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An Acousto-Optic Spectrum Analyzer for
Plasma Diagnostics

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ABSTRACT

An acousto-optic RF spectrometer (AOS) has been designed and constructed for use on the CONSTANCE B and TARA mirror experiments at MIT. The AOS is an analog preprocessor of data that can come from a variety of sources including RF probes and microwave/laser scattering experiments. The output of the AOS is the Fourier transform amplitude of the input in a parallel format suitable for computer acquisition. The spectrometer, having a bandwidth of 500 MHz and a resolution of 1 MHz, together with its receiver is capable of looking at fluctuations anywhere in the frequency range of a few MHz up to 4 GHz. Power levels of a few nanowatts can be detected. Complete 500 MHz wide spectrums can be processed and acquired at the rate of 1 every 10 μ S. The optical components, receiver, and data acquisition interface will be discussed, and initial data taken on the CONSTANCE B experiment will be shown.

INTRODUCTION

Plasma experiments generate the need to analyze and store data over a very broad spectrum of frequencies. In most cases this is done by utilizing fast data acquisition modules to sample the data at rates above the Nyquist frequency and then Fourier analyzing the results. In experiments with long pulse lengths, ordinary analog spectrum analyzers can be used. In experiments where the experimental time scales are short, and the frequencies of interest high, no diagnostic really exists with which to easily make measurements. The AOS fits into this slot by reducing the bandwidth needed to monitor high frequency short duration fluctuations. It preprocesses the incoming analog signal and produces an output signal in a parallel format that can be acquired by the computer at a very high effective data rate. The theoretical background for such a device was outlined well before laser and Bragg cell technology could provide the means for their construction^{1,2,3}. Today such devices are used with some regularity for the analysis of radio telescope data⁴, and of course, for electronic counter measure applications⁵. We report here on a device built specifically as a diagnostic of high temperature plasmas.

I. THEORY OF OPERATION

Fig. 1 shows a schematic diagram of an acousto-optic spectrometer. Light from a He:Ne laser is first spatially filtered and collimated before illuminating a Bragg cell. The signal from a probe in the plasma (or the output from a scattering experiment) is then used to drive the Bragg cell, generating acoustic waves in the Bragg cell that propagate normally to the incoming laser beam. The waves modulate the index of refraction of the Bragg cell and set up what is essentially a diffraction grating. The light, on exiting the Bragg cell, is then focused by the Fourier transform (FT) lens. The zeroth order light is focused into a light dump while the first order light is focused onto a detector. The light at the detector obeys the simple grating formula

$$n\lambda = d\sin(\theta) \quad (1)$$

where n is the diffraction order, λ is laser wavelength, d is the grating spacing, and θ is the angle of diffraction. Noting that the grating spacing is just v/f , where v is the sound velocity of the waves in the Bragg cell and f is the frequency, we have

$$n\lambda = (v/f)\sin(\theta) \quad (2)$$

which gives

$$f = (v/n\lambda)\sin(\theta). \quad (3)$$

For small angle diffraction we find that the frequency of the signal input into the Bragg cell is proportional to the angle of diffraction. Therefore, if the optics are designed carefully, one finds at the output of the optical chain, in the case of a single frequency signal, a single spot of light. The input frequency can then be determined by measuring the diffraction angle. It can also be shown that the intensity of the light is proportional to input signal power and that in the case of a complex signal, the output of the device is in fact the Fourier transform amplitude of the input signal⁶. Thus the AOS effectively takes an analog signal, calculates its Fourier transform, and displays it in a parallel format at the focal plane of the FT lens. If we now place at the focal plane not one, but a large number of detectors, we can read out the Fourier transform very quickly by reading the data into the computer simultaneously into several analog-to-digital channels. In the AOS built for the CONSTANCE B and TARA experiments, for example, a Reticon array with 512 detectors is used. If the detectors were all read out in series, the bandwidth needed to digitize the detector signals

would be the same as needed to digitize the original signal. The Reticon CCPD-512 array, however, breaks up the array into 8 arrays of 64 diodes each which are read out simultaneously. We therefore gain a factor of eight in the bandwidth needed to digitize the signal and calculate its frequency spectrum. One can also gain a considerable amount of digitizer flexibility by accepting longer diode integration times and therefore slower array readouts, as the application allows.

The AOS designed for use on the CONSTANCE B and TARA experiments was built primarily to look at high frequency fluctuations that are difficult to study in any other way. The bandwidth of 500 MHz fits together well with the 512 diode Reticon array that was used as the detector. This combination allowed us to fully exploit the 1 MHz resolution of the Bragg cell.

Fig. 2 is a schematic of the full AOS system. Its major components consists of the Bragg cell and associated optics, broadband receiver, readout control electronics, and data system interface.

