AUTOCORRELATION SPECTROMETERS FOR SPACE BORNE (SUB)MILLIMETRE SPECTROSCOPY

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ABSTRACT
The autocorrelation spectrometer is one of four types of spectrometers being considered for space based (sub)millimetre heterodyne systems. The potential advantages of the digital autocorrelation spectrometer compared to Chirp Transform, Acousto Optical and Filterbank spectrometers are: stability, compactness, high reliability and variability in bandwidth and resolution. The disadvantages for some applications are slightly reduced sensitivity (-10 to -15 %) and higher power consumption.

The results of a parametric study of autocorrelation spectrometers for the Master, Soprano and First projects will be described as well as the design of an autocorrelation spectrometer being developed for the ODIN satellite. In addition, a possible realization of the FIRST spectrometer will be outlined.

1. INTRODUCTION
In many applications when a signal is analysed with high spectral resolution, sometimes in the order of ten to the power of six or higher, heterodyne receivers are employed. In signal to noise limited applications, such as (sub)millimetre astronomy, the system is often divided into a low noise "Front-End" and a spectrometer type "Back-End".

In its most general form, a spectrometer can be considered to be a device that receives an input signal, which is variable in time, and estimates its power spectral density. The estimate is given sampled at N equidistant frequency points, or channels, \( f_0, f_1, \ldots, f_{N-1} \), separated in frequency by \( B/(N-1) \), where \( B \) is the bandwidth of the signal. Critical parameters are the total bandwidth, the transfer function of each channel, \( H(f) \), and the stability of the spectrometer.

Even if the noise level of the spectrometer is uncritical, it must be very efficient, i.e. a commercial swept filter spectral analyser, that process only one "channel" at a time, will not do. The special environment of a satellite will add additional constraining requirements on the design of a "Back-End" spectrometer, such as low power consumption, size and weight. Of course, the quality aspects, such as radiation tolerance, must be considered all through the design work.

The most widely used spectrometers in radio astronomy are; the Acousto-Optical Spectrometer, the Autocorrelation Spectrometer and the Filterbank Spectrometer. Spectrometers based on all types of technology, except the Autocorrelation type, must be designed with fixed bandwidth and resolution, i.e. they are very inflexible for different kinds of observations. The Autocorrelation Spectrometer is in this regard flexible, but can suffer from a comparably high power consumption when processing very wide bandwidths.

Figure 1. Submillimetre heterodyne system.

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The main part of the processing as well as the detection function in the autocorrelation spectrometer is done in the time domain. This has many advantages, one being that the signal can be digitized with few quantisation levels, and high speed digital electronics can be used for the processing with all the advantages of stability and system integration. State of the art autocorrelators use two-bit precision with about 90% efficiency.
To be able to process extremely wide bandwidth signals (1-4 GHz), most spectrometers must use a pre-filtering stage to reduce the wide signal band into several less wide sub-bands, thus using a hybrid technique. The bandwidth of the filters can be 1-1.5 GHz for the AOS, 0.3-0.5 GHz for the CTS and 0.2-1 GHz for autocorrelation spectrometers.

In addition, there can be system operational advantages of utilising several subbands with covering different frequency bands and/or with different bandwidths and resolution.

2. SPECIFICATIONS

There are six spectrometer specifications that are used as reference in this paper. In Table 1, the given bandwidth and resolution specifications are listed, complemented with estimated conditions.

<table>
<thead>
<tr>
<th></th>
<th>Bandw. (GHz)</th>
<th>Resol. (MHz)</th>
<th>PWR (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FIRST</td>
<td>0.25-2</td>
<td>0.25-2</td>
<td>25</td>
</tr>
<tr>
<td>ODIN</td>
<td>0.8</td>
<td>0.1-1</td>
<td>12</td>
</tr>
<tr>
<td>SOPRANO HR</td>
<td>0.02</td>
<td>0.3</td>
<td>3</td>
</tr>
<tr>
<td>SOPRANO WB</td>
<td>5</td>
<td>3</td>
<td>25</td>
</tr>
<tr>
<td>MASTER HR</td>
<td>0.6</td>
<td>3</td>
<td>8</td>
</tr>
<tr>
<td>MASTER WB</td>
<td>10</td>
<td>50</td>
<td>30</td>
</tr>
</tbody>
</table>

Power consumption is estimated for all but the ODIN case which is based on measurements.

