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A simple parameterization of columnar aerosol optical thickness

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Abstract. A simple engineering method for calculating the aerosol optical thickness at 500 nm (AOT500) is proposed for Estonian summer conditions. The method is expressed by a single formula and represents a simplified version of a more complicated model developed at Moscow University, which assumes fulfilment of the Ångström formula. For the input our method uses three parameters: (1) the Ångström wavelength exponent (α), which can be given as its seasonal climatological mean; (2) broadband Bouguer coefficient (p_2) of atmospheric transparency for optical mass $m = 2$ (solar elevation $\approx 30°$); and (3) the amount of columnar precipitable water vapour (W). The method was evaluated using the AERONET Tõravere data on aerosol optical thickness for three summer months (JJA) during 2002–2004. Because of the absence of high quality data on precipitable water, it was estimated approximately using surface water vapour pressure. Evaluation of the method demonstrated a good overall agreement with the observed AERONET 418 summer values of the AOT500 from 2002–2004. The evaluation also raised doubt that precipitable water is underestimated in our model compared to the AERONET Level 2 Version 1 observations. Due to its simplicity the method can be used for express estimations of the AOT500 under summer conditions in regions with similar climates to the Estonian one. Transition to other wavelengths is available using the Ångström formula.

Key words: AERONET, aerosols, Ångström formula, broadband direct irradiance, spectral aerosol optical thickness.

INTRODUCTION

Successful start and expansion of the NASA AERONET global network of groundbased autonomous solar photometers provides the scientific community with massive high quality standardized information on optical properties of aerosol particles. In Estonia, an AERONET CIMEL photometer began observations on

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3 June 2002. It is located at Tõravere (58°15′, 26°27′, 70 ASL), on the territory of Tartu–Tõravere Meteorological Station. The Station is included into the Baseline Radiation Network (Kallis et al., 2005). Simultaneous registration of both spectral and broadband irradiances provides an opportunity to develop approximate methods for the calculation of spectral aerosol optical thicknesses, AOTλ, using only broadband irradiance and traditional meteorological information on atmospheric humidity. Suitable accuracy of approximate methods would enable an alternative evaluation of AOTλ for locations or periods where/when spectral observations are/were not available, e.g. for quick correction of satellite remotely sensed data, for retrospective retrieval of time series of AOTλ for periods in the past when spectral measurements were not available, etc.

The necessity of parameterization of the AOTλ has been highlighted by the high initial cost of solar photometers and their expensive regular maintenance (change of filters and recalibration, once a year, in the conditions of a cloudless sky, high Sun, and very clear atmosphere). The enthusiasm of the AERONET team is acknowledged and the US Government is appreciated for funding this tremendous project. However, if the number of simultaneously monitoring autonomous photometers decreased and the project commercialized, Estonia would not be able to continue solar spectral monitoring using national resources only due to lack of sufficient funding.

As a basic model for transition from broadband irradiance to AOTλ we used a model created at Moscow University by Tarasova & Yarkho (1991a, b). By reducing the number of input parameters to three (the atmospheric integral transparency coefficient, precipitable water, the Ångström wavelength exponent) and the associated formulas to one (instead of 13), we succeeded in considerable simplification of the initial model and converted it to a handy and flexible tool for the calculation of AOTλ.

Plotting the predicted AOT500 values against those observed by AERONET at 500 nm demonstrated a very high correlation of the two sets in Estonian summer conditions during 2002–2004.

METHODOLOGY

In 1991 Tarasova and Yarkho from the University of Moscow published a model for the determination of atmospheric aerosol optical thickness, AOT550, i.e. the AOT at 550 nm, from ground-based measurements of integral (broadband) direct solar irradiance. We designate it as the *Moscow model*. The model assumes fulfilment of the Ångström formula for the description of spectral variations of aerosol optical thicknesses, AOTλ:

$$\mathrm{AOT}\lambda = \beta\left(\frac{\lambda}{1000\ \mathrm{nm}}\right)^{-\alpha}, \tag{1}$$

where wavelength λ is in nm, β is the Ångström turbidity coefficient, and α the wavelength exponent (Ångström, 1929, 1930; Shifrin, 1995). The model consists of 13 analytical equations and enables calculation of the AOT550. The model uses the following parameters as input:

- solar elevation, h
- broadband direct solar beam irradiance, S_h
- precipitable water vapour, W
- the Ångström wavelength exponent, α; the model allows α to vary within the limits $\alpha = 0.0{-}2.0$, a simplified version of the model uses as a standard value $\alpha = 1.0$.

