TOTAL COLUMN OZONE CONTENT AND AEROSOL OPTICAL THICKNESS MEASUREMENTS: INSTRUMENT PERFORMANCE ANALYSIS

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Abstract

Measurements of total ozone content (TOC) and aerosol optical thickness (AOT) at 1020 nm are fulfilled with microprocessor-controlled hand-held ozonometer MICROTOPS (MTOPS) #7351 at the ground-based station at the Institute of Applied Physics since July 2003. It was shown that MTOPS readings are very sensitive to errors resulting from mispointing of the instrument to the Sun. The errors in retrieved TOC values may reach up to 50% depending on Sun's spot position in the sun targeting window of the ozonometer. MTOPS calibration characteristics are analyzed with the Langley calibration plots for clear cloudless days at the Chisinau site. Variability of evaluated calibration characteristics of instrument during period of observation consists of less than 2%. AOT values at 1020 nm retrieved from MTOPS measurements are found to be smaller than AOT from CIMEL sunphotometer operating at the Chisinau site within framework of the Aerosol Robotic Network (AERONET) under the supervision of NASA/GSFC. Discrepancy between AOT values from MTOPS and CIMEL consists, on an average, ~0.028 and this is due to the absence of temperature correction of 1020 nm channel of MTOPS. Mean ratio of daily TOC from Total Ozone Mapping Spectrometer (TOMS) aboard of Earth Probe (EP) satellite divided by TOC from MTOPS and mean ratio of daily TOC from Ozone Monitoring Instrument (OMI) aboard of Aura satellite divided by TOC from MTOPS is 0.960 and 0.990, respectively.

1. Introduction

Ozone and aerosol particulates in atmosphere exert an essential influence upon the solar ultraviolet (UV) radiation falling onto the Earth's surface through the modulation of it intensity. Among them ozone component plays the main role in UV radiation absorption. Total ozone content in a column of atmosphere is defined from the ratio of direct solar UV radiation measured at two wavelengths, one with strong absorption and another with weak absorption of radiation, within the spectral range of 290–320 nm. This method is known as differential absorption technique. It is widely used in ground-based ozone monitoring instruments such as Dobson (with a quartz prism as dispersing element) spectrometers developed in 1920s and modern automated Brewer (with a diffraction grating as dispersing element) spectrophotometer available since 1980s. These instruments are used as basic ones at the UV and ozone monitoring network stations worldwide due to their high accuracy and reliability in long-term measurements, but at the same time instruments are expensive, large, bulky and need a labour-intensive maintenance of instrumentation. Filter ozonometers represent other group of instruments to measure ozone amounts, which operate at a fixed set of wavelengths. These instruments are equipped with the narrow-band-pass interference filters having a full-width half-maximum (FWHM) band pass of 2-5 nm. The key limitations of using these instruments consist in variation of filter properties due to temperature dependencies, out-of-band radiation leakage, aging (increase of attenuation and shifting of the center wavelength) caused by an excessive solarization and moisture influence, and repeatability of spectral transmission functions of filters during manufacturing process. MICROTOPS II ozonometer (Solar Light, Inc) represents a state-of-the-art miniature hand-held instrument equipped with high-quality UV interference filters and electronics, which permits to fulfill fast signal processing and data saving. This instrument is now used at the Chisinau ground-based station for regular measurements of TOC, water vapor and aerosol optical thickness. Some performances of MTOPS operation at the site, such as analysis of errors due to mispointing of instrument to the Sun and temperature dependence of readings, and stability of calibration characteristics, will be presented. Data on TOC measured at the Chisinau site will be compared with data retrieved from satellite platforms equipped with TOMS and OMI instruments. MTOPS readings of AOT at 1020 nm are compared with AOT measured with CIMEL sunphotometer operating within the framework of the AERONET.

