NBS TRANSLATION

6027

CONCERNING A MICROWAVE REFRACTOMETER

(Communication from the Heinrich Hertz Institute of the German Academy of Science at Berlin; Berlin-Adlershof)

by

R. Schunemann and W. Steffen

Translation by

Albrecht P. Barsis and Moody C. Thompson, Jr.

NBS

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS
BOULDER LABORATORIES
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IMPORTANT NOTICE

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Radio waves within the ultra-shortwave range are scattered in the atmosphere just like light waves. There is, however, a substantial difference between the scattering of light and the scattering of these radio waves. In the case of light, the scattering particles are small as compared to the wave length (molecular structure of the air), whereas in the case of radio waves, they are of the same order of magnitude, or larger (fine structure of the atmosphere). Thus the scattering in this case is highly directional (forward scattering). Processes of this kind which are caused by tropospheric inhomogeneities are the cause for the observed field strength values at ultra-short waves within distances ranging from approximately 100 to 600 kilometers. Here the field strength values caused by diffraction over the earth and refraction in the atmosphere drop below any measurable amount. Knowledge of the origin and the properties of tropospheric inhomogeneities can be obtained only by measurements using very sensitive instruments. The precision of the known temperature and humidity measuring devices is not sufficient for investigations of this kind, especially because of their inertia.

It is known that turbulent eddies are caused by varying incident radiation from the sun, by the shape of the earth's surface, by soil properties, and by stratification of air currents having different temperatures and velocities. One also knows that these eddies constantly subdivide until that size is reached where a change to heat is produced by molecular viscosity. Therefore, it may be assumed that eddies of such a dimension which favors scattering processes of ultra-shortwaves are constantly present. However, only the development of microwave refractometers made it possible to measure the intensity as well as the spatial and temporal distribution of such eddies. These refractometers also permitted investigations of the refractive index fluctuations with the necessary degree of accuracy. [1 - 5]

The refractive index of the air is only slightly different from unity. Its value depends principally on the type of molecules, their concentration, and their temperature. It is approximately given by

$$n = 1 + \left[\frac{77.5}{T} + \left(\frac{P + 4860e}{T} \right) \right] \times 10^{-6}$$

where P is the atmospheric pressure in millibars, e is the vapor pressure in millibars, and T is the temperature in degrees Kelvin.

Generally, n varies between 1.000000 and 1.000400. If $(n - 1) \times 10^{6}$ is designated as N, the complete recording of a refractive index profile covers a maximum of 400 N-units. But the instrument also has to produce a measureable deflection for variations as small as 0.1 N-unit.

Principles of the Refractometer Construction

The refractometer utilizes as an indicator the dependence of the resonant frequency of a cavity resonator on the dielectric constant of the medium within. If this dielectric constant is varied--e.g. by an increase in temperature--the frequency change caused thereby is proportional to the variation.

In the method described here a frequency-modulated signal from an oscillator is supplied simultaneously to two cavities. These are acting as circuit elements and do not influence the oscillator frequency as such. If the dielectric constants of the media within the resonators, and with them the resonant frequencies differ, the oscillator resonant peaks will appear at different times. This time difference is a direct measure of the difference in the refractive indices. If one cavity is open to the air (measuring cavity), variations of the refractive index may be recorded if the other cavity (reference cavity) is evacuated and sealed. The variations of interest here- - Δn of about 10^{-6} or 10^{-7} as compared to the mean value- -produce only small differences of the resonant frequencies, and the time difference to be measured is very small. Its determination requires high-Q circuits. This requirement and reasonable dimensions of the cavities necessitate the use of the centimeter-wave region. With 3.2 (cm) wavelength a value of Q of about 15,000 was obtained; this is sufficient for the required accuracy of the measurements.

The device built by us utilizes a type 723 A/B klystron as an oscillator. This is frequency-modulated by a saw-tooth repeller voltage; the amount of frequency shift (and thus the sensitivity of the device) may be varied by a stepped voltage divider which permits repetition of settings. The modulated output is coupled to a rectangular wave guide, and is distributed to the two cavity resonators by a branching-T. Attenuator elements prevent reactions between the various circuits and effects on the oscillator.

Fig. 1 shows the basic circuit.

The branching-T network (Fig. 2) has a discontinuity at the branching point even if the branches are terminated and free of reflections unless special precautions are taken. The resistances of the branches are in series so that the main branch is terminated by twice the resistance value. Such a mismatch is avoided by a tuning screw ahead of the branching point. According to its penetration the tuning screw acts inductively or capacitively and is adjusted for minimum reflection in the main branch. This is measured by a directional coupler ahead of the branching point. The deviation of the electrical field lines at the branching point is improved by a wedge-shaped step (threshold).

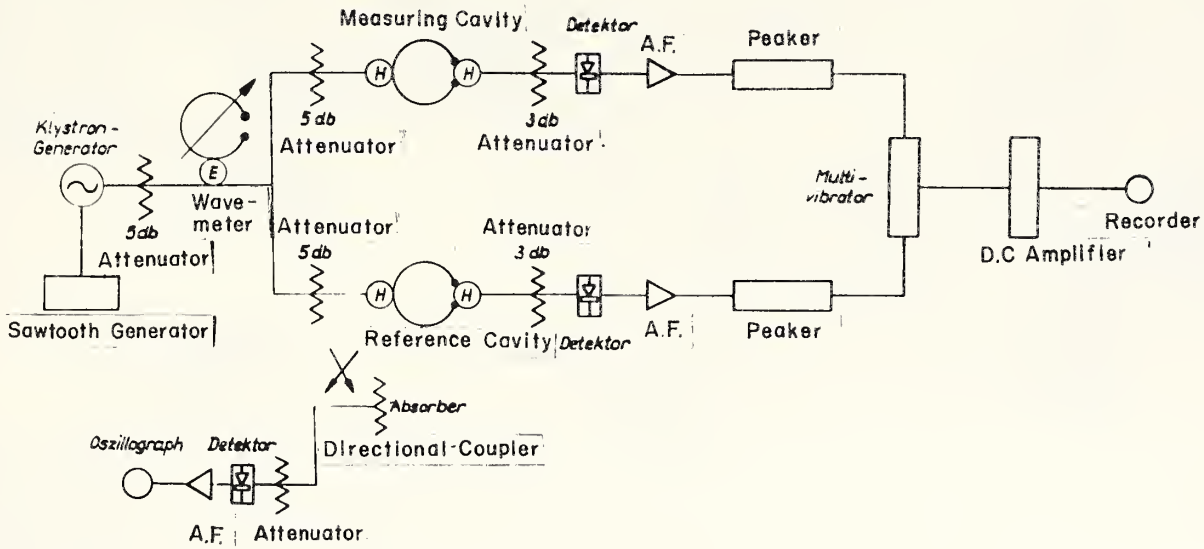
When the klystron frequency is swept, pulses appear in the output of both resonators. These are amplified after having been detected by type OA516 silicon detectors, and produce spikes in blocking oscillator current. Any first spike actuates a multivibrator with the second spike blocking it. Thereby the multivibrator output produces a new pulse, the width of which constitutes a measure of the frequency shift of the measuring cavity compared to the reference cavity. This pulse is finally rectified by a diode; for a fixed reference level the resulting direct current is proportional to the pulse width, and may be utilized for recording.

