Detection of horizontal variations in the atmospheric refraction with the minutes-long periods

V.P. Vasylyev, V.A. Sergeev, S.R. Izmailov, and I.A. Babaev

Solar-Ecological Research Center,
Ukrainian National Center of the International Solar Energy Society, Kharkov

Received May 16, 2001

Horizontal variations of atmospheric refraction (VARs) are sought and analyzed based on the data obtained in the over-two-year photoelectric measurements of temporal parameters of moving images of stars passing at different zenith angles (from 30 to 90 degrees) across the first meridian. The all-year-present horizontal VARs with characteristic amplitudes of some angular seconds have been recorded. The statistical analysis for these VARs and qualitative analysis of their power spectra calculated with the Deeming method are made in the range of periods from tens seconds to tens of minutes. The spectra display two stable peaks with periods of 1 and 2 minutes, becoming more pronounced when approaching sunset. A number of peculiarities in minutes-long periodic VAR components manifesting themselves in essential dependence of the spectra type on the path inclination and north-southern orientation, as well as on season, have been revealed. At the zenith angles from 30 to 70–75 degrees southward from the zenith during near-equinox seasons and in summer, the spectra exhibit one distinct peak in the two-minute periods region. The amplitude of this peak sharply increases with the decrease in the path inclination angle. In the near-zenith zone of 75–90 degrees on the same side from zenith the two-minute peak is not observed, but in the winter-spring season similar peak here manifests itself in the region of one-minute periods. On the northern side (altitudes of 67–90 degrees) both minute-periodic peaks practically are not observed during all seasons. The possible source of the VAR studied is briefly discussed.

Introduction

Optical recording and revealing the nature of various stochastic and quasiperiodic variations of atmospheric refraction (VARs) lie in the foundation of the basic research into the dynamics of the atmospheric near-ground layers. On the other hand, VARs should be taken into account in a wide range of optical experiments with the use of laser sensing, observational methods of positional astronomy, etc. Manifesting themselves as optical instability of the atmosphere, VARs cover a wide range of temporal scales. A great number of experimental and theoretical studies of short-period VARs connected with the turbulent motion of the air mass have been performed up to now (see, e.g., Refs. 1, 2, and references therein). As to the relatively long-period VARs with the periods about a minute, the situation is not clear, in spite of the long-term history of this research.

The existence of minute-periodic VARs was likely noticed for the first time as early as in the beginning of the past century (see Ref. 3 and references therein) from analysis of photographic records of star traces taken with a fixed camera. Later, to separate out purely horizontal VARs, vertical photographic traces of near-polar stars recorded in South-Africa observatories were studied.[3] These studies confirmed the dominantly horizontal character of star image displacements with the period about one minute. Such a conclusion was drawn by Courvoisier and Basel[4] based on visual observations of the dynamics of star images. Later on, Kolchinskii[5] also reported the results of photographic studies of this type of VARs, detailed analysis of which has led him to the assumption on the presence of some atmospheric waves with the periods about one minute. When observing stars with the use of afar more accurate method of color difference of coordinates, similar and, in the authors' opinion, mysterious phenomenon was recorded in two measurement sessions.[6]

In other words, the possibility that dominantly horizontal VARs can exist and the wave type of air motions yielding them is discussed in the literature for already several decades. According to data from Refs. 3–6, the characteristic amplitudes of angular displacements of star image were from tenths to several seconds of arc, and thus they could be measured and separated out against the background of various background effects. However, the episodic character of such measurements, which were conducted using different methods and with the statistics, insufficient for spectral analysis, still does not allow one to draw unambiguous conclusions needed to understand the observed phenomenon.

Note also that photographic methods of VAR detection, with which most of the above-mentioned results were obtained, are not free from limitations of principle importance. For example, at a large field of

0235-6880/01/08 616-05 $02.00

view of a camera, small distortions of star traces reflecting the sought effect becomes hard to detect. At the same time, the use of narrow field of view for stars remote from the pole does not allow achieving time scales of the traces sufficient for revealing minute periodicity. A compromise approach – operation in the tracking mode – does not assure that there is no inseparable masking effect that may arise due to numerous sources of instability in orientation of the device's optical axis. The use of only near-polar stars that move slowly enough in the field of view essentially narrows the general search range. These circumstances widen the uncertainty in obtaining the final answer to the question on the properties of this type of VARs and in searching the regularities of VAR appearance and their peculiarities sufficient for unambiguous theoretical interpretation.