2. Equipment and measurement approach

The study was conducted at the ground-based solar radiation monitoring station [1] at the Institute of Applied Physics, Chisinau, Moldova (47.0013^o N, 28.8156^o E, h=205 m a.s.l) using a hand-held microprocessor controlled MTOPS ozonometer. Instrument is equipped with five high quality interference filters with discrete bands centered at λ= 305.5, 312.5, 320, 936 and 1020 nm. UV channels are being provided with filters having 2.4 nm FWHM band pass and precision of the peak wavelength is ± 0.3 nm; the near IR filters have a FWHM band pass of 10 nm and precision of ± 1.5 nm. Details of MTOPS ozonometer design, optical block with filters, performance, signal processing electronics, and algorithm for TOC retrieving can be found in [2, 3]. Measurements of direct solar UV radiation and retrieving of total column ozone content are fulfilled with MTOPS using three UV channels. Total column ozone is deduced from the ratio of direct solar UV radiation measured at two wavelengths, λ= 305.5 nm and λ= 312.5 nm. Measurements of UV radiation at λ=320 nm are used to account corrections due to aerosol influence and stray light contribution. Water vapor and aerosol optical thickness are measured with MTOPS near IR channels at 936 nm and 1020 nm, respectively. Comparison of this type of modern filter ozonometer with the Dobson and Brewer spectrophotometers shows that MTOPS provides accuracy comparable to these recognizable spectrophotometers and agreement between these types of ozonometers is better than ±1-2% [4]. This makes it possible to use MTOPS as portable and mobile ozonometer in field observations. The reference ozone device for the calibration of MTOPS #7351 instrument in use was the Dobson spectrophotometer #76, which is located at Mauna Loa Observatory. The data for the calibration was taken on June 13, 2003.

Series of observations of TOC, column water vapor and AOT have been starting at the Chisinau site since July 2003. Observations are made regularly for air masses *m* from *m*=3,5AM and up to *m*=3,5 PM. Frequency of measurements strongly depends on sky conditions. As a rule measurements of TOC are carried out for cloudless days in solar culmination during midday hours, when the small values of air mass occur or during the hours with an appropriate weather conditions. In this study we use data from series of measurements fulfilled during clear cloudless days only. TOC measurements are successfully carried out during short time interval of order ~10 sec by pointing instrument to the Sun for clear sky conditions or in the gaps between the broken clouds. Scan length consists of 32 samples from each of 5 channels. Measurements of TOC with MTOPS are carried out simultaneously with sunphotometer CIMEL-318, which is also placed at the Chisinau ground-based station. Sunphotometer operates within the framework of the AERONET under supervision of NASA/GSFC and makes measurements of direct solar and sky diffuse radiances (in almucantar and in solar principal planes) at seven and four fixed wavelengths in visible spectrum range from 340 nm to 1020 nm [5]. Aerosol size distribution, AOT values, refractive index of the atmosphere (real and imaginary parts), water vapor and single scattering albedo are the output products of the retrieving procedure [6, 7]. Values of AOT@1020 nm derived from CIMEL measurements are used as reference ones in comparison with the synchronously measured AOT values from MTOPS.

3. Influence of MTOPS mispointing errors onto the measured TOC values

During the operation of MTOPS in ground observations, the instrument must be pointed directly toward the Sun by adjusting a Sun's bright spot in the center of bull's-eye in sun targeting window built in ozonometer front panel. Targeting window consists of two concentric circles having a common center. Sun's spot must be captured and hold in the center in the course of the time for a single scan for each of measurements. In our case scan duration is ~10 sec. To estimate the value of error in TOC measurements, which may occur during inaccurate pointing the instrument to the Sun, we examine readings of MTOPS from the set of deliberate mispointing positions according to the scheme shown in Figure 1.

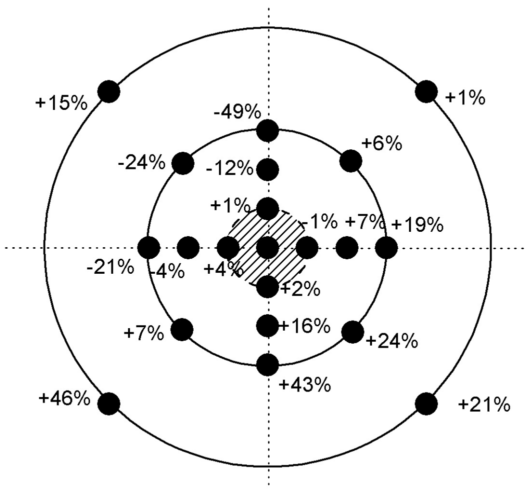

Figure 1. Viewing of the Sun targeting window of MTOPS for different deliberated Sun's spot positions marked as black filled circles. Percentage deviations in TOC readings for each of spots are indicated near the each of spot position.