In order to minimize A.C. hum, the input tube of the audio frequency amplifier has a D.C. filament supply, as its cathode would otherwise be an appreciable source of hum. Current flow via the wave guides between the klystron and the detector mount is prevented by insulated wave guide connectors.

Fig. 3 shows the schematic diagram of the phase meter.

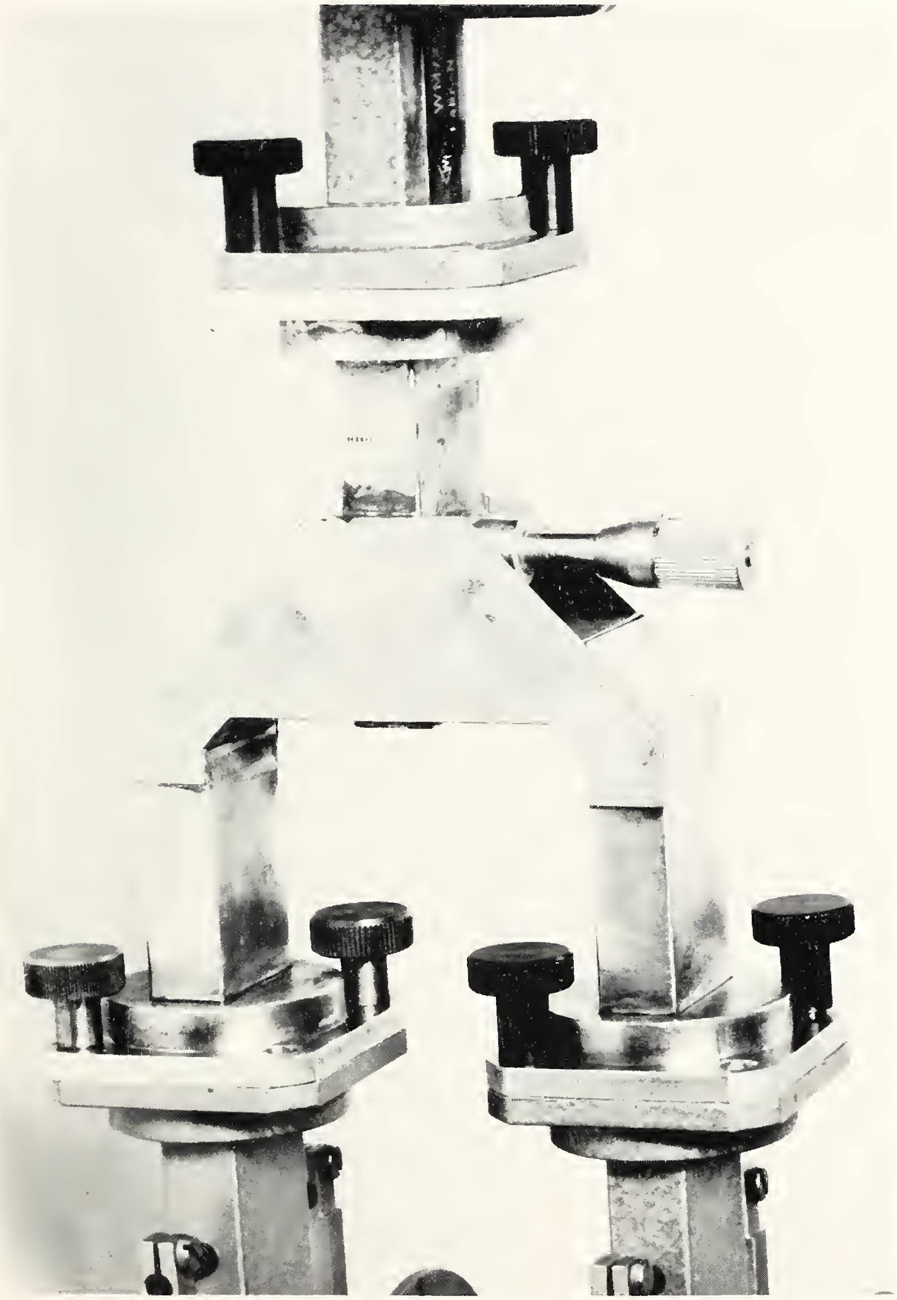
The Cavity Resonator

The Q of a cavity resonator depends on the choice of the mode of oscillations, the condition of the surface, and on the ratio of diameter to length. In order to obtain high values, undesired modes must be suppressed and coupling has to be loose. For the device described here the coupling holes have a diameter of 4 millimeters, and the wall thickness is 0.5 millimeters. The walls are silver-plated and highly polished. Indentations behind the end plates which are connected with