In this paper, we undertake an attempt to detect and tentatively study the peculiarities of minute-periodic horizontal VARs based on material of systematic observations obtained with a one and the same, sufficiently accurate, photoelectric technique with the statistical confidence allowing correct analysis by the methods of spectral assessment.

Experimental data and processing technique

To search for horizontal VARs, we used routine data of astrometric observations of stars by S.R. Izmailov on the APM-1 transit No. 540001 (objective diameter of 100 mm, focal length of 1000 mm) in the Astronomic Observatory of Kharkov University (latitude of 50°) in 1980 to 1982. The recording instrumentation was described in Ref. 7, and observations by the standard technique consisted in differential photoelectric recording of absolute moments of strictly horizontal passage of star image centers through a microgrid of two sets of equidistant reference systems (14 narrow strips of metal film on transparent substrate) arranged vertically nearby the focal plane of the transit objective. The measurement accuracy of roughly 10^{-3} seconds of arc is sufficient for this study of VARs. Actually, even at the highest speed of motion of the image of a star on the celestial equator ($\delta = 0$), this accuracy corresponds to the angular value of 0.015 seconds of arc, which is much less than the characteristic VAR amplitudes. In observations, the optical axis of a device of this type is oriented immovable in the plane of the main meridian, i.e., the passage of stars is recorded at their strictly horizontal motion at culmination. Therefore, with no instrumental jitter and refraction distortions of the wave front, the speed of image motion in the horizontal direction is constant and the time interval $\Delta t(\delta)$ between the moments in time, at which its center intersects the neighboring boundaries of fixed reference systems is the same at the unchanged star declination δ. Such a stationary, within the given instrumentation, value of the time interval can be easily determined from the angular width of the reference systems or the distance between them in the projection on the coelosphere with the allowance made for the image scale. In our case, this distance was 20.48 arcsec, corresponding to the time interval $\Delta t = 1.365$ s if $\delta = 0$. As δ increases, this difference increases proportionally to sec δ.

If distortions caused by horizontal refraction are present on the line of sight, then the experimental (actual) difference $\Delta t_e(\delta)$ between the times of intersection varies according to changes of the instantaneous speed of image motion. As this takes place, the parameter

$$\Delta\rho = 15\Delta t_e(\delta) - 20.48 \sec\delta \qquad (1)$$

characterizes the absolute value of horizontal refraction-induced displacements of the star image center from its true position in seconds of arc. In this connection, we can assume that the characteristic frequencies of probable instrumental vibrations and the local air microturbulence are much higher than the thought VAR frequencies and therefore they do not affect the obtained results. In these observations, the measurement session lasted up to several hours, and the characteristic time between the passages of different stars through the reference system for one session varied from tens of seconds to tens of minutes depending on δ with the number of stars up to several tens for one session.

In this work, using 1247 horizontal star passages through the main meridian in different seasons of the over-two-year period (a total of 53 dates), we have determined 15744 values of $\Delta t_e(\delta)$ and then using Eq. (1) we have calculated the same number of $\Delta\rho$ values. To do this, we used the stars passing through the main meridian at different altitudes above the horizon in the range from 30° and more both southward and northward from the zenith at sufficiently random character of their coordinates during each measurement session. The needed characteristics of the array of $\Delta\rho$ values obtained after accounting for systematic errors are shown in Figs. 1 and 2. This array was then used for calculation of temporal spectra.

Results and discussion

As seen from Figs. 1–2, the amplitude of the whole set of $\Delta\rho$ varies widely (from tenths to tens of seconds of arc), but they mostly do not exceed 3–4 arcsec, thus being somewhat larger than the typical values obtained by other authors and pertinent only to minute-periodic VARs.

Analysis did not reveal any dependence of the characteristic amplitudes of horizontal VARs on the altitude of the observed stars above the horizon (Fig. 2). At the same time, the dynamics of statistical parameters of the array of $\Delta\rho$ values shows the relation between the long-term changes of the VAR structure and the time elapsed from sunset. This relation is demonstrated by the curves in Fig. 3 obtained from averaging the statistical parameters of VAR at the corresponding instants for all dates of observations. Such a dynamics of horizontal VARs reflects typical state of the gas medium during and after a distortion, in this case it is likely the evening (transient) atmospheric instability.

