Comparison of measured and simulated NO2 integral content in the lower troposphere in Moscow region

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Abstract. We presented preliminary results of a comparison of the NO2 integral contents (IC) measured by the DOAS technique and simulated by the COSMO-Ru7-ART chemical transport model at Zvenigorod Scientific Station (ZSS) located in 38 km west from Moscow. The comparison covers January and July of 2014 when background and polluted by Moscow air masses were observed at ZSS. The measured NO2 IC in the atmospheric boundary layer observed at ZSS does not exceed $0.5 \times 10^{16}$ molec×cm$^{-2}$ in background conditions of the atmosphere when non-east wind direction dominated. It grows up to $5.4 \times 10^{16}$ molec×cm$^{-2}$ when polluted air masses come from Moscow megacity. Simulated NO2 IC has similar behaviour. As a whole, a good agreement between measured and simulated datasets is observed. Some overestimation of the NO2 emission presents for sources located to the south and north-east from ZSS. Underestimation of the NO2 emission presents for sources located inside of Moscow megacity and located to south-west from ZSS.

Keyword: Nitrogen compounds, nitrogen dioxide, DOAS technique, COSMO-Ru7-ART, atmospheric pollutions, megacity ecology

1. Introduction
The task of estimating emissions of NOx is an important problem of the forecast of the air quality. Combined usage of measured and simulated variations of NOx content in different conditions of the atmosphere nearby to its sources allows refining the power of NOx emission. Besides that, measurements of nitrogen compounds give significant data for verification of parameters of chemical transport models (CTMs).

Nitrogen oxides (NOx =NO+ NO2) are an important component in the ozone chemistry. In the lower atmosphere, high NOx concentration leads to a good condition for the ozone generation. Nitrogen compounds are related also to hydroxyl radical content, which, due to highly reactivity, is not measured by direct methods. Main source of hydroxyl radical in the morning is the rapid photolysis of nitrous acid (HNO2) [1]. However, chemical reactions involving HNO2 is not understood enough. The main source of HNO2 is heterogeneous reactions involving nitrogen oxides NOx. Because chemical reactions involving NO2 is well known, the ratio of the measured concentrations of [HNO2]/[NO2] is proposed to use for evaluating the content of HNO2 in CTM [2][3][4][5]. This ratio is used for CTMs parameters verification if one implemented a forecast of the content of HNO2.
Because both NO2 and HNO2 has structured absorption cross-section in visible and UV spectral regions, their content in the atmosphere can be measured by the DOAS method. First results of the comparison of measured and simulated NO2 variations in atmospheric boundary layer in Moscow region were described in [6]. As a whole, comparison shown a good agreement between measured and simulated datasets and revealed the remaining inaccuracies in the determination of location and power of NOx sources.

In this paper we present an algorithm and some experimental results of measurements of NO2 integral content in the atmospheric boundary layer performed at Moscow Region together with CTM simulation results. In contrast to [6], in this paper we used results of simulations of NO2 variations carried out using COSMO-Ru7-ART chemical transport model [7], which used TNO inventory data to specify characteristics of NOx sources.

2. Measurements of NO2 integral content in the atmospheric boundary layer

A.M. Obukhov Institute of Atmospheric Physics (IAP) of Russian Academy of Sciences performs DOAS measurements of gas contents in the atmosphere at Zvenigorod Scientific Station (ZSS, Moscow Region) and Moscow. ZSS instruments perform measurements in UV and visible spectral regions, which we use for determination of NO2 and HNO2 content in atmospheric boundary layer respectively. ZSS is located in Moscow region in 38 km west from Moscow (55°41'49''N, 36°46'29''E). The station is a member of Network for the Detection of Atmospheric Composition Change (NDACC) as a station for complimentary measurements of NO2 total column. ZSS is the main station of the IAP DOAS network [8]-[20]. Because western winds prevail in this region, ZSS is a background station the most part of time. But in cases of eastern wind, the air quality at ZSS is affected by Moscow megacity, and polluted air masses formed above Moscow can reach station in 2–4 hours.

In this study, we used mainly data of a DOAS spectrometer mounted at ZSS. The spectrometer records spectra between 405 and 475 nm. Spectral resolution (full width at half maximum – FWHM) of the instrument is about 0.5 nm at wavelength equal to 435 nm.

