Dynamic Moon: New Impacts and Secondaries Revealed in High Resolution Temporal Imaging. E. J. Speyerer[1], M. S. Robinson[1], R. Z. Povilaitis[1], and R. V. Wagner[1], [1]School of Earth and Space Exploration, Arizona State University, Tempe, AZ (espeyere@asu.edu)

Introduction: The Lunar Reconnaissance Orbiter Camera (LROC) began systematically mapping the Moon in the summer of 2009 with the goal of acquiring a comprehensive image dataset to facilitate future exploration [1]. With the aid of the second extended science mission, we discovered hundreds of new, resolved impact craters and thousands of smaller primary and secondary surface changes using repeat observations under identical lighting conditions with the high-resolution Narrow Angle Camera (NAC) and a custom automated change detection algorithm.

Temporal Dataset: As of 1 May 2015, LROC has acquired over a million NAC images of illuminated terrain. From this total, 14,182 are images acquired of regions of the Moon where previous NAC observations exist with similar lighting and observation geometry (i.e. incidence angle difference <3°, incidence angle < 50°, and nadir pointing). These before and after image pairs, called *NAC temporal pairs*, enable the search for a meter scale changes, including new impact craters, formed between the two observations; delta-time between individual temporal pairs currently span 176 to 1241 Earth days.

New Impact Craters: Our ongoing analysis of NAC temporal pairs has uncovered over 200 resolved impact craters ranging in diameter from 1.5 to 43 m. Unlike the database of recorded impact flashes, the new craters discovered with NAC temporal pairs are distributed across the lunar surface (nearside and farside) over a variety of terrain types (**Fig. 1**). Furthermore, reimaging of two of the largest impact flashes recorded on 17 March 2013 and 11 September 2013 revealed 18 and 34 m diameter craters, respectively (**Fig. 1**) [2-4], which are helping to calibrate the models that predict resulting impact energy and crater size from the magnitude of the flash.

Using ratio images created from the before and after temporal pairs, insight in to the amount (i.e., reflectance change) and expanse of surface changes associated with each impact is analyzed. **Fig. 2** shows the result of an impact that created an 18 m crater (42.6.°N, 257.8°E). From the crater rim outwards, a proximal high reflectance zone was created from the emplacement of immature regolith ejected from the deepest portion of the crater cavity. This zone exhibits a 15-25% increase in the observed surface reflectance when compared to the before image. Next, a proximal low reflectance zone, which we assume to be either mature ejecta from shallow portions of the crater or an increase in the local surface roughness caused by churning of the regolith as discontinuous ejecta impacts the terrain (or a combination of both processes).

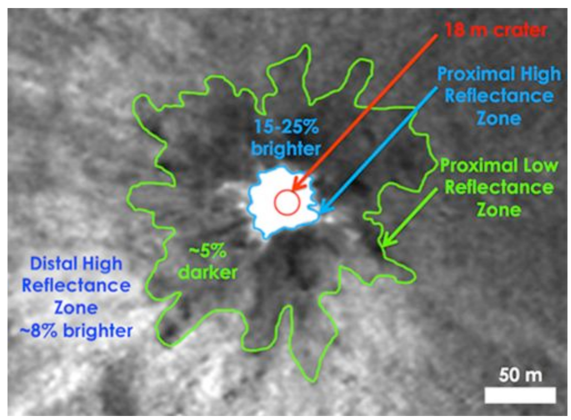

Fig. 2- Ratio image of an 18 m crater showing a series of distinct ejecta zones, a distal low reflectance zone occurs outside the image area.

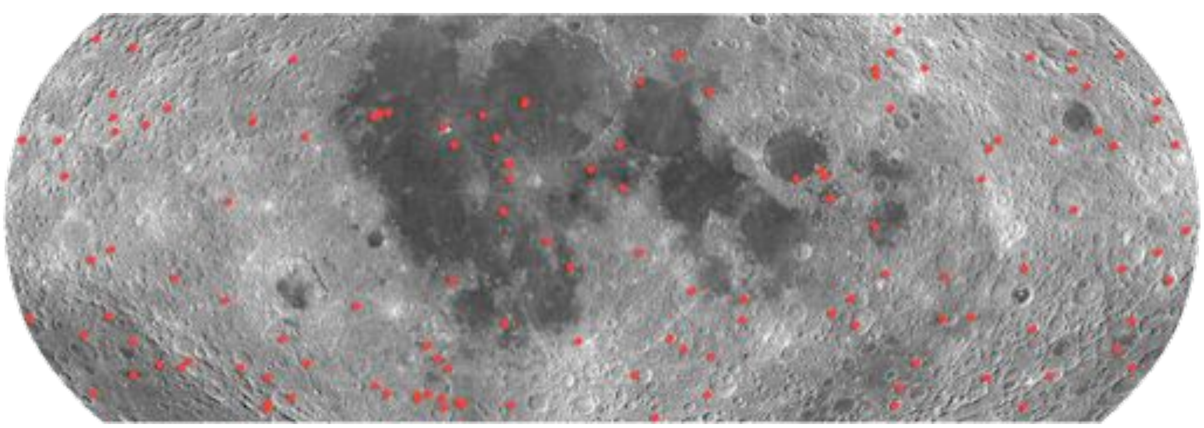

Fig. 1- Location of new impact craters. The red dots show the location new impact discovered with NAC temporal pairs and the blue dots show the location of the two craters located with the help of impact flash observations [3-5].

