# AVN Training 2017

Digital Autocorrelation Spectrometers

For spectral line observations

# Overview

- Brief discussion of radio spectral lines, especially the discovery of the hydrogen line at 1420 MHz.
- Instruments for observing spectral lines
- Advantages and disadvantages of different instruments
- The digital autocorrelation spectrometer - the HartRAO Woodhouse correlator, a case study.
- How observations are made and eliminating instrumental effects.

# Radio Spectral Lines – an historical diversion

- The first discoveries in radio astronomy were continuum emission from the Milky Way and the Sun.
- Prof Jan Oort, of Leiden University in the Netherlands realised the potential of radio spectral lines and asked a PhD student, Henk van der Hulst to investigate the possibility of radio spectral lines.
- Very small energy changes, **ΔE,** in atoms and molecules could result in emission or absorption, (depending on the sign of **ΔE**) of radio emission according to:
- **ΔE = hν (H = Planck's constant, ν = frequency)**
- Van der Hulst found that a change in the electron spin in neutral atoms (e.g. spin up to spin down) would result in radiation at 1420 MHz or 21 cm wavelength.
- They set out to observe this but before they could a fire destroyed part of their equipment.

# First detection of the 21 cm Hydrogen line

- Several other groups considered searching for the hydrogen line.
- Russian theoreticians and experimentalists discussed the possibility, but concluded that the transition probability and density of hydrogen were unknown and likely to be very small, they abandoned plans search for the emission.
- The Australians also discussed looking, but decided to continue with their own successful projects.
- Two Americans at Harvard, Edward Purcell and PhD student Harold Ewen decided to take the chance, although they did worry that the Russians may get there first. Ewen and Purcell were the first to succeed.

# • Ewen's Receiver

## Ewen and Purcell's project

Ewen and Purcell applied for $500 funding.

This was largely for the construction of the horn and part of the receiver.

The receiver was designed to scan across a range of frequencies ccentred on the expected line frequency.

The horn was pointed out of a window for their laboratory.

402 The 21 cm hydrogen line

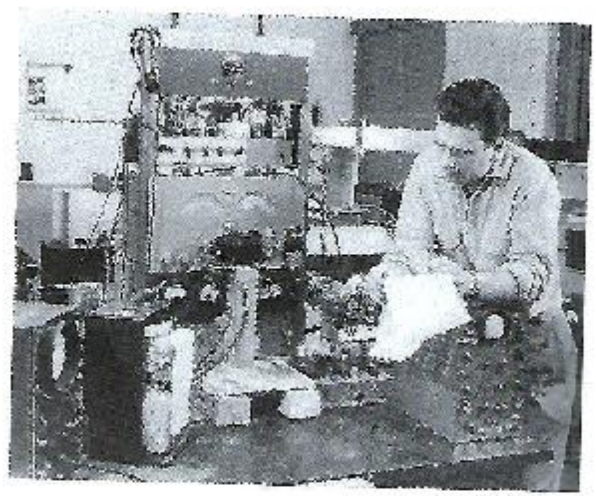


Figure 10.4 Ewen and part of his 21 cm spectrometer. The 27 MHz IF amplifier, a modified version of a [illegible] was [illegible] by the [illegible] mounted on the wooden post. Above this is the lock-in amplifier necessary for [illegible] and to the lower left is the strip chart recorder. The waveguide leading to the horn [illegible] window can be seen [illegible]

# The horn used for the detection of the hydrogen line at Harvard



Figure 16.[illegible] The pyramidal horn antenna (copper-clad plywood) at Harvard's Lyman Laboratory with which Ewen and Purcell detected the 21 cm hydrogen line from the Milky Way on 25 March 1951.

