
SPECTROSCOPY
OF AMBIENT MEDIUM

Retrieval of Carbon Monoxide Total Column in the Atmosphere from High Resolution Atmospheric Spectra

T. Yu. Chesnokova^{a, *}, M. V. Makarova^b, A. V. Chentsov^a, Yu. V. Voronina^a, V. I. Zakharov^{c, d},
N. V. Rokotyanc, and B. Langerock^e

^a*V.E. Zuev Institute of Atmospheric Optics, Siberian Branch, Russian Academy of Sciences, Tomsk, 634055 Russia*

^b*St. Petersburg State University, St. Petersburg, 190334 Russia*

^c*B.N. Yeltsin Ural Federal State University, Yekaterinburg, 620002 Russia*

^d*Institute of Mathematics and Mechanics, Ural Branch, Russian Academy of Sciences, Yekaterinburg, 620990 Russia*

^e*Royal Belgian Institute for Space Aeronomy BIRA-IASB, Brussels, 1180 Belgium*

**e-mail: ches@iao.ru*

Received February 8, 2019; revised February 21, 2019; accepted February 22, 2019

Abstract—Carbon monoxide (CO) is a marker of the atmospheric pollution caused by fires and combustion engine emissions. The regular monitoring of the CO content in the atmosphere is needed to control air quality. In this work, the results of CO atmospheric total column retrievals from the solar spectra recorded by Fourier-transform spectrometers at the St. Petersburg (59.88° N, 29.83° E) and Kourovka (57.038° N, 59.545° E) stations are presented. The impact of differences in CO absorption line parameters in modern spectroscopic databases on the accuracy of the CO atmospheric total column retrieved from high resolution spectra is estimated.

Keywords: carbon monoxide, atmospheric transmission, spectroscopic databases

DOI: 10.1134/S1024856019040031

INTRODUCTION

Carbon monoxide (CO) is a toxic gas emitted into the atmosphere in abundance during the work of multiple engine types. It is also a marker of the biomass burning and anthropogenic pollution [1, 2]. CO plays an important role in atmospheric chemistry: it affects the concentration of hydroxyl (OH) and favors the formation of atmospheric ozone. During fires, the CO concentration in the atmosphere increases by several orders of magnitude [3]. To estimate the air quality and reveal the pollution sources, regular satellite and ground-based monitoring of the CO content in the atmosphere is carried out. Satellite spectroscopic measurements allow mapping the CO global distribution with a good spatial and temporal resolution. To determine CO, atmospheric spectra in thermal and near-IR ranges are used. For example, MOPITT satellite radiometers [2] record two CO absorption bands: 2.3 and 4.6 μm . The TROPOMI instrument installed at the European satellite *Sentinel* measures in the 2.3- μm band. The CrIS instrument onboard *Suomi* records in the band 4.6 μm [4]. Ground-based spectrometer measurements with high spectral resolution in the same absorption bands supplement satellite measurements and are used for satellite data validation.

A significant difference between the satellite and ground-based measurements is noted in [3, 5]. Thus,

the CO total column (TC) measured by satellite instruments was by 2–3 orders of magnitude lower as compared to ground-based solar spectrometer measurements during fires in certain summer days of 2010 in Moscow [3]. In that case, satellite data also significantly differed between each other. In order to use ground-based measurements for validation of satellite data, it is necessary to estimate spectroscopic errors appearing when solving the inverse problem of retrieval of the CO total column from high resolution solar spectra.

It was shown in [6, 7] that the use of various spectroscopic databases with absorption line parameters of atmospheric gases in the retrieval of TC of greenhouse gases, such as CH₄ and CO₂, from solar radiation spectra measured with the ground-based Fourier spectrometer can result in TC differences up to 2%. The use of the last versions of the spectroscopic databases does not always lead to a best agreement between the measured and modeled atmospheric spectra. It would be interesting to study the influence of spectroscopic errors on the CO TC retrieval.

This work aims to estimate the effect of the difference in CO absorption lines in the present-day spectroscopic databases on the accuracy in the retrieval of the CO atmospheric total column from high resolution spectra in the CO absorption bands 2.3 and 4.6 μm

