ACOUSTO-OPTIC SPECTROMETER FOR RADIO ASTRONOMY[*]

Gordon Chin and David Buhl
Code 693, Infrared and Radio Astronomy Branch
NASA/Goddard Space Flight Center, Greenbelt, MD 20771

Jose M. Florez
Code 728, Instrument Data Management Branch
NASA/Goddard Space Flight Center, Greenbelt, MD 20771

ABSTRACT

One of the most significant developments in radio astronomy has been the recent discovery of over 50 different molecules in the interstellar medium. These observations have changed our picture of the distribution of mass in the galaxy, altered our understanding of the process of star formation, and has also opened up a new and lively field of interstellar chemistry. This achievement was made possible not only by the development of sensitive heterodyne receivers (front-end) in the centimeter and millimeter range, but also by the construction of sensitive RF spectrometers (back-end) which enabled the spectral lines of molecules to be detected and identified. Traditionally spectrometers have been constructed as banks of discrete adjacently tuned RF filters or as digital auto-correlators. However, a new technique combining acoustic bending of a collimated coherent light beam by a Bragg cell followed by detection by a sensitive array of photodetectors (thus forming an RF acousto-optic spectrometer (AOS)) promises to have distinct advantages over older spectrometer technology. An AOS has wide bandwidth, large number of channels, high resolution, and is compact, lightweight, and energy efficient. These factors become very important as heterodyne receivers are developed into the submillimeter, far infrared, and 10 micron spectral ranges and as more observations are performed from remoté, airborne, or spaceborne platforms.

We give a short description and report of existing AOS back-ends in Australia and Japan but will concentrate on our recent construction of a proto-type AOS at Goddard Space Flight Center. The GSFC AOS uses a discrete bulk acoustic wave Itek Bragg cell, 5 mW Helium-Neon laser, and a 1024 element Reticon CCPD array. The analog signals from the photodiode array are digitized, added and stored in a very high-speed custom built multiplexer board which allows us to perform synchronous detection of weak signals. The experiment is controlled and the data is displayed and stored with an LSI-II microcomputer system with dual floppy disks. We will report the performance of the GSFC AOS obtained from our initial tests.

We also will give a description of an integrated SAW Bragg cell which will miniaturize a complete AOS system into a 2.5 X 7.6-cm (1 X 3-in) package.

INTRODUCTION

A recent compilation of observed interstellar molecules[1] lists forty-six molecular species with close to 600 different observed transitions. The actual number of observed molecules is now over fifty with this figure constantly increasing. Observed molecular lines range in frequency from 1 to $\sim$ 345 GHz. A variety of receiver front-ends are needed to cover this extremely broad frequency spectrum[2]. Below 20 GHz the signals may be amplified directly by transistor, parametric, or maser amplifiers. These receiver systems range in system temperature from 50K for the 20 GHz ruby-maser receiver to $\sim$400K for the 50 MHz transistor receivers. Above 20 GHz, the lack of suitable pre-amplifiers forces the signal to be mixed (heterodyne) with a local oscillator (LO) and the intermediate frequency (IF) amplified by a low noise system. Heterodyne receivers in the 80-120 GHz range have achieved system temperatures of 500-1000K single side band (SSB) per channel by efficiently coupling signal and LO into cooled Schottky diode mixers followed by cooled parametric amplifiers. A room temperature heterodyne mixer receiver in the 130-170 GHz range has a system temperature of 2000K SSB while a bolometer receiver operating in the 250 GHz range has a system temperature of 30000K. Recently heterodyne techniques have been employed in the 10μm infrared band, i.e. 3×10^{13} Hz, using broad band infrared detectors as photo-mixer and 10μm CO_2 laser as local oscillator[3]. Work has been done on Josephson mixer receivers for 115 GHz and for higher frequencies[4].

The thrust of receiver development is towards high frequency heterodyne systems particularly in the millimeter, submillimeter, far infrared, and 10μm spectral ranges. The motivation for this development comes from the need to determine the chemical composition of the interstellar medium and to achieve a thorough understanding of the excitation of interstellar molecules. The most important constituent of the interstellar medium after molecular hydrogen is carbon monoxide (CO) which has its rotational transitions at 115.3, 230.5, 345.8 GHz, etc., while hydroxyl (OH), an equally important constituent, has its ground-state rotational transition at 2508 GHz. In general, the lighter the molecule, the higher its ground-state transitions which fall often above currently accessible receiver ranges.

