Comparison of Two Multisheet Transmission Windows for Millimeter-Wave Radiometers

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Abstract—The design and performance of a triple-sheet Mylar window and a Teflon and foam window are studied theoretically and experimentally to determine which window produces the smaller brightness temperature variations and, therefore, leads to better accuracy of radiometers operating at frequencies of 20–90 GHz. Theoretical brightness temperatures due to emission and reflection by the windows are calculated and compared, and experimental measurements obtained by using the clear atmosphere as a radiation source are compared. Both theory and experiment indicate that the Teflon and foam window produces smaller brightness temperature variations at these operating frequencies. Effects of the windows on integrated water vapor and liquid measurements are also examined; errors are significant for the triple-sheet Mylar window but are negligible for the Teflon and foam window. It is observed that use of the Teflon and foam design results in acceptable small errors in radiometric measurements of water vapor and cloud liquid.

I. INTRODUCTION

FOR THE PAST several years the National Oceanic and Atmospheric Administration (NOAA) has successfully operated a dual-channel (20.6 and 31.6 GHz) steerable radiometer in the measurement of water vapor and cloud liquid. A shielded triple-sheet Mylar microwave window [1] has been used to provide operation under all-weather conditions. Water vapor is determined primarily by measurement of the brightness temperature from emission at 20.6 GHz and the amount of liquid water contained in clouds primarily by emission at 31.6 GHz. Recently, a third radiometric channel operating at 90.0 GHz was installed with the dual-channel radiometer. The additional channel was added chiefly to increase the sensitivity to liquid water in clouds (often super-cooled liquid). The goal is to find a window that is satisfactory from an applications point of view, at 90.0 GHz along with 20.6 and 31.6 GHz as well as frequencies in the 50 GHz band. Fig. 1 shows a cross section of the triple-channel steerable instrument. A heat pump and air conditioner (both not shown) are used to stabilize the temperature of the insulated trailer housing. The azimuth flat and bearing are protected with a weather-tight cover fitted with the recessed triple-sheet window. The window is formed of three Mylar sheets 0.05 mm thick, each separated by an air gap of about 50 mm. Mylar was chosen initially because of its mechanical strength and

Fig. 1. Side view of steerable triple-channel radiometer; path of central ray from the zenith is shown as dashed lines with arrows. These radiometers emit about 318 K (reference load temperature) when in antenna mode (i.e., viewing atmosphere).

satisfactory electrical properties at 20.6 and 31.6 GHz. The triple-sheet window helps prevent condensation on the outer surface during warm humid conditions, protects the radiometers from the weather, and helps maintain a constant ambient temperature for the millimeter-wave and electronic components. An external heater and blower on the floor of the cowling can be added if condensation on the outer sheet is still objectionable.

II. WINDOW CONSIDERATIONS

A transmission window modifies the transiting wavefronts through absorption, reflection, refraction, and scattering. These undesirable modifications are a function of the window material and thickness. Radiometric instruments that can detect noise changes of less than 1 K are especially sensitive to the effects of transmission windows. For ground-based radiometric instruments operating under all-weather conditions multisheet windows (dielectric sheets separated by air gaps) are used instead of single windows (one dielectric sheet) in part because they prevent condensation on the outer surface during warm humid conditions, thus avoiding the undesirable effects of a wetted window [2]. The rationale is that a multisheet window provides good thermal insulation. To produce the smallest possible distortion of the incoming radiation, the thickness and dielectric properties of the sheets are chosen to be as small as possible. However, the thin

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dielectric sheets are flexible, and when winds or other forces impinge upon a multisheet window the spacing between adjacent sheets may vary, thereby inducing changes in the transmission (and reflection) behavior. This sheet movement is analogous to a varying air-gap spacing which creates a fluctuating energy reflection because of interference. Minimization of the energy fluctuations is a critical factor in the design.

