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Response of NBS Microwave Refractometer Cavities to Atmospheric Variations[1]

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The sampling cavity of the NBS refractometers has been evaluated in a wind tunnel, a water flow tunnel, and in the free atmosphere. The cavity is slightly velocity-sensitive. It is also aspect-sensitive, an error being introduced when the wind is oblique to the axis of the cavity affecting the level of the spectrum. The characteristic flushing length of the cavity in normal operation is estimated as 0.75 meters when the wind is into the cavity and considerably more when the wind is at an oblique angle. A modified cavity has been developed which appears to substantially improve the response of the refractometer.

1. Introduction

Microwave refractometers [Crain, 1950; Birnbaum, 1950; Vetter and Thompson, 1962] have been used extensively to measure directly the radio refractive index of air [Bean, 1962]. Although these instruments have been in use for many years, little information is available as to their limitations as a probe of atmospheric variations. Recent tests on the National Bureau of Standards refractometers indicate that under some conditions these limitations are not negligible.

2. Refractometer Sampling Cavity

In both the NBS absolute refractometer [Vetter and Thompson, 1962] and the NBS relative refractometer [Birnbaum, 1950] the sampling cavity, placed in the free atmosphere, is a significant source of inaccuracy of the instrument. The reference cavity is a sealed cavity normally protected from the changing conditions of the free atmosphere and can be considered to produce negligible effects on the accuracy of the short-term (10-min samples) measurement of air refractivity. The desired measurement by the sampling cavity is the time variations of the refractive index of the air at a point, but these variations are modified by changes in cavity temperature, wind speed and direction, as well as by limitations due to the finite size of the cavity.

2.1. Temperature Coefficient of the Sampling Cavity

Cavities are made of invar, which has a linear temperature coefficient of approximately one part per million per degree centigrade. This is equivalent to one *N* unit per degree centigrade. Temperature compensation, which reduces this to one or two tenths of an *N* unit per degree centigrade, is easily achieved. Compensation for as low as 0.03 *N* units per degree centigrade has been achieved with some difficulty [Crain and Williams, 1957; Vetter and Thompson, 1962]. It has been found that the statically determined temperature coefficient cannot be used to yield a correction for dynamic temperature variations, but it does permit a fair estimate of the error.

2.2. Aspect Sensitivity of the Sampling Cavity

The NBS sampling cavity is a cylindrical barrel with ventilated end plates. When used on an aircraft the air sample enters along the axis of the barrel. In a typical ground-based location the air sample may arrive at any angle relative to the cavity axis. It would be impractical in many cases to vary the aspect of the cavity to enable it to face into the wind. To determine any effect caused by the aspect of the cavity relative to the direction of the mean wind, multiple cavities were mounted at fixed angles relative to the air flow. Each of the following tests was conducted with an array of cavities, and aspect sensitivity was considered as a parameter in each test.

2.3. Velocity Sensitivity of the Sampling Cavity

The pressure within a sampling cavity placed in the airstream varies with air speed. To determine this pressure effect a plastic duplicate of the NBS sampling cavity was tested in a wind tunnel. The difference in pressure between inside the cavity and that of the undisturbed airstream outside the cavity were measured with a differential manometer over a velocity range from 0.5 to 30.5 meters per second (m/s). [Thermocouples used to measure differential temperature over a velocity range of 0.5 to 16 m/s indicated variations of no more than several hundredths of a degree. Thus, the temperature changes would not be expected to affect the results.]