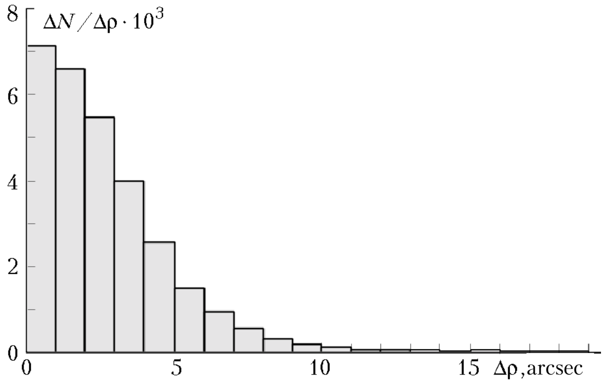

Fig. 1. Diagram of distribution of VAR amplitude Δρ.

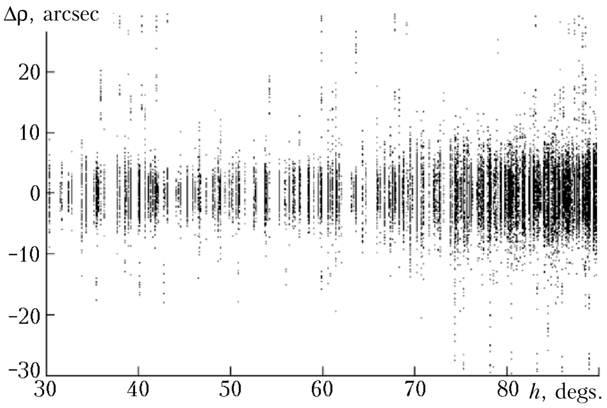

Fig. 2. Distribution of VAR amplitude Δρ vs. the altitude h of star passage above the horizon (path inclination).

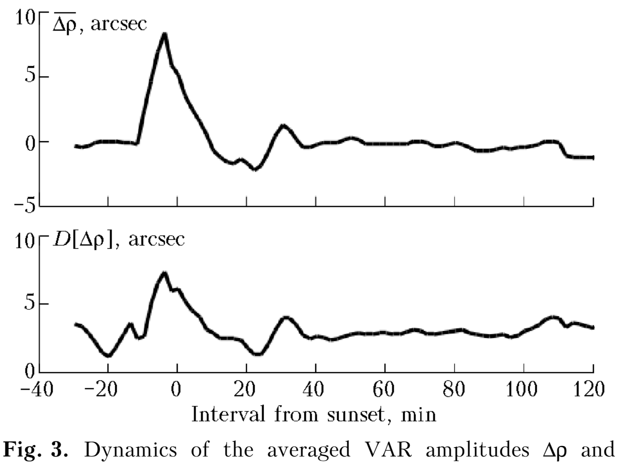

Fig. 3. Dynamics of the averaged VAR amplitudes Δρ and their variance $D[\Delta\rho]$ during sunset and after it.

By calculating the Fourier transform of non-equidistant points with normalization to the spectra of time windows (Deeming method[8]), we have obtained the frequency spectra of the power of the VARs recorded. Since the duration of the measurement session and the volume of data for different dates differ widely, besides VAR spectra for the whole session, we used also the spectra of data in time windows. The windows were chosen so that their duration and information content are roughly the same. Each window chosen in such a way covered, on the average, the interval about one hour and included about 240 points. Positioning of such windows, arranged sequentially during each measurement session, allowed analysis of the dynamics of VAR spectra depending on the change in the general state of the atmosphere during and after sunset.

Analysis showed that in spite of the wide variety of spectral peculiarities of horizontal VARs caused by a number of atmospheric factors, most of the spectra are characterized by the presence of at least one of two pronounced peaks in the range of cyclic frequencies from 0.03 to 0.14 rad/s. The vortices of these peaks correspond to the periods roughly equal to 2 and 1 min, and their widths and amplitudes correspond to the characteristic values of horizontal VARs equal to tenths of an arc second, what coincides with the results of other authors.[3–6] This peculiarity is most pronounced in the evening: the amplitude of minute-periodic peaks usually increases as sunset approaches. The increase occurs both in the absolute value and in the stochastic variations of the horizontal refraction, whose amplitudes are larger during the sunset than at night. Figure 4*a* shows an example of the power spectra. It is significant that as the time intervals with transient (evening) atmospheric processes are excluded from measurement sessions, minute-periodic peaks on the spectra disappear (curve *3*). The spectrum averaged over a large part of windows of all measurement sessions (Fig. 4*b*) also reflects these general tendencies in the dynamical structure of VARs.

