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# A SURVEY OF THE TECHNIQUES OR MEASURING THE RADIO REFRACTIVE INDEX

R. E. MCGAVIN

S. DEPARTMENT OF COMMERCE

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# NATIONAL BUREAU OF STANDARDS *Cechnical Mote*

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MAY, 1962

## A SURVEY OF THE TECHNIQUES FOR MEASURING THE RADIO REFRACTION INDEX

R. E. McGavin

NBS Boulder Laboratories

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#### ABSTRACT

The radio refractive index can be measured either directly or indirectly. The former method is utilized by radio frequency refractometers; the latter method involves measurement of temperature, pressure and humidity and conversion to refractive index. In terms of convenience and accuracy the direct method is superior; however, lack of the universal use of refractometers requires the use of weather service type of data for the bulk of refractive index structures. Meteorological sensing is limited mainly by the inaccuracy in measuring humidity which under ideal conditions appears to limit the accuracy to ± 1.0 N. Gradient measurements utilizing radiosondes reflects an accuracy no better than ± 3 N units. Radio frequency refractometers are capable of accuracies as much as an order of magnitude better than that achieved by meteorological sensors. Lightweight refractometers have been devised for balloon-borne and dropsonde measurements reflecting accuracies inferior to the conventional refractometer but superior to the radiosonde.

# A SURVEY OF THE TECHNIQUES FOR MEASURING THE RADIO REFRACTIVE INDEX

by

R. E. McGavin

#### 1. INTRODUCTION

The radio refractive index has been measured extensively by many experimenters, especially in recent years. Methods vary with the individuals. This review attempts to assemble and to discuss the different methods for determining the radio refractive index of air with some analysis of the expected accuracies for the different methods.

#### 2. THE RADIO REFRACTIVE INDEX

The radio refractive index is central to any study of radio wave propagation. The gradient of the refractive index determines refraction through the medium, its turbulence determines the scattering of radio energy, sharp discontinuities in the refractive index profile produce reflections. The results of many investigations yield an expression of the refractive index as a function of the three parameters of the atmosphere. In the temperature range of  $-50^{\circ}$ C to  $+40^{\circ}$ C, the refractive index can be expressed with negligible error as:

$$N = (n-1)10^{6} = \frac{k_{1}}{T} \left( P + \frac{k_{2}e}{T} \right)$$
(1)

where

- N = refractivity
- n = refractive index
- T = temperature
- P = total atmospheric pressure
- e = partial water vapor pressure.

The Smith and Weintraub constants [1953] adopted by CCIR\* in 1959 result in the following expression:

$$N = (n-1)10^{6} = \frac{77.6}{T} \left(P + \frac{4810 e}{T}\right)$$
(2)

where T is measured in degrees absolute and P and e are in millibars. This expression is sometimes written

$$N = (n-1)10^{6} = \frac{77.6}{T} \left( P + \frac{4810 e_{s}(RH)}{T} \right)$$
(3)

where e is the saturation vapor pressure in millibars at temperature T and RH is the relative humidity in per cent.

#### 3. THE MEASUREMENT OF THE RADIO REFRACTIVE INDEX

The radio refractive index is defined as the ratio of the velocity of propagation of radio energy in a vacuum to the velocity in a specified medium. Hence the radio refractive index may be measured directly if the measuring instrument is sensitive to the velocity of propagation. The refractive index is measured indirectly by measuring temperature, pressure and humidity with consequent conversion to refractive index by means of (3). The direct method is employed by radio frequency refractometers; the indirect method is utilized where standard weather observations are used to determine the refractive index. It is apparent that the direct method should be superior since the accuracy is a function of a single sensor rather than three, and since the results are in a form requiring no conversion. However refractometers are relatively complex and expensive devices requiring some degree of skill to operate. Hence, as yet refractometers are not in general use or even in sufficient quantity to permit large scale mapping of refractive index structures. The bulk of the

<sup>\*</sup> International Radio Consultative Committee

synoptic and climatological mapping of refractive index is, as yet, based on the indirect method of measurement [Bean, Horn, Ozanich, 1960]. It seems that although the refractometer is a superior device for such investigation, indirect measurement of the refractive index will continue to play the major role in producing information on large scale refractive index structures.

One of the difficulties of indirect measurement is the laborious task of conversion of the measured parameters to refractive index especially for large quantities of data. This problem has been somewhat alleviated by the development of special analogue computers [Johnson, 1953]. In addition, digital computers have been used for such conversion.

### 3.1. The Indirect Method of Measuring the Radio Refractive Index.

a. The Required Accuracy of Meteorological Sensors.

