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Soviet lunar sample return missions: Landing site identification and geologic context

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ABSTRACT

The Lunar Reconnaissance Orbiter Camera (LROC) imaged the landing sites and spacecraft from the Soviet Union's Luna robotic sample return program (Luna 16, 20, and 24) allowing their locations to be determined with unprecedented precision and, more importantly, for the geologic context of the landing sites to be firmly established. Uncertainties in the position of the landing sites are now 25 m (or better), as opposed to kilometers prior to LROC observations. Because of the past uncertainty of the locations, as well as the fact that two of the Luna missions were conducted at night, the geologic context of the samples was only poorly known. LROC images reveal that the Luna 24 sample was collected on the rim of a small impact crater, providing an explanation for the compositional and maturity discrepancy that has existed for the past three decades between samples and remote sensing of the Mare Crisium surface. The location of the unsuccessful Luna 23 spacecraft is also determined and the nature of the failure confirmed.

1. Introduction

In the 1960s and 1970s the United States launched a series of robotic and crewed missions to the Moon to provide in-situ measurements and, in some cases, to return samples to the Earth. Subsequent to the Apollo 12 mission, the Soviet Union successfully executed robotic missions that returned samples of the lunar regolith from three locations. The coordinates of the landing sites were well constrained for the American Apollo missions and traverse sampling sites as well as the Surveyor in-situ analyses, meaning that the sample and measurement locations were accurately understood in the context of orbital measurements and surface geology. For the Soviet missions (Luna landers, Lunokhod rovers, Luna sample returns), the locations were not as well constrained (uncertainties of the order of kilometers), and thus it was difficult or impossible to place the results from those missions in a detailed geologic context (Table 1). Moreover, some of the sample return missions were conducted during the lunar night, thus, there was no imaging to provide specific geologic context for the returned samples. The Soviet sample return missions provided only comparatively small masses of regolith; however, these materials are important because they sampled areas different from the Apollo collection, outside of the Procellarum KREEP terrane (Jolliff et al., 2000). Luna 16 and 24 returned samples from two different mare locations and Luna 20, from a highland location.

Lunar Reconnaissance Orbiter Camera (LROC) Narrow Angle Camera (NAC) (Robinson et al., 2010) images were acquired of each Soviet landing site, enabling accurate determination of the coordinates for each spacecraft, and providing the means to interpret their geologic context. Here, we report the coordinates of the Luna 16, 20, and 24 descent stages, along with the position of Luna 23, which was an unsuccessful sample return mission. We also discuss the meter-scale geologic context of the landing sites.

2. Data acquisition

The LROC system (Robinson et al., 2010) consists of a pair of monochrome NACs and a multispectral Wide Angle Camera (WAC). Each NAC consists of a 700 mm focal length, f/3.58 Richey–Chretien telescope with a 2.85° field of view, and a 5064-pixel line array detector (Kodak KLI-5001 G) with 7-micrometer pixels (10 micro-radian instantaneous field-of-view (IFOV)). The left NAC is offset 2.85° from the right NAC, resulting in a combined field of view of 5.7°. From a nominal 50 km altitude, the IFOV corresponds to 0.5 m on the surface, and the typical combined across-track width of the left and right cameras

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Table 1
LROC NAC-derived locations of Soviet hardware.

Spacecraft	LROC				Lavochkin		n
	Latitude (°)	Longitude (°)	Elev. (m)	σ (m)	Lat. (°)	Long. (°)	
Luna 16	-0.5134 ± 0.0006	56.3638 ± 0.0006	−2452	27	−0.68	56.31	11
Luna 20	3.7866 ± 0.0005	56.6242 ± 0.0004	−1780	19	3.53	56.55	10
Luna 23	12.6671 ± 0.0006	62.1512 ± 0.0003	−3668	19	12.68	62.28	12
Luna 24	12.7146 ± 0.0006	62.2129 ± 0.0006	−3670	25	12.75	62.20	10

Latitude and Longitude are the median values for the individual measurements. σ Lat. and σ Long. uncertainties (±) represent the individual standard deviations of the latitude and longitude positions. Elevation is derived from NAC stereo models tied to LOLA elevation profiles (Tran et al., 2010). σ Position is the uncertainty calculated from$=\sqrt{((\text{Latitude uncertainty})^2+(\text{Longitude uncertainty})^2)}$. Lavochkin Association positions were provided by Basilevsky (personal communication, 2011). *n*: Number of independent frames examined.

is 5 km, and 26 km downtrack. The WAC is a push-frame camera with separate optics for the ultraviolet (UV) and visible (VIS) bands. In seven color mode, the VIS field of view is 61° and in monochrome mode it is 90°. The VIS bands have a 1.5 mrad IFOV allowing 75 m/pixel scale from 50 km orbit altitude. The UV channels have a 2.0 mrad IFOV, and pixels are summed four-by-four during readout, resulting in 375 m/pixel scale from 50 km altitude.