# Hydrogen line scan with Ewen’s receiver

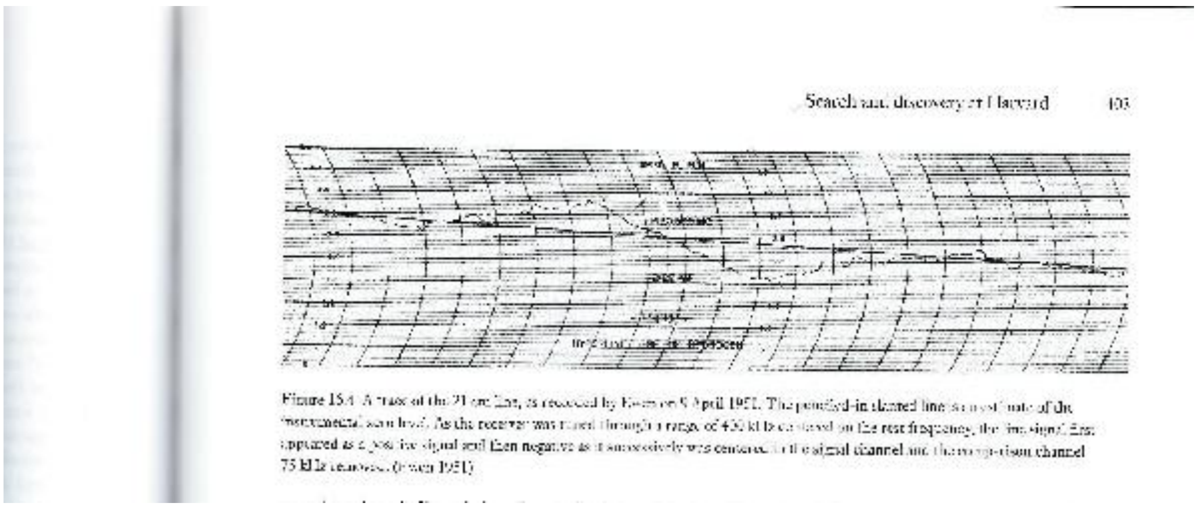

Search and discovery at Harvard 103

Figure 15.4 A trace of the 21 cm line, as recorded by Ewen on 5 April 1951. The penciled-in slanted line is an estimate of the instrumental scan level. As the receiver was tuned through a range of 450 kHz centered on the rest frequency, the line signal first appeared as a positive signal and then negative as it successively was centered in the signal channel and the comparison channel 75 kHz removed. (Ewen 1951)

# Importance of spectral lines

- Hydrogen is the most abundant element in the universe, and atomic hydrogen was previously undetected.

- Radio observations measure the velocity from Doppler shifts and show the distribution of hydrogen in the Galaxy and in external Galaxies,  allowing for studies of their structure.

- Spectral lines therefore provide more information than continuum measurements do. This will be covered in other lectures today.

- There have been searches for other atomic and molecular species which have enriched our knowledge the Galaxy.