The LO, LO coupler, and mixer present difficult challenges as the range of the receiver is extended towards higher frequencies. Klystrons which are already expensive and short-lived in the 3 millimeter range become impractical at shorter wavelengths forcing development of frequency doubling or tripling mixers utilizing cheaper and more robust lower frequency LOs. In the 10μm band CO_2 gas laser-heterodyne systems, with its various isotopic mixtures, can cover only about 10% of the spectral band due to the limited tunability of the gas laser transition and limited bandwidth response of mixers. Work is presently underway in this laboratory to construct a diode heterodyne system which will have a 2μm continuously tunable range. RF tuned cavity LO couplers which work well in the 3 millimeter wavelength become highly lossy in the millimeter range forcing development of quasi-optical techniques to combine signal and LO efficiently

to the mixer. Mixer development is also continuing to extend usable range of mixers into the far infrared and 10μm bands.

Common to all heterodyne systems is a RF spectrometer (back-end) which recovers the power spectrum of the signal from the IF. Traditionally the spectrometer is a bank of discrete adjacently tuned RF filters or a digital auto-correlator. Most radio telescopes have 256 or 512 channels at 1 MHz or 0.25 MHz resolution. Heterodyne receivers in the millimeter, submilli-meter, or far infrared will be operated from remote mountain, airborne, balloon-borne, or spaceborne platforms to avoid the severe atmospheric attenuation in the 20μm to 1 mm range. This will place severe demands of size, weight, and energy usage on the back-end which RF filters may not be able to satisfy. A feasibility study of placing a submillimeter telescope on the space shuttle has been made at JPL[5]. A recent study of a 10μm heterodyne receiver on the Upper Atmospheric Research (UARS)[6] satellite shows that a 20-channel filter bank requires ~25% of the volume, ~33% of the weight, and ~30% of the power of the total instrument. A back-end using RF filters which can provide bandwidth and resolution coverage comparable to ground-based installations will prove prohibitive with respect to volume, weight, and power requirements in any free flying spaceborne experiment.

<div align="center">ACOUSTO-OPTIC SPECTROMETER (AOS)</div>

Recent developments in acousto-optic techniques and in photodetector arrays have made feasible a new type of RF spectrometer [7,8] offering the advantages of wide bandwidth, high resolution, large number of channels in compact, lightweight, energy efficient, and relatively low cost systems. Such a system employs an acousto-optic diffraction cell which serves the key role of converting RF signals to ultrasonic traveling-waves modulating the optical index of the cell. The cell is illuminated across its aperture by a monochromatic laser beam. A fraction of the light is diffracted by the acoustic waves; the angle of diffraction is determined by the frequency while the intensity of the diffracted light is proportional to the power of the input RF signal. (The major portion of the laser beam at zero order passes through the cell undeflected.) A focusing lens follows the cell and essentially performs a Fourier transform of the RF signal into a far-field intensity pattern. The output intensity distribution is typically received by a linear array of photodetectors whose output is the RF power spectrum we seek. The advantages of an AOS are due to the simplicity arising from the small number of components needed to build up the system.

Currently there is intense commercial interest in applying acousto-optic techniques to electronic warfare (EW), electronic countermeasures (ECM) and electronic support systems (ESM)[9,10] which is spurring rapid technical advancements in the field. The Air Force and Navy, in a joint effort, are funding research at GTE-Sylvania, ATI-Itek, ESL, Teledyne-MEC, and Rockwell International in bulk Bragg cell AOS components. One benefit from this research is the commercial availability of 1 GHz bandwidth, 1 MHz resolution Bragg cells. The Air Force and the Navy have also funded Hughes Research and Westinghouse in an effort to further miniaturize an acousto-optic system by integrating all its components on a single

substrate. These recent developments have made acousto-optic techniques increasingly attractive for use in astronomical applications.

Radio Astronomy

Commonwealth Science and Industry Research Organization (CSIRO) in Australia and the Tokyo Astronomical Observatory in Japan have taken the lead in using acousto-optic techniques in astronomical applications. The first practical device was successfully made at CSIRO for obtaining dynamical spectrographs of solar radio emission[11,12] using a Data Light SLM 100 quartz modulator with LiNbO$_3$ transducer. This instrument has a bandwidth of 100 MHz centered on 150 MHz although the performance of the modulator was actually less. The output of the modulator is detected by a 512 element Reticon array (RL512C/12), corrected by a minicomputer, and subsequently stored on photographic film. The instrument provided time resolution of 0.06 sec.

CSIRO has also constructed prototype AO back-ends for spectral line observations on the Parkes radio telescope[13,14]. Typical galactic molecular lines are very weak compared to receiver noise figures; e.g. 1 K signals on top of ~1000K receiver noise. The standard approach to recover the weak spectral line signal from the receiver noise is to subtract a background when the telescope is pointed off source from the receiver output when the telescope is pointed on source (or some other form of Dicke switching). The CSIRO backends used both a quartz and a water-medium modulator to recover the galactic OH maser spectra on the Parkes telescope. The quartz modulator system obtained 80 MHz bandwidth at 200 kHz resolution, while the water modulator achieved an effective resolution of 20 kHz and a bandwidth of 1.5 MHz. The background subtraction was performed by a minicomputer system with gain variations removed by observation of a broadband noise source.

