Application of Radiative Transfer Theory to Microwave Transmission Medium Calibrations

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Precise determinations of the transmission medium loss and noise temperature contribution are important to the performance characterization of low noise microwave receiving systems and thermal noise standards. Tropospheric loss is frequently inferred from microwave radiometer noise temperature measurements. Interpretation of these measurements requires an inversion of the radiative transfer integral equation. This is inconvenient even with computer techniques. Although there have been many published studies of the radiative transfer equation, this article provides a very accurate solution in terms of a rapidly convergent power series. This solution is applicable to a low-loss medium with either uniform or nonuniform loss distributions. A four-layer atmosphere model is investigated to demonstrate the accuracy of the solution relative to the model. These solutions for total loss range in accuracy from about 0.001 dB (≃0.06 K) at 0.1 dB loss to about 0.01 dB (≃0.6 K) at 1 dB total loss. Applications include thermal noise standards and single- and dual-frequency water vapor radiometers.

I. Introduction

Precise determinations of the transmission medium loss and noise temperature contribution are important to the performance characterization of low noise receiving systems (Ref. 1) and thermal noise standards (Ref. 2). Tropospheric loss is frequently inferred from microwave radiometer noise temperature measurements (Ref. 3). Interpretation of these measurements requires an inversion of the radiative transfer integral equation (Refs. 4, 5, 6). This is inconvenient even with computer techniques. Although there have been many published studies (Refs. 7, 8, 9) of the radiative transfer equations, this article clearly details the solution and applications, including thermal noise standards and single- and dual-frequency water vapor radiometers. The solutions are applicable to a low loss medium with either uniform or nonuniform loss distributions described analytically or in discrete steps.

II. Theory

The total loss through a transmission medium (Figs. 1 or 2) is given by (neglecting scattering[1])

$$L = e^{\tau}, \text{ratio} (\geqslant 1) \tag{1}$$

[1] Scattering should be considered for the troposphere for rain above ≃10 GHz and for clouds above ≃100 GHz (Ref. 10).

where

τ = total attenuation (optical depth), nepers

$$[\tau\,(\text{nepers})] = [L(\text{dB})/10 \log e] \simeq [L(\text{dB})/4.343]$$

$$= \int_0^{\ell} \alpha(x)\, dx$$

$$= \alpha_0 \ell \text{ for } \alpha(x) = \alpha_0, \text{ uniform loss}$$

$\alpha(x)$ = absorption coefficient of the medium at x, nepers/m

x = distance along the propagation path, m (x = 0 at surface, = ℓ at "top")[2]

ℓ = total path length, m

From the theory of radiative transfer (neglecting scattering),

$$T = (T_s/L) + \int_0^{\ell} T(x)\, \alpha(x)\, e^{-\tau(x)}\, dx, \text{K} \tag{2}$$

where

T_s = source temperature, K

$T(x)$ = physical temperature of medium at x, K

$\tau(x)$ = attenuation between 0 and x, nepers

$$= \int_0^{x} \alpha(x')\, dx'$$

This can be integrated directly or solved stepwise (Ref. 12). For small transmission loss (expanding $e^{-\tau}$ and $e^{-\tau(x)}$ in power series)

$$T \simeq T_s + A\tau + B\tau^2 + C\tau^3 + \cdots \tag{3}$$

where

$A = T_p - T_s$

T_p = weighted physical temperature of the transmission medium, K

$$= \int_0^{\ell} T(x)\, [\alpha(x)/\tau]\, dx$$

$$B = -\left\{ \int_0^{\ell} T(x)\, [\alpha(x)/\tau]\, [\tau(x)/\tau]\, dx - (T_s/2) \right\}$$

$$C = (1/2) \int_0^{\ell} T(x)\, [\alpha(x)/\tau]\, [\tau(x)/\tau]^2\, dx - (T_s/6)$$