For this experiment it was chosen clear cloudless day, March 29, 2005. Series of measurements was fulfilled during the middle day hours when the Sun was in culmination with solar zenith angle (SZA), $\theta=44^o$. Interval of observations was short enough to assume constant solar angles. Stability of optical properties of atmosphere during test series of TOC measurements was checked through the synchronous measurements of AOT values at λ=340, 380 and 500 nm with CIMEL sunphotometer. Values of AOT $\tau_a(\lambda)$ for these wavelengths didn't vary significantly in the course of test series. Mean values of AOT were $\tau_a(340)=0.13\pm0.02$, $\tau_a(380)=0.12\pm0.01$, and $\tau_a(500)=0.08\pm0.01$ (with daily average values $\tau_a(340)=0.17$, $\tau_a(380)=0.16$ and $\tau_a(500)=0.11$). Test series consisted of 39 measurements, 15 of which were made for centered Sun's spots. Overall duration of test series was ~34 minutes taking into account that individual measurement had scan length of 32 samples from each of 5 channels. Mean value of TOC computed for central spot position was ~350 DU. For another Sun's spots percentage deviations in TOC readings were calculated relatively to the central spot position. Black filled circles indicate deliberate positions of bright Sun's spots in the targeting window (Figure 1). Deduced errors of TOC readings are presented near each of black filled circles. It is clearly seen that TOC readings are very sensitive to the position of the Sun's spot in the targeting window during the measurement and mispointing to the Sun may lead to errors in TOC values up to 50%. MTOPS is designed to be used for hand-held operation. To obtain high accuracy of pointing the instrument toward the Sun and stable capturing of the Sun's spot in the center of targeting window during the measurement cycle MTOPS has to be rested against a rigid surface.

4. MTOPS calibration coefficients

MTOPS #7351 is used at the Chisinau ground-based solar monitoring station more than 33 months. Within this period of observations there were selected 6 days, which may be characterized as clear cloudless days. TOC variation during these days was less than 5-6 DU, or 2% that falls within the range of instrument precision. Stability of optical properties of the atmosphere was confirmed by AOT values synchronously measured with CIMEL sunphotometer. These days were used to carry out investigations of the variability of calibration coefficients by comparison with those ones defined at the factory and validated with using Langley calibration method [2, 8, 9] during calibration of instrument at Mauna Loa in June 2003. Calibration of MTOPS instrument is based on assumption of validity of the Lambert-Beer law, which is applied to the intensity of direct solar radiation measured at each channel. Taking into account ozone absorption and Rayleigh scattering this relationship is written as follows [2]:

$$I(\lambda) = I_0(\lambda) \cdot e^{-\alpha \cdot \mu \cdot \Omega - m \cdot \beta \cdot P/P_o},$$

where $I_o(\lambda)$ is solar irradiance of a particular wavelength λ at the top of the atmosphere and $I(\lambda)$ is the irradiance attenuated by column of atmosphere and measured with instrument at fixed wavelength (irradiances are converted to respective voltage readings V_λ according to the channel's calibration factors); Ω is TOC in the column of atmosphere, in DU; $\alpha=\alpha(\lambda)$ is ozone absorption coefficient and $\beta= \beta(\lambda)$ is Rayleigh scattering coefficient at wavelength λ; μ and m are optical air mass for ozone and for air (these parameters represent the ratio of the actual and vertical path lengths through ozone layer, and the ratio of the actual and vertical path lengths through the whole atmosphere to the sensor, respectively); P and P_o are the measured pressure of atmosphere and standard pressure (1013.25 mb).

