WASP: A WIDEBAND ANALOG AUTOCORRELATION SPECTROMETER

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Abstract

We describe the design and realization of a new type of wideband, moderate resolution backend spectrometer for heterodyne spectroscopy. WASP, a Wideband (analog) Autocorrelation SPectrometer, combines direct analog multiplication with transmission line delays to achieve a bandwidth of 3250 MHz at a resolution of 33 MHz. This combination of bandwidth and resolution is well matched to the requirements of submillimeter-wave studies of interacting galaxies, active galactic nuclei and high redshift objects. The spectrometer is compact, low-power (75 W) and integrates stably for many hours.

1 Introduction

Improvements in the sensitivity of millimeter and submillimeter-wave heterodyne SIS receivers permit observations of spectral line emission from increasingly distant objects (Brown & Vanden Bout 1991, Ohta et al. 1996, Omont et al. 1996, Guilloteau et al. 1997). As one moves to near-submillimeter-wavelengths it is, however, the bandwidth rather than the sensitivity of the receiver that becomes the limiting factor in observations of several classes of object (eg. Harris et al. 1991). Spectral line widths are set by physical conditions of the emitting gas within an astronomical object. Current receivers and backend spectrometers have analysis bandwidths of 1 GHz. At 1 THz this corresponds to a velocity bandwidth of only 300 km/s, sufficient for studies of many galactic objects but inadequate for observations of astronomically interesting objects such as interacting galaxies, ultraluminous galaxies and active galactic nuclei, and more locally planetary atmospheres. Large bandwidths are also important in searches for molecular and atomic line emission from objects at very high redshifts (quasars and their host galaxies), where uncertainties in the optically determined redshifts as well as systemic redshift offsets can be more than a few hundred km/s. A new generation of wideband receivers and spectrometers is thus required.

We have designed and built a prototype wideband analog autocorrelation spectrometer at the Universities of Massachusetts and Maryland. Known as WASP (the Wideband Analog Autocorrelation SPectrometer), the spectrometer has a contiguous bandwidth of 3250 MHz, with a modest resolution of 33 MHz. WASP has been designed to match the bandwidth and resolution requirements of submillimeter-wave and far-infrared line observations of molecular and atomic gas in local and distant galaxies. WASP will be used in conjunction with the new generation of wideband receivers to make high-frequency observations of a range of extra-galactic objects. The contiguous bandwidth is essential for line searches in the most distant objects, where baseline structure introduced by stitching together narrower band spectrometers can mimic the weak and wide spectral line emission features that are being sought. Wideband correlators can also be used effectively in studies of the terrestrial atmosphere and in interferometer phase correction spectrometers (eg. Ruf & Swift 1992, Staguhn et al. 1998), and as cross-correlation spectrometers for aperture synthesis arrays.

2 Backend Spectrometers

Observations of line emission and absorption at millimeter- and submillmeter-wave lengths are in general made using heterodyne detection techniques. The down-converted signal may be analyzed in one of two domains: the frequency domain, where the signal power spectrum $S(f)$ is subdivided into narrow frequency bins prior to analysis, and the time (lag) domain, where the autocorrelation function of the signal, $R(\tau)$, is determined by multiplying the signal with time-delayed versions of itself, $V(t).V(t+\tau)$. The signal power spectrum and the autocorrelation function are related by the Fourier transform relationship known as the Wiener Khinchin Theorem:

$$S(f) = \int_{-\infty}^{\infty} R(\tau) cos(2\pi f \tau) d\tau \qquad (1)$$

The instrument used to analyse the signal is colloquially referred to as the backend, of which there are several different types in common use.

Filter banks and acousto-optical spectrometers (AOS) operate in the frequency domain. Filter banks are made up of many contiguous filters, and can have large bandwidths with high spectral resolution. They are, however, often massive, and can be difficult to stabilize over long integrations. An AOS is compact, however the bandwidth for a single spectrometer is limited to approximately 1 GHz. Hybrid spectrometers made up of multiple 1 GHz subbands are under development at the University of Köln (see poster contribution by Horn et al. in this volume).

Digital autocorrelation spectrometers (DAS) are the most common form of backend in use at millimeter and submillimeter telescopes today. The signal delay and cross-multiplication is performed in digital circuitry, with the maximum operation bandwidth of a single DAS determined by the clock rate used. Bandwidths as large as 200 MHz have been achieved (communication, Lavera), again with larger bandwidths realized by stitching together multiple subbands. Digital correlators are typically used where high to medium spectral resolution is required.