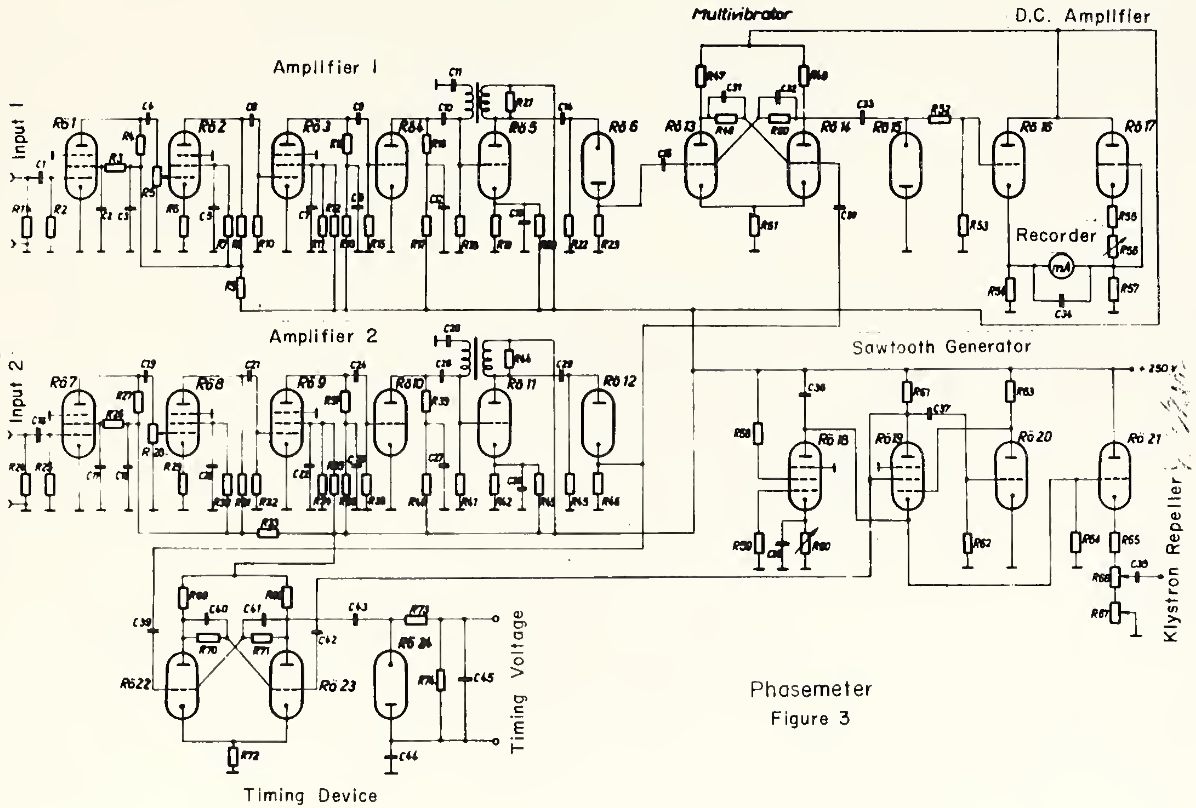


Basic Circuit of the Refractometer

Figure I



Branch - T
Figure 2



Phasemeter
Figure 3

the active portion of the cavity by small slots (see Fig. 8) cause undesired oscillation modes to be shifted in frequency such that the desired mode is not affected.

The type H_{011}-wave is utilized. For this mode maximum Q for the cavity is gained by unity ratio of diameter d and length ℓ.

The limiting wave length λ_k and the wave guide wave length λ_H are calculated from:

$$\lambda_k = 0.82\ d$$

and

$$\lambda_H = \frac{\lambda_0}{\sqrt{1 - (\lambda_0/\lambda k)^2}}$$

(λ_0 is the free space wave length)

For H_{011} resonance $\lambda_H = 2\ell$, one has

$$2\ell = \frac{\lambda_0}{\sqrt{1 - (\lambda_0/\lambda k)^2}}$$

and thus: $\ell = d = 1.318\ \lambda_0 = 4.22$ centimeters for $\lambda_0 = 3.2$ centimeters. Depth of penetration into the metal is very small because of the skin-effect. For silver it is given by:

$$s = 6.4 \frac{1}{\sqrt{\text{feps}}}$$

resulting in 0.66 microns for f = 9400 MC.

If the circuits are not loaded the value of Q is found to be 30,900 for this case from:

$$Q = 0.61\ \frac{\lambda_0}{s}\ \frac{[\ 1 + 0.17\ (d/\ell)^2\ ]\ \ 3/2}{[\ 1 + 0.17\ (d/\ell)^3\ ]}$$

In practice, values between about 15,000 and 20,000 are obtained. The desired high sensitivity requires that the cavity dimensions are affected exactly alike by temperature variations. As the measuring cavity is permeated by the medium, and the reference cavity is sealed, this requirement is difficult to fulfill, and without special precautions one has to take measurement errors into consideration.

The first laboratory model had both cavities mounted into one brass block (see Fig. 4); it was assumed that by good heat conduction adequate heat exchange occurred.

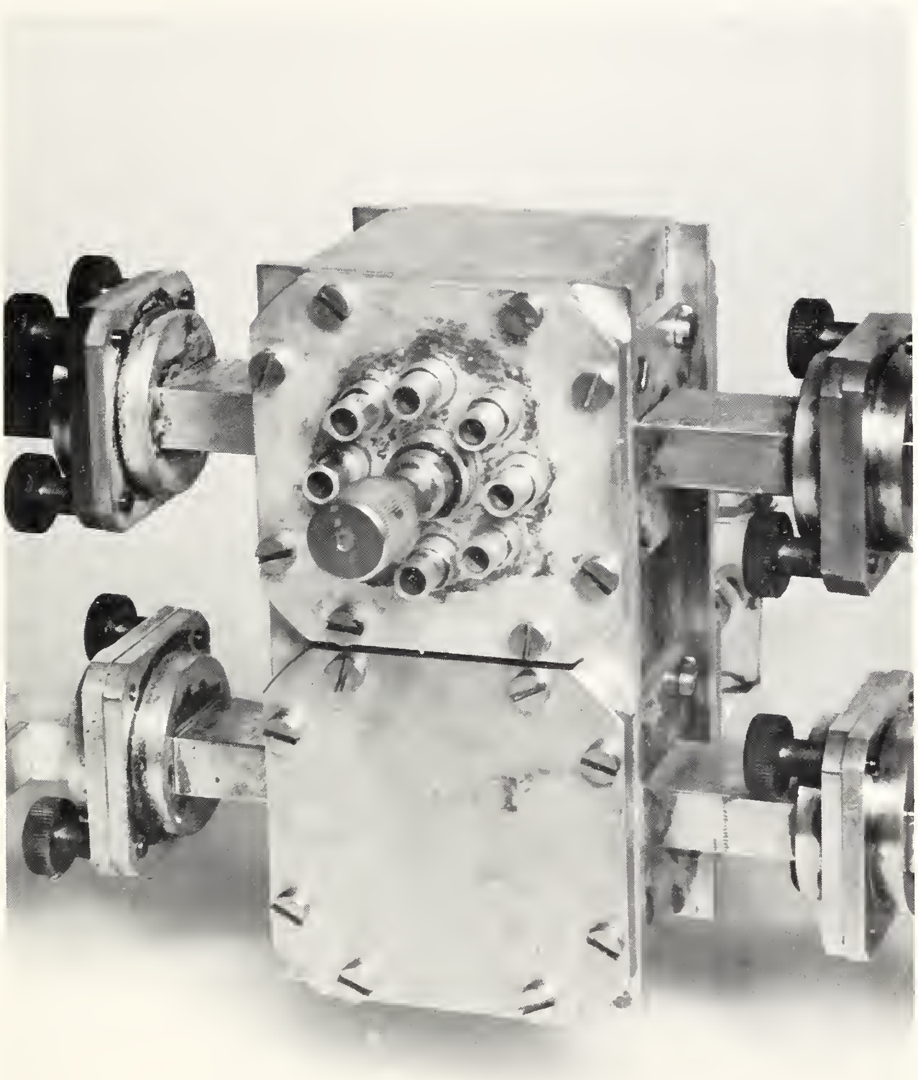
However, tests showed that this arrangement is insufficient to prevent errors. A 10 degree (centigrade) change in the room temperature caused a 25 kc/s difference of the resonance frequencies; this was caused principally by non-uniform expansion of the cavities. This frequency difference simulated a 2.7 N-unit variation in the refractive index. Therefore, further development included the use of Invar in the fabrication of the resonators; steel end plates will approximately compensate for the small thermal expansion of Invar.