These differential measurements were made for various aspect angles relative to the air flow. A

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pressure coefficient (similar to the drag coefficient [Schlichting, 1960, p. 15]) can be defined as

$$C_p = \frac{\Delta p}{\frac{1}{2}\rho u^2}, \tag{1}$$

where Δp is the difference between the pressure inside the cavity and that in the unobstructed tunnel, and $\frac{1}{2}\rho\, u^2$ is the pressure reading measured between two ports of a pitot static tube. The results are shown in figure 1. At velocities less than 2.2 m/s there is a large variation in C_p as a function of both velocity and aspect, although the absolute pressure changes are small. Above 4.5 m/s the distribution attains a shape independent of velocity, indicating fully developed turbulence. Because of the complex shape of the cavity and its end plates, it is not possible to define a critical Reynolds number. These results indicate that laminar flow becomes unstable flow at very low velocities and that the flow becomes fully turbulent at velocities between 2.2 and 4.5 m/s. The error in the mean refractivity caused by the velocity of the airstream as a function of aspect angle is shown in figure 2. The error was calculated from the measured pressure drop in the cavity. The 45° aspect offers the minimum induced error in refractivity because of the pressure drop. Apparently the location of this mimimum is due to the shape of the temperature-compensating disks within the cavity.

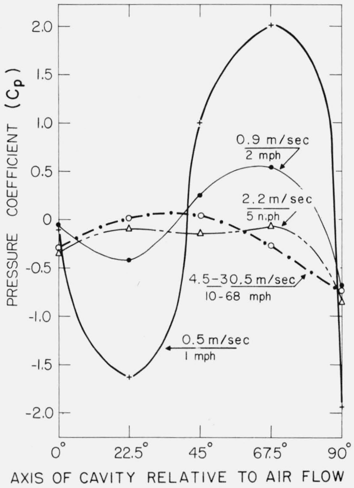

FIGURE 1. *Pressure coefficient of NBS microwave sampling cavity as a function of aspect angle for varying wind speed.*

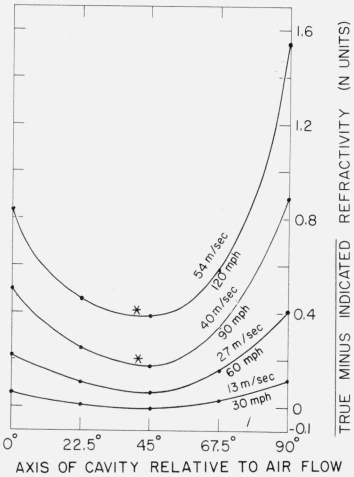

FIGURE 2. *Calculated error in refractivity measurements from differential pressure measurements.*

* The curves for 40.2 and 53.6 m/s are extrapolated from data.

2.4. Spatial Resolution of the Sampling Cavity

Because of the external electric field, the cavity measures a weighted average of the variations of a volume of air somewhat larger than its dimensions. The aerodynamic characteristics of the cavity, determined largely by the end plate and compensating disks, limit the ability of the refractometer to resolve the difference between the refractive index of closely spaced air parcels passing through the cavity. When the flow through the cavity is turbulent there is increased mixing, and a particular sample tends to remain in the cavity longer than it would if the flow were laminar at the same wind velocity. This is equivalent to filtering out the fast fluctuations of an air sample.

In a slowly moving atmosphere, which is homogeneous, at least over the face of the end plate of the cavity, an analysis by Hartman [1959] indicates that the cavity should resolve individual air samples separated by a distance comparable to the dimensions of the cavity. It would appear that at velocities where the flow through the cavity is not laminar (at least, i.e., for velocities in excess of 4.5 m/s), further filtering of the refractivity variations should occur, and the practical limit of spatial resolution is further restricted. An experimental estimate of the filtering action of the NBS cavity was obtained by using a transparent plastic duplicate of the sampling cavity immersed in a water flow tunnel. The principle of similarity states that for geometrically similar bodies the flow of different fluids displays geometrically similar stream lines for the same Reynolds number. Hence the results of the water tunnel experiment should be applicable to air flow if the Reynolds number is the same in both fluids. Blobs of colored dye were injected upstream from the cavity and permitted to flow through the cavity. Colored motion pictures were taken of the flow around and through the cavity for the same aspect angles mentioned above. The time required for the dye to flush completely from inside the cavity for several flow velocities was obtained from *visual inspection* of the motion pictures.