Solving for τ in a power series,

$$\left.\begin{aligned} \tau = {} & [L(\text{dB})/4.343] \simeq [(T - T_s)/(T_p - T_s)] \\ & - (B/A)\, [(T - T_s)/(T_p - T_s)]^2 \\ & + [2\,(B/A)^2 - (C/A)]\, [(T - T_s)/(T_p - T_s)]^3 + \cdots \end{aligned}\right\} \tag{4}$$

A, B and C can be solved and treated as "constants," assuming the physical temperature and loss distribution of the medium are known. For a transmission medium composed of discrete sections ($\ell = n\Delta x$ and $x = i\Delta x$)

$$T_p = \sum_{i=1}^{n} T_i\, \Delta k_i$$

$$B = -\left[\sum_{i=1}^{n} T_i\, \Delta k_i k_i - (T_s/2) \right] \tag{5}$$

$$C = (1/2) \sum_{i=1}^{n} T_i\, \Delta k_i k_i^2 - (T_s/6)$$

where

$$\Delta k_i = \alpha_i\, \Delta x/\tau \simeq \Delta L_i(\text{dB})/L(\text{dB})$$

$$k_i = (\tau_i/\tau) = \sum_{j=1}^{i} \Delta k_j$$

$$\sum_{i=1}^{n} \Delta k_i = 1, (0 \leqslant k_i \leqslant 1)$$

The last terms of Eqs. (3) and (4) are small and provide an indication of the number of terms required and the accuracy

[2] It is sometimes convenient to integrate from the "top" to the surface (Ref. 11).

of the power series expansion. Only one or two terms are required for most applications. For many applications, it is suitable to use $(B/A) \simeq -(1/2)$ and $[2(B/A)^2 - (C/A)] \simeq (1/3)$ as obtained from the exact solution for a uniform loss and temperature distribution. Then

$$T \simeq T_s + (T_p - T_s)\,[\tau - (1/2)\,\tau^2 + (1/6)\,\tau^3 + \cdots] \qquad (6)$$

and

$$\tau \simeq [(T - T_s)/(T_p - T_s)] + (1/2)\,[(T - T_s)/(T_p - T_s)]^2$$
$$+ (1/3)\,[(T - T_s)/(T_p - T_s)]^3 + \cdots \qquad (7)$$

III. Nonuniform Loss

Example 1:

Consider a two-layer nonuniform loss stratified transmission medium with $\Delta k_1 = \Delta k$ for the first (surface) layer. This implies that $\Delta k_2 = 1 - \Delta k$, $k_1 = \Delta k$ and $k_2 = 1$.

Then

$$\left.\begin{aligned} T_p &= T_1\,\Delta k + T_2\,(1 - \Delta k) \\ B &= -\,[T_1(\Delta k)^2 + T_2\,(1 - \Delta k) - T_s/2] \\ C &= (1/2)\,[T_1(\Delta k)^3 + T_2\,(1 - \Delta k)] - T_s/6 \end{aligned}\right\} \qquad (8)$$

For a numerical atmospheric example, assume that T_1 = 300 K, T_2 = 200 K, T_s = 3 K, (cosmic background), $\Delta k = 2/3$, so that from Eq. (5)

$$T_p = 266.667 \text{ K}$$

$$B = -198.50 \text{ K}$$

$$C = 72.80 \text{ K}$$

From Eq. (3) using L(dB) = 0.10,

$$T \simeq 3 + 6.071 - 0.105 + 0.001 = 8.967 \text{ K}$$

and from Eq. (4) using T = 8.97 K,

$$L(\text{dB}) \simeq 0.0983 + 0.0017 + 0.0000 = 0.10$$

Example 2:

Consider (Fig. 3) a four-layer nonuniform loss stratified transmission medium example with T (measured) of 13 K. Assume $\Delta k_1 = 0.4$, $\Delta k_2 = 0.3$, $\Delta k_3 = 0.2$, $\Delta k_4 = 0.1$, T_1 = 280 K, T_2 = 240 K, T_3 = 220 K, T_4 = 200 K and T_s = 3 K, so that

$$T_p = 248.0 \text{ K}$$

$$B = -153.3 \text{ K}$$

$$C = 53.9 \text{ K}$$

and from Eq. (4)

$$L(\text{dB}) \simeq 0.177 + 0.004 + 0.000 = 0.181$$

This can be verified within approximately 0.001 dB ($\simeq$0.06 K), solving for T with direct stepwise calculations. Eqs. (3) and (4) have been verified with this model to within 0.01 dB ($\simeq$0.6 K) up to 1 dB overall loss. Increased accuracy requires additional terms in the expansions of Eqs. (3) and (4).