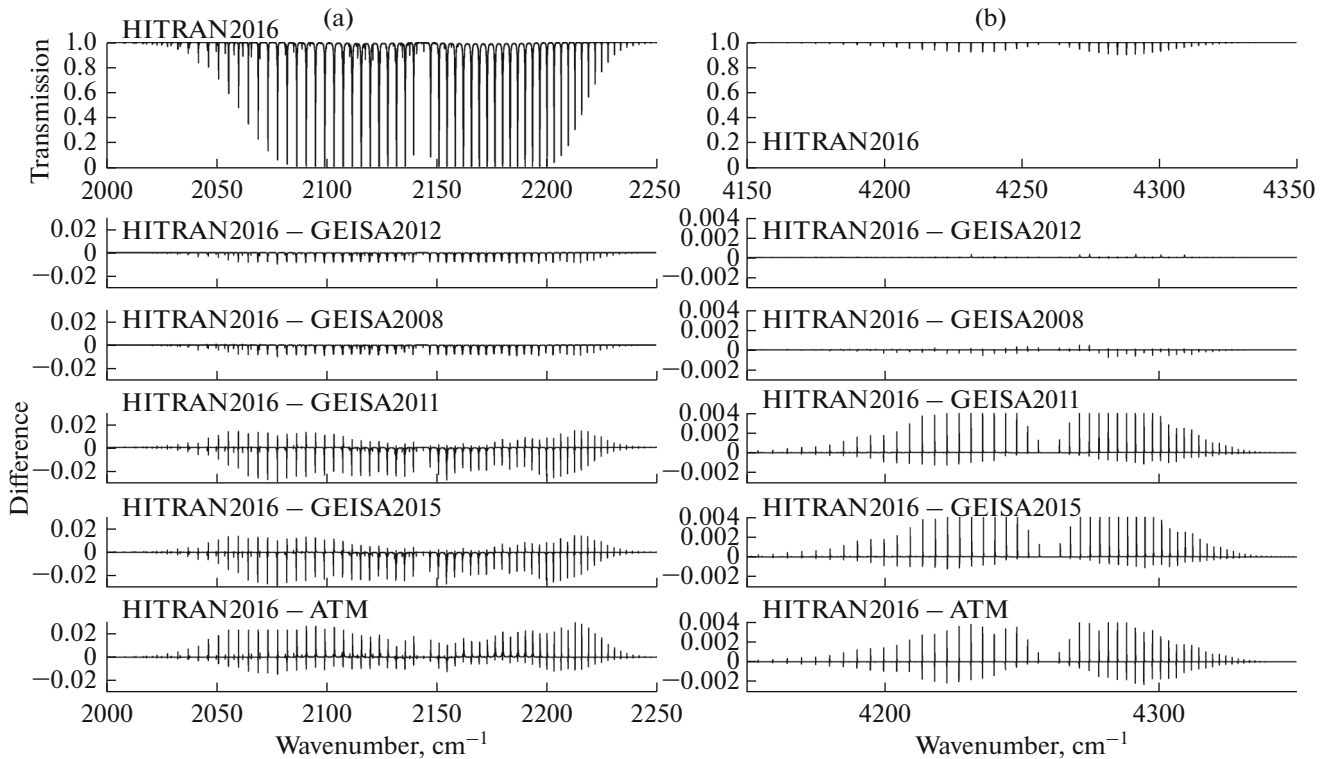


Fig. 1. CO atmospheric transmission and the difference in atmospheric transmission calculated with CO absorption lines from different spectroscopic databases, in the ranges (a) 2000–2250 and (b) 4150–4350 cm^{-1} (a slant path at a zenith angle of 30° throughout the atmosphere).

based on results determining the CO TC from the ground-based FTIR at the St. Petersburg and Kourouka stations.

COMPARISON OF THE ATMOSPHERIC TRANSMISSION CALCULATED USING DIFFERENT DATA ON CO ABSORPTION LINES

CO absorption line parameters from spectroscopic databases (DB) HITRAN2008 [8], HITRAN2012 [9], HITRAN2016 [10], GEISA2011 [11], GEISA2015 [12] are currently used in atmospheric applications, and from the databank ATM [13], which is used to estimate the gas total column at the NDACC international network [14]. Contrary to GEISA, where, beginning from the version of 2003, the information on CO lines was not upgraded, the data in HITRAN have been regularly upgraded, and even the closest versions differ significantly. Particularly, the information in the last version HITRAN2016 is based on the new databank of vibrational–rotational absorption lines of nine CO isotopologues [15], which are supplemented by experimental values of line center positions [16–19]; the line intensity is limited to $10^{-31} \text{ cm}^{-1}/(\text{mol cm}^{-2})$ everywhere except for the microwave range.

We have line-by-line [20] calculated the atmospheric transmission for carbon monoxide based on parameters from spectroscopic databases HITRAN, GEISA, and ATM with a spectral resolution of 0.01 cm^{-1} , along a slant path throughout the atmosphere, at a zenith angle of 30° (Fig. 1). We considered the spectral ranges of 2.3 and 4.6 μm (2000–2250 and 4150–4350 cm^{-1}), which are used for retrieval of atmospheric CO TC. Profiles of the air temperature and pressure and CO concentration were specified according to the AFGL meteorological model for the midlatitude summer [21] with a background CO TC of 0.1 ppm.

Even for CO background concentrations, sufficiently noticeable differences were observed in the transmittance calculated with the absorption lines from different databases. Thus, the difference in the transmittance (0.03) was maximal between HITRAN2016 and GEISA in the region 2000–2250 cm^{-1} . A similar difference was observed between the HITRAN and ATM. In the region 4150–4350 cm^{-1} , the differences calculated with HITRAN2016 and GEISA databases were lower and did not exceed 0.004. In the real atmosphere, the CO concentration can increase by an order of magnitude during fires; hence, when determining the CO concentration by spectroscopic methods, the differences in the absorption lines more strongly affect the calculation of the transmittance in the direct problem.

CO TC MEASUREMENTS

CO TC was determined from solar radiation spectra recorded at the ground-based Fourier spectrometers located in St. Petersburg and the Kourovka stations.

Measurements at St. Petersburg

The St. Petersburg station is situated at Peterhof, a suburb of St. Petersburg (59.88° N, 29.83° E, 20 m above sea level) [22]. The spectral measurement complex consists of the Bruker IFS 125HR Fourier spectrometer, which records spectra with a resolution of up to 0.002 cm⁻¹, and a sun-tracking system developed and produced at the Department of the Atmospheric Physics of St. Petersburg State University [23]. In 2016, the station was included in the international measurement network NDACC (IRWG-NDACC) [14]. In this work, the data on the total CO column was derived with a unified optimal technique which provides for high-quality data on OC TC/profile in the atmosphere. This technique was developed within the international project QA4ECV (Quality Assurance for Essential Climate Variables, under the guidance of BIRA-IASB) for use at the network of IRWG-NDACC stations [24]. The standard strategy of CO TC/profile retrieval developed at IRWG-NDACC was taken as a basis, where three spectral microwindows were used: 2057.70–2058.00; 2069.56–2069.76; and 2157.50–2159.15 cm⁻¹.