The accuracy of the determination of the refractive index will be limited by the accuracy of the individual sensors. The degree of accuracy demanded of the sensors can be estimated by differentiation of (2).

$$dN = \left(\frac{\partial N}{\partial T}\right) dT + \left(\frac{\partial N}{\partial e}\right) de + \left(\frac{\partial N}{\partial P}\right) dP$$
(4)

which can be expressed for average conditions and for small changes in N:

$$\Delta N = a\Delta T + b\Delta e + c\Delta P.$$
 (5)

Typical values of the constants a, b, and c based on the ICAO atmosphere and assuming a relative humidity of 60 percent can be expressed as a function of the altitude. Table I expresses this function for several values of the altitude.

T		1	1		
	2	n		0	
-	4	~	-	<u> </u>	

<u>Alt. in km</u>	Temp( <sup>o</sup> C)	e(mb)	P(mb)	a	b	
0	15.0	10.2	1013	-1.27	4.50	0.27
1	8.2	6.5	893	-1.09	4.72	0.28
10	-50.3	0.04	262	-0.50	7.52	0.30

It can be noted that the effect of pressure variation is relatively constant with altitude, and the effect of temperature variation decreases with altitude but that the effect of water vapor pressure increases with altitude. Hence the requirements for sensor accuracy increases for humidity sensors as the altitude is increased.

Figure 1 illustrates the degree of accuracy to be expected in the measurement of the refractive index as a function of the accuracies of the sensors for sea level conditions. It is assumed that the errors are additive; hence this should reflect the maximum error to be expected. Planes of equal accuracy are shown for accuracies of  $\pm 0.1$  N,  $\pm 0.5$  N,  $\pm 1.0$  N, and  $\pm 2.0$  N. It can be seen that a measurement error of  $\pm 1.0$  N can be contributed by each sensor if the accuracy of the sensors are not within;  $\pm 0.8$  °C for temperature,  $\pm 3.7$  mb for total pressure and  $\pm 0.22$  mb for vapor pressure measurements. Since the total error will be a combination of these errors considerably better accuracy than this is required.

It is apparent that extreme accuracy is required in the measurement of the water vapor pressure. The temperature can be measured easily to within several tenths of a degree, and the total atmospheric pressure can be measured to within several millibars. If an Assman, or wet and dry bulb, hygrometer is used to measure the humidity, the Sprung [1888] psychrometric formula may be used to determine the water vapor pressure:



$$e = e_{s} - c \frac{(\Delta T)P}{566} , \qquad (6)$$

where

- e = the water vapor pressure (mb);
- e = the saturation water vapor pressure at the temperatures of the wet bulb (mb).
  - c = hygrometer constant (c = 50 for a water covered bulb; c = 43 for an ice covered bulb).
- $\Delta T$  = difference between the dry bulb and wet bulb temperatures (degrees centigrade).
- P = barometric pressure corrected for temperature (mb). The degree of accuracy becomes a function of temperature; at  $35^{\circ}C$  the relative humidity must be accurate to within 0.33 percent while at  $0^{\circ}C$ an accuracy of 3.0 percent is necessary. Experimenters at the National Physical Laboratories [1960] have shown that when an Assman hygrometer is used with thermometers accurate to within 0.1°C the optimum expected accuracy in the determination of the water vapor pressure is 0.2 mb, and errors three times as great can be expected at extreme conditions. Hence it would appear that the optimum measurement of water vapor limits the accuracy of the determination of the refractive index to approximately  $\pm$  1.0 N unit.
  - b. Surface Measurements of Refractive Index.
    - (1) Sources of Data.
      - (a) Weather Services.

Surface observations of temperature, pressure, and humidity are standard measurements of the weather services around the world. Methods of measuring these parameters are somewhat standard with all weather services. Usually the temperature is read from mercurial

or alcohol thermometers, the pressure from mercurial barometers. and the humidity from a conversion of wet and dry bulb thermometers. The degree of accuracy of these measurements is usually a function of the care and exactitude of the observer. Thermometers protected by radiation shields are usually accurate to within 0.1°C, barometers to within ± 1.0 millibars. Reading errors can easily be in excess of the instrument error. Especially in the determination of humidity is care in measurement essential. The measurement of the wet bulb depression is subject to many sources of error. Contamination of the wick or water, insufficient wetting, and inadequate aspiration are common sources of error. The wet bulb determination can be used below freezing, if proper precautions are observed. When the bulb is wetted, the water freezes releasing the heat of fusion (80 calories/gm) which tends to raise the temperature of the wet bulb. Sufficient time must be permitted to elapse before reading the thermometer to allow this heat to be totally dissipated. The thermometer then must be observed when it arrives at its minimum temperature, indicating the maximum effect of evaporation.

