASIC (2 x 256 channels) and one CMOS ASIC (512 channels).

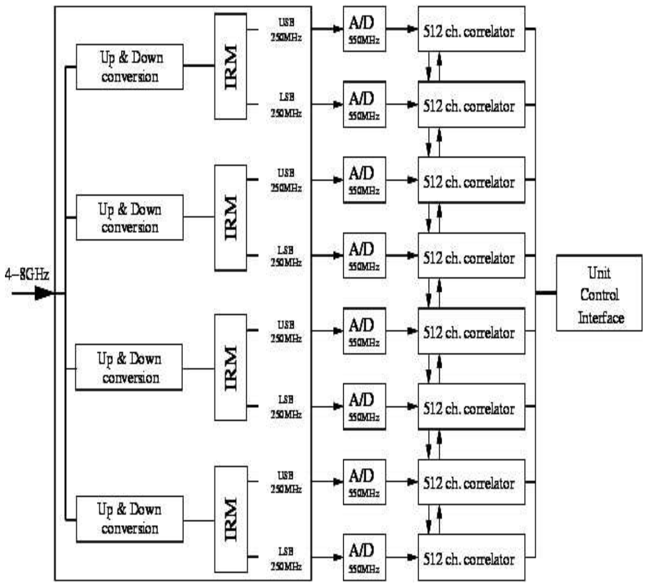


Fig. 1 : Architecture of the HSO ACS. Sub-bands of 250 MHz are produced by the upper and lower side-bands (USB and LSB) of image rejection mixer (IRM). 2, 4 or 8 of them are digitized and analyzed by 8 correlator modules of 512 channels each for a total of 4196 channels. The Up & Down converter allows to set the different subband independently in the 4-8 GHz frequncy range.

Analog To Digital Conversion And Efficiency

Before autocorrealtion computation, the input analog signal is digitized (sampled and quantized). Data sampling consists in locking the signal value for a duration T_s where $f_s = 1/T_s$ is the sampling frequency. The sampled signal is quantized using n_b bits. The value of n_b and therefore the encoding quality has to be chosen carefully because the quantization of the signal adds an extra noise, the *quantization noise*. The *efficiency* η (1) of a digital spectrometer is defined as the ratio of its signal to noise ratio in terms of detected power to the signal to noise ratio of an equivalent analog spectrometer (e.g. a filter bank).

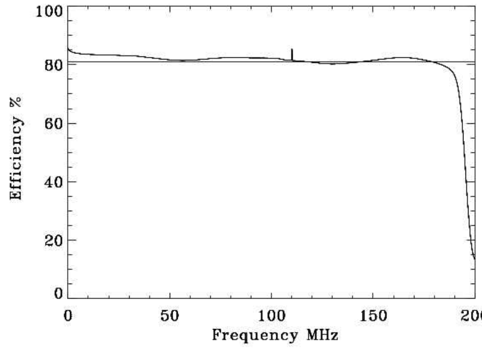
$$\eta = \frac{(s/n)_{dig}}{(s/n)_{ana}} \tag{1}$$

High values of n_b provide good efficiency but make the correlator design more complex. The simpler the encoding is, the faster the correlator is. We choose a 2 bit / 3 level code for the ACS. The optimal quantization is achieved when the comparison levels $+V_s$ and $-V_s$ are placed at $0.612/\sigma_x$ where σ_x is the standard deviation of the analyzed signal (assimilated to a gaussian white noise). In this case, we know from [3] that the efficiency is η = 81%. To compensate for the quantization noise, the integration has to be performed on a higher number of samples and the integration duration increases by the factor $(1/0.81)^2 = 1.52$ (see [1], [3] and [7]).

In practice, the analyzed signal is amplified and filtered so that its band shape is not perfectly flat. We note in this case that the efficiency is not equal to 81% on the whole analysed band. Measurments done on our prototype spectrometer have shown that the efficiency is frequency dependant. We managed to establish (2) that explains the relation between the efficiency and the analysed signal band shape. This equation is in agreement with our measurments (see Fig. 2).

$$\eta = \frac{1}{1 + \frac{B}{sp(f)}} \tag{2}$$

Where f is the frequency, sp(f) is the power spectrum of the input signal and B is the quantization noise spectrum (constant on all the bandwidth [4]).



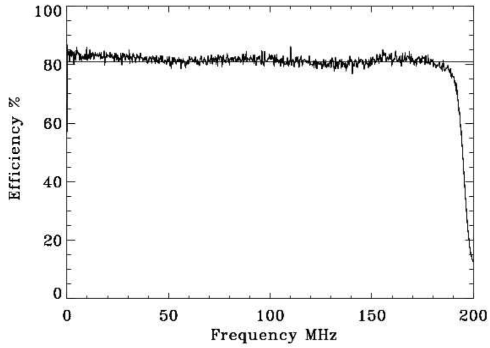


Fig. 2 . Left : the estimated efficiency using (2). Right : the measured efficiency.

