ENGINEERING RESEARCH INSTITUTE
THE UNIVERSITY OF MICHIGAN
ANN ARBOR

PRESSURE AND DENSITY MEASUREMENTS THROUGH PARTIAL PRESSURES OF ATMOSPHERIC COMPONENTS AT MINIMUM SATELLITE ALTITUDES

Report CS-5

H. S. Sicinski
N. W. Spencer
R. L. Boggess

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ABSTRACT

Pressure and density measurements made from a satellite at altitudes of from 400 to 900 kilometers are expected to range from 10^{-10} to 10^{-8} mm Hg and 10^6 to 10^8 particles per cubic centimeter. These measurements are initially complicated by the lack of knowledge concerning the gas composition at these altitudes. Data from ionization gage type pressure gages would provide ambiguous results since the responses of these devices vary with the nature of the gas. Until the time when the composition is better defined, a measure of the partial pressure of the components will be a more useful approach to defining this region.

Knowledge of the composition, density, and pressure can be had simultaneously through the use of a device which in principle is a modified "Omegatron or Synchrometer" as described by Sommer, Thomas, and Hipple. This device in its later forms is simple in structure and operation, being capable of high sensitivity similar to the conventional ionization gages. Unlike the conventional ion gage, which ceases to function as a pressure gage below 10^{-8} mm Hg, the modified "Synchrometer" continues operation into the range of 10^{-10} mm Hg. The principle of operation is similar to a cyclotron. A small beam of ionizing particles is passed parallel to a magnetic field, causing local ionization along the beam. These ions are then accelerated by the alternating potential between two parallel plates. As in the cyclotron, when the r-f frequency is equal to eH/M, the ions of mass M and charge e are accelerated in orbits of increasing size and eventually strike an ion collector. If the ionizing beam is kept constant in value along with the electric and magnetic field, the ion collector current is a measure of the partial pressure of the gas of this charge to mass ratio. A lightweight instrumentation is possible through the use of "tuned gages" having permanent magnets for their magnetic field. This approach reduces the complexity of scanning and its associated field measurements and provides partial pressure for one component. Additional weight reduction follows from the replacement of the filament with a photosensitive source of ionizing radiation. This feature with its dependence on sunlight should serve to separate the ionized population from the un-ionized, in addition to providing the opportunity to study the earth's atmosphere in the presence and absence of sunlight. (The research reported in this document has been made possible through support and sponsorship extended by the Geophysics Research Division of the Air Force Cambridge Research Center, under Contract No. AF 19(604)-545.)

ENVIRONMENT FOR PRESSURE AND DENSITY MEASUREMENTS

The environment for a satellite about the earth having an elliptical orbit with a perigee of 300 to 800 km is somewhat speculative; thus an examination of the many possible models will demonstrate only the lack of knowledge concerning this region. The model shown in Fig. 1 is as reasonable as any for the purpose of establishing the orders of magnitude for the composition, particle density pressure, and temperature. The assumptions fundamental to this model are: (1) temperature distribution with altitude above 100 km is taken with a slope of 4 degrees Kelvin per kilometer; (2) oxygen dissociation starts at 94-km level, and (3) is essentially 100 percent at 100-km level, the dissociation increasing linearly. With such assumptions, the region of perigee will expose the instrumentation to pressures in the range $10^{-10} \geqq P \geqq 10^{-8}$ mm Hg (see Fig. 1), temperatures in the range $1500 \geqq T \geqq 3000°K$, particle density (no./cm^3) in the range $10^{+5} \geqq \rho \geqq 10^8$, and a varying composition of ionized and neutral particles.

DISCUSSION

Pressure measurements made on a minimal-altitude satellite are expected to be of the range $10^{-10} \geqq P \geqq 10^{-8}$ mm Hg. There are at least three devices which will produce pressure data electrically in this range: (1) the Bayard-Alpert gage,[1] (2) the modified Bayard-Alpert gage developed by W. G. Nottingham,[2] and (3) the mass spectrometer. Both (1) and (2) are modifications in ion-gage configurations such that it is possible to reduce the low-pressure limit of an ordinary ionization gage by a factor of 1000 or more. This is accomplished by reducing the solid angle available to x-rays formed by electrons striking the electrodes of the ionization gage. If gages (1) or (2) were used immediately in a satellite instrumentation, the resultant data would be subject to interpretation according to the assumed gas composition. This follows from the marked sensitivity for the gas composition possessed by ionization gages.

