NBS

Technical Note No. 66

Boulder Laboratories

RADIO REFRACTOMETRY

BY JACK W. HERBSTREIT

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

THE NATIONAL BUREAU OF STANDARDS

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July 1960

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I. Introduction

The fact that the sun can be seen to rise some three minutes before it is actually above the geometrical horizon of an observer has long been known to astronomers. The fact that the twinkling light from stars is more pronounced near the horizon than at the zenith is also well known. The shimmering of light waves as they pass through the atmosphere above a heated highway or desert is commonly observed. Less common, but frequently reported, are the appearances of mirages. All of these phenomena are governed by the same basic physical principle, the passage of electromagnetic energy through a medium of variable refractive index. Radio waves, although not being visible to our eye, are known to be affected in a similar manner as they are propagated through an atmosphere of variable refractive index above the large refractive index discontinuity where the atmosphere meets the earth. Thus, radio waves originating at an aircraft or earth satellite are known to be bent downward as they pass through the thin outer layer of the atmosphere of refractive index near that of a vacuum (unity), into the heavier region of the atmosphere near the earth's surface just as the rays of the sun are bent downward when the sun appears to rise before geometrical sunrise. The intensity of radio waves twinkles and the apparent direction of arrival shimmers, just as in the optical case.

The optical refractive index is known to be determined principally by the temperature and pressure of the atmosphere, whereas the radio refractive index is, in addition, affected by the water content of the atmosphere, the relationship between these quantities being expressed in the following way:

$$N = (n-1)\,10^6 = \left(\frac{77.6}{T}\right)(P+[4810e/T]) \qquad (1)$$

where total air pressure P, and water vapor e, are in millibars, and the temperature T is in degrees Kelvin [Smith, 1953]. The quantities P, e, and T have long been routinely measured at the surface of the earth by standard weather bureau stations. For some time they have been measured from the surface up to great heights using balloon-borne radiosonde equipment at a large number of places over the earth's surface. More recently, equipment has been developed to measure rapidly and directly the radio refractive index of the atmosphere using radio techniques. The measurement of the radio refractive index properties of the atmosphere and the application to radio propagation problems is the subject of this paper.

II. Surface Measurements

The temperature, pressure and humidity at the surface of the earth has long been observed in almost every country of the world. These observations have been the basis of the study of the world's weather. These data form the basis for calculations of the radio refractive index throughout the world using equation (1). Long term means of the meteorological data have been published monthly by the United Nations in their publication, "Climatic Data for the World." The computation of a large number of radio refractive indices by manual methods is generally tedious and time consuming and special computer aids have been developed to assist in these calculations [Johnson, 1952]. More recently, large scale digital computers have been put to use in this regard. A radio refractive index data center has been established at the National Bureau of Standards where data from approximately 300 locations throughout the world have been collected to date.

III. Radiosonde Measurements

In addition to easily obtained data concerning the surface values of radio refractive index, the refractive index as a function of height above the surface is of importance. There exists a large number of weather observatories which regularly send aloft balloons carrying with them temperature and humidity elements that transmit information to the ground by radio as the balloon ascends to heights of the order of 20 or 30 kilometers. These observations are normally made twice daily, at 0300 and 1500 GMT. The temperature elements carried by these balloons are either of the bimetallic or thermistor type. The humidity elements are in general either hair hygrometers or a specially prepared strip of lithium chloride whose resistivity changes with water vapor content. Small thermistor temperature elements have a relatively rapid response to changes in temperature. However, bimetallic temperature elements and commonly used humidity elements are notably sluggish in response, and with a rapidly ascending balloon will not record the variations in the radio refractive index of the atmosphere with sufficient speed to detect the existence of rapid changes of radio refractive index with height. Radiosonde measurement techniques used by the weather services also involve a sampling process whereby the temperature is recorded for a short period and then the humidity for a short period, so that simultaneous observations of both of these quantities are not obtained. During recent years a number of radio meteorologists have developed special radiosonde devices to attempt to overcome some of these difficulties. One of these developed in France [Misme, 1956] rapidly switches between temperature, pressure and humidity at the balloon borne element. A device developed in the United States combines the information from the temperature and humidity elements in such a way that the radio refractive index itself is telemetered to the ground [Clinger, 1960]. A similar device developed in Japan utilizes a small thermistor wetted from cotton threads to serve as a wet bulb thermometer in combination with a thermistor for the dry bulb thermometer to provide radio refractive index data directly [Hirao, 1957]. The use of barium fluoride films rather than lithium chloride films for humidity sensing elements, which offer promise of providing a very rapid response, is at present being investigated in the United States [Jones, 1958].