#### (b) Automatic Recording Systems for Particular Investigations.

Automatic recording systems have been devised for measurement of temperature, pressure, and humidity. The simplest devices are the hygrothermograph and the microbarograph. In these devices the sensors are connected by mechanical linkages to pens on chart recorders. The pressure is recorded by means of an aneroid capsule, the temperature b, means of a bimetal strip or a curved bourdon tube, the humidity by means of a hair hygrometer. The accuracy of such devices is relatively poor and the measurement of the refractive index should not be considered accurate to more than two or three N units for long-term averages.

Sensors producing electrical outputs are used to measure meteorological parameters in a variety of automatic recording systems, such as strip-chart recorders, punched-paper tape, and magnetic-tape recorders. The common methods of measuring temperature include sensors such as resistance thermometers, thermocouples, and thermis-The platinum resistance thermometer, an international standard, tors. is capable of measuring temperature to within  $\pm 0.05^{\circ}$ C if used in a well compensated bridge circuit. However since significant current is necessary to achieve accuracy and resolution the platinum resistance thermometer is velocity sensitive in a moving air stream. Thermocouples avoid the problem of sensitivity to velocity and yield accuracies of approximately  $\pm 0.1^{\circ}$ C. Thermistors reflect accuracies equivalent to the platinum thermometer for short-term measurements but the long term drift is undesirable. The chief advantage of small bead thermistors is the very fast response; time constants measured in milliseconds render thermistors ideal for higher frequency variations.

The total atmospheric pressure can be measured by a variety of electrical sensors. The simplest device is the pressure potentiometer where an aneroid capsule is mechanically linked to the wiper of a potentiometer. Inertia and friction as well as the resolution of the resistance are limitations to its accuracy and time constant. One to two millibars can be considered the limit of accuracy in a differential device operating over a range of  $\pm$  100 millibars with reference to an average value. Time constants of the order of five milliseconds are possible. The capacitive microphone is capable of very good accuracy and resolution if used over a restricted range. Accuracies of  $\pm$  0.01 mb and time constants of several milliseconds have been achieved with capacitive microphones measuring variations over several millibars. The resolution diminishes as the range of operation increases, and a resolution of  $\pm$  0.1 millibars

would be expected over the normal range of variations of atmospheric pressure. Unfortunately unlike the pressure potentiometer, the capacitive microphone is temperature sensitive and requires correction for temperature variations of 5 to 10 degrees. Strain gauge pressure transducers have approximately the same characteristics as capacitive microphones with some degradation in time constants. Differential strain gauge transducers operating over a range of four to five millibars may yield accuracies of several hundredths of a millibar. Fortunately strain gauge transducers are relatively free of temperature effects over the normally encountered ranges of the atmosphere.

The relative humidity which requires the most exactitude in measurement is the one parameter most poorly measured. Sensors for measuring the humidity directly do not produce the accuracy desired. The common lithium chloride strip even under optimum conditions cannot be expected to produce accuracies to within better than 5 percent in relative humidity. In general the time constant is of the order of 6 to 8 seconds. Other sensors show promise but are either in the developmental state or have not been fully evaluated as yet. The Barium Fluoride strip [Jones and Wexler, 1960 yields accuracies, hysteresis effects, and response times far superior to Lithium Chloride but has the disadvantage of calibration shift due to ageing. Phosphorous pentoxide sensors and aluminum oxide sensors have been used and appears to correct some of the deficiency of the conventional sensor. The optimum method, at present, to measure relative humidity is the wet-dry bulb technique using electrical thermometers. With care, accuracies of  $\pm 0.02$  millibars can be approached. The lag coefficient will be relatively large being a function of the wick, the rate of aspiration, and even the relative humidity itself. The limitation of the wet-dry bulb technique is noted for extreme temperatures. Below -24 °C this method is inconclusive.

#### c. Measurement of the Gradient of Refractive Index.

 Low Level Measurement of the Radio Refractive Index.

Low level measurements of the gradient of refractive index can be accomplished utilizing towers. Towers up to 300 meters are practical for such probing. Simultaneous sampling of the atmosphere can be accomplished using many sensors along the tower. Using electrical sensors permits a differential method of recording which increases the accuracy and eliminates some of the necessary computations. These, combined with a single measurement of the absolute surface value, yields the profile of refractive index over the vertical interval.

Higher elevation measurements up to several thousand feet can be made using tethered balloons or wiresonde. It is necessary to send aloft only the sensors with all other ancillary devices on the ground. Long cables are used to transmit the information from the sensors to the recording equipment.