Example 3:

It is frequently convenient to perform an antenna "tipping" measurement to evaluate atmospheric loss. In this measurement technique, the difference in antenna temperature between two elevation angles is measured. This simplifies the calibration requirement from an absolute to a relative temperature measurement. Assuming an infinitely narrow antenna beamwidth and stratified atmosphere, the difference temperature between antenna angle Z (Fig. 2) and zenith is (using Eq. (3) with $T(z = 0°) = T_z$ and $\tau(Z = 0°) = \tau_z$)

$$\begin{aligned} T &= T - T_z \\ &\simeq A\,(\tau - \tau_z) + B\,(\tau^2 - \tau_z^2) + C\,(\tau^3 - \tau_z^3) + \cdots \end{aligned} \qquad (9)$$

By analogy with Eq. (4),

$$\begin{aligned} (\tau - \tau_z) &= [L(dB) - L_z(\text{dB})]/4.343 \\ &= [\Delta T/(T_p - T_s)] - (B/A)\,[\Delta T/(T_p - T_s)]^2 \\ &\quad + [2(B/A)^2 - (C/A)]\,[\Delta T/(T_p - T_s)]^3 + \cdots \end{aligned} \qquad (10)$$

If T is measured at $Z = 60°$, $\tau = 2\tau_z$ and then (using $T(Z = 60°) - T(Z = 0°)) = \Delta T_z$, $(B/A) \simeq -(1/2)$, $[2(B/A)^2 - (C/A)] \simeq (1/3)$,

$$\tau_z \simeq [L_z(\text{dB})/4.343] \simeq [\Delta T_z/(T_p - T_s)] + (1/2)\,[\Delta T_z/(T_p - T_s)]^2 + (1/3)\,[\Delta T_z/(T_p - T_s)]^3 + \cdots \tag{11}$$

If this measurement is performed near the water vapor resonance frequency of $\simeq$22 GHz, the integrated water vapor content in the line of sight is proportional to τ_z. Measurements of τ_z with a water vapor radiometer allow monitoring of the integrated water vapor when proper calibration constants are obtained (from weather balloon calibrations, etc.). Usually only one or two terms of Eq. 11 with $(B/A) \simeq -(1/2)$ are required. These equations can be suitably expanded to include two frequencies (Ref. 13) so that two equations with two unknowns are obtained. It is then possible to monitor both liquid and water vapor in the line of sight. A simple single-frequency "fair weather" water vapor radiometer may be of interest for some applications. Cloudy weather is "handled" by simply discarding data taken under these conditions. One- and two-frequency water vapor radiometers are analyzed in Appendices A and B.

IV. Uniform Loss

For uniform loss, $\alpha(x)\ell = \tau$ and $\tau(x) = x\tau/\ell$ (usually applicable to thermal noise standards), so that the average physical temperature of the transmission line is given by, from Eq. (3),

$$T_p = \frac{1}{\ell}\int_0^{\ell} T(x)dx = \frac{1}{n}\sum_{i=1}^{n} T_i$$

$$\left.\begin{aligned} B &= -\left[\frac{1}{\ell^2}\int_0^{\ell} xT(x)dx - (T_s/2)\right] \\ &= -\left[\frac{1}{n^2}\sum_{i=1}^{n} iT_i - (T_s/2)\right] \end{aligned}\right. \tag{12}$$

$$C = \frac{1}{2\ell^3}\int_0^{\ell} x^2 T(x)dx - (T_s/6) = \frac{1}{2n^3}\sum_{i=1}^{n} i^2 T_i - (T_s/6)$$

These solutions for T_p, B and C for uniform loss are directly applicable to the solutions for T and $L(\text{dB})$, Eqs. (3) and (4).