MTOPS output readings in mV for each of UV channels were processed for every clear day and linear regression fits between natural logarithm of measured signal $ln(V_\lambda)$ and ozone air mass μ, known as Langley calibration plots, were constructed. Langley plots were used to retrieve calibration constants $V_0(\lambda)$ for each of UV channels. Values of $V_{0,\lambda}=V_0(\lambda)$ represent zero-air-mass photometer voltages as a response from the extraterrestrial solar radiation falling upon the top of the atmosphere at fixed wavelengths λ and these values are determined from the extrapolation of the Langley plots with values of measured signal V_λ to ozone air mass μ=0. Average column optical depths $\tau(\lambda)$ at these wavelengths may be also deduced from individual Langley plots. Theoretical expression to derive of TOC from two pairs of UV channels includes combined extraterrestrial constants [2], $L_{12} = L_1\text{-}L_2 = ln(V_{0,1}/V_{0,2})$ with indexes corresponding to wavelengths λ_1=305.5nm and λ_2=312.5nm, and $L_{23} = L_2\text{-}L_3 = ln(V_{0,2}/V_{0,3})$ with indexes corresponding to wavelengths λ_2=312.5nm and λ_3=320nm (see Figure 2). Equation to deduce corrected TOC values (with diminishing errors due to aerosol absorption and scattering on each of UV channels) is based on measurements of direct solar UV irradiances on two pairs of wavelengths: 305.5/312 and 312.5/320 nm. This equation for corrected total ozone content calculation is as follows [3]:

$$\Omega = \frac{[L_{12} - \ln(\frac{I_1}{I_2})] - [L_{23} - \ln(\frac{I_2}{I_3})] - (\beta_{12} - \beta_{23}) \cdot m \cdot \frac{P}{P_0}}{(\alpha_{12} - \alpha_{23}) \cdot \mu},$$

where Ω is TOC expressed in Dobson units or DU, L_{12} and L_{23} are combined extraterrestrial constants, I_k are measured solar irradiances and converted into signals at k=1,2,3 UV channels, α_{12}, α_{23} and β_{12}, β_{23} are ozone absorption and Rayleigh scattering cross-sections for respective pairs of wavelengths. These constants L_{12} and L_{23} are the basic ones, which define the accuracy of ozone retrieving. They have been carefully derived from Langley plot calibration at Mauna Loa in June 2003 and they are used as factory coefficients. Constants L_{12} and L_{23} were found to be equal to 1.0580 and 0.6393, respectively. In order to control the variability of L_{12} and L_{23} coefficients in the course of the operation period we choose only those clear cloudless days when optical properties of atmosphere were stable. Such criterion of stability is based on assumptions that AOT values are low in comparison with the respective multi-year mean values and with small variation. AOT values were retrieved from CIMEL sunphotometer measurements of solar direct and sky diffuse radiances at the Chisinau site during these days. MTOPS output readings in mV were processed and Langley plots in terms of natural logarithm of measured signal V_λ for each of UV channels versus the ozone air mass μ were constructed for every clear day. Ozone air mass ranges from 1.1 to 3.5. Constants L_{12} and L_{23} are simply deduced from Langley plots. As an example, for clear day of September 6, 2004, Langley calibration plots for MTOPS #7351 UV channels are shown in Figure 2. Retrieved values of L_{12} and L_{23} are equal to 1.0557 and 0.6403, respectively, and as can be seen they are very close to the constants retrieved from Langley calibration at Mauna Loa Observatory. This day was cha-