Until such time as the composition of the environment at the extreme altitudes is known, a measure of the partial pressure of the gas components will be a useful approach to defining this region, in preference to ion gages.

[1]Bayard and Alpert, Rev. Sci. Inst., 21, 571 (1950).
[2]W. G. Nottingham, "Design and Properties of the Modified Bayard-Alpert Gauge," Vacuum Symposium Transactions, 1954, p. 76.

Such a device is embodied in a modified mass spectrometer; however, because of the severe weight restrictions on the satellite instrumentations the conventional d-c and r-f mass spectrometer does not at this time seem suitable because of the desire to identify the gas components while determining the component's pressure and/or density.

Presently, it does not appear necessary to make preliminary experiments to determine the gas composition before proceeding with density and pressure determinations. Density and pressure can be had simultaneously through the use of a device using cyclotron resonance phenomenon as its principle of operation. In contrast to the usual mass spectroscopic method, where stringent geometrical conditions are necessary, cyclotron resonance detection requires precision care only in the uniformity of the magnetic field.

PRINCIPLES OF OPERATION

For purposes of completeness a brief summary of the action of a charged particle under the influence of an electric and magnetic field will be given before discussion the "Synchrometer."

A uniform magnetic field constrains a moving ion to follow a circular path, and requires the time for the ion to traverse the circle to be a constant for a given ion and magnetic field and does not depend on the speed of the ion. This is true also for half a circle, so that in cyclotron applications the ion increases its velocity as it progresses such that the length of the path increases in correct relationship to keep the time of travel constant between accelerations. This means that a potential source of constant frequency can be used to make the electrodes alternately plus and minus under the influence of a steady magnetic field. This can be shown analytically by using an ion of charge e moving in a plane normal to the magnetic field B with a velocity v in a space free from electric fields. The magnetic field will exert a force equal to Bev on the ion normal to both its direction of motion and to the magnetic field. Using Newton's second law, we have

$$Bev = mv^2/r \quad , \tag{1}$$

where m is the mass of the ion and r is the radius of the circular path. Solving $v = eBr/m$, the time required to traverse a full circle is

$$T = 2\pi r/v \quad , \tag{2}$$

or

$$T = 2\pi m/eB \quad , \tag{3}$$

which is independent of the velocity of the ion. Also the frequency $f = w/2\pi$ of the alternating potential required for the electrodes is

$$f = 1/T = eB/m2\pi \quad . \tag{4}$$

The kinetic energy gained by the ions when they have reached the exit at radius R can be expressed in terms of the equivalent voltage V which would give them the same energy.

$$Ve = mv^2/2 \tag{5}$$

or

$$V = eB^2R^2/2m \quad , \tag{6}$$

which in electron volts would be

$$W = Z^2B^2R^2\ (4.8 \times 10^{-5})/A \text{ electron volts} \quad , \tag{7}$$

where Z is the number of electronic charges on the ion and A is the atomic number, B in oersteds, R in cm. Similarly, the frequency

$$f = ZB\ (1.53 \times 10^3)/A \text{ cycles per second} \quad . \tag{8}$$

In the discussion so far we have neglected the increase of mass with velocity which from the special relativity theory is

$$m = m_o \Big/ \sqrt{1 - (v/c)^2} \quad . \tag{9}$$

Substituting this change of mass into Equation 4 we see that in order to keep the frequency constant as the velocity increases, that is, to maintain the resonance condition, the magnetic field should increase proportionately with the mass m. This effect leads to the defocusing and loss of the ions such that the conventional cyclotron has difficulty attaining adequate resolution in mass measurements; however a number of important advances in this field make it possible to use this principle in the construction of a pressure-density gage for use in regions of unknown gas composition.[3] As shown in Fig. 2 a small beam of ionizing particles is passed parallel to a magnetic field, causing local ionizations along the beam. These ions are then accelerated by the alternating potential between two parallel plates. As in