Accurate brightness temperature measurements of the atmosphere are necessary to determine precisely the amounts of water vapor and liquid water in the atmosphere along the antenna beam. The observed brightnesses, expressed as absorption values, are combined in simultaneous equations to yield independently the amounts of liquid water and water vapor within the antenna beam. Equations for calculating the vapor and liquid are given in Section III. An absolute brightness temperature measurement is obtained by properly calibrating the instrument, using what is commonly called a tipping curve calibration [1]. These measurements are made on cloudless days when the emission from the atmosphere is unchanging. By scanning the elevation, absorption measurements can be plotted against the number of air masses (linear versus secant of the zenith angle). This calibration accounts for losses and emissions between the elevation flat and the radiometer detector output. Thus the effects of a multisheet window on the incoming radiation are taken into account for the mean air gap thickness existing during the calibration. However, when the dielectric sheets begin to move (a wind can cause this), the air-gap thickness varies, thereby inducing changes in the electromagnetic interaction behavior between the sheets. The variation may produce significant differences between the measured and actual sky brightness temperatures. This fluctuating energy is of concern because it can constitute a significant source of contamination of the brightness temperature measurements (as does a wet reflector [3] and/or window).

Since the required accuracy of the triple-channel radiometer is less than 0.5 K, it is necessary to minimize the brightness temperature variations (peak-to-peak) produced by the multisheet window to within a few tenths of a Kelvin. To determine which produces the smaller brightness temperature variations, two multisheet windows are considered: the triple-sheet Mylar window and a Teflon and foam window. To the best of our knowledge, the Teflon and foam window was first implemented by James R. Jordan of the Wave Propagation Laboratory.

III. THEORY AND COMPUTATION

A simple but realistic model is used to determine if either of the multisheet windows will produce no more than a few tenths of a Kelvin peak-to-peak brightness temperature variation at 20.6, 31.6, and 90.0 Ghz. The observed brightness temperature T_b at the offset paraboloid (Fig. 1) is the sum of the transmitted atmospheric brightness temperature TT_a (where T is the power transmission of the multisheet window), the brightness temperature from the multisheet window T_{bw} , and the reflected reference load temperature $R_r T_r$ (where R_r is the power reflection of the multisheet window as viewed from the

paraboloid). Thus

$$T_b = TT_a + T_{bw} + R_r T_r \quad (1)$$

where T_a is the atmospheric brightness temperature and T_r the thermodynamic temperature of the waveguide reference load.

From Kirchhoff's law and by conservation of energy, the brightness temperature of the multisheet window is given by

$$T_{bw} = (1 - T - R_a) T_w \quad (2)$$

where T_w is the thermodynamic temperature of the multisheet window (K) and R_a the power reflection of the multisheet window as viewed from the atmosphere. Substituting (2) into (1),

$$T_b = TT_a + (1 - T - R_a) T_w + R_r T_r. \quad (3)$$

The atmospheric brightness temperature T_a is measured by the radiometer and the temperature of the multisheet window T_w and the temperature of the reference load T_r by thermistors.

To obtain an estimate of the power reflections R_a and R_r and power transmission T , we deal with the simplest possible model: an ideal antenna with no sidelobes and smooth dielectric (window) sheets of uniform thickness of infinite extent, separated by a uniform air-gap thickness. In addition, we employ monochromatic frequencies at normal incidence. A full-wave calculation is necessary to include irregular sheet thickness, irregular air gap thickness, finite sheet area, and finite bandwidth, but the improved accuracy over the simple model for this application is not enough to justify its use. Thus a transmission line equivalent circuit for the multisheet window can be used (see Fig. 2) to calculate R_a , R_r , and T . The propagation constants and characteristic impedances of the different media are defined in [4]:

$$\gamma = i2\pi f \sqrt{\mu_0(\epsilon' - i\epsilon'')}, \quad \text{propagation constant (m}^{-1}\text{)} \quad (4)$$

$$z = \sqrt{\frac{\mu_0}{\epsilon' - i\epsilon''}}, \quad \text{characteristic impedance (}\Omega\text{)} \quad (5)$$

where

$$\begin{aligned} i &= \sqrt{-1}, \\ f &= \text{frequency under consideration (Hz)}, \\ \mu_0 &= 4\pi \times 10^{-7}, \text{ free-space permeability (H/m)}, \\ \epsilon' &= \epsilon_r / \mu_0 c^2, \text{ (F/m)}, \\ \epsilon_r &= \text{relative permittivity (dimensionless)}, \\ c &\sim 3 \times 10^8, \text{ speed of light in a vacuum (m/s)}, \\ \epsilon'' &= \epsilon' \tan \delta \text{ (F/m)}, \\ \tan \delta &= \text{loss tangent (dimensionless)}. \end{aligned}$$