Control Devices

The klystron repeller voltage has to be adjusted so that a maximum amount of power is delivered. In the vicinity of this maximum the modulation frequency varies approximately as a linear function of time by use of a saw-tooth shaped repeller voltage.

Out of the various regions of the klystron oscillations that one has to be chosen which delivers the greatest amount of power for the smallest change in frequency per volt of repeller voltage (Mc/V). The resonant frequencies of the cavities should be within the immediate vicinity of this maximum.

Such an adjustment is made possible by observing that portion of the wave which is decoupled and reflected by the directional coupler



First Version of the Mounted Cavity Resonator
Figure 4

in front of the reference cavity; this portion is recorded by an oscillograph after detection and amplification. This also furnishes continuous control of the operation. Necessary calibrations may be easily accomplished by a wave meter situated between the klystron and the branching-T.

Calibration

The measuring range is first extended by a factor of 10 with reference to the most sensitive adjustment by use of the stepped voltage divider of the saw-tooth generator. The wave meter causes a small saddle in the klystron curve as it draws some power; this is recorded on the control oscillograph. One places the saddle at the beginning and at the end of the curve and reads the corresponding frequency shift on the wave meter. As the potentiometer adjustment is reproducible, one also knows the frequency shift for the most sensitive range of the device. For this position it is now investigated what change in the cavity resonant frequency corresponds to this frequency shift. This is done at the resonator by a small tuning piston with micrometer graduation. As the cavity draws power at resonance, another saddle appears on the control curve. If one now changes the resonant frequency by the tuning piston, the oscillograph saddle shifts, together with the working point on the saw-tooth characteristics. The change in the reflected pulse which appears as well, is not noticeable because of the short return-time of the saw-tooth wave; these pulses may be used as marker points for the beginning and the end of a saw-tooth. If now the resonance saddle is adjusted to these points successively, the deflection of the recorder at the output furnishes the desired sensitivity value in milliamps per megacycle.

At the most sensitive adjustment 50 kc/s was measured for full deflection of a 1 mA recorder. From the relation:

$$\Delta f / f_0 = \Delta n;$$

one therefore calculates $\Delta n = 8 \times 10^{-8} = 0.08$N-units for 1 millimeter deflection.

The calibration was checked by filling the test cavity with a pure gas having a known dielectric constant at various pressures.

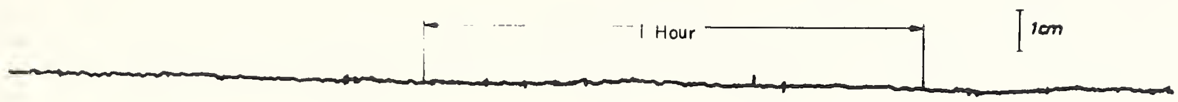
Stabilization and Stability of the Device

In order to obtain consistent readings, the electrical stability of the apparatus has to be especially considered. The power supplies are regulated electronically; the klystron and the other circuits have separate power supplies. Uncontrolled variations in the working point of the saw-tooth characteristics may simulate refractive index variations. Such errors are prevented by automatic readjustment of the repeller voltage. Pulses from the return of the saw-tooth and spikes from the reference cavity regulate another multivibrator; this produces an irregular square wave which effects the readjustment.

In considering instability of the device, long-term and short-term variations have to be distinguished. If operating conditions are sufficiently stable, long-term variations may be traced to different effects of meteorological parameters on the cavity dimensions. Here humidity has no influence, and pressure effects may be eliminated by rigid construction. The only remaining source of error is thermal expansion as an effect of temperature variation. The use of Invar will permit a reduction of the variations to the necessary low level.

Short-term variations are caused by the electrical instability of the apparatus. Fig. 5 shows recordings taken with closed cavities at maximum sensitivity. The first recording, a portion of which is shown in the upper drawing, was taken using a one-second time constant. The trace was completely smooth over several hours time. For a recording with a 30 millisecond time constant (lower drawing) the

Refractometer Recording
With Closed Cavity, 1 Sec. Time Constant at 120 mm/hour,
Sensitivity 20 ma/mc = 0.08 N/mm



Refractometer Recording
With Closed Cavities Without Time Constant (30 ms. According
to Text-Trans. Note), 120 mm/hour, Sensitivity 20 ma/mc = 0.08 N/mm

Figure 5

deviations were below one millimeter. In both cases, naturally, inertia and friction of the recording pen contribute (to the time constant).

Measurement Errors Originating With Air Passage

The quantities ΔT and Δe of a volume of air which flows through the cavity influence the state of the cavity, but are also affected themselves by the state of the container. The air temperature within the cavity tends toward equalization with the temperature of the walls. In laboratory experiments Birnbaum and Bussey (3) found measurement errors in ΔT up to 30% with a 4.5 meters/second speed of the airflow. This error is reduced to 15% if the speed is increased to 13 meters/second. The effect on the value of Δn, however, was negligible if Δe constituted the principal source of variations in n.

It was also observed that with Invar cavities a refractive index change of 2 to 3 N-units is simulated if the temperature of one cavity is increased by 1 degree centigrade. The thermal time constant in this case was four minutes for an airstream velocity of 4.5 meters/second. At this velocity 1 degree centigrade was the maximum possible difference between cavity material and air temperature; at 1.3 meters/second this difference was increased to 2 degrees centigrade.