The radio astronomy group in Japan has chosen to bypass the traditional RF filter and auto-correlator backends in favor of the acousto-optic techniques for the 6-m millimeter wave telescope at the Tokyo Astronomical Observatory[15]. They have constructed their own Bragg modulators from bonding a cross-cut LiNbO$_3$ transducer on a TeO$_2$ crystal (2-cm length) with a Pb acoustic attenuator bonded on the other end. The Bragg cell is illuminated by a 5 mW HeNe laser and the output is detected by a 256-element Reticon photodetector array (RL256C/17). The achieved RF bandwidth was 10.4 MHz at 40.7 kHz resolution. The image is integrated on the Reticon for 40 ms in conjunction with 2 sec cycle chopping wheel. The output is digitized, stored, and calibrated by a minicomputer system. Their reported spectra showed 5K SiO maser emission at 86.2 GHz (v=1, J=2 → 1) from the evolved variable star Mira (o Ceti) after 5-6 hours integration with a SSB receiver temperature of 3500K.

Prototype AOS at GSFC

Although there is extensive commercial development in AO techniques in this country, all of the applications are geared towards military needs. A thorough evaluation of AO techniques for astronomical use is in order, especially since the thrust in receiver developments is to higher frequency

and wider bandwidth and because of encouraging reports of successful AO back-ends in Australia and Japan.

The GSFC prototype AOS uses a discrete bulk acoustic wave Itek/Applied Technology Bragg cell with 300 MHz bandwidth (specified) 0.67 MHz resolution (~500 resolution elements), 5 mW Spectrophysics Model 120 helium-neon laser, and a 1024-element Reticon CCPD array. The system is mounted on stainless steel and anodized aluminum optical assembled bench components from Klinger Scientific (see figure 1).

The length of the stainless-steel rods is 1 meter, and although the optical layout is fairly compact, no attempt was made to optimize the unit for size. The laser is located on the bottom of a two tier construction, with the beam directed to the upper level by guiding mirrors. A beam expander (16X) is placed in front of the Itek Bragg cell with the cell mounted on X-Z position translators. An aberration-minimized bi-convex lens 80 mm diameter with a 47 cm focal length follows the Bragg cell. The diffracted light is then guided downward by a flat mirror, and the output light is detected by a 1024 element CCPD Reticon array mounted on precision rotation and translation stages. The interlocking construction of the Klinger assembly gives the system very good rigidity, and once the optical path has been aligned retains its alignment even after movement of the assembly as a unit. Although no attempt has been made to temperature control the assembly, the AOS appear to drift less than 1 channel over a 24-hour period.

The Itek/Applied Technology Bragg cell is made from a 1 cm optical aperture LiNbO$_3$ crystal with a specified 300 MHz bandwidth centered at 450 MHz. The interaction time is ~1.5μs with a time-bandwidth factor of ~450. The diffraction efficiency of the cell is reported to be 7%/watt of RF power. The deflection angle as a function of frequency is given by

$$\frac{\Delta\theta}{\Delta f} = \frac{\lambda}{v_s} \frac{.6328 \times 10^{-4} \,(cm)}{6.57 \times 10^5 \,(cm/s)} \simeq 9.6 \times 10^{-5} \text{ rad/MHz} \tag{1}$$

where v_s the speed of sound in LiNbO$_3$. The resolution is given by

$$\delta\theta \simeq \frac{\lambda}{D} \simeq \frac{.6328 \times 10^{-4} \,(cm)}{1 \,(cm)} \simeq 6.328 \times 10^{-5} \text{ rad} \tag{2}$$

and

$$\delta f = \frac{\delta f}{\Delta\theta} \, \delta\theta \simeq 657 \text{ kHz} \tag{3}$$

This is consistent with the time bandwidth product:

$$\delta f = \frac{\Delta f}{N} = \frac{300 \text{ MHz}}{\sim 450} = 667 \text{ kHz} \tag{4}$$

The 1024-element Reticon CCPD array has 15μm center to center. In order to match the detector element to the frequency resolved light spot (using 2 detector elements/resolution unit),

$$F = \frac{\Delta}{\delta\theta} = \frac{30 \times 10^{-6} \text{ m}}{6.328 \times 10^{-5}} \simeq 0.47 \text{ m} \tag{5}$$

where F is the focal length of the Fourier transform lens, and Δ is the 2 element spacing of the Reticon array. We will see that the actual deflection for the Bragg cell appears larger and that the Reticon array is over illuminated with a 47-cm focal length lens.

