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Some Considerations of Spectral Line Capability with the VLA

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There are a number of astronomical problems which the VLA will be useful in resolving. The principle frequencies of the instrument will be at 1.3-1.8 GHz, 4.5-5.0 GHz, 14.4-15.4 GHz and 22.0-24.0 GHz. This will include spectral lines of HI, OH, H_2CO, H_2O and NH_3 as well as a number of recombination lines (HII) and several less abundant molecules.

Sensitivity and Resolution

In table 1 the performance of the VLA for a 10^h integration period is given. The sensitivity is dependent on the receiver system temperature, the spectral resolution, the beam dilution (ratio of synthesized beam to primary beam), integration time and number of elements. By assuming a constant frequency resolution (100 KHz) and system temperature (100 K) the sensitivity is independent of operating wavelength. In actual practice the bandwidth and system temperature will be smaller at the lower frequencies, however these two effects will cancel to a certain extent. To first order the sensitivity is dependent only on the configuration and the table indicates that the inner two configurations will be the most useful for spectral line observations. In addition the spectra from each telescope can be combined to provide a high sensitivity spectrum of the entire primary beam of the antenna. This may be done simultaneously with the high resolution observations.

Line Observing Programs

A number of possible astronomical programs are summarized in tables 2 and 3. For HI several estimates are made of the expected brightness temperature and compared with the expected pp noise at resolutions of 1' and 10" arc. Similar considerations are given to possible observations of H_2CO, NH3, and H_2O. The baseline configuration labeled 0.2 km refers to a possible compact configuration which will probably not be available. Most of the possible cloud sizes and temperatures are estimates based on extrapolation of present results.

Correlator

Because of the high cost of the spectral line correlator, the present number of frequency channels will be 64 by 351 antenna pairs. Several types of observing requirements for resolution and total bandwidth are presented in table 4. For most experiments more channels would be desirable. A 5 MHz correlator is presently anticipated which can be run in a parallel mode to produce a 10 MHz spectrum. The cost of either doubling the number of channels or the bandwidth of the correlator is of the order of $700K. Possibly other techniques would provide more channels at less cost but ultimately at least 64x351=22464 correlations have to be done.

Spectral Line Computing

Barry Clark has outlined one possible system for handling the spectral line data. A block diagram of this system is shown in Fig. 1. The notation PT refers to process time for that block and SR refers to the sample rate or frequency of data transmission. For the On line or synchronous system the data output is 50K words every 30 sec. for 64 complex spectral points. In the data reduction stage the main bottle neck is in the sort-merge step which requires 5 hours. This is the main area where large improvements in the data handling could be made.

The data display is the most difficult area to define. The volume of data in a 64 channel map which is 4 dimensional is difficult to present in a simple form to the observer. The dimensions one has available for display are 3 space coordinates, color, intensity and time. The principle methods are stereo views, color photos and movies. In addition the data is probably complex enough that a computer will be needed to analyse the data based on questions asked by the observer. Probably some overall view of the complete data map should be presented to the observer so he can choose the interesting parts for study. This might be done with a color image where the color represents velocity. He should then be able to zoom in on an interesting area for study and be able to ask the computer questions about the temperature, velocity, mass, density of this area, possibly fitting some simple models to the observed data. It is not clear whether this would be better done with a mini-computer at the site or with a large, general purpose computer. In any case it will be essential to have some minimal data display facilities at the site to allow the observer to optimize his observing program.

After 10 hours of observing the on line processing system has produced $\sim 10^8$ words of data. An Ampex video tape recorder can pack $\sim 10^9$ words on a 2" wide reel of tape. Although the raw data can be stored, the time required for editing and sort-merging is almost real time so there would be little opportunity for rerunning the raw data through the data reduction computer. To keep the VLA from drowning in bits and tape, it would be preferable to archive only the final data arrays from the map. This involves $\sim 10^6$ words which means that several maps can be stored on one 9 track tape.

Barry Clark has suggested that for an interim period the continuum computer be used to process spectral line observations. The computing load depends mainly on the data array size and not on the number of antennas. For a 64 frequency channel array the system would be able to handle a 256x256 map in the minimum case, a 128x128 array with a comfortable system and a 64x64 array with the use of Clean. Even with a small number of antennas in the early VLA, the data display problem will involve the same size map arrays as with the final instrument. Thus one of the critical problems of allowing the astronomer to immerse himself in his data without drowning will have to be solved soon.