II. AOS OPTICAL DESIGN

Fig. 3 is a drawing of the AOS optical system. To keep the optical chain compact, a two level system was designed with the 5 mW laser occupying the lower level, and the collimator, spatial filter, FT lens, and detector array the upper level. The laser light, on leaving the laser, reaches the upper level via a periscope arrangement that provides a great deal of adjustment in both the lateral and vertical position of the beam as it enters the collimator. The collimator consists of a short focal length precision cylindrical lens that focuses the beam through a $25 \mu M$ wide slit, providing the necessary spatial filtering. The second lens recollimates the light, but now as a fan shaped beam approximately a factor of 10 wider than the original laser beam. The beam is now properly tailored to the Bragg cell aperture. On exiting the Bragg cell the beam is focused onto the diode array. The diode array and readout electronics are mounted on a precision translation stage which allows very careful focusing to be obtained. Lateral motion of the translation stage allows the diodes to be set on the proper frequency.

III. AOS RECEIVER CAPABILITY

The Bragg cell's bandpass is centered at 1 GHz. Therefore any plasma signal we want to study must either lie in the frequency range of 750 to 1250 MHz, or must be mixed into that passband. The receiver shown in Fig. 4 was designed to do both the frequency conversion and also provide 60 dB of RF gain. It is an 8 band receiver covering the 5 MHz to 4 GHz frequency range while incorporating the 500 MHz IF needed for the AOS. This extremely wide IF bandwidth makes it a somewhat novel design. All the local oscillators, mixers, and filters shown in the figure can be switched in and out automatically from a single front panel bandswitch. Provisions for external local oscillator/mixer pairs are also made so that the frequency coverage of the receiver can be extended (to around w_{ce} , for example). The theoretical spectrum acquisition rate of the AOS is one spectrum every $2.5 \mu S$. This is the propagation time of a wave across the Bragg cell and is therefore the maximum rate at which a spectrum can change. The real speed limitation of the present AOS system is readout speed of the diode array combined with signal level. The Reticon array used requires at least $10 \mu S$ to be read and is therefore the speed-limiting

factor in the design (assuming free choice of digitizers). Also of a practical nature is the signal to noise ratio of the detector array which increases with integration time. Weak signals must be acquired more slowly than strong ones. All VCO's in the system have bandwidths of less than 100 KHz and are thus well within the Bragg cell bandwidth of 1 MHz. Well regulated, low drift power supplies were used to minimize drift in the the VCO circuits.

IV. DATA INTERFACE

The data interface of the AOS must perform three major functions. First of all, it must generate the master clock for the Reticon array and the digitizers. Looking at Fig. 5, this function is performed by the 74LS123 chip and several counter/divider chips. Secondly, the interface must produce the necessary sync signals so that the data system will know where a spectrum begins and ends. In Fig. 5 the 74LS76 flip flop changes state at the beginning of every spectrum so that when this signal is digitized, the analysis program can decide how to interpret the spectrum. Finally, because of the enormous amount of data that could be produced if the AOS was allowed to 'free run', the interface is capable of counting a set number of spectra before digitizing one.

Fig. 6 shows the spectra counting circuit. It consists primarily of a set of thumbwheel switches that control the reference count set on the 74LS85 digital comparators. This board generates a gate to the clock board that is used to run the digitizer.

The data is read from the detector array into Lecroy 2264 8 bit digitizers. The analysis program on our VAX11/750 computer system then takes the data and pieces together the spectra. Diode to diode calibrations and baseline corrections are then made, and the data displayed as shown in Fig. 7.

V. RESULTS

Fig. 7 is a spectrum obtained on the Constance B quadrupole mirror experiment. A four turn magnetic probe was used to obtain the data. The probe was placed about 10 cm from the machine midplane and about 10 cm off axis. We observed very broadband emission over nearly the entire 4 GHz range of the AOS. The data in Fig. 7 was obtained on the 2.5 to 3.0 GHz band. To obtain data over the whole shot, only every 30th spectra is digitized. Integration times of about 2 mS were used because of the weak signal strength. The Constance

experiment uses an 11 GHz, 600 watt klystron to produce hot electron plasmas. In Fig. 7 the klystron is turned on 1 second into the shot, and turned off at 3 seconds. The AOS sees a large burst in RF noise when the klystron turns off, followed by the slow .5 second decay of the plasma. Because the integration time is so long, it is almost certain that the spectrum is 'smeared' out as the spectrum changes with time.

Finally, in Fig. 8 we show data from the AOS running with a 250 μ S integration time. An external oscillator-mixer has been installed to allow us to look in the band of frequencies around 8 GHz. It is clear that the emission spectrum from the ECH generated plasma can change very quickly. Here we see much more structure than in Fig. 7.

VI. CONCLUSIONS

We have built and successfully operated an AOS on the Constance B experiment. If anything, the experiment has been too successful in that it has often provided much more data than we can hope to analyze properly. This problem should be alleviated with better analysis software.

