THE UNIVERSITY OF MICHIGAN
COLLEGE OF ENGINEERING
Department of Aerospace Engineering
In Conjunction with
Program in Aeronomy and Planetary Atmospheres

Final Report

AN INSTRUCTIONAL LABORATORY IN AERONOMY

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INTRODUCTION

Reported herein is an experience at The University of Michigan in establishing and conducting an instructional laboratory in Aeronomy. The laboratory course is offered to first year graduate students of Michigan's interdepartmental Program in Aeronomy and Planetary Atmospheres. In addition to the formal course elected by eight students three of these students have, in the first year, undertaken special projects for extra credits using the equipment. This will be a continuing feature of the lab. A further educational experience was gained by two graduate Teaching Fellows, Douglas O. ReVelle and James B. Russell, who helped to design the experiments, install the equipment, teach the students and prepare parts of this report.

Because the laboratory exercises and equipment are moderately sophisticated, it is arranged that the students take the laboratory course after they have completed certain lecture courses which cover the physical/geophysical phenomena treated in the laboratory. Further, an Instructional Laboratory Guide of a comprehensive nature has been prepared for each exercise. These average 75 pages in length of which about two-thirds was newly prepared and devoted to the theory of the measurement. The other third covers manipulative techniques and came in part from equipment manufacturers. The guides cover the theory, equipment, and manipulations in considerable detail. The descriptions of the experiments in this report are brief summaries.

The total cost of the laboratory was \$76,000 of which \$55,000 was furnished by NSF and \$21,000 by The University of Michigan College of Engineering. Of the total, about \$50,000 was expended for equipment either as direct purchase or for technician labor at the University. During the course of the work an Interim Report dated February 1970 was prepared for NSF. The laboratory is housed in space provided by the High Altitude Engineering Laboratory of the Departments of Aerospace Engineering and Meteorology and Oceanography.

CONCEPT OF THE LABORATORY

The laboratory was conceived as providing an experience in measurement to masters' and Ph.D. candidates whose courses in aeronomy are exclusively of the lecture type. A lectures-only approach to a field has certain apparent limitations, especially for those Ph.D. aspirants who choose thesis projects which are completely or partly experimental. It was thought that the laboratory learning situation would be more vital if actual upper air parameters were measured or, when that was not possible, would provide physical data of significance to aeronomical research. Finally, much consideration was, and continues to be, given to the extent of student participation which, in simple terms, can be steered somewhere between the completely "canned" vs. "free lance" modes of laboratory procedure.

The five experiment-demonstrations chosen were:

(a) Measurement of atmospheric ozone with the Dobson prism-type UV spectrophotometer.

(b) Measurement of response of the ionosphere to solar events with a very low frequency (VLF) receiver and demonstration of the VLF whistler phenomenon.

(c) Measurement of the morphology and intensity of airglow, particularly of the red and green lines of atomic oxygen at midlatitude with a tilting filter photometer.

(d) Demonstration of "classical" vacuum system technology to about 10^{-6} torr with mechanical and diffusion pumps and conventional gages. Measurement of the thermal conductivity of air and of the thermal accommodation coefficient of air on metal surfaces.

(e) Demonstration of advanced vacuum methods capable of achieving 10^{-11} torr with a modern all-metal sorption, cryopump, ion pump, sublimation system, and appropriate gages.

There are many experiments, demonstrations, and physical phenomena which could be considered for inclusion in an aeronomy laboratory. Our selection was limited in the first place to subjects included in the curriculum of the Program in Aeronomy and Planetary Atmospheres. That includes, in addition to the physics of the atmosphere above 30 km, the area of science and technology having to do with the remote observation of the atmosphere below 30 km from above. This discipline which involves absorption, emission, and scattering of radiation in the visible and infrared portions of the spectrum, is often called for want of a better term, satellite meteorology.

A list of 24 possible experiments was obtained by assigning to individual students in a lecture course on aeronomical measurements the preparation of a seminar on a suitable laboratory exercise. From these the above five experiments were chosen on the basis of scientific interest, difficulty, pedagogy, and availability of equipment at suitable cost. The experiments were then prepared by three faculty and two students. The only omission from the above list is the demonstration of whistlers in (b). Upon completion of the VLF receiver part of (b) it was realized that the supporting theory for VLF phenomena is sufficiently profound and difficult that the students would be fully occupied without adding whistlers.

Two additions to the list are planned. A demonstration of mass spectrometry will be added to the high vacuum exercise (e) and an experiment in measuring clear air and cloud temperatures by remote infrared sensing will constitute a sixth experiment:

(f) Measurement of the radiance of zenith sky in the 1-15 micrometer band. Determination of thermal structure of clear air and of cloud altitude and cloud type.

The foregoing complement, in our experience, is quite sufficient to occupy a graduate student in a two-hour course at the level of understanding which we require.

DESCRIPTION OF THE EXPERIMENTS

(a) OZONE

Ozone is important in meteorology as a tracer of stratospheric circulation. At higher altitudes it is the cause of the thermal stratopeak and its radiative transfer reactions contribute to the thermal budget of the lower mesosphere. It is possible by the method of Mecke (1931) or other to predict the vertical distribution of ozone, an exercise which introduces the concepts of reaction cross sections and rate coefficients. See Götz (1951). The calculation of ozone distribution is a simple example of a general methodology used in cases of other minor species with more elaborate photochemistry. See, for example, the calculation of the distributions of N and NO by Ghosh (1968). Total ozone has an annual variation and a strong positive correlation with solar output. Recently, Steblova (1968) showed an ozonospheric response to flares, an effect not previously observed.

In classroom work prior to taking the laboratory course the student is introduced to various aspects of the ozone phenomenon. The photochemical production and loss processes are discussed and the calculation of an equilibrium concentration is carried out. The morphology of ozone distribution is discussed and the correlation with other phenomena treated. Finally, various ozone measuring techniques are presented.

The ozone spectrophotometer used in the laboratory is a double monochromator instrument of the Littrow-type designed in the 1920's by G.M.B. Dobson at Cambridge University. Our instrument is the commercial version built by R. and J. Beck of Watford, England. It was obtained through the courtesy of W. D. Komhyr of ESSA, Boulder, Colorado.

The instrument receives mild ultraviolet radiation in the range 3055Å to 4536Å. Light from the zenith blue sky, the sun, the moon, or the zenith cloudy sky (in that order of preference) are used in the measurement. A pair of wavelengths, one strongly absorbed by ozone and the other not, are dispersed by the input prism. The stronger is quantitatively absorbed with an optical wedge to the point that the two beams are of equal intensity. The chopped beams are compared for a null reading in the photomultiplier. Unwanted light of other colors is kept from the photomultiplier by a second prism and an interference filter. Total ozone can be calculated from the comparison of a single pair, but the use of the two pairs can much reduce errors caused by the so-called "atmospheric correction" and errors due to Mie scattering.

