Mem. S.A.It. Vol. 75, 282

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A wideband spectrometer for the SRT

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Abstract. A radiotelescope operating at millimeter wavelengths must be able to analyze an instantaneous bandwidth of at least a few GHz in spectroscopic mode, with a number of spectral points of the order of thousands. Two solutions are examined. In the first, it is assumed that a multi-channel digital spectrometer, with a bandwidth of the order of 100 MHz for each channel, will be available. In this case, a digital filterbank derived from the experience with the ALMA correlator could be used to synthesize a total bandwidth of 1-2 GHz. For wider bandwidths, an acousto-optical spectrometer is proposed. The experience at IRA, Sez. di Firenze with these instruments is presented, and possible solutions are outlined.

1. Introduction

A spectrometer operating at millimeter wavelengths must be able to analyze a very large instantaneous bandwidth. For example, to be able to cover a velocity span of 600 km s^{-1} at 100 GHz, an instantaneous bandwidth of at least 200 MHz is required. Even wider bandwidths are required in extragalactic observations, for example for a molecular survey in a cluster of galaxies.

Other observations require very wide frequency coverage, as for example searches for CO lines against strong background continuous sources, or molecular line surveys. In these observations it is important to explore the maximum instantaneous receiver bandwidth, which is typically greater than 2 GHz.

A spectrometer with an instantaneous bandwidth of 2 GHz can be reasonably built using well-proven technologies. In this work we will present some possible solutions, together with similar solutions already developed for other applications by our group.

In Sect. 2 we will present some possible solutions using a digital spectrometer. Solutions using acousto-optical spectrometers are presented in Sect. 3.

2. Digital wideband spectrometers

The current limit for a wideband digital spectrometer is imposed by thermal dissipation, and is currently in the range of 50-200 MHz. Faster instruments are limited by the maximum number of spectral channels, and are used in particular applications, like space-borne instruments, where size and total power consumption are of paramount importance.

Maximum speed depends also on the instrument's architecture. An autocorrelation spectrometer, with a small and repetitive basic unit, is intrinsically faster than a FFT spectrometer. The current tendency is however towards the latter, for their superior spectral purity and intrinsic immunity to interference.

It is possible to extend the bandwidth of a digital instrument using several spectrometers in parallel. The total bandwidth increases linearly with the *multiplexing factor N*, i.e. the number of spectrometers that operate together.

A particularly attractive feature of this approach is that a multi-channel spectrometer must be present in any radiotelescope, to support multi-pixel receivers. Receivers with 16 channels (8 channels times 2 polarizations) or more will be employed in the SRT. Therefore it can be assumed that a 16-channel spectrometer, needed for such an instrument, will be available. In this case, a $N = 16$ multiplexed wideband spectrometer will be easily implemented with a small additional cost.

The two possible approaches are:

- Time division multiplexing. Each spectrometer analyzes a subset of the samples in a given time frame.
- Frequency division multiplexing. Each spectrometer analyzes an independent portion of the input bandwidth, that has been previously split by a filterbank.

A time-division spectrometer is intrinsically simpler than a frequency-division instrument, but has a lower number of spectral points. Both approaches can be used either with FFT or autocorrelation spectrometers.

2.1. Time-division spectrometers

In this approach, the sampled radio signal is divided into large frames, e.g. 1 ms long. Each frame is stored into a large memory, and further divided into N contiguous segments. Then each segment is *played back* at a reduced speed, and analyzed by a separate spectrometer.

Each spectrometer produces in this way a spectrum compressed by a factor N. For example, if the original bandwidth is 2 GHz wide, and N=32, the spectrometer produces a spectrum 125 MHz wide, representing the original bandwidth. To reconstruct the original spectrum, all N spectrometer outputs are co-added, and the spectral scale is re-expanded by a factor N.

This approach is very cheap and easy to implement, as it requires essentially a large memory and some simple framing logic. The main disadvantage is that the spectral resolution of the correlator is also expanded by a factor N, or that the total number of independent spectral points is equal to the number of spectral points in a single spectrometer. In the previous example, if the individual spectrometer has a resolution of 1 MHz (125 points per spectrometer), the final spectral resolution is 16 MHz, or we are using 16 125-point spectrometers to obtain a single 125-point final spectrum.

Examples of this approach are provided by the GBT and ALMA spectrometers (Escoffier et al. 2005).

2.2. Frequency-division spectrometers

In this approach, the initial bandwidth is divided into several sub-bands, and each of them is separately analyzed by a spectrometer.

