SIMPLIFICATION OF THE OXYGEN-ABSORPTION COEFFICIENT FORMULA IN MICROWAVE BAND

Zhao Bolin (赵柏林), *Liu Wen* (刘 雯) and *Tang Chengxian* (唐承贤)

Department of Geophysics, Peking University, Beijing

Received June 14, 1989

ABSTRACT

Study of the oxygen-absorption coefficient in 5mm wave band is important for remote sensing of the atmospheric temperature profile from satellites or ground. In order to obtain the atmospheric temperature profile rapidly and accurately, it is necessary to have a simple, but accurate formula of the oxygen-absorption coefficient. In this paper, formulae of the oxygen-absorption coefficient in a certain range of temperature-pressure and at a standard isobaric surface have been derived. These formulae may substitute for Meeks-Lilley formula in remote sensing of the atmosphere.

I. SIMPLIFICATION OF THE OXYGEN-ABSORPTION COEFFICIENT FORMULA IN 5mm BAND

In 5 mm band, atmospheric emission is mainly caused by oxygen molecules. This wave band is usually used in remote sensing of the atmospheric temperature profile. From radiative transfer equation, it is obvious that the oxygen-absorption coefficient at different temperatures and pressures must be known in advance in remote sensing of the atmospheric temperature.

In microwave band, 46 resonant lines are produced by the transitions of quantum state of molecular oxygen and can be differently broadened with changing temperature and pressure. Therefore, it is very complicated to derive the oxygen-absorption coefficient. Van Vleck and Weisskopf (1945) and Gross (1955) derived a quantum-mechanical formula for microwave absorption coefficient and its pressure line broadening factor. Meeks and Lilley (1963) suggested an oxygen-absorption formula from semi-classical and semi-quantum theory. Carter et al. (1968) observed atmospheric emission and absorption from the surface and high altitudes and derived the line shape parameter from observational data with maximum likelihood method. The formula derived by Van Vleck et al. is often used in remote sensing. But it has complicated characteristics and requires too much calculation time. Recently remote sensing has been used in weather forecasting, especially in nowcasting, so it is necessary to save calculation time. Many scientists begin to search for some simplified formulae of the oxygen-absorption coefficient. For example, Poon (1977) suggested an exponential function, which can be used in the absorption band instead of Meeks-Lilley formula,

$$A=K_s\left(\frac{p}{p_s}\right)^x\left(\frac{T}{T_s}\right)^y,$$

where K_s, x and y are functions of frequency. Compared with Meeks-Lilley formula, however, the mean deviation of the above formula reaches 8%. This accuracy is insufficient for remote sensing of the atmospheric temperature. In order to meet the demand of nowcasting and reduce computing time, it is necessary for remote sensing of the atmospheric temperature to develop a new, simple and accurate formula of the oxygen-absorption coefficient.

1. *Principle*

In remote sensing of the atmospheric temperature, the absorption of molecular oxygen is chosen to investigate. Retrieval of the atmospheric temperature profile is conducted by means of analysis of radiative intensity of molecular oxygen. The microwave spectrum of O_2 consists of 45 lines in the wavelength range from 4 to 6 mm and a single line at 2.53mm.

The oxygen-absorption formula derived by Meeks-Lilley (1963) and verified by Carter et al. (1968) is

$$\alpha_{O_2}=CPT^{-3}\nu^2\sum_N S_N \exp\left(-\frac{E_N}{kT}\right)\mathrm{dB/km}\ , \tag{1}$$

$$N=1,3,\cdots,45,$$

where $C=2.6742$, P is pressure (mmHg), T temperature (K), ν frequency (GHz), k Boltzmann constant and E_n energy level. Note that

$$\frac{E_N}{kT}=2.06844\frac{N(N+1)}{T},$$

$$S_N=|\mu_{N+}|^2F_{N+}+|\mu_{N-}|^2F_{N-}+|\mu_{N0}|^2F_0,$$

with

$$|\mu_{N+}|^2=\frac{N(2N+3)}{(N+1)},$$

$$|\mu_{N-}|^2=\frac{(N+1)(2N-1)}{N},$$

$$|\mu_{N_0}|^2=\frac{2(N^2+N+1)(2N+1)}{N(N+1)},$$

$$F_{N+}=\frac{\Delta\nu}{[(\nu_{N+}-\nu)^2+\Delta\nu^2]}+\frac{\Delta\nu}{[(\nu_{N+}+\nu)^2+\Delta\nu^2]},$$