Given that there was considerable uncertainty in the location of the Soviet spacecraft (Table 1), a wide area of the lunar surface around the nominal location of the landing site was imaged. NAC images were collected during several opportunities in an iterative process until the Luna spacecraft was located. Once the location was determined, subsequent observations were acquired with varying illumination geometry to enable morphologic, topographic, and albedo studies; and to provide more precise surface coordinates.

Using the Integrated Software for Imagers and Spectrometers (ISIS) developed by the U.S. Geological Survey (Anderson et al., 2004) and spacecraft location and pointing information provided by the LRO project in SPICE format (Acton, 1996), the coordinates of each spacecraft were accurately determined (Table 1).

3. Luna landing sites

Table 1 lists location coordinates and uncertainties, based on an analysis of all existing LROC images, and compares the positions with those estimated by the Lavochkin Associates (Basilevsky 2011, personal communication). Tables A1–A4 detail position determinations from each image used in the analysis, and includes the sample and line position in the original (not projected) NAC image, along with the corresponding latitude, longitude, and elevation. The positions listed in Table 1 include the mean and the standard deviation of the individual position determinations, assuming a lunar radius of 1737.4 km and a spherical Moon, in the lunar planetocentric mean Earth system. Images acquired before 1 January 2011 use spacecraft positions updated from laser imaging crossover analysis (Mazarico et al., 2011).

Each of the Luna sample return missions consisted of three landed flight elements; the descent stage upon which was mounted the ascent stage and Earth-return vehicles. After sample collection, the ascent stage and Earth-return vehicle were launched, leaving the descent stage on the surface. Ultimately only the Earth-return vehicle entered the Earth's atmosphere with the regolith sample. It is the descent stage that is imaged by LROC, except for the ill-fated Luna 23, whose ascent stage and Earth-return vehicle did not leave the Moon. The entire landed system was about 4.2 m tall and 4.8 m wide (from footpad to footpad); the descent stage was about 2.0 m tall.

3.1. Luna 16

Luna 16 was the first robotic mission to return a sample from the Moon, and the third mission to return a sample (Vinogradov, 1970, 1971a, 1971b, 1971c; Harvey, 2007), the first two being Apollo 11 and Apollo 12. Luna 16 was launched from the Baikonur Cosmodrome on 12 September 1970, landed on the Moon on 20 September, lifted off on 21 September, and landed on Earth on 24 September. Operations, including sampling, were conducted entirely during the lunar night. As a result, no images were acquired of the landing site from the surface, and thus no detailed information concerning the local geology was known.

The Luna 16 landing site (Figs. 1,2) is on the flat (Fig. 3) basaltic plains of the Imbrian age Mare Fecunditatis (Sea of Fertility) (McCauley and Scott, 1972; Gurshteyn and Shingarev, 1971; Florensky et al., 1974). Crater morphologies range from fresh, with high-reflectance rays, to degraded and subdued. Fresh craters within a kilometer or so of the lander are <100 m in diameter, and there are numerous highly degraded craters up to 1 km diameter in the region. The vehicle landed in a shallow degraded crater ~15 m in diameter, adjacent to a smaller 8 m crater to the west. The freshest craters in the region include an 83 m diameter crater about 500 m to the northeast, and a 47 m diameter crater some 830 m to the west. There are no detectable boulders near the lander; the closest recognized rocks are associated with the fresh craters noted above.

Luna 16 obtained a core extending 35 cm into the regolith, and returned ~101 g of sample (Fig. 4). The material is a mature mare regolith, rich in fused soil and glass fragments. Coarse components include basalt fragments (~10–30%), basaltic microbreccias and agglutinates (50–70%), glass (8–15%), mineral grains, breccias, and non-mare materials such as anorthosite, anorthositic norite, olivine norite, and troctolite (Bence et al., 1972; Jakes et al., 1972; Keil et al., 1972; Reid et al., 1972; Simon et al., 1982). Highland material constitutes about 5–10% of the Luna 16 regolith sample (Simon et al., 1982). Rays from the craters Langrenus (132 km diameter; 280 km distant), Taruntius (56 km diameter; 350 km distant), Theophilus (100 km diameter; 970 km distant), and Tycho (86 km diameter; 2230 km distant) all cross the Luna 16 site and are source candidates for the highland material. Elongate clusters and chains of secondary craters from Langrenus crater are in close proximity to the landing site. Thus, the dominant source of the highland components in Luna 16 regolith was suggested to be from the crater Langrenus (Florensky et al., 1972a; McCauley and Scott, 1972).

The sampled basalts have intermediate TiO_2 concentrations (~5 wt%) and relatively high Al_2O_3 (13–14 wt%) compared with other lunar basalts and have crystallization ages of ~3.4 Ga (Papanastassiou and Wasserburg, 1972; Taylor et al., 1991; Papike et al., 1998; Cohen et al., 2001). Previous workers suggested that the basaltic fragments in the sample originated from