This approach has recently evolved with the availability of fast digital filters. The possible architectures for the filterbank are thus:

- Analog filterbank: requires a complete receiver for each sub-band, including a separate digitization stage. It is expensive, and difficult to correctly calibrate.
- Digital passband filter: (Nyquist filtering) a set of N filters with a band comprised between iB/N and $(i+1)B/N$ ($i = 0 \dots N-1$). The signal is downconverted by decimating it at a frequency $2B/N$, according to the sampling theorem. The filter shape must be very sharp, to reduce the amount of data lost in the filterband edges.
- Polyphase filterbank: is basically an N-point FFT, performed by a small and fast FFT engine, preceded by a narrow filter. The filter response is translated by the FFT processor, producing N adjacent replicas of its passband. This approach produces a set of disjoined sub-bands similar to the previous case, but with a much simpler hardware.
- Digital BBC: is composed of N complete digital receivers, each one independently tunable across the filterbank. In this way, the individual sub-bands may overlap, easing the requirements on the filter sharpness and allowing a very large operational flexibility.

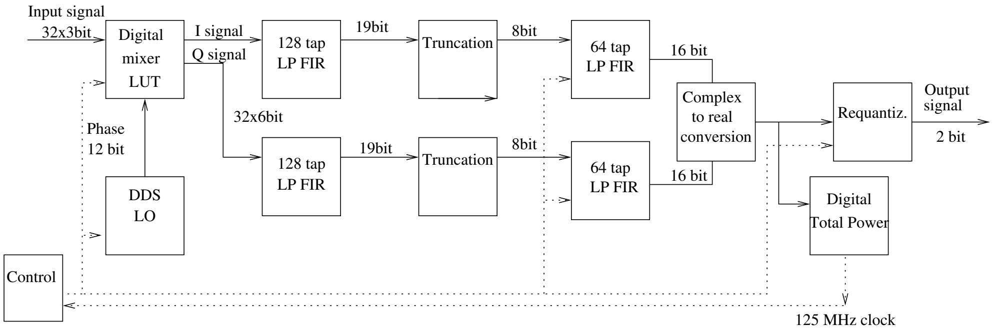

Fig. 1. Schematic of a BBC for the ALMA correlator.

The advantages of the frequency division approach is that the spectral resolution of the original spectrometers is preserved, allowing for a much higher number of independent spectral points across the bandwidth. It is possible to use only arbitrary portions of the original bandwidth, allowing for ”zooming” modes in which individual spectral features are analyzed in greater detail.

The filterbank is however relatively complex to build, and individual sub-bands must be carefully calibrated to avoid degradation in the composite spectrum quality, especially for analog filterbanks. The spectral quality degrades at the sub-channel edges, especially for polyphase and Nyquist filtering, but the problem can be afforded using digital BBCs.

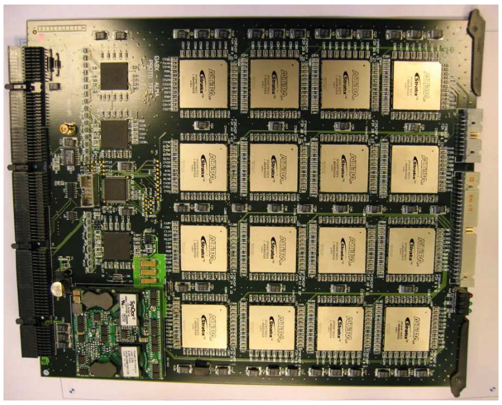

Fig. 2. Filterbank board for the ALMA correlator.

The availability of large field programmable gate arrays (FPGA) allow large filterbanks to be economically implemented. The Arcetri observatory has been involved in the design of a 32-channel filterbank used in the ALMA correlator (total bandwidth 2 GHz, N=32) (Quertier et al. 2003). Each BBC (Fig. 1) is independently tunable, with a resolution of 30 kHz, across the whole 2 GHz input band. The passband is determined by a complex 2-stage low-pass filter, with a relative bandwidth of 94% and 0.3dB flatness.

The filterbank fits in a single board (Fig. 2), for which a prototype has been built at the Observatory of Bordeaux. The prototype cost is around 7000 Euro, with an estimated production cost of 3000 Euro. Performances have been tested in the correlator and correspond to the design specifications.