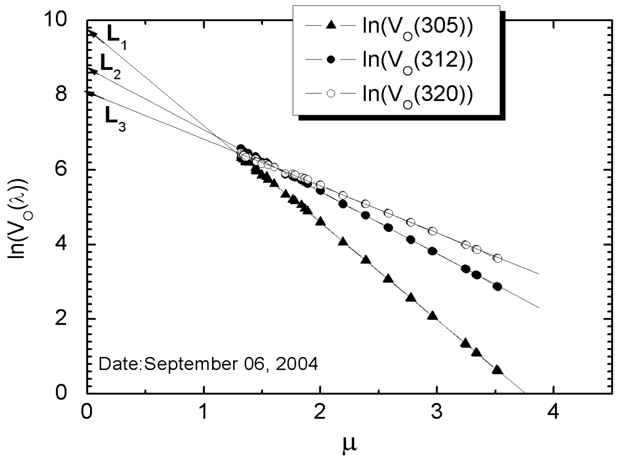

Figure 2. Langley calibration plots for UV channel of MTOPS with fixed wavelengths λ=305.5, 312.5 and 320 nm. Natural logarithms of signals $ln(V_\lambda)$ for these λ as a voltage response to the extra-atmospherical solar irradiance at the top of atmosphere are obtained from extrapolation each of plots to ozone air mass μ=0.

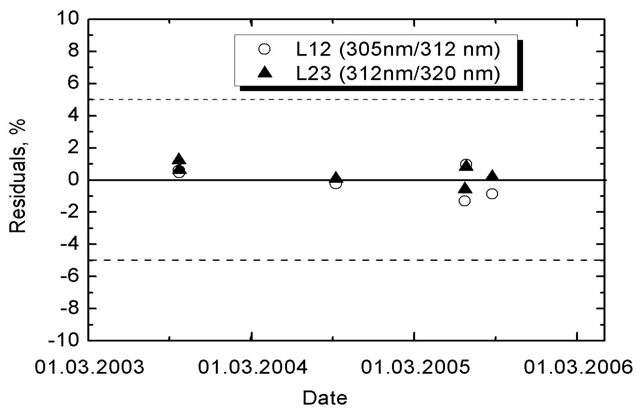

Figure 3. Time series of the MTOPS #7351 calibration constants measured at the Chisinau site during a number of clear days. Extra-terrestrial constants L_{12} and L_{23} are found to be equal to 1.0580 and 0.6393 from the Langley calibration at Mauna Loa in June 2003. Dashed lines depict the region of ± 5% deviation of residuals from these calibration constants.

racterized as clear one with stable optical parameters of atmosphere. Daily mean values of AOT measured with CIMEL sunphotometer were characterized with low AOT and low standard deviations: $\tau_a(340)=0.14\pm0.02$, $\tau_a(380)=0.12\pm0.02$ and $\tau_a(500)=0.08\pm0.01$ (with multi-year daily mean AOT values which amounted to 0.36, 0.32 and 0.23). Daily mean value of TOC measured with MTOPS this day was 293.2 ±1.2 DU. This procedure was applied to determine L_{12} and L_{23} values for all selected clear days in order to evaluate variability of them during the 33 months of MTOPS operation at the Chisinau site. Time series of calculated residuals for MTOPS calibration coefficients is shown in Figure 3. Residuals for each pair of coefficients L_{12} and L_{23} are computed relatively to the coefficients initially determined during the calibration at Mauna Loa. It is clearly seen from this figure that during the entire period of observation variability of MTOPS constants L_{12} and L_{23} is mostly less than 2% without any trend. Large values of residuals were due to change of ozone content (~5-6 DU) or some increasing turbidity of atmosphere at the selected days of calibration. Drift of calibration constants is not detected over of 33-months period of MTOPS operation.

5. Comparison of AOT values at 1020 nm from MTOPS and CIMEL sunphotometer

MTOPS #7351 instrument, which has built-in two near IR channels equipped with the interference filters at 936 nm and 1020 nm represents an opportunity to measure AOT. The fact that CIMEL sunphotometer is in operation at the Chisinau site during all the time of MTOPS work and measurements of AOTs are made at seven wavelengths from 340 nm to 1020 nm, makes it possible to use CIMEL's AOT@1020 nm values as reference ones to evaluate the accuracy of AOT values from MTOPS.