The equation used for calculating total ozone is:

$$x_{AD} = \frac{N_A - N_D}{[(\alpha-\alpha')_A-(\alpha-\alpha')_D]\mu} - \frac{[(\beta-\beta')_A-(\beta-\beta')_D]m}{[(\alpha-\alpha')_A-(\alpha-\alpha')_D]\mu} - \frac{[(\delta-\delta')_A-(\delta-\delta')_D]\sec z}{[(\alpha-\alpha')_A-(\alpha-\alpha')_D]\mu}$$

where x_{AD} = Total ozone in cm STP as measured using wavelength pairs A and D.

N_A = Log $I_{o\lambda}/I_{o\lambda'}$ - log $I_\lambda/I_{\lambda'}$, I being the intensity at the instrument, I_o the intensity at the top of the other wavelength of pair A.

α = Absorption coefficient for ozone.

β = Scattering coefficient for air molecules.

δ = Scattering coefficient for particulate matter.

m = Equivalent relative path length of sunlight allowing for refraction and earth curvature.

μ = Relative path length through ozone layer.

z = Zenith angle of the sun.

Simplifications can be made from the following facts and assumptions:

(1) $m \cong \mu \cong \sec z$ for moderate zenith angles.

(2) The combined atmospheric correction $(\beta-\beta')_A-(\beta-\beta')_D/(\alpha-\alpha')_A-(\alpha-\alpha')_D$ is so small that multiplying by P/P_o, the station pressure correction, has no effect.

(3) $(\delta-\delta')_A$ and $(\delta-\delta')_D$ are nearly equal so that the third term on the right-hand side is zero.

The final result is an equation for x in which the absorption due to ozone is by far the largest factor.

Measurements of the amount of ozone as a function of altitude are also possible with the Dobson spectrometer. The method, due to Mecke (1931) and to Götz, Meetham, and Dobson (1934) makes use of the change in the relative amounts of absorption and scattering suffered by two different wavelengths as the zenith angle of the sun changes. The instrument observes zenith light throughout. It is widely accepted that the "best" way to measure vertical distribution is with balloon-borne ozonesondes and, indeed, these do give results with smaller errors and less ambiguity than the spectrometric Umkehr (reversal) technique. However, the ground spectrophotometer or Umkehr (reversal) method was widely used during the IGY when many Dobson instruments were in operation and methods of improving ground-based spectroscopy are still actively sought, especially in Canada. Grazing incidence spectroscopic techniques for satellites have recently been developed. See Hays and Roble (1969).

The student exercise is comprised of two parts of which the first is learning to manipulate and calibrate the spectrophotometer. The quick prismatic interchange among the four spectral wavelengths used requires a certain skill. In addition various temperatures, voltages, and times must be kept track of. The primary data, which consist of time averages of a dial position controlling the null of the output meter, are recorded and averaged with a clever clockwork stylus attached to the dial. The whole operation requires skill and understanding but the instrument design reduces the likelihood of error to an acceptable level. The measurements performed by the first class, then, were of total ozone using zenith blue light and direct sunlight. Special problems consisted of:

(1) Measuring the optical angle of acceptance of the spectrometer when used with the periscope.

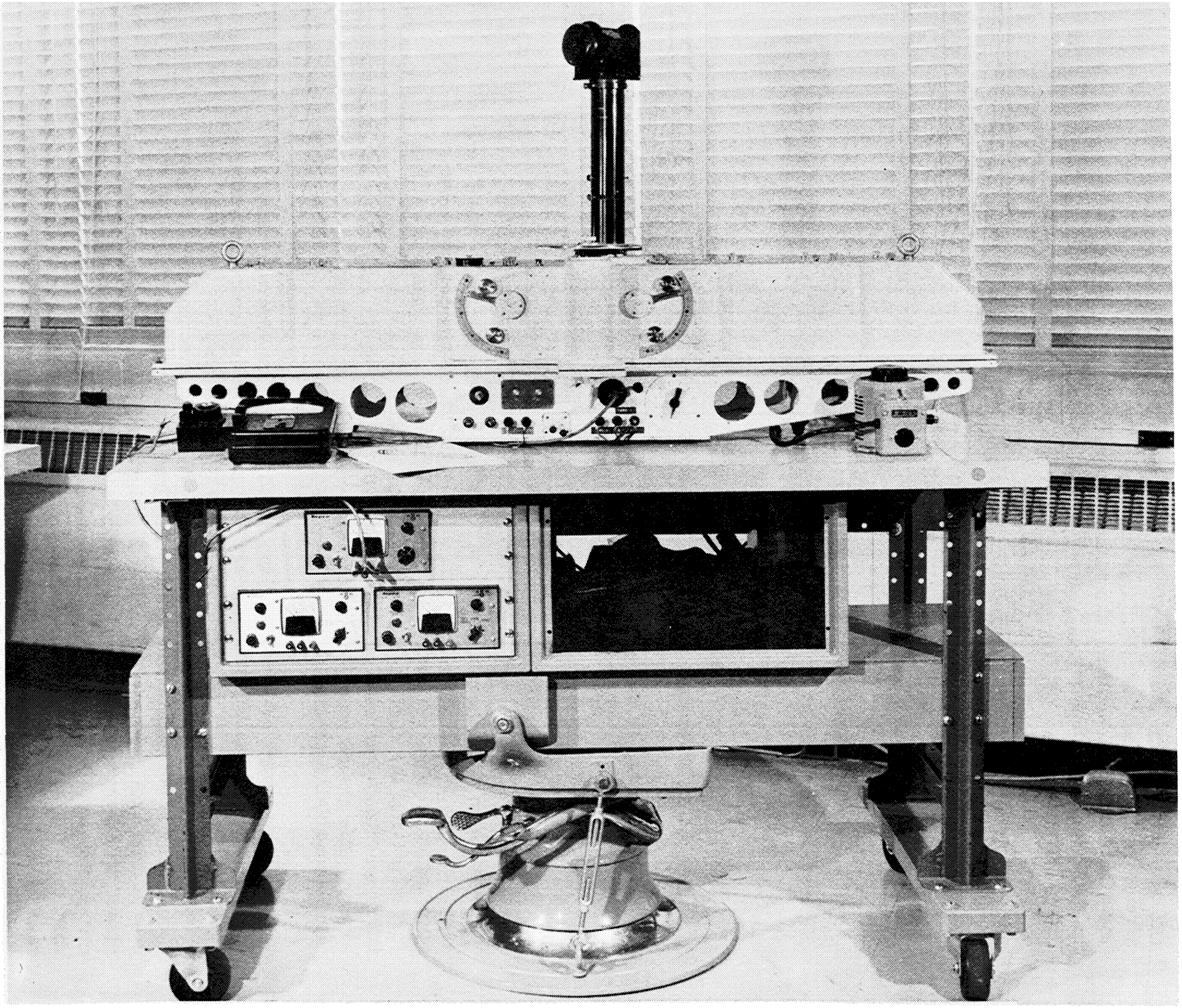
(2) Verifying that the periscope did not introduce polarization errors and

(3) Adjusting the verticality of the optical input axis. Succeeding class will measure ozone vertical distribution by the Umkehr method and will measure daily and flare-related variations.

