WIDEBAND SPECTROMETERS FOR MILLIMETRE WAVELENGTHS

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FREQUENCY RESOLUTION AND COVERAGE NEEDED

Millimetre-wave spectral lines show a wide range of linewidths, from 0.1 km s^{-1} in dark clouds to 30 km s^{-1} in some massive molecular clouds; at 100 GHz the corresponding Doppler widths range from 33 kHz to 10 MHz. SiO masers at 86 GHz have two lines typically 1 MHz wide spaced by 6 MHz. For most applications a resolution of 100 or 250 kHz is suitable.

Frequency coverage is also important. 115 GHz CO observations near the galactic centre call for a coverage of 300 km s^{-1} $\equiv$ 115 MHz. A wide frequency coverage has also proved valuable for line searches, allowing simultaneous observations of known lines near the search frequency. Wide coverage is needed for extragalactic observations, ideally 500 km s^{-1}.

How do the filter bank, the digital correlator and the acousto-optical spectrograph satisfy the frequency resolution and coverage implied in these examples, or corresponding values scaled for other frequencies?

FILTER BANKS

Many observatories have long experience with filter banks, which have excellent performance in terms of sensitivity stability and flexibility. The NRAO design (Mauzy, 1974) is widely used; at Kitt Peak the options available are:

Frequency Resolution	Frequency Coverage
1 MHz	256 MHz
500 kHz	128 MHz
250 kHz	64 MHz
100 kHz	25.6 MHz
30 kHz	3 MHz

B. H. Andrew (ed.), Interstellar Molecules, 619–623.

The 250 kHz filters are widely used, offering 0.75 km s^{-1} resolution and 192 km s^{-1} coverage at 100 GHz. The Kitt Peak filter bank is normally used in the total-power mode with an off-source reference taken at intervals of a few minutes. The noise has been found to decrease as $(\text{time})^{-\frac{1}{2}}$ for up to 24 h.

DIGITAL CORRELATORS

With modern ICs a 1000-channel digital correlator is not difficult to design. For one-bit sampling there is a $\pi/2$ degradation in sensitivity to 64% of filter bank sensitivity. Noise decreases as $(\text{time})^{-\frac{1}{2}}$ for many hours. The resolution can be changed very simply, but the coverage is limited to half the sampling frequency. The special IC chips built for the VLA can operate at a sampling frequency of 160 MHz; for 1024-channels this would allow (at 100 GHz) a resolution of 0.5 km s^{-1} and a coverage of 240 km s^{-1}. A 1024-channel correlator (Mark IV) using the VLA chips is currently being tested at NRAO (Shalloway, private communication).

The asynchronous correlator proposed by Ables is being developed in Sydney (Frater, private communication). This would greatly simplify the construction of a high-speed correlator since it is not necessary to distribute the clock pulses. The clock signal for each module is derived from the preceding module, so each operates at its own local clock phase.

ACOUSTO-OPTICAL SPECTROGRAPH

The acousto-optical spectrograph (AOS) was invented by Lambert (1962). It has taken many years to be developed into an operational spectrometer for millimetre wavelengths, mainly because of problems of vibration and thermal instability. There are operational AOS in Australia (Milne and Cole, 1979) and Japan (Kaifu et al., 1977). The performance of these AOS is listed in Table I.

TABLE I. AOS PERFORMANCE

Parameter	AOS model			
	CSIRO 1	CSIRO 2	Tokyo 1	Tokyo 2
Ultrasonic material	Quartz	$LiNbO_3$	TeO_2	TeO_2
Centre frequency (MHz)	135	405	65	360
Overall bandwidth (MHz)	90	270	41	200
Number of channels	512	256	1728	1728
Frequency resolution (kHz)	240	1050*	38	250
I.F. drive power (mW)	200	500	10	500
Frequency drift (kHz h^{-1})	7	-	1	2
Linearity	<1%	-	<2%	<3%
Readout noise (dB below saturation)	-24	-	-	-

*Set by number of channels; expected maximum resolution about 500 kHz (interaction length 1.8 μs). This AOS has so far only been used for pulsar and scintillation observations.

