TYING LRO DATA TO THE FUNDAMENTAL LUNAR LASER RANGING REFERENCE FRAME.

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Introduction: The coordinates of lunar *l*aser *r*anging *r*etro*r*eflectors (LRRR) (e.g., Figure 1) define a fundamental sub-meter level lunar reference frame. However, with only 4 observable (of 5) near side points, it is not a very accessible frame. Other existing and planned lunar datasets are not well or easily tied to it, and suffer lower positional accuracy as a result. The absolute positional accuracy of data from *L*unar *R*econnaissance *O*rbiter (LRO)[1] and indeed all lunar datasets could be improved by tying and controlling them to the *l*unar *l*aser *r*anging (LLR) frame. We describe here plans to make such connections for LRO data in the LLR frame.

Solutions for the LRRR positions and other parameters (e.g., lunar and Earth orientation, lunar orbit, relativity) are occasionally performed [2]. A new LLR frame is derived in each solution. However, at the meter (m) level of accuracy we are concerned with here, the frames are essentially identical. We also assume the LLR frame can be expressed in the mean Earth/polar axis as opposed to the principal axis reference system in which such solutions are often done [3]. At the m to tens of m accuracy, relative coordinates between the Apollo landing sites have also been measured using early *V*ery *L*ong *B*aseline *I*nterferometer (VLBI) measurements of the locations of the *A*pollo *L*unar *S*urface *E*xperiment *P*ackage (ALSEP) sites [4]. Davies and Colvin [5] used LLR and VLBI results to determine the coordinates of many features (human artifacts and small craters near the LRRR and ALSEP sites) in the LLR frame.

The accuracy of the absolute location of data obtained by the LRO spacecraft is limited by the accuracy of knowledge of the LRO spacecraft position and orientation as well as LRO instrument timing and boresight positions. Initially, these determinations are on the order of 100 m, as demonstrated by early LROC [6] and LOLA results. It is expected that these determinations will eventually be improved to the order of tens of m via various calibrations and the use of LOLA crossover solutions [e.g., 7].

However, if the LRO data can be tied to the LLR frame directly, the opportunity arises to position LRO (and other) lunar datasets globally to levels approaching the 5 m (spot size) resolution for LOLA. The procedure to do this involves 3 steps: 1) locate the LRRR in individual LROC Narrow Angle Camera (NAC) images and corresponding digital terrain models (DTMs); 2) locate LOLA ground points within those same images and/or models; and 3) constrain or at least check the position of the corresponding LOLA points in the LOLA crossover solutions. Where overlapping LROC NAC images exist, they can be photogrammetrically controlled to each other. This geometry provides a powerful constraint on the simultaneously acquired LOLA data, in essence providing for a new form of "crossover" limited only by the accuracy of knowledge of the LOLA-LROC boresight positions. Below we describe work underway to make initial ties to the LRRR and between the simultaneous LROC NAC images and LOLA data.

LLR to LROC NAC Frame Ties: Step 1 is to locate the LRRR (and other nearby artifacts listed in [5]) in NAC images (e.g., Figure 2). This is now being done by some of us (Danton and [7]) initially to measure the orientation of the NAC cameras relative to LRO and measure any LROC-to-LRO timing discrepancies. Several groups are also now making DTMs at the Apollo sites [7, 8]. Tying to these LRRR related features will allow the coordinates of these sites to be expressed absolutely in the LLR frame at approximately the image resolution (discounting for now possible rotation of the images/DTMs, since such a rotation is not constrained well by the few points at the given sites). Aside from being used to position LROC and LOLA data, these new measurements can also be used to: a) update the coordinates of the Davies and Colvin features, both by checking the surface LRRR to ALSEP package geometry (in some cases, only estimated from surface photos) and by remeasuring the location of various features; and b) fill in eventual LOLA topography models, since the LOLA instrument is not operated within about 1 km of the LRRR sites to avoid possible damage to the LOLA detectors.

LOLA to LROC Frame Ties: Step 2 is to locate the position of the LOLA boresight relative to the two LROC NAC camera boresights. These cameras were aligned on LRO so that the spots nominally will fall in the ~126 pixel overlap region of the two side-by-side NAC cameras. However, the exact location of the spots relative to camera pixels (and after accounting for relative pointing and timing errors between LRO, LROC, and LOLA) needs to be measured. This can be done initially by a manual comparison of the tracks of the 5 LOLA beams relative to features in the NAC images. It then will be improved by comparison of the

LOLA track data relative to the DTMs or a joint photogrammetric adjustment of the NAC images (overlapping and/or stereo) and the LOLA points. Accounting for thermal changes may also be necessary. This work is now underway. It should also be possible to compare eventual regional (or global) LOLA DTMs with local LROC DTMs to assess offsets or discrepancies.

LOLA frame to LLR frame: Step 3 is to use the reference frame connections to check the positions of the LOLA data relative to the LLR frame and possibly adjust the LOLA data to more accurately fit that frame. The latter can be done to first order by global rotation of the LOLA frame, or more accurately by constraining the position of the relevant track data in a global LOLA solution. Further "crossover-like" constraints between LOLA track data can be applied when overlapping NAC images are controlled to each other.

