CONTRIBUTION TO THE QUESTION OF OPTIMIZING THE PARAMETERS OF ULTRAVIOLET SPECTROMETRIC OZONOMETERS

A.N. Krasovskii, A.M. Lyudchik, L.Ch. Neverovich, N.V. Sergeeva, L.N. Turyshev and A.F. Chernyavskiĭ

Scientific-Research Institute of Applied Physics Problems, Belorussian State University, Minsk
Received December 2, 1988

Theoretical and experimental investigations of the errors in measurement of the total ozone content in the atmosphere performed with ultraviolet spectrometric ozonometers are analyzed and the basic sources of error are identified. The technical characteristics of an apparatus giving high measurement accuracy are discussed. The construction of the Pion solar UV spectrometric ozonometer, designed so as to meet these requirements, is described.

The most accurate and widely employed method for monitoring the state of the ozone layer of the atmosphere is to perform spectrophotometric measurements of the direct solar ultraviolet radiation in the range 290–340 nm reaching the earth's surface. There is an entire series of devices for measuring the total ozone content in the atmosphere (TOC)[1,2] that operate on this principle, but the measurement accuracy achieved thus far does not permit evaluating unequivocally the degree to which man-made factors affect the state of the atmospheric ozone. The most reliable and accurate instrument that has been employed for decades at stations in the worldwide ozonometric network is the Dobson ozonometer[1,2], while the parameters of the best modern instruments can only approach those of the Dobson instrument.

The reason for this situation obviously lies in the technical deficiencies of the designs being developed and the inadequacy of the methods employed. At the design stage special attention should be devoted to a complex approach for the purpose of taking into account correctly all factors that can significantly affect the accuracy with which the TOC is determined. In this connection it is impossible not to mention Ref. 3, where based on comparison of the readings of different instruments and an unconvincing analysis of the possibilities for increasing the accuracy of ozonometers it is concluded that "...there are currently no simple ways to reduce the error in the measurement of TOC", and it is doubted that TOC meters operating on the principle of spectrophotometric measurement of the solar UV radiation can be improved. The results of Ref. 4, where the difference in the indications of the Dobson and Brewer ozonometers was reduced to less than 1% by means of comparative calibration, refute the conclusions drawn in Ref. 3 and provide further motivation for improving ozonometric apparatus.

In this paper we discuss the technical requirements that an instrument which measures the TOC with high accuracy must meet. A solar ultraviolet spectrometric ozonometer, whose construction meets these requirements, is described.

FIELD OF VIEW OF THE INSTRUMENT

It is believed[5] that the linear field of view should not exceed 2–2.5°, so that the solar radiation scattered in the atmosphere and entering the instrument would not appreciably affect the strength of the recorded signal. Even better results are achieved by reducing the field of view to 35–40′, but this requires more accurate sighting on the sun, whose angular size equals 32′. Further reduction of the field of view can increase the error in the TOC owing to the difference in the brightness of separate sections of the solar disk and the drop in the signal strength.

Aside from the conditions that must be met in order to record radiation levels with high accuracy of sighting on the sun must also meet certain requirements in the case when the zenith angle Z of the sun, employed in calculations of the relative sizes of the air, ozone, and aerosol masses, is judged from the orientation of the pointed device. Starting from the approximate expression for the relative mass $\mu \approx 1/\cos Z$, it is easy to show that the contribution to the error in the determining the TOC in the range $0 \le Z \le 80°$ does not exceed 1%, if the error in the angle Z does not exceed 10′.

SPECTRAL RANGE

The working wavelength of the Dobson ozonometer range from 305 to 450 nm. It is shown in Ref. 5 that shifting the short-wavelength edge of the range into the region 290–295 nm can substantially reduce the effect of practically all sources of error on the accuracy of the measurements of the TOC. However the significant attenuation of the direct solar radiation owing to the increase in the absorption by ozone at short wavelength increases the recording error considerably, and in the case of large zenith angles of the sun the possibility of measuring the signal itself becomes problematic. For this reason, depending on the state of the atmosphere and the zenith angle of the sun, the optimal short-wavelength boundary of the working range shifts in either direction along the wavelength scale.

SPECTRAL RESOLUTION OF THE INSTRUMENT

The effect of the width of the transmission band of the spectrometer on the accuracy of TOC measurements has been studied in many works (see Refs. 1 and 2). In Ref. 7 it is pointed out that in the range ≥ 295 nm the deviations from Bouguer's law owing to the variability of the absorption coefficient of ozone in the transmission band of the instrument lead to an error in the ozone measurements of not more than 1%, if the instrumental half-width does not exceed 0.2 nm. The existence of fine structure in the spectral trace of the absorption coefficient of ozone strongly affects the results. For this reason the restriction mentioned above can be reduced somewhat by optimizing the choice of working wavelengths of the ozonometer. When the short-wavelength boundary of the working range is shifted toward longer wavelengths the admissable half-width of the transmission band increases.