$$F_{N-}=\frac{\Delta\nu}{[(\nu_{N-}-\nu)^2+\Delta\nu^2]}+\frac{\Delta\nu}{[(\nu_{N-}+\nu)^2+\Delta\nu^2]},$$

$$F_0=\frac{\Delta\nu}{(\nu^2+\Delta\nu^2)},$$

where $|\mu_{N+}|^2$, $|\mu_{N-}|^2$, $|\mu_{N0}|^2$ are the squares of matrix element for transition of molecular oxygen, F_{N+}, F_{N-}, F_0 the factors of line shape, ν_{N+}, ν_{N-} the resonant frequencies (see Appendix I).

The half-width of the line $\Delta\nu$ is given by

$$\Delta\nu=g^*(p)\left(\frac{p}{p_0}\right)\left(\frac{T_0}{T}\right),$$

where $p_0=1013.25$hPa, $T_0=300$K, p is pressure (hPa), T temperature (K), and

$$g^*(p)=\begin{cases}0.64\mathrm{GHz}\ , & p\geqslant 333\mathrm{hPa}\\ 0.64+0.717\dfrac{333-p}{333-25}, & 25<p<333\mathrm{hPa}\\ 1.357\mathrm{GHz}. & p\leqslant 25\mathrm{hPa}\end{cases}$$

The above formula is available in the atmosphere below 40 km.

For atmospheric remote sensing, the radiative transfer equation is

$$T_b=T_\infty e^{-\int_0^\infty \alpha\sec\theta dz}+\int_0^\infty T\alpha\sec\theta e^{-\int_0^z \alpha\sec\theta dz}dz, \quad (2)$$

where T_b is the brightness temperature measured at the ground surface, T_∞ the cosmic background temperature (~2.7K), and α the absorption coefficient, which is the sum of absorption coefficients of oxygen and water vapor.

Brightness temperature may be measured with angle scanning or frequency scanning, then the atmospheric temperature profile can be derived from Eq. (2).

In angle scanning observations the frequencies $\nu=52.8$—52.9GHz and $\nu=54.4$—54.5 GHz are often used for retrieval of the atmospheric temperature. The former is used for remote sensing of the atmospheric temperature below 10 km, and the latter for below 3 km.

2. *The Method of Formula Simplification*

The oxygen-absorption coefficient changes with pressure, temperature and frequency, which can be expressed as

$$\alpha_{O_2}=T^x p^y f(T,p).$$

(1) *Temperature range*

There are two domains: high and low temperature domains. The average temperature lapse rate $\gamma=0.0065$°C/m≈0.05°C/hPa (see Fig. 1).

At 1000hPa level, the central temperature of high temperature domain (265—315K) is 290K. For the low temperature domain (225—275K), its central temperature is 250K. Let the central temperature T_0 vary with height as follows:

$$T_0=T_0^*+\frac{p}{20}\mathrm{K}.$$

where $T_0^*=200$K for the low temperature domain, and $T_0^*=240$K for the high temperature domain. Both of domains have a temperature range of 50K. p is pressure (hPa).

(2) *Pressure parameter*

1) The oxygen-absorption coefficient on certain standard isobaric surfaces

From the surface upward, a set of isobaric surfaces are divided. The regression of the oxygen-absorption coefficient on isobaric surfaces with different temperatures has been carried out. The isobaric surfaces are taken as 1040, 1020, 1000, 970, 930, 900, 850, 800, 700, 600, 500, 400, 300 and 200hPa.

The regression formula is

$$\alpha_{O_2}=T^{C_0}\exp[C_1(T_1-T_0)^2+C_2], \quad (3)$$

where C_0, C_1 and C_2 are parameters changing with pressure and frequency. Their dependence on pressure is shown in Figs. 2—4.

2) The oxygen-absorption coefficient under different pressures

$$\alpha_{O_2}=T^{ap^2+bp+c}p^d\exp\left[(\gamma p+S)\left(T-T_0^*-\frac{p}{20}\right)^2+K(p-p_0)^2+C_3\right], \quad (4)$$

where parameters a, b, c, d, γ, S, K, C_3 and p_0 change with pressure. Their dependence on pressure is shown in Appendix 2.