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[3] S. A. Goudsmit, Phys. Rev., 74, 622 (1948).
J. A. Hipple and H. A. Thomas, Phys. Rev., 75, 1616 (1949).
Richards, Hays, and Goudsmit, Phys. Rev., 76, 180(A) (1949).
Hipple, Sommer, and Thomas, Phys. Rev., 76, 1877 (1949).
F. Bloch, Phys. Rev., 79, 234(T) (1950).
L. G. Smith, Phys. Rev., 81, 295 (1951).

the cyclotron when the value of the r-f frequency is equal to the frequency eH/M, the ions of mass M and charge e are accelerated in orbits of increasing size (Archimedes' spiral) and eventually strike an ion collector. If the ionizing beam is kept constant in value along with the electric and magnetic fields, the ion collector current is a measure of the partial pressure of the gas of this charge to mass ratio.

Under the influence of an r-f electric field $E = E_o \sin \omega t$ applied normal to a steady magnetic field B, a particle of charge to mass ratio e/M will describe a spiral locus with an angular velocity of $(\omega + \omega_c)/2$, where ω_c is the cyclotron resonance frequency. The radius at any instant is given by

$$r = (E_o/B\epsilon) \sin (\epsilon t/2) \quad . \tag{10}$$

At resonance for a particular particle, $\epsilon = 0$ and Equation 10 becomes

$$r = E_o t/B2 \quad . \tag{11}$$

Given any fixed value of E_o/B, there is a critical value for ϵ, $\epsilon' = E_o/R_oB$ where R_o is the distance of the collector from the origin.

RESOLUTION

The resolution can be defined as the mass of the particle divided by the mass error, or $M/\Delta M$. This is also equivalent to the cyclotron resonance frequency divided by the frequency error, where the frequency error is measured at the base of the resonance peaks. It follows

$$M/\Delta M = R_oB^2e/2E_oM \quad . \tag{12}$$

At the critical value of $\epsilon = \epsilon'$ the time required for the ions to reach the collector is $t' = \pi/\epsilon'$, the resolution becomes

$$(M/\Delta M) = \omega_c t'/2\pi \quad \text{or} \quad = n' \quad , \tag{13}$$

where n' is the number of revolutions the ions make before reaching the collector.

The maximum radius r_m attained by nonresonant ions differing in mass by M from the resonant ions is given by

$$r_m = 2MR_o/(n\pi\Delta M) \quad . \tag{14}$$

Equation 3 indicates that for a constant magnetic field B the resolution varies inversely with the mass. If E_0 is decreased as the mass is increased correctly the resolution will be constant.

DATA OUTPUT CHARACTERISTICS

A typical output curve from which pressure and density can be deduced is shown in Fig. 3. A calibration will provide the mass number associated with each frequency, while the current will provide information for calculating the density and pressure.

It can be shown from Equation 12 that by scanning magnetically ΔM remains constant. This is an advantage since the width of the recorded peaks remains constant. Thus, the instrument can be set for maximum scanning rate over the entire mass range, and a linear mass scale will be recorded if the magnetic field is made to vary linearly with time. In order to increase resolution, it is necessary either to increase the number of revolutions or to determine more critically a change in phase of the circulating ions. The number of revolutions corresponding to a minimum detectable ion current may be increased by increasing the magnetic field, by increasing the sensitivity of the detector, or by increasing the trapping efficiency.