We now have plans for upgrading the device in the near future with a higher power laser and a more up-to-date diode array and read-out. The data will be digitized by a camac module designed specifically for acquiring diode array data. These improvements should increase the signal to noise ratio of the AOS by a factor of ten, without making any changes to the receiver.

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FIGURE LEGENDS

Fig. 1. Diagram illustrating operation of the AOS optical components.

Fig. 2. A signal from an RF probe or scattering system is first mixed into the Bragg cell passband and amplified. The detected signal from the Reticon board is split up into 8 parallel analog signals, each one containing the data from 64 diodes. Each of the signals is then buffered out to the data acquisition system. Because such large amounts of data can be generated, the spectrum counting circuit is used to select only every Nth spectrum for acquisition. This technique allows very fast acquisition times for individual spectrums while allowing long time scale events to be studied.

Fig. 3. In the AOS optical system, a He:Ne laser beam first goes through a spatial filter and beam expander consisting of L1, S1, and L2. On reaching the Bragg cell, the laser beam has been collimated and expanded to fill the cell aperture. L3 forms the Fourier transform lens which images the spectrum onto the Reticon diode array.

Fig. 4. Bands A and B of the AOS receiver are double conversion superheterodyne designs so that local oscillator products are kept out of the Bragg cell passband. Bands C through H are single conversion stages.

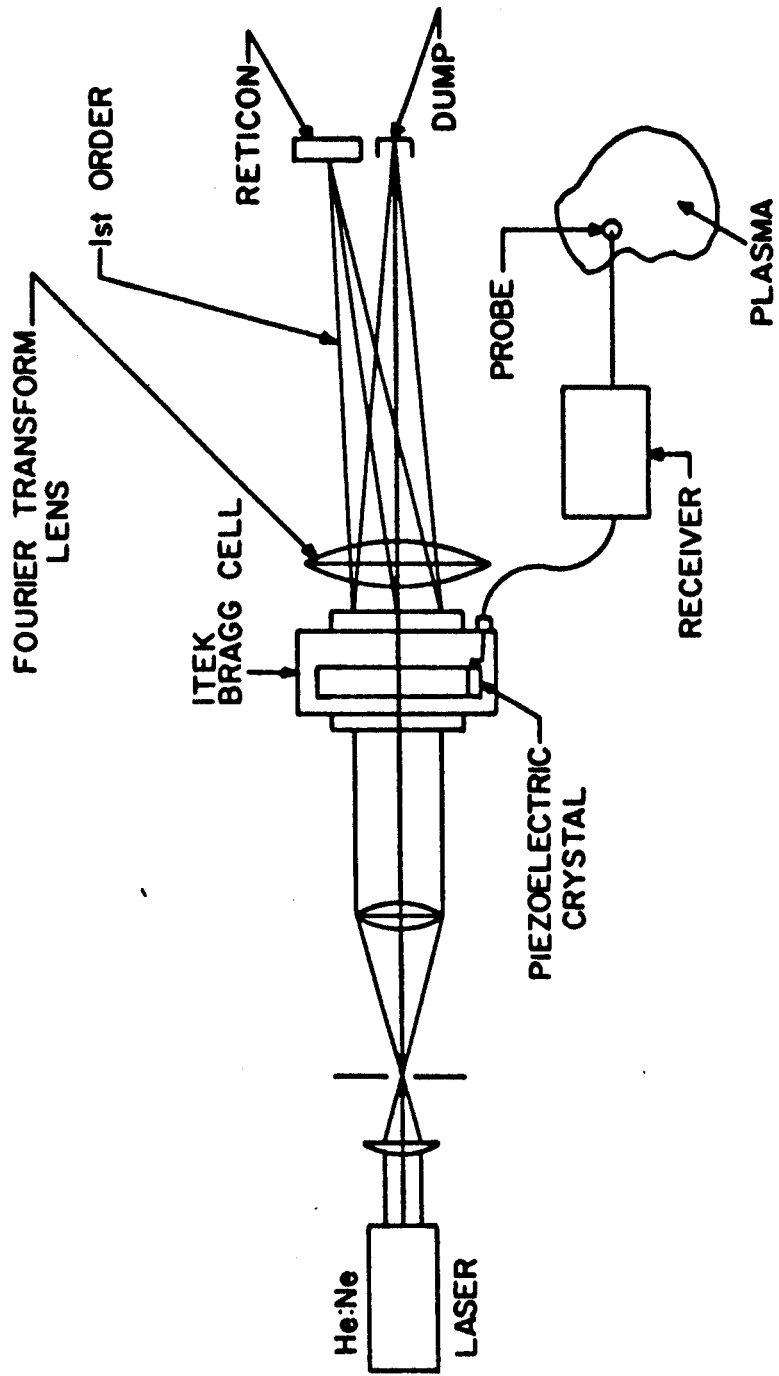
Fig. 5. Thumbwheel switches are used to select how often spectrums are acquired by the data system. A sync pulse is also generated at this time that is digitized with the AOS data and used by the AOS program to detect the beginning and end of each spectrum.