To facilitate the use of the transmission line analogy in Fig. 2, the multisheet two-port network (dielectric sheet 1-air gap-dielectric sheet 2-air gap-...-dielectric sheet n -1-air gap-dielectric sheet n) is cascaded into an equivalent network. Computational effort in the analysis of cascaded two ports, as in Fig. 2, can be simplified using the $ABCD$ matrix representation [5]. The elements in this matrix are defined in terms of voltages and currents at the two ports of the desired

Fig. 2. Transmission line equivalent circuit for multisheet window. Propagation constants and characteristic impedances are given by $\gamma_0, \gamma_1, \gamma_2, \dots, \gamma_{n-1}, \gamma_n$, and $Z_0, Z_1, Z_2, \dots, Z_{n-1}, Z_n$, respectively. Atmospheric and reference load radiation sources are V_a and V_r , respectively.

network. The $ABCD$ matrix is especially suited for cascading several two-port networks and is obtained by multiplying the individual $ABCD$ matrices together in the proper order. For Fig. 2 this is readily shown to be

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} C_1 & Z_1 S_1 \\ \frac{S_1}{Z_1} & C_1 \end{bmatrix} \begin{bmatrix} C_0 & Z_0 S_0 \\ \frac{S_0}{Z_0} & C_0 \end{bmatrix} \begin{bmatrix} C_2 & Z_2 S_2 \\ \frac{S_2}{Z_2} & C_2 \end{bmatrix} \cdots \begin{bmatrix} C_{n-1} & Z_{n-1} S_{n-1} \\ \frac{S_{n-1}}{Z_{n-1}} & C_{n-1} \end{bmatrix} \begin{bmatrix} C_n & Z_n S_n \\ \frac{S_n}{Z_n} & C_n \end{bmatrix} \quad (6)$$

where

$$\begin{aligned} C_i &= \cosh(\gamma_i d_i), \\ S_i &= \sinh(\gamma_i d_i), \\ Z_i &= \text{impedance of medium } i \text{ } (\Omega), \\ d_i &= \text{medium } i \text{ thickness (m)}, \\ \gamma_i &= \text{propagation constant in medium } i \text{ } (\text{m}^{-1}), \end{aligned}$$

for $i = 0$: air gap,

$$\begin{aligned} 1 &: \text{dielectric sheet 1,} \\ 2 &: \text{dielectric sheet 2,} \\ &\vdots \\ n &: \text{nth dielectric sheet.} \end{aligned}$$

To obtain the amplitude reflections (r_a and r_r) and transmission (t), we convert the overall $ABCD$ matrix in (6) to a scattering matrix; for a reciprocal network this gives [5]

$$r_a = \frac{AZ_0 + B - CZ_0^2 - DZ_0}{G} \quad (7)$$

$$r_r = \frac{-AZ_0 + B - CZ_0^2 + DZ_0}{G} \quad (8)$$

TABLE I
ELECTRICAL PROPERTIES OF MYLAR [6], TEFLON [7], [8], AND LOW-LOSS FOAM AT 20.6, 31.6, AND 90.0 GHZ

Frequency (GHz)	Material	ϵ_r	$\tan \delta \times 10^{-4}$
20.6	Mylar	3.0	50
	Teflon	2.08	6
	Foam	1.03	1
31.6	Mylar	3.0	50
	Teflon	1.99	2
	Foam	1.03	1
90.0	Mylar	3.0	50
	Teflon	2.06	2
	Foam	1.03	2

$$t = \frac{2Z_0}{G} \quad (9)$$

where

$$G = AZ_0 + B + CZ_0^2 + DZ_0.$$

The power reflections and transmission are

$$R_a = |r_a|^2 \quad (10)$$

$$R_r = |r_r|^2 \quad (11)$$

$$T = |t|^2. \quad (12)$$

The magnitudes of (10), (11), and (12) are obtained from the approximate values of dielectric constant and loss tangent for Mylar, Teflon, and low-loss foam given in Table I for the three frequencies of interest. An approximate window temperature of 298 K is used (see discussion of the controlled experiment in Section IV). Given these constants, theoretical and experimental results can be compared. The dielectric properties of Mylar are only approximately known above 10 GHz (the last published data point we located was at 8.6 GHz [7]). Even though the foam has been tested only up to 10 GHz, its dielectric properties are assumed not to change significantly through 90 GHz, as is shown in Table I. Teflon, on the other hand, has been tested to 100 GHz, and its dielectric properties are apparently known accurately for the frequencies of

interest. The low-loss foam used (ECCOFOAM PP-2) is manufactured by Emerson and Cuming, Inc.