The recent introduction of wideband microwave monolithic integrated circuit (MMIC) multipliers has meant that wideband analog autocorrelation spectrometers can now be built. WASP combines the wideband MMIC multipliers with analog delays introduced by sections of microstrip transmission line. The maximum achievable contiguous bandwidth is set by the shortest length of delay between two channels, and the maximum response frequency of the MMIC multiplier.

3 WASP: A Wideband Analog Autocorrelation Spectrometer

3.1 The Signal Path Through WASP

A schematic of the signal path through WASP is shown in Figure 1. The input signal is split into two. The two counter-propagating signals pass through anti-aliasing filters and power amplifiers before being correlated in one of 8 multiplier modules. Each module contains 16 multipliers and signal delays. The modules are connected in parallel using cable delays, spaced to realize a near-equally spaced chain of 128 lags. The signal is phase-switched by 180 deg at 770 Hz - synchronous

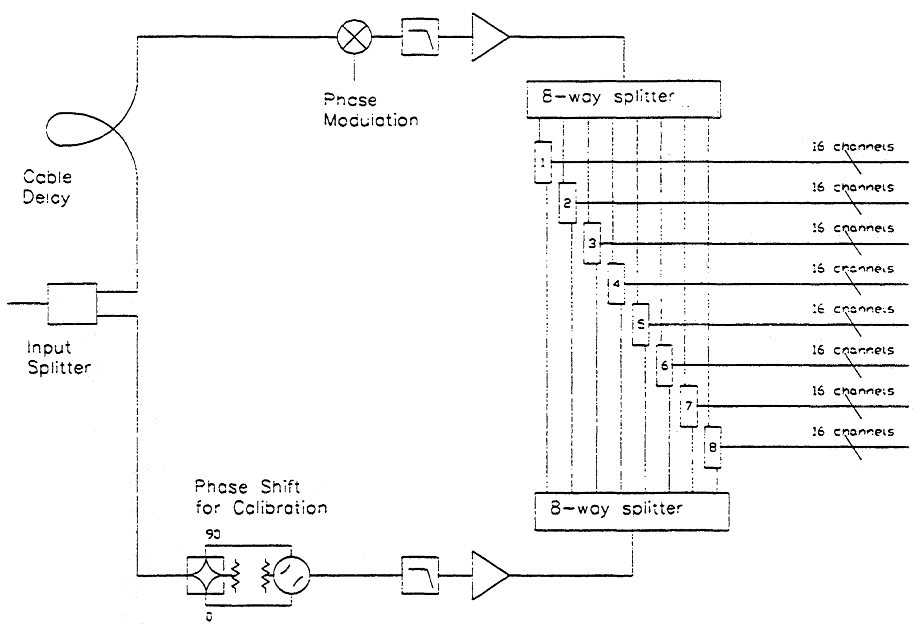

Figure 1: A schematic of the signal path through WASP.

detection is used in the low-frequency signal-processing electronics to recover the multiplier signal, reducing the effects of drift in the DC electronics. The electrical length of a microwave connector is longer than the spacing between adjacent multipliers, and so at least two strings of multipliers are required to achieve equal lag spacing. Each half of the initial signal is in fact further split into eight to minimize the difference in power at the ends of the modules, the splitters in addition providing isolation between modules. Given that the autocorrelation function of a real signal is symmetric in time, it is necessary to measure only either positive or negative lags. An additional signal delay is therefore inserted in one arm of the spectrometer, placing the zero path difference lag at one end of the lag chain. A transfer switch and 90 deg hybrid combination is used to change the phase in one arm, enabling the signal delay at and amplitude response of each multiplier to be measured.

3.2 The Multiplier Modules

Each module houses 16 MMIC multipliers, spaced uniformly along microstrip transmission lines (Figure 2). The multipliers are MMIC active mixers (Hewlett Packard IAM-81008), based on a classical Gilbert multiplier core (Gilbert, 1968). The mixers are consequently good analog multipliers when LO-starved. Measurements suggest that the multipliers are very linear below an input power level of -15 dBm, over a power range of least 50 dB power for equal-power signals as well as power differences of up to 10 dB between inputs.