Fig. 6. The system clock provides both the reticon board and the data system digitizers with the required clocks. The gate pulse from the spectrum counter is used to gate the digitizers into operation.

Fig. 7. Early results from the AOS in use on the Constance B mirror experiment show broadband RF generated by the hot electron plasma. The signal was coupled to the AOS receiver via a four turn b-dot probe 10 cm from the axis of the machine and also 10 cm from the midplane. 600 watts of ECH at 11 GHz is applied 1 second into the shot. Three seconds into the shot the ECH is turned off resulting in a burst of RF emission. A long integration time of 2 mS was used because of low

signal levels.

Fig. 8. Narrow band emission around 8 GHz with a shorter integration time than in Fig. 7. Spectra are separated by 250 μS . The spectra number is displayed in the upper right hand corner of each frame.



SCHMATIC OF ACOUSTO
OPTIC SPECTROMETER

Figure 1

AOS RF SPECTRUM ANALYZER SYSTEM

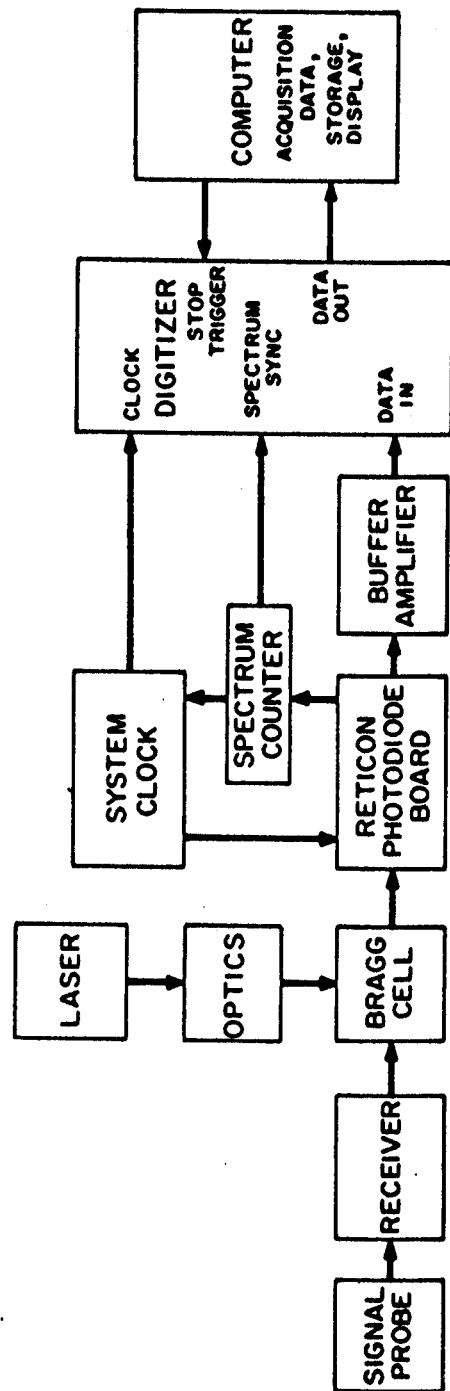
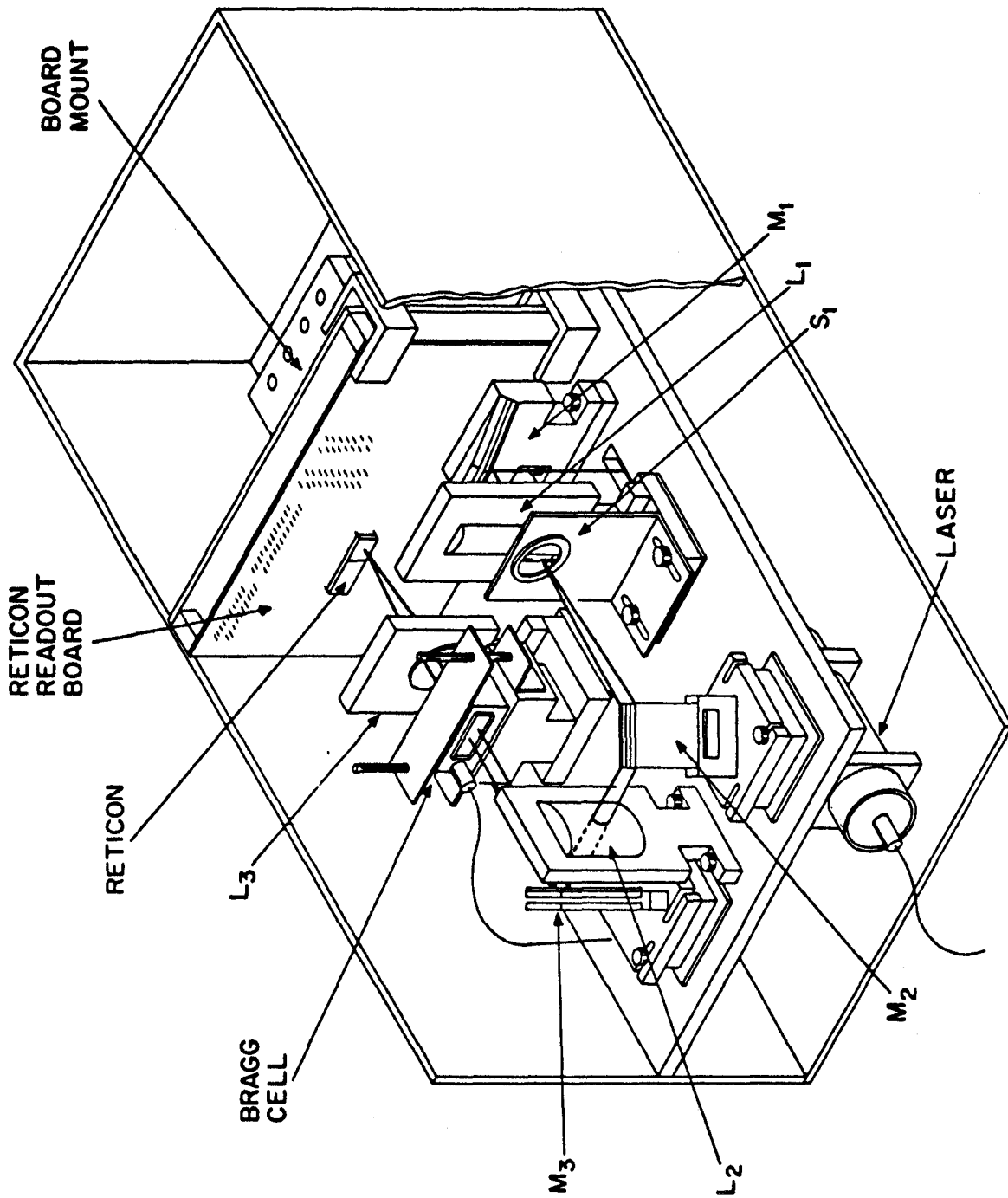