The Moscow model also assumes a fixed columnar O_3 content, 0.3 cm, while the NO_2 column is not considered. Transition from the basic AOT550 to AOT at other wavelengths, AOTλ, is available using Eq. (1). The model was used by Yarkho-Gorbarenko to analyse spatial and temporal variability of the AOT550 according to the broadband observations from 155 actinometric stations on the territory of the Soviet Union (Gorbarenko, 1997).

We chose the Moscow model because of its simplicity (the model consists only of 13 formulas) and the possibility of changing the Ångström wavelength exponent. However, in order to create a more handy engineering method for quick AOT determinations under Estonian summer conditions, we have made three principal changes in the model.

First, keeping in mind multiannual time series of the Atmospheric Integral Transparency Coefficients (AITC), p_2, composed and archived for many actinometric stations on the territory of the former USSR, we replaced broadband direct irradiance, S_h, with its counterpart AITC, p_2. The latter corresponds to the Bouguer–Lambert coefficient p_2 of atmospheric transparency at atmospheric optical mass $m = 2$ (solar elevation ≈30°):

$$p_2 = \left(\frac{S_2}{S_0} \right)^{\frac{1}{2}}, \tag{2}$$

where S_2 is the broadband direct irradiance at $m = 2$ and S_0 is direct irradiance at the top of the atmosphere (i.e. solar constant corrected for the Sun–Earth distance). The AITC p_2 enables easy calculation of two important broadband parameters of atmospheric turbidity – the Linke turbidity factor and the broadband optical depth (Okulov et al., 2001). Therefore, it can be considered as a central broadband parameter of optical properties of the atmospheric column. Three simple formulas for transition from S_h to p_2 are described and intercompared by Ohvril et al. (1999).

Secondly, using the least square method, we replaced 12 coefficients (given by 12 equations) of the Moscow model by linear functions of the Ångström wavelength exponent α. Thirdly, in order to get better approximations of the AOT500 values for Estonian conditions, we reduced predictions by 5%. These three changes led us to a single expression that depends on three parameters, α, W (cm), and p_2:

$$\begin{aligned}\mathrm{AOT500} = (1.1^{\alpha})[(-0.7199\alpha - 0.6246)W^{(-0.0173\alpha-0.0039)}\ln(p_2) \\ + (-0.1414\alpha - 0.0925)W^{(-0.0243\alpha+0.1646)}],\end{aligned} \tag{3}$$

where the expression in the square brackets gives the value of the AOT550, and the coefficient $(1.1)^{\alpha}$, according to the Ångström formula, transforms it to AOT500. For example, suppose that $\alpha = 1.5$, $W = 1.5$ cm, and $p_2 = 0.75$. Under this scenario, AOT500 = 0.189 is obtained. Fixing the Ångström wavelength exponent, $\alpha = 1.3$, the three-parameter expression (3) changes to a two-parameter one:

$$\mathrm{AOT}(1.3;500) = -1.766W^{-0.0264}\ln(p_2) - 0.313W^{0.133}, \tag{4}$$

fixing $\alpha = 1.5$:

$$\mathrm{AOT}(1.5;500) = -1.967W^{-0.0298}\ln(p_2) - 0.351W^{0.128}. \tag{5}$$

The amount of precipitable water vapour, W, usually changes only slightly during a 24-h period and has a good correlation with surface humidity parameters. In this research we applied a parameterization for Tõravere developed for Tallinn 12 UTC clear sky radio soundings (Okulov et al., 2002):

$$W(\mathrm{cm}) = 0.148e_0 + 0.040, \tag{6}$$

where e_0 is the 12 UTC water vapour pressure in hPa (mbar). It should be underlined that although the amount of precipitable water vapour is quite stable during a day, its counterpart, surface water vapour pressure is characterized by a significant diurnal course. Therefore, when applying correlative methods like Eq. (6) for the estimation of W, it is necessary to use the values of e_0 for the given time, in the present case for 12 UTC. Obviously, an estimated W is constant during a day.

