Planetary and Space Science 75 (2013) 28–36

Contents lists available at SciVerse ScienceDirect

Planetary and Space Science

journal homepage: www.elsevier.com/locate/pss

# Lunar surface traces of engine jets of Soviet sample return probes: The enigma of the Luna-23 and Luna-24 landing sites

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ARTICLE INFO

*Article history:*
Received 7 August 2012
Received in revised form
20 October 2012
Accepted 22 October 2012
Available online 7 November 2012

*Keywords:*
Lunar surface
Regolith structure
Phase ratio
Lunar probes
Luna-16
Luna-20
Luna-23
Luna-24
Landing sites

ABSTRACT

We use a photometric method called phase-ratio imaging to study the landing sites of the Soviet Luna-16, Luna-20, Luna-23 and Luna-24 probes using the survey data of the lunar surface, which was carried out with the Narrow-Angle Cameras (NACs) of the Lunar Reconnaissance Orbiter (LRO) spacecraft. The phase-ratio images clearly show diffuse features associated with structure perturbations of the lunar regolith. We suggest that these features are caused by the impact of the gas jets from the rocket engines. The photometric anomalies around the landing sites suggest that the impacts smooth out the surface, destroying the primordial "fairy castle" structure that effectively produces the shadow-hiding effect. The same characteristic features have been found previously for the Apollo spacecraft landings, but over larger spatial scales. The only exception is the landing site of the Luna-24 probe, for which the feature of the possible impact of the gas jets is shifted to the northwest by approximately 150 m. As the Luna-24 descent module worked in the regular mode and could not allow such a shift as the probe was descending vertically, a possible explanation is that the sites of Luna-23 (an unsuccessful sample return mission) and Luna-24 are misidentified. The distance between the sites is about 2 km, which is within the inaccuracy of their coordinate determination. We suggest that because of faulty processing of the radar system for distance/speed control, the incorrectly operated engine and/or thrusters of Luna-23 produced the 150 m lateral drift before final deactivation and hard descent. To better understand the geologic situation, we produce brightness and phase-ratio anaglyphs for the vicinity of the landings.

## 1. Introduction

Each soft landing of a manned or robotic spacecraft causes a disturbance of the lunar regolith, leaving a characteristic signature on its surface. These disturbances can be from the jets of spacecraft engines, regolith spreading from the descent module contact with the lunar surface, astronaut activities, etc. The detection of these signatures with lunar orbital images is possible only at very high resolution. Such appropriate images have been taken with the Lunar Reconnaissance Orbiter (LRO) that was launched in June 2009. The main goal of the LRO mission is to search for prospective areas for future explorations of the Moon (Chin et al., 2007; Robinson et al., 2010). In particular, the LRO scientific payload includes two Narrow-Angle Cameras (NACs) in the Lunar Reconnaissance Orbiter Camera (LROC) system. Each NAC uses the Kodak KLI-5001G CCD array with a dynamic range of 12 bits. The camera has a field of view of 2.85°. The LROC NAC spectral sensitivity band covers the range from 400 to 750 nm (Robinson et al., 2010, 2012). The spatial resolution of the camera reaches 50 cm/pixel from a 50 km orbit. Such a resolution allows one to identify the landing stages of the Apollo and Luna probes. Unfortunately, the anthropogenic signatures are not strong, and they are masked on the typical intensity images by albedo and topographic patterns.

The detection reliability of fresh structure perturbations of the uppermost regolith layer may be improved significantly using phase-ratio imagery. This is a branch of lunar photometry that has been developed and applied recently (Shkuratov et al., 1994, 2010, 2011, 2012; Kreslavsky and Shkuratov, 2003; Kaydash et al., 2009, 2011, 2012; Clegg and Jolliff, 2012).

The phase-ratio technique can be used to gather sub-resolution surface roughness information. At different points of the lunar surface, the phase function $f(\alpha)$, representing the brightness dependence as a function of phase angle $\alpha$, is different. As phase angle $\alpha$ increases, the brightness rapidly decreases. The rate of the brightness decrease can be characterized by the phase function slope. This slope depends on the degree of surface roughness, since the shadowing effect increases with increasing

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0032-0633/$ - see front matter Published by Elsevier Ltd.
http://dx.doi.org/10.1016/j.pss.2012.10.016

roughness (e.g., Hapke, 2012). Thus, the structure variations of the surface can be assessed with the ratio of two coregistered images acquired at different phase angles (Shkuratov et al., 1994). This approach resembles color ratio imaging, but the phase ratio is determined with the images obtained at different phase angles, not at different wavelengths.

Regions with unusual roughness can appear in the phase-ratio images as anomalies. There are several examples of successful applications of this technique. For instance, the phase-ratio method allowed us to find several photometric anomalies of the lunar surface in Oceanus Procellarum; they are likely recent impact regions of small meteoroid swarms that left shallow footprints in the lunar regolith layer (Shkuratov et al., 2010). The spatial extension of the regolith disturbances caused by the Apollo landing modules and human activity also has been detected with the phase-ratio method (Kreslavsky and Shkuratov, 2003; Kaydash et al., 2011, 2012; Kaydash and Shkuratov, 2012). In the present paper we use the LRO data to examine the landing sites of the Luna-16, Luna-20, Luna-23, and Luna-24 probes.