We developed a new algorithm for the retrieval of NO2 integral content (IC) in the atmospheric boundary layer (ABL) from the ZDOAS instrument. The algorithm based on DOAS technique [21][22][23] and consists in two steps. In the first step slant column density is obtained by DOAS fitting, and in the second step NO2 integral content is retrieved from slant column densities.

2.1. NO2 SCD retrieval

The first step of the algorithm is the retrieval of NO2 slant column density S. It is a common procedure for all algorithms based on DOAS technique.

We used single reference spectrum for the NO2 slant column density retrieval for whole measurement period. Single reference allows comparing with higher accuracy retrieved slant column densities. Because some content of NO2 presents in the atmosphere during reference spectrum registration, the result of DOAS fitting is differential slant column density DS, and, hence, S will be calculated as

$$S = DS + S_R$$

where $S_R$ is the NO2 slant column density during reference spectrum registration. To estimate the $S_R$ we used an approach described in [24].

$DS$ were calculated using minimization algorithm setting which was used during CINDI-2 campaign [25][26]. For $DS$ retrieval we used spectral region from 411 to 445 nm. In the DOAS procedure, we took into account other gases, which have absorption cross-section in this spectral region. They are listed in Table 1 together with other algorithm minimization settings.
Table 1. DOAS settings for NO2 retrieval.

| Parameter       | Specification          |
|-----------------|------------------------|
| Wavelength range| 411-445                |
| Cross-sections  | NO2(298K), NO2(220K), O3, Ring, O4, H2O |
| Polynomial degree| Order 4 (5 coefficients) |
| Intensity off-set| Constant               |

Errors of DS retrieval are caused by measurement noise, errors of wavelength calibration of measured spectra, temperature drift of device characteristics due to changes of spectrometer characteristics related to changes of outdoor temperature, changes of atmosphere condition during single measurement, and et al. Covariation matrix of DOAS error $\Theta$ is estimated (see eq. 8.3 in [27]) by

$$\Theta = \frac{1}{M-N-L} e^T e \left( X^T X \right)^{-1}$$  \hspace{1cm} (2)

and dispersion $\sigma^2$ of the distribution of NO2 DS is one of the diagonal element of $\Theta$. Here $M$ is the number of wavelengths, $N$ is the number of species involved into the DOAS analysis, $L$ is the number of polynomial terms in the DOAS analysis (including zero term), $e$ is the vector of residual of DOAS analysis ($e$ length is $M$), $X$ is the matrix of cross-sections of all species and polynomial terms involved to the DOAS analysis (number of columns of $X$ is $N+L$, number of rows of $X$ is $M$).

2.2. NO2 integral content in the atmospheric boundary layer retrieval

NO2 slant column density $S$ is a weighted average

$$S = \int m(h)n(h)dh$$  \hspace{1cm} (3)

of the NO2 number density $n(h)$ along height $h$. The weighting coefficient $m(h)$ of the integral coincides with the efficient layer (box) air mass factor (AMF) [28], which can be calculated using linearized radiative transfer model (RTM) [28][29][30]. The NO2 integral content (IC) in the ABL $V_{ABL}$, the value in which we are interested in, is determined as

$$V_{ABL} = \int_{ABL} n(h)dh$$  \hspace{1cm} (4)

Hence, estimation of NO2 IC in the ABL $\hat{V}_{ABL}$ may be calculated using equivalence

$$\hat{V}_{ABL} = F \cdot \left( S - \int_{STRATO} m(h)n(h)dh \right)$$  \hspace{1cm} (5)

where the coefficient

$$F \equiv \frac{1}{\int_{ABL} \bar{m}(h)\bar{k}(h)dh}$$  \hspace{1cm} (6)

depends on the estimation of the layer AMFs $\bar{m}(h)$ and shape of NO2 vertical profile in the ABL $\bar{k}(h)$. We determine the shape $\bar{k}(h)$ as the normalized gas number density: $\int_{ABL} \bar{k}(h)dh = 1$. The layer AMFs $\bar{m}(h)$ may be estimated using radiative transfer model if we know scattering characteristics and strong absorbers of the atmosphere in time of the observation. $\bar{k}(h)$ may be set using some model assumptions.
In our algorithm we use DS obtained from spectra measured for the zenith viewing direction. At small solar zenith angle \( \theta \) (\( \theta < 70^\circ \)) \( m(h) \approx \frac{1}{\cos \theta} \), therefore equation (5) can be written as follows

