LROC: TEN YEARS EXPLORING THE MOON. N. M. Estes, M. S. Robinson, and the 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 the Moon's orbit on 30 June 2009 just after 15:00 UTC. LROC captured the images near Shackleton crater (90°S, 0°E) at an incidence angle of ~90° (Fig. 1). In the nearly ten years since first light, LROC has downlinked >310 trillion (3E14) pixels and released to the Planetary Data System (PDS) >15 million files including PDS product, browse images, histograms, and other ancillary data. LROC downlinks up to 450 Gib/day, and through decompression, decompanding, and calibration, this data volume grows ~7x times the downlinked size after Experiment Data Record (EDR) and Calibrated Data Record (CDR) PDS products are created.

Processing & Storage: Managing a dataset this large without automation would be a near impossible task, so automated pipelines ingest and catalog raw instrument data [1], SPICE kernels, command loads, and other files and product 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. This storage system consists of two data pools separated by ~20 miles and connected by a 10 Gib Geomax circuit, and has a combined raw disk space (before redundancy and file system overhead) of 5.28 PiB.

Distribution: The LROC SOC archives all data into the NASA Planetary Data System (PDS); however, due to the large size of the LROC PDS volumes (973 TiB as of the March 2019 release) the LROC PDS archive resides on the LROC SOC Isilon storage system [4], making delivery and management of this vast archive faster and simpler. In addition to the standard PDS search tools, the LROC SOC maintains a PDS search interface that specializes in searching for LROC data [5]. Quickmap is also available to search and view LROC data, and provides basic Geographic Information System (GIS) functionality in the web browser, and it even includes full 3D functionality [6]. For users of desktop GIS applications, Lunaserv, developed by the LROC SOC, exposes LROC data via with Web Map Service (WMS) protocol [7,8,9] allowing direct data import into ArcMap, QGIS, JMARS [10], or other WMS-capable GIS software. Areas of particular interest, such as Apollo landing sites, new impacts, and other popular sites are available in the LROC Featured Sites interface. An LROC team-developed kiosk provides the same functionality, available at the LROC SOC (Tempe, AZ), the National Air and Space Museum (Washington DC), the New Moon Rises traveling museum exhibit [11], and the Ries Crater Museum (Nördlingen, Germany) [12]. A brochure is available from the LROC SOC titled "Navigating LROC Data" that outlines the various data products, search interfaces, and data portals and maps them to common use cases to help users easily navigate this large dataset.

Extent of the Data: To date, the LROC science team has used this extensive dataset to produce a long list of Reduced Data Products (RDR):

- WAC global morphology map [13]
- WAC color photometrically normalized maps [14, 15]
- 253 NAC controlled mosaics [16]
- 541 NAC digital terrain models (DTMs) [17]
- 12 NAC photometric series [18]
- NAC temporal change detection [19]

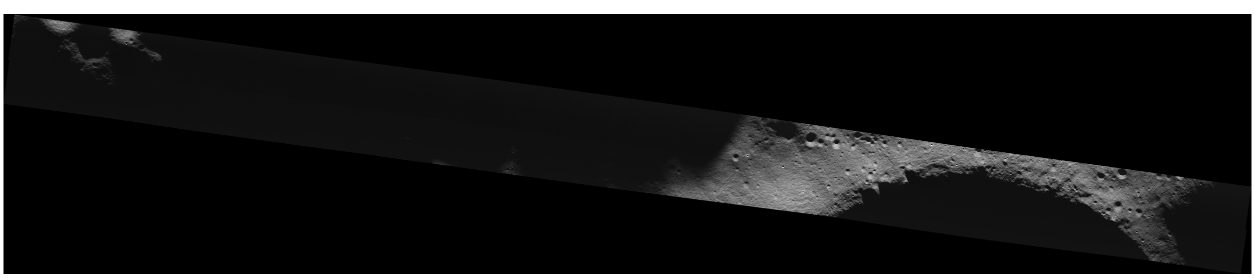

Figure 1: LROC NAC M101013931LR was the first NAC pair acquired on 30 June 2009.The distinct arc on the right is the rim of Shackleton crater (~19 km diameter), image width is ~58 km. http://lroc.sese.asu.edu/posts/789

Latitude Range	i < 45	45 < i < 80	i < 80	β < 45	45 < β < 80	β < 80
± 75°	58	94	99	88	93	99
± 65°	62	94	99	87	93	99
± 55°	69	93	99	87	92	99
± 45°	79	92	99	86	91	99
± 35°	83	91	99	86	90	99
± 25°	85	90	99	86	89	99
± 15°	85	89	99	86	88	99
± 5°	85	88	99	86	88	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 from 2009/06/30 through 2019/03/15.

- NAC north pole gigapan (2 m/px from 60° to the north pole) [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).

Conclusions: The LROC observations represent the largest NASA planetary dataset collected by a single instrument.. Ongoing temporal imaging, geostereo observations, NAC coverage filling, and other imaging opportunities continue to expand and improve our knowledge of the Moon. Managing this dataset and making it easily accessible have been challenging; however, automation, and a variety of tools giving fast and accurate access to the dataset provide the means for the lunar science community to make the best use of this extensive dataset in further understanding the Moon.

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