As is seen from the above-said, prevalence of minute-periodic components is, in fact, the only one stable peculiarity in the spectra of horizontal VARs (obtained within both individual temporal windows, as well as in the averaged ones) in the range of periods from tens of seconds to tens of minutes.

Statistical characteristics of the data array used allowed us to study qualitatively the behavior of spectra in different altitude ranges of star passage above the horizon, as well as in different seasons. This study revealed a number of interesting and surprising peculiarities of the horizontal VARs. These peculiarities are partially reflected by the averaged spectra shown in Fig. 4*c*. It turned out that the two-minute peak is most pronounced only in the spectra corresponding to slant paths – altitudes roughly up to 70–75° above the horizon southward from the zenith. Moreover, as seen from comparison of the curves, as the path inclination increases, the value of the two-minute peak increases sharply. At high altitudes up to the zenith on the same side from it, only one-minute peak is pronounced.

Calculation of the spectra for intermediate altitude ranges shows that this spectrum transformation is connected with the existence of each of the peaks in its own altitude range rather than with the shift of the two-minute peak toward higher frequencies with the growing altitude. Northward from the zenith, the minute-periodic peculiarities in the spectra are suppressed in the entire range of altitudes represented by the data on VARs (67–90°).

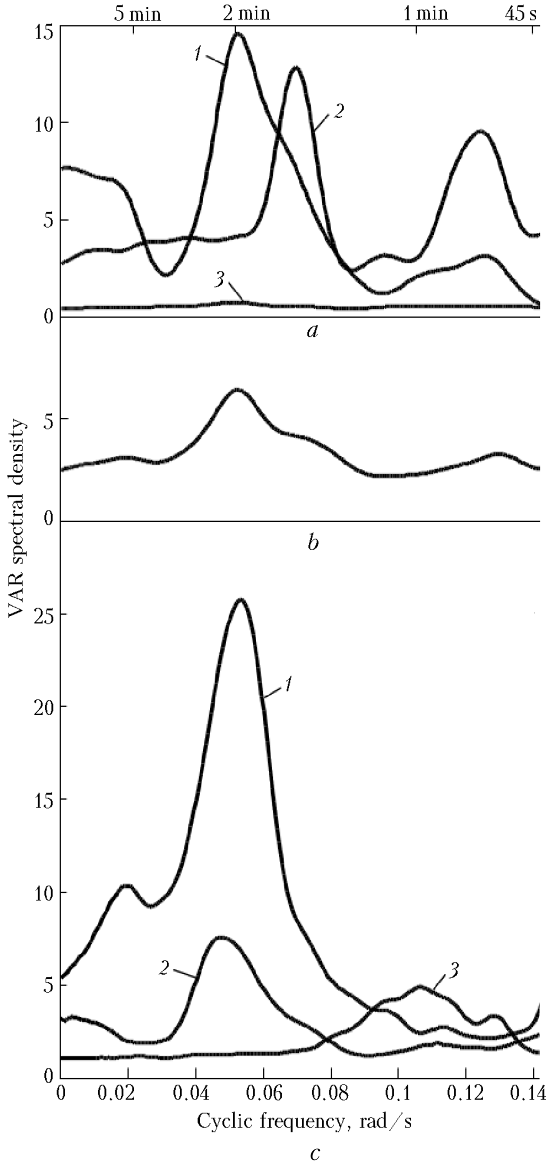

Fig. 4. Peculiarities of temporal spectra of horizontal VARs: examples of spectra (*a*): during sunset (curve *1*), immediately after sunset (curve *2*), and at night (curve *3*); spectrum averaged over most temporal windows for different measurement sessions, during which minute-periodic VARs manifest themselves (*b*); spectra averaged over different altitude sectors of the path inclination above the horizon southward from zenith (*c*): altitude range 30–50° (near-equinox seasons) (curve *1*), altitude range 50–70° in the same seasons (curve *2*), altitude range 85–90° (winter-spring seasons) (curve *3*).

It also turned out that these peaks with two-minute periods are, as a rule, separated not only in the altitude, but also in the season. Thus, the two-minute peak on the slant paths is most pronounced in near-equinox seasons and in summer, whereas the one-minute peak on the near-zenith paths is most pronounced in winter-spring season. Consequently, for this latitude of the measurement site in the range of altitudes larger than 30° southward and northward from zenith, we can separate roughly three sectors, in each of which the minute-periodic horizontal VARs are either clearly pronounced in different frequency regions and in different seasons or almost not pronounced. It is important to note that without separation into seasons for all these three sectors the sum distributions of the intervals of star passage (recording) on the time axis were practically identical (including the position with respect to the sunset point) and therefore they could not cause such differences in the spectra.