Example 4:

Consider the solution of Eq. (3) for a linear physical temperature distribution, $T(x) = T_1 + (T_2 - T_1)x/\ell$ (applicable to a thermal noise standard consisting of a source at temperature T_s and a transmission line with a linear temperature distribution between T_1 and T_2). We have

$$\left.\begin{aligned} T_p &= (T_1 + T_2)/2 \\ B &= -(T_1 + 2T_2 - 3T_s)/6 \\ C &= (T_1 + 3T_2 - 4T_s)/24 \end{aligned}\right\} \tag{13}$$

resulting in

$$\left.\begin{aligned} T \simeq\ & T_s + [L(\text{dB})/4.343]\,(T_1 + T_2 - 2T_s)/2 \\ & - [L(\text{dB})/4.343]^2\,(T_1 + 2T_2 - 3T_s)/6 \\ & + [L(\text{dB})/4.343]^3\,(T_1 + 3T_2 - 4T_s)/24 + \cdots \end{aligned}\right\} \tag{14}$$

in agreement with Ref. 2, p. 648. Also

$$[L(\text{dB})/4.343] \simeq [2(T - T_s)/(T_1 + T_2 - 2T_s)] + 4\,(T - T_s)^2\,(T_1 + 2T_2 - 3T_s)/3\,(T_1 + T_2 - 2T_s)^3 + \cdots \tag{15}$$

V. Conclusion

The radiative transfer equation has been evaluated assuming known transmission medium temperature and loss distributions. A rapidly convergent power series solution is given for the total transmission medium loss in terms of these distributions and the measured radiometric noise temperature. A four-layer atmospheric model is investigated to demonstrate the accuracy of the solution relative to the model. These solutions for total loss range in accuracy from about 0.001 dB at 0.1 dB to about 0.01 dB at 1 dB total loss. Applications include thermal noise standards and single and dual frequency water vapor radiometers.

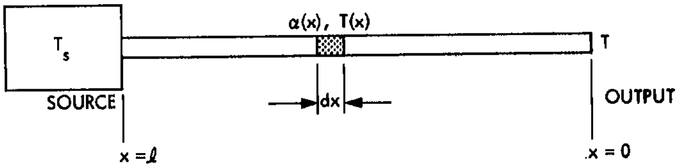

Fig. 1. Representation of a thermal noise standard consisting of a source and a lossy transmission line

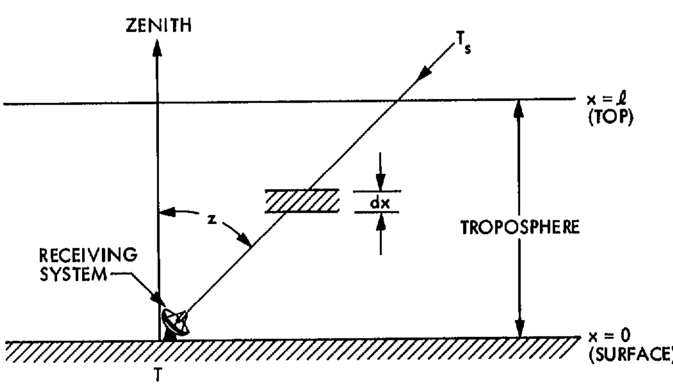

Fig. 2. Representation of a receiving system with signal propagating through a lossy medium