SATELLITE INSTRUMENTATION

The block diagram in Fig. 4 demonstrates the principles for an instrumentation using a varying magnetic-field intensity and fixed electric-field frequency. The equipment consists of a filament power supply, electrometer and associated d-c amplifier, fixed-frequency oscillator, and a magnetic-field intensity control driving an electromagnet. Figure 5 on the other hand, using the varying electric-field frequency with a fixed magnetic-field principle, consists of a filament power supply, electrometer and associated d-c amplifier, sweep frequency generator, and a permanent magnet. Both systems provide the desired data with the resolution as discussed previously. Among the major problems involved with taking density or composition measurements is that of the contamination by the missile. This contamination might be reduced substantially by taking advantage of the sun's heating and the infinite pumping speeds available for outgassing of surfaces present. If active data sampling is delayed for a period of several days to a week, the missile could be constructed so that the temperature could be elevated several hundred degrees throughout this period and the contamination would become negligible in time. The gage should be mounted in such a manner that the sampling elements are not restricted by the conductance of an opening or connecting tubulations, but mounted above the missile surface directly exposed to the environment, leaving the associate equipment below the missile surface. Since the resolutions of both systems are comparable, weight could be the deciding factor for a choice. A very substantial reduction in weight is possible through the use of a permanent magnet as a field source. The magnetic field could, for example, be made to vary in the desired manner by moving the permanent magnet in and out of the magnetic circuit surrounding the sampling chamber.

IONIZED AND UN-IONIZED ENVIRONMENT

The presence of extreme ultraviolet radiation at extreme altitudes suggests the possibility of determining the gas composition with regard to the ionized and un-ionized population through use of a photoelectric source in place of a filament. The work of H. E. Hinteregger[4] and others[5] suggests that an ionizing source might be fashioned using beryllium plates exposed to the sun's radiation. In these circumstances it might be possible to separate the ionized composition from the un-ionized composition each time the satellite rotated to shield the instrument from the sun. Likewise the device would provide the opportunity to compare the environment of the earth's atmosphere on the dark side of the planet with that of the lighted side with each rotation about the earth.

TUNED GAGES

The problems in scanning can be eliminated completely by using several gage systems where the electric and magnetic fields are set to some predetermined value necessary to capture only oxygen or nitrogen, for example. One magnet could conceivably serve all the systems using the air gap to determine the field strength at a particular sampling chamber. A single electrometer-amplifier system likewise could serve all the tuned gages to provide the partial pressure of any component present by means of high-speed switching or communtating.

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[4]H. E. Hinteregger, Phys. Rev., 96, 538 (1954).
[5]J. Weiss and W. Bernstein, Phys. Rev., 98, 1829 (1955); C. Maunsell, Phys. Rev., 98, (1955); J. D. Craggs and C. A. McDowell, Rep. Prog. in Physics, Vol. XVIII, 1955, p. 374.