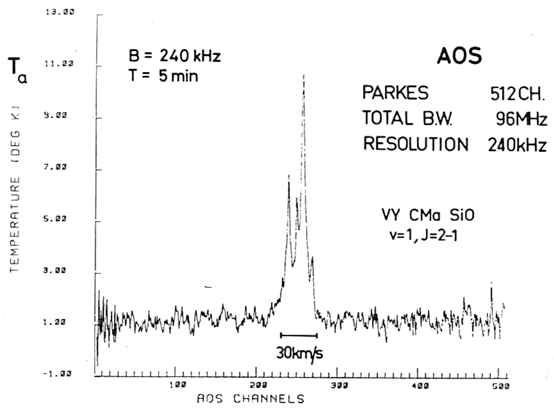

Fig. 1 - 86 GHz SiO maser emission from VY CMa recorded with 512-channel AOS on 17-m telescope.

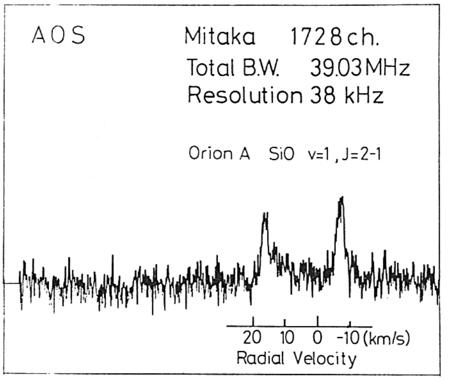

Fig. 2 - 86 GHz SiO maser emission from Orion with 1728-channel AOS on 6-m telescope.

Spectra of 86 GHz SiO masers obtained with CSIRO 1 and Tokyo 1 are shown in Figures 1 and 2. In Figure 1 the ultrasonic modulator response is down 9 and 6 dB at the left and right ends of the spectrum and readout noise is becoming significant. With beam switching at a 2 s rate the sensitivity of CSIRO 1 over the central 80 MHz band (3 dB modulator response) has been measured as 1.5 times that of the Parkes digital correlator under the same operating conditions (an ideal AOS would be a factor $(0.64)^{-1} = 1.56$ better than an ideal one-bit correlator). The noise of CSIRO 1 decreases as $(\text{time})^{-\frac{1}{2}}$ for an interval of at least 3 h.

For long switching times ($\gtrsim 10$ s) a fraction of the profiles recorded with CSIRO 1 have sloping or curved baselines. The curvature appears when T_{sky} is varying rapidly. Tests are under way to establish whether the link between baseline shape and T_{sky} variations results from a relatively slow sequential readout of the photodiodes.

Maintenance on an AOS is extremely simple because of the small number of components (laser, beam-spreading optics, ultrasonic modulator, Fourier transform lens, photodiode array and serial readout circuitry). CSIRO 1 has required no maintenance in the last year of operation. The reliability and ruggedness of the photodiode array are extremely high.

A $LiNbO_3$ ultrasonic modulator with a bandwidth of 1 GHz has been made by ITEK (Hecht, 1977). The same paper describes a GaP modulator with a bandwidth of 630 MHz with much higher efficiency. The number N of resolution elements is limited by the transit time of the ultrasonic wave along the aperture; for the 1 GHz modulator $N \doteqdot 1100$, while for the 630 MHz modulator $N \doteqdot 400$.

SPECTROMETER COSTS

Figures obtained from various groups lead to approximate component costs per channel and man-years for construction as follows:

Type	Cost per channel	Man years
NRAO-type filter bank	\$50 to \$80	2
Digital correlator	\$40 to \$50	7*
Acousto-optical spectrograph	\$15 to \$30	2

*Includes design effort.