To determine the effect of the multisheet window on the atmospheric brightness temperature, the atmospheric brightness temperature is subtracted from (3), giving the "difference temperature"

$$T_d = (T - 1)T_a + (1 - T - R_a)T_w + R_r T_r. \quad (13)$$

This brightness temperature difference gives the contribution of the multisheet window to the apparent sky brightness temperature. $T_d = 0$ K when the multisheet window is removed. A positive T_d indicates that additional energy is received at the paraboloid because of reflection by and emission from the window.

Recovery of the amounts of atmospheric water vapor and liquid water from trifrequency radiometer measurements involves a statistical inversion [1], [9], [10]. Application of this procedure results in the following expressions for integrated water vapor V (cm) and liquid water L (cm):

$$V = C_{0V} + C_{1V}T_{dry} + C_{2V}P + C_{3V}RH \\ + C_{20V}\tau_{20} + C_{31V}\tau_{31} + C_{90V}\tau_{90} \quad (14)$$

$$L = C_{0L} + C_{1L}T_{dry} + C_{2L}P + C_{3L}RH \\ + C_{20L}\tau_{20} + C_{31L}\tau_{31} + C_{90L}\tau_{90} \quad (15)$$

where T_{dry} , P , and RH are the physical temperature (K), pressure (mb), and relative humidity, respectively, at the earth's surface, and the C 's are the retrieval coefficients calculated from a multiyear sample of radiosonde observations made at or near the location where the radiometric measurements are to be made.

In (14) and (15), τ_{20} , τ_{31} , and τ_{90} are the total atmospheric absorptions; these are computed from the brightness temperatures $T_{b(f)}$, measured by the radiometer using the relationship [1]

$$\tau_{(f)} = -\ln \left(\frac{T_{mr(f)} - T_{bb(f)}}{T_{mr(f)} - T_{bb}} \right) \quad (16)$$

where $T_{mr(f)}$ is an effective atmospheric radiating temperature at each operating frequency f , T_{bb} is the cosmic background temperature (2.9 K), and the absorption $\tau_{(f)}$ is in nepers. It is customary to calculate the T_{mr} values in (16) from a multiyear sample of radiosonde data measured at or near the location where the radiometric measurements are to be made.

To determine the effect of the multisheet window on the measurements of water vapor and liquid, the differences between the water vapor and liquid measurements with and without the window are taken:

$$V_d = V_{(\text{with window})} - V_{(\text{without window})} \quad (17)$$

$$L_d = L_{(\text{with window})} - L_{(\text{without window})}. \quad (18)$$

Calculated plots of brightness temperature difference T_d , water vapor difference V_d , and liquid difference L_d versus air-gap thickness for the Teflon and foam window are shown in Fig. 3; similar curves exist for the triple-sheet Mylar window.

These curves were calculated from (3), (13), (17), and (18), and several values of the atmospheric brightness temperatures T_a were used. The window temperature T_w and the reference load temperature T_r are fixed at 298 and 318 K, respectively, for all five graphs. The Teflon and foam window consists of one Teflon sheet 0.05 mm thick and one low-loss foam sheet 6.4 mm thick (thinnest available) separated by a 50-mm air gap. The column labeled "theory" in Table II gives the theoretical mean and peak-to-peak values for brightness temperature difference T_d for the two types of windows. As mentioned in Section II, the maximum variation in T_d for a particular window should be on the order of a few tenths of a Kelvin to permit accurate brightness temperature measurements of the atmosphere. Based on the theoretical values in Table II, the triple-sheet Mylar window performance is unsatisfactory at all three frequencies (i.e., T_d (peak to peak) is greater than a few tenths of a Kelvin), and the mean differences are quite large. On the other hand, the Teflon and foam window performs well at these three frequencies (i.e., T_d (peak to peak) is on the order of a few tenths of a Kelvin) and the mean difference is small. Computed variations (peak to peak) in water vapor V_d and liquid water L_d produced by the Teflon and foam window are negligible (see ordinates of Fig. 3(d) and (e)) since these values are near or below the noise level of the radiometer but corresponding variations (peak to peak) of about 3 and 0.01 mm, respectively, are produced by the triple-sheet Mylar window. The measured values of T_d , V_d , and L_d are discussed in Section IV.