One possibility for the LRO Science Mission phase is to obtain global coverage of the Moon with the LROC camera at 2 m/pixel. If such coverage is obtained, then all of the simultaneously acquired LOLA profiles could be constrained together with the NAC images through a global photogrammetric solution. In effect, the NAC images constrain the locations of the LOLA tracks over short distances of 10's-100's km, and the LOLA global solution constrains the LROC image positions over global arc distances. Although simulations would better quantify the accuracy of such solutions, it appears the only limit will be the accuracy with which the LOLA tracks can be located in LROC images (i.e. on the order of the LOLA 5-m spot size). *The final outcome would be global mapping of the Moon not only at comparable resolution to the Earth but perhaps at better absolute accuracy as well.*

Other Data: Since other LRO optical instruments are of significantly lower resolution on the lunar surface than the NAC and LOLA instruments, the primary issue in dealing with them is confirming or remeasuring their instrument boresights relative to LROC or LOLA. Those datasets then "fall into place" using the updated spacecraft position and pointing-derived LOLA solution and any future LRRR/LROC constrained LOLA solution.

Mini-RF and other mission data (past, present, future) will require being tie-pointed to the NAC or LOLA data and then geodetically controlled to the LOLA frame. The ULCN 2005 [9] and possible follow-on solutions already includes tie points that link many legacy datasets into a common reference frame. The relatively simple step of tie-pointing a subset of these legacy images to the new, LRO-derived solutions will, after an additional ULCN photogrammetric solution, bring the full set of legacy data into the LLR frame.

Prospects: Steps 1 & 2 here are now underway and progress will be reported at LPSC 41. The LOLA data will be processed in a "classic" global crossover solution following the LRO one-year nominal Exploration mission.

However, the additional steps of globally registering the LROC and LOLA data (and other datasets) to the LLR frame are not yet fully planned or funded. The NASA Lunar Mapping and Modeling Project [10] is funding the control of some LRO data, but not this additional work. Such an effort will not be trivial, but if completed will assure registration of the LRO data and, if extended further, all other lunar datasets so that they can be used together with confidence at known levels of high accuracy, in most cases down to the resolution of the data. Such work follows the recommendations of the NASA Advisory Council [11] and will allow for the common and reliable use of all lunar datasets for exploration and science.

References: [1] Chin, G. et al. (2007). *SSR*, 129:391–419; Robinson, M.S. et al. (2005). *LPS XXXVI*, Abstract #1576; Smith, D.E. et al. (2009). *SSR*, DOI 10.1007/s11214-009-9512-y. [2] Williams, J. et al. (2006). *ASR*, 37, 1, 67-71. [3] Seidelmann, P.K. et al. (2007). *Cel. Mech. Dyn. Ast.*, 98, 155-180; LGCWG and LRO (2008). Version 5. http://lunar.gsfc.nasa.gov/library/LunCoordWhitePaper-10-08.pdf. [4] King, R. et al. (1976). *JGR*, 81, 6251-6256. [5] Davies, M. and Colvin, T. (2000). *JGR*, 105:20277–20280. [6] Neumann, G. A. et al. (2001). *JGR*, 106, 23753-23768. [7] Oberst, J. et al. (2010). This meeting. [8] Beyer, R. A. et al. (2010). This meeting. [9] Archinal, B. A. et al. (2006). USGS *OFR* 2006-1367, http://pubs.usgs.gov/of/2006/1367/. [10] Noble, S. et al. (2009). LEAG, *LPI Cont.* 1515, 48. [11] NASA Adv. C. (2007). Recommendation S-07-C-13, p. 14, http://www.nasa.gov/pdf/314931main_Recommend-5-07.pdf. [12] Faller, J. E., et al. (1972). In "Apollo 15 Preliminary Science Report", p. 14-3.

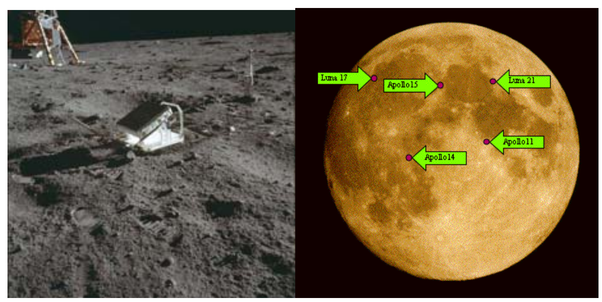

Figure 1: (*Left*) The Apollo 11 LRRR as placed on the Moon. The array size is 68.6 x 66.0 cm [12]. NASA photo AS11-40-5952 by N. Armstrong. (*Right*) LRRR sites on the Moon. Image courtesy M. Torrence and the ILRS (http://tinyurl.com/yeudjyk).

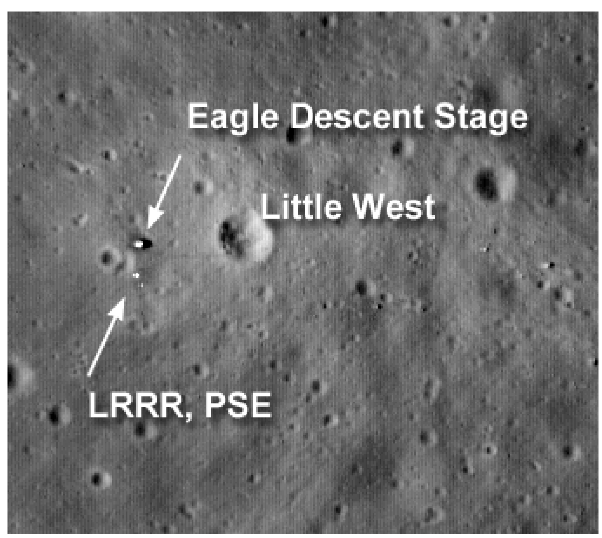

Figure 2: The LRRR are visible in LROC images, as in this one of the Apollo 11 landing site showing the Eagle descent stage and the LRRR as the bright spot just below it. The *P*assive *S*eismic *E*xperiment (PSE) is just to the lower right. Image width is approximately 410 m. (Image credit: NASA/GSFC/Arizona State University.)