for every initial image, accounting for dark current, non-linearity, and flat field. To account for the non-linearity effect we performed a laboratory calibration of the cameras. For high level signals this effect is significant. We seek to use a linear portion of the characteristic curve when the correction coefficient differs from unity within 1–2%.

To bring all data to the same photometrical conditions, i.e. to compensate for systematic brightness gradients that are due to varying i and e across the disk, we used an empirical lunar disk function that provides very good fitting with experimental data (Akimov, 1979):

$$D(\alpha,\beta,\gamma)=\frac{\left(\cos^{q+1}\left(\gamma-\frac{\alpha}{2}\right)-\sin^{q+1}\frac{\alpha}{2}\right)}{\cos\gamma\left(1-\sin^{q+1}\frac{\alpha}{2}\right)}\cos^{q}\beta, \tag{1}$$

where $q = 0.3\alpha$, and α is measured in radians. The photometric coordinates α, β, and γ depend on the azimuth angle φ, angles of incidence and emergence, i and ε, as follows (e.g., Hapke, 1993):

$$\left.\begin{array}{l}\cos\gamma=\cos e/\cos\beta\\ \cos\alpha=\cos i\cos e+\sin i\sin e\cos\varphi\\ \cos\beta=\sqrt{\frac{(\sin(i+e))^2-\left(\cos\frac{\varphi}{2}\right)^2\sin 2e\sin 2i}{(\sin(i+e))^2-\left(\cos\frac{\varphi}{2}\right)^2\sin 2e\sin 2i+(\sin e)^2(\sin i)^2(\sin\varphi)^2}}\end{array}\right\}. \tag{2}$$

Compensating for the global brightness trends of the initial images using Eq. (1) allows us to produce images of the phase ratios $f(\alpha_1)/f(\alpha_2)$. The precision of this approach is estimated to be 1–2% (Akimov, 1979). We again emphasize that Eq. (1) does not take into account resolved local slopes of the lunar surface.

We here used the empirical lunar disk function given by Eq. (1). However, there is a very elegant theoretical scattering law also suggested by Akimov (1979, 1988).

$$D(\alpha,\beta,\gamma)=\frac{\cos\left[\frac{\pi}{\pi-\alpha}\left(\gamma-\frac{\alpha}{2}\right)\right]}{\cos\gamma}(\cos\beta)^{\frac{\alpha}{\pi-\alpha}}. \tag{3}$$

The law somewhat is inferior to the empirical one in precision, but this is more accurate than the Lommel–Seeliger, Minnaert, and "Lommel–Seeliger + Lambert" scattering laws that are widely used yet in planetary photometry. We note that Eq. (3) can be derived rigorously as a particulate case from a general consideration of photometric properties of pre-fractal rough dark surfaces with Gaussian statistics of local slopes (Shkuratov et al., 2003). The concept of fractality (self-similarity at different scales) is rather productive for description of the lunar surface (e.g., Shepard et al., 1995; Shkuratov and Helfenstein, 2001). In particular, the fractality may imply a hierarchical structure, when a randomly rough surface of a larger characteristic scale can be considered as the reference surface for a similar roughness of a much smaller scale. If the number of such scale generations is finite, the structure is a prefractal; otherwise, it is a fractal.

Albedo variations are mainly suppressed on phase-ratio images $f(\alpha_1)/f(\alpha_2)$. Therefore, the images exhibit the effect of macroscopically resolved topography (i.e. the influence of local slopes) and the effect of spatially unresolved surface roughness. Thus areas with flat large-scale topography allow qualitative studies of the unresolved surface roughness under resolution. Remnants of albedo variations can be seen on the phase-ratio images, as the slope of phase curves ($f(\alpha_1)/f(\alpha_2)$ ratios) may correlate with albedo.

The resolved topography (craters and mountains) strongly affects the $f(\alpha_1)/f(\alpha_2)$ images, hampering their interpretation. This effect potentially can be weakened either using the digitized global distribution of heights of the lunar relief recently obtained with the Laser Altimeter (LALT) aboard the spacecraft Kaguya (JAXA) (Araki et al., 2009) or using a photoclinometry technique that includes analysis of several images of the same scenes acquired at different photometric conditions (Korokhin and Akimov, 1997; Korokhin et al., 2010). In this paper we deal with the phase-ratio analysis of mare regions without compensation for the resolved topography effect.

For each scene captured at a given phase angle α many images and scans were obtained. These were averaged with an algorithm that accounts for large-scale image distortions related to the Earth atmosphere. The distortions were determined using a technique referred to as a running window or soft image co-registering. The technique suggests scanning pairs of original images with the same window that is small enough. For each pair small image portions cut with the window for each window position are aligned by maximizing their cross-correlation function.

Thus, one initial brightness image actually is a result of the soft co-registering and averaging 10–30 sub-images obtained with the Canon cameras. This procedure increases the photometric accuracy of processed data, though somewhat decreases the final spatial resolution to approximately 0.7–0.8″. Averaging of the LineScan camera images also involves many scans, thus the resulting resolution is approximately 1″. Using the atmospheric distortion correction algorithm described above, we co-registered images acquired at different phase angles in order to obtain then a phase-ratio image. Acceptable results of the soft co-registering are always achieved when α_1 and α_2 are rather close to each other, otherwise the cross-correlation function can be too flat and the algorithm may be unstable.

The component images used for the phase-ratio technique should have the same spatial resolution. However, images acquired at different dates inevitably may have different acutance. If the resolution is noticeably distinct, the phase-ratio images exhibit false details that are results of spatial filtration. Indeed, any image divided by itself with lower acutance produces an image with high spatial-frequency artifacts. These artifacts may be manifested as edging halos around contrast details. Because of atmosphere turbulence the spatial resolution can vary even over a single image. This introduces additional imperfections in imaging phase ratios.

In our photometric data there are many different combinations of α_1 and α_2. We focus on phase angles large enough to avoid the influence of the opposition effect on phase ratios. We started with whole-disk data acquired by the refractor. A synthetic phase-ratio image $f(21°)/f(46°)$ has been produced (Kaydash et al., 2009b) from averaging two phase-ratio images having almost the same phase angles with opposite signs (before and after full-Moon). The two phase-ratio images were co-registered and averaged for the western and eastern portions of the lunar nearside at opposite illumination angles. In spite of the low resolution of the refractor observations, our analysis of the synthetic image revealed a group of unusual details located in the south-west portion of the lunar disk. The details are more clearly seen in phase-ratio images obtained using higher resolution data from the 50-cm reflector (Gerasimenko et al., 2008); whereas they weakly manifest themselves in albedo.

3. Possible shallow swirls

A scene of the south portion of Oceanus Procellarum is presented in Fig. 1. This is a typical brightness image obtained with an Earth-based telescope in green filter ($\lambda = 0.53$ μm) at $\alpha = 23°$. The crater Euclides (7.4°S, 29.5°W) with its ray system and Montes Riphaeus (7°42′S, 28°06′W) are seen near the center of the scene. Three outlined and numbered areas in Fig. 1 are the photometric anomalies that we here analyze. The phase-ratio image $f(23°)/f(44°)$ is shown in Fig. 2; brighter shades here correspond to higher values of the ratio, i.e. steeper phase curves. The largest photometric anomaly (numbered with 3 in Fig. 1) is ~70 km in size. Like that