These cost estimates do not include a minicomputer or interfacing hardware. Because the AOS has serial readout, interfacing to a computer is particularly simple.

REFERENCES

Hecht, D.L.: 1977, IEEE Ultrasonics Symposium Proceedings.
Kaifu, N., Ukita, N., Chikada, Y., and Miyaji, T.: 1977, Publ. Astron. Soc. Japan 29, p. 429.
Lambert, L.E.: 1962, I.R.E. Int. Conv. Rec. 10, Pt. 6, p. 69.
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Milne, D.K., and Cole, T.W.: 1979, Proc. Inst. Radio Electron. Eng. Aust. 40, p. 43.

DISCUSSION FOLLOWING ROBINSON

Gillespie: What is the dynamic range of the acousto-optical spectrometers?

Robinson: For the AOS used on the 4 metre telescope at Epping the dynamic range from readout noise to photodiode saturation is 24 db. This gives a 5 dB margin below the $\sqrt{B\tau}$ noise with B=240 kHz and τ=30 ms. The margin could be improved by reducing the interval τ between readouts of the photodiodes; a compensating increase in I.F. drive power would be required. The linearity of the device is very good but when saturation occurs there is a very sharp cut-off. A variety of attenuators must be used to keep the signal within range if a number of services of greatly different intensity are being observed.

Linke: Is it possible to build an AOS with adjustable resolutions?

Robinson: The resolution is the reciprocal of the transit time of the acoustic wave along the aperture. We have changed the resolution by changing the Bragg cell (e.g. Cole and Ables, Astron. Astrophys. 34, 149 (1974)). At Tokyo Astronomical Observatory they have built *two* AOS giving a 6:1 ratio of resolution (see Kaifu et al. 1977). The AOS thus lacks the flexibility in resolution of the digital correlator.

Morimoto: In our case we use the AOS at maximum resolution and maximum bandwidth.

Robinson: I understand that an AOS is also in use at Kisarazu Technical College for a CO survey. This AOS has 230 MHz bandwidth, but the resolution is only 2 MHz, while 250 kHz should be attainable with more readout channels.

Bieging: A number of firms are developing integrated optical circuits to incorporate the components of an acousto-optic spectrograph onto a monolithic silicon substrate, including detectors. If this work is successful, it will almost certainly reduce dramatically the cost per channel, compared to acousto-optic spectrographs constructed with discrete components.

Robinson: This is a most significant development. One fringe benefit of the compact monolithic construction should be a reduced sensitivity to vibration, which has been a problem with the "optical bench" type of AOS.

R. Wilson: I would add one device to your list. P.S. Henry has built a spectrum expander which in effect allows one to have a filter bank with simply adjustable resolution. Our expander lets us use 128 channels of our 0.25 MHz per channel filter bank at resolutions of 12.5 kHz to 100 kHz per cahnnel. The device is relatively inexpensive to build.

Robinson: Henry's device (Rev. Sc. Instrum. 50, 185 (1979)) uses a recirculating loop memory to achieve higher resolution when only a coarse filter bank is available. We await a real-time device to expand the bandwidth instead!

T. Wilson: The NRAO autocorrelator achieves its 80 MHz bandwidth by offsetting 2 samplers, which are driven at 80 MHz, by 12.5 μs. This causes a reduction in the number of channels, from 1024 to 512. At bandwidths of 40 MHz and less, 1024 channels are available.

Robinson: You are quite correct. My figures are in error. On the subject of digital correlators, I should add that in Sydney a scheme was devised by A. Bos to build a wideband digital correlator using a high-speed sampler with the samples multiplexed down parallel chains of low-speed logic. However, the sensitivity is degraded. Dr. Morimoto informs me that in Tokyo a sophisticated hard-wired FFT system (see Yen, Astron. Astrophys. Suppl. 15, 483 (1974)) has been designed to process the output of a 160 MHz sampler with 10 MHz logic without loss of sensitivity.