The measured values in each channel can have certain errors associated with them, usually a sum of the noise, non-linearity errors and spurious signals. While the noise is unavoidable, it will decrease with integration time and the noise bandwidth of each detector channel, i.e. \( \approx \) the resolution:

\[
\text{Noise} = \frac{T_{sys}}{\text{Integration time} \cdot \text{Resolution}}
\]

For a well designed system, this term will dominate the error in the measured values. With a stable system combined with well planned measurement methods, this equation can be valid for up to several hours.

For very high signal to noise ratios, non-linearity errors can dominate the measurement accuracy. For all types of spectrometers, there is a certain amount of non-linearity in the IF-chain, inside or outside the spectrometer. For an AOS or a Filterbank there is also a non-linear behavior associated with each frequency channel as these use independent detectors.

The Noise level in itself sets the requirements for long term stability and for the FIRST and ODIN case, were in some situations the integration time could be several hours, this must be considered. However, the spurious responses are usually determined by layout, shielding and other such measures, and levels that would allow several hours of integration time is achievable.

3. AUTOCORRELATION SPECTROMETERS

The autocorrelation spectrometer is based on Wiener-Khintchine theorem:

\[
S(\omega) = \int R(\tau) e^{-j\omega\tau} d\tau
\]

where

\[
S(\omega) = \text{power spectrum}
\]
\[
R(\tau) = \text{autocorrelation function}
\]

This is the theoretical foundation of the autocorrelation spectrometer, but the digital implementation differs in a number of points from the equations outlined above. The main differences are:

(i) the data is discrete in time
(ii) the data is discrete in amplitude
(iii) the data set is finite

Point (i) is taken care of by the Nyquist criteria, i.e., as long as we sample with a rate twice the input bandwidth or higher, the sampled values contains all the spectral information. In reality, the signal is sampled at a slightly higher rate to accommodate the finite slope of the filter preceding the digitizer.

That the data is sampled with very coarse accuracy, usually with one or two bit precision, has two implications. The major is that the signal to noise ratio is degraded, but for a 2-bit autocorrelator, the degradation factor is only about 0.88. The actual degradation depends on the number of bits used, the decision levels in the quantizer, on the multiplication scheme and on the statistics of the input signal. The other implication is that the correlation estimate is biased, but this is easily taken care of in the processing steps preceding the Fourier-transform.

In a physical realisation of the ACS, the signal is frequency translated, filtered and conditioned before the digitization and correlation.

The digitized signal is delayed in a number of discrete steps, and the delayed samples are multiplied with an undelayed version of the same signal. The products from the multiplications are then integrated and accumulated separately for each of the delay stages. After a specified integration period, usually of the order of seconds, the autocorrelation function is transformed to the frequency domain to form the power spectrum.
4. ODIN SPECTROMETER
The ODIN satellite is a joint aeronomy and astronomy mission. The main payload consist of four tunable heterodyne schottky receivers in the frequency range 480-570 GHz and one fixed tuned 119 GHz heterodyne system. In addition, there is a UV-spectrometer.

There are four back-end spectrometers connected to the five heterodyne systems, two autocorrelation spectrometers, one AOS and one 3-channel filterbank.

![Figure 3. ODIN spectrometer breadboard.](image)

Omnisys Instruments are has designed the ACS, the filterbank and the Front-End control electronics, including reference oscillators and PLL systems for the 600 GHz LO system.

The ODIN ACS highlights
- 100-800 MHz bandwidth in steps
- 0.13-1.1 MHz resolution
- 1 kg
- 220x180x30 mm
- 12 W
- Full custom ADC ASIC
- Full custom Correlator ASIC
- MCM-L SSB subsystem at 4 GHz
- MCM-L correlator module, 8 ADC + 8 correlator chips
- 6-way input multiplexer
- 16-bit CPU controller

![Figure 4. MCM with two correlator ASIC’s.](image)

The development of the ACS has included two ASIC designs, one correlator chip (CC) and one Analog to Digital Converter (ADC). The CC is manufactured in MHS 0.6 um, 3ML, radiation tolerant process and performs 21 billion correlations per second at 380 mW power consumption. The ADC is manufactured in the Ericsson P28 bipolar process and consumes 180 mW.

Several of the subsystems in the spectrometer is now in manufacturing for a prototype/EM model test. The first tests of a fully assembled spectrometer is now being performed in the lab. In Figure 3, an early breadboard is shown and the MCM close-up in Figure 4 shows two correlator ASIC’s.