# Early hydrogen line receiver

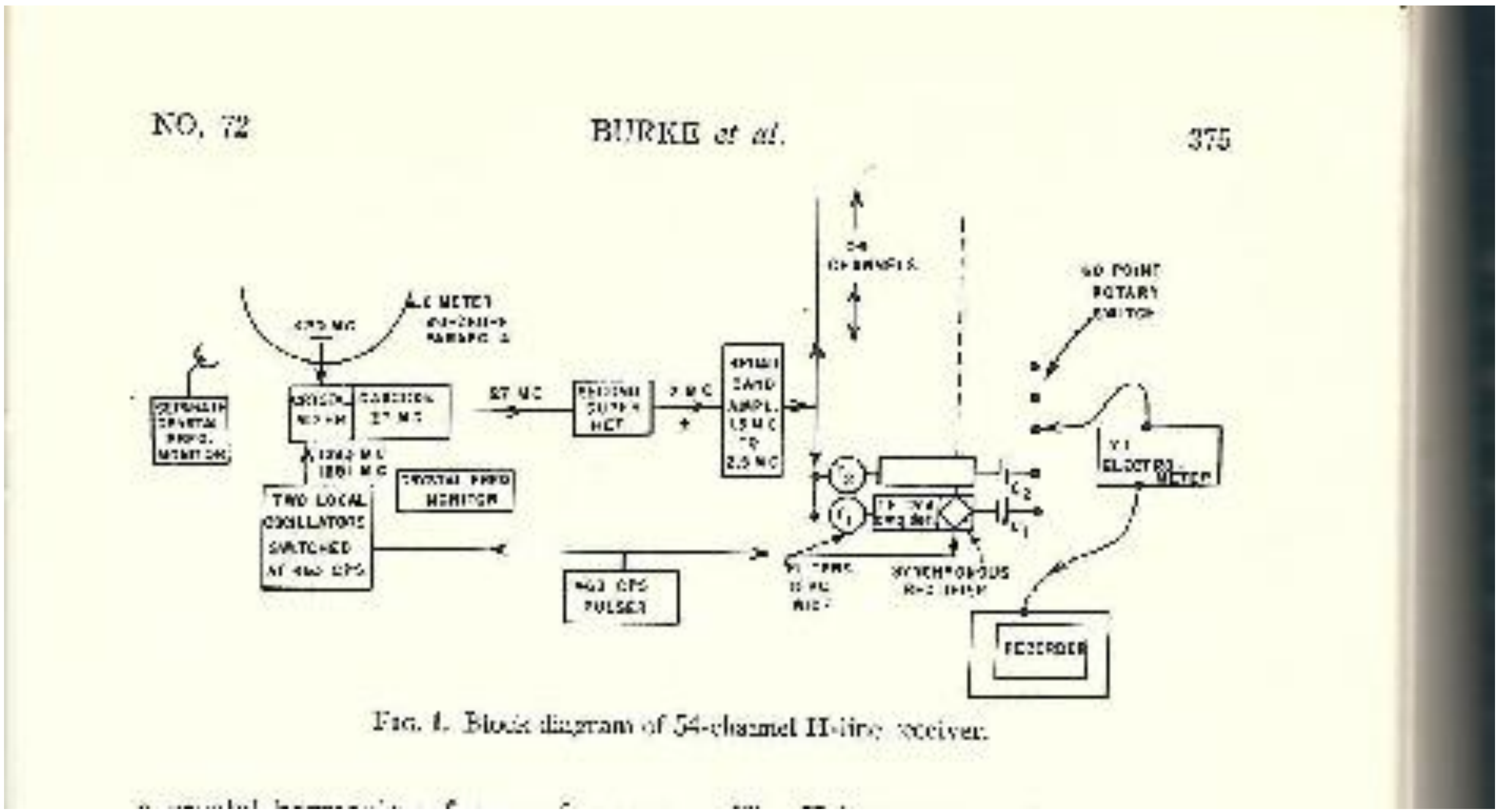
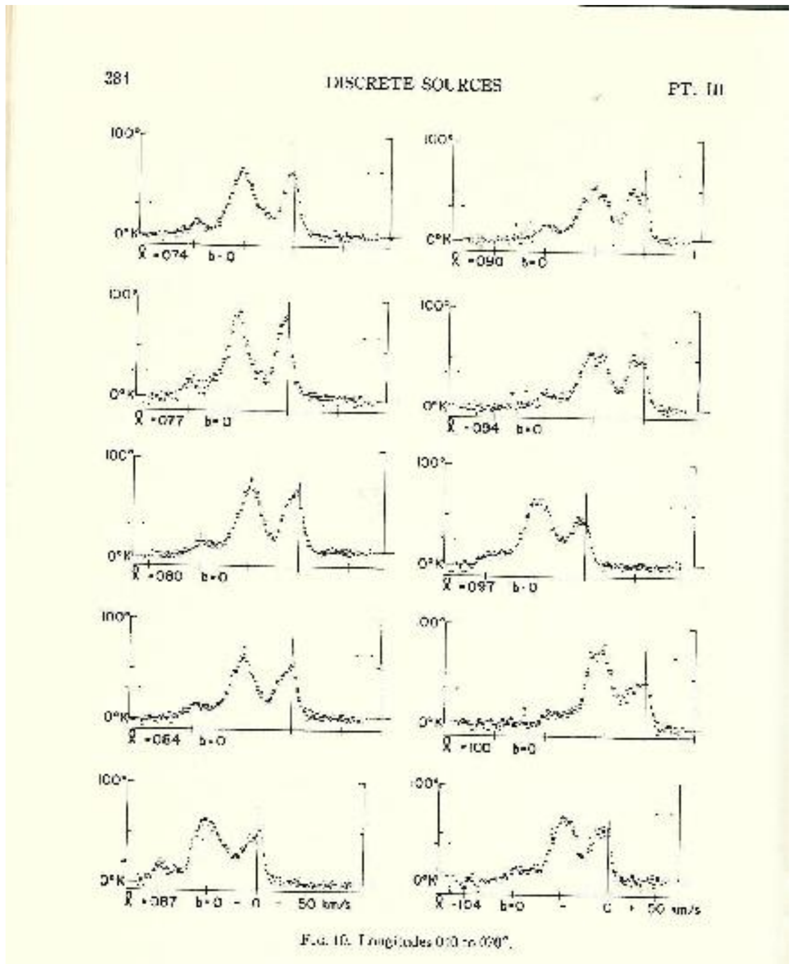

