

A CONSENSUS CRATER CATALOG OF PLUTO, CHARON, AND NIX. S.J. Robbins^{0,1}, K.N. Singer¹, V.J. Bray², P. Schenk³, W.B. McKinnon⁴, K. Runyon⁵, H.A. Weaver⁵, A. Zangari¹, L.A. Young¹, R.A. Beyer^{6,7}, S. Porter¹, T.R. Lauer⁸, J.M. Moore⁷, C.B. Olkin¹, K. Ennico⁹, S.A. Stern¹, the *New Horizons* GGI Theme Team, *New Horizons* Pluto Encounter Team, *New Horizons* LORRI Instrument Team, and *New Horizons* MVIC Instrument Team. ⁰stuart@boulder.swri.edu, ¹Southwest Research Institute, 1050 Walnut Street, Suite 300, Boulder, CO 80302. ²Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ. ³Lunar and Planetary Institute, Houston, TX. ⁴Washington University in St. Louis, St. Louis, MO. ⁵The Johns Hopkins University, Baltimore, MD. ⁶Sagan Center at the SETI Institute. ⁷NASA Ames Research Center. ⁸National Optical Astronomy Observatory, Tucson, AZ. ⁹NASA Ames Research Center, Moffett Field, CA 84043.

Introduction: NASA's *New Horizons* mission to the Pluto-Charon system is the first mission to explore the last of the classical planets and objects in the third region of the solar system: The Kuiper Belt. The data gathered in July 2015 provided a first look at the largest known Kuiper Belt Object and the largest binary planetary system known in the solar system. The system is embedded within the inner edge of the Kuiper Belt, and so it is impacted by a distinct population of bodies that we cannot probe from gas giant planet moons, and detection technology from Earth can only probe the largest impactor bodies. Therefore, the crater population of Pluto and Charon was modeled, but unknown, and any possible geologic activity could modify the recorded crater population formed by those impactors. Therefore, mapping the crater population of Pluto and Charon is an important probe into not only the impactor population, but also geologic processes occurring on both bodies.

Background and Motivation: Work by Robbins *et al.* [1] demonstrated that crater identification and measurement is far from the objective process that planetary scientists often assume, or at least hope. Variation in mapping can be as much as a factor of five rather than \sqrt{N} Poisson counting errors; even a single crater analyst can vary by >10% in measuring a degraded crater's diameter. With this motivation, a self-assigned goal by some within the *New Horizons* crater mapping group was to not assign different regions to different people, but to have at least one person (Robbins) map craters on all images returned, others map over most surfaces (Singer, Bray), and other analysts map craters over other regions as time and interest allowed (Runyun, Schenk, Grundy, and Weaver (to-date)). By having significant overlap by multiple researchers, and even repeat mapping by the same researcher over different images that cover the same area, we can achieve a substantially more robust catalog of impact craters than would otherwise be possible.

This is important when we want to use impact craters for important geophysical and dynamical applications, such as understanding surface ages and the impactor population. To our knowledge, this is the first time a mission team has specifically worked to build a consensus crater database for a planetary body.

Crater Mapping Process and Data Used: We used both LORRI (LOng-Range Reconnaissance Imager) [2] and MVIC (Multi-spectral Visible Imaging

Camera) [3] images, for, while each provided overlapping data, each provided the best pixel scales over different areas of each body. Fig. 1 illustrates the cumulative fraction of each body covered at what pixel scale.

Pluto and Charon are both spherical worlds, each having a well defined coordinate system (as opposed to the small, irregular satellites). For this reason, classic methods of mapping impact craters could be employed, so long as one was willing to wait. At issue was the time it takes to create a geodetic control network. This is a process whereby the same feature on multiple images are manually identified as needing to be mapped to the same coordinates. Ideally, this would happen if the trajectory and pointing information of the spacecraft and instruments were precisely known *a priori*, but this is never the case. It also assumes that the camera models used to correct for distortions are well modeled, but issues arose with MVIC that took time to work out. Additionally, the data downlink process was very slow, and only in January 2016 did the final images at <1 km/px arrive at Earth. For those reasons, we were faced with three choices: Map craters on (1) unprojected images, (2) early projections that would need to be updated, or (3) wait for a final coordinate system or one that is "close enough."

Robbins opted for both the first and third choices. He mapped craters in pixel space on every image returned by *New Horizons* starting 5 days before the closest approach (earlier images showed no identifiable craters) through the end of encounter. The pixels could then be projected into the latest control network with updated SPICE data when available using the USGS's *ISIS* package. Early positions (mapped in September 2015) changed by as much as 5–10° from later positions (December 2015 is the latest, as of mid-January 2016), corresponding to shifts on early-returned images of as much as 150 km on Pluto and 35 km on Charon. Robbins will also use the final maps, when available, produced by the control network team (Schenk and Beyer) to do another redundant crater mapping on both bodies.

The other crater mappers involved opted for the more straightforward options two and three. As new images that corresponded to one observation set were sent to Earth (*e.g.*, a LORRI ride-along of an MVIC scan), mosaics would be produced by the control network team and some of the analysts would use those mosaics on which to map. As time allowed, they

would move to the next image set, but that might correspond to an improved control network version, until the final version is produced.