In summary the ozone experiment proved to be a successful exercise in ultraviolet spectroscopy and the measurement of an important geophysical parameter.

(b) VERY LOW FREQUENCY (VLF)

Background for the VLF experiment is gained in an aeronomy course on the ionosphere and thermosphere. The course emphasis, however, is on ionospheric physics rather than wave propagation. The VLF experiment is designed to show how wave propagation can be used in geophysical probing and to show the effect of solar events on D-layer height and electron density. The measurements are made on a commercial VLF receiver (with simple accessories) which measures: (1) relative changes in phase between transmitter and receiver recorded in microseconds as a function of time, and (2) the relative amplitude of the incoming wave. The receiver is connected to a steerable loop antenna.



Ozone spectrophotometer with power supplies and height/azimuth base.

The diurnal and solar event response of the D-layer can be observed through the shift in phase caused by the change in path length as the effective reflecting height of the layer changes. The phase change $\Delta\Phi = 2\pi f \Delta t$. The time of transit between transmitter and receiver is $t = d/v_p$, where v_p is the effective phase velocity derived from waveguide mode theory. Davies (1965) gives v_p as

$$v_p \simeq c \left\{ 1 - \left[\frac{\left(n - \frac{1}{2}\right)\lambda}{2h} \right]^2 \right\}^{-1/2} \left(1 - \frac{h}{2a}\right) \tag{1}$$

where n = Order of the mode

c = Velocity of light in vacuo

h = Height of ionospheric reflecting layer

a = Radius of the earth

λ = Wavelength

For a single mode, it can be shown that

$$\Delta t = \frac{10^6 d}{c} \left[\frac{h}{2a} + \frac{\lambda^2}{16h^2} \right] \frac{\Delta h}{h} \tag{2}$$

Where Δt is in microseconds; d, h, a, λ in km; and c in km/sec. This is the equation used to calculate the change in height Δh of the D-layer corresponding to an observed change in phase specified by Δt. Various methods for estimating the absolute altitude needed in Eq. (2) are used but we have found the 80 km mean between 70 km (day) and 90 km (night) to be as good as any. For a more complete treatment of response to diurnal and flare changes see Westfall (1961).

A more elaborate experiment leading to values for electron density in the D-region is possible with VLF equipment. The method compares measured reflection coefficients of the real wave with those predicted by full wave theory through postulated D-region distributions of electron density (May 1966). The relationship between the measured values and the "best fit" chosen from the library of theoretical solutions is not unique and one must resort to other data or to a priori knowledge of the "climatology" of the D-region for justifying the match, a process not unknown in other branches of science. The equipment required for exploiting the technique would ideally measure amplitudes of the horizontally and vertically polarized components of the wave at both the transmitter and receiver, as well as the absolute phase difference between the two stations. The latter is impractical in that it requires a portable atomic clock. Since most VLF stations transmit only a vertically polarized wave, one component is not available at the transmitter. Further, our antenna is sensitive only to the vertical wave so that only the $_{\|}R_{\|}$* component can be measured. With these equipment limitations we can only indicate what would be possible with a better set-up. Nevertheless, such a demonstration can be quite instructive and we have proceeded with this in mind. It is hoped, also, to add in the future an antenna that can receive both $\|$ and $\perp$ components of polarization, amplitude calibration and to receive a station transmitting both components.

The description to the students of the theoretical model starts with Maxwell's equations and a constitutive relation:

$$\nabla \times \vec{H} = \epsilon_o \frac{\partial \vec{E}}{\partial t} + \frac{\partial \vec{P}}{\partial t} \tag{3}$$

$$\nabla \times \vec{E} = -\mu_o \frac{\partial \vec{H}}{\partial t} \tag{4}$$

$$\vec{P} = \epsilon_o \tilde{M} \cdot \vec{E} \tag{5}$$

where $\vec{H}$ = Magnetic field vector

$\vec{E}$ = Electric field vector

$\vec{P}$ = Electric polarization

ϵ_o = Permittivity of free space

μ_o = Permeability of free space

t = Time

$\tilde{M}$ = Susceptibility matrix

Next the application of the classical Appleton (1932) and Hartree (1931) treatment to the special conditions of the D-region as given by Budden (1961), Pitteway (1965), Scarabucci (1969), and others is presented.

By assuming that the ionospheric medium is horizontally stratified and that the time dependence of the wave field is harmonic, Eqs. (3), (4), and (5) can be reduced to a set of four linear, coupled, ordinary differential

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*Electric vector polarization in the plane of propagation is denoted by $\|$ and electric vector polarization normal to the plane of propagation by $\perp$.

equations written in compact form as

$$\frac{d\vec{e}}{dz} = -i\, k\tilde{T} \cdot \vec{e} \tag{6}$$

$\vec{e}$ is a column vector given by

$$\vec{e} = \begin{bmatrix} E_x(z) \\ -E_y(z) \\ z_o\, H_x(z) \\ z_o\, H_y(z) \end{bmatrix} \tag{7}$$

where $z_o = (\mu_o/\epsilon_o)^{1/2}$, E_x, etc., are the z dependent portions of the field vectors, and k is the propagation constant. $\tilde{T}$ is a matrix whose elements are a function of the susceptibility matrix $\tilde{M}$.