The Nyquist sampling criterion requires that a signal is measured at least once per half wavelength. The counter-propagating signals in the two arms of WASP are delayed by equal amounts at the two inputs of the multiplier (Figure 2) and one quarter of the wavelength of the highest frequency signal that can be fully sampled is equal to the spacing between adjacent multipliers. The physical size of the packaged multipliers limits this spacing to 0.265 inches which, on the 0.05 inch thick Duroid circuit board (ϵ_r=10), sets the maximum frequency at just over 4200 MHz. A short tab extending from the transmission line demarks the position of

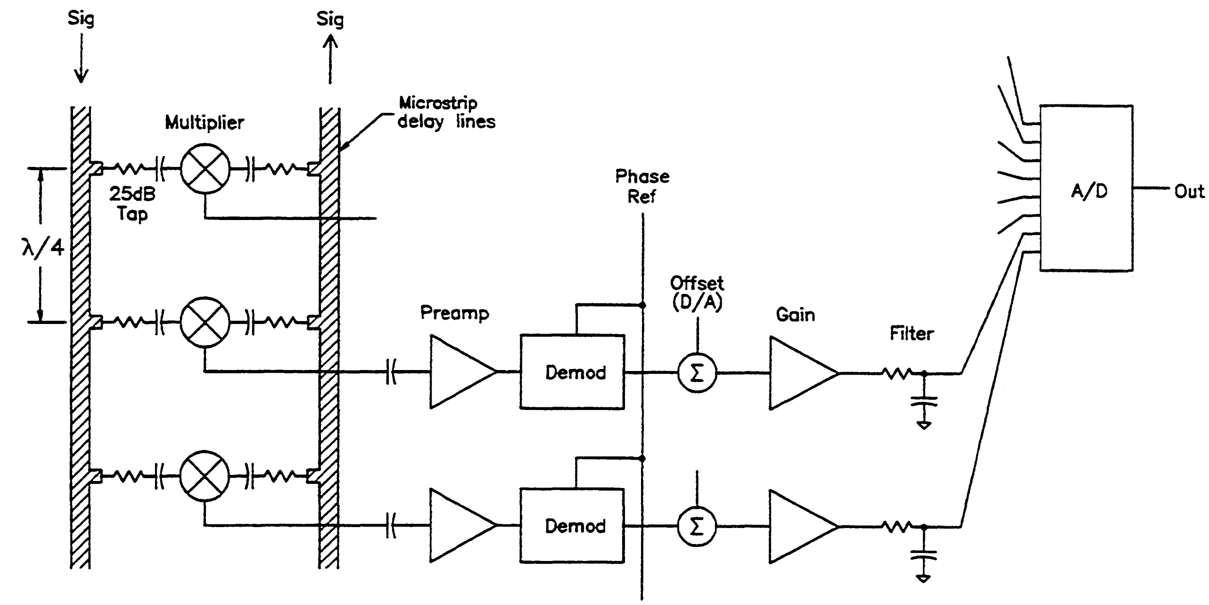

Figure 2: A schematic view of a section of the multiplier/delay chain and the low-frequency signal-processing electronics.