Formulae (3) and (4) have been obtained independently in statistics. Tables 1 and 2 present their characteristics.

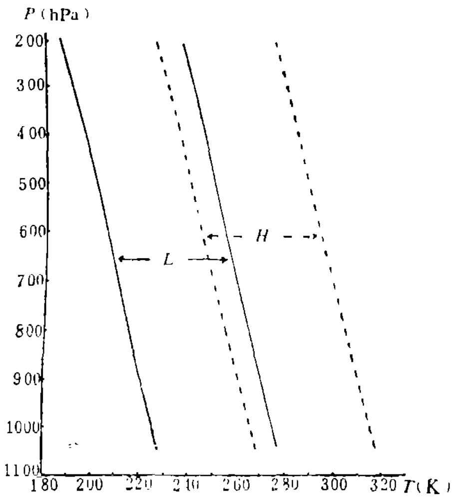

Fig. 1. Temperature range.
L: low temperature domain;
H: high temperature domain.

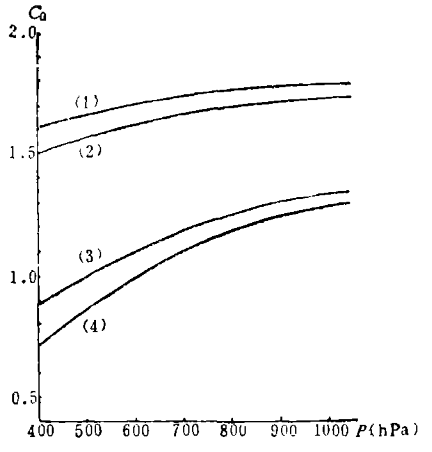

Fig. 2. C_0 vs pressure.
Curves 1 and 2 are for 52.8 and 52.9 GHz low temperature domains, respectively; 3 and 4 for 52.8 and 52.9 GHz high temperature domians.

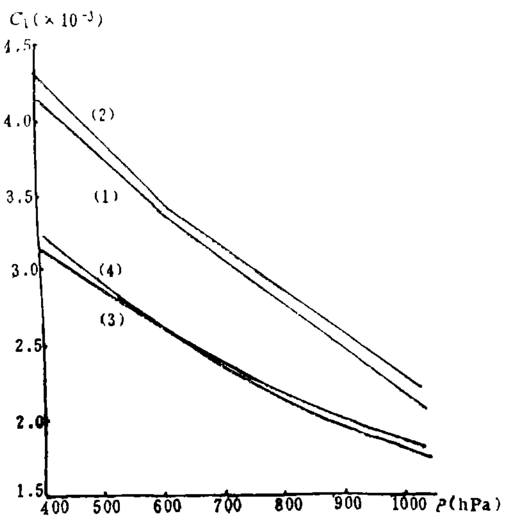

Fig. 3. As in Fig. 2, but for C_1.

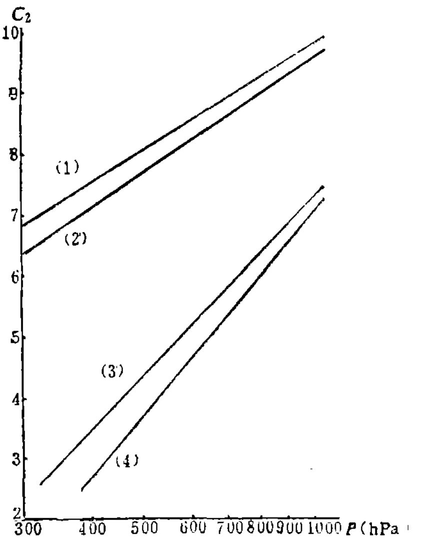

Fig. 4. As in Fig. 2, but for C_2.

3) Discussion

Poon (1977) suggested a power function to express the oxygen-absorption coefficient, i.e., $\alpha_{O_2}=CT^x p^y$.

If frequency is at the valley between two resonant lines, then $0<y<2$ and y is closer to 2; if frequency is at the center of resonant frequency, then y approximates zero. The chosen frequencies 52.8, 52.9, 54.4 and 54.5 GHz, are all located at the valley of oxygen absorption spectrum, hence $y=2$. However, from formula (4) we have

$$\frac{d\ln \alpha_{O_2}}{d\ln p}\approx 2.$$

The result is in agreement with that of Poon. However, the error of Poon's formula in remote sensing of the lower atmospheric temperature is too much.