In Figure 2, a spectrum with 300 kHz resolution is shown, comparable to the First specification.

5. ESTEC STUDY
This evaluation was part of a proposed three year study, with the first year focusing on system level design issues, quality aspects and comparison of different design strategies and technologies. In total, ASIC subcircuits in ten different technologies and architectures have been designed and simulated, using extracted data from layouts.

The main results were:

Best candidates for Correlator Chip implementation
- 0.5-0.6 um CMOS, (rad tolerant from MHS)
- Full custom GaAs can be alternative for wide bandwidth/low resolution
- 5-10 mW / ch /GHz possible

Best candidates for ADC Chip implementation
- GaAs for 2 GHz + operation
- Advanced bipolar for < 1.5 GHz

This development is scheduled to continue starting in June-97 and continue for about two years. Although the target for the planned demonstrator spectrometer based on new ASIC’s is the Master specifications, the results can be applied for a FIRST spectrometer.

6. FIRST SPECTROMETER
There are several ways of realising an autocorrelation based spectrometer for FIRST and three alternatives are:

- **Option A:**
  Use ODIN Correlator and ADC Chip
  New MCM module, modified IF processing
  250 kHz resolution over 800 MHz: 18 W.

- **Option B:**
  Port ODIN chip design to 0.5 um Matra process
  8 x 200 MHz sub-bands (individual tuning)
  250 kHz resolution over 1.6-2 GHz: 22-25 W.

- **Option C:**
  New design for 0.5 um Matra process
  4 x 500 MHz sub-bands, (individual tuning)
  250 kHz resolution over 2.0 GHz: 25 W.
It seems that option B is perhaps the best compromise in terms of performance and cost. The main features would be:

• Optional input mux
• 4 GHz input bandwidth
• 1.6-2 GHz processed bandwidth
• 4000 or 8000 processed channels
• 4 individual subband systems
• inherent redundancy

with and estimated specification of:

• Size: 300x200x40 mm
• 4000 channels: 23 W
• 8000 channels: 30 W
• Weight: 1 kg

![Figure 5. A FIRST ACS realisation.](image)

A block diagram is shown over the proposed FIRST ACS system. The specification and realisation must of course be adapted to the final requirements of the mission, but this is easily accomplished with the basic building blocks.

With the experience from the ODIN ACS, the development should take about 3 years and 15 manyears divided on in the following way:

- CC ASIC: 2 my
- ADC ASIC: 1 my
- IF processor: 1 my
- SSB system: 2 my
- MCM: 1 my
- CPU+PWR: 1 my
- Instrument: 1 my
- Production+Quality: 4 my
- Project management: 2 my

7. QUALITY ASPECTS

For the autocorrelator spectrometer to be competitive, it must be based on full custom ASIC circuits. In addition, the technology must be advanced with the best speed / power combination possible. This indicates that a power penalty must be taken if conservative, technology is chosen.

For the high performance needed for some of the instruments discussed, MCM (Multi Chip Module) technology seems like the logical choice. Even if high speed interconnects constitutes a potential problem area, the architectures are simple with short interconnects with matched lengths and no global timing required. The total number of interconnects is also comparably low.

8. CONCLUSION

As a result from recent work, a general conclusion is that autocorrelation spectrometers can be very competitive with other type of spectrometers for space based (sub)millimetre radiometry. The main advantages are compact implementations, scalability and versatility in bandwidth and resolution combinations combined with potentially very high stability. The disadvantages can be lower efficiency (85-95 %) and for some cases higher power consumption.

For the autocorrelator spectrometer to be competitive, it must be based on full custom ASIC circuits. In addition, the technology must be advanced with the best speed / power combination possible. However, suitable processes is or will be available in near future, i.e. MHS rad tolerant 0.5 um, 3 ML process.

The relative complexity and qualification problems of designing ASIC’s should be compared with the development and qualification of components needed for other types of spectrometers, i.e. lasers, bragg cells and CCD:s for the AOS, and Chirp filters for the CTS.

Despite the low budget for the development of the ODIN ACS, it will consume less power than specified, i.e. 12 W instead of 15-18 W. Based on this experience, the development of an ACS for FIRST will be comparably straightforward and qualification methods for the various components and subssystems exist.

9. REFERENCES