\[
\n_{\text{ABL}} = F \cdot \left( S - \frac{V_{\text{STRATO}}}{\cos \theta} \right)
\]

where \( V_{\text{STRATO}} \) – NO2 IC in the stratosphere. In this work we use results of measurements of NO2 IC in the stratosphere during morning and evening twilight as a source of \( V_{\text{STRATO}} \) values. Such measurements carried out at ZSS from 1990 [31].

To estimate \( V_{\text{ABL}} \) we used layer AMF calculated by a radiation transfer model MCC++ [28][29]. The model is linearized to obtain layer (box) AMFs. It takes into account multiple scattering and polarization in a spherical atmosphere. To run the radiative transfer model it is necessary to define a scenario of atmospheric parameters which most possibly corresponds to time of observation. An important parameter for the calculation of F coefficient is the shape of the vertical profile of NO2 in troposphere. In this study we suppose that 90% of tropospheric NO2 is located in the ABL with constant mixing ratio. Above ABL the concentration of NO2 decreases exponentially. The upper boundary of the atmospheric boundary layer was extracted from archive of HYSPLIT model [32].

The developed algorithm of the NO2 IC retrieval can be used both for clouds-free conditions of the atmosphere and for overcast [8]. Similar algorithm for retrieval of NO2 IC from spectra measured from space is under development now [9][10][11] as so for formaldehyde IC for clear sky [14][13][14] and for overcast[15][16].

3. Simulations of NO\(_2\) integral content
For the simulation of NO2 variations at ZSS we used the COSMO-Ru7-ART chemical transport model (CTM) developed at the Karlsruhe Institute of Technology. The COSMO- ART CTM consists of the COSMO (COnsortium for Small-scale MOdelling) mesoscale nonhydrostatic model and ART (Aerosols and Reactive Trace gases) atmospheric chemistry module. The Hydrometcenter of Russia is a full member of the COSMO consortium. The COSMO-Ru7 mesoscale weather forecast system have been introduced to the operational practice since April 2011 as the base model for the numerical prediction of the following meteorological parameters presented in the form of fields and meteograms: precipitation, air temperature, air humidity, and background surface wind. The COSMO-ART chemical transport model was adapted to the use on the computer complex of the Roshydromet Main Computer Center in the framework of the COSMO-Ru7-ART system; some changes were made in the program code of the ART chemical weather unit jointly with the developers [6].

The COSMO-ART model simulates chemical transformations of gaseous substances, photodissociation, coagulation, condensation, nucleation, deposition, removal, and washout of aerosols and takes into account the aerosol chemistry, aerosol-radiation interaction, emissions of sea salt, mineral dust, and pollen, biogenic emissions of hydrocarbons, and heterogeneous reactions. Chemical processes in the troposphere are represented by 172 reactions. The important feature of COSMO-ART is the joint simulation of meteorological parameters and chemical transformations at each time step that allows taking into account the aerosol feedback on radiation and meteorological conditions of the atmosphere.

The COSMO-Ru7-ART system was implemented at the Hydrometcenter of Russia for the territory of the Central Federal District (CFD, Figure 1) with the horizontal grid spacing of 7 km (135x150 grid points), 40 vertical levels, and the time step of 40 s. As well as the COSMO-Ru7 weather forecast system, COSMO-Ru7-ART utilizes the spherical coordinate system with the displaced North Pole. Since December 2012, COSMO-Ru7-ART has been used for the daily quasi-operational forecast of the concentration of pollutants for the territory of CFD.

The forecast results include data not only on the concentration of aerosols (particulate matter with the diameter of particles of less than 10 mm) and gaseous substances (including carbon monoxide, ozone, and nitrogen oxides) but also on meteorological parameters. The obtained data are recorded in the GRIB format using the spherical coordinate system with the displaced pole.
Figure 1. The domain of the quasi-operational forecast provided with the COSMO-Ru7-ART system.