Table 1. The Oxygen-Absorption Coefficient under Different Temperatures and Pressures

Frequency (GHz)	Formula*	Valid range	Maximum error	Speed ratio**
52.8 52.9	$\alpha_{O_2}=T^{ap^2+bp+c}p^d\exp\left[(\gamma p+s)\times\left(T-T_0^*-\frac{p}{20}\right)+K(p-p_0)^2+C_3\right]$	400hPa$\leqslant p\leqslant$1040hPa	5‰	15
54.4 54.5	ibid	650hPa$\leqslant p\leqslant$1040hPa	5‰	15

* Parameters a,b,c,d,γ, s,K,C_3 and p_0 change with frequency (see Appendix).
** Speed ratio is defined as a reciprocal of ratio of the time needed for calculating the oxygen-absorption coefficient on microcomputer in terms of the simplified formula to formula (1).

Table 2. The Oxygen-Absorption Coefficient under Certain Standard Pressures and Different Temperatures

Frequency (GHz)	Formula*	Valid range	Maximum error	Speed ratio
52.8 52.9 54.4 54.5	$\alpha_{O_2}=T^{c_0}\exp[C_1(T-T_0)^2+C_2]$	any pressure	8×10^{-4}	40

* Parameters C_0, C_1 and C_2 change with pressure and frequency (see Appendix).

Let the oxygen-absorption coefficient formula be

$$\alpha_{O_2}=C'T^{\gamma' p+s'}p^{d'}.$$

At frequencies 52.8, 52.9, 54.4 and 54.5GHz, the maximum deviation between the results obtained from formula (1) and the above formula reaches 15%. It is obvious that the error is too much in remote sensing of the atmospheric temperature. This fact implies that the dependence of the oxygen-absorption coefficient on temperature-pressure is complicated.

In spite of the complexity of the relation between the oxygen-absorption coefficient in absorption band and temperature-pressure, we can still use formula (3) or (4) instead of (1). This is because their accuracy meets the demand of remote sensing and the calculation time of these formulae is 15—40 times shorter than that of formula (1).

II. THE SIMPLIFICATION OF OXYGEN-ABSORPTION COEFFICIENT FORMULA IN MICROWAVE WINDOW

1. *Formula Simplification*

9.37, 19.4, 22.235, 35.3 and 90GHz are often used as frequencies of remote sensing. Take the oxygen-absorption coefficient calculated with formula (1) as a standard and make a comparison between it and the result of simplified formula. The simplified formula can be obtained by regression:

$$\alpha_{O_2}=C'T^{\gamma' p+S'}p^{d'}\text{dB/km}, \tag{5}$$

where $\gamma'=7\times10^{-6}$, $S'=-2.97$, $d'=1.97$ and parameter C' changes with frequency. It is available for both high and lower temperature domains when $340\leqslant p\leqslant 1050$hPa (see Table 3).

Table 3. Parameter C' vs Frequency

Frequency (GHz)	9.37	19.4	22.235	35.3	90
C'	0.2004	0.2444	0.2695	0.5985	1.8885
Maximum relative error(%)	<1.5	<1.5	<1.5	<1.5	<1.5

2. *Discussion*

In microwave window, the simplified formulae of the oxygen-absorption coefficient are discussed hereafter.

(1) *The first simplified type*

In waveband $\lambda=0.8-0.3$cm, the oxygen-absorption coefficient may be expressed as

$$\alpha_{O_2}=C_\lambda p^2T^{-2.8}, \tag{6}$$

where p is pressure in mmHg (1mmHg=1.333hPa), and $C_\lambda=0.662$, 0.328, 0.131, 0.108 for $\lambda=0.8$, 1.0, 2.0, 3.0 cm, respectively. The deviation between the oxygen-absorption coefficients derived from formulae (6) and (1) reaches 10%. For remote sensing, the accuracy of formula (6) is not enough.