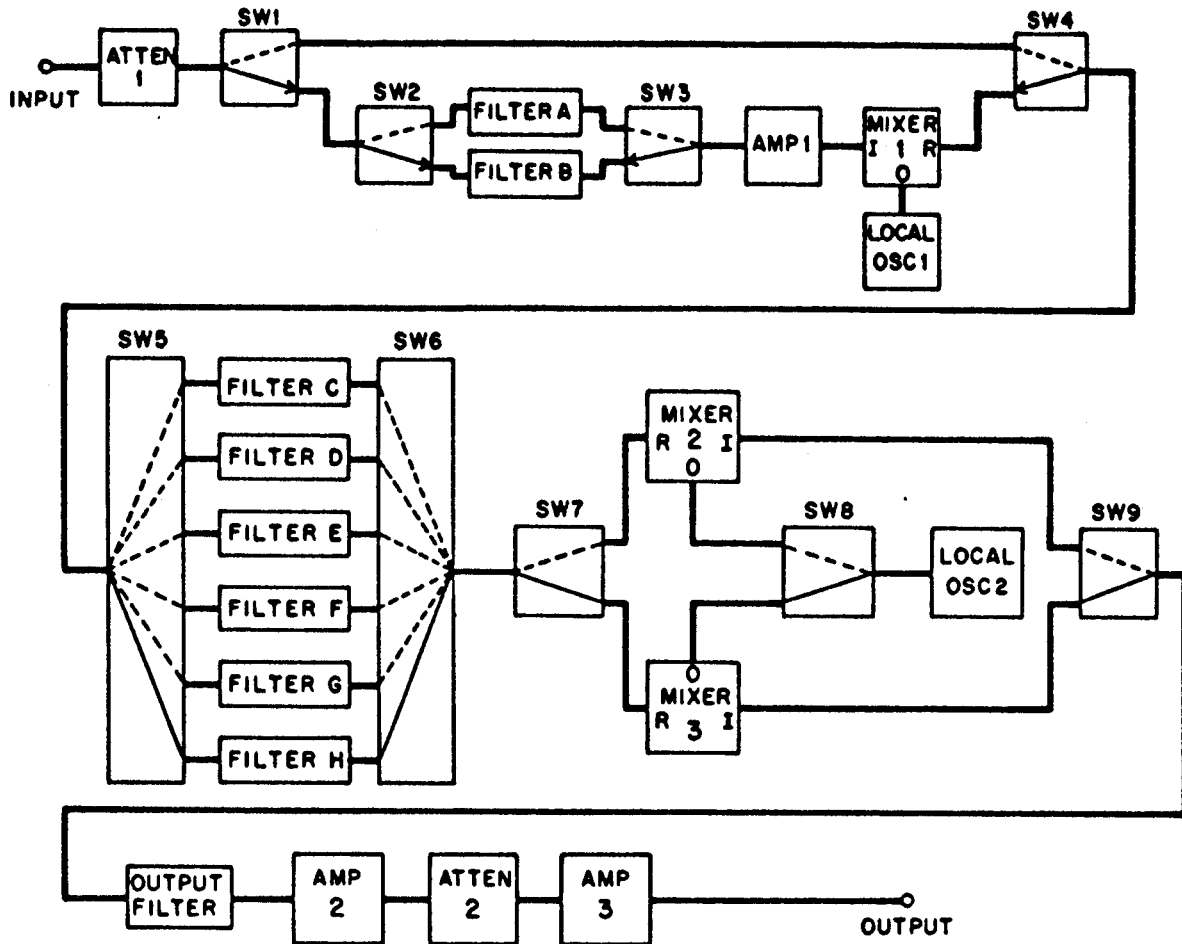
Figure 2



AOS OPTICS

Figure 3

AOS RECEIVER DIAGRAM



Attenuator 1 : 0 to 60 db in 10db stops
 Attenuator 2 : -6 db
 Amplifier 1 : WJA31-1
 Amplifier 2 : WJ6610-502
 Amplifier 3 : Mini 6610-502 ZHL-42
 Mixer 1 : WJM15C
 Mixer 2 : WJM15C
 Mixer 3 : WJM2GC
 Local Osc. 1 : WJU302 3.0 GHz
 Local Osc. 2 : WJU302 2.0-4.0 GHz

Filters : A : DC-500 MHz
 B : 500-1000 MHz
 C : 1000-1500 MHz
 D : 1500-2000 MHz
 E : 2000-2500 MHz
 F : 2500-3000 MHz
 G : 3000-3500 MHz
 H : 3500-4000 MHz
 OUTPUT: 750 -1250 MHz