DATABASES FOR AERONET AND ACTINOMETRIC SUMMER MEASUREMENTS AT TÕRAVERE

During the 2002–2004 summer months – June, July, August (JJA) – the AERONET photometer at Tõravere made 3284 Level 2 Version 1 full observations of AOT in 180 days, i.e. about 18 observations per day. The nominal time interval between successive observations was 5 min. *Full observation* means a set of AOTλ measurements at all seven wavelengths, i.e. at approximately 340, 380, 440, 500, 675, 870, and 1020 nm. However, when calculating the Ångström coefficients, α and β, we used exact values of λ, slightly different from the approximate ones. Note that the AERONET server calculates α and β using three to four wavelengths only, not all seven wavelengths, and it never uses $\lambda = 1020$ nm.

Averaging the daily Ångström wavelength exponent α for each of the three summer months (JJA) and then over the three months of a given year (June–August), the following mean summer values were found: $\alpha = 1.45$, 1.41, and 1.63, for 2002, 2003, and 2004, respectively. The average value for the summers of 2002–2004 was $\alpha = 1.50$. This value characterizes the mean summer columnar composition of aerosol particles at Tõravere.

In parallel, broadband direct solar irradiance S_h was registered at Tõravere every 3 min (an AT-50 actinometer was used as an operational pyrheliometer). The plot of this time series was visually inspected to eliminate periods with abrupt changes. In cases when there was doubt about the presence of clouds in front of or around the solar disc, a diary of cloudiness observations (every 60 min, e.g. 9:30, 10:30, 11:30, etc., true solar time) was used to check the presence of clouds. For the clear solar disc periods, the values of S_h were picked up, usually at intervals of 30 min, and the AITC p_2 was calculated.

When joining the two databases, we selected only observations made in a time interval of 10 min when both spectral and broadband irradiances were available. The joint database for the summers of 2002–2004 lists 418 integrated observations in 72 days. Compared with the whole set of AERONET observations at Tõravere (3284 observations in 180 days of JJA, 2002–2004), this selection contains considerably fewer data. For both sets, a general review of the number of observational days, observations, and the main observed optical parameters in the summers of 2002–2004 is given in Table 1.

Table 1. General information in optical observations at Tõravere, Estonia, in June, July, and August, 2002–2004. Coefficients α and β were calculated using seven wavelengths in 340–1020 nm

	Days	Observations	α	β	AOT500	p_2
			2002			
AERONET data	68	1602	1.45	0.091	0.246	
Joint database	36	201	1.52	0.081	0.236	0.730
			2003			
AERONET data	49	650	1.41	0.057	0.152	
Joint database	18	70	1.51	0.046	0.134	0.756
			2004			
AERONET data	63	1032	1.63	0.045	0.134	
Joint database	18	147	1.85	0.028	0.096	0.773
			2002–2004, mean			
AERONET data	180	3284	1.50	0.064	0.178	
Joint database	72	418	1.63	0.052	0.155	0.753

It is noteworthy that for the selection the average values of parameters of turbidity and transparency were shifted towards a cleaner atmosphere. For example, averaging results of observations over days, months, and summers, the summer mean values of the Ångström wavelength exponent α were 1.52, 1.51, and 1.85, for 2002, 2003, and 2004 respectively. The average value for the summers of 2002–2004 was 1.63. All these values of α are slightly higher compared with those for the whole AERONET Level 2 Version 1 database. Apparently they correspond to smaller particles in the atmospheric column. All averages of both turbidity parameters (the Ångström coefficient β and AOT500) for the joint database are systematically smaller than for the AERONET database.

The discrepancy between the AERONET and the joint database can be explained by the fact that in several cases when the solar disc was considered to be free of clouds for the AERONET automated observations, it was considered 'cloud contaminated' for the observations of broadband direct irradiance, S_h, after a manual inspection. Because of that, several AERONET observations were discarded for inclusion in the joint database. Usually 'cloud contaminated' means the presence of *Cirrus* clouds, which, as a rule, can be easily detected by a professional meteorologist-observer. However, the summer of 2002 was exceptional in Estonia, being very dry and hazy. Haziness was caused by forest and bog fires in Estonia and neighbouring Russian territories and often by intrusion of contaminated air from east and south. As result, the summer of 2002 is characterized by a low value of the AITC: $p_2 = 0.730$. On very hazy days, registration of the presence and type of cloudiness was difficult even for an experienced observer.