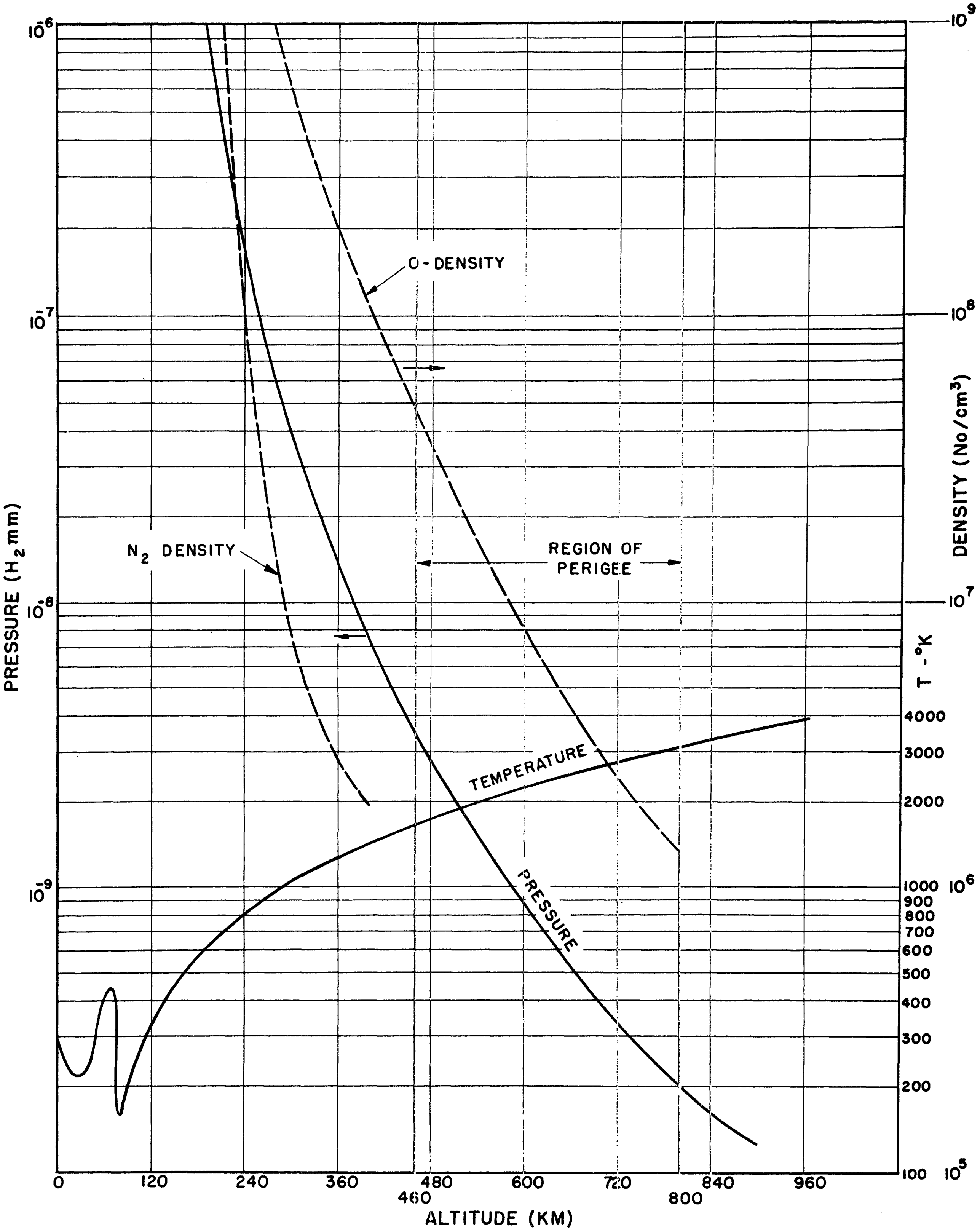

FIG. I MODEL ATMOSPHERE FOR EXTREME ALTITUDES

——— PRESSURE ——— – – – DENSITY