Figure 4

AOS SYSTEM CLOCK GENERATOR

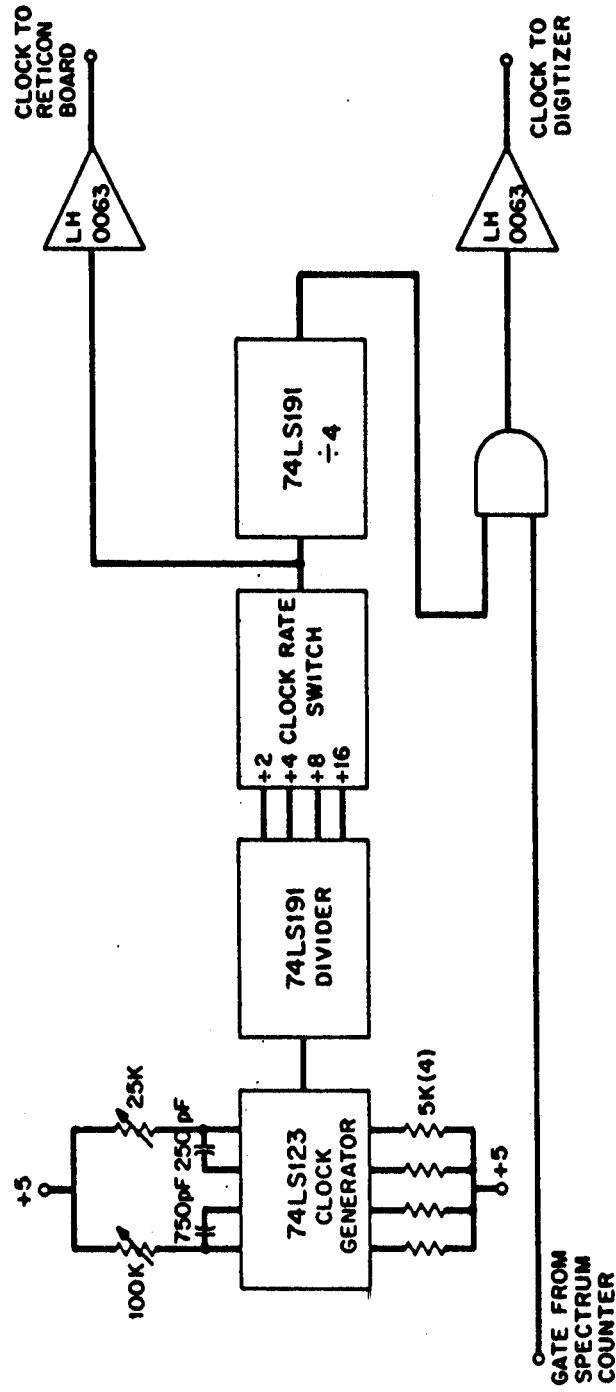


Figure 5

AOS SPECTRUM COUNTER