To recalculate the experiments for the period of January and July of 2014 year ERA-Interim data was used as initial and boundary meteorological conditions. The data with horizontal grid step of 0.7° was recalculated to the 13 km grid using COSMO model, that data was used by COSMO-Ru7-ART afterwards. The forecast is calculated on 24 hours for every day. For the initial conditions of pollutant concentrations the forecast on 24 hour lead time from the previous day was used, with climatologic concentrations as boundary conditions.

Besides the meteorological parameters computed by the meteorological module, the chemical module of COSMO-Ru7-ART utilizes additional input data. Land use data are based on the data of the Global Land Cover 2000 project. The TNO (Netherlands Organization for Applied Scientific Research) inventory data are used to specify anthropogenic emissions of polluting substances.

4. Data analysis

January and July of 2014 were chosen for the preliminary comparison of measured and simulated data. The air temperature and wind direction were changed in wide limits during these periods (see Figure 2). Because of ZSS location relative to Moscow megacity, we expect higher NO2 content when east wind direction is dominate. Therefore periods with east wind direction are of prime interest for validation of NO2 emissions in Moscow megacity. Also, comparison of NO2 content during non-east wind direction is important for validation of NO2 emissions in background areas.

A few algorithms of screening of quality of experimental data were applied. The data obtained at high solar zenith angle (>70°) were removed from the analysis to minimize the uncertainties of stratospheric air mass factor calculations. The data corresponding to the cloud cover less than 20% as reported by METAR message of Vnukovo airport (~32 km from ZSS) were selected for the analysis using the clouds-free version of the algorithm [13][14], and the data corresponding to 100% cloud cover were selected for the analysis using the overcast version of the algorithm [15][16]. The data obtained in presence of broken or scattered cloudiness was removed from the analysis. In this reason the experimental data in first half of January 2014 is absent.

The measurements of NO2 in the atmospheric boundary layer are shown in the Figure 2 together with results of COSMO-Ru7-ART simulation results. The experimental NO2 integral content in the ABL does not exceeds $0.5 \times 10^{16}$ molec×cm$^{-2}$ in the background conditions. An episode with the extremely high values (up to $5.4 \times 10^{16}$ molec×cm$^{-2}$) is observed on January 28–29th, 2014. It is related
to significant wind from Moscow megacity for these days. The low temperature in this period additionally contributes to high content of the NO2 IC. It should be separately noted that the same NO2 content is observed on January 16th, 2014 in the similar atmospheric conditions. The NO2 content on January 16th was obtained using version of the retrieval algorithm designed for the overcast. Good agreement between data obtained in these days points to good quality of both version of the algorithm (overcast and clear sky).

![Figure 2](image_url)

**Figure 2.** a) NO2 in the atmospheric boundary layer measured at clear-sky and overcast conditions (red dots and blue crosses respectively) and simulated using COSMO-Ru7-ART (black line); b) azimuth of wind direction (with respect to north direction), green line – west wind direction, red line – east wind direction; c) air temperature.

As a whole, there is a good agreement between the simulated and measured NO2 ICs. As the measured NO2 IC, the simulated contents do not exceed $0.5 \times 10^{16}$ molec$\times$cm$^{-2}$ in background conditions and grows up to $(4–6) \times 10^{16}$ molec$\times$cm$^{-2}$ in polluted conditions. The simulation regularly shows the high NO2 IC in January in background conditions. Apparently, it is related to increasing of NO2 transported from Moscow due to increasing lifetime at the lower temperature. The same episodes on 17–18th July require separate and special consideration.
The comparison of the measured and simulated NO\textsubscript{2} contents is shown in Figure 3. Measured NO\textsubscript{2} IC regularly exceeds simulated one when east wind direction is prevailed (16, 28–30 January, 13 July). Because ZSS is located 30 km west from Moscow, period with such wind directions corresponds to the polluted condition of the atmosphere. Exceeding of the measured NO\textsubscript{2} IC over simulated one in such conditions may be explained by underestimation of emission from sources of NO\textsubscript{2} inside Moscow megacity in the TNO inventory used in COSMO-Ru7-ART. Because of increased NO\textsubscript{2} lifetime at lower temperature. Such effect is more noticeable in January data (Figure 3a). Because of increased NO\textsubscript{2} lifetime at lower temperature, this assumption looks very likely. Similar systematic exceeding of the measured NO\textsubscript{2} IC over simulated one is observed during south-west wind direction domination (31 January, 14–15 and 29–31 July). It is may be explained by underestimation of NO\textsubscript{2} emissions from background sources located to south-west from ZSS.

