The slopes of a brightness phase function at different α ranges correlate with surface roughness, all other conditions being equal. Unfortunately, for the Moon it is almost impossible to select physical effects that dominatingly influence $f(\alpha)$ in specific ranges of phase angles. One can say only that: (1) at $1° < \alpha < 5°$ the coherent backscatter enhancement and shadow-hiding effect in the regolith are important, (2) at $5° < \alpha < 40°$ the shadow-hiding effect and contribution of single-particle scattering are major, and at $\alpha > 40°$ the shadow-hiding effect on all roughness scales, including the scales of surface topography, becomes significant (e.g., Hapke, 1993). With regard to the shadow-hiding effect in regolith media, we also imply the influence of multiple light scattering within and between particles, which produce secondary illumination of shadows weakening their effect.

Mapping of the lunar phase function $f(\alpha)$ parameters was first carried out by Wildey (1978) and Akimov and Shkuratov (1981). The technique of phase-ratio images was suggested by Akimov and Shkuratov (1981) who presented images of the ratio $f(3.2°)/f(14.5°)$ at two wavelengths in the visible spectral range. Analysis of images of the phase ratios $f(1°)/f(6°)$, $f(6°)/f(12°)$, and $f(12°)/f(96°)$ (Shkuratov et al., 1994) has shown their dependence on albedo and surface roughness. When Korokhin and Akimov (1997) mapped the parameter k approximating the lunar phase function as an exponential $\exp(-k\alpha)$, a complicated relationship between the parameter k and albedo was revealed.

The NASA-DoD Clementine and ESA Smart-1 lunar missions provided extensive high-resolution images that could be used to apply the phase-ratio technique. In particular, the opposition effect was studied with this technique using Clementine data by Shkuratov et al. (1999a), and Kreslavsky et al. (2000). Regions with anomalous photometric properties, e.g., ejecta blankets around young craters, were found (Kreslavsky and Shkuratov, 2003). The AMIE/Smart-1 data also revealed photometric anomalies having sizes from sub-kilometer to tens of kilometers (Kaydash et al., 2009a).

Earth-based telescope observations show that there are many photometric anomalies on the lunar surface, which are associated with different geological units (Shkuratov et al., 1994; Korokhin and Akimov, 1997; Kaydash et al., 2009b; Gerasimenko et al., 2008); mainly these are young craters with bright halos that reveal unusually steep phase function gradients.

Some patches of swirl areas are also examples of photometric anomalies (Kreslavsky et al., 2000; Kaydash et al., 2009a). Swirls are characterized by intricate albedo patterns, which may cover highland as well as mare topography (El-Baz, 1972; Schultz, 1976; Schultz and Srnka, 1980). An example of a swirl on the Moon is the Reiner-γ formation (7°30′N, 59°00′W). This formation is located in the western portion of the nearside and shows up even at large phase angles near terminator, whereas bright halos of young craters disappear at this illumination/observation condition (e.g., Schultz, 1976; Schultz and Srnka, 1980). Such behavior was interpreted that Reiner-γ demonstrates prominent forward scattering. At the spatial resolution of the Clementine UVVIS camera (100 m per pixel) the Reiner-γ regolith is mainly characterized by a lower slope of the phase function as compared to that of the surrounding mare regions (Kreslavsky and Shkuratov, 2003). This might result from higher albedo of the Reiner-γ material, as high albedo increases the contribution of multiple scattering in the regolith layer, which decreases the slope. Several other swirls reveal the same behavior. This was demonstrated with AMIE/Smart-1 observations (Kaydash et al., 2009a).

A few mechanisms for swirl formation have been previously considered (e.g., Schultz and Srnka, 1980; Hood and Schubert, 1980; Hood and Williams, 1989; Pinet et al., 2000; Starukhina and Shkuratov, 2004). In particular, Starukhina and Shkuratov (2004) concluded that scouring of the lunar regolith by small dense meteoroid swarms might be considered as a probable cause of the swirl formation. The swarms presumably are remnants of small comet nuclei. Owing to meteoroid scouring, the regolith surface in swirl areas becomes rougher than in surrounding regions. When the scouring is rather powerful, which reaches deeper regolith layers, the surface becomes brighter, as immature bright material is excavated to form the swirl pattern. This appears to be the case of the Reiner-γ formation, for the generation of which we might suggest an impact velocity of several tens of kilometers per second (Starukhina and Shkuratov, 2004). However, if the scouring is shallow, the albedo effect should be weak, and such faint swirls are expected to reveal themselves mainly as roughness features, which can be detected with the phase-ratio image technique. The shallow scouring could be produced by small grit/dust swarms which are compact remnants of freshly decayed comet nuclei that have relatively low velocities of colliding with the Moon, ~10 km/s. We suppose that the characteristic scale of the roughness generated by such swarms could be millimeter–decimeter. Of course, details of the scales are not resolvable in Clementine, Smart-1, Kaguya, Lunar Orbiters, and Apollo orbital images. However, if the scale is larger, the roughness can be imaged as a topographic anomaly with the LRO Narrow-angle cameras (Chin et al., 2007).

In this manuscript we continue our photometric studies of the Moon (Akimov and Shkuratov, 1981; Shkuratov et al., 1994; Korokhin and Akimov, 1997; Kreslavsky and Shkuratov, 2003; Gerasimenko et al., 2008; Kaydash et al., 2009b), presenting results of imaging phase ratios using Earth-based telescope observations. We describe here photometric anomalies located in Oceanus Procellarum, which presumably may be faint swirls.

2. Photometric data processing

We carried out two sets of photometric and polarimetric observations of the Moon using several telescopes equipped with CMOS and CCD cameras as light detectors. The first lunar survey was performed in 2005 with the 60-cm reflector (Zeiss-600) of the Simeiz Observatory (Crimea, Ukraine) using a CCD LineScan camera Sony ILX707. The western portion of the lunar nearside was studied with the 2048-pixel line array in two wide spectral bands with $\lambda_{\text{eff}} = 0.42, 0.65$ μm (Shkuratov et al., 2007b). We scanned the lunar disk over a wide phase-angle range; the best resolution we achieved in this observational campaign is about 0.7″ (~1.3 km in the lunar disk center). The electronic calibrations needed to reduce the line scanner data (dark signal, flat field, and non-linearity) were applied routinely; thus, we converted the pixel counts to values proportional to brightness of the lunar surface. Then we geometrically transformed the scans to bring them into the same projection with zero lunar libration, allowing images to be matched and averaged. In such a way we are able to apply the phase-ratio method with the aim to examine the lunar photometric function. Details of the polarimetric data processing are reported by Shkuratov et al. (2007b, 2008).

The other lunar imaging campaign was organized during two months in 2006 with the Kharkov 15-cm refractor and the 50-cm reflector at the Maidanak Observatory (Uzbekistan, Middle Asia). The observatory is situated in a region that affords many clear nights (~300) and low atmospheric turbulence. Some lunar images obtained with the 50-cm instrument have an angular resolution as high as 0.5″ (~900 m). We used Canon EOS 300D and 350D cameras as image detectors for the entire-disk (the 15-cm refractor) and regional (the 50-cm reflector) surveys, respectively. Both cameras are equipped with CMOS light sensors. These are exploited using raw format imaging in three wide spectral bands ($\lambda_{\text{eff}} = 0.47$, 0.52, 0.61 μm for 300D and $\lambda_{\text{eff}} = 0.47, 0.53, 0.60$ μm for 350D). We converted the pixel counts to numbers proportional to brightness of the lunar surface. For this purpose we carried out corrections