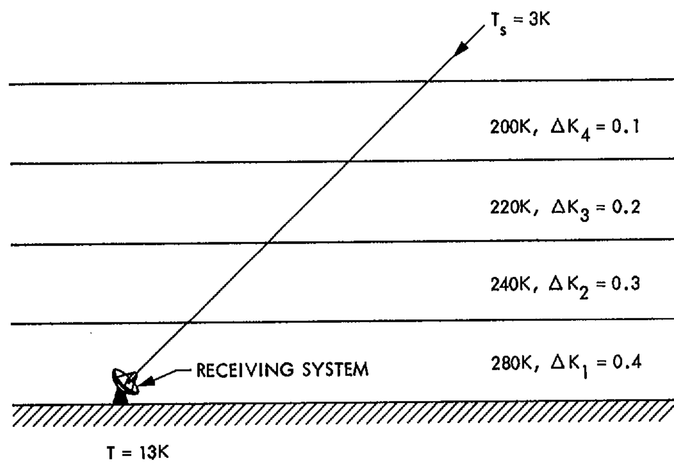

Fig. 3. Representation of a four-layer nonuniform loss atmospheric model for example calculation

Appendix A
Single-Frequency Water Vapor Radiometer

The single-frequency water vapor radiometer is useful for clear weather tropospheric water vapor density calibrations. A stratified troposphere and pencil beam antenna pattern with negligible sidelobes is assumed. The total attenuation of zenith angle Z in terms of the increased antenna noise temperature due to the troposphere is

$$\tau = [(T - T_s)/(T_p - T_s)] - (B/A)\,[(T - T_s)\,(T_p - T_s)]^2 + \cdots \qquad \text{(A-1)}$$

This loss consists of a stable oxygen component τ_0 [τ_0(zenith) $= \tau_{0z}$] assumed known, $\simeq$0.124 nepers at 20.6 GHz (Ref. 13, p. 38) assuming 5.4 km scale height and an unknown water vapor component τ_V (assuming no clouds or rain)

$$\tau \simeq \tau_V + \tau_0 \qquad \text{(A-2)}$$

The precipitable water vapor along the line of sight (for a 2-km scale height troposphere with 7.5 gm/m^3 water vapor density, M_V = 1.5 cm at zenith) is given by

$$M_V = \tau_V/k_V \qquad \text{(A-3)}$$

where

k_V = normalized water vapor attenuation coefficient per unit precipitable water, nepers/cm ($k_V \simeq 0.0426$ at 20.6 GHz; k_V has greater uncertainty at 22.2 GHz, Ref. 4)

Combining Eqs. (A-2) and (A-3),

$$M_V = (\tau - \tau_0)/k_V \qquad \text{(A-4)}$$

In terms of the measured antenna temperature from Eq. (A-1),

$$M_V = a_1(T - T_s) + a_2(T - T_s)^2 + a_3, \text{ cm} \qquad \text{(A-5)}$$

where (assuming $(A/B) \simeq -(1/2)$, as in Eq. 7)

$$a_1 \simeq 1/k_V\,(T_p - T_s)$$

$$a_2 \simeq a_1/2\,(T_p - T_s)$$

$$a_3 \simeq -\tau_0/k_V$$

Using the "tipping" measurement technique of Example 3,

$$M_V \simeq (\cos Z/k_V)\,\{[\Delta T_z/(T_p - T_s)] + [\Delta T_z/(T_p - T_s)]^2 - \tau_{0z}\}, \text{ cm} \qquad \text{(A-6)}$$

As an example, at 20.6 GHz, $(T_p - T_s) \simeq 280$ K, $k_V \simeq 0.0426$ (Ref. 14, p. 479), $\tau_{0z} \simeq 0.0124$ (Ref. 13, p. 38, assuming 5.4-km scale height), so that

$$M_V \simeq \cos Z\,[0.084\,\Delta T_z + 0.00015\,(\Delta T_z)^2 - 0.29], \text{ cm} \qquad \text{(A-7)}$$

The precipitable water vapor content at zenith angle Z is monitored by repeated "tipping" measurements or by switching between horns mounted at suitable zenith angles. For clear sky conditions, this technique has the simplicity and accuracy of a relative measurement of ΔT_z as compared to the difficulty of the absolute measurements required for the two-frequency instruments described in Appendix B.