IV. Radio Frequency Refractometers

One of the most important developments in the past decade is a radio frequency device for measuring directly the radio refractive index of the atmosphere. Since the velocity of propagation of radio waves is a direct function of the radio refractive index, the resonant frequency of cavity resonators and tuned resonant frequency devices in general are also a direct function of the radio refractive index of the material within the resonant cavity or the dielectric material in the capacitor determining the frequency of resonance. There appeared in the literature, almost simultaneously, descriptions of devices which measure the radio refractive index of the atmosphere in terms of the resonant frequency of microwave cavity resonators which contain as a dielectric a sample of the atmosphere under study. One of these devices developed by Crain [1950] employs two microwave resonant cavities, one sealed to exclude changes in composition of the air inside it to serve as a reference cavity, and the other having small holes at strategic locations in the ends of the cavity to allow the passage of a sample of the atmosphere through it. These two cavities serve as the resonant circuits for two highly stabilized microwave oscillators, the frequency difference of which is a measure of the variations of the radio refractive index of the atmosphere in the sampling cavity. The other device developed by Birnbaum [1950] uses two similar cavities as passive resonant circuits which are excited by a klystron oscillator that is swept linearly with time across the slightly different resonant frequencies of the two cavities. Variations between the time of passage of the oscillator between the two resonant frequencies of the cavities, is a measure of the variations of the radio refractive index of the air in the sampling cavity. The degree to which the sampling cavity may be open to the atmosphere is limited in the case of the Texas unit, which requires relatively high Q cavities for operation, while the Birnbaum cavities may be opened to a greater extent to the atmosphere [Thompson, 1959] and still provide satisfactory operation. On the other hand, the accuracy of the Birnbaum unit depends on the ability to obtain a very linear frequency sweep for the klystron oscillator.

The key to the satisfactory operation of both of these units is the cavity resonators themselves. Invar with a temperature coefficient of approximately one part per million per degree centigrade has been the principal material from which these cavities have been prepared. By judicious design it has been possible to compensate these cavities, at least on a long term basis, so that the temperature coefficient is of the order of 0.1 part per million, i.e., 0.1N, per degree centigrade. Recent investigations have been conducted into the possibility of fabricating cavities from extremely low temperature coefficient ceramics [Thompson, 1958]. These cavities have been found to be very easy to fabricate and to be made conductive by the use of silver paint. However, they are relatively fragile and porous, the latter being at this time the most serious problem. Temperature coefficients of several ceramic cavities which have been prepared are of the order of 0.1 part per million per degree centigrade.

Recent developments in microwave refractometry have been concerned with the reduction in their size and weight so that they may be readily carried aloft by small aircraft to study the detailed refractive index structure of the atmosphere above the earth. A recent application of servo techniques to refractometers by Vetter [1960] has resulted in an extremely stable unit with the ability to measure the absolute refractive index of the atmosphere, rather than just relative values. In this new instrument, the problems of stability of the electronic circuitry have been practically eliminated, permitting the realization of excellent long term instrument calibration stability. Microwave refractometers of the Crain type have been used extensively for measurement of refractivity in the United States. Units of the Birnbaum type have been built and operated successfully in the United States, Canada [Adey, 1957], United Kingdom [Lane, 1960], Sweden [Johansson, 1959], and Germany [Schunemann, 1958]. All three types of instruments-Crain, Birnbaum and Vetter-are now commercially available from several U. S. manufacturers.

Most refractometer measurements which have been made to date have been either on the ground or in an aircraft. The theory of long distance propagation of radio waves through the troposphere indicates that the variations of refractive index as a function of altitude are of most importance, although the complete volumetric structure is involved. In an effort to determine the vertical refractive index structure in more detail Deam [1959] has recently developed a drop-sonde type of unit using the cavity resonator principle. This unit uses a single cavity open to the atmosphere with its resonant frequency stabilized by a pound oscillator at approximately 400 Mc/s in the band allocated for radio meteorological purposes. The radio frequency power from this oscillator is radiated to the ground where it is received and the variations of frequency recorded as a measure of the variations of the radio refractive index of the sample of air in the cavity. Another miniaturized version of the radio refractometer has been developed by Hay [1959]. This unit contains two 5 Mc/s oscillators, the inductance and capacitance of the resonant circuit of one of which is closed off from the atmosphere, whereas the frequency controlling capacitance of the second oscillator is exposed to the atmosphere. Thus, the frequency difference of the two oscillators is a measure of the variations of the refractive index of the atmosphere. Considerable care is taken in the design of the frequency controlling capacitor as regards its thermal stability and the provision for a free flow of the sample of air through the capacitor plates.