An expression for the susceptibility matrix as a function of N(z) and $\nu(z)$ can be obtained by solving the appropriately simplified linearized conservation of momentum equation given here for V_e'.

$$m_e \frac{\partial \vec{V}_e'}{\partial t} = e(\vec{E} + \vec{V}_e' \times \vec{B}_o) + m_e\, \nu_e\, \vec{V}_e' \tag{8}$$

Noting that $\vec{V}_e' \simeq \partial r/\partial t$ and that $\vec{P} \equiv e\, N\vec{r}$, then

$$\frac{\partial \vec{P}}{\partial t} = e\, NV_e' \tag{9}$$

If V_e' from (9) is substituted into (8) and solved for $\vec{P}$ in terms of $\vec{E}$ an expression of the form of (5) is obtained where $\tilde{M}$ can then be defined as

$$\tilde{M} = \frac{-X}{U(U^2-Y^2)} \begin{bmatrix} U^2 & -U\zeta Y & iU\gamma Y \\ iU\zeta Y & U^2-\gamma^2Y^2 & -\gamma\zeta Y^2 \\ -iU\gamma Y & -\gamma\zeta Y^2 & U^2-\zeta^2Y^2 \end{bmatrix} \tag{10}$$

where $0,\gamma,\zeta$ = Direction cosines of the earth's magnetic field vector B.

$$X = \frac{N_e e^2}{\epsilon_o m_e \omega^2} = \frac{\omega_p^2}{\omega^2} \qquad (11)$$

$$Y = \frac{e\vec{B}_o}{m_e \omega} = \frac{\omega_H}{\omega} \qquad (12)$$

$$U = 1 - iZ = 1 - \frac{i\nu_e}{\omega} \qquad (13)$$

Next (6) was solved for $\vec{e}$ and combined with the definition of reflection coefficient to obtain $\vec{R}$, the value of which is compared with measured values. The basic assumptions, of course, are the electron and collision frequency distributions $N_e(z)$, $\nu_e(z)$. These profiles are juggled until the measured R's agree with the predicted.

The student exercise is limited to predicting the R's corresponding to assumed N_e's and ν_e's and to making two of the six measurements required for a satisfactory verification. Nevertheless, this much experience taken together with the measurement of height changes constitutes, we think, a good laboratory project.

A special project was carried out by a graduate student during the summer of 1970. The first steps were taken to observe wave phenomena in the D-region by pursuing the method described by Brady and Crombie (1963). The technique used is one of Fourier analyzing the relative phase data recorded by the VLF receiver. The physical basis for suspecting that information about waves is available lies in the fact that the neutral air density in the D-region is great enough for the neutral air to carry the electrons with it in its motion. This process results in a change of the effective reflecting height of the ionosphere and a resulting change of phase in the received VLF signal. Computer programs to perform the Fourier analysis were written by the student.

A Model 599J VLF/LF Tracking Receiver manufactured by Tracor, Inc., is used to monitor relative phase and signal level. The phase is recorded on a Rustrak strip-chart recorder with a 100 μsec full scale sensitivity. The signal level is recorded on an external recorder manufactured by Esterline-Angus. The transmitting station used in electron density determining experiments was an OMEGA navigation station at Forestport, N.Y., transmitting at 12.5 kHz.

VLF receiver and recorder.

(c) AIRGLOW AND AURORA

According to Chamberlain (1961) airglow is "the nonthermal radiation emitted by the earth's atmosphere, with the exception of auroral emission and radiation of cataclysimic origin, such as lightning and meteor trains." Various criteria for distinguishing bright airglow from weak aurorae have been advanced and although none is completely satisfactory it would appear that OH bands are characteristic of the former and the First Negative bands of N_2^+ of the latter. The aeronomy student at Michigan is exposed to both phenomena in a three-hour lecture course covering spectra, morphology, geophysical correlations, and observations. Selected advanced students may then participate in the program of the Michigan Airglow Observatory, (MAO) established by Professors P. B. Hays and A. F. Nagy, in which observations are made on turret and tilting-filter photometers and on a superb Fabry-Perot assembled by Hays and Roble (1968).

An intermediate experience is available to first-year graduate students using a tilting filter photometer designed and built specifically for the laboratory of the report. The photometer, described below, has just been completed and placed in operation and thus was not available for the first class in May and June 1970. This group used the equipment of the MAO including the Fabry-Perot which has sufficient resolution to measure doppler temperatures in addition to other observations. In the future the tilting filter instrument will be used exclusively and, although it does not have doppler resolution, it does have the advantages of simplicity and reliability.

The student observations are limited primarily to twilight and nightglow and aurorae as seen with four tilting filters whose untilted responses (a little above the line wanted) are 6308Å, 5585Å and 4866Å, and 4283Å which are chosen to cover the 6300Å and 5577Å lines of atomic oxygen, the Hβ line at 4861Å and 4278Å [(0-1) Band First Negative System] for estimating the electron-excited N_2^+ contribution to an aurora.

The red line of atomic oxygen exhibits pre-dawn and post-twilight enhancements and a high altitude (350-600km) mid-latitude arc-like distribution. The green line of atomic oxygen accounts for just under 10% of the total visual brightness of the night sky. It is always present but shows considerable variability or patchiness as described by Roach (1963), and others. In auroral zones the weak chemically excited airglow is contaminated by auroral, particle excited, emissions. The airglow contribution can be sorted out provided that the proton excited contribution is measured then the Hβ intensity and the electron excited contribution by monitoring an appropriate line which we take to be 4278Å of N_2^+. Thus it can be seen that several interesting airglow and auroral systems can be examined with the use of as few as four wavelengths.

The tilting filter photometer combines the moderately high resolution

(2Å) of an interference filter with the ability to scan over something like 50Å. The filter is a special case of the Fabry-Perot etalon having a high throughput. (Throughput is the product of collecting area, collecting solid angle, and transmission.) The design of the Michigan instrument is based upon the work of Eather and Reasoner (1968) who have been using the instrument in auroral and airglow work since 1962.

In addition to the high throughput and moderately high resolution, interference filters have good signal to noise characteristics and are small in size, lightweight, simple, and inexpensive. The latter characteristics are especially attractive in a device to be used by students. The resolution and sensitivity are quite good enough to examine low intensity lines and the ability to scan permits evaluating the contribution of the background continuum to the intensity of the specific wavelength being studied.

The interference filter is a Fabry-Perot etalon with a solid dielectric spacer medium of zinc sulphide or cryolite. There are many reflecting layers of quarter-wave dielectric layers having alternate high and low indices of refraction. When the filter is tilted through an angle θ to the light beam the wavelength of peak transmission shifts to the short side. The shift is accompanied by a broadening and a measurable, but tolerable, loss in transmission. There are many theoretical and practical considerations between this simple description and the manufacture of workable filters. However, such filters are made in the visible portion of the spectrum in about 5 cm dia and with 2Å resolution and 50Å tilting (10°) scan as noted above.

Our four filters are mounted in a filter wheel which is rotated by a small motor which permits changing the filters in succession at will. The entire filter wheel and motor assembly is tilted on bearings by a motor driven cam. The motor has a variable speed drive permitting tilt cycles of 1/6, 1/12, 1/24, 1/48, 1/96, and 1/192 per sec. The tilt-angle vs. time profile may be changed by changing the shape of the cam. The most useful scan is linear in wavelength vs. time which requires a cam that corrects for the $\Delta\lambda = k(\Delta\theta)^2$ characteristic of the filter.