RESULTS OF PREDICTION OF THE AOT FOR ESTONIAN SUMMER CONDITIONS

In the first run of our approximation we used a value $\alpha = 1.50$ for the Ångström wavelength exponent. This value (see above), according to all 3284 AERONET JJA observations, represents the mean summer aerosol composition above Tõravere during 2002–2004. After fixing $\alpha = 1.50$, our general formula (3) results in simplified Eq. (5). Then, inserting 418 values of the broadband transparency p_2 observed at Tõravere and the precipitable water vapour W derived from Eq. (6), we calculated the first set of AOT500 values. The predicted results should be considered successful: the coefficient of determination is high, $R^2 = 0.98$. According to the trendline, $y = 1.023x$, the modelled values of the AOT500 seem to overestimate the reference AERONET values by only 2.3% (Fig. 1). If this is so, the method can be used, as a first approximation, for indirect quick estimations of AOT500 on the basis of routine surface meteorological and actinometrical measurements.

However, a comment is necessary here. In the first run of our model we inserted the average value of $\alpha = 1.50$. This value corresponds to the entire database of 3284 AERONET 2002–2004 summer observations, when the averaging

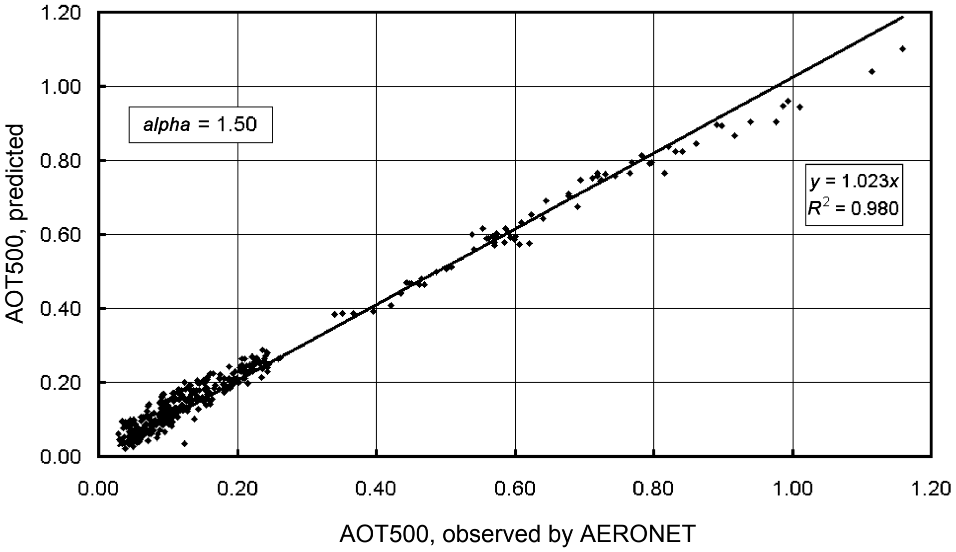

Fig. 1. Modelled versus measured AOT500 for summer (June, July, August, 2002–2004) conditions at Tõravere, Estonia. Equation (5) and a fixed Ångström wavelength exponent, $\alpha = 1.50$, are used for all 418 points. Trendline $y = 1.023x$ indicates that the model slightly overestimates (by 2.3%) the measured AERONET AOT500 values.

of single observations was first made over days, second over a month, then over the three summer months (JJA), and finally over the three years, 2002–2004. For the smaller database of 418 observations, considering each observation equal and independent, i.e. neglecting affiliation to a certain date, the average value for the Ångström wavelength exponent $\alpha = 1.566$. In the second run we inserted this value into Eq. (3). Now, according to the trendline, $y = 1.055x$, the overestimation rose to 5.5%. In the third run with $\alpha = 1.60$, the overestimation was even higher, at 7.2%. This means that our approximation systematically overestimates the AERONET reference values. The coefficient of determination kept its high value and was the same for all three runs, $R^2 = 0.98$. This would allow us to insert an additional coefficient 1/1.023 = 0.977 into Eqs (3)–(5), and to proportionally reduce the modelled values of AOT500 in order to secure a better fit to match the ideal plot, $y = 1.000x$.

Nevertheless, we would not rush to add more empirical constants. There are two reasons for this. First, our database of joint spectral and broadband observations allows modelling the AOT for the summer months. During other seasons, as demonstrated by our preliminary estimations, columnar optical parameters are different from the summer ones. However, the number of joint observations for other seasons is by far insufficient. Second, models for transition from broadband columnar optical parameters to spectral ones always contain precipitable water, *W*.

As an approximation, we estimated W at Tõravere using parameterization (6) derived for Tallinn. Perhaps this parameterization underestimates W for Tõravere. Underestimation of W leads to an overestimation of AOT. Comparison of the results obtained for W by Eq. (6) and by the AERONET Level 2 Version 1 special 940 nm channel supports this approximation. In the frames of joint 418 observations the AERONET estimations for W were on average 14% higher compared to parameterization (6). Below we shall examine how increased precipitable water influences the predictions of AOT. Improvement of W parameterizations will be part of our future work.