Meanwhile, Nix is one of the four known small satellites of the Pluto-Charon system, and it is irregular in shape, similar to many other small satellites across the solar system. It was the best imaged of the small satellites during the *New Horizons* flyby. Because of its shape, we cannot easily map it onto a sphere with well defined latitude and longitude, and so we assume that the surface is a single unit and simply map craters in pixel space. We then use the spacecraft trajectory information with resolution and focal length of each camera to determine pixel scale to convert the pixel measurements to crater diameter.

Combining Results with a Clustering Code: Mapping the impact craters through the process described above resulted in over 14,000 identifications (as of mid-January, 2016), and some features were mapped as many as 19 times. Consequently, we used an automated cluster code to merge multiple markings into a single, final candidate impact crater for both the Pluto and Charon databases. We used a DBSCAN algorithm [4] that had already been modified for impact craters and demonstrated reliable results [1]. This code can factor in a weighting, and the three main crater analysts assigned subjective confidence levels to their markings; others' were assigned a 75% confidence (where 50% means a 50/50 chance the feature is not an impact crater). We can also give lesser weights to the locations of craters that were mapped in early mosaics, such that their non-final positions do not pull the crater from its more correct position given the latest maps and SPICE data (and we plan to manually check the code's output – see "Continuing Work," below). After running the code, we reduced the impact craters to ≈ 4900 final candidates on Pluto and ≈ 3700 on Charon; these are shown in Figs. 2 and 3.

Because we have pixel locations as opposed to distinct coordinates for Nix's crater population, the clustering to combine different researchers' results was done manually. This was a manageable task because we have only 50 markings (to-date) that were reduced to 29 final craters (see "Continuing Work," below).

Continuing Work: For the figures and numbers in this abstract, Robbins', Weaver's Nix, and some of Singer's results are represented, but Singer's, Bray's, and others' will be included in the catalog shown at LPSC in March 2016. Additionally, because of the importance of this crater database, we plan to manually examine the DBSCAN output to ensure the code did not merge distinct craters or not merge the same features, and we will correct the database as necessary.

Additional Cataloging: While mapping impact crater locations and diameters is important, additional morphology and morphometry is of interest for different studies. We are concurrently in the process of adding these data to the consensus catalog, including

topographic data as the digital terrain models improve.

References: [1] Robbins, S.J. *et al.* (2014) doi: 10.1016/j.icarus.2014.02.022. [2] Cheng, A.F. *et al.* (2008). [3] Reuter, D.C. *et al.* (2008). [4] Ester *et al.* (1996) ISBN 1-57735-004-9.

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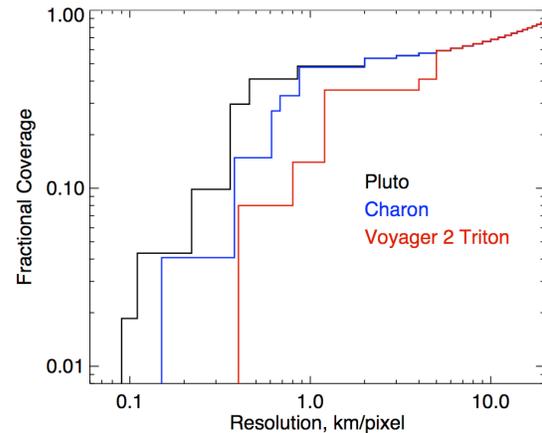


Figure 1: Resolution and fractional global coverage of *New Horizons* imaging of Pluto and Charon, compared to *Voyager 2* imaging of Triton. (see abstract by Spencer *et al.*, this volume, for more about this Figure)

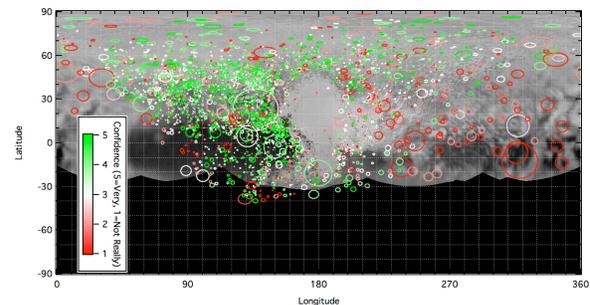


Figure 2: Map of Pluto with craters overlaid. Craters are color-coded based on confidence. Some craters are beyond the image basemap because the basemap cuts off slightly before the terminator, but it was possible to map impacts on the edge of this region.

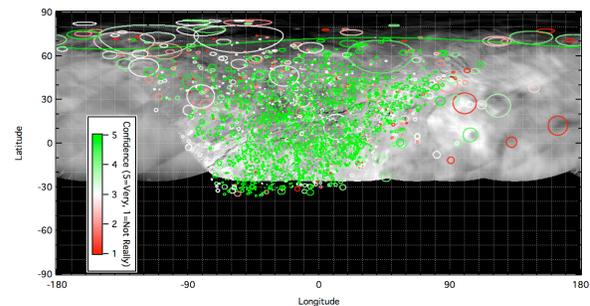


Figure 3: Charon with craters overlaid. See caption for Fig. 2 for additional information. Confidence for craters on Charon was generally higher than on Pluto.