The instrument path of the atmospheric emissions starts at the roof periscope. This periscope can be operated to perform various kinds of scans in a hemisphere and directs a 5° beam of light vertically into the airglow photometer (or ozone spectrophotometer, or infrared spectrophotometer). The beam then traverses the tilting filter, an f5.6 lens, a field stop iris, and a protective shutter into the photomultiplier. The photomultiplier is an ITT/EMI FW-130 cooled by a Products for Research thermoelectric refrigerator to lower the dark current. The current is further lowered by using photon counting mode for which a scalar-counter and D to A converter is supplied. The final output is recorded on both a strip chart recorder and X-Y plotter.

A special investigation related to the airglow exercise was carried out by a student following the lab course. Reduction of airglow observations made with a Fabry-Perot interferometer requires knowledge of the variations in certain instrument parameters. The two investigated by the student were reflectivity and sagitta (a function of curvature) of the etalon plates. The study was made at 6328Å using laser light. A continuing set of observations reduced by a computer program which the student developed provided a ready monitor of the two parameters.

(d) VACUUM TECHNOLOGY

In situ probes on rockets and satellites have contributed enormously to aeronomy. These instruments must both sense and survive a wide range of vacuum conditions. In the earth's atmosphere the pressure at 600 km is less than that readily achieved by common vacuum systems. In order to give the student experience with vacuums and vacuum instruments, two systems were installed. One is a "conventional" or "classical" system using mechanical and diffusion pumps and a variety of gages with overlapping ranges from 760 torr down to the system limit of about 10^{-6} torr. The second is a "modern" system with cryogenic, ion, and sublimation pumping. This metal system is capable of 10^{-10} torr.

The following components make up the conventional system and instruction on all of these was given.

Mechanical pump
Oil diffusion pump
Thermocouple gage
Pirani gage
Open end U-tube manometer
McLeod gage
Ionization gage
Cold traps

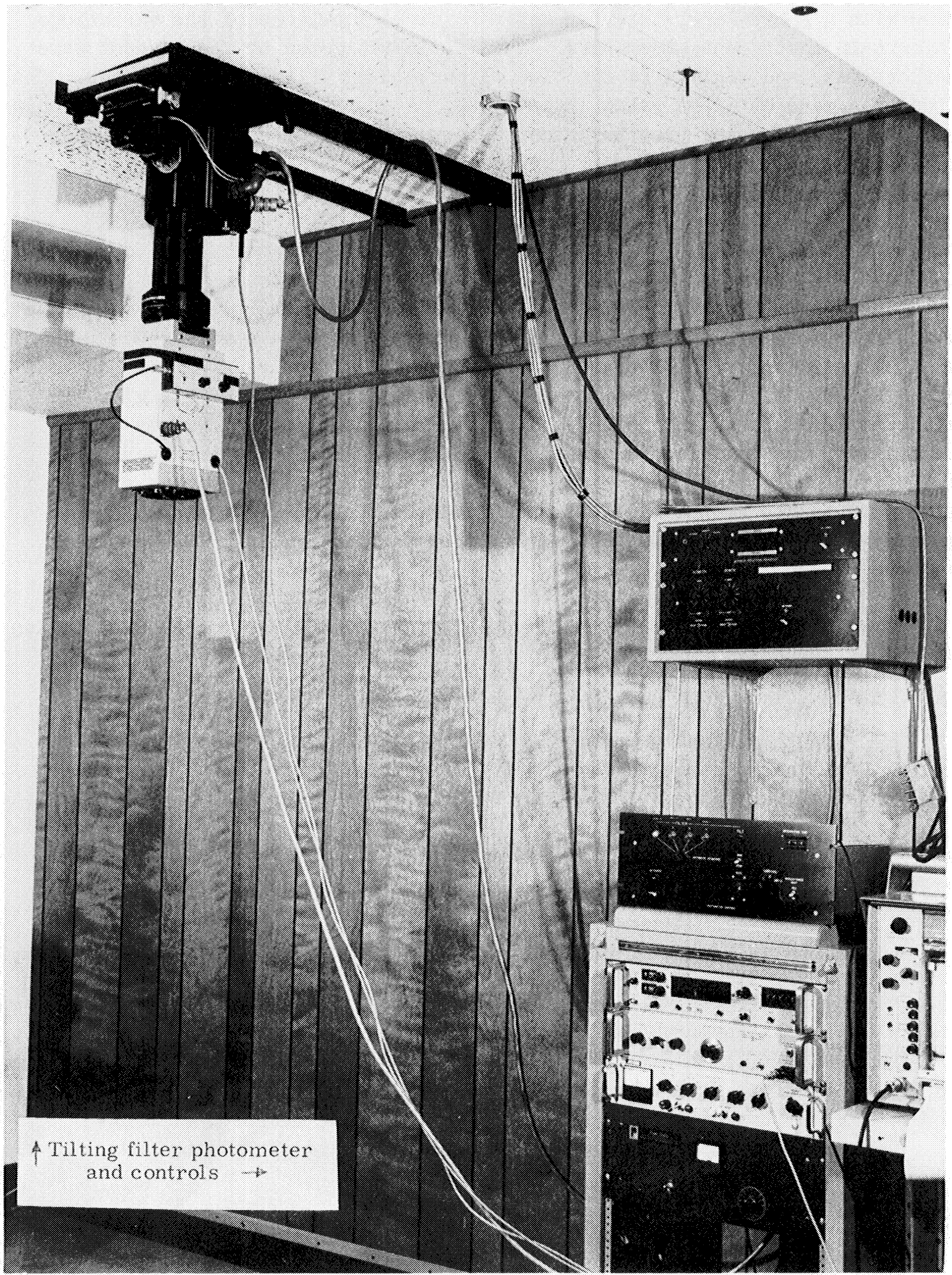
The time available for the conventional system was evenly divided between discussion of theory (conductance, pumping speeds, etc.) and demonstrations on the system as follows:

(1) The mechanical pump and diffusion pump were utilized in pressure staging with the various metal and glass valves to reach the ultimate vacuum of the system.

(2) Pressure measurements were made at various vital points during the pumpdown, and problems associated with measurement accuracy, trapping techniques, conductance, and outgassing and system leakage were pointed out.

(3) Leak detection using a spark coil was demonstrated.

(4) General and specific pumpdown and gaging problems and precautions were discussed and subsequently demonstrated.