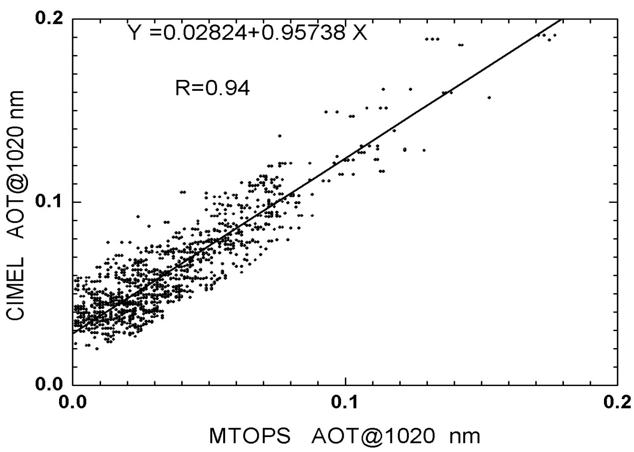

Figure 4. Scatter plot of AOT@1020 nm values derived from synchronous measurements with MTOPS #7351 ozonometer and CIMEL-318 sunphotometer at the Chisinau site during 24 months period from October 2003.

MTOPS data are measured synchronously with the CIMEL-318 sunphotometer. AERONET AOT data of Level 2.0 (cloud screened and quality assured) are used successfully for analysis and comparison readings from the MTOPS near IR channel at 1020 nm. Time series of such joined measurements consists of more than 1400 measurements started from the October 2003. Scatter plot of AOT@1020 nm values derived from synchronous measurements with the MTOPS #7351 ozonometer and CIMEL-318 sunphotometer at the Chisinau site is shown in Figure 4. As can be clearly seen, readings from the MTOPS and CIMEL show very good correlation, R~ 0.94. The line represents a linear least squares fit applied to the all measured data. Parameters of the fit are listed at the top of the plot. At the same time, it was found that the difference between AOT@1020nm values derived from measurements with CIMEL and MTOPS instruments, reveals distinct seasonal variability (see Figure 5). Temperature of MTOPS's optical block, which shows seasonal variation, is also presented at the top of Figure 5. AOT values at 1020 nm from CIMEL has been corrected on temperature dependence during the instrument operation (temperature from radiation sensor in optical block of CIMEL is constantly measured). These corrected AOT values are used as reference ones because of multistage and careful calibrations of instrument at the NASA/GSFC laboratories. Figure 6 shows the existence of the temperature dependence in the difference between values of AOT@1020 nm measured simultaneously with CIMEL and MTOPS.

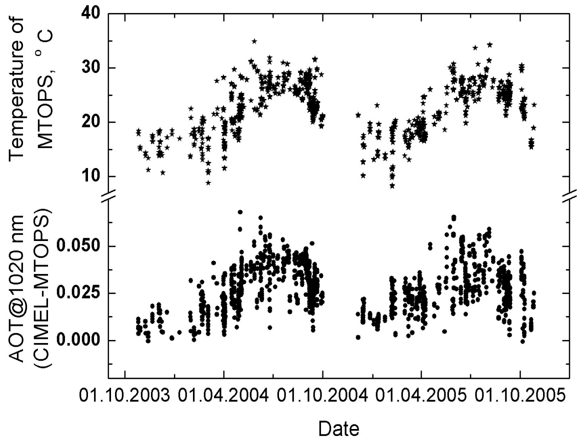

Figure 5. Seasonal variation of the difference between AOT@1020nm values derived from CIMEL and MTOPS instruments. Temperature of MTOPS optical block is shown at the top of plot.

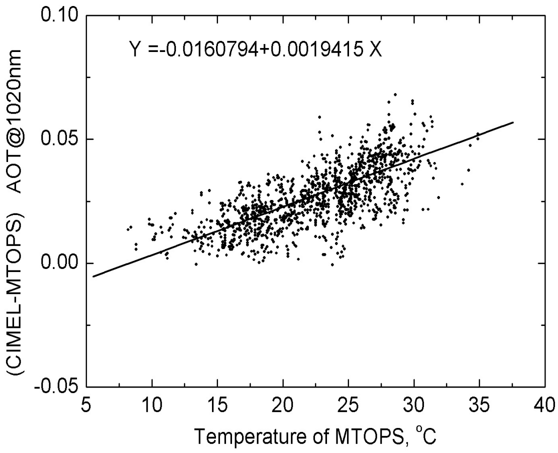

Figure 6. Temperature dependence of the difference between AOT@1020nm values derived from CIMEL and MTOPS instruments.