Figure 2a shows measured spectra of the direct solar radiation passed through the atmosphere, the model spectra, and the difference between them for the abovementioned spectral intervals. The direct solar radiation spectra, recorded by the Bruker IFS 125HR Fourier spectrometer with a resolution of 0.005 cm⁻¹ were processed by the SFIT4 program [25] based on the optimal estimation method. Simultaneously with the CO profile, the atmospheric profiles of N₂O and O₃ were determined, as well as total columns of CO₂, H₂O, and OCS, with the use of NCEP meteorological data [26, 27]. The a priori atmospheric gas profiles were specified in accordance with the WACCM model [28]. The primary difference between QA4ECV and standard IRWG-NDACC methods is in the restriction of CO profile variations in the upper atmospheric layers: SD(Sa) = 0.01 for the mesosphere and thermosphere. This was made in order to exclude the appearance of negative CO concentrations, which sometimes occurs for the standard IRWG-NDACC method.

Measurements at Kourovka

The direct solar radiation spectra were measured at the Ural atmospheric station located in the Kourovka Astronomical Observatory of the Ural Federal University, Yekaterinburg (57.038° N, 59.545° E) [29], with the ground-based Bruker IFS 125M Fourier-

transform spectrometer conjugated with the Bruker A547 solar tracker. The Fourier-transform spectrometer is used for routine measurements of atmospheric spectra in the near-IR region 4000–11000 cm⁻¹ with a spectral resolution of 0.02 cm⁻¹ and with the accuracy required by standards of the international network for measuring greenhouse gases TCCON [30]. The station is situated in a forested area with a background atmosphere. The spectra were measured any sunny day of the year, except for winter months (from the middle of November to the middle of February), when the Sun height above the forest level does not allowed us to image it on the spectrometer diaphragm.

The simulation of spectra and retrieval of CO TC were performed with the use of the SFIT4 [25]. To determine the CO column, three spectral intervals were chosen: (4235.7–4236.2; 4274.5–4275.0; and 4281.3–4281.9 cm⁻¹; Fig. 2b), which include the strongest lines of the given region with the smallest overlapping by interfering gases. When simulating the atmospheric radiation transfer, the primary absorbing atmospheric gases: H₂O, CO₂, CH₄, N₂O, CO, O₃, O₂, and the extraterrestrial solar spectrum were taken into account. Altitude profiles of the temperature, pressure, and concentration of atmospheric gases were taken from NCEP/NCAR reanalysis data [26, 27], which were supplemented with measured local values of temperature, pressure, and humidity near the surface when the spectra were recorded in Kourovka. The measured solar spectra and model spectra in the spectral intervals, from which the CO TC was determined in Kourovka, are compared in Fig. 2b.

ANALYSIS OF THE SPECTROSCOPIC INFORMATION EFFECT ON CO TC RETRIEVAL

For the strategies of retrieving the CO TC/profile used in the spectra processing at St. Petersburg and Kourovka stations, the influence of different versions of spectroscopic databases HITRAN, ATM, and GEISA on the measurements of the CO total column is analyzed. No input parameters were changed, except for the spectroscopic information on CO lines (for other gases, retrieved simultaneously with CO, it was not changed). The basic results of our tests, obtained for FTIR spectra, are shown in Tables 1 and 2 for measurements at the St. Petersburg and Kourovka stations, respectively, where the following information is given:

(1) RMS is the root-mean-square deviation of the modeled spectrum from the measured one (“the best” database will provide for the minimum of this magnitude).

(2) DOFS is the number of degrees of freedom for the studied gas; DOFS ≥ 1.0 means a possibility to determine the CO total column; DOFS ≥ 2.0 means that it is also possibly to determine elements of the CO vertical