V. Applications of Radio Refractometry to Radio Propagation Problems

The literature concerning the application of radio refractive index studies to radio propagation problems has been growing at a very rapid rate and only a few selected references are included in this paper. Contributions to the XIII th General Assembly of the International Scientific Radio Union sessions on radio meteorology have included mention of extensive work being done in the United States [U. S. Nat. Com. Rpt.], France [Misme, 1960], Italy [Bonavoglia, 1958], Germany [Brocks, 1959a, b], Sweden [Johansson, 1959], Japan [Ugai, 1959], Belgium, Czechoslovakia [URSI Bulletin No. 113], and the United Kingdom [Saxton, 1960]. The largest portion of this work considers either the surface values of the refractive index, or gradient of the refractive index from the surface to one kilometer above the surface [Bean, 1959a, b; Fehlhaber, 1957, 1959; Ikegami, 1960].

The Consultative Committee for International Radio at its Los Angeles Plenary Assembly adopted procedures for estimating tropospheric wave field strengths at large distances which take into account the refractive index gradient at the earth's surface, or the surface value of the refractive index in Recommendation No. 312 of this Assembly. Climatic charts of refractive index parameter Δn, were prepared for various regions of the world in CCIR Report No. 147. CCIR Report No. 146 gives the basis for application of radio refractive index parameters to the climatic variability of radio field strengths. CCIR Study Programme No. 138 outlines the areas of research which require further study, and encourages the International Radio Scientific Union to persue these studies. In CCIR Recommendation No. 309, a definition of a basic atmosphere with height is given.

The extensive use of radar for accurately determining the position of aircraft and the advent of artificial earth satellites, depending upon direction finding for accurate position determination have given impetus to the study of the bending of radio waves passing through the atmosphere [Beckman, 1958; Anderson, 1958, 1959; Bean, 1960]. Such bending is critically dependent upon the vertical gradient of the refractive index, particularly in the lowermost regions of the atmosphere [Bean, 1959c, d].

All theories of tropospheric propagation far beyond the radio horizon require a knowledge of the refractive index of the atmosphere in one form or another to explain in detail the distance and frequency dependence of such propagation. The character of the variations of refractive index has been the subject of extensive study using the rapidly responding microwave refractometers. These studies have not only attempted to include the spatial variability of the radio refractive index, but also its time variability [Gossard, 1960]. However, to date, a satisfactory description of the refractive index structure which will adequately satisfy the requirements of the various theoreticians has not as yet been obtained, particularly in regard to the possible differences between the wave number spectra in the space domain and frequency spectra in the time domain as well as the degree of anisotropy involved in these spectra [Norton, 1960]. For example, aircraft refractometer measurements give principally the variations in the horizontal plane and involve a mixture of the space and time spectra. Several excellent review papers concerning the present status of the theory of tropospheric propagation far beyond the horizon [DuCastel, 1958, 1959; Saxton, 1960; Wheelon, 1959], together with reports of the application of refractometry to the understanding of the detailed refractive index structure of the atmosphere [Bauer, 1958; Norton, 1959] have appeared in the recent literature.

Finally it should be noted that a high degree of accuracy of temperature, pressure and water vapor pressure measurements are necessary for precise determinations of the refractive index for certain applications. The following equation relates small changes in ΔN with small changes in temperature, pressure and vapor pressure:

$$\Delta N = a\Delta T + b\Delta e + c\Delta P \tag{2}$$

with temperature expressed in degrees centigrade, and with both pressure and vapor pressure expressed in millibars, typical values of the constants a, b and c, based on the ICAO standard atmosphere and assuming 60% relative humidity, are given in the following table for various altitudes, h

h (kilometers)	N	T(^{o}C.)	p(mb)	e(mb)	a	b	c	d
0	319.	15.0	1013	10.2	-1.27	4.50	0.27	-7.05
1	277.	8.2	893	6.5	-1.09	4.72	0.28	-5.66
3	216.	- 4.5	701	2.6	-0.86	5.17	0.29	-3.79
10	92.	-50.3	262	0.04	-0.50	7.52	0.30	-
20	20.	-56.5	55	0	-0.09	7.96	0.35	-
50	0.2	9.5	0.8	0	-0.0008	4.67	0.27	-

In case measurements of e are made in terms of a difference $\delta = T - T'$ between wet and dry bulb temperatures we may replace the term $b\Delta e$ in (2) by $d\Delta \delta$ and the coefficient d is also given in the above table. At 10 km and above the wet and dry bulb technique of measuring e is impractical.

It is clear that radio wave refractometry has contributed considerably to our knowledge and understanding of tropospheric radio propagation both within [Thompson, 1960] and beyond the radio horizon [Ament, 1959; Katzin, 1960; Moler, 1960], just as optical refractometry is being used to explain the phenomena of early sunrise, twinkling stars and mirages. It is also clear that considerably more effort must be expended in the field of radio refractometry to more completely explain and understand the detailed nature of the refractive index structure of the atmosphere, and its correlation with radio propagation phenomena. The reports of the various national committees of International Scientific Radio Union indicate that well planned scientific programs in this field are to be conducted. It is expected that the research evolving from these programs will be of utmost value to our international family of radio scientists.

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THE NATIONAL BUREAU OF STANDARDS

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