For steady air velocity and rapid refractive index fluctuations, no measurement error in Δn was found. For usual meteorological conditions Birnbaum observed recording shifts of not more than 0.2 N-units over several minutes time. Our own investigations using steel-compensated Invar are in progress.

No effect was observed on the water vapor content of the medium as a result of water vapor absorption at the walls. However, for condensation with 0.03 millimeter thickness of the water layer variations up to 1 N-unit were measured.

Construction of the Device

Fig. 6 shows the test rack. The two lower chassis contain power supplies; above them is the phase meter and on top is the control panel. The reference cavity is mounted directly on the front panel of the phase meter; it may be tuned by means of the graduated knob of the micrometer located on its base. The connection to the wave guide leading to the measuring cavity is located on the left side of the rack.

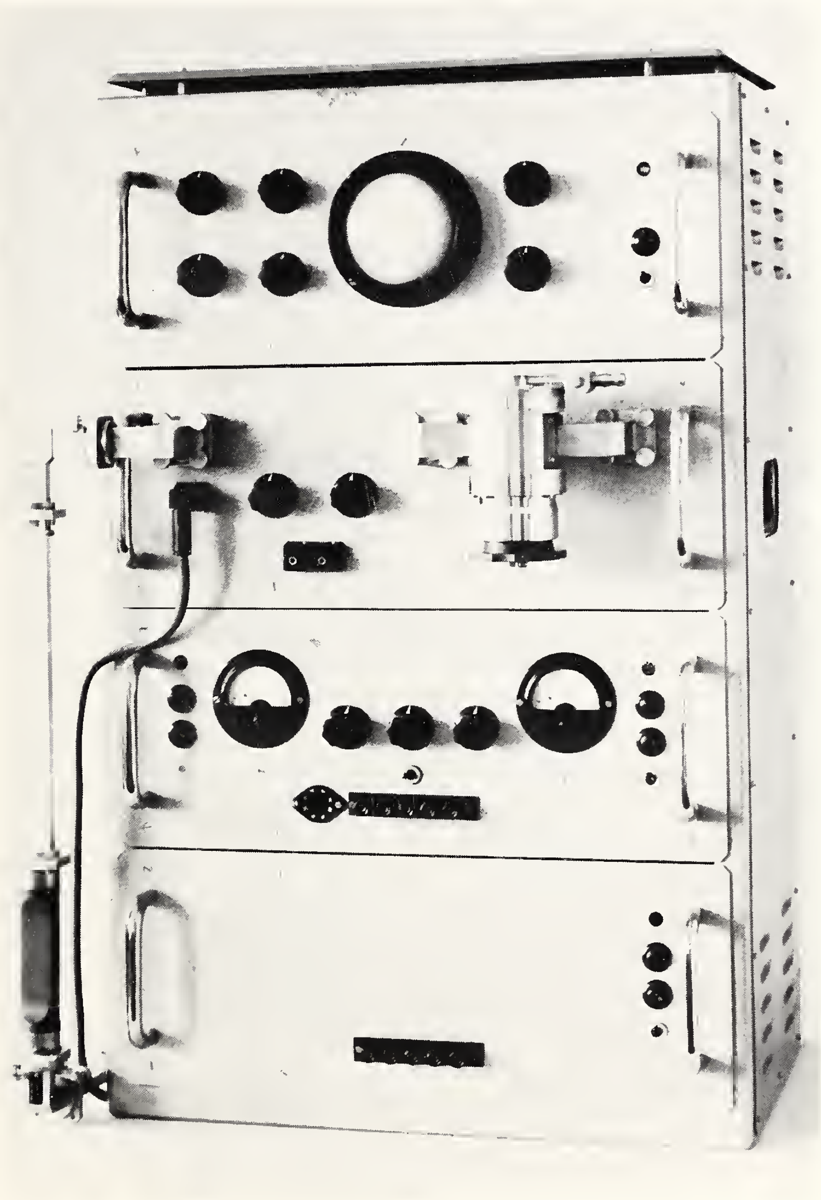
Figs. 7 and 8 show the construction of the cavity resonators. The reference cavity has the tuning piston attached to metal bellows which keep the cavity air-tight; the piston penetrates the cavity through the bottom plate. A compression spring is used to compensate for the exterior air pressure and thus, tuning is facilitated.

In order to improve the passage of the airstream through the measuring cavity in case larger openings are used, the diameter of the steel end plates is reduced as much as permissible for the required Q.

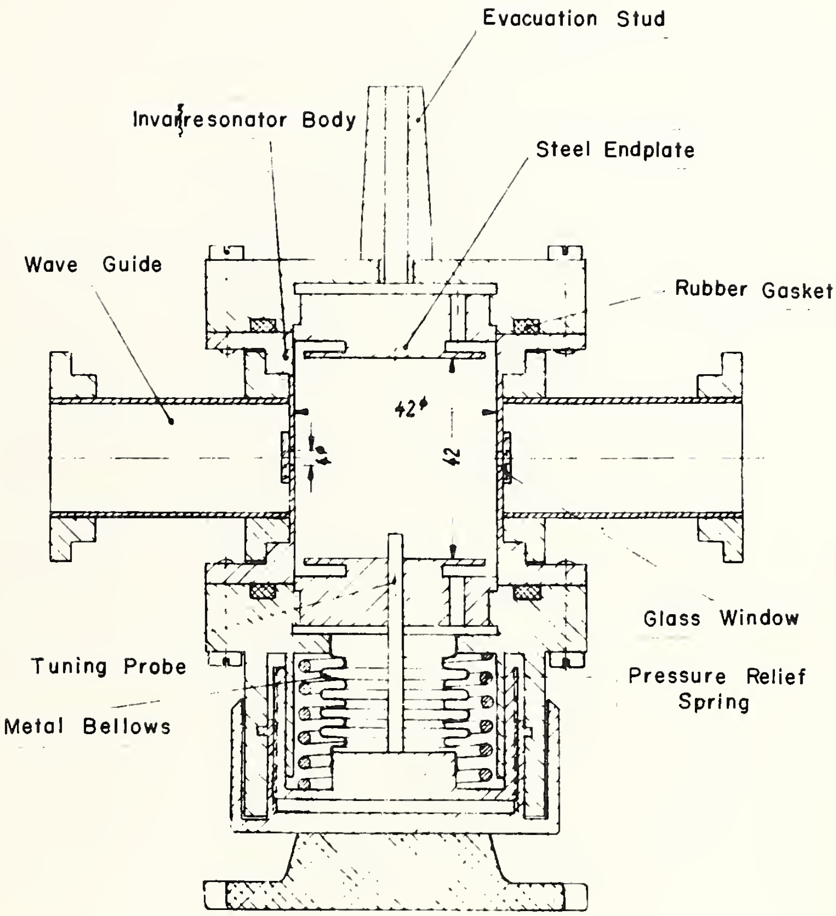
Initial Test Result

Initial recordings were performed on the roof of the institute building. The direct effect of the sun on the cavity was prevented by a large sheet metal cover which was open in the direction of air passage. A small fan provided a steady air stream.

