LROC: Ten Years Exploring the Moon. N. M. Estes, M. S. Robinson, and the entire LROC team. School of Earth and Space Exploration, Arizona State University, nme@ser.asu.edu.

Introduction: The Lunar Reconnaissance Orbiter Camera (LROC) launched with six other instruments onboard LRO on 18 June 2009 at 21:32 UTC. After a short cruise, orbital insertion, and an engineering checkout period, LROC took its first Wide Angle Camera (WAC) and Narrow Angle Camera (NAC) images from lunar orbit on 30 June 2009, just after 15:00 UTC. LROC captured the images near Shackleton crater (-89.67°, 129.78°) with an incidence angle of 90° (**Fig. 1**). In the nearly ten years since first light, LROC has downlinked >310 trillion pixels and released to the Planetary Data System (PDS) >15 million files: PDS products, browse images, histograms, and other ancillary data. On average, 340 Gib of LROC data is downlinked per day, and through decompression, decompanding, and calibration, this data volume grows to ~7 times that size after producing Experiment Data Record (EDR) and Calibrated Data Record (CDR) PDS products.

Processing and Storage: Managing a dataset this large without automation would be a herculean task, so automated pipelines ingest and catalog raw instrument data [**1**], SPICE kernels, command loads, and other files and produce EDRs, CDRs, as well as related ancillary files and metadata. This automated processing is driven by a redundant PostgreSQL database and managed by the LROC Science Operations Center (SOC) developed Rector software [**2,3**]. Storage of the raw data as well as all the processed products is on a redundant Isilon storage system.

Distribution: The LROC SOC archives all data into PDS; however, due to the large size of the LROC PDS volumes (1.03 PiB as of the January 2020 release) the LROC PDS archive resides on the LROC SOC Isilon storage system [**4**] making delivery and management of such a vast archive faster and simpler. In addition to the standard PDS search tools, the LROC SOC maintains a PDS interface that specializes in searching for LROC data [**5**]. Quickmap is also available to search for and view LROC data, and it allows for some basic Geographic Information System (GIS) functionality directly in the web browser and even includes full 3D functionality [**6**]. For users of desktop GIS applications, Lunaserv, developed by the LROC SOC, exposes LROC data via the Web Map Service (WMS) protocol [**7,8,9**] simplifying the task of incorporating LROC data into ArcMap, QGIS, JMARS [**10**], or other WMS capable GIS software without any additional download or processing steps required. Sites of particular interest, such as Apollo landing sites, new impacts, and other popular sites are available in the LROC Featured Sites interface. This interface is also available on a kiosk at the LROC SOC in Tempe, AZ, the National Air and Space Museum in Washington DC, the New Moon Rises traveling museum exhibit [11], and the Ries Crater Museum in Nördlingen, Germany [12]. A brochure is available from the LROC SOC titled “Navigating LROC Data” that lists the various data products, search interfaces, and data portals available and maps them to common use cases to help the community easily find data within this large dataset.

Extent of the Data: To date, the LROC science team produced valuable data products including:

- WAC global morphology map [**13**]
- WAC normalized reflectance map [**14**]
- WAC color photometrically normalized maps [**15**]
- NAC controlled mosaics [**16**]
- NAC digital terrain models (DTMs) [**17**]
- NAC photometric series [**18**]
- NAC temporal change detection [**19**]
- NAC north pole gigapan (2 m/px 60°N - 90°N) [**20**]
- and much more!

The repeat global coverage of the WAC allows for analysis of the WAC data at a wide variety of lighting conditions anywhere on the Moon, and while not complete, NAC coverage now exists for much of the Moon’s surface in different lighting conditions (**Fig. 2**). When there are opportunities to take repeat NAC images in similar lighting conditions to existing NAC coverage, these temporal pairs are analyzed to find new impacts on the surface. This temporal imaging