> (2) High Altitude Measurement of the Radio Refractive Index.

For high altitude measurement of the meteorological parameters influencing the refractivity, the radiosonde is in almost universal use. There are many models of the radiosonde, however, the principle of operation for present American radiosondes is standard as illustrated in figure 2. An aneroid capsule is used as the active element of a baroswitch. The temperature sensor, humidity sensor, and a reference resistance are alternately switched into the grid circuit of a blocking oscillator as the baroswitch wiper moves under the action of decreasing pressure. The blocking oscillator controls the pulse rate of the RF transmitter.



## Figure 2 BLOCK DIAGRAM OF THE RADIOSONDE

Hence the pulse rate of the transmission is indicative of the value of the sensor being sampled. The number of the contact energized is a measure of the pressure; the switching sequence permits identification of temperature and humidity values. A constant rate of ascent of the balloon is assumed hence the values of the parameters can be identified with the proper altitude (the assumption of a constant ascent rate has proven to be accurate especially at the higher altitudes).

(a) Sensors for the Radiosonde.

Radiosondes are used throughout the world, however there is no uniformity in the selection of sensors. Hence, it is difficult to compare measurements from different countries. At one international comparison at Payerne, Switzerland in 1956, fourteen nations participated. The results indicated significant differences. Temperature measurements corresponded to within  $\pm 1.5^{\circ}$  for night flights but corresponded only to within  $\pm 3.5^{\circ}$  for day time flights. Pressure measurements agree well at low altitudes but indicated a dispersion of  $\pm 1.5$ mb above 9000 meters (29,000 feet), and  $\pm 2.5$  mb above 16,000 meters (50,000 feet). Humidity comparisons were poor indicating that at best 15 percent would be the most optimistic estimate of the standard deviation from the mean for all flights. The American sonde in most cases approached the mean value. On the average it is estimated that the standard American temperature sensor indicated a value approximately 1.5°C below the mean for all sondes used in the test, the pressure determination was below the mean by .5 mb, whereas the humidity sensor although approaching the mean cannot be quantitatively evaluated.

No attempt was made at these comparison trials to determine the absolute accuracy of any radio sonde. Although the absolute accuracy of the American sonde has not been determined, statistical evaluation of the uniformity of American radiosondes have been conducted by both the U. S. Air Force and the U. S. Army Signal Corps. Statistical evaluation of radiosondes sent aloft in groups have been conducted. Results indicate a standard deviation for the temperature sensor of  $0.8^{\circ}$ C to 6000 meters and  $1.0^{\circ}$  above that altitude. The standard deviation for the pressure determination was 2.2 mb below 9000 meters and 1.1 mb above 9000 meters. The humidity sensor (lithium chloride) exhibited the poorest comparison. Under ideal conditions the standard deviation was 5 percent. This accuracy is possible only if the element is not subjected to high humidity (95 to 100 percent) or saturation by liquid water and only if the temperature is above  $0^{\circ}C$ . The response of the element is especially poor where both temperature and humidity is low. The evaluation means little if the relative humidity is below 15 percent at a temperature of  $20^{\circ}$ C, or 20 percent at a temperature of  $0^{\circ}$ C, or 30 percent at a temperature of -30°C. Hence "under ideal conditions" at sea level, reflecting the accuracies as stated, the standard deviation in the determination of the refractivity from radiosonde data is approximately 3 N units; at one kilometer the standard deviation would be approximately 2 N units. This then would appear to be the ultimate precision which the present conventional radiosonde sensors can yield the refractivity in a static condition.

In addition to the inherent accuracy, the time constant or lag coefficient of the sensors are of importance. Since the sonde is rising at a relatively rapid rate, it passes into regions of changing refractivity before the sensors are aware of it. The lag coefficient associated with



the radiosonde introduces an error in the estimation of the true gradient. The lag coefficients of the sensors have been analyzed by Wexler [1949] and by Bean and Dutton [1961] and there are indications that some correction can be made to the radiosonde data. Wexler, in figure 3, shows that the lag coefficient of the lithium chloride strip is a function not only of the temperature but also of the absolute value of the relative humidity as well as the size and direction of the gradient.