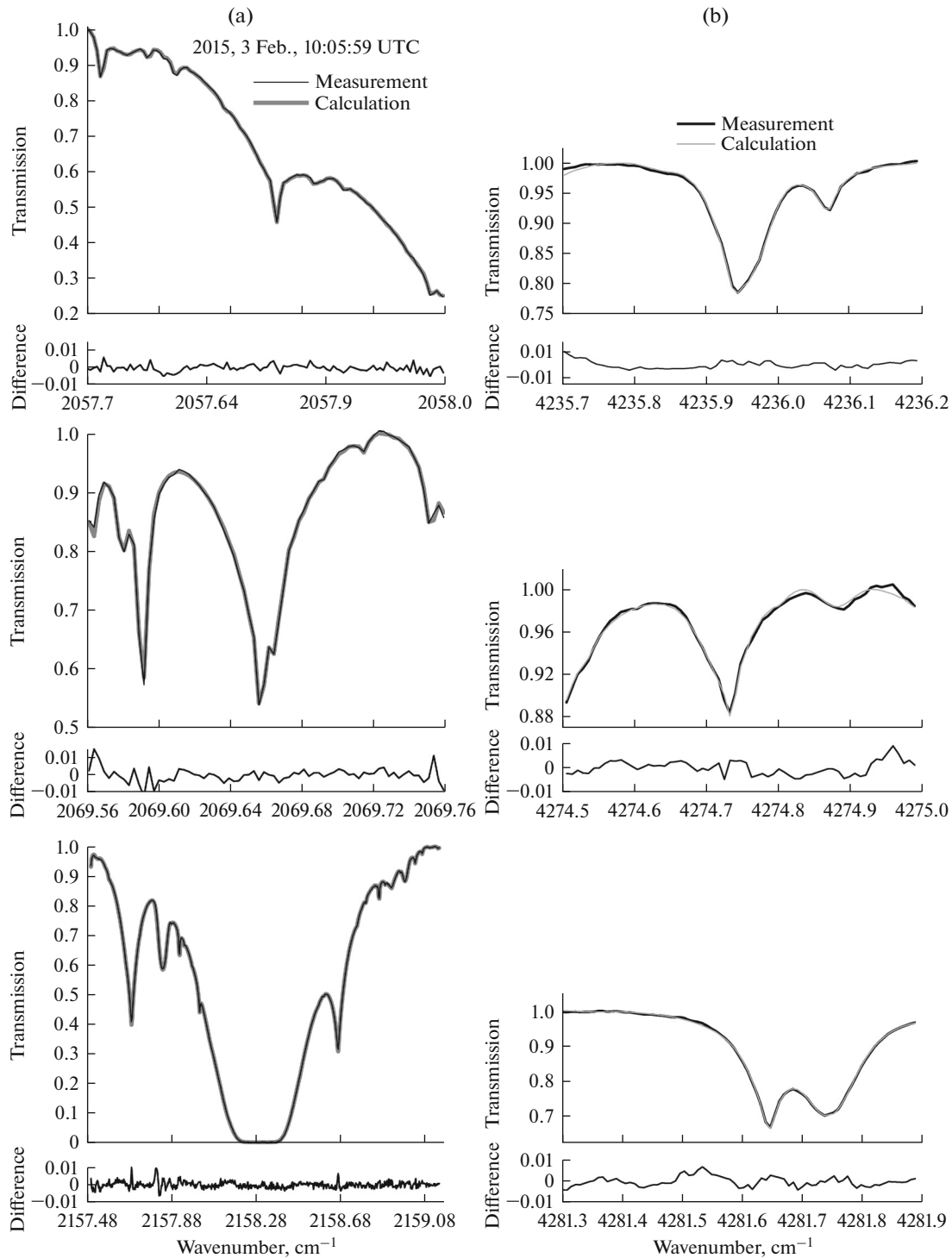


Fig. 2. Spectral microwindows used for determination of CO TC (measured atmospheric solar spectra, calculated spectra, and difference between them) in (a) St. Petersburg and (b) Kourovka.

distribution in the atmosphere; DOFS is proportional to the number of the retrieved gas layers (the best database provides the maximum of this magnitude).

(3) χ^2 is the homogeneity criterion (the best database provides for the minimum of this magnitude).

(4) The random and systematic errors, the error of smoothing (it is supposed that the best spectroscopic database provides for the minimum of these magnitudes; in this case, the primary attention is paid to the random error).

Table 1. Errors in determination of CO TC (RMS, DOFS, χ^2) and daily average variations in CO TC obtained from processing of FTIR spectra of the direct solar radiation in 2015 at St. Petersburg station

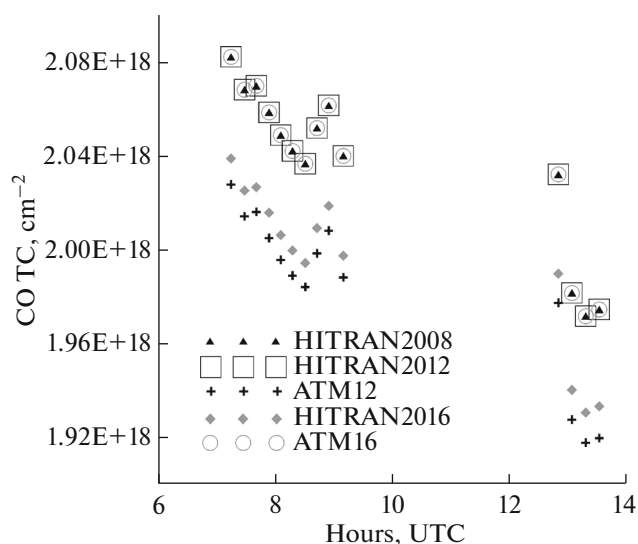
Spectroscopic DB	Number of spectra	Mean value of error, %			RMS	DOFS	χ^2	Mean value of the CO TC daily variation, 10^{16} cm^{-2}
		smoothing	random	systematic				
HITRAN2008	428	0.089	2.15	2.93	0.348	2.61	0.93	1.8 ± 1.7
HITRAN2012	428	0.089	2.15	2.93	0.332	2.61	0.84	1.8 ± 1.7
ATM12	428	0.089	2.16	2.92	0.358	2.65	0.90	1.8 ± 1.7
HITRAN2016	428	0.088	2.15	2.93	0.331	2.63	0.83	1.7 ± 1.6
ATM16	428	0.089	2.15	2.93	0.332	2.61	0.84	1.8 ± 1.7

Table 2. Errors in CO TC (RMS and χ^2) and DOFS, obtained from processing of FTIR spectra of direct solar radiation from March to August of 2015 at the Kourouka station (spectral regions 4235.7–4236.2; 4274.5–4275.0; and 4281.3–4281.9 cm^{-1})

Spectroscopic database	The number of spectra	RMS, %	χ^2
ATM	540	0.32001	0.74953
GEISA2015	540	0.32002	0.74954
HITRAN2008	540	0.30794	0.69391
HITRAN2016	540	0.30516	0.6815

(5) The average value of the gas TC variation during a day (the best database provides for the minimum of this magnitude).

The given criteria, generally, characterize the quality of the solution of the inverse problem of atmospheric optics. This allows us to decide between the tested spectroscopic databases on the basis of the data given in Tables 1 and 2.

**Fig. 3.** Single measurements of CO TC on July 21, 2015, St. Petersburg, using different spectroscopic information.

It is seen that values of RMS, DOFS, errors in the determination of the CO total column, as well as day-average variation of the CO TC are very close for all five spectroscopic databases which we used to determine the CO TC/profile in the atmosphere. However, the use of the spectroscopic information from HITRAN2016, when solving the inverse problem, allows us, though insignificantly, to improve values of the parameters analyzed, for example, to decrease RMS, χ^2 , and daily averaged variations, as well as the random and smoothing errors.

In addition, for illustration of the effect of the spectroscopic information, we present results of determining the CO TC from the longest measurement series of 2015, recorded on June 21 at the St. Petersburg station (14 single spectra in total, Table 3 and Fig. 3).

This example is a descriptive illustration of systematic differences in the CO TC, which appear when using different spectroscopic databases. Single values of the CO TC, and, consequently, daily averaged and values of daily variation on July 21, 2015, coincide for HITRAN2012 and ATM16; values of CO TC from the HITRAN2008 database are very close to them: for the series of spectra recorded on that date the relative difference between single values of CO TC for HITRAN2008 and HITRAN2012 varies from 0 to 0.006%. These values are lower by 2.1 and 2.7% for HITRAN16 and ATM12, respectively. Note that the maximal daily variation that day was received from the processing of FTIR spectra with the use of ATM12.