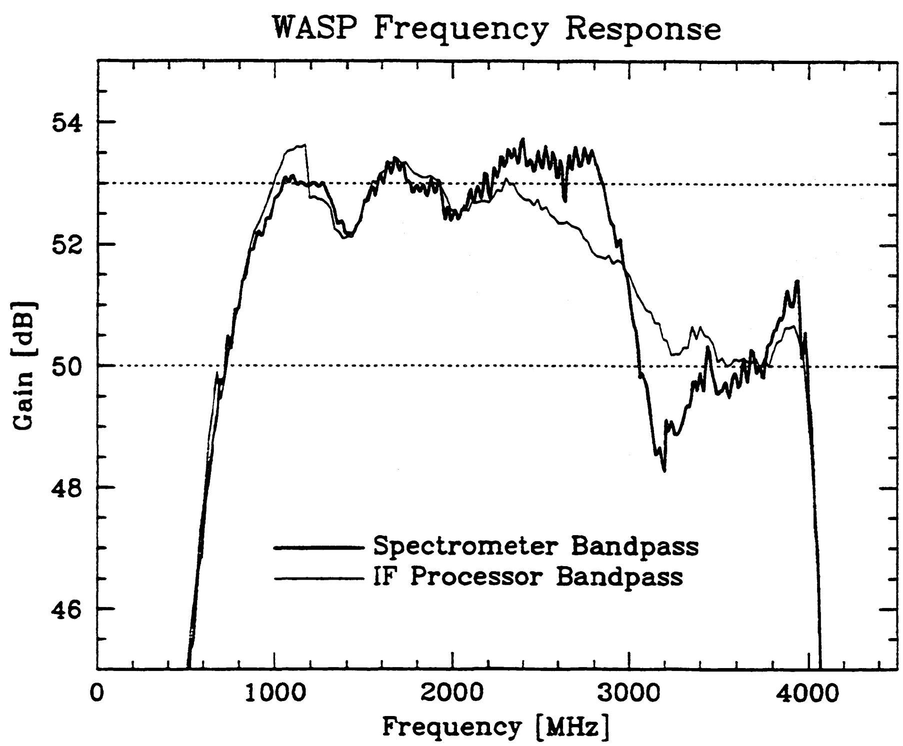

Figure 3: A plot of the WASP passband (heavy line) superposed on the passband of the IF processor (all electronics preceding the 8-way power splitters). A ratio of the two indicates that the response of the multiplier modules is quite flat, except in the region near 3000 MHz.

each multiplier. This tab accurately locates one end of a chip capacitor that forms a broadband resistive power divider that weakly connects the line and multiplier input. The coupling between the transmission line and the multiplier input is around -25 dB at low frequencies, rolling up by 8 dB at the top of the frequency band. This roll-up, caused by the shunt capacitance in the chip resistors, compensates nicely for fall-off in multiplier sensitivity with increasing frequency.

3.3 Signal Processing Electronics

Circuitry at the IF output of each multiplier blocks the DC bias level, and then amplifies, demodulates and low-pass filters the correlated signal. The resultant DC signal is then digitized prior to digital averaging in a PC (Figure 2). The whole spectrometer is read out at a rate of just over 13Hz, keeping the aliased DC noise of the two-pole low-pass filter to below one percent. This data rate is compatible with those attainable using serial input/output analog-to-digital (A/D) converters, and requires a clock frequency that is low enough that connections between the correlator boards and the computer can be made using ribbon cable.

The required dynamic range of the spectrometer readout-electronics is determined by the intrinsic dynamic range of the input signal, and the internal noise floor of the spectrometer. For a bandwidth of 3250 MHz and a sampling interval of 73 ms, the minimum dynamic range needed is just over 14 bits. Further range is required to allow for variations in multiplier sensitivity, differences in power level along the delay line and to sample the noise more finely than the minimum level. This translates to a total range of 17 or 18 bits, achieved using the combination of a 12-bit analog-to-digital converter and a programmable offset (digital-to-analog converter) (Figure 2). The dynamic range requirement relaxes with increasing lag as the size of the correlated signal decreases, and so offsets are included on the first 64 lags only.

3.4 Mechanical Structure

WASP is fully contained within a half-height rack. Each multiplier module is mounted onto a correlator board that also contains the low-frequency signal-processing electronics for all 16 channels. The eight correlator boards are mounted in a standard 3U VME crate which in turn sits in the half-height rack along with the IF processor, power supplies and the rack-mounted PC.

4 Spectrometer Performance

4.1 Amplitude and Phase Response

The amplitude response of the spectrometer is shown in Figure 3. The passband of the IF electronics in front of the 8-way splitters (IF processor) shows a fair amount of structure (Figure 3 light line), due in the main to the mixer used to phase modulate the signal prior to correlation. The multipliers and their coupling circuits also introduce some structure, particularly noticeable around 3000 MHz (a comparison of the light and heavy lines). This dip in response is seen in each multiplier, and is tentatively attributed to a roll-off in amplifiers at the LO-input of the multipliers. Detailed measurements of the multiplier and coupling circuit properties are being made to investigate this.

The phase response of the spectrometer can also be readily determined. This is done using two measurements (at each frequency) of the autocorrelation function, with and without a known phase inserted into one of the two arms of the spectrometer. In an ideal correlator, with perfectly uniform sampling, the phase difference between adjacent multipliers would increase linearly with increasing frequency. In general this is not the case in WASP, as dispersion and roll-off in the multiplier amplifiers as well as low-level reflections within the module affect the measured phases: at low frequencies the averaged phase difference does increase linearly, however at higher frequencies, and particularly around 3000 MHz, the phase shift per lag deviates quite markedly. The Nyquist frequency of the spectrometer, given by the frequency at which the phase change between adjacent multipliers is π, can be determined from an extrapolation to phase change measurements made at the low-end of the band. This suggests a maximum frequency of just over 4200 MHz, above the cutoff of the anti-aliasing filters included in the IF processor.