↑ Tilting filter photometer
and controls →

This classical vacuum system was later used in a separate experiment in the laboratory course in which the thermal conductivity of a gas and the thermal accommodation coefficient were measured.

In recent years advanced fluidless pumping systems capable of achieving vacuums several orders lower than is possible with conventional systems have been developed. To give an experience in this area a commercial system with the following components was purchased:

Sorption pump
Sputter ion pump
Titanium sublimation pump
Cryogenic pump
Thermocouple gage
Ion pump gage
Bayard-Alpert ionization gage

Here again the time was equally divided between discussion and manipulations necessary for the following demonstrations:

(1) The sorption pump, ion pump, sublimation pump, and cryogenic pump were utilized in pressure staging with the various metal valves to reach the ultimate vacuum of the system.

(2) Pressure measurements were made at various vital points during the pumpdown and problems associated with measurement accuracy, location of the gages, conductance, and system outgassing and leakage were pointed out.

(3) Leak detection methods were discussed and the methods available for metal, high and ultrahigh vacuum systems were compared with the method used in the classical vacuum system.

(4) Sonic degassing techniques were demonstrated.

(5) General and specific problems and precautions with the system were discussed and demonstrated.

The modern system is relatively forgiving of mistakes and it is feasible to let the students perform the relatively few manipulations. The whole exercise, in fact, is simple and straightforward enough that more elaboration is desirable. This might involve, for example, the addition of a mass spectrometer to the exercise. Both magnetic and quadruple spectrometers are important flight instruments in aeronomy. The latter, having been flown on both rockets and satellites by the Department of Aerospace Engineering, is available and a likely candidate for inclusion.

The conventional vacuum system, in contrast to the modern, is a frail and cantankerous assemblage. Trouble with the system was anticipated on the basis of experience in research laboratories at Michigan and other places, but the educational benefits were thought to be worth the trouble. The ultimate outcome, with the first class, was that the instructor performed the demonstrations as the students watched. Under these circumstances the equipment performed well and the accessories operated reliably most of the time.

The educational experience gained by the students was not nearly as satisfying however. The "best" way to teach a course is very difficult to find especially the first time through. In this case the students, of necessity, had to spend much time watching demonstrations that were neither exciting nor quickly revealing. Nevertheless, they were necessary and very important to the overall goal. Thus the experiment is really not an experiment, but a group of related techniques and demonstrations required in understanding how atmospheric conditions can be simulated in the laboratory.

For the future we hope to improve the apparatus and reduce the manipulative skill required to the point where the students can participate more than they did the first time. We feel that the first experience was uninteresting rather than uninstructive because most of the difficulties of the vacuum art were amply illustrated if not experienced first hand.

(e) THERMAL CONDUCTIVITY AND ACCOMMODATION COEFFICIENT

In order to fully understand the thermal structure of the upper atmosphere, it is vital to know the thermal conductivity of air. For large values of mean free path heat conduction varies linearly with pressure and the concept of the thermal accommodation coefficient is needed to explain the heat transfer process between molecules and surfaces. In satellite drag studies, the thermal accommodation coefficient, used with certain limiting assumptions, is functionally related to the drag coefficient C_D. Since the eventual application of C_D is in the determination of ambient density from the observation of satellite drag, a precise knowledge of thermal accommodation coefficient is desirable. The aeronomy curriculum does not contain a separate course in the rarefied gas dynamics. However, various topics in this field are introduced throughout the curriculum and some students take specific courses so that there is typically additional background to that provided in the laboratory lecture.

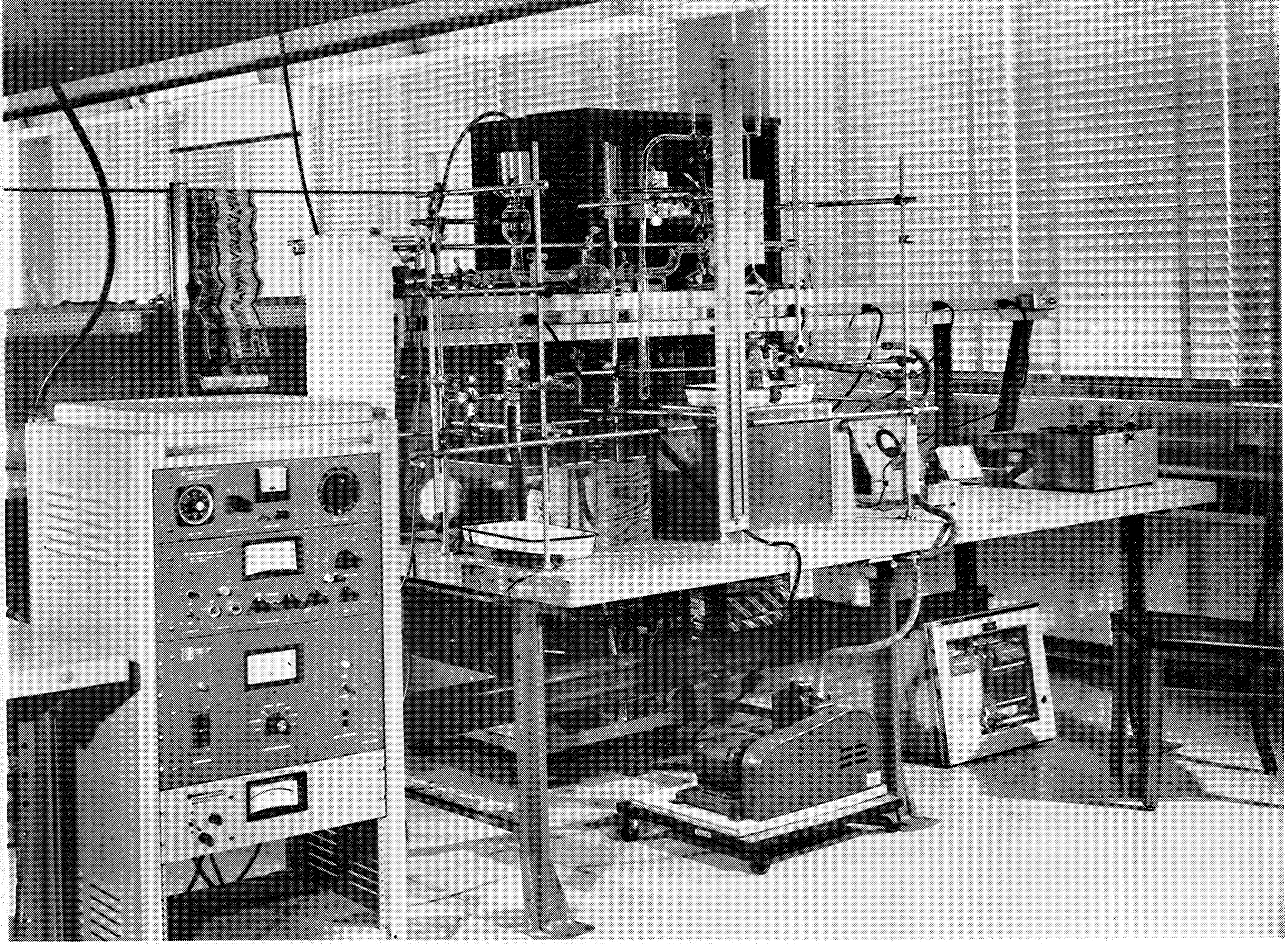
The required apparatus for the experiment is as follows:

(1) Test cell

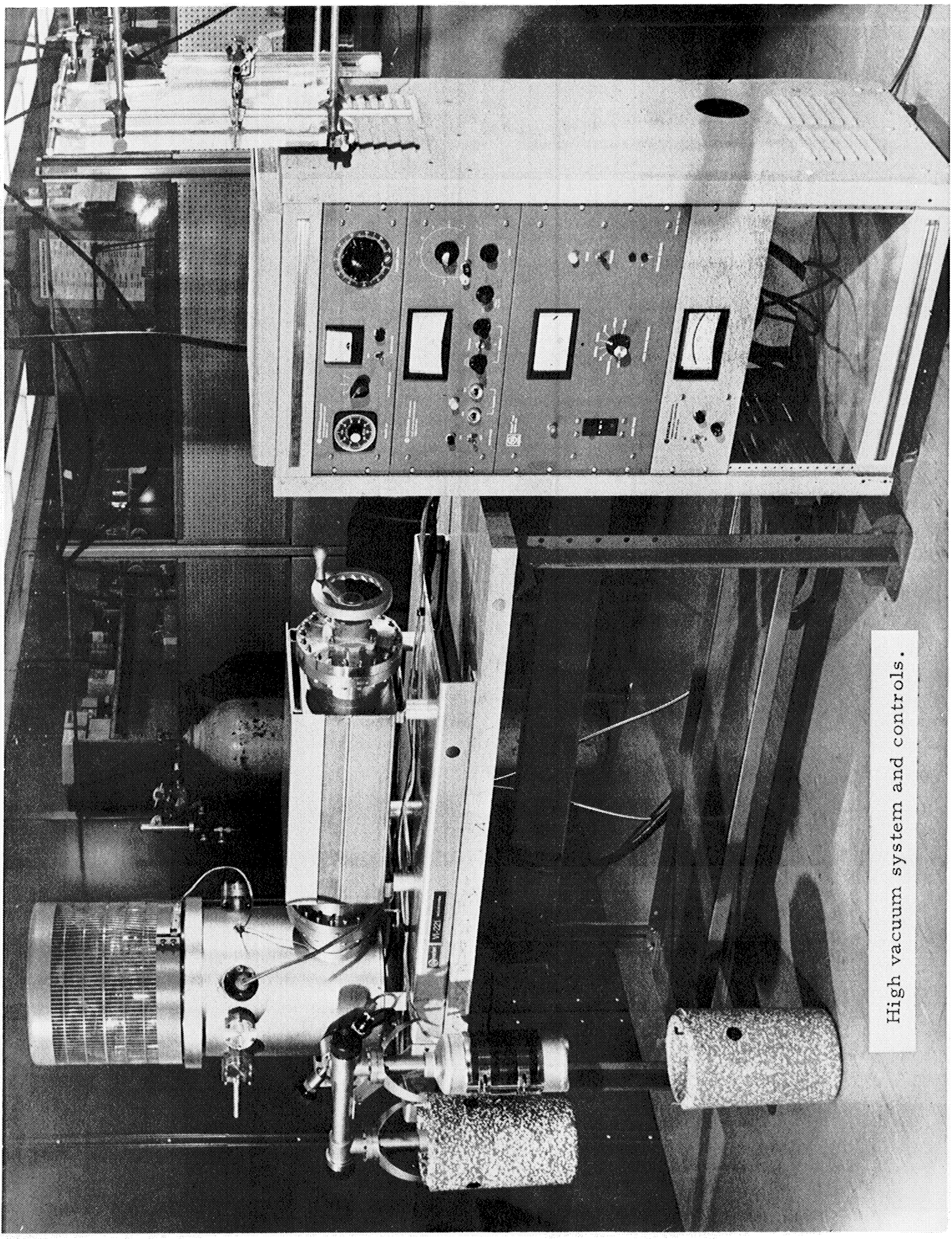
(2) Glass vacuum system (capable of 10^{-6} torr)

(3) Constant temperature bath surrounding test cell

(4) Gas admittance valves (with desiccator)



Medium vacuum system including thermal conductivity and accommodation coefficient cell.



High vacuum system and controls.

(5) Vacuum pressure gages

(6) Electrical heating and measuring circuits

The glass test cell, containing a fine platinum wire vertically mounted and accurately centered, is connected to the vacuum system. The outside of the cell is held at nearly constant temperature by surrounding it with a water bath. The platinum wire is connected by leads of known resistance to a simple series circuit. This circuit contains the following components:

(1) Variable d.c. power supply

(2) Experimental test wire

(3) Standard resistor

(4) Potentiometer-galvanometer circuitry

During the experiment, for a fixed system pressure and bath temperature, the voltage drop across the standard resistor is measured using the potentiometer galvanometer circuits; then the voltage drop across the test wire is measured. Both of these are done for several values of current while maintaining constant initial conditions of system pressure and bath temperature. Applying Ohm's law to the measurements and given the temperature resistance coefficient of the wire, the heat conducted away from the wire by the gas for a given temperature difference, ΔT, between them, can be calculated. Once this is known, thermal conductivity and accommodation coefficient can be calculated using theory appropriate to the dynamic flow regime.

In continuum flow ($Kn < 0.01$), the thermal conductivity is independent of pressure and the transfer of heat by gas conduction (for small temperature gradients) is described to a good approximation by Fourier's law.

$$Q_K = -\bar{K} A \frac{\Delta T}{\Delta y} \qquad \bar{K} > 0$$

where Q_K = Heat conducted by the gas per unit time across an area A

$\bar{K}$ = Thermal conductivity of a gas averaged over the temperature interval ΔT

$\frac{\Delta T}{\Delta y}$ = Temperature gradient

For our coaxial cylinder Fourier's law is written

$$Q_K = \frac{2\pi \bar{K} L \Delta T}{\ln\left(\frac{r_2}{r_1}\right)}$$

where L = Length of the test wire

r_2 = Radius of the glass cell

r_1 = Radius of the wire

ΔT = Temperature difference between the wire and the gas

Under equilibrium conditions between the electrical heat input to the wire and the heat conducted away by the gas, the following equation is valid

$$Q_T = Q_K + Q_C + Q_R + Q_{EL}$$

where Q_T = Total power developed across the test wire

Q_K = Conduction power loss to the gas

Q_C = Convection power loss to the gas

Q_R = Radiation power loss from the test wire and supports

Q_{EL} = Conduction end losses from the test wire and supports

This equation can be rewritten as:

$$Q_T = Q_K + Q_{VAC}$$

where $Q_{VAC} = Q_R + Q_{EL}$

and convection losses are assumed negligible. At very low pressures (where $Q_K \sim 0$) Q_{VAC} is measured and assumed constant independent of pressure.