TABLE 1

VLA Spectral Line Sensitivity and Resolution

	L	21 km	7 km	2 km	700 m	Antenna Elements (25 m)	ΔV
λ	$\Delta T_{A,pp}$	500°K	50°K	5°K	0.5°K	$.016°K/\sqrt{27} = .003°K$	
21 cm		2"	7"	20"	70"	2210" = 37'	21 km/s
6		0.5"	1.5"	5"	15"	630" = 11'	6
2.0		0.2"	0.7"	2"	7"	220" = 3'	2.0
1.3		0.1"	0.3"	1"	3"	140" = 2'	1.3

$$\Delta T_{A,pp} = \frac{10 \times T_s}{\sqrt{B\tau N(N-1)}} \frac{\Omega \text{ prime}}{\Omega \text{ synth}} = \frac{10 \times 100}{\sqrt{10^5 \times 10 \times 3600 \times 702}} \left(\frac{L \times 10^3}{25}\right)^2$$

$\Delta T_{A,pp} \sim L^2$ (°K peak to peak where L is in km)

($T_s = 100°K$, $B = 100$ kHz, $\tau = 10^h$, $N = 27$, $d = 25$ m)

TABLE 2

Predicted Peak Brightness Temperature and Noise for 21 cm Observations (M. S. Roberts)

Distance Mpc.	$M_{HI}/M_\odot$	V (1) km/s	FHPBW	Expected (2) $T_{B,pk}$	5xRMS (3) (T_B)	Linear Size	Remarks
12	10^9	200	1'	23°K	0.7	3.5 KPc	Distance of Virgo Cluster
36	10^9	200	1'	2.6	0.7	10.5 Kpc	Moderate size galaxy
12	10^8	200	1'	2.3	0.7	3.5 Kpc	Elliptical galaxy in Virgo Cluster
.69	10^3	10	10"	5.0	36	33 pc	HI concentration in M31
.69	10^5	20	1'	7.0	0.7	200 pc	" " " "
2 kpc	10	20	1'	83	0.7	0.6 pc	" " in our galaxy
2 kpc	10^{-1}	10	10"	60	36	0.1 pc	" " " " "

(1) 100 khz filters assumed for V $\geq$ 20 km/s, 50 khz filter for V = 10 km/s.

(2) From $M_{HI}/M_\odot = 1.5 \times 10^3 \, T_{B,pk} \, V \, \theta^2 \, D^2_{Mpc}$

where $T_{B,pk}$ is peak brightness temperature

V is total halfwidth of an assumed Gaussian velocity profile in km/s

θ is beam-broadened total halfwidth of radiation distribution in arc minutes

D is distance.

Above is based on optically thin case.

(3) From C. M. Wade, Draft dated 10/22/70, equation (5)

$$T_{B,min} = 5209 \, \lambda^2 \, \beta^{-2} \, [BH]^{-1/2}$$

where λ is wavelength in cm
β is synthesized HPBW in arc seconds
B is i.f. bandwidth in Hz
H is observing time in hours, 8 hours used.

TABLE 3

MOLECULAR CLOUD PROGRAMS FOR THE VLA

Molecule	Source	Distance (kpc)	Diameter (pc)	Diameter (ℓ)	Resolution (ℓ)	Line Temp. (°K)	Noise Temp. (°Kpp)	Velocity Resolution (km/s)	Baseline (km)
H_2CO	Galactic Background	3*	10*	10'	10'	≥.005*	.002	6	any
	Hyperfine	0.2	5	2°	10'	0.5	.015	0.1	any
	Orion	0.5	5	30'	50"	0.1	.05	6	0.2†
	Dust Cloud	0.2	5	2°	50"	0.5	0.1	1	0.2†
	Galactic Center	10	30	10'	15"	5	0.5	6	0.7
	Andromeda	700	30*	10"	15"	5*	0.5	6	0.7
	Strong HII	5	1	30"	5"	≥10*	5	6	2.1
NH_3	Weak	2	1*	2'	2'	≥.005*	.002	1	any
	Orion	0.5	1*	10'	10"	1	.05	1	0.2†
	Andromeda	700	30*	10"	10"	2*	.02	10	0.2†
	Galactic Center	10	30	10'	3"	2	0.2	10	0.7
	M81	3000	30*	2"	3"	2*	0.2	10	0.7
	Strong	5	1*	30"	1"	≥10*	5	1	2.1
	Virgo	12000	30*	0.5"	1"	≥10*	2	10	2.1
H_2O	Thermal	2	1*	2'	2'	≥.005*	.002	1	any
	Weak	10	1*	20"	10"	≥0.1*	.05	1	0.2†
	W49	15	0.1	1"	1"	$5x10^6$	5	1	2.1
	Andromeda	700	0.1*	.03"	1"	2000*	5	1	2.1
	M81	3000	0.1*	.006"	1"	100*	5	1	2.1
	Virgo	12000	0.1*	.002"	1"	8*	5	1	2.1
	W49	15	0.1	1"	0.1"	$5x10^6$	500	1	21