The record shown on Fig. 9 was obtained on January 10, 1958, with partially clear and partially cloudy sky. It is seen that clouds passing in front of the sun are noticeable at once by a change in the refractivity of the order of magnitude 1×10^{-6}, or 1 N-unit. The small fluctuations which are always apparent amount to about 2×10^{-7} to



Test Rack
Figure 6



Reference Cavity

Figure 7

Heinrich-Hertz-Institut
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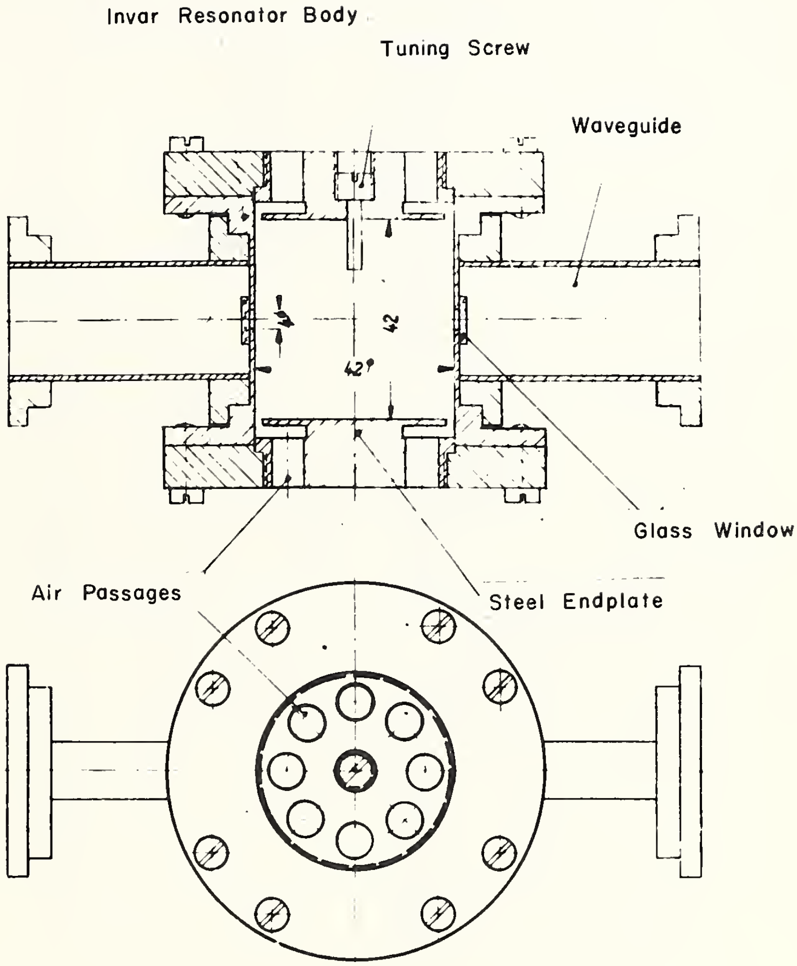

Measuring Cavity
Figure 8

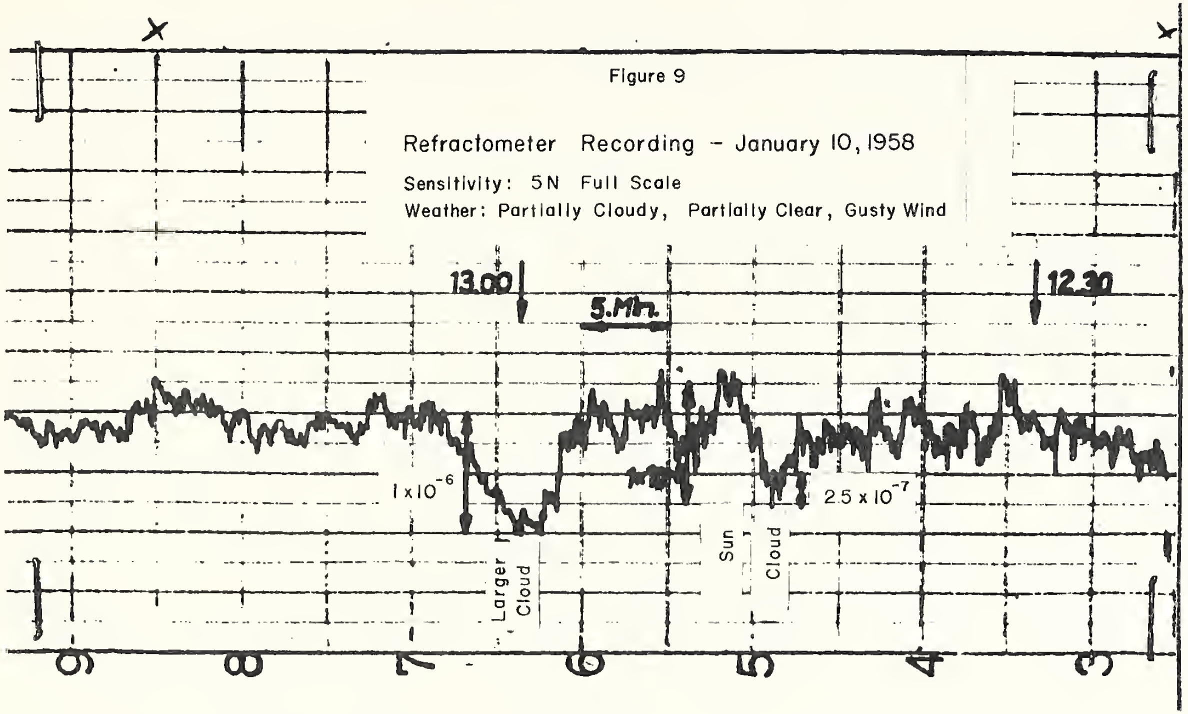

Figure 9

Refractometer Recording - January 10, 1958

Sensitivity: 5N Full Scale

Weather: Partially Cloudy, Partially Clear, Gusty Wind

3×10^{-7}, or 0.2 to 0.3 N-units; a single oscillation lasted for 15 to 20 seconds. For an air stream velocity of 2 to 3 meters per second, the horizontal dimension (of the blob) amounts to 30 - 60 meters, and the gradient to values from 0.3×10^{-8} per meter to 1×10^{-8} per meter.