On an average, AOT readings from MTOPS are lower and they have small bias of order ~0.028, relatively to CIMEL data. This means that for very clear days, AOT@1020nm values from MTOPS instrument may be equal to zero or to small negative values. To carry out reliable AOT@1020nm measurements with MTOPS it is necessary to account temperature corrections of retrieved values. Parameters of linear least squares fit of differences between readings from CIMEL and MTOPS instruments are listed at the top of the plot in Figure 6.

6. Comparison of TOC values retrieved from MTOPS and satellite platforms

One of the mean to verify MTOPS performances consists in comparison of TOC values from MTOPS with data retrieved from ozone measuring instrumentation placed aboard of satellite platforms being in operation. TOC values obtained from measurements at the Chisinau ground-based station with MTOPS instrument are compared with the ozone amounts retrieved from measurements with TOMS instrument onboard of Earth Probe platform and with OMI instrument onboard of AURA platform. For the purpose of intercomparison gridded data retrieved from satellite platforms were interpolated for particular coordinates of Chisinau ground station. Respective data are downloaded from the TOMS and OMI databases located at sites ftp://toms.gsfc.nasa.gov/pub/eptoms/ and ftp://toms.gsfc.nasa.gov/pub/omi/ from Ozone Processing Team, NASA/GSFC, code 613.3.

A part of the time series of daily mean values of TOC measured simultaneously with three instruments during January-March, 2005 is shown in Figure 7. TOC data agree reasonably well with each other. Mean ratio of the TOMS divided by the MTOPS was 0.960 with a standard deviation of 0.0278 and the mean ratio of the OMI divided by the MTOPS was 0.990 with a standard deviation 0.0189. These ratios are deduced with use of daily mean values of TOC for the period of simultaneous observation from January to December, 2005. Overall correlation coefficients between these datasets for MTOPS versus TOMS and MTOPS versus OMI are equal to 0.97 and 0.99. Mean values of TOC retrieved from these instruments for this period of observations consist of 336.6 DU for MTOPS, 323.4 DU for TOMS and 333.1 DU for OMI. Values of TOC obtained from MTOPS are systematically larger than both from TOMS and OMI instruments. On an average, these residuals consist of ~15.1 DU or ~4.6% and ~2.6 DU or 0.8%. It is clear seen from Figures 7 that MTOPS data bear a very good resemblance both with TOMS and OMI daily average TOC data, in particular with the last one. Figure 8 shows also a good resemblance in seasonal variation of monthly mean values of TOC from MTOPS with data retrieved from TOMS and OMI. Existence of some "offset" between monthly mean values from MTOPS and TOMS can be seen from Figure 8. This "offset" may be connected with the instrument's errors and measurement techniques, which are used in TOMS and MTOPS. Both instruments use a differential optical absorption technique in the UV wavelength range. The difference consists in solar radiation measurement. TOMS measures backscattered UV solar radiances from the Earth's surface and from atop of clouds. Possible source of errors may be following: errors in the measurement of the radiances, errors in the values of input physical quantities obtained from laboratory calibration measurements, errors in the parameterization of atmospheric properties used as input to the radiative transfer computations, errors due to degradation of optical elements, etc. [10]. MTOPS ozonometer utilizes classical optical scheme of direct solar UV radiances measurements [2, 3]. In this case main errors are due to technique applied to direct solar radiances measurements, clearness of entrance window and experience of observer, which exert an influence upon accuracy and quality of TOC data.