During domination of west wind direction a good agreement between measured and simulated NO\textsubscript{2} IC is observed with exception of 21 and 24 January, when the measured NO\textsubscript{2} IC exceeds over simulated one. Such episodes can be explained by the possible influence of clouds on the interpretation of the measurement results. Our algorithm of cloud detection can interpret 20% cloud coverage as clear sky. Therefore our retrieval algorithm for the clear sky may be mistakenly applied for data obtained in presence of some clouds. It could lead to the overestimation of measured NO\textsubscript{2} IC. The reverse situation can also occur: there are no clouds, but the retrieval algorithm for overcast can be used for the NO\textsubscript{2} IC retrieval. It could lead to underestimation of the NO\textsubscript{2} contents; such underestimations may happen in episode of 26th January, when during all day clear sky was observed but one moment with overcast appears.

Simulated NO\textsubscript{2} content systematically exceeds measured one when the north and north-east wind direction prevailed (25 January, 7–10 July, 19, 22 July in the Figure 2, Figure 3b). It probably can be explained by overestimation of the NO\textsubscript{2} emission located to the north and north-west from ZSS. Such effect is less noticeable in January data. Probably, it is related to small amount of data in January obtained during north and north-east wind direction.

![Figure 3](image-url)

**Figure 3.** The average measured and simulated NO\textsubscript{2} IC in the ABL (in 10\textsuperscript{16} molec\times cm\textsuperscript{-2}) in dependence on the wind direction: a) winter dataset, b) summer dataset, c) summer and winter datasets together. Number near points means number of measurements for averaging.

5. **Conclusions**

We developed the algorithm for the retrieval of the NO\textsubscript{2} integral content (IC) in the atmospheric boundary layer (ABL) and applied it to spectra measured at Zvenigorod Scientific Station (ZSS) of A.M. Obukhov Institute of Atmospheric Physics (IAP) located in 38 km west from Moscow. The retrieved NO\textsubscript{2} IC in the ABL we compared with one obtained using the chemical transport model COSMO-Ru7-ART. The comparison covers January and July of 2014 when background and polluted
by Moscow air mass observed at ZSS. The measured NO2 IC in the ABL observed at ZSS does not exceed $0.5 \times 10^{16}$ molec$\cdot$cm$^{-2}$ in background conditions of the atmosphere when non-east wind direction dominated. It grows up to $5.4 \times 10^{16}$ molec$\cdot$cm$^{-2}$ when polluted air masses come from Moscow megacity. Simulated NO2 IC has similar behavior. As a whole, a good agreement between measured and simulated datasets is observed. Some overestimation of the NO2 emission presents for sources located to the south and north-east from ZSS. Underestimation of the NO2 emission presents for sources located inside of Moscow megacity and located to south-west from ZSS.