A custom-built multiplexer unit controls the operation of the AOS by controlling the readout, digitization, and storage of the integrated spectrum (see figure 2). Two 1024x32 bit buffer memories are necessary so that signal and reference can be subtracted to retrieve small signals by synchronous detection. The multiplexer is interfaced to a LSI-11 microcomputer system where scans are calibrated and displayed on Tektronix terminal and stored on dual-density floppy disks.

The Reticon array is read out every 15 ms with each 1024 photodetector element transferred in parallel to on-chip buffers then read out sequentially. The analog signals from the array are digitized to 10-bit accuracy and added to 32-bit memory. The standard CCPD evaluation board was used to provide the four-phase clocking to the detector chip with a primary clock signal from the multiplexer unit. The multiplexer is designed to run at a maximum rate of 1 MHz, i.e. 1 μsec to digitize and to add to memory, providing ∼1msec integration on the detector chip. We hope to run experiments varying the photodetector integration period from 1 to 20 msec to evaluate the performance of the detector chip at different read out rates. A balanced set of signal and reference must be obtained and usually a multiple of ∼40 secs total integration time, 20 sec on signal, 20 sec on reference, is used in conjunction with 15 msec Reticon integration and readout.

Bandwidth and Frequency Linearity

Figure 3 shows the direct readout of the 1024-element Reticon array. The AOS was operated without a light box at ordinary room illumination. The lower trace shows the detector readout after 20 sec integration at ambient light level. The two spikes are defects on the glass covering the detectors. The upper curve shows the spectrometer response to broadband noise (300K/ 50Ω terminator after ∼ 120 dB gain) and is the response of the Reticon array to the diffracted laser beam. The horizontal tic marks indicate 256 channel divisions and the 450 MHz mark is at the center position of this scan. A frequency comb with signals starting at 300 MHz separated by 25 MHz each (we could not cover the full 300 MHz range of the cell due to frequency limitation of our signal generator and the over illumination of the Reticon array) was used to produce Figure 4, which graphically displays the frequency as a function of channel number (the uncertainty in both channel number and frequency are smaller than the size of the dots). Figure 4 shows that the

AOS is very linear with frequency although the deflection is greater than what is calculated by equation 1. The Reticon array covers ~235 MHz range rather than the 300 MHz implied by using a lens with a focal length given by equation 5. We also see from Figure 3 that the 3 dB bandwidth for this Itek Bragg cell is closer to 150 MHz than the reported 300 MHz. The response of the spectrometer at 300 MHz bandwidth appears to be down by at least 8 dB.

Sensitivity

The AO spectrometer is a very sensitive device in detecting weak signals. We simulated observation of a spectral line by using the chopper square wave drive from the multiplexer to amplitude modulate a 450 MHz -30 dBm signal to the Bragg cell from the signal generator (we achieved ~70% AM). The unmodulated signal is stored in the signal memory while the modulated signal is stored in the reference memory. Figure 5 shows the difference between signal and reference after 40 sec. total integration (20 sec on signal plus 20 sec on reference). We get a signal to noise of better than 50:1, but more importantly the noise spectrum away from the signal is flat without any systematic pattern. We have used the AOS to detect a -40 dBm signal to the Bragg cell by integrating over 24 hrs achieving better than 30:1 signal to noise, and again with no systematic errors over the 1024 channels. Using this synchronous detection mode the dynamic range of the AOS is better than ~40 dB.

The response of the AOS to a given RF signal is given by

$$v_i = G_i I_i + Z_i \tag{6}$$

where v_i is the output voltage at the i-th channel, G_i is the i-th channel gain of the system (Bragg cell, amplifier, and detector array gains), I_i is the RF input signal, and Z_i is the zero offset of the i-th channel (Reticon zero-th level, ambient light, and laser scattered light). The systematic gains of the AOS may be removed by forming the ratio

$$\frac{S_i - R_i}{R_k - Z_i} \tag{7}$$

where

$$S_i - G_i I_i \text{ (signal)} + Z_i$$
$$R_i = G_i I_i \text{ (reference)} + Z_i \tag{8}$$

The difference between the upper and lower curves in Figure 3 gives essentially the result for $R_i - Z_i$ over the 1024 channels. The RMS noise of equation 7 should give us

$$\Delta \frac{S-R}{R-Z}_{RMS} = \frac{1}{(B\tau)^{1/2}} \tag{9}$$

where B is the bandwidth of the measurements and τ is the integration time. Figure 6 displays graphically the expected $1/(B\tau)^{1/2}$ for B = 333 kHz at 40 sec τ increments for the upper solid curve and for the lower solid curve, B = 3.3 MHz at 40 sec τ increments. Measured values at 40 sec integration time increments are given by points surrounded by boxes. We see that the measured noise of the AOS follows the $1/\tau^{1/2}$ law very well for over the 2000 sec (33 minute) period of the measurement. This indicates that there is no correlated noise source associated with the instrument. The AOS noise should follow the upper curve, which it does not. But this is not to say that the frequency resolution of the AOS is 3 MHz. The lower scale of measured points is due to uncertainty in measuring R-Z, and is caused by fluctuating ambient light levels and slow drifts in Reticon zero levels. The important result of this measurement is that the prototype system has no indication of correlated noise which limits the length of integration. However, we have not yet established the scale of the noise level.