The measurement error for M_V (neglecting the effects of a nonstratified trospheric pointing error, etc.) is

$$\delta(M_V) \simeq [\cos Z\,0.084\,\delta(\Delta T_z)^2 + (\delta a_3)^2]^{1/2} \qquad \text{(A-8)}$$

Using $Z = 60°$, $\delta(\Delta T_z) \simeq 1$ K and $\delta a_3 \simeq 0.12$ ($\simeq$20%), results in $\delta(M_V) \simeq 0.2$ cm. The measurement error for neglecting the $(\Delta T_z)^2$ term for $\Delta T_z \simeq 30$ K is $\simeq$0.27 cm out of $\simeq$2.3 cm or $\simeq$12%.

The increase in propagation path length due to the total precipitable water vapor is (Ref. 15)

$$\Delta \ell_V \simeq 6.48\,M_V, \text{ cm} \qquad \text{(A-9)}$$

or, in terms of ΔT_z, from Eq. (A-7),

$$\Delta \ell_V \simeq \cos Z\,[0.54\,\Delta T_z + 0.00010\,(\Delta T_z)^2 - 1.9], \text{ cm} \qquad \text{(A-10)}$$

Although the single-frequency water vapor radiometer will perform well in clear sky conditions, serious performance degradation occurs during cloudy weather. Some applications allow the selection of good data, while discarding poor data.

Appendix B
Dual-Frequency Water Vapor Radiometer

The dual-frequency water vapor (Refs. 16, 17) radiometer is useful during cloudy weather to determine both tropospheric water vapor and liquid content. A pencil beam antenna pattern with negligible sidelobes is assumed. The equations for determination of the total attenuation obtained from radiometer noise temperature calibrations for frequencies f_1 and f_2 are,

$$\tau_1 \simeq [(T_1 - T_s)/(T_p - T_s)] - (B/A)\,[(T_1 - T_s)/(T_p - T_s)]^2 + \cdots, \text{ nepers} \tag{B-1}$$

and

$$\tau_2 \simeq [(T_2 - T_s)/(T_p - T_s)] - (B/A)\,[(T_2 - T_s)/(T_p - T_s)]^2 + \cdots, \text{ nepers} \tag{B-2}$$

Using subscripts V, L and 0 for water vapor, water liquid, and oxygen,

$$\tau_1 \simeq \tau_{V1} + \tau_{L1} + \tau_{01}, \text{ nepers} \tag{B-3}$$

and

$$\tau_2 \simeq \tau_{V2} + \tau_{L2} + \tau_{02}, \text{ nepers} \tag{B-4}$$

The total precipitable water vapor through the tropospheric line of sight is

$$\left.\begin{aligned} M_V &= \tau_{V1}/k_{V1} \\ &= \tau_{V2}/k_{V2} \end{aligned}\right\} \text{ cm} \tag{B-5}$$

and the total precipitable water liquid is

$$\left.\begin{aligned} M_L &= \tau_{L1}/k_{L1} \\ &= \tau_{L2}/k_{L2} \end{aligned}\right\} \text{ cm} \tag{B-6}$$

where

K_V, k_L = proportionality constants relating precipitable water to attenuation, nepers/cm

Also,

$$\begin{aligned} \tau_{V2}/\tau_{V1} &= k_{V2}/k_{V1} \\ &= K_V \end{aligned} \tag{B-7}$$

and

$$\begin{aligned} \tau_{L2}/\tau_{L1} &= k_{L2}/k_{L1} \\ &= K_L \end{aligned} \tag{B-8}$$