NO. 72 BURKE *et al.* 375



FIG. 4. Block diagram of 54-channel H-line receiver.

# Hydrogen spectra (Burke et al, 1958)

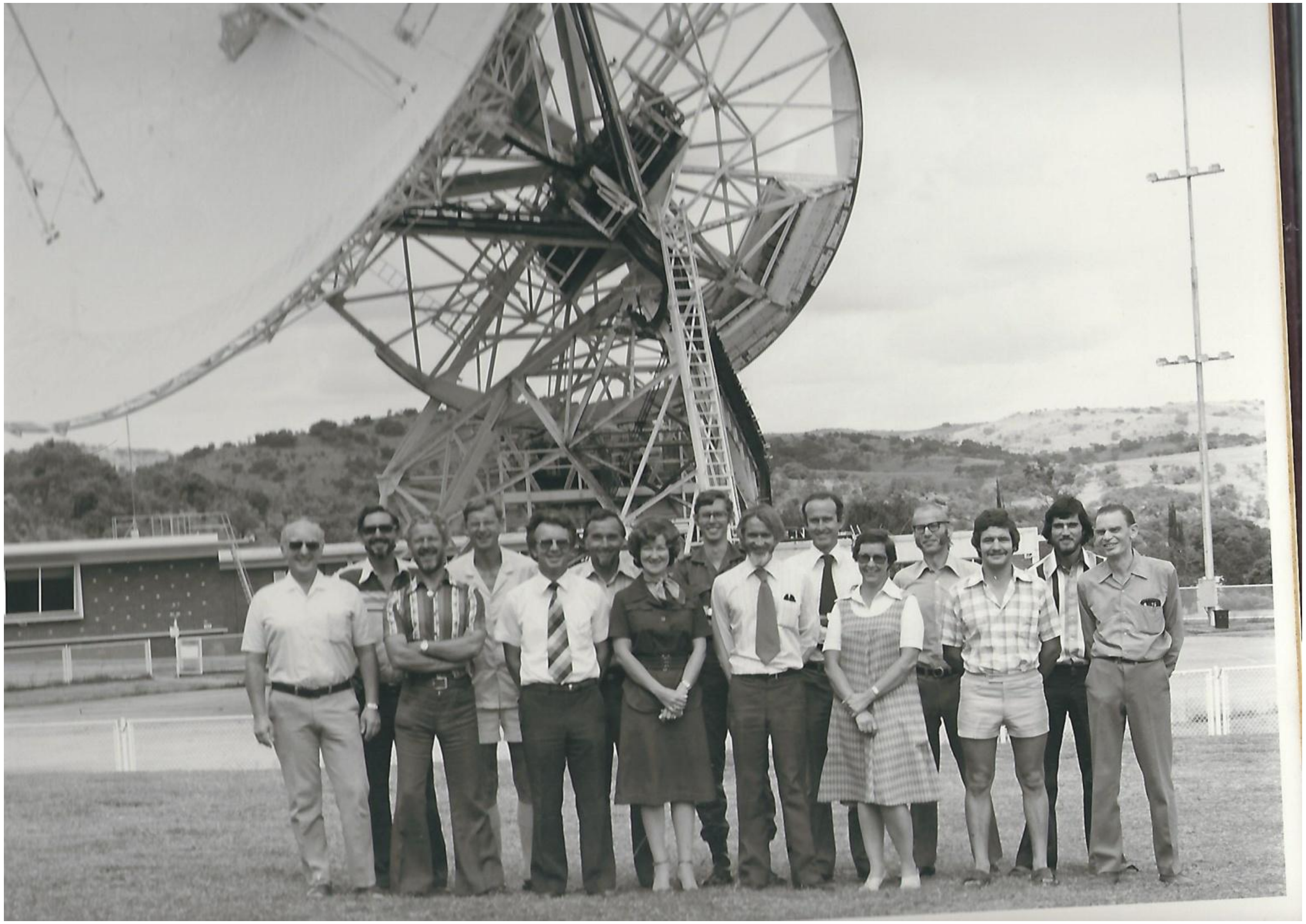


# Disadvantages of multi-channel spectrometers

- Multichannel receivers worked well when there was only one spectral line to study.
- The discovery of Hydroxyl at 1665/1667 MHz revealed much narrower lines requiring finer filter resolution, so mutiple filters say v.
- Subsequent discoveries included formaldehyde at 4830 MHz, water vapour at 22 GHz, methanol at 12.2 GHz and 6.7 GHz, plus many other species at millimetre wavelengths.