Systematic differences caused by different spectroscopic data and shown by measurement on July 21, 2015, at the St. Petersburg station, are kept on the whole throughout the year of measurements. This is shown in Fig. 4, where the annual cycle of the CO TC with variations for each month are presented, and in Table 4, where its amplitude and monthly averaged values of CO TC in minimum and maximum of the annual cycle are given. It is seen that the annual cycle of the CO TC for HITRAN2008, HITRAN2012, and ATM16 is similar. HITRAN2016 gives lower values as compared to three abovementioned spectroscopic databases, in extreme points of the annual cycle (by 2.1 and 2.7% in the maximum and the minimum, respec-

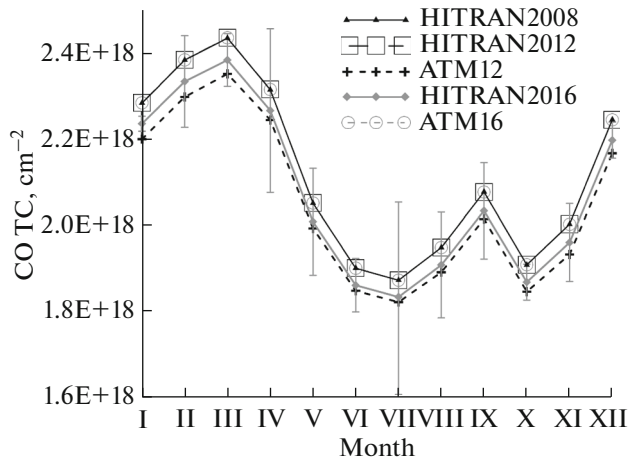


Fig. 4. Annual cycle of CO TC (St. Petersburg station, 2015) with variations for each month; results are obtained with the use of different spectroscopic information.

tively). The annual cycle has the lowest values with ATM12: in July the monthly averaged values are lower than those for the HITRAN2012, by 2.7%; in March, by 3.4%.

Figure 5 shows monthly averaged CO TC values and their variations in Kourovka obtained with the use of several databases, including CO absorption line parameters. The yearly behavior and monthly averaged values for Kourovka in 2015 were similar to those measured at St. Petersburg, with the maximum in March and the minimum in the summer months.

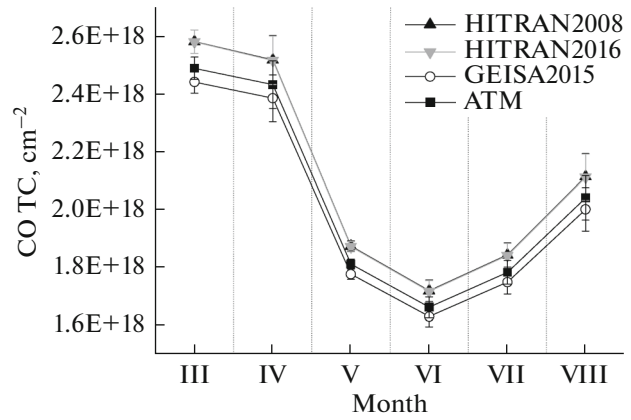


Fig. 5. Monthly averaged values of atmospheric CO TC and its variations, obtained with different spectroscopic databases (Kourovka, 2015).

Weaker variations during a month were observed in Kourovka than in St. Petersburg. This can be explained by the fact that Kourovka station is situated in a forest with fewer CO sources as compared to St. Petersburg, and also by fewer measurement days because of clouds.

Figure 6 shows relative differences in monthly averaged values of CO TC in Kourovka in 2015 obtained with the use of different databases which include CO absorption line parameters. Sufficiently large differences are seen between CO TC values found with the use of CO line parameters from the GEISA database and other calculations: 2% for ATM and up to 5.5% for

Table 3. Daily averaged value of CO TC and its variations for July 21, 2015, (St. Petersburg station) obtained from processing the spectra with the use of different spectroscopic databases

Spectroscopic database	Daily averaged value, 10^{18} cm^{-2}	Daily variation (standard deviation), 10^{16} cm^{-2} , %
HITRAN2008	2.037	3.5 (1.70)
HITRAN2012	2.037	3.5 (1.70)
ATM12	1.984	3.5 (1.76)
HITRAN2016	1.995	3.4 (1.70)
ATM16	2.037	3.5 (1.70)

Table 4. Characteristics of CO TC annual cycle for the St. Petersburg station, 2015 (for different databases of the spectroscopic information)

Spectroscopic database	Amplitude of the CO TC annual cycle, 10^{18} cm^{-2} , %	Minimal and maximal monthly average CO TC (\pm variation), 10^{18} cm^{-2}
HITRAN2008	0.281 (13.4)	March 2.436 ± 0.063 ; July 1.874 ± 0.23
HITRAN2012	0.282 (13.5)	March 2.436 ± 0.062 ; July 1.874 ± 0.23
ATM12	0.265 (13.1)	March 2.353 ± 0.061 ; July 1.823 ± 0.22
HITRAN2016	0.275 (13.4)	March 2.385 ± 0.061 ; July 1.834 ± 0.22
ATM16	0.282 (13.5)	March 2.436 ± 0.062 ; July 1.874 ± 0.23