Correlation Product Computation

The correlation product computation begins in GaAs ASICs at high speed, using the multiplication table given in table 2.

Table. 2. The true multiplication table (left) generates positive and negative values. The multiplication table used in the correlator ASIC (right) is shifted and multiplied by 1/2 to obtain only positive values.

x	-1	0	+1
-1	+1	0	-1
0	0	0	0
+1	-1	0	+1

x	-1	0	+1
-1	+1	1/2	0
0	1/2	1/2	1/2
+1	0	1/2	+1

The CMOS ASIC ends the hardware computation of the correlation coefficients at a lowest speed and allows the data readout.

Rounding Of The Correlation Coefficients

During an integration the correlator accumulates N correlation produtcs, the radiometric noise increases proportionately to $N^{1/2}$ while the correlation coefficient increases proportionately to N. Because the less significant bits are noised, only the most significant bits are meaningful and have to be read. This allows to reduce the data amount to be transmited. But in order not to spoil the correlator efficiency, the value of the most significant truncated bits has to be smaller than the radiometric noise. Therefore, to define the correlator architecture, we established a relation between the noise in a correlation channel and the integration duration (assuming that the input signal is a gaussian white noise), given by :

$$\sigma_n = \sqrt{d \times f_s}\,\frac{\sigma_x^2}{2}\sqrt{2\left(\frac{m_x}{\sigma_x}\right)^2 + 1} \qquad (3)$$

where σ_n is the radiometric noise in a channel, d is the total integration duration, f_s is the sampling frequency, m_x is the input signal average and σ_x is the input signal standard deviation.

Moreover, simulations show that if the less significant bit read is less than half (corresponding to one extra bit) the σ_n (determined from (3)) the correlator efficiency will be reduced by less than 1%. For the HSO-HIFI correlator, the minimum integration duration being about 100 ms and the maximum efficiency degradation acceptable being 1%, we discard the 9 less significant bits in the correlator.

Spectrum Computation

In an ACS the power spectrum is obtained by computing the Fourier transform of the autocorrelation function by means of a fast Fourier transform algorithm (FFT). Before FFT computation, the correlation coefficients of the input analog signal is computed from the correlation coefficients of the digitized signal, using a three dimension table. This table takes also into account the input signal power and offset (Fig. 3). The power σ_x and the offset m_x of the input signal are computed using :

$$\begin{cases} \sigma_x = \dfrac{V_s}{\phi^{-1}((2+m_{x_q}-C_{x_q}(0))/2)} \\ m_x = \sigma_x \phi^{-1}((2-m_{x_q}-C_{x_q}(0))/2) \end{cases} \tag{4}$$

where ϕ^{-1} is the reverse function of the gaussian repartition function, m_{xq} is the digitized signal offset (computed in real time in the correlator) and $C_{xq}(0)$ is the correlation coefficient 0 of the autocorrelation function.

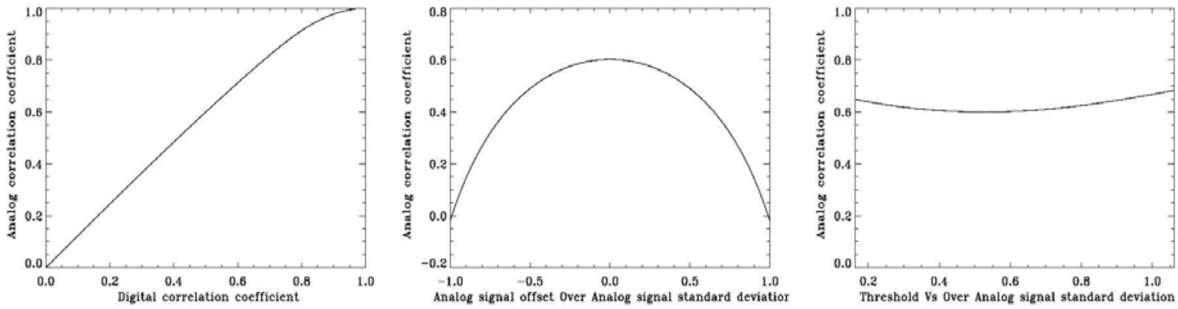


Fig. 3. Presentation of the three parameters taked into account in the three dimension correction table.

CONCLUSION

We present here some parts of the design characteristics and the architecture concept of the HSO-HIFI Auto Correlation Spectrometer. The prototype model allowed us to highlight some critical parameters. We may cite : i) the signal band shape has a direct influence on the digital spectrometer efficiency. ii) because the comparison thresholds cannot be tuned rigorously, an offset is introduced on the input signal and has to be corrected, during the data processing, using the three dimension correction table presented above.

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