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References
[1] Young C J, Washenfelder R A, J M Roberts, Mielke L H, Osthoff H D, Tsai C, Pikelnaya O, Stutz J, Veres P R, Cochran A K, VandenBoer T C, Flynn J, Grossberg N, Haman C L, Lefer B, Stark H, Graus M, de Grouw J, Gilman J B, Kuster W C, Brown S S 2012 Vertically resolved measurements of nighttime radical reservoirs in Los Angeles and their contribution to the urban radical budget, Environ. Sci. Technol. 46 10965–10973 doi:10.1021/es302206a.
[2] Elshorbany Y F, Steil B, Bruhl C, Lelieveld J 2012 Impact of HONO on global atmospheric chemistry calculated with an empirical parameterization in the EMAC model. Atmos. Chem. Phys. 12 9977–10000 doi:10.5194/acp-12-9977-2012.
[3] Wojtal P, Halla J D, McLaren R 2011 Pseudo steady states of HONO measured in the nocturnal marine boundary layer: a conceptual model for HONO formation on aqueous surfaces. Atmos. Chem. Phys. 11 3243–3261 doi:10.5194/acp-11-3243-2011.
[4] Hendrick F, Muller J-F, Clmer K, Wang P, De Maziure M, Fayt C, Gielen C, Hermans C, Ma J Z, Pinardi G, Stavrakou T, Vlemmix T, Van Roozendael M 2014 Four years of ground-based MAX-DOAS observations of HONO and NO2 in the Beijing area. Atmos. Chem. Phys. 14 765-781 doi:10.5194/acp-14-765-2014.
[5] Sorgel M I, Trebs I, Serafinovich A, Moravek A, Held A, Zetzsch C 2011 Simultaneous HONO measurements in and above a forest canopy: influence of turbulent exchange on mixing ratio differences Atmos. Chem. Phys. 11 841–855 doi:10.5194/acp-11-841-2011.
[6] Borovski A N, Elansky N F, Ponomarev N A, Postlyakov O V 2019 Comparison of measured and simulated by SILAM NO2 integral content in atmospheric boundary layer in Moscow region Proc. SPIE 11152 111520P doi:10.1117/12.2535492.
[7] Vl’fand R M, Kirsanov A A, Revokatova A P, Rivin G S, Surkova G V 2017 Forecasting the Transport and Transformation of Atmospheric Pollutants with the COSMO-ART Model Russian Meteorology and Hydrology 5 292–298.
[8] Ivanov V A, Elokhov A S, Postlyakov O V 2012 On the possibility of estimating the volume of NO2 emissions in cities using zenith spectral observations of diffuse solar radiation near 450 nm. Atmos. and Ocean. Optics 25 (6) 434-439 doi:10.1134/S1024856012060061.
[9] Postlyakov O V, Borovski A N, Makarenkov A A 2017 First experiment on retrieval of tropospheric NO2 over polluted areas with 2.4-km spatial resolution basing on satellite spectral measurements Proc. SPIE 10466 104662Y doi:10.1117/12.2285794.
[10] Postlyakov O V, Borovski A N, Elansky N F, Davydova M A, Zakharova S A, Makarenkov A A 2019 Comparison of space high-detailed experimental and model data on tropospheric NO2 distribution Proc. SPIE 11208 11208S doi: 10.1117/12.2540770.
[11] Postylyakov O V, Borovski A N, Davydova M A, Makarenkov A A 2019 Preliminary validation of high-detailed GSA/Resurs-P tropospheric NO2 maps with alternative satellite measurements and transport simulations Proc. SPIE 11152 111520F doi:10.1117/12.2535487.

[12] Postylyakov O V, Borovski A N, Ivanov V A, Dzhola A V, Grechko E I, Kanaya Y 2016 Formaldehyde integral content in troposphere of Moscow Region: preliminary results of 6 years of measurements using DOAS technique Proc. SPIE 10035 100353A doi: 10.1117/12.2248630.

[13] Postylyakov O V, Borovski A N 2016 Measurement of formaldehyde total content in troposphere using DOAS technique: improvements in version 1.3a of IAP retrieval algorithm Proc. of SPIE, 9876 98761N doi:10.1117/12.2229231.

[14] Borovski A N, Dzhola A V, Grechko E I, Postylyakov O V, Ivanov V A, Kanaya Y 2015 Measurements of formaldehyde total content in troposphere using DOAS technique in Moscow Region Proc. SPIE 9680 96804Q doi: 10.1117/12.2205933.

[15] Postylyakov O V, Borovski A N 2014 Measurements of formaldehyde total content using DOAS technique: a new retrieval method for overcast Proc. SPIE 9259 925918 doi: 10.1117/12.2069595.

[16] Ivanov V A, Borovski A N, Postylyakov O V 2017 First comparison of formaldehyde integral contents in ABL retrieved during clear-sky and overcast conditions by ZDOAS technique Proc. SPIE 104244 1042440 doi: 10.1117/12.2278235.

[17] Elansky N F, Mokhov I I, Belikov I B, Berezina E V, Elokhov A S, Ivanov V A, Pankratova N V, Postylyakov O V, Safronov A N, Shumsky R A 2011 Gas composition of the surface air in Moscow during the extreme summer of 2010 Doklady Earth Sciences 437(1) 357-362 doi: 10.1134/S1028334X11030020.