DISCUSSION

Estimation of aerosol optical properties for very clean atmospheric conditions, with low content of aerosol particles, is highly uncertain, especially in regard to the Ångström wavelength exponent. Low aerosol turbidity produces large relative errors for AOTλ. Also the Ångström formula performs worse, which is apparently due to deviation of the aerosol size distribution from the power law (the Junge distribution) in the case of a low aerosol concentration (Teral et al., 2004; Carlund et al., 2005).

Let us examine one exceptional day with a very clean atmosphere, which occurred on 8 July 2004, the day after a heavy rain. Parameters of a coincident, AERONET Level 2 Version 1 and actinometric determinations, at 08:26 UTC, were as follows: AOT340 = 0.0852, AOT380 = 0.0573, AOT440 = 0.0506, AOT500 = 0.0377, AOT670 = 0.011, AOT870 = 0.00466, AOT1020 = 0.00063, W(AERONET) = 1.88 cm, W[Eq. (6)] = 1.67 cm, $m = 1.343$, $S_m = 0.9546$ kW/m^2, $p_m = 0.7654$, $p_2 = 0.7846$. The Ångström wavelength exponent, $\alpha(340–1020) = 4.015$, was calculated from the seven AOTλ values. This was the highest of all AERONET full observations during all seasons of 2002–2004 (in total 6399 full observations, at all seven wavelengths, were made), the only value exceeding the physically justified maximum, equal to 4.0 for molecular (Rayleigh) scattering.

Although the Moscow original model was actually developed for $0 < \alpha \le 2.0$, we tested it by inserting $\alpha = 4.015$, $W = 1.88$ cm, and $S_m = 0.9546$. It gave AOT500 = 0.267, which exceeds the AERONET observed value by a factor of 7.1. Inserting precipitable water from Eq. (6), i.e. using an input set of $\alpha = 4.015$, $W = 1.67$ cm, and $S_m = 0.9546$, the output gave AOT500 = 0.322, which exceeds the AERONET value even by a factor of 8.5.

If the first respective input ($\alpha = 4.015$, $W = 1.88$ cm, and $p_2 = 0.7846$) is used for our approximation, Eq. (3), the new AOT500 = 0.184, which again significantly exceeds the reference value, by a factor of 4.9. By inserting for our model precipitable water from Eq. (6), i.e. $\alpha = 4.015$, $W = 1.67$ cm, $p_2 = 0.7846$, AOT500 = 0.202 was obtained, which exceeds the AERONET value by a factor of 5.4.

A plot of 418 Ångström wavelength exponents, $\alpha(340–1020)$, against AOT500 (note that the plot is not presented) demonstrated that for very clean atmospheres, when AOT500 < 0.2, the exponent changed between significant limits, from 1.0 to 4.015. Now we tested both the Moscow original model and our approximation by inserting its individual known value of the Ångström wavelength exponent for each observation. It did not improve the predictions of AOT500. In view of that, in cases of very clean atmospheres, considerably better predictions can be obtained using a fixed seasonal value of the Ångström wavelength exponent. In very clean atmospheric conditions, observed individual values of the Ångström $\alpha(340–1020)$, quantitatively expressed by AOT500 < 0.2, are not reliable and lead to a physically unjustified scatter of predicted AOT500 values. Substitution of observed single values of α with their seasonal mean significantly reduces the scatter and enables better predictions.

Variability of Ångström coefficients during summer at Tõravere, Estonia, was studied by Teral et al. (2004), who also observed deviation from the Ångström formula on very clear days. They found that on these days the spectral behaviour of AOTλ is often anomalous in the region of 670–1020 nm and does not fit the Ångström formula. In the cases of greater turbidity, when AOT500 > 0.2, the Ångström formula fits well, the correlation between ln(AOTλ) and ln λ is high, as usual $|R| > 0.97$.

However, for a very turbid atmosphere the Ångström wavelength exponent demonstrated stability. For our set of 418 summer observations during 2002–2004, when AOT > 0.7, the exponent was $1.1 < \alpha < 1.4$, which is close to the conventional value of 1.3.