The different characteristics of the Teflon and foam sheets are the key factors that minimize the unwanted noise fluctuations. The first-order explanation for this minimization is that the brightness temperature caused by the Teflon sheet is due mainly to reflections at the air-Teflon interfaces (because the relative permittivity is fairly high) and not by emission (because the loss tangent is small). On the other hand, the brightness of the foam sheet is caused mainly by the absorption in the foam (the sheet is fairly thick) and not by reflection (because the relative permittivity is near unity). Because of these different characteristics, little energy interaction occurs between the two sheets, which means that a minimal fluctuating brightness temperature will be set up by the window. Table III lists relative absorption (emission) and reflection of the Teflon and foam window at the three frequencies of interest.

IV. MEASUREMENTS

On August 15, 1986, the NOAA steerable triple-channel radiometer was used to test the theory by viewing in the zenith direction with and without both types of window. Weather conditions had a critical role in the experiment, i.e., cloudless skies were required to ensure that the atmospheric zenith brightness temperature would remain fairly constant during the measurements. To obtain a fluctuating energy pattern, the window frame was physically shaken to simulate a typical windy condition. Fig. 4 is a photograph of the Teflon and foam window used in this experiment; the triple-sheet Mylar window is similar in appearance.

Before the brightness temperature on the two windows was measured, three tipping curve calibrations were performed

Fig. 3. Computed (a)–(c) brightness temperature difference T_d , (d) apparent water vapor difference V_d , and (e) liquid water difference L_d values versus air gap thickness for Teflon and foam window with $d_1 = 0.05$ mm (Teflon) and $d_2 = 16.4$ mm (foam). T_w and T_r are fixed at 298 and 318 K, respectively, for all five graphs.

TABLE II
THEORETICAL AND EXPERIMENTAL BRIGHTNESS TEMPERATURES FOR THE TWO MULTISHEET WINDOWS (T_w AND T_r ARE FIXED AS MEASURED AT 298 AND 318 K, RESPECTIVELY); USING THE PRESENT TECHNIQUE, PEAK-TO-PEAK FLUCTUATIONS WERE NOT MEASURABLE AT 20.6 AND 31.6 GHz

Frequency (GHz)	Window	Peak-to-Peak T_d		Mean T_d	
		Theory (K)	Measure (K)	Theory (K)	Measure (K)
20.6	Mylar	1.3	na	0.9	1.5
	Teflon/foam	0.1	na	0.1	0.0
31.6	Mylar	3.0	na	1.9	3.1
	Teflon/foam	0.3	na	0.3	0.2
90.0	Mylar	21.7	6.4	11.9	15.2
	Teflon/foam	0.3	0.5	1.4	0.6

TABLE III
EMISSION AND REFLECTION FROM A TEFLON AND FOAM WINDOW AT 20.6, 31.6, AND 90.0 GHz (T_w AND T_r ARE FIXED AT 298 AND 318 K, RESPECTIVELY)

Frequency (GHz)	Power Emission		Power Reflection	
	Teflon (K)	Foam (K)	Teflon (K)	Foam (K)
20.6	0.01	0.08	0.04	0.01
31.6	0.00	0.13	0.09	0.06
90.0	0.01	0.73	0.79	0.01

Fig. 4. Teflon and foam window.

with the triple-sheet Mylar window, and Teflon and foam window, and no window in place. These calibrations allow for precise brightness temperature measurements for each type of window. With no window present the brightness temperature of the atmosphere, T_a , alone is measured; thus the brightness temperature caused by a multisheet window can then be found by comparison.

The data were collected in the following way: with no window present the atmospheric zenith brightness temperatures at 20.6, 31.6, and 90.0 GHz were measured for about 5 min. Then the Teflon and foam window was inserted and physically shaken for about 5 min; during this time the zenith brightness temperatures were measured. Next the triple-sheet Mylar window was inserted and shaken for about 5 min, and the zenith brightness temperatures measured. This process was repeated several times (the data are shown in Fig. 5); the unprocessed data were written on a removable magnetic disk every 5 s. The data consist of average values obtained from five 1 s samples (the radiometer time constant is 1 s). Note the large brightness temperature difference between the triple-sheet Mylar window and the "air" window and the small difference between the Teflon and foam window and the "air" window.