4.2 Stability

WASP has proved to be very stable, due mainly to the internal phase switching and subsequent synchronous detection of the input signal. There are, however residual drifts that occur at a low level. Temperature changes are the dominant cause of drift. In particular, small temperature changes produce changes in multiplier sensitivity and the delays between multipliers: a change of 4 K in temperature results in a 1% change in responsivity and delay. The modules are temperate-regulated using heaters, though both the delay change and multiplier responsivity can be corrected for. The temperature sensitivity of the digital-to-analog converters used to increase the dynamic range of the low-frequency signal processing electronics is a more significant source of drift. The drift time scales, however, are long compared to typical sky-chop frequencies used during observing. Again, heaters are used to stabilize the temperature of the programmable offsets. A small change in the layout of the low-frequency signal processing electronics would produce an order of magnitude reduction in the sensitivity to temperature.

Very low-frequency noise in the multiplier power supply manifests itself as small offsets in the measured autocorrelation function. The offset at any time is the same for all channels and therefore transforms to δ-function at zero frequency, without affecting the power spectrum within the spectrometer passband.

Long integrations on the noise diode simulating sky-chop observations at 0.25 Hz show that spectrometer noise integrates down as the square root of the integration time over periods in excess of 10 hours. These time scales agree with measurements of the Allan variance of individual channels.

5 The Recovery of Power Spectra

5.1 The Method

The power spectrum of a correlation spectrometer input signal can be obtained by the inversion of its autocorrelation function (ACF). An ACF that is uniformly sampled in delay may be inverted using a Fourier transform (Equation 1). The small deviations in sampling caused by phase errors in the multipliers and dispersion in the microstrip transmission line distort the sampling of the WASP ACF, with the result that a WASP ACF cannot be inverted analytically. A linear technique has been developed to reconstruct the power spectra from WASP ACFs. Calibration measurements are made of the spectrometer response to a series of monochromatic signals spanning the input band of WASP, spaced at 10 MHz intervals. These ACF measurements are then used to determine a set of basis functions which are then used to reconstruct the power spectrum. The ACF at each lag, $R(\tau)$, though a function of frequency and non-uniformly sampled, changes very little with time and temperature, and so occasional calibrations only are needed.

The linear reconstruction scheme is described in more detail in Isaak, Harris and Zmuidzinas (in prep.). Nonlinear, iterative inversion techniques are also being developed that will be used when WASP is operating in cross-correlation mode.

5.2 Power Spectra

A variety of different power spectra have been recovered from various WASP autocorrelation functions using the linear reconstruction technique.

Figure 4 is the laboratory spectrum of a 1000 MHz bandpass filter and noise source, normalized by the passband of the spectrometer. The spectrum has a dynamic range of greater than 100 (20 dB), sufficient for extra-galactic astronomy.

WASP has also been used for preliminary observations at the Caltech Submillimeter Observatory. Shown in Figure 5 are two superposed CO J = 4–3 spectra of the star-burst galaxy, M82, taken with the 1000 MHz bandwidth 460 GHz facility receiver. The spectra have been binned to a resolution of 30 MHz. The heavy line traces the line profile measured with WASP, while the light line traces the line profile measured using the facility AOS backend - the agreement between the two spectra is good, and the origin of the small differences between the two spectra is currently being investigated.

WASP will be used in conjunction with a wideband 700 GHz SIS receiver that is being built at Caltech. It is intended that the instantaneous bandwidth of the receiver will match the input bandwidth of WASP. This wideband combination will be used to study the warm and dense gas in external galaxies.

6 Conclusions

We have designed and built a wideband analog autocorrelation spectrometer. WASP has a contiguous bandwidth of 3250 MHz with a resolution of 33 MHz, a bandwidth that is a factor of a few larger than other spectrometers. WASP is stable over integration periods of greater than 10 hours, and produces spectra with dynamic range of greater than 100. The spectrometer is compact, physically robust and, inspite of not being optimized at all for low power comsumption, consumes only 75 W excluding computer. Prototype low-power correlator boards are being designed to explore the possibilities of power reduction.