(2) *The second simplified type*

When frequency is smaller than 45GHz, the effect of the resonant line $\nu_{1-}=118.7503$ GHz may be neglected. With the summation over the rotational states specified by $N<39$ (except ν_{1-}), the resulting expression for the oxygen-absorption coefficient is

$$\alpha_{O_2}=1.1\times10^{-2}\nu^2\left(\frac{p}{1013}\right)\left(\frac{300}{T}\right)^2\Delta\nu\left[\frac{1}{(\nu-60)^2+\Delta\nu^2}+\frac{1}{(\nu+60)^2+\Delta\nu^2}\right], \tag{7}$$

where

$$\Delta\nu=\Delta\nu_0\left(\frac{p}{1013}\right)\left(\frac{300}{T}\right)^{0.85}\text{GHz}$$

$$\Delta\nu_0=\begin{cases}0.59, & p\geqslant 333\text{hPa}\\ 0.59[1+3.1\times10^{-3}(333-p)], & 25\leqslant p\leqslant 333\text{hPa}\\ 1.18. & p\leqslant 25\text{hPa}\end{cases}$$

Note that pressure p is measured in hPa. The result of formula (7) is always smaller than that of formula (1), and the accuracy of formula (7) can not meet the demand of remote sensing.

In microwave window band, the deviation between the oxygen-absorption coefficients derived with formulae (5) and (1) is less than 1.5%, and calculation time of formula (5) is 40 times shorter than that of formula (1).

In atmospheric remote sensing, the iterative method is often used in retrieval process. Thus calculation needs to be done again and again and a lot of time is occupied to deal with the oxygen-absorption coefficient. In view of this problem, we suggest that formulae (3)—(5) may be used in calculation of the oxygen-absorption coefficient. They have not only enough accuracy for remote sensing, but also much faster speed than that of formula (1), saving much time in data processing and hence convenient for nowcasting.

APPENDIX 1. OXYGEN TRANSITION FREQUENCY

N	ν_{N^+}(GHz)	ν_{N^-}(GHz)
1	56.2648	118.7505
3	58.4466	62.4863
5	59.5910	60.3061
7	60.4348	59.1642
9	61.1506	58.3239
11	61.8002	57.6125
13	62.4112	56.9682
15	62.9980	56.3634
17	63.5685	55.7839
19	64.1272	55.2214
21	64.6779	54.6728
23	65.2240	54.1294
25	65.7626	53.5960
27	66.2978	53.0695
29	66.8313	52.5458
31	67.3627	52.0259
33	67.8923	51.5091
35	68.4205	50.9949
37	68.9478	50.4830
39	69.4741	49.9730
41	70.0000	49.4648
43	70.5249	48.9582
45	71.0497	48.4530

APPENDX 2. PARAMETERS OF FORMULA

$$\alpha_{O_2}=T^{ap^2+bp+c}p^d\exp\left[(\gamma p+s)\left(T-T_0^*-\frac{p}{20}\right)^2-K(p-p_0)^2+C_3\right]\text{dB/km}$$

(T in K, p in hPa)

(1) *High temperature domain* $T_0^*=240\text{K}$, $\Delta T=50\text{K}$

Frequency (GHz)	$a(\times10^{-7})$	$b(\times10^{-3})$	c	d	γ	s	$K(\times10^{-6})$	C_3	p_0
52.8	5.93	−1.53	−0.368	4.23	-2×10^{-8}	3.4×10^{-5}	−1.44	−21.843	812
52.9	5.93	−1.53	−0.368	4.21	-2×10^{-8}	3.4×10^{-5}	−1.44	−21.645	812
54.4	2.42	−1.1	−0.185	4.40	-7.2×10^{-10}	6.7×10^{-6}	1.0	−23.568	765
54.5	2.42	−1.1	−0.185	4.35	-7.2×10^{-10}	6.7×10^{-6}	1.0	−23.160	765

(2) *Low temperature domain* $T_0^* = 200\text{K},\ \Delta T = 50\text{K}$

Frequency (GHz)	$a(\times 10^{-7})$	b	c	d	$\gamma(\times 10^{-8})$	$s(\times 10^{-5})$	$K(\times 10^{-8})$	C_3	p_0
52.8	3.7	-7.68×10^{-4}	−1.358	2.71	−3.2	5.4	−1.32	−8.774	720
52.9	3.7	-7.68×10^{-4}	−1.358	2.68	−3.2	5.4	−1.32	−8.515	720
54.4	6.98	-1.8×10^{-3}	−0.140	4.35	−1.3	2.7	−1.8	−22.006	815
54.5	6.98	-1.8×10^{-3}	−0.140	4.30	−1.3	2.7	−1.8	−21.584	815