- Study of these requires a versatile spectrometer  which can integrate for long periods for weak sources, and operate with different resolutions if required.
- The solution is the digital autocorrelation spectrometer.

# The HartRAO Woodhouse correlator

## Staff photograph in 1978 showing key players



# First HartRAO MSc Thesis on Instrumentation

Dr Peter Harvey, a half-time staff member with a PhD from Jodrell Bank proposed building the correlator.

Guy Woodhouse, an electronics engineer at our parent laboratory, had spare time as his project had ended.

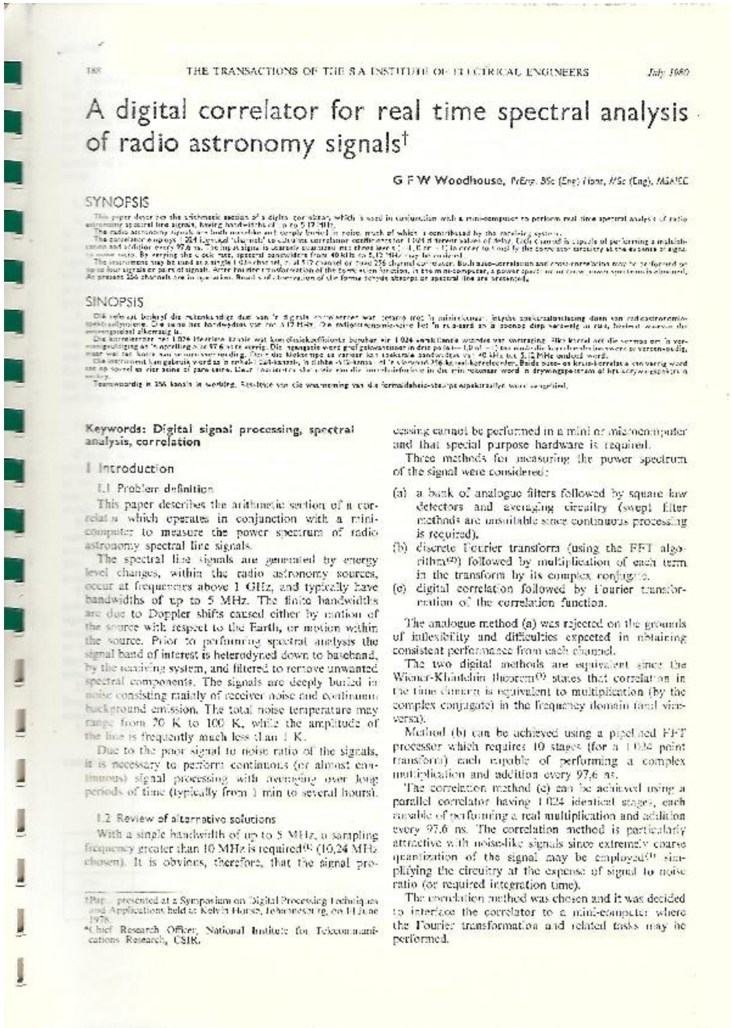
He used the project as an MSc topic

Jan Marben laid out and built all the printed circuits. The full design required over 5000 integrated circuits.