Combining and solving for M_V and M_L, in terms of T_1 and T_2, assuming all constants are "known,"

$$M_V \simeq a_1\,(T_1 - T_s) + a_2\,(T_1 - T_s)^2 + a_3\,(T_2 - T_s) + a_4\,(T_2 - T_s)^2 + a_5, \text{ cm} \tag{B-9}$$

and

$$M_L \simeq b_1\,(T_1 - T_s) + b_2\,(T_1 - T_s)^2 + b_3\,(T_2 - T_s) + b_4\,(T_2 - T_s)^2 + b_5, \text{ cm} \tag{B-10}$$

where (assuming $(B/A) \simeq -(1/2)$ as in Eq. 7),

$$a_1 = -k_L/kk_{V1}\,(T_p - T_s) \qquad b_1 = k_V/kk_{L1}\,(T_p - T_s)$$

$$a_2 = a_1/2(T_p - T_s) \qquad b_2 = b_1/2(T_p - T_s)$$

$$a_3 = 1/kk_{V1}\,(T_p - T_s) \qquad b_3 = -1/kk_{L1}\,(T_p - T_s)$$

$$a_4 = a_3/2(T_p - T_s) \qquad b_4 = b_3/2\,(T_p - T_s)$$

$$a_5 = -(\tau_{02} - k_L\,\tau_{01})/kk_{V1} \qquad b_5 = (\tau_{02} - k_V\,\tau_{01})/kk_{L1}$$

$$k = k_V - k_L$$

This allows monitoring of M_V and M_L from measurements of T_1 and T_2. S. C. Wu (Ref. 17) has investigated optimum frequency selection. The constants in Eqs. (B-9) and (B-10) can either be evaluated from the definitions above or from direct tropospheric calibrations (from radiosonde balloons, etc.). For estimates of these constants, use the same values as in the example (or Appendix A for f_1 = 20.6 GHz and for f_2 = 31.6 GHz, $k_{V2} \simeq 0.0256$ (Ref. 14), $k_{L1} \simeq 0.743$ (Ref. 16), $k_{L2} \simeq 1.75$ (Ref. 16), $\tau_{02z} \simeq 0.0224$ (Ref. 13)) to obtain[3]

$$M_V \simeq \left.\begin{array}{l} 0.11\,(T_1 - T_s) + 0.00020\,(T_1 - T_s)^2 \\ -\,0.048\,(T_2 - T_s) - 0.000086\,(T_2 - T_s)^2 \\ -\,0.064 \cos Z \end{array}\right\} \text{cm} \tag{B-11}$$

[3]Hogg (Ref. 18) has $M_V \simeq 0.11\ T_1 - 0.053\ T_2 - 0.18$ and $M_L \simeq -0.0011\ T_1 + 0.0027\ T_2 - 0.17$ appropriate for the zenith climatology of Denver, Colorado. The biggest difference between these expressions is the constants term for M_L (accounting for $T_s \simeq 2.7$ K).

and

$$M_L \simeq \left.\begin{array}{l} -\,0.0016\,(T_1 - T_s) - 0.0000029\,(T_1 - T_s)^2 \\ +\,0.0027\,(T_2 - T_s) + 0.0000048\,(T_2 - T_s)^2 \\ -\,0.013 \cos Z \end{array}\right\} \text{cm} \tag{B-12}$$

The increase in propagation path length due to both water vapor and liquid water is (Ref. 15)

$$\Delta\ell \simeq 6.48\,M_V + 1.45\,M_L,\ \text{cm} \tag{B-13}$$

or, in terms of T_1 and T_2, for this example,

$$\Delta\ell \simeq \left.\begin{array}{l} 0.71\,(T_1 - T_s) + 0.0013\,(T_1 - T_s)^2 \\ -\,0.31\,(T_2 - T_s) - 0.00056\,(T_2 - T_s)^2 \\ -\,0.43 \cos Z \end{array}\right\} \text{cm} \tag{B-14}$$

Inspection of the above equations indicates that most of the tropospheric delay is due to the water vapor and very little from the liquid water. The primary effect of the liquid water is to alter the noise temperature measurements.

If it is required that the constants of Eqs. (B-13) and (B-14) be determined from direct radiometer calibrations, constants a_2, a_4, b_2 and b_4 might best be determined analytically as in the example. This is suggested due to the difficulty of direct calibration of these small second-order terms.

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