ACCURACY OF WAVELENGTH TUNING

The reproducibility of wavelength tuning depends on the quality of the drive mechanism employed in scanning spectrometers and is most accurate in instruments with fixed (for example, with the help of several immobile spectral targets) working wavelengths. The question of wavelength calibration (referencing) is equally acute for both types of instruments. It is shown in Ref. 8 that it is very difficult to reduce the wavelength referencing error to values less than 1/10 of the instrumental half-width. However, the indicated accuracy of referencing when operating in the range 295–320 nm is acceptable only for instruments whose instrumental half-width does not exceed 0.5 nm.

RECORDING ACCURACY

The relative error in recording the signal can realistically be reduced to a level of 1–2%. In the case of weak signals, however, this can be accompanied by an excessive increase in the recording time[6,9]. Precisely this situation arises for large zenith angles of the sun, when rapid change in the relative air and ozone masses limits the measurement time. This is another argument in favor of shifting the working range in such cases into the longer- wavelength part of the UV spectrum.

Different fluctuations in the atmosphere along the radiation path can appreciably affect the accuracy with which the direct solar radiation is recorded. This question, however, remains little studied in application to ozonometry.

SPECTRAL SENSITIVITY

The sharp reduction of the signal strength accompanying a shift into the short-wavelength region can be partially compensated by correspondingly increasing the spectral sensitivity of the ozonometer. As a result photodetectors whose sensitivity is maximum in the short-wavelength part of the working range are employed in spectrometers-ozonometers. In many cases additional measures are taken to attenuate the signal in the long-wavelength part of the spectrum.

DYNAMIC RANGE

Depending on the position of the sun and the state of the atmosphere (ozone content and presence of aerosols) the strength of the direct ultraviolet solar radiation reaching the earth's surface varies over wide limits, and the greatest changes occur at the short-wavelength edge of the working range. The electronic system employed to record the signal should have a wide dynamic range (not less 150 dB) in order that the indicated changes not limit the possibilities for performing measurements.

REPRODUCIBILITY OF CHARACTERISTICS

To ensure that the readings of the spectrometric ozonometer remain stable as the temperature of the surrounding medium changes different types of compensators can be inserted into the optical scheme of the instrument (Dobson ozonometer) or corrections can be introduced into the method employed to calculate the TOC from the measurements. For small devices thermal stabilization of the entire optical-mechanical part of the spectrometer is a promising method.

METHOD FOR CALCULATING THE TOC FROM THE MEASUREMENTS

Parameters of the method. Depending on the model adopted for aerosol attenuation (non-selective, linear), in order to determine the TOC in the atmosphere it is sufficient to measure the intensity of the direct solar radiation at two or three-four wavelength[1,2].

Both variants of the method employed to determine the TOC can be extended to measurements at many wavelengths and further calculation of the TOC by the least-squares method[11,10]. Such an extension is obviously aimed at reducing the random errors in the measurements at the expense of substantially increasing the number of additional parameters appearing in the calculations. The same effect could also possibly be achieved by the simpler method of accumulating many measurements at the minimum required number of working wavelengths. We note that the analysis, made in Ref. 12, of the effect of random errors on the accuracy of measurements of the TOC was not accurate enough (for example, errors in all exoatmospheric constants and absorption coefficients of ozone were considered to be random). As a result it was incorrectly concluded that the randomness of the error in determining the TOC by the multiwavelength method is higher than for the two-wavelength method.

To calculate the TOC from the results it is necessary to know the so-called exoatmospheric parameters of the instrument[1,2], the absorption coefficient of ozone, and the Rayleigh scattering coefficients at selected wavelengths. The latter coefficients is known with adequate accuracy, but data on the absorption coefficient of ozone do not yet make it possible to determine the TOC with high accuracy[13]. The accuracy of the data on the exoatmospheric solar spectrum is also low[6], so that as a rule preference is given to Bougier's method for determining the exoatmospheric constants of spectrometric ozonometers[1,2]. A generalization of this method that makes it possible to determine more accurately the exoatmospheric constants of the instrument (and also, in part, the parameters associated with the absorption coefficient of ozone) on the basis of one of the variants of the multiwavelength method by accumulating measurements of the TOC is proposed in Ref. 14.

The effect of changes in the vertical distributions of ozone and the temperature on the effective values of the absorption coefficients of ozone and the relative mass of ozone could be significant for precision measurements of the TOC. The problems arising can in principle be solved by improving the method employed to calculate these parameters and are not associated with the structural characteristics of ultraviolet spectrometric. ozonometers.

INTERACTION OF THE INSTRUMENTAL PARAMETERS WITH THE PARAMETERS OF THE METHOD

The optical arrangement of the ozonometer must make it possible to obtain the required technological characteristics of the instrument and to realize the selected method for calculating the TOC. It is precisely at the stage when the optical scheme is being designed that the interaction of most of the instrumental characteristics mentioned above is manifested, and the need for examining them together becomes obvious. Thus, for example, simply increasing the resolution of the spectrometric ozonometer, holding the other parameters fixed, decreases the useful signal, increases the noise owing to the radiation scattered inside the instrument, increases the recording time, increases wave length-tuning errors[3], etc.