Originally designed for 1024 channels, only 512 were implemented.

Don Cameron wrote the initial software.

Mike Gaylard was given responsibility for commissioning the correlator and he and others used it for over twenty years before it was replaced with the current unit.



188 THE TRANSACTIONS OF THE S A INSTITUTE OF ELECTRICAL ENGINEERS July 1980

## A digital correlator for real time spectral analysis of radio astronomy signals†

G F W Woodhouse, PrEng, BSc (Eng) Hons, MSc (Eng), MSAIEE

SYNOPSIS

SINOPSIS

Keywords: Digital signal processing, spectral analysis, correlation

### 1 Introduction

1.1 Problem definition

This paper describes the arithmetic section of a correlator which operates in conjunction with a mini-computer to measure the power spectrum of radio astronomy spectral line signals.

The spectral line signals are generated by energy level changes, within the radio astronomy sources, occur at frequencies above 1 GHz, and typically have bandwidths of up to 5 MHz. The finite bandwidths are due to Doppler shifts caused either by motion of the source with respect to the Earth, or motion within the source. Prior to performing spectral analysis the signal band of interest is heterodyned down to baseband, by the receiving system, and filtered to remove unwanted spectral components. The signals are deeply buried in noise consisting mainly of receiver noise and continuum background emission. The total noise temperature may range from 70 K to 100 K, while the amplitude of the line is frequently much less than 1 K.

Due to the poor signal to noise ratio of the signals, it is necessary to perform continuous (or almost continuous) signal processing with averaging over long periods of time (typically from 1 min to several hours).

1.2 Review of alternative solutions

With a single bandwidth of up to 5 MHz, a sampling frequency greater than 10 MHz is required[1] (10,24 MHz chosen). It is obvious, therefore, that the signal processing cannot be performed in a mini or microcomputer and that special purpose hardware is required.

Three methods for measuring the power spectrum of the signal were considered:

(a) a bank of analogue filters followed by square law detectors and averaging circuitry (swept filter methods are unsuitable since continuous processing is required).
(b) discrete Fourier transform (using the FFT algorithm[2]) followed by multiplication of each term in the transform by its complex conjugate.
(c) digital correlation followed by Fourier transformation of the correlation function.

The analogue method (a) was rejected on the grounds of inflexibility and difficulties expected in obtaining consistent performance from each channel.

The two digital methods are equivalent since the Wiener-Khintchin theorem[3] states that correlation in the time domain is equivalent to multiplication (by the complex conjugate) in the frequency domain (and vice-versa).

Method (b) can be achieved using a pipelined FFT processor which requires 10 stages (for a 1024 point transform) each capable of performing a complex multiplication and addition every 97,6 ns.

The correlation method (c) can be achieved using a parallel correlator having 1024 identical stages, each capable of performing a real multiplication and addition every 97,6 ns. The correlation method is particularly attractive with noise-like signals since extremely coarse quantization of the signal may be employed[4] simplifying the circuitry at the expense of signal to noise ratio (or required integration time).

The correlation method was chosen and it was decided to interface the correlator to a mini-computer where the Fourier transformation and related tasks may be performed.

†Paper presented at a Symposium on Digital Processing Techniques and Applications held at Kelvin House, Johannesburg, on 14 June 1978.

*Chief Research Officer, National Institute for Telecommunications Research, CSIR.

# How Does it work ?

- Several principles are essential to understand the operation of digital spectrometers.

1. The sampling theorem:

- To adequately sample a band-limited signal of width B MHz requires 2*B samples independent per second.

2. The Wiener-Khinchin Theorem:

- The power spectrum of a signal is Fourier Transform of its Autocorrelation function.

# Some definitions

- Power spectrum: Power over a finite number of channels for a band limited signal.
- Fourier Transform: Mathematical process for transforming from one domain to another: e.g.

  - Signal processing: Time sampled signal to frequency spectrum
  - Antenna theory: Spatial field distribution across an antenna aperture to the radiation pattern
  - Interferometry: Complex cross correlation visibility to brightness distribution

- Joseph Fourier developed the theory while studying thermal heat transfer across a surface and vibrations in a membrane. Gauss is also recognised for similar work relating to the orbits of asteroids.
- There will be a lecture on Fourier transforms as part of the interferometry lectures where it forms the basis for producing images.
- So please take these results on faith until then.