SUMMARY

The preliminary results of tests with the GSFC AOS are encouraging. We have determined that the instrument is linear in frequency, has high dynamic range, is sensitive in retrieving weak signals, and has no correlated noise which limits integration time. However, we note that the bandwidth of the Itek Bragg cell is not as wide as advertised ($\sim$ 1/2 to 2/3 of the 300 MHz specified width), but this is not an intrinsic limitation to this technique since, hopefully, there are Bragg cells which do meet their specification. At this point we are ready to move the instrument to an existing radio telescope to perform actual observations.

Future Developments

We are planning to test a 1 GHz bandwidth 1 MHz resolution Itek Bragg cell on the existing optical setup. The only change necessary is to obtain a Fourier transform lens which will match the 1 MHz resolution light spot to the 15μm Reticon detector elements.

A more exciting development is the possibility of using integrated optics to miniaturize a complete AOS system on a single substrate of $LiNbO_3$ with dimensions of 1 in x 3 in. This concept involves using surface acoustic waves (SAW) to diffract a laser beam traveling in a single-mode wave guide formed by indiffusing Ti on a $LiNbO_3$ substrate[16]. The laser source is a GaAs diode laser in the near infrared butt coupled to one end of the substrate, while the photodetectors would be butt-coupled to the other end. Two geodesic lenses form concave aspheric surfaces which are diffraction limited lenses to collimate and focus the laser beam. We hope to acquire a hybrid integration AOS in the near future for evaluation from Westinghouse Baltimore. In place of the GasAs diode laser we will end-fire couple an HeNe laser as a first phase project. We will evaluate and test a completely integrated unit for the second phase. The integrated AOS will have 400 MHz bandwidth with 100 channels at 4 MHz resolution.

REFERENCES

1. Lovas, F.J., Snyder, L.E., and Johnson, D.R.: Recommended Rest Frequencies for Observed Interstellar Molecular Transitions. Ap. J. Supplement Series, Vol. 41, pp. 451-480, November 1979.

2. NRAO Front-end Box Status, Technical Data Sheet No. 12, National Radio Astronomy Observatory, May 1977.

3. Mumma, M.J., Kostiuk, T., Buhl, D.: A $10\mu m$ Laser Heterodyne Spectrometer for Remote Detection of Trace Gases. Optical Engineering, Vol. 17, No. 1, pp. 50-55, January-February 1978 and references within.

4. Taur, Y., Kerr, A.R.: Low Noise Josephson Mixers at 115 GHz Using Recyclable Point Contacts. Applied Physics Letters, Vol. 32, p. 775, 1978.

5. Gulkis, S., Kuiper, T.B.H., Swanson, P.N.: Scientific and Technical Prospects for Submillimeter Wavelength Radio Astronomy from Space, Jet Propulsion Laboratory, report 750-90, February 1977.

6. Mumma, M.J., et al.: Determination of Global, Absolute, Vertical Concentration Profiles of $C\ell O$ in the Earth's Stratosphere, A Proposal Submitted in Response to AO-OOS-3-78, for Upper Atmospheric Research Satellite (UARS) 1978.

7. Lambert, L.B.: Wideband Instantaneous Spectrum Analyzers Employing Delay Line Modulators. IRE National Convention Record Vol. 10, Part 6, pp. 69-78, March 1962.

8. Hecht, D.L.: Spectrum Analysis Using Acousto-Optic Devices. Optical Engineering, Vol. 10, No. 5, pp. 461-466, September-October 1977.

9. Peliotis, S.: Acousto-optics Light the Path to Broadband ESM Receiver Design. Microwaves, pp. 54-58, September 1977.

10. Oakley, W.S.: Acousto-optical Processing Open New Vistas in Surveillance and Warning Receivers. Defense Electronics, pp. 91-101, October 1979.

11. Cole, T.W.: An Electro-Optical Radio Spectrograph. IEEE Proc. Vol. 61, No. 9, pp. 1321-1323, September 1973.

12. Cole, T.W., Stewart, R.T., Milne, D.K.: An Acousto-Optical Solar Radio Spectrograph. Astron. Astrophys. 67, pp. 277-279, 1978.

13. Cole, T.W., Ables, J.G.: An Electro-Optical Spectrograph for Weak Signals. Astron. Astrophys. 34, p. 149, 1974.

14. Milne, D.K., Cole, T.W.: An Acousto-Optical Spectrometer for Radio Astronomy. Digest for Inst. Radio Eng. Aust. 16th Intl. Conf., Melbourne, p. 295, August 1977.