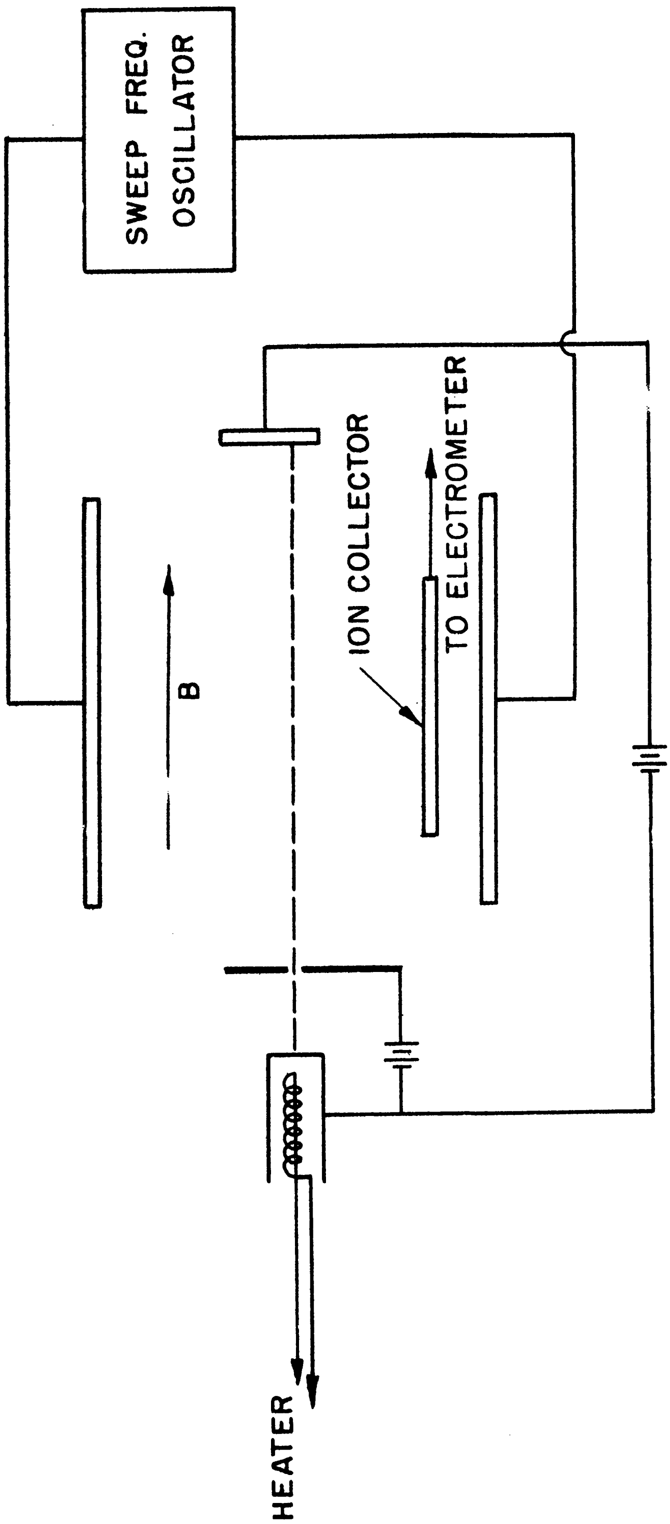

FIG. 2 CYCLOTRON RESONANCE PRINCIPLE FOR PARTIAL-PRESSURE-DENSITY GAUGE.