The effect of rain is shown on Fig. 10 for the same recording day. After a relatively smooth behavior the beginning rain produced at once larger variations on the order of 0.4 to 0.8 N-units. The time period was approximately the same.

The next recording of February 13, 1958, shows a much more perturbed character (Fig. 11). This day fell within the period of an extreme warm front passage with more than 10 degrees centigrade temperature increase. The small variations here were as large as 1.4 N-units. Besides that,larger fluctuations were observed extending over 12 to 18 minute periods, and having amplitudes up to 5 N-units. For 2 to 3 meters per second air stream speed, a long dimension of 1.5 to 3 kilometers is obtained. In accordance with experience one may assume that such atmospheric formations have even stronger refractive index variations with height, as the vertical changes in gradient are generally larger than the horizontal ones. In the course of diversity measurement over a 360 kilometer path, we have frequently encountered scattering formations which had comparable dimensions and were moving with the wind at wind velocities.

A very substantial change amounting to 6 N-units over a period of 45 minutes was noticed somewhat later on the same day (see Fig. 12). Although the mean gradient was only 1×10^{-9} per meter, individual small variations reached 2 N-units with a gradient between 3 and 7×10^{-8} per meter.

Recordings for the previous day were relatively uniform, as seen by Fig. 13. However, even then the rapid fluctuations showed amplitudes up to 1 N-unit.

The unstable behavior of the refractive index was observed yet on February 14, 1958. Fig. 14 shows one of the fluctuations with 3.6 N-units amplitude observed on that day.

During those days we also observed a marked increase in received signal strength over a test path using transmissions at a wave length of 10 centimeters. Besides that, deviations of the field strength behavior as a function of the antenna azimuth were noted which were different from the usual values recorded over longer periods of time.

Currently test series are being conducted near the ground, at various levels on a 80-meter tower, and also in an aircraft.