15. Kaifu, N., Ukita, N., Chikada, Y., Miyaji, T.: A High Resolution
    Acousto-Optical Radio Spectrometer for Millimeter-Wave Astronomy.
    Publ. Astron. Soc. Japan, Vol. 29, pp. 429-435, 1977.

16. Hamilton, M.C., Wille, D.A., Miceli, W.J.: An Integrated Optical RF
    Spectrum Analyzer. Optical Engineering, Vol. 16, No. 5, pp. 475-478,
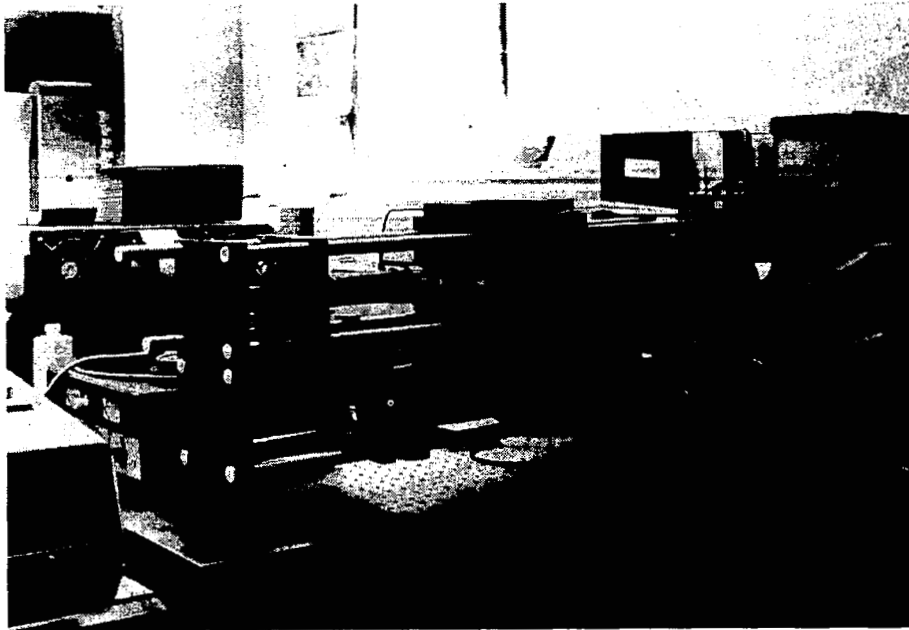   Spetember-October 1977.

Figure 1.- GSFC acousto-optic spectrometer mounted on stainless steel and anodized aluminum optical bench. HeNe laser is located on lower level and beam is directed to upper level where Itek Bragg cell is located. The 1024 CCPD Reticon array is mounted on right.