## 2. General description

In the Soviet Union there were several attempts at lunar sample return missions. Among them the missions Luna-16, Luna-20, and Luna-24 were successful, and these probes delivered regolith samples from mare and highland regions. All automatic lunar probes were launched from the Baikonur cosmodrome.

We generate phase-ratio images for their landing sites. The Luna-23 lunar sample return mission was not successful; however, we also study its landing site with the same approach. We use the official S. A. Lavochkin Association website: http://www.laspace.ru/rus/luna.html for mission information. Coordinates of the landing sites are given in Table 1 using the LRO (Robinson et al., 2012) and S. A. Lavochkin data.

The Luna sample return probes included descent and ascent stages and return capsules. When a probe landed on the lunar surface, the sample was collected and placed into the capsule, and then the ascent stage was launched to the Earth. Thus, the descent stages of the Luna-16, Luna-20, and Luna-24 probes were left on the surface. As for the Luna-23 probe, the entire spacecraft remained on the surface, since it had experienced a hard landing and was not able to return a regolith sample.

**Table 1**
Coordinates of the Soviet lunar sample return missions in (°).

| | Latitude, LROC | Longitude, LROC | Latitude, Lavochkin | Longitude, Lavochkin |
|---|---|---|---|---|
| Luna-16 | −0.5134 | 56.3638 | −0.68 | 56.31 |
| Luna-20 | 3.7866 | 56.6242 | 3.53 | 56.55 |
| Luna-23 | 12.6671 | 62.1512 | 12.68 | 62.28 |
| Luna-24 | 12.7146 | 62.2129 | 12.75 | 62.20 |

From the LRO image collection, we use images obtained for the same regions at different phase angles $\alpha_1$ and $\alpha_2$, but at close illumination and solar azimuth angles. The latter conditions allow us to reduce the influence of the resolved topography on the resulting phase-ratio images (Kaydash et al., 2012). In this paper, when calculating the ratio $f(\alpha_1)/f(\alpha_2)$, we assume hereafter that $\alpha_2 < \alpha_1$. This ratio depends not only on the shadowing effect, but also on the multiply scattered light that brightens the shadows of particles and their aggregates. This leads to the correlation usually observed between $f(\alpha_1)/f(\alpha_2)$ and surface albedo (Kaydash et al., 2009, 2011, 2012; Shkuratov et al., 2010, 2012). Substantial deviations from this correlation are photometric anomalies that can be interpreted as anomalies of surface roughness. To obtain the phase ratios, the images must be coregistered accurately at a subpixel level. We apply an algorithm called the "rubber-sheet geometric transformation" that has a coregistering accuracy of 1/10 of a pixel (Kaydash et al., 2012).

The "soft" coregistering procedure allows for the calculation of mutual shifts of all the image details, obtaining parallaxes caused by local topography observed at different emission angles. Thus with this method we are able to produce both phase ratios and anaglyphs of the scenes with the parallax data (Kaydash et al., 2012). Anaglyphs of brightness distributions and phase ratios provide a 3D (stereoscopic) effect. The latter shows photometric anomaly variations in a presentation favorable for geologic analysis. Thus, this new photometric technique can be considered a powerful tool for lunar remote sensing (Kaydash et al., 2012).

The mentioned algorithms were applied to the calibrated LRO images of the landing sites of the Luna-16, Luna-20, Luna-23, and Luna-24 probes (see Table 2). The calibration pipeline for the LROC NACs converts the raw signal in radiance factor units $I/F$, accounting for exposure time, dark image, flatfield, solar irradiance at a distance of 1 AU, and the Sun–Moon distance at the time of image acquisition.

## 3. Luna-16

This automatic lunar probe was launched on September 12, 1970 using the four-stage "Proton-K" missile. The landing vehicle provided the correction of the flight trajectory to the Moon after the booster separation. The probe was near the Moon by 17 September. The landing module carried out the deceleration in the vicinity of the Moon to form a circular lunar orbit with an inclination of 70° from the lunar equator, the secondary deceleration, and a soft landing on the lunar surface. A soil intake device and rocket system delivering the return capsule was on this module. The module began the landing procedure using the main

**Table 2**
Characteristics of images acquired with LROC NAC for the Luna-16, Luna-20, Luna-23, Luna-24 landing sites.

| Mission | NAC image ID | Resolution (m/pix) | Emission angle (°) | Incidence angle (°) | Phase angle (°) | Subsolar azimuth (°) |
|---|---|---|---|---|---|---|
| Luna-16 | M159589596L | 0.59 | 38.66 | 43.26 | 81.89 | 185.4 |
| | M159582808L | 0.48 | 0.88 | 44.2 | 43.32 | 182.85 |
| | M139538002R | 0.52 | 9.22 | 10.95 | 1.85 | 184.24 |
| | M154867363R | 0.48 | 3.20 | 10.38 | 7.26 | 170.80 |
| Luna-20 | M177264491R | 0.51 | 15.82 | 66.56 | 82.37 | 175.95 |
| | M177257719R | 0.52 | 22.81 | 67.48 | 44.72 | 177.26 |
| Luna-23 | M144212439R | 0.50 | 6.75 | 45.81 | 39.35 | 165.51 |
| | M144219225R | 0.56 | 26.91 | 44.98 | 71.22 | 158.65 |
| Luna-24 | M144212439L | 0.50 | 3.91 | 45.74 | 41.96 | 165.23 |
| | M144219225L | 0.57 | 29.77 | 44.89 | 73.91 | 157.26 |