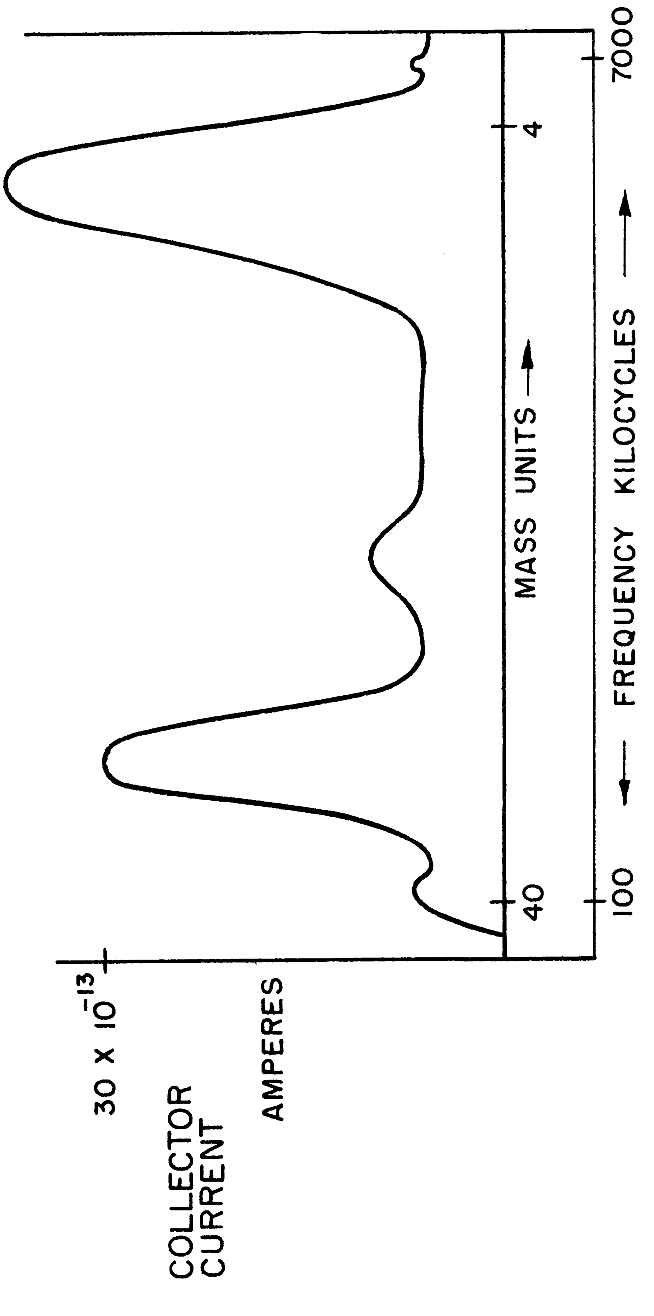

FIG. 3 OUTPUT DATA

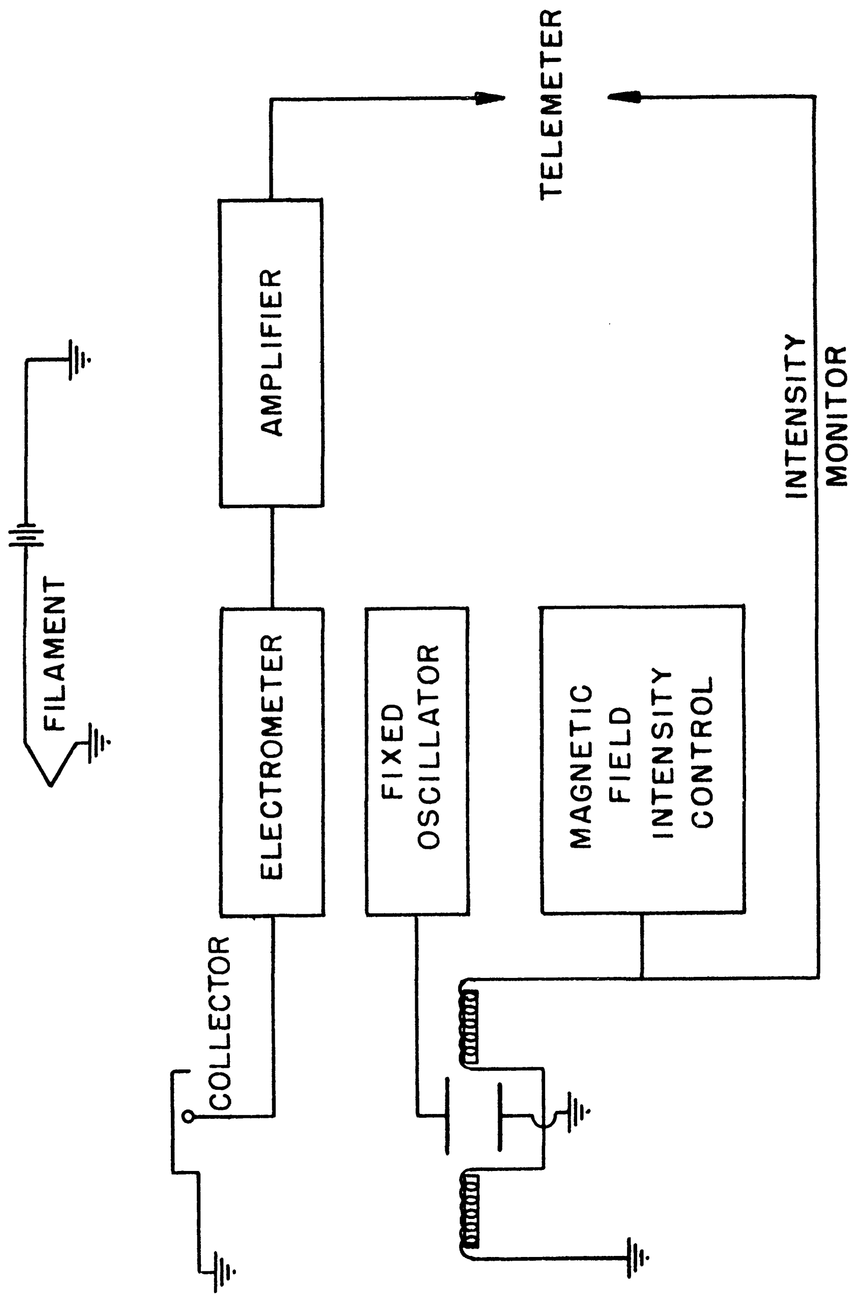

FIG. 4 BLOCK DIAGRAM OF APPARATUS

(VARYING MAGNETIC FIELD, FIXED ELECTRIC FIELD)