As mentioned above, the idea for a possible underestimation of the precipitable water vapour was also tested in a run of our model. When each value of *W*, as calculated by Eq. (6), was increased by 14%, the graph achieved a near perfect fit, $y = 1.001x$. This result emphasizes the necessity to improve our parameterization of precipitable water.

SUMMARY AND CONCLUSIONS

A simple parameterization for the calculation of the aerosol optical thickness at 500 nm, AOT500, is proposed for Estonian summer conditions. The method, given by Eq. (3), represents a simplified and adjusted version of a more complicated *Moscow model* developed by Tarasova & Yarkho (1991a, b). Our broadband version uses the Atmospheric Integral Transparency Coefficient, (AITC p_2), which actually is a common Bouguer coefficient of columnar broadband transparency, reduced to optical mass $m = 2$ (solar elevation $\approx 30°$). AITC p_2 was a central broadband parameter of columnar transparency in the USSR. Its time series has been calculated for several decades, in some locations since the 1930s. The second input parameter, the columnar precipitable water vapour, *W*, was estimated by

Eq. (6) as a linear fit to the surface water vapour pressure. For the third input parameter, the Ångström wavelength exponent, α, we would recommend the use of its average seasonal climatological value, especially in the cases of very low turbidity.

A test of the model, by predicting summer AOT500 values observed by the AERONET photometer at Tõravere in 2002–2004, demonstrated a high coefficient of determination ($R^2 = 0.98$). For very clear atmospheric conditions (AOT500 < 0.2) the method never predicted unnatural negative values, which sometimes occurs in modelling the AOT under extremely low atmospheric turbidity conditions (Gueymard, 1998). However, a plot of the 418 predicted AOT500 values against the observed ones revealed an overestimation of 5.5% on average. At the same time, there is doubt that Eq. (6) underestimates precipitable water by an average of 14% compared to the AERONET 940 nm channel observations. When we increased the W values by 14% and ran our model again, the overestimation was eliminated.

As said above, the improvement of the parameterization of the precipitable water will be part of our future work, but besides the AERONET 940 nm channel data we would wait for an enhancement of the GPS stations' network for the Estonian territory, which would provide an alternative opportunity for W estimations. Extension of this study to other seasons (autumn, winter, spring) requires increasing the number of joint spectral–broadband observations.

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Õhusamba aerosooli optilise paksuse lihtne parametriseerimine

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On esitatud vertikaalses õhusambas olevate aerosooliosakeste (suits, tolm, udu) optilise paksuse AOT500 lihtne arvutusmeetod lainepikkuse 500 nm jaoks. Aluseks on võetud T. A. Tarassova ja E. V. Jarho (Moskva ülikool) 13 valemist koosnev mudel, mis eeldab aerosooli optilise paksuse spektraalse käigu sõltuvust Ångströmi valemi järgi. Artiklis esitatud mudeli lihtsustatud, nn inseneriversioon, koosneb ainult ühest valemist ja kasutab kolme sisendparameetrit: 1) Ångströmi valemi lainepikkuse eksponenti α; 2) atmosfääri integraalset (kõiki lainepikkusi hõlmavat) Bougueri läbipaistvuskoefitsienti p_2; 3) õhusamba veeaurusisaldust (*precipitable water*) W.

Meetodi kontrolliks on kasutatud Tõraveres aastate 2002–2004 suvekuudel mõõdetud õhu integraalse läbipaistvuskoefitsiendi p_2 väärtusi ja keskmist lainepikkuse eksponendi α väärtust. Atmosfäärisamba veeaurusisaldust W on hinnatud ligikaudselt, maapealse veeaururõhu järgi. Tulemusi on võrreldud Tõraveres töötava AERONET-i võrgustiku fotomeetri poolt mõõdetud AOT500 väärtustega. Kokku on toimunud 418 optilise paksuse üksikväärtuse võrdlust. Kuigi arvutus- ja mõõtmistulemuste vaheline korrelatsioon on kõrge (determinatsioonikoefitsient $R^2 = 0,98$), ülehindab mudel tegelikkust – keskmiselt 5,5% –, mille põhjuseks võib olla õhu veeaurusisalduse alahindamine. Veeaurusisalduse valemi korrigeerimine likvideerib AOT500 ülehindamise.

Esitatud arvutusmeetod on kasutatav AOT500 ekspresshinnanguteks Päikese otsekiirguse spektraalmõõtmiste puudumisel, sh satelliidikujutiste korrigeerimiseks traditsioonilise maapealse aktinomeetrilise ja meteoroloogilise info alusel.