Such a nontrivial geometry and spatiotemporal relation of the localization of minute-periodic VARs, we have found, call for further detailed analysis within the framework of theoretical models of the process of their appearance. However, these peculiarities themselves indicate that the source of horizontal fluctuations of the atmosphere yielding this type of VARs is nonisotropically distributed in it and is subjected to seasonal variations at the globally permanent, on the whole, character.

Conclusion

Thus, based on the results obtained, we can believe that the fact of existence of horizontal minute-periodic VARs is finally proved and determine the following set of their main properties and spatiotemporal peculiarities:

1) permanent existence of horizontal VARs in the evening-night atmosphere at independence of the whole set of their absolute amplitudes (characteristic values about several seconds of arc) on the altitude of the line of sight above the horizon (at least, within angles larger than 30°) and its orientation with respect to the zenith;

2) the presence and stability of one-minute and two-minute periods corresponding to the amplitudes of horizontal VARs about tenths of an arc second;

3) the increase of the probability of appearance of the horizontal minute-periodic component of VAR as approaching the sunset – its intensity increases significantly both in the absolute value of spectral peaks and in relation to time-local background perturbations in the transient hours, when the atmosphere, as a whole, is less stable;

4) north-south asymmetry (at least, in the range of zenith angles up to 23° southward and northward from the zenith): horizontal minute periodicity of VARs is pronounced in all seasons mostly on the paths of southern orientation at the measurement site;

5) altitude differences of VAR spectra in south directions of the line of sight: slant paths correspond to the period of two minutes, whose amplitude increases sharply as the inclination angle decreases, and the paths more close to the vertical correspond to the period of one minute;

6) seasonal variations of spectra: in near-equinox period and in summer mostly two-minute period arises, whereas the one-minute period is typical of winter-spring season.

The certainty of the above conclusions is provided for by the sufficient statistics of the data used (15744 experimental values of the VAR amplitude, $\Delta\rho$, for all seasons during two years).

The properties and the peculiarities of the observed VARs found are indicative of the globally permanent character of the source of wavy perturbations yielding VARs. This conclusion agrees well with the earlier results of other authors, who observed VARs episodically with intervals up to tens of years using different methods at different sites sometimes even situated in different hemispheres. Besides, these peculiarities are indicative of the relation between its appearance in the latitude zone below the latitude of the measurement site and the sunset period. Therefore, the most probable source of such a kind is a solar thermal terminator moving through the atmosphere. This terminator is a longitude-localized area of relatively large temperature drop that persists for a long time in the coordinate system bound with it. As was shown earlier, in midlatitudes this source can provide tropospheric generation and horizontal intensification of just the minute-periodic part of the acoustic spectrum of atmospheric waves in the so-called speed resonance mode (see Ref. 9 and references therein).

To confirm this interpretation of the results obtained in the study of horizontal VARs, of great interest are the search and detailed analysis of parameters of this effect at different latitudes during and after sunrise, when its probable source is most pronounced as compared with the longitude-symmetric evening part.

References

1. A.V. Alekseev, M.V. Kabanov, and I.F. Kushtin, *Optical Refraction in the Earth's Atmosphere (Slant Paths)*, ed. by V.E. Zuev (Nauka, Novosibirsk, 1983), 232 pp.
2. Sh.P. Darchiya, ed., *Optical Instability of the Earth's Atmosphere* (Nauka, Moscow–Leningrad, 1985), 246 pp.
3. G. Land, Astron. J. **59**, No. 1213, 19–26 (1954).
4. L. Courvoisier and Z. Basel, Astrophys. Nachr. **277**, 259–263 (1949).
5. I.G. Kolchinskii, *Optical Instability of the Earth's Atmosphere as Judged from Star Observations* (Naukova Dumka, Kiev, 1957), 184 pp.
6. L.Yu. Sorokin and A.A. Tokovinin, Pis'ma Astron. Zh. **11**, No. 7, 542–554 (1985).
7. V.I. Turenko, A.F. Vantsan, and N.G. Litkevich, Vestn. Kharkovskogo Universiteta, No. 160, 36–42 (1977).
8. T.J. Deeming, Ap. Space Sci. **36**, No. 1, 137–158 (1975).
9. V.P. Vasylyev and V.A. Sergeev, Earth, Moon and Planets **84**, No. 2, 81–93 (2000).