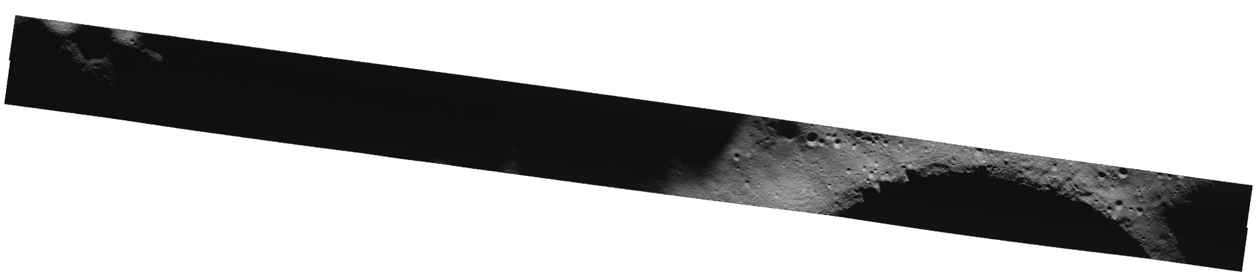

Figure 1: LROC NAC M101013931LR in a polar stereographic projection. This was the first NAC pair taken by LROC on 30 June 2009.

campaign is improving knowledge of current impact rates and surface churn [**19**]. Repeat NAC coverage of an area at different incidence and phase angles are used to create photometric sequences. These sequences are co-registered to a NAC DTM and allow photometric analysis of the surface [**18**].
The orbit inclination of LRO is decreasing, opening a gore over the poles. This limits the ability to gather new data at the poles.

Conclusions: LROC observations have resulted in a large archive of images and derived data products. Ongoing temporal imaging, geostereo observations, NAC coverage filling, and other imaging opportunities continue to expand and improve the NAC and WAC coverage under varying lighting conditions. The challenges of managing this enormous dataset and providing easy access to the public has been a challenge; however, automation and a variety of tools providing intuitive access have enabled a large science and exploration return.

References: [**1**] Paris, K. N., et al, April 2018, Planetary Science Informatics and Data Analytics, #6059 [**2**] Estes, N. M., et al, June 2012, Planetary Data Workshop, High Performance Computing with Rector [**3**] Estes, N. M, et al, April 2018, Planetary Science Informatics and Data Analytics, #6039 [**4**] http://lroc.sese.asu.edu/data/ [**5**] http://wms.lroc.asu.edu/lroc/search [**6**] https://quickmap.lroc.asu.edu [**7**] http://webmap.lroc.asu.edu [**8**] http://lunaserv.lroc.asu.edu [**9**] Estes, N. M, et al, June 2015, Planetary Data Workshop, #7035 [**10**] Christensen, P.R., et al, http://adsabs.harvard.edu/abs/2009AGUFMIN22A..06C [**11**] A New Moon Rises https://www.sites.si.edu/s/topic/0TO36000000aIGbGAM/a-new-moon-rises [**12**] Ries Crater Museum http://www.rieskrater-museum.de/index.php/de [**13**] Wagner, R. V., et al, 2015, LPSC 46, #1473 [**14**] Boyd, A. K., et al, 2012, LPSC 43, #2795 [**15**] Sato, H., et al, 2017, Icarus, 296, 216-238. 10.1016/j.icarus.2017.06.013 [**16**] Klem, S. M., et al, 2014, LPSC 45, #2885 [**17**] Henriksen, M.R., et al, 2016, Icarus, 10.1016/j.icarus.2016.05.012dtms [**18**] Martin, A. C., et al, 2018, LPSC 49, #2083 [**19**] Speyerer, E. J., et al, 2016, Nature 538, p. 215-218, 10.1038/nature19829 [**20**] Wagner, R. V., et al, 2016, LPSC 47, #1582

Latitude Range	i < 45	45 < i < 80	i < 80	β < 45	45 < β < 80	β < 80
± 75°	59	95	99	89	94	99
± 65°	63	94	99	88	93	99
± 55°	70	94	99	88	93	99
± 45°	81	93	99	87	92	99
± 35°	84	92	99	87	91	99
± 25°	86	91	99	87	90	99
± 15°	87	90	99	87	89	99
± 5°	87	89	99	87	89	99

i = Incidence Angle
β = Beta Angle

Beta is the angle between the LRO orbit plane and the sub-solar vector

Figure 2: Percent LROC NAC Nadir Coverage in various lighting conditions as of 2019/08/15.