This low reflectance zone has ~5% lower surface reflectance than the preexisting terrain. Next, for this particular impact event, there are two distal zones with high (~8%) and low (~3%) reflectance signatures that extend many crater diameters away from the primary crater. The distal high reflectance zone may be the result of regolith disturbance caused by jetting vapors that are similar to blast zones around landing sites [2, 5]. Finally, the distal low reflectance zone, which is outside the field of view in **Fig. 2**, may be the result of churning of the regolith caused by small (sub-mm) ballistic ejecta impacting and modifying the surface roughness.

These complex patterns and reflectance zones are present at multiple new impact craters, including the 17 March 2013 impact crater [2]. **Fig. 3** Shows an example of the result of a 12 m crater and the distal low reflectance zone expanding over 1800 m (150 crater diameters) from the rim of the crater.

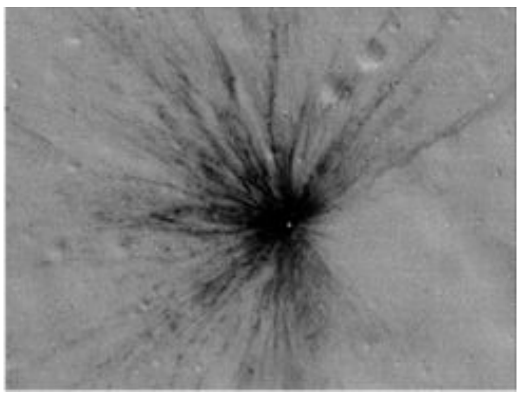

Fig. 3- Ratio image showing the extent of surface changes that are the result of an impact event that created a 12 m crater. The image is 2700 m across.

However, these zones are not always present at a given impact crater. Local topography and regolith thickness, impact angle, bolide size, and impact velocity likely modify the shape, extent, and existence of each of these four zones. Many smaller impact events often fail to create all four zones seen in the example shown in Fig. 2 and in the 17 March 2013 impact event described in [2].

Other Surface Changes: In addition to capturing new impact craters, NAC temporal pairs have also uncovered small reflectance changes, or "splotches". These splotches do not exhibit visible crater rims, but only modify the observed surface reflectance (**Fig. 4**). They are thought to be the result of small primary events in which the resulting impact crater is smaller than the resolution limit of the temporal pair, or by a secondary disturbance caused by a nearby primary event. In several cases, these splotches show clear directional indicators pointing back to a larger primary crater [2] confirming an origin as secondary features for some of the splotches.

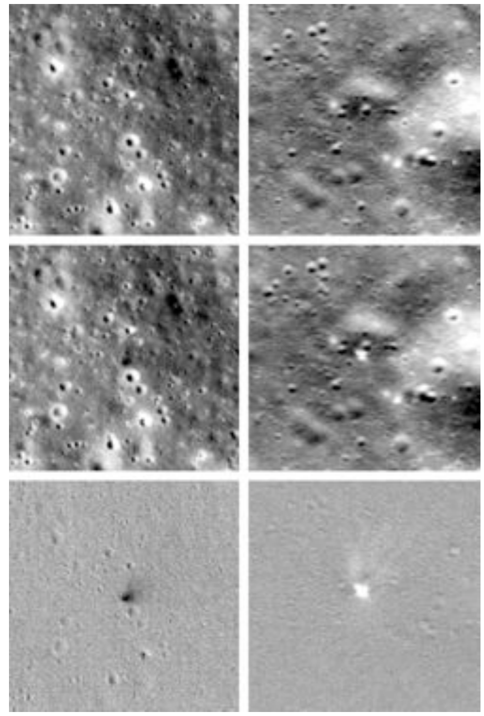

Fig. 4- Example of low (left column) and high (right column) reflectance splotch identified with NAC temporal pairs. The top row consists of a pair of before images, the middle row is a pair of after images, and the bottom row is a ratio of the after/before observation. Each image is 250 m across.

Summary: As of 1 May 2015, we have scanned and classified changes in 14,182 NAC temporal pairs using our automated change detection tool leading to the discovery over 200 impact craters ranging in size from 1.5 to 43 m. In addition, we also identified thousands of other surface changes, including about:

- 44,000 low reflectance splotches
- 3,500 high reflectance splotches
- 850 mixed reflectance splotches
- 1 Chinese lander/rover

Throughout the second extended science mission and future mission phases, the LROC team will continue to acquire and scan high resolution temporal pairs. A great advantage of a continuing campaign is an increased delta-time within temporal pairs. From this new dataset, we plan to refine flux estimates of small (>0.5 m) bolides in the inner solar system as well as quantify secondary impact related hazards on the Moon.

References: [1] Robinson M.S. et al. (2010) *Space Sci. Rev.*, 150, 1-4, 81-124. [2] Robinson M.S. et al. (2015) *Icarus,* 252, 229-235. [3] Madiedo J.M. et al. (2014) *MNRAS*, 439, 3, 2364-2369. [4] http://lroc.sese.asu.edu/posts/810. [5] Clegg R.N. et al. (2014) *Icarus*, 227, 176-194.