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# Computer Program Descriptions

## TROPOSPHERIC ABSORPTION AND DISPERSION OF MILLIMETER AND SUBMILLIMETER WAVES

NAME: TROPOSPHERIC ABSORPTION AND DISPERSION FOR TERRESTRIAL OR EARTH-SATELLITE PATH.

PURPOSE: To compute the complex refractive index of the troposphere for frequencies from 1 to 1000 GHz: in particular, the amplitude and phase dispersion due to molecular oxygen and water vapor lines and the attenuation by suspended water droplets (radii $\leqslant$ 20 $\mu$m) such as haze, fog, and clouds.

LANGUAGE: Extended Basic (HP 9845S).[1]

AUTHORS: K. C. Allen and H. J. Liebe are with the National Telecommunications and Information Administration, Institute for Telecommunication Sciences, Boulder, CO 80302.

AVAILABILITY: ASIS-NAPS document NAPS-03988.

DESCRIPTION: This is a user-oriented program with descriptive comment statements. Inputs are prompted interactively on the cathode-ray-tube (CRT) display. Graphical output is selectively displayed on the CRT or plotted in ink on paper (e.g. with an hp 9872A).[1] A tabular output is available on the internal line printer.

The three components for air of the complex refractivity $N$ (in units of parts per million)

$$N = N_0 + D(f) + jN''(f) \tag{1}$$

namely, the frequency independent refrac..vity $N_0$ plus a refractive dispersion $D(f)$ and absorption $N''(f)$ are computed by this program. The frequency $f$ is in GHz throughout. The frequency-independent refractivity is computed using

$$N_0 = (n-1)10^6 = [2.589p + (41.6\theta + 2.39)e]\theta \tag{2}$$

where $n$ is the dimensionless refractive index, $p$ is the dry air pressure in kPa, $e$ is the water vapor partial pressure in kPa (barometric pressure $P = p + e$), and $\theta = 300/T$ is the relative inverse temperature (T in K), [1].

The computation of $D(f)$ and $N''(f)$ is based on the model of Liebe [2]. The imaginary (absorption) part of the refractive index is computed according to

$$N''(f) = \sum_i (SF'')_i + N_c'' + N_w''. \tag{3}$$

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[1] This is not an endorsement of these items.

and the real (dispersive) part follows analogously from

$$D(f) = \sum_i (SF')_i + N_c' + N_w'. \tag{4}$$

The summations represent the contributions of the resonant line spectra of atmospheric species where $S$ is the line strength in kilohertz and the line shape factors are $F'$ and $F''$ in (GHz)$^{-1}$. Water vapor lines above 1 THz are lumped into the continuum terms $N_c''$ and $N_c'$. The contribution from suspended water droplets are represented by the terms $N_w'$ and $N_w''$. The summations are computed for 44 $O_2$ lines plus 29 $H_2O$ lines below 1 THz (line spectra of trace gases, $O_3$, CO, $N_2O$, $SO_2$, $NH_3$, etc. are neglected). Also, weaker $H_2O$ lines, with center line intensity less than $2 \times 10^{-3}$ dB/km, are not considered. These simplifications result in a large increase in computation efficiency compared with line-by-line programs such as the Air Force Geophysical Laboratory tape [3].

The Van Vleck-Weisskopf line shape factors

$$F'' = \left(\frac{f}{\nu_0}\right)\left[\frac{\gamma - (\nu_0 - f)\delta}{(\nu_0 - f)^2 + \gamma^2} + \frac{\gamma - (\nu_0 + f)\delta}{(\nu_0 + f)^2 + \gamma^2}\right] \tag{5}$$

and

$$F' = \left[\frac{(\nu_0 - f) + \gamma\delta}{(\nu_0 - f)^2 + \gamma^2} + \frac{(\nu_0 + f) - \gamma\delta}{(\nu_0 + f)^2 + \gamma^2} - \frac{2}{\nu_0}\right] \tag{6}$$

as modified by Rosenkranz [4] are used where $\nu_0$ is the line center frequency, $\gamma$ is the line width (both in GHz), and $\delta$ is the overlap interference parameter. A line-data base [2] consisting of $\nu_0$ and the spectroscopic coefficients $a_{1-5}$ and $b_{1-3}$ is used with the meterological conditions to compute the line parameters as follows. For $O_2$ in air:

$$S = a_1 p\theta^3 \exp[a_2(1-\theta)] \tag{7a}$$

$$\gamma = a_3(p + 1.3e)\theta^{0.9} \tag{7b}$$

$$\delta = a_4 p\theta^{a_5}. \tag{7c}$$

For $H_2O$ in air:

$$S = b_1 e\theta^{3.5} \exp[b_2(1-\theta)] \tag{8a}$$

$$\gamma = b_3(4.80e + p)\theta^{0.6} \tag{8b}$$

$$\delta = 0. \tag{8c}$$

The continuum spectrum $N_c''$ consists of $N_v''$, the far-wing absorption by strong infrared $H_2O$ lines, plus $N_d''$, the nonresonant dry air spectrum. The dispersive part, $N_c'$, which is nearly zero, is neglected. Absorption by the infrared lines is computed by

$$N_v'' = 1.9fep\theta^{3.1} \times 10^{-6}. \tag{9a}$$

Equation (9a) is an empirical expression [5] which, so far, has not found a generally acceptable theoretical explanation. The non-resonant air spectrum is computed using

$$N_d'' = 6.2fp\theta^2 \times 10^{-4} \cdot \{[\gamma_0/(f^2 + \gamma_0^2)] + 2.1p\theta^{0.5} \times 10^{-7}\} \tag{9b}$$