# The Autocorrelation Function

- Consider a band limited signal (B) sampled for N samples at a rate 1/(2B).

- The autocorrelation function is defined as a series of N samples given by the following sequence of N samples:

$$s_{N*}s_{N},\ s_{N*}s_{N-1},\ s_{N*}s_{N-2},\ s_{N*}s_{N-3}, \ldots\ldots\ s_{N*}s_{1}$$

- The Fourier transform of this signal yields the power spectrum of the sampled signal spanning N independent channels.

# Operation of the Autocorrelator

The signal to the correlator is fed via a low pass filter that defines the signal bandwidth, B.  This can be optimised for each particular observation.

The sampling speed is adjustable to match  the bandwidth, i.e. 2*B.

Samples are shifted across a shift register block and each delayed signal is multiplied with the current sample.

The results are accumulated over a preset integration period and then transferred to the computer.

A  Fourier transform is performed to provide the resulting power spectrum.

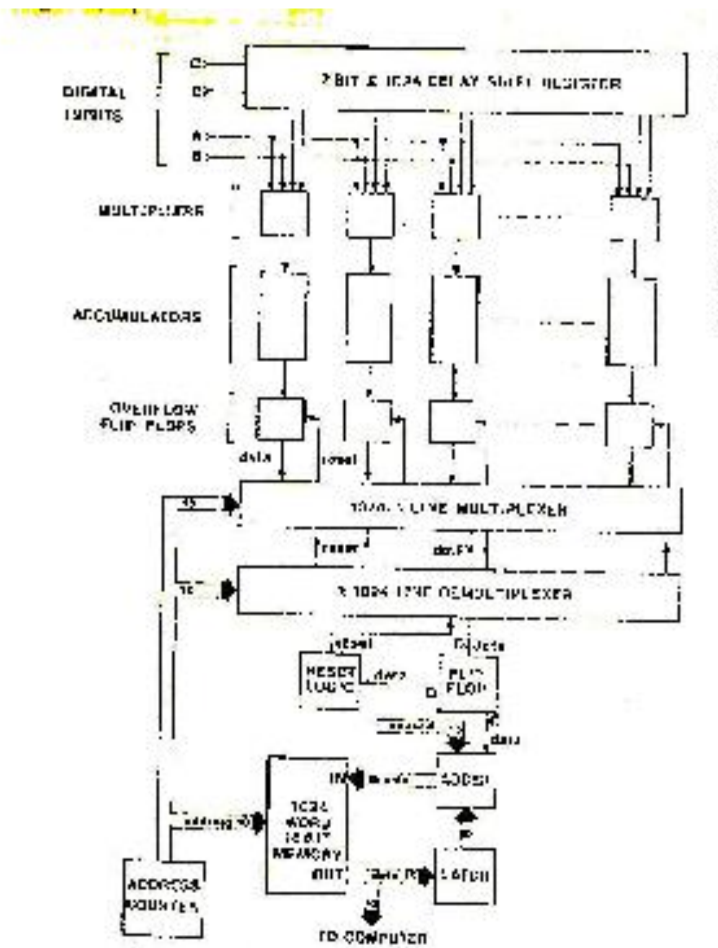
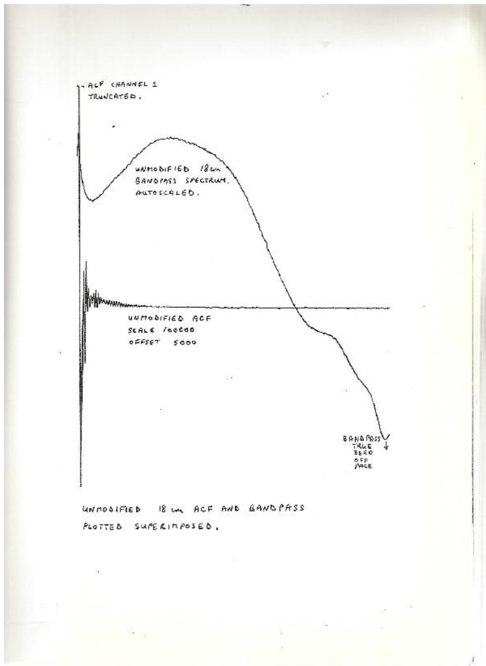