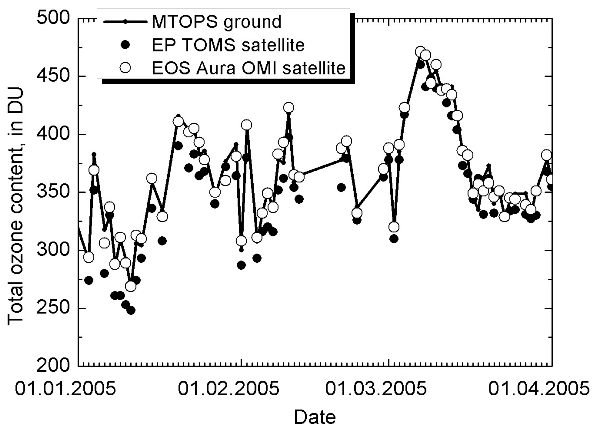

Figure 7. Time series of daily mean values of TOC for 3 months in 2005 at the Chisinau site obtained from ground measurements with MTOPS and from satellite platforms with TOMS and OMI instruments.

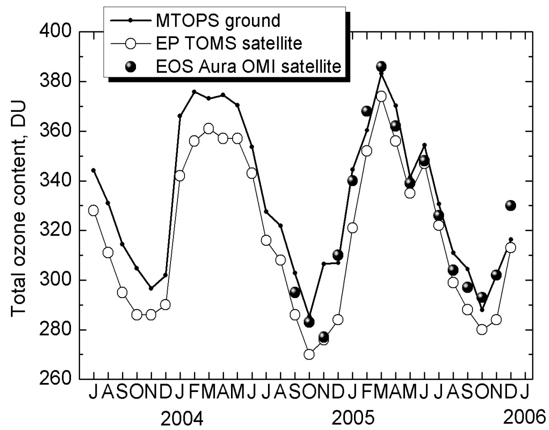

Figure 8. Seasonal variation of monthly mean values of TOC for July 2003 -March 2006 at the Chisinau site obtained from ground measurements with MTOPS and from satellite platforms with TOMS and OMI instruments.

4. Summary and conclusions

Performances of MTOPS operation during TOC measurements at the Chisinau site are analyzed. It was shown that MTOPS mispointing errors have a bearing upon the measured TOC values. Test experiment was conducted in conditions when atmosphere optical properties are considered to be stable: negligible variation of AOT and with low values of AOT. MTOPS readings are very sensitive to the position of the Sun's spot in the targeting window during the measurement and mispointing to the Sun may lead to errors in TOC up to 50%. Stability of the combined extraterrestrial constants L_{12} and L_{23} for two pairs of UV channels with 305.5/312.5 nm and 312.5/320 nm, was analyzed during the entire 33-months period of operation. Retrieved residuals, which were calculated relative to the initial values of L_{12} and L_{23} from calibration at Mauna Loa, showed their variation less than 2%. Large values of residuals were due to change of ozone content (~5-6 DU) or increasing turbidity of atmosphere at the selected days of calibration. Comparison of AOT values at 1020 nm measured synchronously from MTOPS and from CIMEL sunphotometer, operating at the Chisinau site within the AERONET under supervision of NASA/GSFC, reveals the existence of the temperature dependence in the difference between simultaneously measured values of AOT@1020 nm. On an average, AOT readings from MTOPS are lower and they have bias of order ~0.028, relatively to CIMEL data. To overcome this difficulty it is necessary to make temperature correction of MTOPS readings. Results of TOC measurements with MTOPS were compared with the TOC retrieved from TOMS and OMI instruments abroad at the satellite platforms. Mean ratio of the TOMS divided by the MTOPS was 0.960 with a standard deviation of 0.0278 and the mean ratio of the OMI divided by the MTOPS was 0.990 with a standard deviation 0.0189. Overall correlation coefficients between these datasets for MTOPS versus TOMS and MTOPS versus OMI are equal to 0.97 and 0.99. Values of TOC obtained from MTOPS are systematically larger than both from TOMS and OMI instruments. On an average, these residuals or "offsets" consist of ~15.1 DU or ~4.6% and ~2.6 DU or 0.8%. Techniques of UV solar radiation measurement applied in each of instrument and related errors (during measurement and processing steps, instruments internal inaccuracies due to degradation optical elements, etc) may be possible reasons of these "offsets".

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