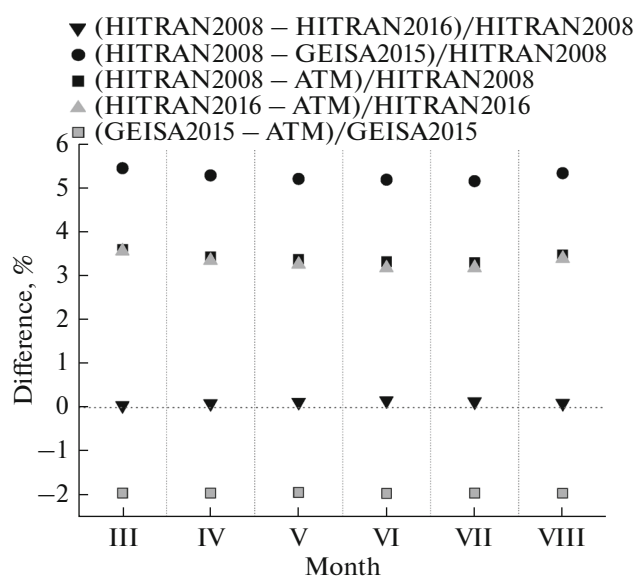


Fig. 6. Relative difference in monthly averaged values of atmospheric CO TC, obtained with different databases of parameters of CO absorption lines (Kourovka, 2015).

HITRAN2016 data. It should be noted that the spectroscopic information on CO absorption lines in the GEISA database has not been upgraded for more than 15 years. Possibly, this is a cause of such large differences.

CONCLUSIONS

On the example of HITRAN2008, HITRAN2012, ATM12, HITRAN2016, ATM16, and GEISA2015 databases we have shown the effect of the CO absorption line spectroscopic information from these databases on the results of retrieval of the CO TC/profile from FTIR measurements of the solar radiation spectra in different spectral regions.

Test calculations performed using atmospheric FTIR high-resolution spectra, recorded in 2015 at St. Petersburg station in spectral ranges used by IRWG-NDACC, have shown the following.

(1) Values of the CO total column found from the spectra processing using the ATM16 and HITRAN2012 databases coincide; for databases HITRAN2008 and HITRAN2012 they almost coincide; for HITRAN2016 and ATM12 the values are by 2–3% lower than the similar values for HITRAN2012.

(2) By a series of criteria (the random error of CO total column retrieval, quality of fitting the calculated spectrum to the measured one, daily average variations in the CO total column), the HITRAN2016 database provides the best results in the solution of the inverse problem of atmospheric optics on retrieving the CO total column, as compared to HITRAN2008, HITRAN2012, ATM12, and ATM16 databases.

Calculations with the use of FTIR solar spectra recorded at the Kourovka station in 2015 within the spectral region 4235–4281 cm^{-1} have shown the following:

—HITRAN2016 gives the best results in retrieving the CO total column by RMS and χ^2 criteria both for St. Petersburg and Kourovka stations.

—The data on the CO total column obtained with the help of HITRAN2008–2016 versions differ insignificantly.

—Significant relative differences are observed in monthly averaged values of the CO total column in Kourovka retrieved with data from GEISA and other databases. The differences can reach 5.5% for HITRAN2016 and GEISA2015.

FUNDING

This work were financially supported by the Program of Fundamental Investigations by State Academies of Sciences (project AAAA-A17-117021310147-0) and the Russian Foundation for Basic Research (grant no. 18-05-00011 “Study of reactive gases in the atmosphere by means of FTIR spectrometry”), as well as the project No. 3.6064.2017/8.9 within the basic part of the state assignment and the financial support by Resolution no. 211 of the Russian Federation Government, contract No. 02.A03.21.0006. The discussion of the results and preparation of the publication were supported by the Russian Foundation for Basic Research (grant no. 18-55-53062 “Monitoring and study of gaseous and aerosol pollution of the atmosphere and greenhouse gases in Moscow and Beijing, based on satellite and ground high resolution spectroscopic technologies”).

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

REFERENCES

1. T. T. Van Leeuwen and G. R. van der Werf, “Spatial and temporal variability in the ratio of trace gases emitted from biomass burning,” *Atmos. Chem. Phys.* **11** (8), 3611–3629 (2011).
2. Z. Jiang, J. R. Worden, H. Worden, M. Deeter, D. B. A. Jones, A. F. Arellano, and D. K. Henze, “A 15-year record of CO emissions constrained by MOPITT CO observations,” *Atmos. Chem. Phys.* **7** (17), 4565–4583 (2017). <https://doi.org/10.5194/acp-17-4565-2017>
3. L. N. Yurganov, V. Rakitin, A. Dzhola, T. August, E. Fokeeva, M. George, G. Gorchakov, E. Grechko, S. Hannon, A. Karpov, L. Ott, E. Semutnikova, R. Shumsky, and L. Strow, “Satellite- and ground-based CO total column observations over 2010 Russian fires: Accuracy of top-down estimates based on thermal IR satellite data,” *Atmos. Chem. Phys.* **15** (11), 7925–7942 (2011).