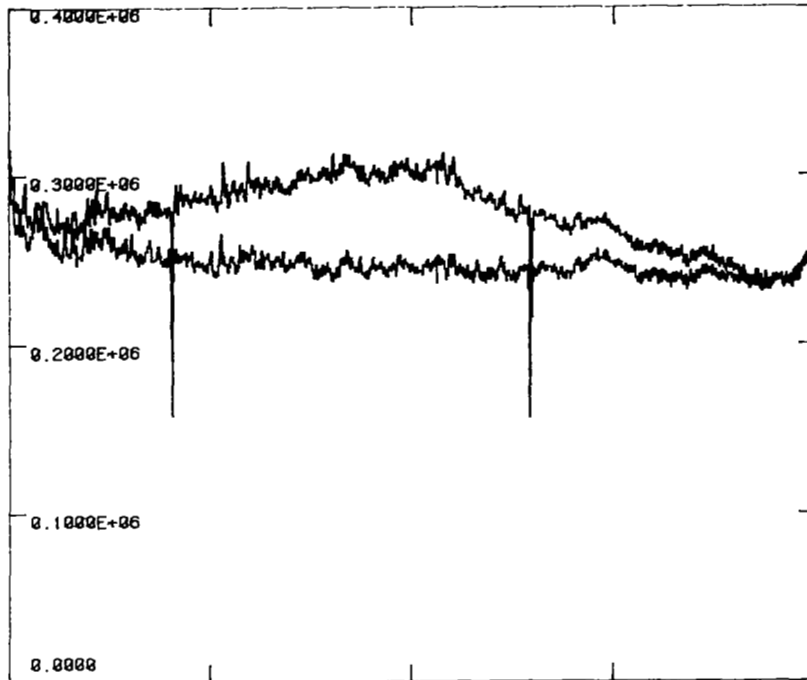**HIGH SPEED MULTIPLEXER BLOCK DIAGRAM**
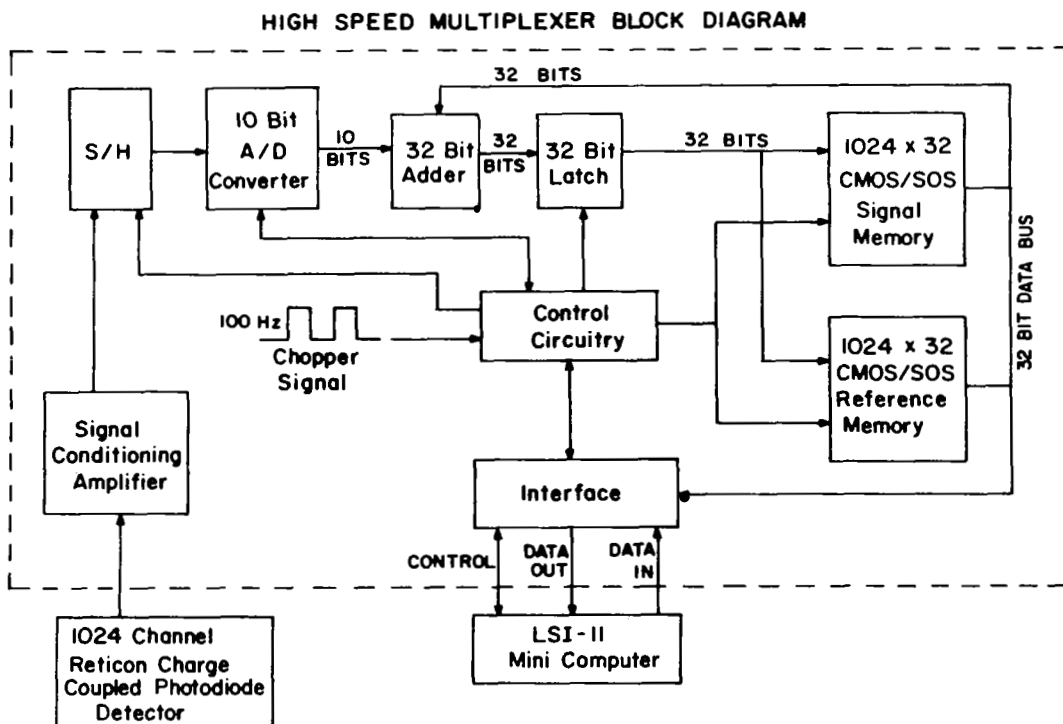
Figure 2.- Block diagram for the high speed AOS multiplexer.