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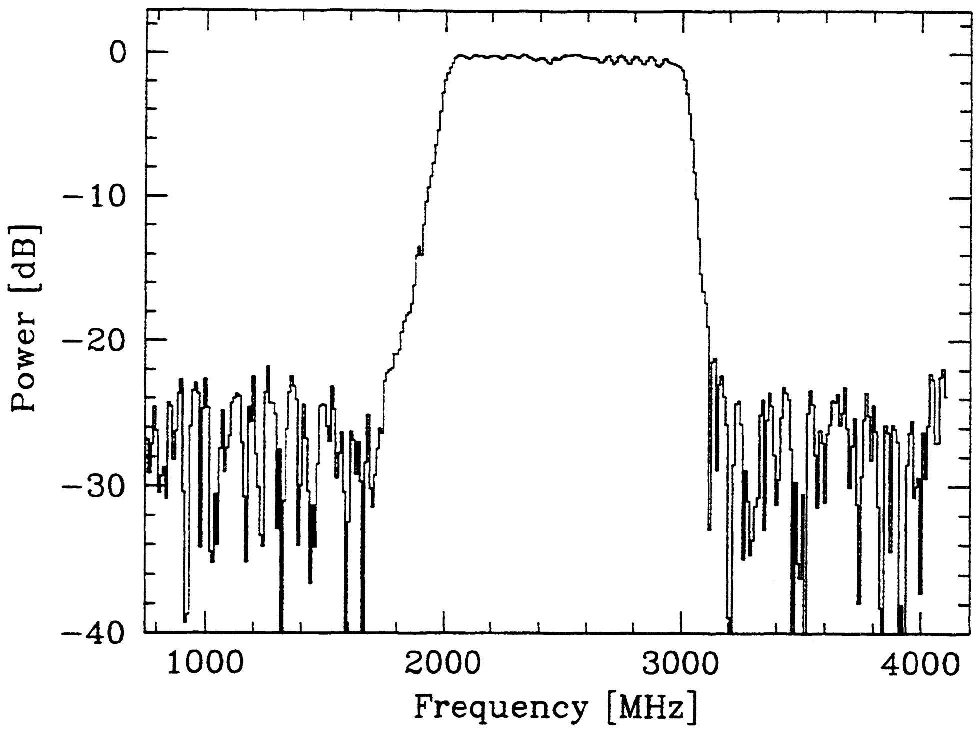

Figure 4: A WASP spectrum of a 1000 MHz-wide bandpass filter and noise diode. A measure of the dynamic range of WASP, the noise level in the power spectrum is a factor of more than 100 lower than the peak signal. The spectrum was reconstructed using the linear scheme.

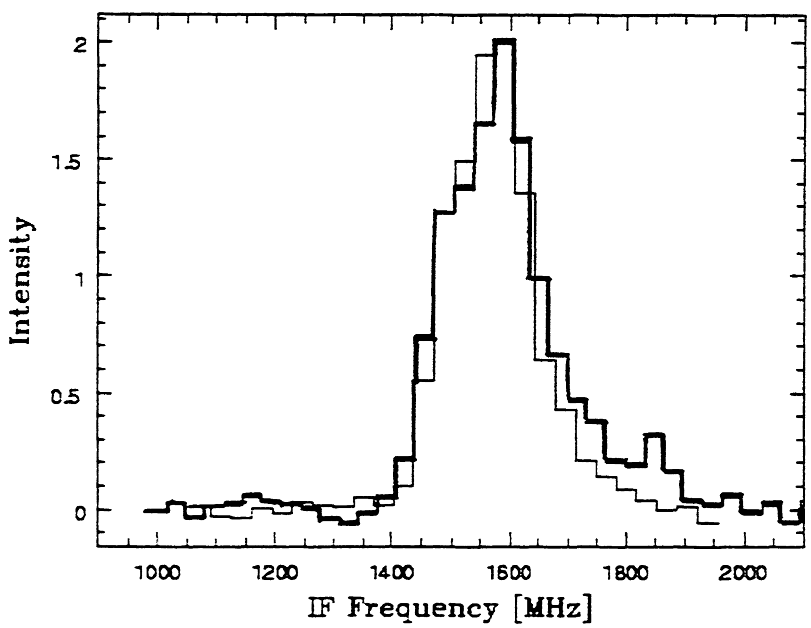

Figure 5: Spectra of the star-burst galaxy M82, taken in the CO(4-3) transition at the Caltech Submillimeter Observatory in January 1998. The heavy line traces the spectrum measured using WASP, and the light line the spectrum measured using the facility AOS backend: the two spectra show good agreement. The bandwidth of the spectra was limited by the receiver and IF bandwidth. The WASP spectrum is an average of two observations, totaling 4 minutes in integration time, and was reconstructed using the linear scheme. The AOS spectrum represents a single, 2 minute observation.

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