[18] Elansky N F, Mitin I V, Postylyakov O V 1999 Maximum accuracy of Umkehr measurements of vertical ozone profiles Izvestiya - Atmospheric and Oceanic Physics 35(1) 65-77.

[19] Andreev M, Chulichkov A I, Medvedev A P, Postylyakov O V 2014 Estimation of cloud base height using ground-based stereo photography: Method and first results Proc. SPIE 9242 924219 doi:10.1117/12.2069826.

[20] Nikitin S V, Chulichkov A I, Borovski A N, Postylyakov O V 2019 Estimation of cloudiness and aerosol characteristics in the atmosphere from spectral measurements of scattered solar radiation using a neural network Proc. SPIE 11152 111521H doi:10.1117/12.2535490.

[21] Platt U, Stutz J 2008 Differential Optical Absorption Spectroscopy, Principles and Applications, (Springer, Berlin).

[22] Postylyakov O V, Belikov I B, Elansky N F, Elokhov A S 2006 Observations of the ozone and nitrogen dioxide profiles in the TROICA-4 experiment Adv. Space Res. 37(12) 2231-2237 doi:10.1016/j.asr.2005.07.023.

[23] Elansky N F, Grechko G M, Plotkin M F, Postylyakov O V 1991 The OZAFS experiment: observing the fine structure of the ozone and aerosol distributions in the atmosphere from the Salyut 7 orbiter. Part III: Experimental results J. Geophys. Res. 96 (D10) 18661-18670 doi: 10.1029/91JD01394.

[24] Herman J, Cede A, Spinei E, Mount G, Tzortziou M, Abuhassan N 2009 NO2 column amounts from ground-based Pandora and MFDOAS spectrometers using the direct-sun DOAS technique: Intercomparisons and application to OMI validation J. Geophys. Res. 114 D13307 https://doi.org/10.1029/2009JD011848, 2009.

[25] Borovski A, Postylyakov O, Elokhov A, Bruchkovski I 2017 Study of different operational modes of the IAP 2-port-DOAS instrument for atmospheric trace gases investigation during CINDI-2 campaign basing on residual noise analysis Proc. SPIE 10466 104662Z doi: 10.1117/12.2285798.

[26] Borovski A, Elokhov A, Postylyakov O, Bruchkovski I 2017 Study of different operational modes of the IAP 2-port-DOAS instrument for investigation of atmospheric trace gases during CINDI-2 campaign Proc. SPIE 104240 104240Y doi: 10.1117/12.2278234.
[27] Borovski A N, Dzhola A V, Elokhov A S, Grechko E I, Postylyakov O V, Kanaya Y 2014 First measurements of formaldehyde integral content at Zvenigorod Scientific Station. Int. J. of Remote Sensing 35(15) 5609-5627 doi:10.1080/01431161.2014.945011.

[28] Postylyakov O V 2004 Linearized vector radiative transfer model MCC++ for a spherical atmosphere J. Quant. Spectrosc. Radiat. Transfer 88(1-3), 297-317 doi:10.1016/j.jqsrt.2004.01.009.

[29] Postylyakov O V 2004 Spherical radiative transfer model with computation of layer air mass factors, and some of its applications Izvestiya - Atmospheric and Oceanic Physics 40(3) 276-290.

[30] Postylyakov O V 2004 Radiative transfer model MCC++ with evaluation of weighting functions in spherical atmosphere for use in retrieval algorithms Adv. Space Res. 34(4) 721-726 doi:10.1016/j.asr.2003.07.070.

[31] Gruzdev A N, Elokhov A S 2011 Variability of stratospheric and tropospheric nitrogen dioxide observed by the visible spectrophotometer at Zvenigorod, Russia, International Journal of Remote Sensing 32:11, 3115-3127.

[32] Draxler R R, Rolph G D 2013 HYSPLIT (HYbrid Single-Particle Lagrangian Integrated Trajectory) Model access via NOAA ARL READY Website (http://ready.arl.noaa.gov/HYSPLIT.php). NOAA Air Resources Laboratory, Silver Spring, M.