From the measured flushing time and the flow tunnel velocity, the estimated minimum spatial resolution of the cavity oriented into the air flow was found to be approximately 0.75 meters under turbulent conditions, whereas the cavity oriented 90° to the air flow indicated a minimum resolution of 1.75 meters (see fig. 3).

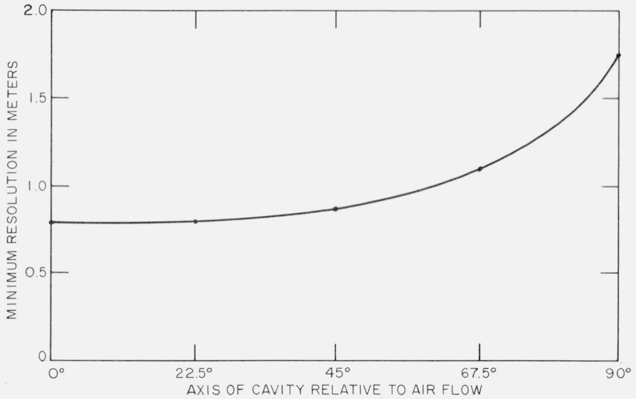

FIGURE 3. *Estimated minimum spatial resolution of the NBS microwave refractometer cavity (from water flow tunnel observations).*

It should be noted that these values were found under static conditions where the direction of the air flow was constant. Attempts to improve the spatial resolution of the sampling cavities by forced ventilation techniques are described in the literature [Crain and Gerhardt, 1950].

2.5. Spectral Characteristics of the Sampling Cavity

Tests were conducted in a wind tunnel and in the free atmosphere. Spectral analysis was performed on the refractivity obtained from three sampling cavities oriented at 0°, 45°, and 90° to the wind. In a wind tunnel having a 6-ft-sq cross section, the sampling cavity array was placed 2 ft down from the top and 2 ft from the side walls. To create the turbulent atmosphere, louvers were placed in the wind tunnel. A water jet pulsed water vapor into the tunnel to enhance the variability of the refractive index. The wind tunnel tests indicated that the sampling cavity whose axis was 90° to the air flow lowered the spectral density of all frequency components which were measured (0.2 to 10 c/s). In the free atmosphere at 15 meters above ground a different effect was noted. Of the many 10-min samples analyzed, very little difference was noted in the spectra between the 0° and 45° cavities; however, the cavity oriented 90° to the prevailing wind indicated a significantly higher spectral density at all frequencies. Repeated samples indicated similar results.

As a result of these tests a modified cavity (fig. 4) was developed with slots cut into the sides of the barrel with essentially no change in Q ($Q_L = 11{,}500$) or in transmission characteristics. The $1 \times 1/4$ in. slots were located in a region of essentially zero electric field intensity so as not to destroy the circumferential current flow caused by the TE_{01} mode. Negligible radiation from the slots or decrease in the cavity Q is obtained if the slot width does not exceed $5/16$ in. The modified cavity [2] was mounted with its axis parallel to the axis of one conventional cavity and normal to the axis of a second conventional cavity (fig. 5). Samples were procured with the mean wind normal to the first conventional cavity, and also normal to the second conventional cavity. Figures 6 and 7 illustrate the effect of wind direction on the cavity spectral response. Run 1 and run 2 were taken from data gathered in a single 30-min period when the wind fortuitously changed abruptly by 90°. The spectra of the two conventional cavities exactly reversed when the wind direction changed by 90°, whereas the spectrum of the modified cavity remained fixed (the apparent lower level in the spectrum of the modified cavity is due to a calibration bias). The spectrum of the cavity 90° to the wind was higher in both cases. Runs 3 and 4 were taken after recalibration of the equipment. The spectrum of the modified cavity was essentially identical to that of the conventional cavity that faced into the wind, even though the two cavities were orthogonally placed.