Taking into account the interaction of the parameters elevates to a higher level the problem of designing a precision spectrometric ozonometer from simply satisfying a set of constraints: all of the most important characteristics must be optimized taking into account the couplings existing between them. The method employed to calculate the TOC from measurements plays an important role in the system of such couplings. As an example we point out that the error in the determination of the TOC owing to wavelength tuning errors depends on the specific choice of working wavelengths in a fixed spectral range[8].

In a successful design the contribution of different sources to the error in the TOC should be coordinated. It is pointless to try to eliminate the effect of any one of the most important factors determining the measurement accuracy while holding constant the effect of the other factors. The principle of coordination of the errors enables establishing at the initial design stage the ratio between the values of different parameters of the Instrument and then determining the possibility of realizing these ratios on the basis of a specific optical scheme as well as determining the achievable total error in measurements of the TOC.

Analysis shows that in the spectral operating range of the Dobson ozonometer the width of the transmission band, the working wavelengths, and other characteristics are almost optimal and this in many ways determines the high accuracy of the readings of the instrument. The Dobson ozonometer was improved over a period of decades, and its different units were modified as experience in performing measurements was gained.

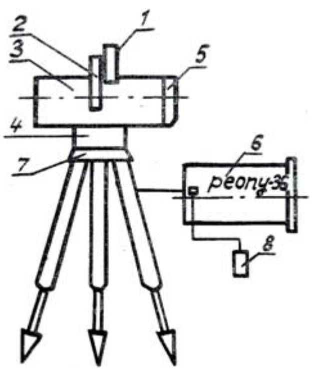

FIG. 1. Overall view of the Pion ozonometer: 1) objective; 2) pointing system; 3) monochromator; 4) azimuthal drive; 5) elevation angle drive; 6) electronics unit; 7) tripod; 8) remote control panel.

A ground-based spectrometric ozonometer of the Pion type has been developed at the A.N. Sevchenko Scientific-Research Institute of Applied Physical Problems at the V.I. Lenin Belorussian State University. The units of this device were designed with the help of the methods of mathematical modeling of the measurement process in order to optimize the parameters of the instrument and to reduce the total error in determining the TOC to a level not. exceeding 1%. Other significant requirements included reducing the size and mass of the instrument (thereby ensuring that it operates in a stable fashion under different conditions), automating the measurement process, and mathematical analysis of the results. A detailed description of the design of the instrument and the results of tests will be given in another paper; here we shall describe only the aspects of the design that are directly associated with the problem of ensuring high accuracy in measuring the TOC. Figure 1 shows an overall of the device.

A special spherocylindrical objective lens is employed to fill the input slit of the spectrometer uniformly with light; this lens, which has a matched aperture, forms in the object space a field of view of 40′×40′. The spectral part of the instrument is built according to the double monochromator scheme with subtraction of the dispersion; this significantly reduces the noise owing to scattering inside the spectrometer. The dispersing element consists of a diffraction grating; the optical arrangement ensures a spectral resolution of ~ 0.35 nm in the working range from 295 to 320 nm. This value corresponds to the recommendations of Refs. 7 and 8 and at the same time permits maintaining a relatively high signal strength.

The spectral scanning mechanism provides well reproducible wavelength tuning, so that for a scanning step of 0.04 nm attention is devoted primarily to the wavelength calibration of the spectrometer. This is performed prior to each measurement based on six lines of the spectrum of a mercury lamp built into the instrument that fall into the working range. The high stability of the radiation of the calibration lamp combined with the original method for calculating the position of the maxima of the reference lines permits reducing the wavelength referencing error to 0.01 nm. The calibration time does not exceed 2 sec.

The scanning mechanism permits recording the spectrum over the entire working range with high signal strengths within 3 sec. In the case of weak signals the signal time can be increase to 6 sec. The duration of the complete measurement cycle including calibration does not exceed 8 sec.

The optical components of the spectrometric ozonometer are attached to a rigid rod structure, which prevents external loads from affecting the optical characteristics of the spectrometer. The instrument contains passive and active systems for stabilizing the temperature at +40°C. The temperature control system stable operation for outside temperatures ranging from −15 to +35°C.

To eliminate operator error the spectrometric ozonometer is pointed toward the sun automatically. The device contains two pointing systems. The first system searches for the sun within the hemisphere and the second system performs precise pointing and holds the device in the working position with an error of not more than 2' . The zenith angle of the sun, necessary for calculating the TOC, is measured simultaneously. The angle sensoris calibrated prior to each series of measurements. The admissable error in measuring the zenith angle equals ±2′.

The unit in which data are processed and all systems of the spectrometer are controlled is based on the Elektronika-60 computer. The basic controlling and processing programs are stored in the computer memory. One of the variants of the multiwave method is employed to calculate the TOC[14]. The programs stored in the computer memory can be replaced and external devices can be connected; this actually transforms the spectrometric ozonometer from a measuring instrument into a research instrument into a research instrument and substantially expands the range of problems that can be solved with its help.

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