One of the disadvantages of the radiosonde is the sampling process whereby the temperature and humidity are measured in sequence rather than simultaneously. Several experimenters devised means to correct this deficiency in the radio sonde. Misme [1956] decreased the cycling time in one refractometer such that many more samples of each parameter were produced per unit time. Clinger and Straiton [1960] developed a radiosonde that combines the parameters such that the output signal is in terms of the refractive index (see figure 4). Since the wet and dry terms are additive, a parallel combination of independent conductances can be used. The dry term sensor has a conductance proportional to temperature and inversely proportional to pressure; the wet term sensor is such that it not only yields a value proportional to the relative humidity but also adjusts the relative magnitude of the two terms. Thiesen [1961] devised a similar radiosonde utilizing two separate sondes on the same balloon. (See figure 5). The temperature and humidity information are combined at the ground station by means of an analogue computer. For captive balloon application, Hirao and Akita [1957] and Crozier [1958] developed similar systems using wet and dry bulb thermistors to produce direct output in refractive index.

Hence it is apparent that the indirect method of determining the refractive index is less than optimum. Not only is the absolute accuracy



Figure 4 CLINGER - STRAITON RADIOSONDE (TRANSMISSION IN N UNITS)



Figure 5 THE SCHEMATIC DIAGRAM OF THE NAVY ELECTRONICS LABORATORY (THEISEN) SYSTEM BUL. AM. MET. SOC. VOL.42 Nº 4 APRIL, 1961 poor even under the most advantageous conditions (several N units) but the necessity for conversion of parameters imposes additional computational work. The limitations are chiefly due to the lack of accuracy in the measurement of humidity. The present work on the development of new hygrometer elements indicates future improvement in the correction of these deficiencies.

#### 3.2. Direct Measurement of the Refractive Index.

#### a. Radio Frequency Refractometers

The development of radio frequency refractometers has eliminated the necessity of measuring the several parameters influencing the refractive index of the atmosphere. Since the radio refractive index is a function of the velocity of propagation, the resonance of tuned circuits can be used as a measure of refractive index. A cavity resonator open to the atmosphere or a capacitor utilizing the atmosphere as a dielectric, have been used as such a measure.

In either case the radio refractive index can be measured as a direct function of the contents of the measuring element. The relationship between the change of the resonant frequency and the change in refractive index is

$$\frac{\Delta f}{f} = \frac{-\Delta n}{n} , \qquad (7)$$

where f is the original resonant frequency of the element whose contents has a refractive index of n. Since n is very close to one the following approximation can be used with negligible error

$$\frac{\Delta f}{f} \approx -\Delta n$$
. (8)

#### (1) Microwave Refractometers.

The resonant frequency of a microwave cavity is a function of its dimensions and the refractive index of its contents. Hence, if a cavity is open to the atmosphere, the resonant frequency changes as the refractive index of the air passing through changes in accordance with (8). If a sealed reference cavity is used for comparison, the difference between resonant frequencies becomes a convenient measure of the refractive index variations in the sampling cavity. This method of measurement was used in two different instruments; the Crain type (University of Texas) and the Birnbaum type (NBS). The Crain refractometer utilizes the cavities as frequency determining elements in ultra-stable oscillators. The difference frequency is then the unit of measure. The Birnbaum refractometer utilizes the cavities as passive elements energized by a klystron oscillator swept across the different resonance frequencies of the cavities. The time difference between resonances is the unit of measure. A third refractometer to utilize this principle is the Vetter refractometer. This instrument utilizes servo techniques to achieve a null system, thus eliminating the necessity for extreme electronic stability.

The cavities are the major components in any of these instruments: Of prime importance is the temperature coefficient of the cavity. Most cavities today are made of invar having a temperature coefficient of approximately one part per million per degree centigrade [Lement, Roberts, and Averback, 1951; Bussey and Birnbaum, 1933]. This is equivalent to 1 N unit per degree centigrade. Further temperature compensation of the cavity has produced temperature coefficients of 0.2 to 0.1 N unit per degree centigrade [Crain and Williams, 1957]. The possibility of improving cavity performance by use of special ceramics have

been investigated [Thompson, Freethey, and Waters, 1958]. Similar temperature coefficient without compensation were found, however the frailty and porosity of the ceramic limits its use.

The response time of the refractometer is a function of how much of the end plates of the cavity can be opened to the air. Unless the cavity is well ventilated, the flushing time will be excessive. Adey [1957] found that by judicious design of the end plates 67 percent of the area could be cut away without appreciable loss of Q. Thompson et al [Thompson, Freethey, and Waters 1959] found that as much as 92 percent of the end plate area could be eliminated without serious degradation of the Q of the cavity. Hence, the flushing time of cavities with such end plates becomes a function of the linear dimensions of the cavity and the velocity of the air flow.

The accuracy of the refractometer is in general several orders of magnitude better than what can be achieved by indirect measurement. With proper care these instruments are capable of discerning changes of the refractive index that are less than a tenth of an N unit. As a relative instrument, i.e., used to measure variations about an undetermined mean, the accuracy and time constant are such as to detect easily very small changes in the refractive index at a rate of up to one hundred cycles per second. Accurate measurement of the gradient of refractive index is now possible using these devices.

