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# Noctilucent cloud particle size determination based on multi-wavelength all-sky analysis

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ABSTRACT

The article deals with the analysis of color distribution in noctilucent clouds (NLC) in the sky based on multi-wavelength (RGB) CCD-photometry provided with the all-sky camera in Lovozero in the north of Russia (68.0°N, 35.1°E) during the bright expanded NLC performance in the night of August 12, 2016. Small changes in the NLC color across the sky are interpreted as the atmospheric absorption and extinction effects combined with the difference in the Mie scattering functions of NLC particles for the three color channels of the camera. The method described in this paper is used to find the effective monodisperse radius of particles about 55 nm. The result of these simple and cost-effective measurements is in good agreement with previous estimations of comparable accuracy. Non-spherical particles, Gaussian and lognormal distribution of the particle size are also considered.

## 1. Introduction

Noctilucent clouds (NLC) are the highest clouds in the Earth's atmosphere, appearing during the summer season in polar and mid-latitudes in the upper mesosphere, at altitudes of 80–85 km. They are also one of the youngest atmospheric objects, first reported in late XIX century (Leslie, 1885). These clouds were of particular interest through the entire XX century (Gadsden and Schröder, 1989). They basically consist of water ice (Hervig et al., 2001), which requires extremely low temperatures in the upper mesosphere (Thomas, 1991). Particles reach the maximum size at the altitude about 80 km (Turco et al., 1982; Rapp and Thomas, 2006; Baumgarten et al., 2010). As the scattering efficiency is strongly dependent on the particle size, it is the largest fraction of ice particles that we see as noctilucent clouds. The size of noctilucent cloud particles is one of basic observational characteristics related with physical conditions in summer polar mesosphere.

First estimations of the particle size were based on polarization measurements from the ground (Witt, 1957) and rockets (Witt, 1960). Until the last years of the XX century, the radius estimations of NLC particles were typically uncertain; sometimes the results were very high – about 100 nm and more. During the recent decades, noctilucent clouds have been intensively studied by different methods, including: lidar sounding (Von Cossart et al., 1997, 1999; Alpers et al., 2000; Baumgarten et al., 2002, 2007, 2008, 2010), rocketborne measurements (Gumbel and Witt, 1998; Gumbel et al., 2001), spaceborne UV-spectroscopy (Carbary et al., 2002; Von Savigny et al., 2004, 2005; Karlsson and Rapp, 2006; Von Savigny and Burrows, 2007), and polarization measurements (Ugolnikov et al., 2016). Reviews of the results are provided in (Kokhanovsky, 2005; Baumgarten et al., 2008).

The majority of optical methods (except rocketborne measurements and the polarization analysis) are based on the intensity comparison of the light scattered by NLC in different wavelengths or spectral bands. Satellite limb spectroscopy is used to build the spectral dependence of scattering properties in the UV-range for the current satellite and NLC position, i.e. for current fixed scattering angle θ. These spectra can be compared with theoretical Mie data to find the particle size.

Ground-based lidar observations are provided in the optical spectral region. The value being measured is the ratio of backscattering coefficients ($\theta = 180°$) in different wavelengths. The use of three or more spectral bands allows finding the mean particle radius and size distribution width (Baumgarten et al., 2010). The experimental cross-polarization scheme (Baumgarten et al., 2002) showed the presence of non-spherical particles. It made necessary to compare the measurement results with T-matrix calculations (Mishchenko, 1992; Mishchenko et al., 1996) for these particles (spheroids, cylinders).

The wavelength dependence of the NLC light scattering properties, used by those methods, points to the possible color effects in the NLC field that can be found. It is obvious that we cannot expect any strong

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spectral variations as observed for polar stratospheric clouds with larger particles. Color changes of NLC are weak to be noticed by naked eye; clouds are always visible as bluish white objects (they are even called “silver clouds” in some languages). Small spectral changes can be registered by sky background photometry. The purpose of this paper is to build a particle size estimation method based on this and verify its accuracy. The technique is ground-based; observations are provided in the visible spectrum region. The procedure must account for the twilight background and variability of solar illumination conditions at the NLC level. However, it has an advantage of the wide range of scattering angles under consideration if the NLC area is expanded in the sky to the dusk-opposite area where scattering angle exceeds 90°.

## 2. Observations

The experimental basis of this study is the all-sky camera installed at Lovozero station (68.0°N, 35.1°E) of the Polar Geophysical Institute, Apatity, Russia. The sky field diameter is 180°; the landscape zenith angle restriction is 65–70° and more. The sky images are fixed by frame with the resolution of 2816 × 2816 pixels; the angular resolution near the zenith is about 17 pixels per degree. Each 2 × 2 square consists of one B, two G, and one R pixel. All three colors correspond to wide spectral bands with the effective wavelength (for NLC conditions) of 463, 526, and 590 nm, respectively. We denote these wavelengths as bands 1, 2, and 3. The brightness of the twilight sky was averaged for each of the three bands inside the circles, 0.5° in radius, in increments of 1° by sky point zenith distance *Z* and azimuth *A* (example of such circle is shown in Fig. 1a). Exact parameters of the celestial sphere transformation into a flat frame were fixed by star images through the standard procedure used in (Ugolnikov and Maslov, 2013a, 2013b). The same data together with twilight cloud-free measurements were used as test of linearity of camera response (Appendix A).