3. Acousto-optical spectrometers

A completely different solution is represented by an acousto-optical spectrometer. In this class of instruments, the radio signal is transformed into an acoustic wave travelling inside a transparent crystal (Bragg cell). The associated density wave diffracts a laser beam, that is focused on a CCD detector, where it forms an image corresponding to the power spectrum of the original radio wave (Fig. 3).

The main advantages of these instruments are their simplicity, based on well-proven concepts, robustness, small volume and power dissipation. Typical weight and power require-

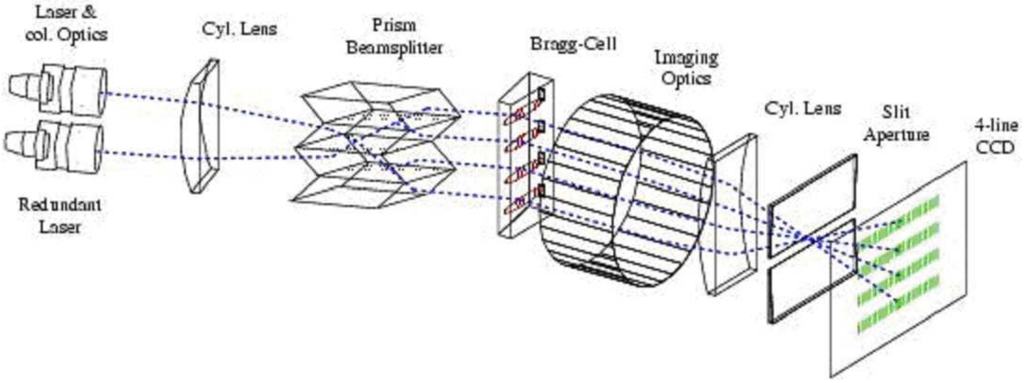

Fig. 3. Schematic of a 4-channel acousto-optical spectrometer.

ments, including the IF processor, are around 10 kg and 100 W.

On the other hand these instruments are rigid, with fixed bandwidth and resolution, and are sensitive to temperature variations and mechanical vibrations.

The Florence group has built several AOS instruments, and in particular:

- A back-end for a 800-810-GHz spectrometer, based on a Lithium Niobate cell. The instrument is a cooperation with Kent University, RAL, Bath University, SRON and IRA, Sez. di Firenze. The instantaneous bandwidth is 1 GHz, and the resolution 0.8 MHz. This instrument has been used at UKIRT to observe the CO J=7-6 line at 806.651 GHz, and CI at 809.345 GHz.
- A 4-channel Li-Nb instrument for the Herschel HiFi instrument (Figs. 3, 4; Schieder et al. 2000). In this instrument the cell is used to observe simultaneously 4 independent radio signals, in order to obtain a total bandwidth of 4 GHz (4×1.1 GHz, with overlaps). The spectral resolution is 1 MHz. The instrument has been built as a cooperation between Köln University, IRA, Sez. di Firenze, MPS Lindau, Galileo Avionica and ASI.

With the available cells, an AOS instrument for SRT could be built using a 2-channel cell, with a total bandwidth of 2 GHz. Rutile (TiO_2) cells may provide a 3-GHz bandwidth,

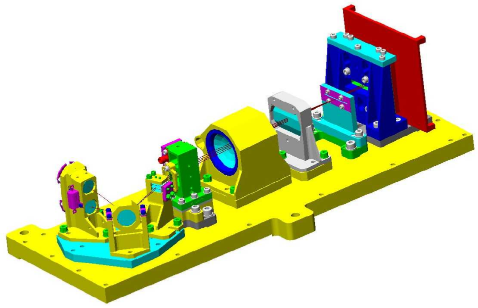

Fig. 4. 4-channel AOS for Herschel HiFi.

if used with a 488-nm laser beam. With these cells, and a 3-channel instrument, it is possible to reach a total bandwidth of 10 GHz .

4. Conclusions

Assuming that the SRT will be equipped with a multi-channel digital spectrometer, with about 16 channels of 100-150 MHz each, it is possible to synthesize a broadband spectrometer using either time-division (multiplexing) techniques, or a fast filterbank, derived from the experience gained with the ALMA correlator. This wideband spectrometer would have a total bandwidth close to the sum of the individual channels of the original spectrometer, i.e. about 2 GHz, sufficient for at least some of the proposed wideband observational projects.

For even wider bandwidths, an AOS instrument must be used. Using new cells and multi-channel configurations, a bandwidth of up to 10 GHz can be obtained.

References

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