APPENDIX 3. PARAMETERS OF FORMUIA

$$\alpha_{O_2} = T^{C_0}\exp[C_1(T-T_0)^2 + C_2]\,\text{dB/km}$$
$$(T \text{ in K},\ p \text{ in hPa})$$

(1) *Low temperature domain* $T_0 = 200 + \dfrac{p}{20}\text{K},\ \Delta T = 50\text{K}$

1) 52.8GHz

p (hPa)	C_0	$C_1(\times 10^{-5})$	C_2	T_0	ΔT	Max. E_R $(\times 10^{-4})$
1040	−1.75733	2.08	9.9258	252	227—277	3
1020	−1.75621	2.14	9.8853	251	226—276	3
1000	−1.75197	2.20	9.8433	250	225—275	3
970	−1.75250	2.30	9.7761	248.5	223—273	3
930	−1.74931	2.41	9.6830	246.5	222—272	3
900	−1.74614	2.50	9.6070	245	220—270	3
850	−1.74020	2.65	9.4718	242.5	217—267	3
800	−1.73299	2.80	9.3231	240	215—265	3
700	−1.71457	3.10	8.9804	235	210—260	3
600	−1.68826	3.40	8.5558	230	205—255	3.5
500	−1.65151	3.80	8.0211	225	200—250	5
400	−1.60208	4.15	7.3402	220	195—245	4.5

2) 52.9 GHz

p(hPa)	C_0	$C_1(\times 10^{-5})$	C_2	T_0	ΔT	Max. E_R $(\times 10^{-4})$
1040	−1.71268	2.20	9.7332	252	227—277	2.5
1020	−1.71090	2.25	9.6804	251	226—276	2.6
1000	−1.70896	2.30	9.6441	250	225—275	2.6
970	−1.70550	2.38	9.5715	248.5	223—273	2.6
930	−1.70061	2.50	9.4705	246.5	222—272	2.8
900	−1.69618	2.57	9.3881	245	220—270	2.7
850	−1.68787	2.71	9.2410	242.5	217—267	2.7
800	−1.67793	2.84	9.0786	240	215—265	2.7
700	−1.65251	3.12	8.7005	235	210—260	2.7
600	−1.61567	3.42	8.2218	230	205—255	3.7
500	−1.56142	4.00	7.5964	225	200—250	3.7
400	−1.47985	4.66	6.7491	220	195—245	4.6

3) 54.4 GHz

p (hPa)	C_0	$C_1(\times 10^{-5})$	C_2	T_0	ΔT	Max. E_R ($\times 10^{-4}$)
1040	−1.28527	1.36	8.2887	252	227—277	3.4
1020	−1.27673	1.40	8.2145	251	226—276	3.4
1000	−1.26786	1.43	8.1380	250	225—275	3.5
970	−1.25346	1.48	8.0160	248.5	223—273	3.4
930	−1.23354	1.54	7.8473	246.5	222—272	3.6
900	−1.21706	1.55	7.7105	245	220—270	3.6
850	−1.18770	1.70	7.4683	242.5	217—267	3.7
800	−1.15527	1.72	7.2044	240	215—265	3.7
700	−1.08102	1.85	6.6070	235	210—260	4.3
600	−0.99086	1.98	5.8924	230	205—255	4.9
500	−0.88356	2.03	5.0424	225	200—250	5.8

4) 54.5 GHz

p (hPa)	C_0	$C_1(\times 10^{-5})$	C_2	T_0	ΔT	Max. E_R ($\times 10^{-4}$)
1040	−1.2786	1.30	8.3167	252	227—277	3.3
1020	−1.2698	1.35	8.2147	251	226—276	3.3
1000	−1.2606	1.36	8.1639	250	225—275	3.3
970	−1.2457	1.40	8.0401	248.5	223—273	3.3
930	−1.2250	1.45	7.8670	246.5	222—272	3.5
900	−1.2143	1.50	7.6681	245	220—270	3.2
850	−1.1769	1.54	7.4795	242.5	217—267	3.5
800	−1.1424	1.60	7.2062	240	215—265	3.6
700	−1.0615	1.82	6.5771	235	210—260	4.1
600	−0.9587	1.94	5.7997	230	205—255	4.6
500	−0.8266	2.10	4.8254	225	200—250	5.7

