Approaches to Detecting Kuiper Belt Objects for NASA's New Horizons Extended Mission: Digging Into the Noise. W. C. Fraser[1] , S. B. Porter[2], H. W. Lin[3], K. Napier[3], J. R. Spencer[2], JJ Kavelaars[1], A. J. Verbiscer[4], F. Yoshida[5], T. Terai[6], T. Ito[6], D. Gerdes[3], S. D. Benecchi[7], S. A. Stern[2], S. Gwyn[1], M. W. Buie[2], L. Peltier[8], K. N. Singer[2], P. C. Brandy[9], the New Horizons LORRI Team the New Horizons GGI Science Team, [1]Herzberg Astronomy and Astrophysics Research Centre (corresponding email: wesley.fraser@nrc-cnrc.gc.ca), [2]Southwest Research Institute, [3]University of Michigan, [4]University of Virginia, [5]University of Occupational and Environmental Health, Japan, [6]National Astronomical Observatory of Japan, [7]Planetary Science Institute [8]University of Victoria, [9]Johns Hopkins Applied Physics Laboratory.

The detection of moving sources in astronomical data is the backbone of many planetary astronomy projects. To date, this task has relied heavily on costly visual vetting to confirm moving sources amongst the much more numerous stationary sources. This is especially true of surveys which search stacks of sequential images that have been shifted at rates of motion relevant to the bodies of interest. When the shift rate matches that of a moving source, a point source is revealed (see Figure 1). Such a process provides a search depth that is comparable to the point-source depth that would be realized from a single, sidereal stack. As sources are not visible in individual frames, the so-called shift'n'stack technique comes at the cost of not being able to link detections as a source moves through the frames acquired at a given epoch. This has the effect of maximizing human search cost, even after applying modern processing techniques such as image subtraction to remove most of the stationary chaff. Here we present new techniques that utilize machine learning (ML) and linking across epochs to identify high probability candidate moving sources, geared specifically for shift'n'stack data. We make use of a multi-layer 3D-convolutional residual neural network (ResNet) to perform the binary classification task: good or not good? Our ResNet is trained on artificial sources that have been injected into the imagery before image subtraction, themselves trailed with rates of motion matching the objects of interest. We have applied this network to search for Kuiper Belt Objects in data from the Hyper Suprime-cam on the Subaru telescope that were acquired as part of a search for targets for NASA's New Horizons Extended Mission. The classification performance of the network for real detections has been extremely good, resulting in a reduction of candidate sources by more than three orders of magnitude. An entire night's worth of search data – typically 110 90s exposures – requires only a few hours of human vetting. We report a detection efficiency of 70% or better for $r<25.5$, with a limiting magnitude of $r\sim26.6$ depending on the night, despite the fact that these data have been acquired at a galactic latitude of ~10 degrees. Like past shift'n'stack searches, the depth of this new technique is ultimately noise limited with false positive detections ramping up quickly faintward of a photometric signal to noise of SNR~7. Our group has experimented with a promising new intra-night orbit linking technique which dramatically reduce the false-positive rate, pushing the noise floor to SNR~4, or ~0.5 magnitudes fainter. The ML-based search resulted in twice as many KBOs when compared to a human search of the same 2020 data. The search results from our 2020 and 2021 observations have detected an increase in density of objects at distances d~80 au, compared to the nearly empty region beyond the outer edge of the Kuiper Belt at d~50 (see Figure 2). This tentative result seems to betray the presence of a hitherto undetected and possibly massive population of planetesimals beyond the known Kuiper Belt. Future ground- and space-based surveys with survey depth $r\gtrsim27$ will be able to confirm this exciting new result.

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Figures:

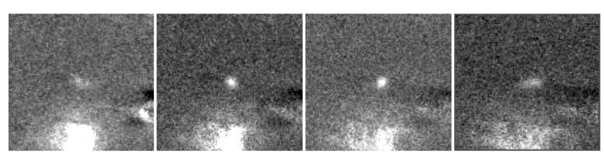

Figure 1: Example of shift'n'stack imagery for a real moving object detected through our pipeline. From left to right, the rates of motion are 1.5"/hr to 3.0"/hr in increments of 0.5"/hr. At this epoch, the target is moving at 2.4"/hr, corresponding to a distance of ~45 AU.

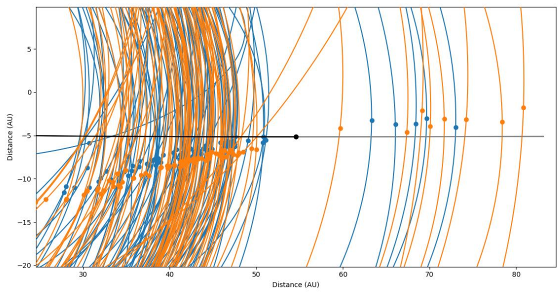

Figure 2: Kuiper Belt Objects detected from the Subaru 2021 (blue) and 2022 (orange) observations. The horizontal black line is the trajectory of New Horizons, the black dot represents the spacecraft's position on 2022-12-15. The coloured dots show the locations of the discoveries at the point on their orbits when the New Horizons is closest to them. For reference, the spacecraft will pass 60 au in October 2024.