4. D. Fu, K. W. Bowman, H. M. Worden, V. Natraj, J. R. Worden, S. Yu, P. Veefkind, I. Aben, J. Landgraf, L. Strow, and Y. Han, "High-resolution tropospheric carbon monoxide profiles retrieved from CrIS and TROPOMI," *Atmos. Meas. Tech.* **9** (6), 2567–2579 (2016).
5. R. R. Buchholz, M. N. Deeter, H. M. Worden, J. Gille, D. P. Edwards, J. W. Hannigan, N. B. Jones, C. Paton-Walsh, D. W. T. Griffith, D. Smale, J. Robinson, K. Strong, S. Conway, R. Sussmann, F. Hase, T. Blumenstock, E. Mahieu, and B. Langerock, "Validation of MOPITT carbon monoxide using ground-based Fourier transform infrared spectrometer data from NDACC," *Atmos. Meas. Tech.* **10** (5), 1927–1956 (2017).
6. T. Y. Chesnokova, A. V. Chentsov, N. V. Rokotyan, and V. I. Zakharov, "Impact of difference in absorption line parameters in spectroscopic databases on CO₂ and CH₄ atmospheric content retrievals," *J. Mol. Spectrosc.* **327**, 171–179 (2016).
7. T. Yu. Chesnokova, A. V. Chentsov, N. V. Rokotyan, and V. I. Zakharov, "Retrieval of content of greenhouse gases from atmospheric spectra of solar radiation with the use of different spectroscopic data on absorption lines," *Atmos. Ocean. Opt.* **28** (5), 469–475 (2015).
8. L. S. Rothman, I. E. Gordon, A. Barbe, D. C. Benner, P. F. Bernath, M. Birk, V. Boudon, L. R. Brown, A. Campargue, J.-P. Champion, K. Chance, L. H. Coudert, V. Dana, V. M. Devi, S. Fally, J.-M. Flaud, R. R. Gamache, A. Goldman, D. Jacquemart, I. Kleiner, N. Lacome, W. J. Lafferty, J.-Y. Mandin, S. T. Massie, S. N. Mikhailenko, C. E. Miller, N. Moazzen-Ahmadi, O. V. Naumenko, A. V. Nikitin, J. Orphal, V. I. Perevalov, A. Perrin, A. Predoi-Cross, C. P. Rinsland, M. Rotger, M. Simeckova, M. A. H. Smith, K. Sung, S. A. Tashkun, J. Tennyson, R. A. Toth, A. C. Vandaele, and J. Auwera Vander, "The HITRAN2008 Molecular Spectroscopic Database," *J. Quant. Spectrosc. Radiat. Transfer* **110** (9–10), 533–572 (2009).
9. L. S. Rothman, I. E. Gordon, Y. Babikov, A. Barbe, Benner D. Chris, P. F. Bernath, M. Birk, L. Bizzocchi, V. Boudon, L. R. Brown, A. Campargue, K. Chance, E. A. Cohen, L. H. Coudert, V. M. Devi, B. J. Drouin, A. Fayt, J.-M. Flaud, R. R. Gamache, J. J. Harrison, J.-M. Hartmann, C. Hill, J. T. Hodges, D. Jacquemart, A. Jolly, J. Lamouroux, R. J. Le Roy, G. Li, D. A. Long, O. M. Lyulin, C. J. Mackie, S. T. Massie, S. Mikhailenko, H. S. P. Muller, O. V. Naumenko, A. V. Nikitin, J. Orphal, V. Perevalov, A. Perrin, E. R. Polovtseva, C. Richard, M. A. H. Smith, E. Starikova, K. Sung, S. Tashkun, J. Tennyson, G. C. Toon, V. G. Tyuterev, and G. Wagner, "The HITRAN2012 Molecular Spectroscopic Database," *J. Quant. Spectrosc. Radiat. Transfer* **130**, 4–50 (2013).
10. I. E. Gordon, L. S. Rothman, C. Hill, R. V. Kochanov, Y. Tan, P. F. Bernath, M. Birk, V. Boudon, A. Campargue, K. V. Chance, B. J. Drouin, J.-M. Flaud, R. R. Gamache, J. T. Hodges, D. Jacquemart, V. I. Perevalov, A. Perrin, K. P. Shine, M. A. H. Smith, J. Tennyson, G. C. Toon, H. Tran, V. G. Tyuterev, A. Barbe, A. G. Csaszar, V. M. Devi, T. Furtenbacher, J. J. Harrison, J.-M. Hartmann, A. Jolly, T. J. Johnson, T. Karman, I. Kleiner, A. A. Kyuberis, J. Loos, O. M. Lyulin, S. T. Massie, S. N. Mikhailenko, N. Moazzen-Ahmadi, H. S. P. Muller, O. V. Naumenko, A. V. Nikitin, O. L. Polyansky, M. Rey, M. Rotger, S. W. Sharpe, K. Sung, E. Starikova, S. A. Tashkun, J. Auwera, Wagner G. Vander, J. Wilzewski, P. Wcislo, S. Yu, and E. J. Zak, "The HITRAN2016 Molecular Spectroscopic Database," *J. Quant. Spectrosc. Radiat. Transfer* **203**, 3–69 (2017).
11. N. Jacquinet-Husson, L. Crepeau, R. Armante, C. Boutammine, A. Chedin, N. A. Scott, C. Crevoisier, V. Capelle, C. Boone, N. Poulet-Crovisier, A. Barbe, A. Campargue, Benner D. Chris, Y. Benilan, B. Bezaud, V. Boudon, L. R. Brown, L. H. Coudert, A. Coustenis, V. Dana, V. M. Devi, S. Fally, A. Fayt, J. M. Flaud, A. Goldman, M. Herman, G. J. Harris, D. Jacquemart, A. Jolly, I. Kleiner, A. Kleinbohl, F. Kwabia-Tchana, N. Lavrentieva, N. Lacome, L. H. Xu, O. M. Lyulin, J. Y. Mandin, A. Maki, S. Mikhailenko, C. E. Miller, T. Mishina, N. Moazzen-Ahmadi, H. S. P. Muller, A. Nikitin, J. Orphal, V. Perevalov, A. Perrin, D. T. Petkie, A. Predoi-Cross, C. P. Rinsland, J. J. Remedios, M. Rotger, M. A. H. Smith, K. Sung, S. Tashkun, J. Tennyson, R. A. Toth, A. C. Vandaele, J. Auwera Vander, "The 2009 edition of the GEISA Spectroscopic Database," *J. Quant. Spectrosc. Radiat. Transfer* **112** (15), 2395–2445 (2011).
12. N. Jacquinet-Husson, R. Armante, N. A. Scott, A. Chedin, L. Crepeau, C. Boutammine, A. Bouhdaoui, C. Crevoisier, V. Capelle, C. Boone, N. Poulet-Crovisier, A. Barbe, Benner D. Chris, V. Boudon, L. R. Brown, J. Buldyreva, A. Campargue, L. H. Coudert, V. M. Devi, M. J. Down, B. J. Drouin, A. Fayt, C. Fittschen, J.-M. Flaud, R. R. Gamache, J. J. Harrison, C. Hill, O. Hodnebrog, S.-M. Hu, D. Jacquemart, A. Jolly, E. Jimenez, N. N. Lavrentieva, A.-W. Liu, L. Lodi, O. M. Lyulin, S. T. Massie, S. Mikhailenko, H. S. P. Muller, O. V. Naumenko, A. Nikitin, C. J. Nielsen, J. Orphal, V. I. Perevalov, A. Perrin, E. Polovtseva, A. Predoi-Cross, M. Rotger, A. A. Ruth, S. S. Yu, K. Sung, S. A. Tashkun, J. Tennyson, V. G. Tyuterev, J. Auwera, Voronin B. A. Vander, and A. Makie, "The 2015 edition of the GEISA Spectroscopic Database," *J. Mol. Spectrosc.* **327**, 31–72 (2016).
13. <http://mark4sun.jpl.nasa.gov/toon/linelist/linelist.html>. Cited September 5, 2018.
14. <http://www.ndsc.ncep.noaa.gov>. Cited May 19, 2016.
15. G. Li, I. E. Gordon, L. S. Rothman, Y. Tan, S.-M. Hu, and S. Kassi, A. Campargue, and E. S. Medvedev, "Rotational line lists for nine isotopologues of the CO Molecule in the X¹Σ⁺ ground electronic state," *Astrophys. J., Suppl. Ser.* **216** (1), 15 (2015).
16. C. R. Pollock, F. R. Petersen, D. A. Jennings, J. S. Wells, and A. G. Maki, "Absolute frequency measurements of the 2-0 band of CO at 2.3 μm; calibration standard frequencies from high resolution color center laser spectroscopy," *J. Mol. Spectrosc.*, No. 99, 357–368 (1983).
17. D. Mondelain, T. Sala, S. Kassi, D. Romanini, M. Marangoni, and A. Campargue, "Broadband and highly sensitive comb-assisted cavity ring down spectroscopy of CO near 1.57 μm with sub-mhz frequency accuracy," *J. Quant. Spectrosc. Radiat. Transfer* **154**, 35–43 (2015).
18. A. Cygan, S. Wojtewicz, G. Kowzan, M. Zaborowski, P. Wcislo, J. Nawrocki, P. Krehlik, Śliwczyński,