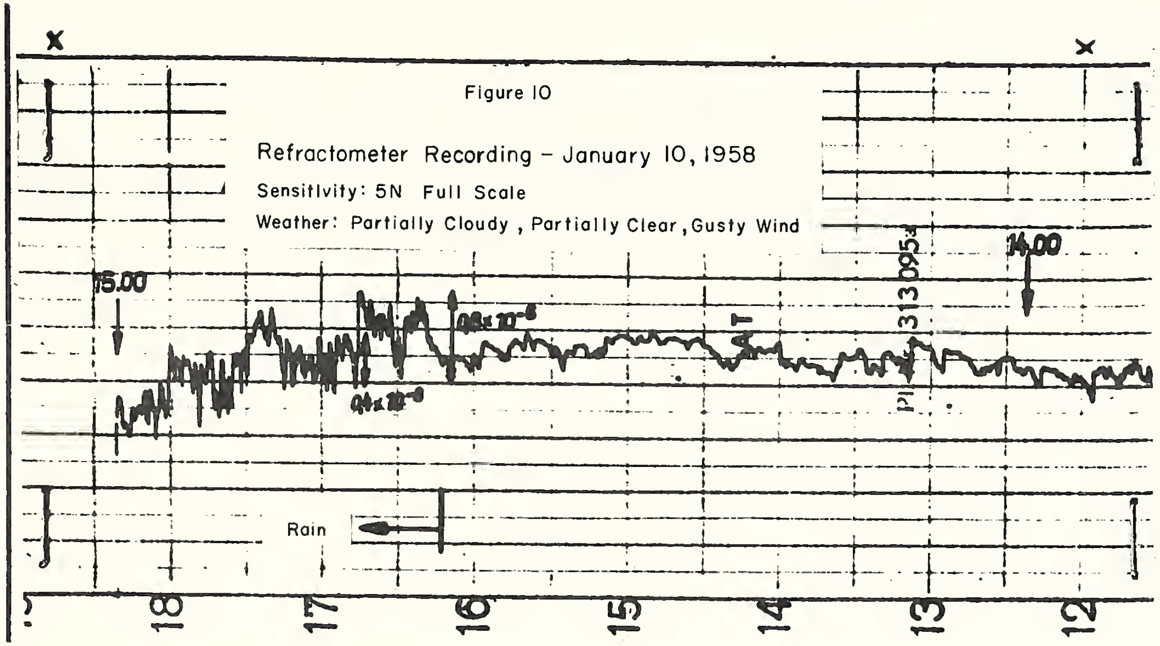

Figure 10

Refractometer Recording - January 10, 1958

Sensitivity: 5N Full Scale

Weather: Partially Cloudy, Partially Clear, Gusty Wind

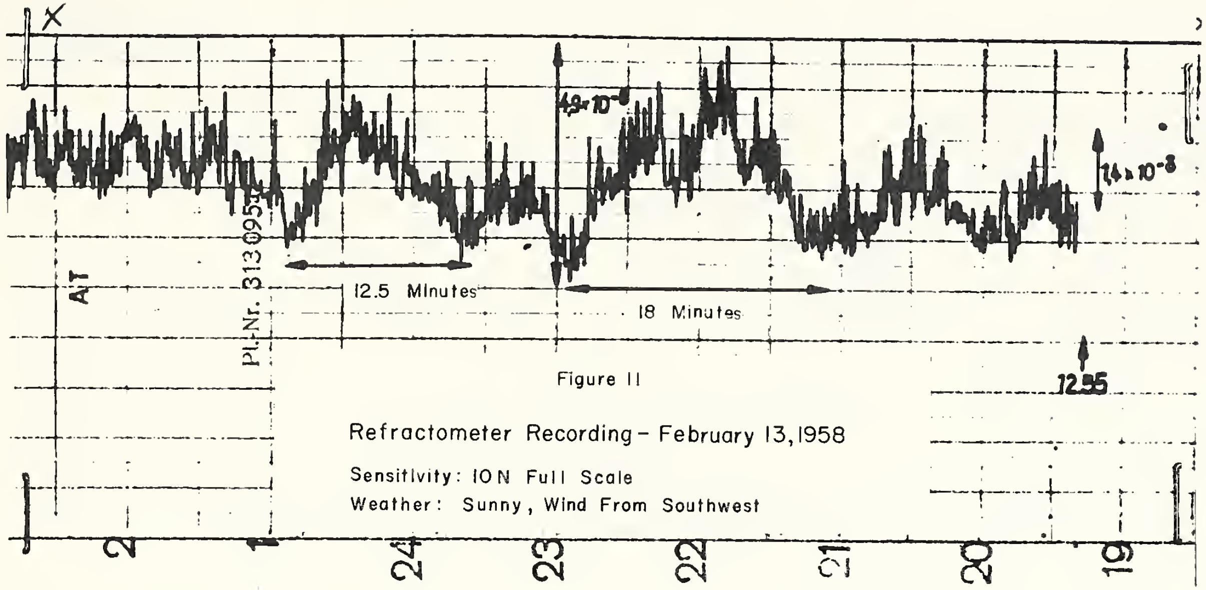

Figure 11

Refractometer Recording - February 13, 1958

Sensitivity: 10 N Full Scale

Weather: Sunny, Wind From Southwest

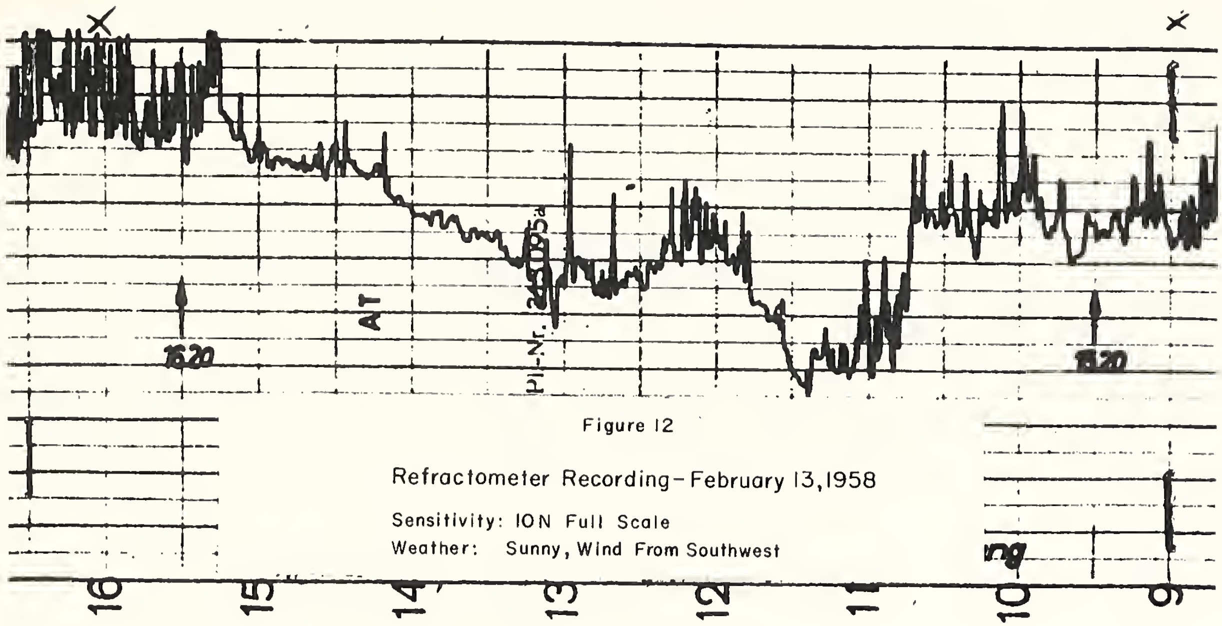

Figure 12

Refractometer Recording - February 13, 1958

Sensitivity: 10N Full Scale

Weather: Sunny, Wind From Southwest

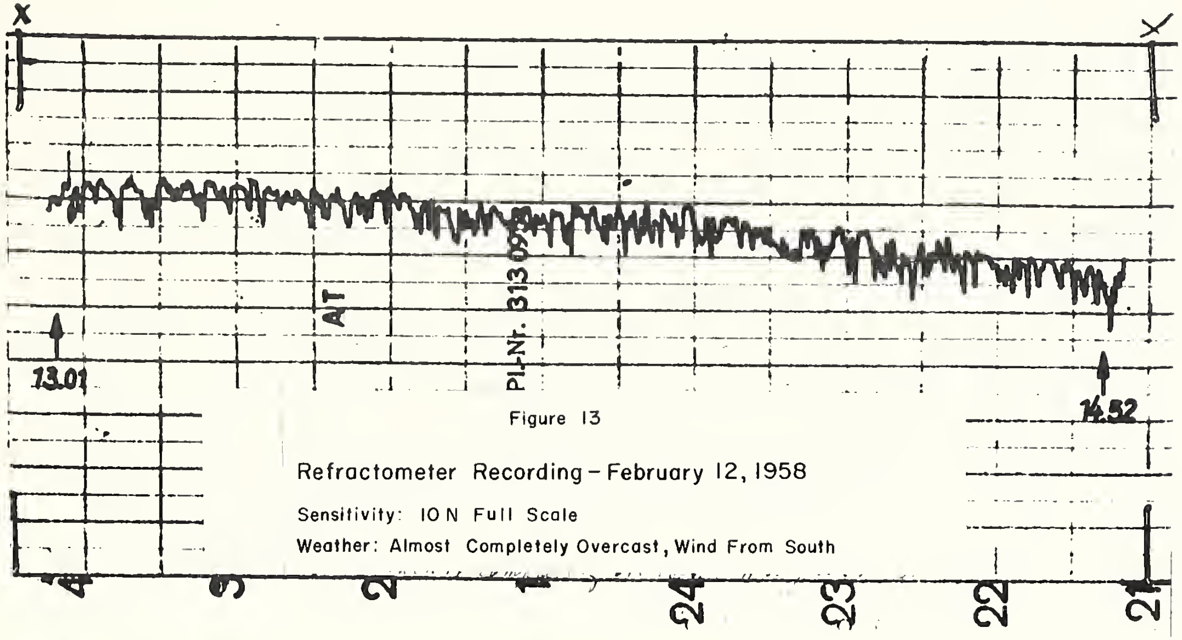

Figure 13

Refractometer Recording – February 12, 1958

Sensitivity: 10 N Full Scale

Weather: Almost Completely Overcast, Wind From South

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