The column labeled "Measure" in Table II shows the experimental peak-to-peak and mean brightness temperature differences (T_d) for the two cases. At 90 GHz, the Teflon and foam window produces much lower peak-to-peak and mean brightness temperature differences than the triple-sheet Mylar window. Note that the Teflon and foam window satisfies the

brightness temperature variation criterion (T_d (peak to peak) = 0.5 K) at 90 GHz, whereas the Mylar window does not (T_d (peak to peak) = 6.4 K). The measured peak-to-peak values for 20 and 30 GHz are not shown in Table II since the variation in air-gap sheet separation caused by shaking was not large enough to produce significant changes in interference at these wavelengths. Theoretical and experimental results for T_d (mean) are in fair agreement with respect to frequency and window material (see Table II). Some of the difference between theoretical and experimental values for T_d (mean) may be due to atmospheric brightness temperature fluctuations and assumptions used in the simplified theoretical model. A measured variation (peak to peak) of about 0.01 mm in apparent liquid water can be produced by shaking the triple-sheet Mylar window. Measured variations (peak to peak) in water vapor for both cases and liquid water using the Teflon and foam window however are negligible; the values are below the noise level of the radiometric system.

V. APPLICATION OF THE RESULTS TO OPERATIONAL RADIOMETERS

Multifrequency radiometric instruments are becoming operational for continuous measurement of profiles of temperature and humidity under almost all weather conditions as well as for integrated water vapor and cloud liquid [11]. These instruments typically employ several channels in the 50–60 GHz range to profile temperature in addition to channels near 20 and 30 GHz. Typically, these systems employ an offset paraboloid antenna inside a building and an exposed 45° flat reflector for directing the beam toward the zenith; between these two is a multisheet transmission window. We computed the performance of the two window designs in the 50–60 GHz region using the analysis method outlined in Section III. Values of dielectric constant and loss tangent were estimated by extrapolating between the 31.6 and 90.0 GHz values in Table I. The performance of the two types of window at the Profiler operating frequencies is summarized in Table IV. As expected, the theoretical brightness temperature fluctuations are much smaller with the Teflon and foam window than with the multisheet Mylar window; therefore, use of the former design would be expected to minimize errors in measurement of temperature and humidity profiles, and it is being used in "operational" Profiler systems.

VI. CONCLUSION

The results presented here provide estimates of the effect of absorption and reflection by two types of multisheet transmission windows on atmospheric brightness temperature measurements. Both theory and experiment show that a Teflon and foam window causes less fluctuation and less difference in absolute value of brightness temperature than a triple-sheet Mylar window. With the Teflon and foam window, fluctuations at frequencies from 20 to 90 GHz are at a level acceptable for maintaining radiometer accuracy. Furthermore, the Teflon and foam window produces much less noise than the triple-sheet Mylar window, thereby permitting precise measurements of integrated water vapor and cloud liquid.

Rigid fixed sheets would prevent sheet movement within a multisheet window and thus reduce the fluctuations in bright-

Fig. 5. Atmospheric brightness temperatures measured at (a) 20.6, (b) 31.6, (c) 90.0 GHz with no window (N), triple-sheet Mylar window (M), and Teflon and foam window (T). Apparent water vapor and liquid contents are shown in (d) and (e), respectively.

TABLE IV
COMPUTED BRIGHTNESS TEMPERATURES FOR THE TWO MULTISHEET
WINDOWS AT CHANNELS IN THE 50-60 GHz RANGE (T_w AND T_r ARE
FIXED AT 298 AND 318 K, RESPECTIVELY)

Frequency (GHz)	Peak-to-Peak T_d		Mean T_d	
	Mylar (K)	Teflon/foam (K)	Mylar (K)	Teflon/foam (K)
52.9	4.0	0.2	2.3	0.2
53.9	2.3	0.1	1.3	0.1
55.5	0.9	0.1	0.5	0.1
58.8	0.8	0.1	0.4	0.0

ness temperature measurements, but they would probably be fairly thick, resulting in considerable emission. However, to the best of the authors' knowledge, no rigid sheet has been successfully implemented to give the low noise level required for sensitive radiometric measurements over a wide band of frequencies.

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Dr. Hogg is a member of the National Academy of Engineering, a member and past United States Chairman of URSI Commission F, and a member AAAS. He is a recent recipient of a silver medal award by the United States Department of Commerce (1983) and of the Distinguished Achievement Award of the Geoscience and Remote Sensing Society of IEEE (1984). In 1985 he presented a series of lectures on Remote Sensing at Institutes in Japan and the People's Republic of China.