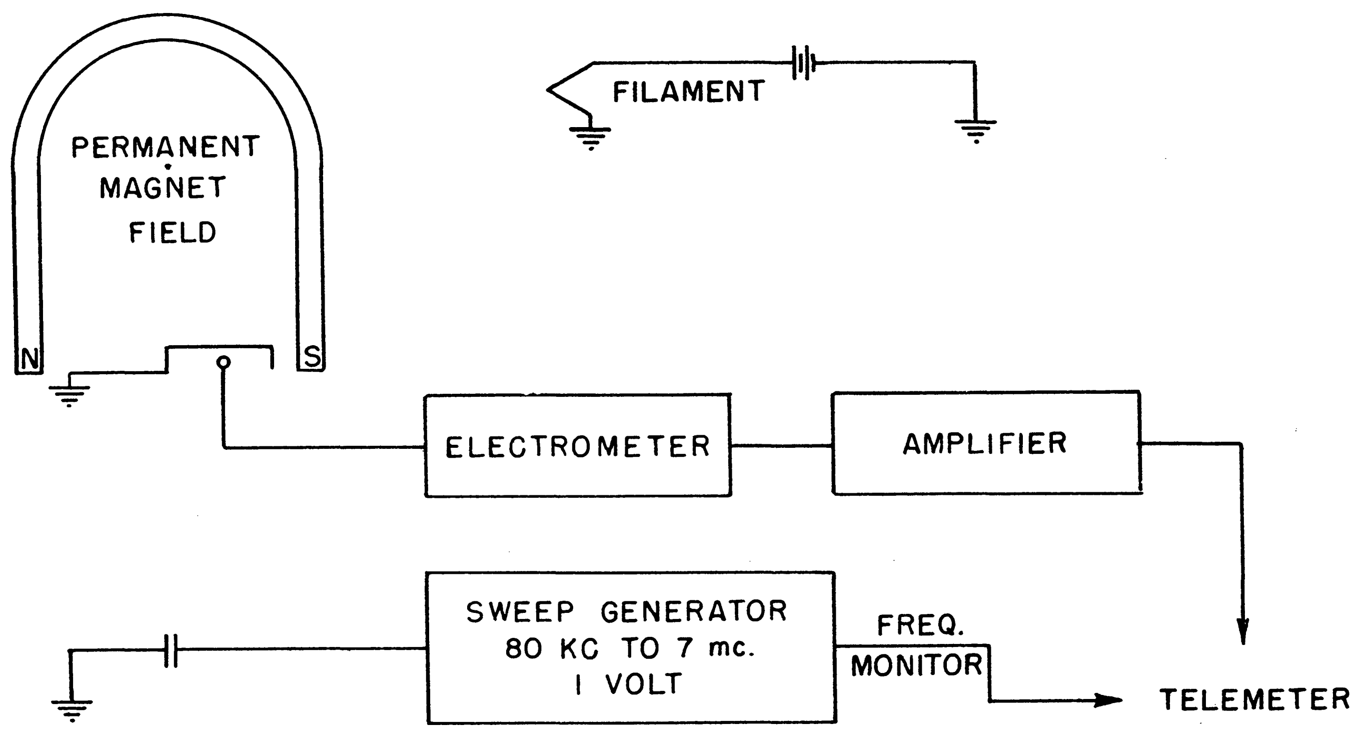

FIG. 5 BLOCK DIAGRAM OF APPARATUS

(VARYING FREQUENCY ELECTRIC FIELD, FIXED MAGNETIC FIELD)