*Estimated
†Compact Configuration

TABLE 4

Notes On the Bandwidth-Resolution Graph

		Resolution	Bandwidth
1.	H cold galactic clouds	0.2 Km/s	40 Km/s
	OH narrow emission lines	0.2	40
2.	H_2CO dust cloud absorption	0.1	20
3.	H_2CO Cas A absorption	0.2	60
4.	H high velocity clouds	1	300
	H galactic structure	1	300
	OH galactic center absorption	1	300
5.	H_2O emission lines	0.2	20
6.	H other galaxies	5	500
7.	H_2O W49-Orion multiple lines	0.1	60
8.	H_2CO galactic center absorption	1	300
9.	NH_3 galactic center emission	1	100
10.	H extragalactic search	50	4000
11.	H/He/C recombination lines (1.3 cm)	50 kHz	20 MHz
	(10 & 11 will use whatever bandwidth is available)		
12.	H/He/C recombination lines (6 cm)	20 kHz	4 MHz
13.	H galactic center	1 Km/s	500 Km/s
14.	OH galactic clouds	0.5	200

In the graph a circle represents the required bandwidth and resolution for each experiment listed above. The bandwidth and resolution available for a 32 through 512 channel correlator is shown by the 45° solid lines. The dotted line indicates a possible Papadopoulos-Ball sampling correlator. Any given correlator will cover all those experiments above and to the left of the line. Experiments below the line can be done, but with less than optimum bandwidth or resolution.

K [redacted] LOGARITHMIC [redacted] 46 75 [redacted]

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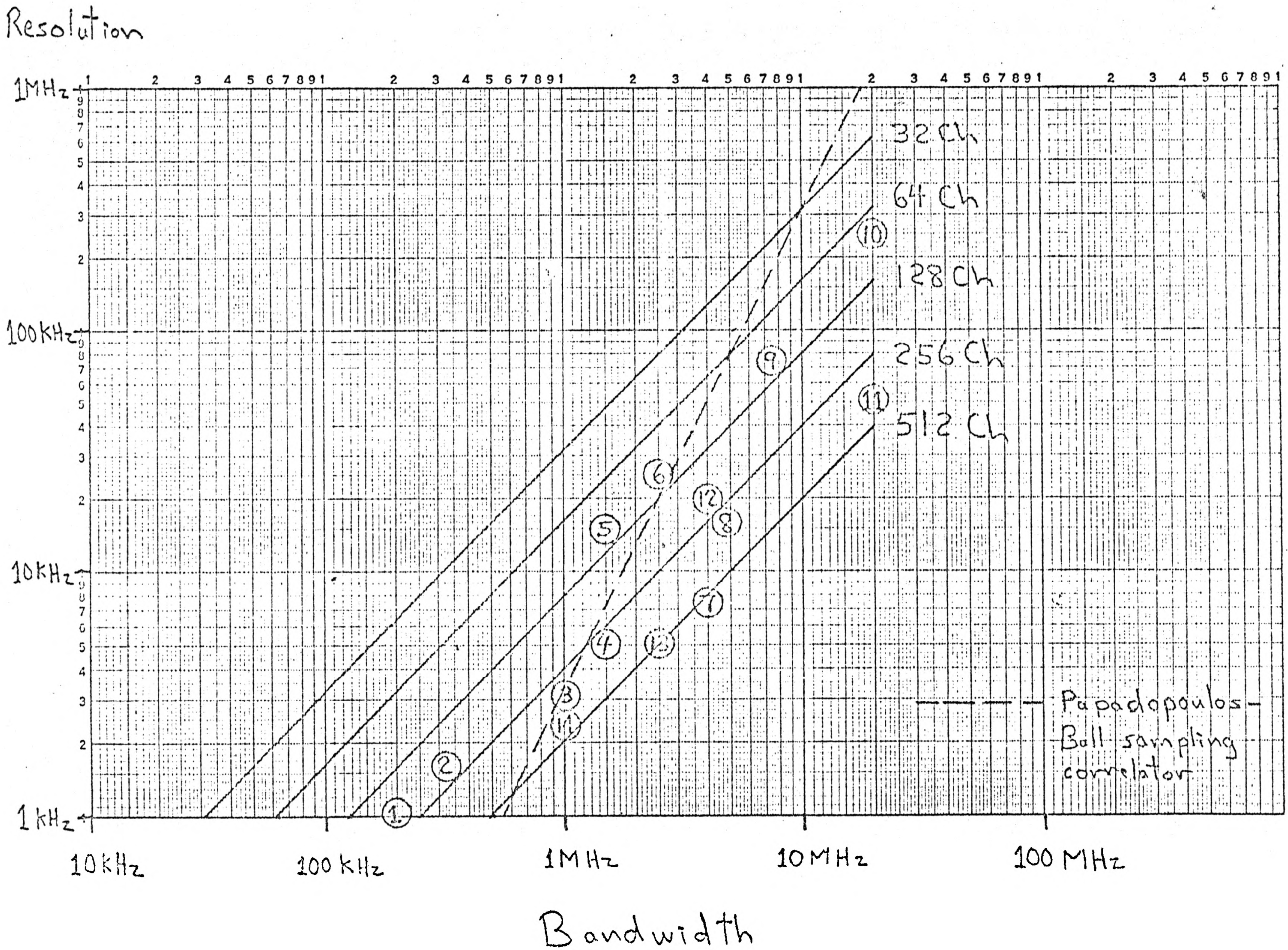