- M. Lipiński, P. Maslowski, R. Ciurylo, and D. Lisak, "Absolute molecular transition frequencies measured by three cavity-enhanced spectroscopy techniques," *J. Chem. Phys.* **144**, 214202–1 (2016).
19. Y. Tan, J. Wang, X. Q. Zhao, A. W. Liu, and S. M. Hu, "Cavity ring-down spectroscopy of the fifth overtone of CO," *J. Quant. Spectrosc. Radiat. Transfer* **187**, 274–279 (2017).
 20. A. A. Mitsel, I. V. Ptashnik, K. M. Firsov, and A. B. Fomin, "Efficient technique for line-by-line calculating the transmittance of the absorbing atmosphere," *Atmos. Oceanic Opt.* **8** (10), 847–850 (1995).
 21. G. Anderson, S. Clough, F. Kneizys, J. Chetwynd, and E. Shettle, "AFGL atmospheric constituent profiles (0–120 km). AFGL-TR-86-0110. Environ. Res. Paper, No. 954 (Air Force Geophysics Laboratory, 1986).
 22. Y. Timofeyev, Y. Virolainen, M. Makarova, A. Poborovsky, A. Polyakov, D. Ionov, S. Osipov, and H. Imhasin, "Ground-based spectroscopic measurements of atmospheric gas composition near Saint Petersburg Russia," *J. Mol. Spectrosc.* **323**, 2–14 (2016).
 23. A. V. Poberovskii, "High-resolution ground measurements of the IR spectra of solar radiation," *Atmos. Ocean. Opt.* **23** (2), 161–164 (2010).
 24. www.qa4ecv.eu. Cited September 5, 2018.
 25. F. Hase, J. W. Hannigan, M. T. Coffey, A. Goldman, M. Hopfner, N. B. Jones, C. P. Rinsland, and S. W. Wood, "Intercomparison of retrieval codes used for the analysis of high-resolution ground-based FTIR measurements," *J. Quant. Spectrosc. Radiat. Transfer* **87**, 25–52 (2004).
 26. <https://www.esrl.noaa.gov/psd/data/reanalysis>. Cited September 5, 2018.
 27. E. Kalnay, M. Kanamitsu, R. Kistler, W. Collins, D. Deaven, L. Gandin, M. Iredell, S. Saha, G. White, J. Woollen, Y. Zhu, A. Leetmaa, B. Reynolds, M. Chelliah, W. Ebisuzaki, W. Higgins, J. Janowiak, K. C. Mo, C. Ropelewski, J. Wang, R. Jenne, and D. Joseph, "The NCEP/NCAR 40-Year Reanalysis Project," *Bull. Amer. Meteorol. Soc.* **77**, 437–471 (1996).
 28. <https://www2.acom.ucar.edu>. Cited September 5, 2018.
 29. K. Gribanov, J. Jouzel, V. Bostikov, J.-L. Bonne, F.-M. Breon, M. Butzin, O. Cattani, V. Masson-Delmotte, N. Rokotyan, M. Werner, and V. Zakharov, "Developing a Western Siberia reference site for tropospheric water vapour isotopologue observations obtained by different techniques (in situ and remote sensing)," *Atmos. Chem. Phys.* **14**, 5943–5957 (2014).
 30. D. Wunch, G. C. Toon, J. F. L. Blavier, R. A. Washenfelder, J. Notholt, B. J. Connor, D. W. T. Griffith, V. Sherlock, and P. O. Wennberg, "The total carbon column observing network," *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.* **369** (1943), 2087–2112 (2011).

Translated by S. Ponomareva