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where the first term in the braces is due to $O_2$ and the second to $N_2$. The width $\gamma_0$ is calculated with (7b) using a spectroscopic coefficient of $a_3 = 0.012$, although the value $a_3 = 0.0056$ was found [1] using Rosenkranz's [4] scheme to fit laboratory data.

The liquid water extinction $N''_w$ (3) of droplets with radii smaller than 20 $\mu$m (cloud, fog, haze, aerosol hydrometeors) is computed with the Rayleigh absorption approximation

$$N''_w = 4.49w\epsilon''/[(\epsilon' + 2)^2 + (\epsilon'')^2] \qquad (10)$$

of Mie scattering losses where $w$ is the liquid water content in g/m$^3$. The $f$- and $\theta$- dependence of dielectric data ($\epsilon'$, $\epsilon''$) of bulk water are calculated with the Debye model detailed in [6]. For frequencies above 300 GHz, the rough approximation

$$N''_w \approx 0.55wf^{-0.1}\theta^{-6} \qquad (11)$$

is used. The dispersive part $N'_w$ is neglected since it is very broad band and is less than 1 ps/km for each 1 g/m$^3$ of liquid water content.

The specific power attentuation $\alpha$ in dB/km and the excess dispersion propagation delay time $t$ in ps/km are computed by

$$\alpha = 0.1820fN'' \qquad (12)$$

and

$$t = 3.336D. \qquad (13)$$

The output of the program is the attenuation and excess dispersion delay for the chosen path. A sample output is given in Fig. 1. When running the program, the minimum, maximum, and spacing of the frequencies for which the refractivity is to be computed are input along with the selection of a terrestrial or earth-satellite path. For a terrestrial path, the barometric pressure, relative humidity, atmospheric temperature, liquid water content in g/m$^3$, and path length are input. If the specific attenuation (dB/km) is desired, then the path length is set to one kilometer. For an earth-satellite path, the path elevation angle and ground terminal elevation above sea level are input. An eight-point tropospheric profile of the meteorologic parameters is read from data statements by subroutine "Profilel" and used for path computations. The user can provide an alternate profile. The cosecant function is used to compute the elevation angle dependence of path attenuation and delay, and therefore the program should only be used for path elevation angles greater than 6°. The attenuation and delay through each layer are summed to give the path total.

Above about 30 km, Zeeman splitting of $O_2$ lines due to the geomagnetic field occurs. Since the program does not include this effect, output for earth-satellite paths may be inaccurate for frequencies closer than 100 MHz to an $O_2$ line. The profile of meteorologic parameters should be extended into the mesophere for high flying aircraft-to-satellite path applications.

Subroutine "Gasl" computes the specific attenuation and delay from the meteorologic data. It is felt that this routine along with the resonance line data would be of interest to users desiring to write programs of their own concerning tropospheric dispersion.

The execution time of the program requires approximately 7 s for each frequency and set of meteorologic conditions. Programs in Fortran IV, including the mesosphere and addressing the Zeeman effect of $O_2$ lines, are available also from the authors.

## REFERENCES


[1] H. J. Liebe, G. G. Gimmestad, and J. D. Hopponen, "Atmospheric oxygen microwave spectrum—Experiment versus theory," *IEEE Trans. Antennas Propagat.*, vol. AP-25, no. 3, pp. 327–335, May 1977.

[2] H. J. Liebe, "Modeling attenuation and phase of radio wave in air at frequencies below 1000 GHz," *Radio Sci.*, vol. 16, no. 6, pp. 1183–1199, Nov.–Dec. 1981.

[3] L. S. Rothman, AFGL atmospheric absorption line parameters computation: 1980 version, *Appl. Opt.*, vol. 20, no. 5, pp. 791–795, 1981.

[4] P. W. Rosenkranz, "Shape of the 5 mm oxygen band in the atmosphere," *IEEE Trans. Antennas Propagat.*, vol. AP-23, no. 4, pp. 498–506, July 1975.

[5] J. R. Waters, "Absorption and emission by atmospheric gases," *Methods of Experimental Physics*, vol. 12B, M. L. Meeks, Ed. New York: Academic, 1976.

[6] A. T. Chang and T. T. Wilheit, "Remote sensing of atmospheric water vapor, liquid water, and wind speed at the ocean rface by passive microwave techniques from the NIMBUS 5 satellite," *Radio Sci.*, vol. 14, no. 5, pp. 793–802, Sept.–Oct. 1979.