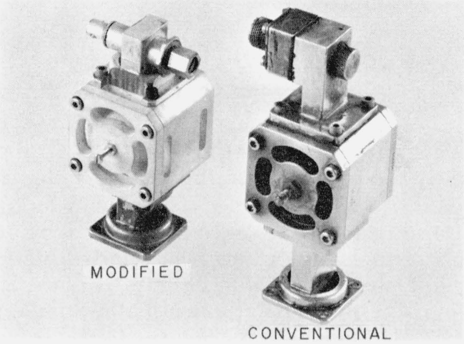

FIGURE 4. *NBS microwave sampling cavities.*

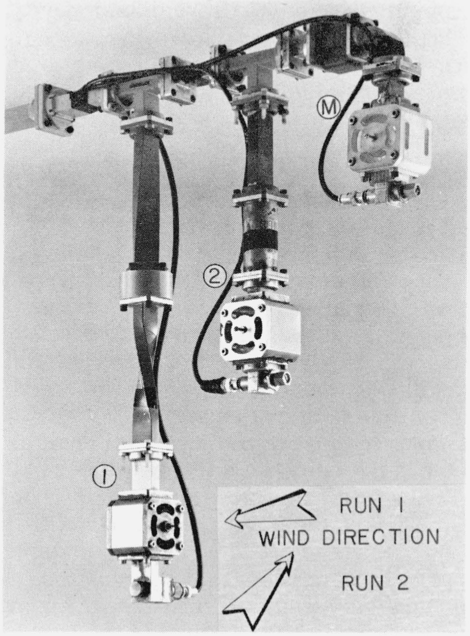

FIGURE 5. *Experimental comparison of NBS microwave cavities.*

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[2] Other approaches to modifying refractometer sampling cavities [Adey, 1957; Thorn, 1958; Thompson et al., 1959; Gilmer and Thorn, 1962] have dealt primarily with variations in the structure of the cavity end plates.

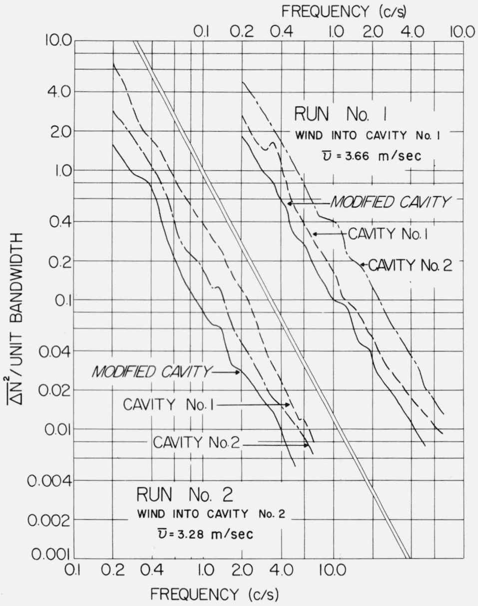

FIGURE 6. *Comparison of spectra of the NBS sampling cavities for winds parallel to and normal to the axis of the cavities.*

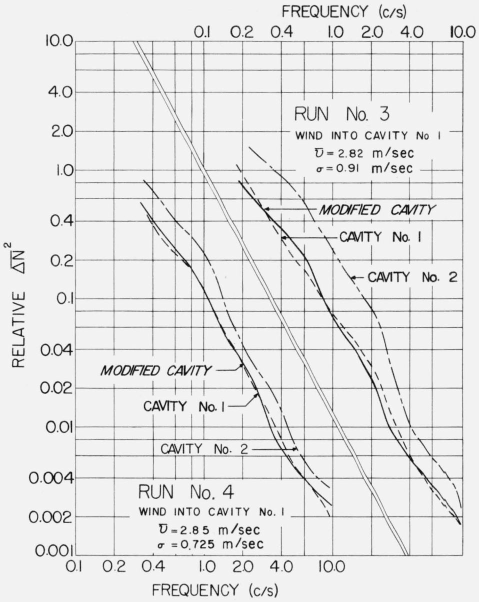

FIGURE 7. *Comparison of spectra of the NBS sampling cavities for winds parallel to and normal to the axis of the cavities.*