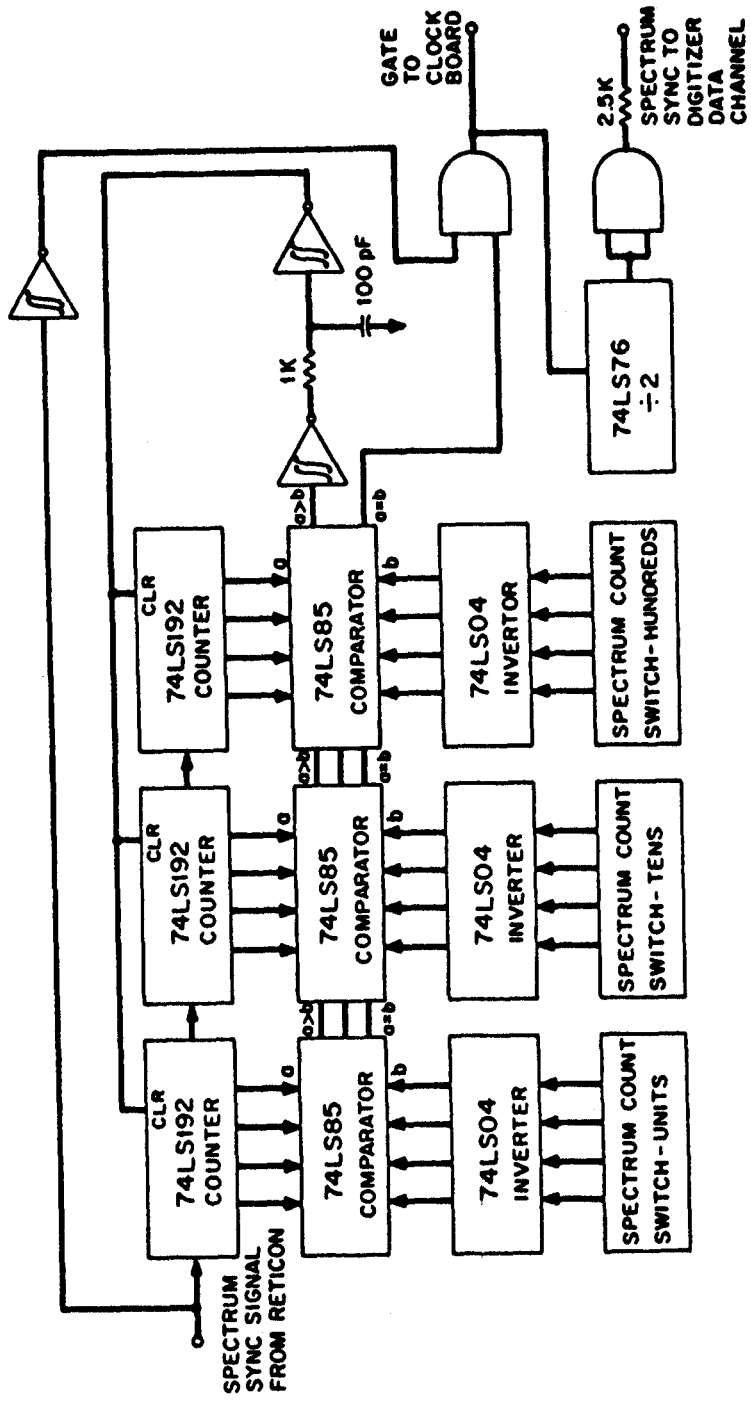
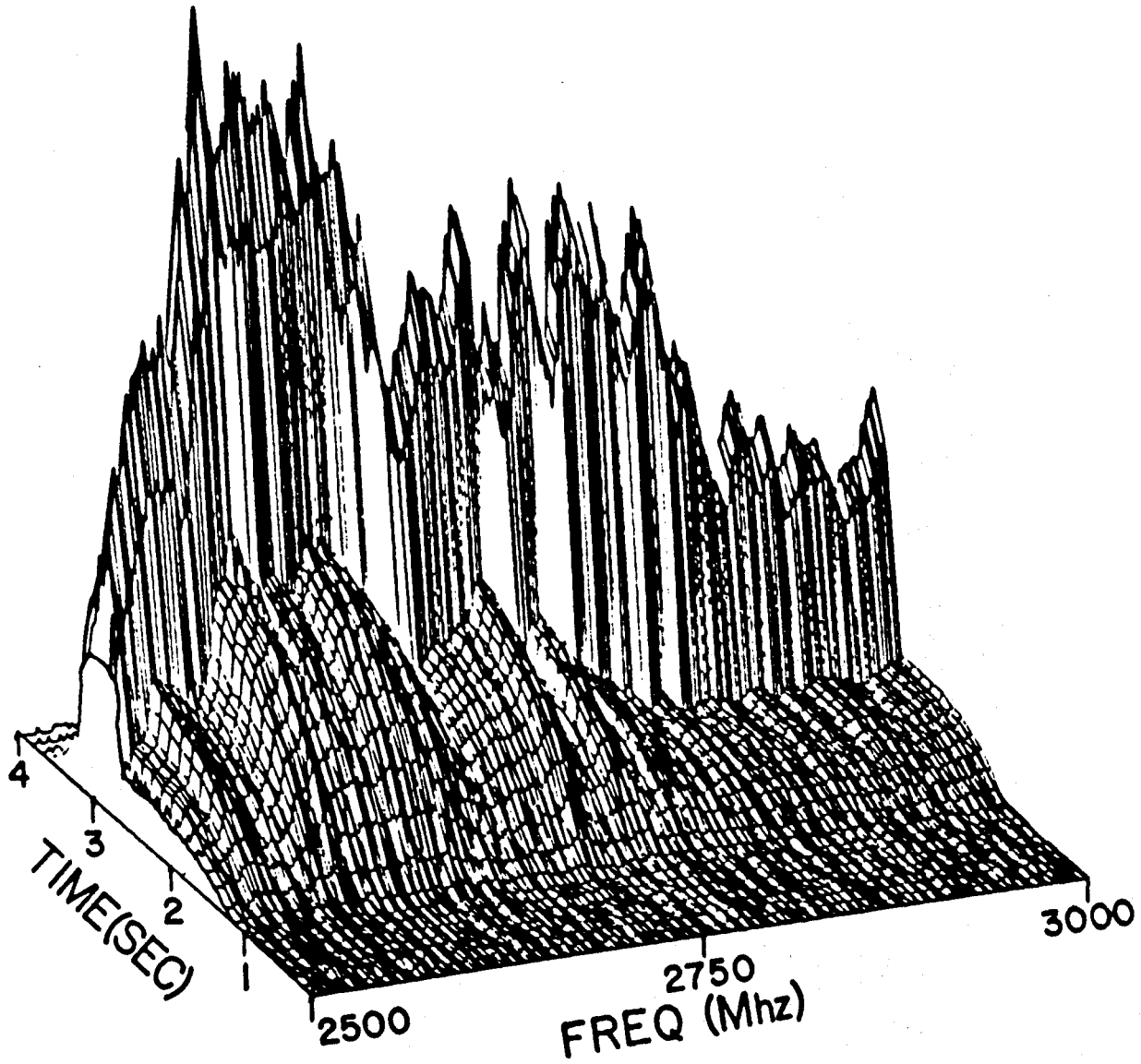