Rewriting the last equation as:

$$Q_K = Q_T - Q_{VAC}$$

$$Q_K = I^2R - (I^2R)_{VAC}$$

where I = Current passing through the wire

R = Resistance of the wire

and knowing the resistance of the wire as a function of temperature from:

$$R = R_o(1 + a\Delta T)$$

where R = Resistance of the wire at some temperature T

R_o = Zero current resistance of the wire corresponding to the bath temperature

a = Temperature resistance coefficient of the wire measured at R_o

ΔT = The temperature difference between the wire and the gas

$Q_K/\Delta T$ and $\bar{K}$ can be calculated for the case of continuum heat flow.

In slip flow $(0.1 < Kn < 0.01)$,

$$Q_K = \frac{2\pi\ Lr_1\ \Delta T\bar{K}}{r_1\left[\ln\left(\frac{r_2}{r_1}\right) + \frac{g_1}{r_1}\right]}$$

where g_1 = Temperature jump distance associated with the test wire

$$g_1 = \frac{2-\alpha_1}{\alpha_1}\left(\frac{2\epsilon}{\gamma+1}\right)\lambda$$

where α_1 = Thermal accommodation coefficient associated with the test wire

λ = Mean free path

$\frac{2\epsilon}{\gamma+1}$ = A constant

both $\bar{K}$ and α_1, can be determined using a graphical procedure after measuring power losses from the wire at two or more pressure points.

In the case of transition flow $(Kn \sim 1)$ a solution for α has not yet been theoretically formulated from first principles. In fact there is conjecture that the slip flow treatment for α is not theoretically rigorous. Using Boltzmann's equation and Lees' (1962) four-moment method an adequate expression (agreeing within a few percent of experimental data) has been obtained for $Q_K/\Delta T$ for the entire range of flow conditions $(10 < Kn < .01)$.

In free molecule flow $(Kn > 10)$ the following equation can be derived.

$$Q_K = \alpha_1 \, p \Lambda_o \, A \Delta T$$

where p = Pressure in the test cell

Λ_o = Free molecule conductivity

ΔT = Temperature difference between the wire and the glass wall

and α_1 can be calculated.

During the laboratory course each experiment was performed by three groups of two students each. This particular experiment in its entirety would take an average group of two students a very long time to accomplish. For this reason it was decided that each group would make complete measurements in only one dynamic flow regime. The additional data needed was provided either by the instructor or by the other students. In the calculation sessions, emphasis was placed on the continuum and free molecule flow results since these were felt to be the most reliable and straightforward to obtain.

In general the measurements, though very time consuming, went rather well in all groups. Errors were discussed and complete error analyses were performed by two of the better students in the class. Other students who weren't familiar with this type of analysis identified potential sources of error. The overall student reaction to the experiment was more enthusiastic than in the case of vacuum technology because of their manipulative participation.

One outcome of the success of the work was a special study directed by the Teaching Fellow during the following semester to one of the better students in the class. Together they have been carefully repeating and intercomparing the critical measurements. The passive water bath surrounding the test cell, was replaced with a precision temperature controlled bath. The results of the measurements now show that the assumed handbook value of the temperature coefficient of resistance is in error by as much as 30% over the temperature range 17°C to 35°C. Fortunately this is a relative error and as such does not affect the absolute magnitude of the results. It does shift slightly however, the temperature range over which the resulting thermal conductivity or thermal accommodation coefficient is valid. This error is explainable since the exact chemical composition of our wire is not known in comparison to the wire which was used to obtain the handbook value of the temperature coefficient. It is also evident one should not expect values of $\bar{K}$ to be measured any better than ± 5%. In free molecule flow, values of α can be obtained to no better than about ± 10% to 20%. These errors could be reduced with very careful (and time consuming) repeated measurements. The gas experiment as it now exists is extremely instructive. The goal is not to obtain the most accurate values of $\bar{K}$ and α by research standards, but to make the student aware of typical errors and how their magnitude may be quantitatively assessed. In the future more emphasis will be placed upon doing a partial quantitative error analysis as a required part of the experiment.

RESULTS

The eight-week lab course was elected in the Spring of 1970 by a class of eight students in addition to which the two Teaching Fellows who helped set-up and teach the course received the normal two hours' credit. Two faculty persons also participated in teaching. Four groups of two performed the experiments in rotation. With these numbers it can be seen that considerable individual attention was possible. A typical allotment of time to an experiment was one session (three hours) devoted to lecture, one or two to manipulation of the equipment and one or two to discussion and calculation of results. A written report was required which was prepared at home.

No spectacular instrumental difficulties were encountered and the pace of the laboratory was about as anticipated. The principle weaknesses uncovered have been mentioned in the descriptions of experiments. Generally they consisted of preparations (including manuals, long computer programs and/or supporting data tables) being not quite complete and of trying to do something more difficult than was appropriate. The former point has now been taken care of. On the latter point it is of interest to note that as preparation of the laboratory proceeded the instructors became sufficiently skilled that the experiments appeared deceptively simple. As a consequence it was thought that each group could do an original project over and above the "standard" exercise. In point of fact the standard exercises (with minor additions and variations) occupied the students' time and intellectual capacity completely. Three students did, however, subsequent to the regular lab course, do extra projects as directed studies and these have been noted in the descriptions of experiments.

It remains to say whether or not the course effectively instructed and stimulated the interest and creativity of the students. A completely objective conclusion is impossible. We have to go on student behavior and comment during the course, the quality of the lab reports, written critiques provided by two students, and our own opinions. We observed that attendance was complete with considerable nonrequired after-hours work; we judged the lab reports to be excellent when compared with others in our experience, the critiques were negative only with regard to specific items with which difficulty was encountered and positive otherwise; and, as noted, three students elected to do additional directed studies. As instructors we found the course and the student interaction as stimulating as any lecture course and hope to maintain the high level in interest which appeared to exist the first time around.

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