A possible explanation of the higher spectral density exhibited by the cavity 90° to the wind may be found in the variability in the wind direction which might "pump" the cavity at extremely oblique angles. (The wind tunnel data where the wind direction was constant did not exhibit this effect.) Figure 8 shows the comparison between the wind direction and the response of the cavities. Variations in the refractivity of the cavity 90° to the wind appears well correlated with the wind direction; there does not appear to be an equivalent correlation between the wind direction and the modified and 0° conventional cavity. The positive correlation between the cavity 90° to the wind and the wind direction seems to indicate an asymetrical cavity effect. It would be expected that the cavity would respond in the same manner whether the wind veered to the right or the left. The results indicate otherwise. There is an indication of such asymmetry in figure 1, but unfortunately no measurements were taken beyond 90° to confirm this.

Of the many samples analyzed, a single exception was noted, i.e., where the level of the spectra for the cavity 90° to the wind was lower than the 0° orientation. This sample was taken at a higher wind velocity and apparently was reproducing the wind tunnel data. It was significant, however, that the modified cavity continued to match the 0° cavity.

Tests similar to those reported above [Thompson and Grant, 1965] have been conducted 1 meter above the ground. They indicated that under the conditions of their experiment the cavity orientation with respect to the wind does not produce any significant effect.

Tests are to be conducted to determine the improvements of spatial resolution and aspect sensitivity of the modified cavity with respect to the conventional cavities.

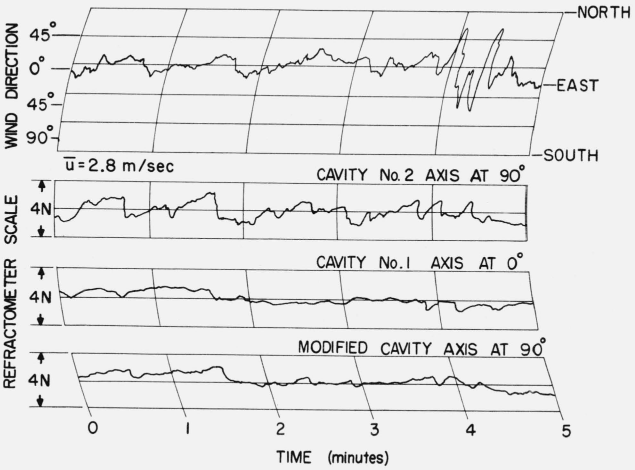

FIGURE 8. *Comparison of measured refractive index and wind variations (relative to mean wind direction of 1°).*

3. Conclusions

Results of these tests indicate the following characteristics of the NBS sampling cavity as a probe of the atmospheric variations:

1. The cavity is slightly velocity-sensitive. Figure 2 gives an indication of the mean error in the measured refractivity as a function of wind speed and direction. On ground-based applications, if the wind speed is less than 13 m/s the error is less than 0.1 N. For airborne operations a correction for wind speed may be made using the extrapolated results in figure 2.

2. When placed in a uniform air flow in excess of 4.5 m/s the NBS cavity is expected to resolve, with essentially no mutual contamination, variations separated by 0.75 meters. Variations separated by 0.3 meters are estimated to be in error by as much as 20 percent, and for separations less than 0.3 meters the resolution falls off rapidly.

3. The conventional NBS refractometer cavity was found to be aspect-sensitive under the conditions described, particularly when the mean air flow was at right angles to the axis of the cavity. In the free atmosphere considerable spectral energy can be added, perhaps because of a "pumping" of the cavity by the variable wind.

A modified sampling cavity has been developed which overcomes some of the limitations of the conventional cavity.

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(Paper 69D9–554)

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