Figure 3.- Output of the 1024 channel AOS. Vertical scale in arbitrary units; horizontal scale indicates channel. Lower curve is output with broadband noise off while upper curve shows the bandpass of the AOS. Spikes are faults on the glass cover of the photodetectors.
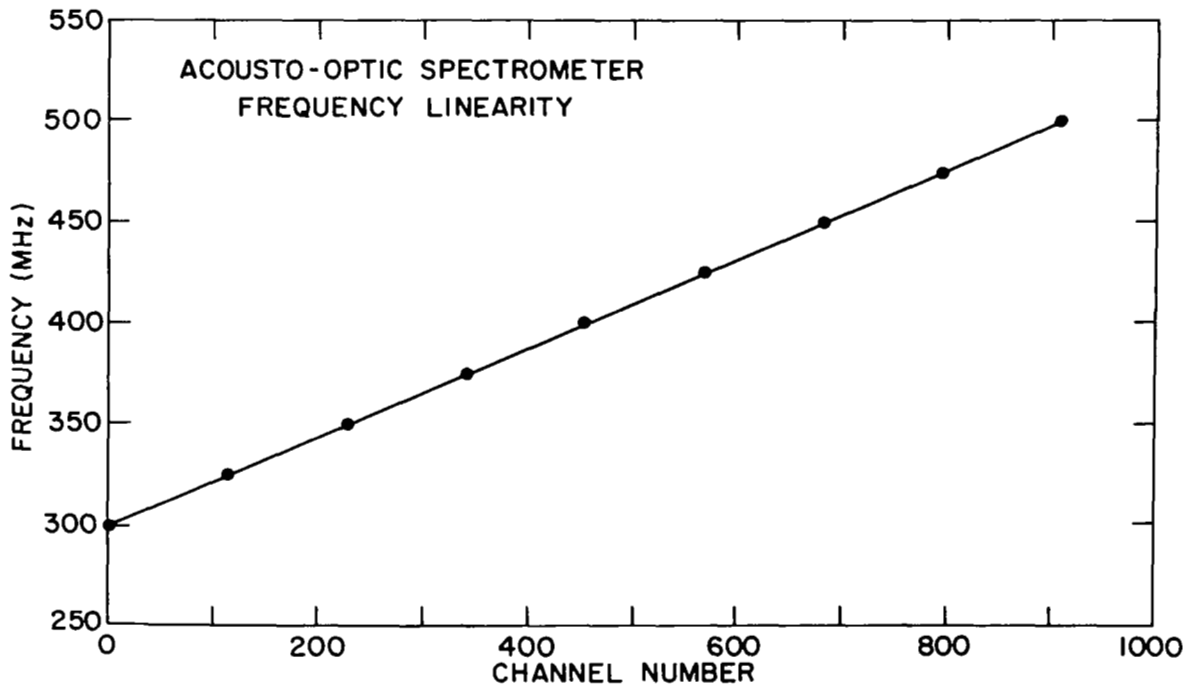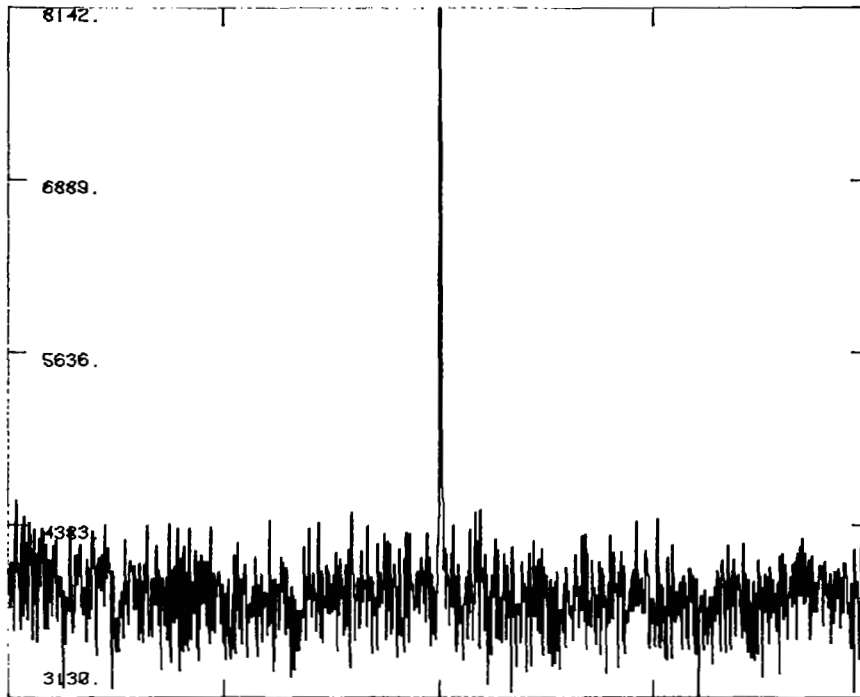

Figure 4.- Frequency linearity of the AOS.

Figure 5.- Simulated observations of 450 MHz spectral line with the AOS. The -30 dBm signal was observed after 40 sec integration. Vertical scale in arbitrary units; horizontal scale indicates channel.
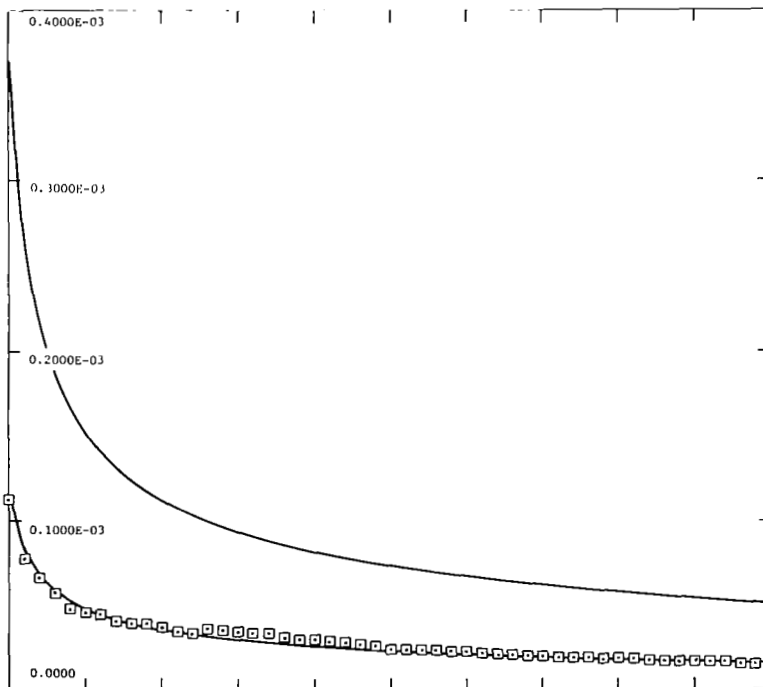

Figure 6.- RMS noise of the AOS falling as $1/\tau^{1/2}$ (τ = 40 sec increments). Solid curves correspond to B = 333 kHz (upper), and B = 3.3 MHz (lower). Observed values are points surrounded by boxes. Vertical scale in arbitrary units; horizontal scale indicates channel.