#### (a) The Crain Refractometer.

The Crain Refractometer [Crain, 1950; 1955] as illustrated in figure 6, utilizes one sealed cavity as a reference cavity and a ventilated cavity as the sampling element. Each of these cavities is the frequency



Figure 6 THE CRAIN REFRACTOMETER

determining element of a stabilized microwave oscillator in the manner devised by Pound [1946]. Hence for optimum operation relatively high Q's are necessary, and thus the end plate opening is of importance with the consequent limitation due to flushing time (operation has indicated that even the earliest models had a sufficiently fast flushing time to discern discontinuities displaced by as little as two feet of atmosphere at normal aircraft speed of 250 feet/sec).

The Crain Refractometer is so designed that the cavity resonators operating in the 9400 megacycle range are displaced in resonant frequency for equal values of refractive index. The resultant difference frequency is the center frequency from which departures due to changing refractive index are measured. Recent models utilize a 43 megacycle center frequency. As the refractive index of the contents of the sampling cavity changes, the difference frequency at the output of the mixer changes according to

$$\frac{\Delta f}{f} = - \Delta n.$$

Then since

$$\Delta N = \Delta n 10^6$$
,

a change of 1 N unit, corresponds to a change in the resonant frequency of the sampling cavity of approximately 9.4 kilocycles if the nominal operating frequency is 9400 megacycles. The output of the mixer is applied through appropriate amplifiers, limiters and discriminators, and the DC output is a function of the changes in the refractive index within the sampling cavity. The linearity of the function will be determined chiefly by the characteristics of the discriminator. A 400 N unit range would require a discriminator having a linear range of 4 megacycles. For the measurement of small scale variations of refractive index a modified Crain refractometer utilizing a 10.7 megacycle center frequency with a 200 kilocycle linear range has been used. Scales of 1 to 20 N units for full scale deflections of a 1 milliampere chart recorder have been used. Since this instrument is relative the position of the zero point is of little consequence, hence the zero can be shifted by means of a tuning slug in the reference cavity.

#### (b) The Birnbaum Refractometer.

The Birnbaum refractometer [Birnbaum, 1950], illustrated in figure 7, applies the principle of resonance in a somewhat different fashion. Both the reference or sealed cavity and the sampling or open cavity are passive elements. The cavities are slightly different in dimensions and are of the transmission type having crystal detectors at the output. A klystron is frequency modulated by a sawtooth voltage such that the output frequency is linear with time. The one klystron excites each cavity in sequence at its respective resonance frequency. During the frequency excursion of the klystron the resonance of each cavity is excited and a pulse is formed at the crystal detector. Since the resonant frequency of the cavities usually differ, the two output pulses will be displaced in time. If the modulation on the klystron is periodic then the output pulses are also displaced in phase. Then the two pulse trains coming from the detectors are displaced in phase, the displacement being a function of the klystron modulation. Any change in the refractive index of the contents of the sampling cavity will alter the phase difference between two pulse trains. The relative phase between the two outputs can then be measured by an electronic phase meter. The phase meter in use is merely a multivibrator having a constant amplitude output. The pulse from each cavity





after shaping alternately switches the multivibrator "on" and "off". The width of the constant amplitude output pulse from the multivibrator is a measure of the time difference between trigger pulses. The resulting train of constant amplitude variable width pulses is then applied to appropriate recording circuits where the time constant may vary from a minimum which is determined by the sweep rate of the modulating voltage on the klystron to a value in excess of this depending upon the averaging time of the recording circuit.

The accuracy of the instrument is dependent upon its ability to maintain a linear frequency sweep. The function of frequency versus time is the determining factor in establishing the relative difference in refractive index. Individual differences between klystrons, as well as different temperature characteristics of individual klystrons, complicate the problem since the sweep characteristics must be matched to the individual klystron. This problem can be circumvented in the manner of Sargent [1959], who modified the Birnbaum refractometer to operate as a microwave hygrometer. A servo system is used to tune the sampling cavity to the resonant frequency of the reference cavity; hence, the instrument is essentially a null device. The servo positions a tuning probe in the sampling cavity. The depth of penetration is the measure of the refractive index of the contents of the sampling cavity. This technique minimizes the dependence on the sweep characteristics of the klystron.

#### (c) The Vetter Refractometer.

The problems associated with the Birnbaum refractometer led to the development of the Vetter refractometer [Vetter, 1962]. This device, figure 8, virtually eliminates the dependence of the refractometer on electronic characteristics and shifts the limitations to the cavities themselves. In addition, whereas the two previous instruments are primarily relative refractive index indicators, the Vetter refractometer is an absolute refractive index device.