The primary purpose of the camera is aurora imaging. The camera started working in early August, after the summer midnight sun break. The case of bright NLC event in the sky without tropospheric clouds at the zenith angles up to 60° was observed at one night, from 21 h to 22 h UT on August 12, 2016. This time period included the local midnight, when the solar zenith angle $z_0$ reached 97.4°. The minimum value of $z_0$ for the observational period is 97.0°. At this position of the Sun, NLC remained well illuminated over the major part of the sky. There were no bright NLC near the zenith, but they formed the long arcs from the north to the east and to the west, expanding the range of scattering angles, that is necessary for the accuracy of size distribution retrieval. The exposure time was equal to 0.25 s, not changing during the same hour. Images were taken twice a minute; therefore, 121 images are considered in this study. The analysis was done along the almucantars (see below) in interval of *Z* from 30° to 60°, where NLC were particularly bright. This sky circle covers the scattering angle range from 40° to 150° (see Fig. 1a).

The physical mesosphere conditions in the night of August 12 were optimal for observing the NLC. This night was the coldest one in the week at the mesopause level above the observation point. According to the EOS Aura/MLS data (EOS MLS Science Team, 2011), the typical nighttime temperature at the NLC altitude (83 km) a week before was 145 K, and in the night of August 12, it decreased to 140 K. The same values for 88 km were 135 K and 128 K, respectively. According to the IMO data (IMO, 2016), the Perseid meteor shower activity reached a maximum about one day before the observations; the radiant was high above the horizon in the observation site. This resulted in a possible increased level of the meteor smoke inflow to the mesosphere.

## 3. Color effects of scattering on ice particles

Multi-color photometric observations of scattered light make it possible to estimate the size of particles owing to wavelength dependency of the scattering function. Scattering on spherical particles is described by the Mie theory (see (Kokhanovsky, 2005) for example). The angular dependence of the scattered light intensity is defined by two dimensionless parameters: particle refractive index *m* and the size parameter (*x*):

$$x = \frac{2\pi a}{\lambda}, \tag{1}$$

where *a* is the particle radius, and λ is the wavelength. In different spectral bands, the same particle corresponds to different *x* values and different angular dependencies of scattered light. Following Iwabuchi and Yang (2011), we took ice refraction index $m = 1.31$ for all spectral bands (this subject was discussed in (Ugolnikov et al., 2016) in more details). Fig. 2 shows dependencies of product of scattering cross section and scattering phase function on scattering angle θ, $S(\theta)$ for spherical particles at a given radius of 57 nm for three instrumental wavelengths. Value *S* increases with a shorter wavelength, which is normal for small particles near the Rayleigh limit. Blue spectral range $\lambda_1$ corresponds to a higher value of $x_1$ and a more significant Mie effect: the excess of $S(\theta)$ for small scattering angles (forward scattering). The scattering coefficient ratios $S_2(\theta)/S_1(\theta)$ and $S_3(\theta)/S_1(\theta)$ become greater as the scattering angle

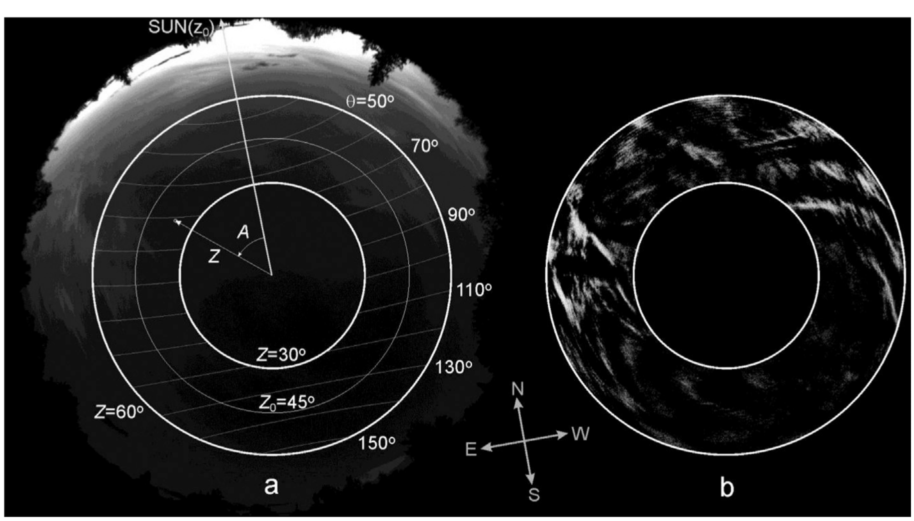


**Fig. 1.** Sky image during the NLC event of August, 12, 2016 (a). Work area is between almucantars with zenith angles *Z* from 30° to 60° (white bold lines), the contours of equal scattering angle θ are denoted. The location of the Sun is shown by arrow. *Z* and *A* is the sky point coordinates, azimuth *A* is counted from the solar vertical. $Z_0$ is the mean zenith angle of work area. (b) Map of short-scale sky brightness variations in the same image.