ΔT: Valid temperature range; Max. E_R: Maximum relative error

(2) *High temperature domain* $T_0=240+\frac{p}{20}\mathrm{K}$, $\Delta T=50\mathrm{K}$

1) 52.8 GHz

p (hPa)	C_0	$C_1(\times 10^{-5})$	C_2	T_0	ΔT	Max. E_R ($\times 10^{-4}$)
1040	−1.32093	1.82	7.4849	292	267—317	3.0
1020	−1.31380	1.85	7.4125	291	266—316	3.0
1000	−1.30638	1.85	7.3337	290	265—315	3.0
970	−1.29437	1.87	7.2152	288.5	263—313	3.0
930	−1.27770	1.97	7.0510	286.5	262—312	3.0

(to be continued)

(continued)

p (hPa)	C_0	$C_1(\times 10^{-5})$	C_2	T_0	ΔT	Max. E_R ($\times 10^{-4}$)
900	−1.26401	2.02	6.9189	285	260—310	3.0
850	−1.23952	2.08	6.6852	282.5	257—307	3.0
800	−1.21252	2.18	6.4313	280	255—305	3.0
700	−1.15076	2.38	5.8631	275	250—300	3.1
600	−1.07575	2.63	5.1770	270	245—295	3.7
500	−0.98617	2.80	4.3647	265	240—290	4.4
400	−0.88385	3.10	3.4086	260	235—285	5.0

2) 52.9 GHz

p (hPa)	C_0	$C_1(\times 10^{-5})$	C_2	T_0	ΔT	Max. E_R ($\times 10^{-4}$)
1040	−1.27835	1.74	7.3005	292	267—317	2.6
1020	−1.27032	1.78	7.2234	291	266—316	2.7
1000	−1.26195	1.81	7.1437	290	265—315	2.7
970	−1.24839	1.86	7.0172	288.5	263—313	2.7
930	−1.22947	1.93	6.8412	286.5	262—312	2.8
900	−1.21382	2.00	6.6989	285	260—311	2.7
850	−1.18564	2.06	6.4460	282.5	257—307	2.8
800	−1.15418	2.17	6.1688	280	255—305	2.7
700	−1.08012	2.34	5.5316	275	250—300	3.4
600	−0.98524	2.66	4.7442	265	245—295	3.8
500	−0.86192	2.95	3.7526	260	240—290	4.5
400	−0.70094	3.24	2.4858	255	235—285	5.6

3) 54.4 GHz

p (hPa)	C_0	$C_1(\times 10^{-6})$	C_2	T_0	ΔT	Max. E_R ($\times 10^{-4}$)
1040	−1.07212	5.94	7.0970	292	267—317	2.0
1020	−1.06129	5.96	7.0109	291	266—316	2.0
1000	−1.05013	5.98	6.9225	290	265—315	2.1
970	−1.03255	6.02	6.7811	288.5	263—313	2.1
930	−1.00834	6.04	6.5932	286.5	262—312	2.1
900	−0.98900	6.06	6.4118	285	260—310	2.0
850	−0.95521	6.11	6.1774	282.5	257—307	2.0
800	−0.91921	6.16	5.8960	280	255—305	1.9
700	−0.84147	6.20	5.2844	275	250—300	2.8
600	−0.75685	6.25	4.6059	270	245—295	3.1

4) 54.5 GHz

p (hPa)	C_0	$C_1(\times 10^{-6})$	C_2	T_0	ΔT	Max. E_R ($\times 10^{-4}$)
1040	−1.07975	5.60	7.2052	292	267—317	1.8
1020	−1.06857	5.64	7.1177	291	266—316	1.9
1000	−1.05701	5.68	7.0275	290	265—315	1.9
970	−1.03872	5.72	6.8858	288.5	263—313	1.9
930	−1.01326	5.78	6.6892	286.5	262—312	1.9
900	−0.99277	5.85	6.5323	285	260—310	1.9
850	−0.95644	5.96	6.2555	282.5	257—307	1.9
800	−0.91693	6.05	5.9566	280	255—305	2.0
700	−0.82794	6.10	5.2874	275	250—300	2.3
600	−0.72910	6.15	4.5034	270	245—295	2.4

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