Figure 8 THE VETTER REFRACTOMETER

If the cavity is a symmetrical filter driven by a klystron which is modulated by a <u>symmetrical</u> signal such as a sine wave, then when the center frequencies of the cavity and the klystron are identical, the output of the cavity will contain only even harmonics of the modulating signal, i.e., no fundamental or odd harmonics of the original modulating signal will be present. If the center frequencies of the cavity and klystron differ then some fundamental of the modulating signal appears at the detector output. If the cavity is above the klystron then there will be an output at fundamental modulating frequency; if the cavity is below the klystron there will again be an output but will be shifted 180° in phase from the former condition. Hence, presence of the fundamental modulating signal is a measure of lack of identity between center frequencies. Such an output can be used as an error signal to tune the klystron to the same frequency as that of the cavity.

The Vetter refractometer utilizes this principle in a null system. The reference cavity is excited by a klystron which is modulated by a small sine voltage on the repeller. Any output at the fundamental modulating frequency at the detector of the reference cavity is compared in phase to the original modulating signal and an error signal is applied to the repeller of the klystron to lock the center frequency of the klystron to the reference cavity. At coincidence, the fundamental disappears in the output of the reference cavity. The same klystron excited the sampling cavity. Any fundamental appearing at the output after phase comparison to the modulating signal develops another error signal. This error signal is used to drive a mechanical servo which tunes the reference cavity to the resonant frequency of the sampling cavity with the concomitant shifting of the klystron center frequency. This then is a double loop system: the reference cavity.

The tuning of the reference cavity is accomplished by a motordriven probe that penetrates the reference cavity. The output of the refractometer is in terms of probe penetration; associated circuitry provides an electrical output in terms of probe positioning. The tuning of the probe is accomplished over a 400 N unit range. Although the range of variations experienced are more of the order of 100 N or less this extended range permits a zero calibration point. The design of the probe is such as to permit very nearly a linear function of  $\Delta N$  versus probe penetration over the range of operation. Once the probe is calibrated with the cavity the relative calibration is static and practically independent of the contents of the cavity, which is usually dry air or an inert gas. The reference cavity is sealed but does not require a vacuum tight seal.

The absolute calibration is accomplished merely by determining the zero point or the intercept where N = 0. This is done by evacuating the sampling cavity. Experience has indicated that a simple vacuum system can be adapted for calibration which will be both rapid and accurate.

It should be noted that the shape of the calibrating curve is independent of the intercept, and consequently the calibration curve of the probe penetration versus  $\Delta N$  can be moved to pass through the intercept. Also it is not necessary that the calibration curve be linear over the range of 0-400 N units; the requirement for linearity is demanded only over the range of operation.

Since the refractometer is mechanically tuned with a servo system having considerable inertia, the high frequency response is relatively poor. Above 10 cycles per second the validity of results is questionable. The accuracy and simplicity of operation are the distinct advantages.

### (2) Light-Weight Refractometers.

Refractometers have been used to measure both the surface value and the gradient of the refractive index. Although the aforementioned units were designed originally as ground-based equipment, modifications have been made to convert them to airborne use. However where vertical gradients to high altitude are desired the airborne version of the refractometer has definite limitations. The turning radius of the aircraft, and the angle and rate of climb or glide are factors influencing this type of measurement. A considerable horizontal component is present which can conceivably be more significant in the measurement than is the vertical component. In addition the time involved in ascent or descent is relatively long and the measurement is valid only under the assumption of relatively static conditions for the total time of the measurement. Due to the expense and weight, the conventional refractometers are not economical or practical to use in balloon ascent whether free or tethered. Hence, the need for light-weight refractometers to be used either in wiresonde, radiosonde or dropsonde applications led to the development of several refractometers for such applications.

#### (a) The Deam Refractometer.

Figure 9 is a block diagram of a light-weight (6 pounds), expendable refractometer developed by Deam at the University of Texas, for use as a balloon-borne unit or as a drop sonde. The device is a Pound oscillator [1946] operating at a nominal frequency of 403 megacycles; the actual frequency is determined by a coaxial cavity. The refractive index is sampled by a cavity and is reflected as a capacitance in the tuned circuit of the oscillator.

The RF oscillator utilizes a tuned transmission line as the resonant circuit. The transmission line is terminated with a semiconductor to allow for adjustment of its electrical length. The correction voltage which



Figure 9 THE DEAM EXPENDABLE REFRACTOMETER (MODIFIED POUND OSCILLATOR) is proportional to the frequency difference between the RF oscillator and the resonant frequency of the cavity, is used to bias the semiconductor changing its capacitance and producing a change in the resonant frequency of the oscillator.