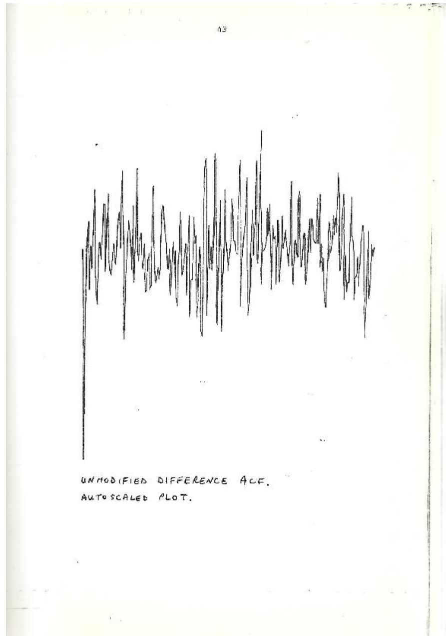

Fig 1 Block diagram of arithmetic section of correlator

# Operation at 18 cm wavelength

## Autocorrelation function and Bandpass from Fourier Transform

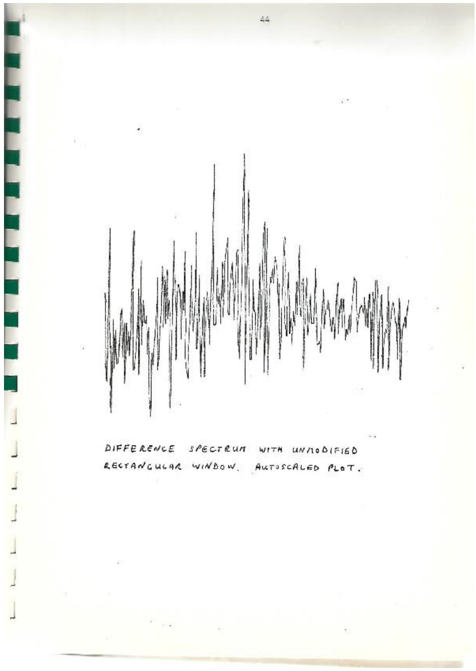



## Difference spectrum

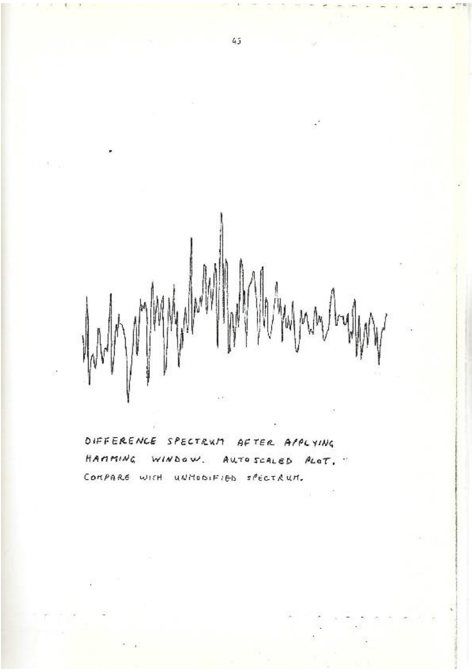


# Processed difference spectrum

## Rectangular window




## Hamming widow



# Advantages of the digital autocorrelation spectrometer.

- The main advantage is its versatility.
- i.e. the bandwidth analysed can be changed by switching in appropriate low pass filters, and adjusting the sampling speed accordingly.
- The sensitivity can be set by changing the number of samples integrated. Increasing the integration time averages out noise, so the signal to noise ratio improves.
- Correlators can usually be reconfigured to provide cross correlations of orthogonal polarisations to produce the polarisation characteristics of the signal being analysed, the so-called Stokes Parameters.
- Finally, because the signal is digitally sampled, these systems are intrinsically stable and amenable to long integrations on weak sources.