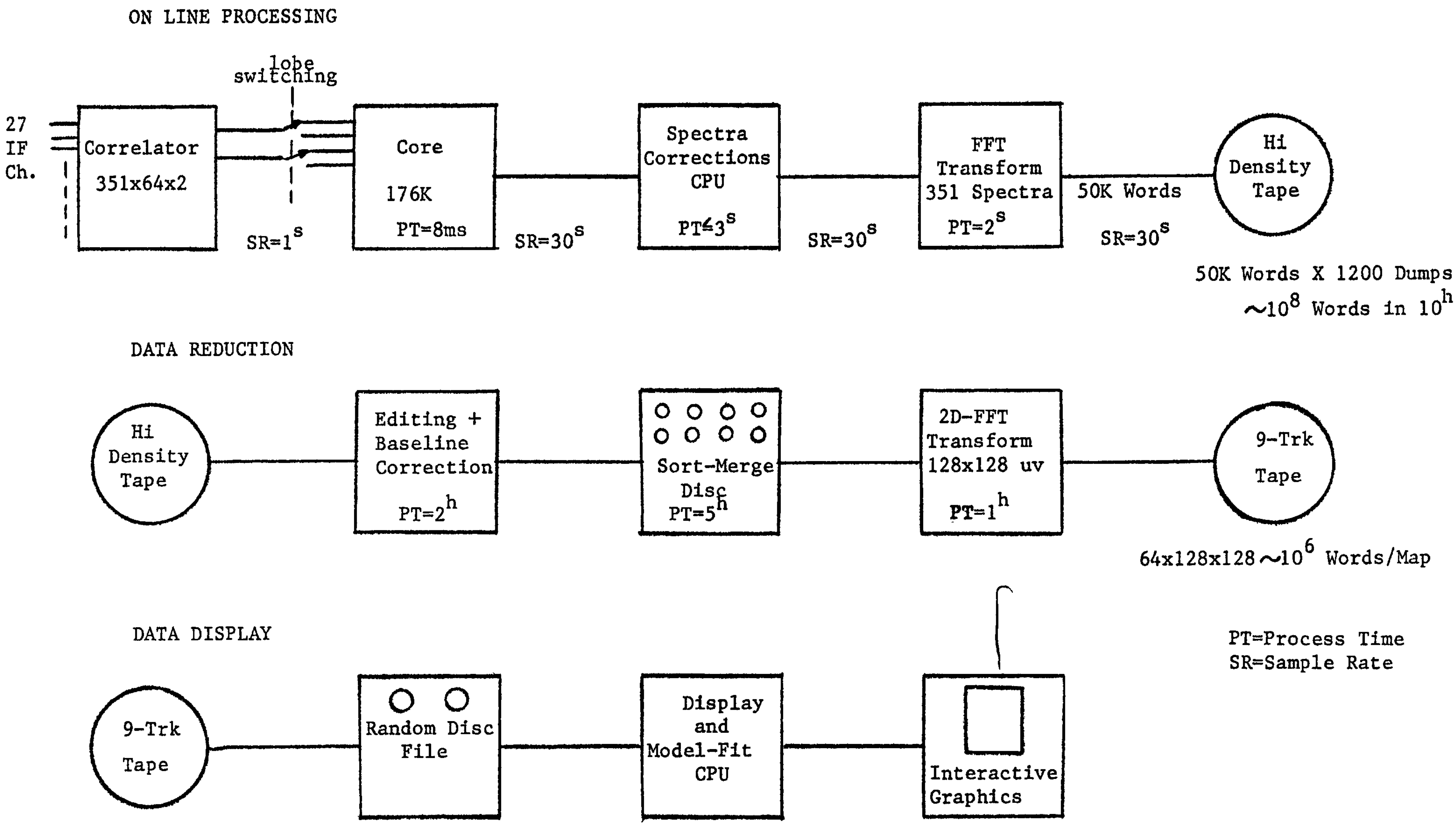

Fig. 1
Spectral Line Computer
(B. G. Clark)