Operational tests indicate that the electronics are sufficiently stable to produce the desired accuracy. Due to the cavity size and mass the time constant is less than desirable. Lag coefficients and temperature coefficients are also characteristics which are not fully evaluated and optimized at this time. Since the expendability of this sonde was a principal consideration in its development, extreme accuracy must be balanced with economic factors. The present accuracy is estimated to be better than  $\pm$  5 N units for a complete profile.

#### (b) The Hay Refractometer.

A refractometer was developed by D. R. Hay, as a compromise between the microwave refractometer and the conventional radiosonde. See figure 10. It lacks by an order of magnitude the accuracy of the microwave refractometer but weighing only six pounds it incorporates the light-weight feature of the radiosonde. Hence as an airborne instrument it fulfills a need for more accurate, faster response, probing of the refractive index at high elevations.

Two Clapp oscillators, operating nominally at 5 megacycles, are used as separate transmitters. They are designed to be identical with the exception of the frequency determining capacitors. One oscillator is the reference oscillator whose capacitor is unaffected by the atmosphere; the other oscillator uses a parallel plate capacitor through which the atmosphere is allowed to pass. Each oscillator or transmitter transmits an independent signal to the ground station. At the ground station the two signals are detected and the audio difference frequency is used as the unit of measure.



Figure 10. THE HAY REFRACTOMETER

Considerable care is necessary to compensate the sensing capacitor for temperature and to provide sufficient air flow over the plates of the capacitor. The capacitor consists of forty-one parallel plates spaced oneeighth of an inch apart, each plate being ten inches long and 0.28 inches wide. A later model of the Hay refractometer utilizes a single oscillator with a carefully designed rotating switch to sample alternately a reference capacitor and the air sampling capacitor. The reference capacitor is sampled for three seconds, the sensing capacitor for eleven seconds. The transmitted signal is 10 megacycles per second. Tests on this device reveal a remarkably fast time constant; a -52 N unit change was indicated in 0.6 seconds.

Temperature compensation is extremely important. Since a 3-cycle change in frequency corresponds to one N unit, frequency drift due to temperature must be minimized by careful design.

### 3.3 Summary.

In comparison between the direct and indirect method of measurement absolute accuracy may not be the only consideration. Although refractometers may be capable of superior accuracy, the factors of requirements, economics, and availability of competent technical personnel may outweigh this advantage. Refractometers are relatively expensive, hence availability in quantity requires a considerable investment. Refractometers are somewhat complex and require competent technical personnel to maintain, calibrate, and operate them.

In many cases where average values or long term statistics are adequate, the use of refractometers may not be indicated. The data on refractive index structure derived from weather service data has been used most successfully for the determination of average conditions. Errors can be assumed to be normally distributed about a value proportional to the true value; hence the average should approach this value. Gradient

measurements do not require the same absolute accuracy as do surface measurements; the change in value with change in height is of chief interest. This implies importance of lag coefficients especially where balloon ascents are concerned. The chief limitation appears to be the lag coefficient of the humidity sensor in the radiosonde, but the gravity of this limitation also is relative. During ascent the lag coefficient introduces an error in the determination of the boundary and height of elevated layers. Sharp discontinuities in the profile are smoothed, and the smoothed edges of the layer appear to be higher. Well above  $0^{\circ}C$  the lag coefficient of the lithium chloride sensor is approximately 10 seconds or less. At a constant rate of ascent of 300 meters per minute, this lag coefficient would cause the sensor to move 50 meters beyond the layer boundary before 63 percent of the change would be noted. At  $-40^{\circ}$  the lag coefficient would be approximately 400 seconds. However at this temperature the saturation water vapor pressure is of the order of 0.1 mb and the contribution to the refractivity will be at most 0.5 N units. At  $0^{\circ}$ , where the contribution can be as high as 25 N units, lag coefficients of 20 to 30 seconds introduce an error of from 100 to 150 meters. These errors, depending upon the application, may or may not be significant.

Where extreme accuracy is required, the use of refractometers is indicated. Radar and radio navigation are several examples where accurate estimates of both surface values and gradient are necessary to determine the refraction through the atmosphere. The necessity for true vertical gradients would demand the use of balloon-borne or dropsonde type of refractometer. In many applications the indirect method may be sufficient, however, an accurate determination of the fine structure of the refractive index can be accomplished only with some type of radio frequency refractometer.

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#### A. V. Astin, Director

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