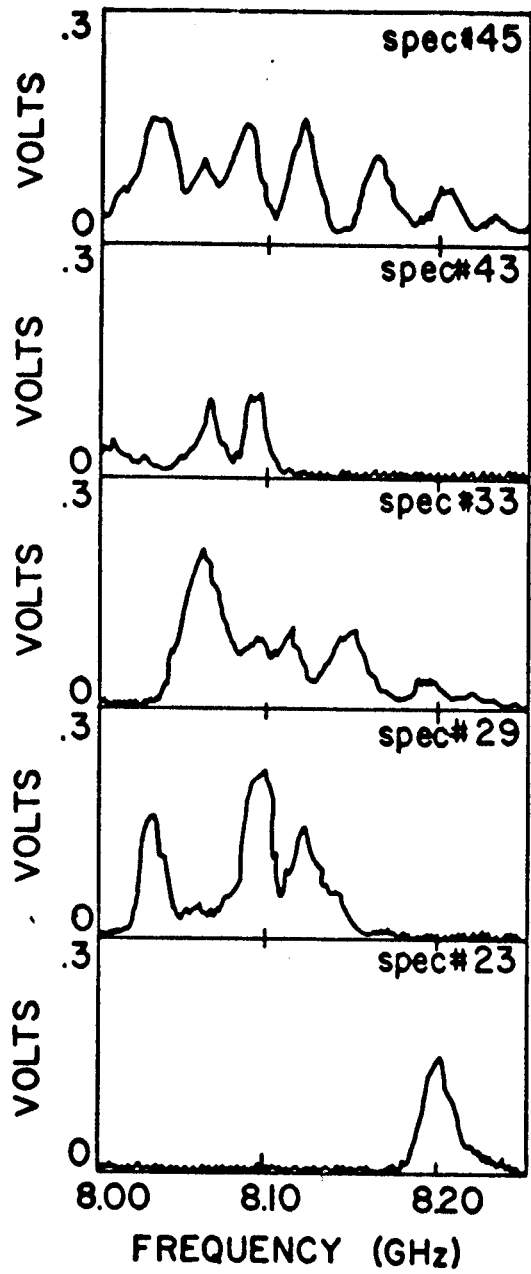


Figure 6



AOS FREQUENCY SPECTRUM

Figure 7



AOS TIME HISTORY

Figure 8