**REPROCESSING WISE SPACE TELESCOPE IMAGERY WITH A MATCHED-FILTER MOVING-OBJECT SOFTWARE PIPELINE** M. J. Mazur[1] A. R. Hildebrand[2] and P. S. Gural[3] [1]Department of Earth Sciences, Western University, 1151 Richmond St. N., London, Ontario N6A 5B7, Canada, mmazur5@uwo.ca, [2]Department of Geoscience, University of Calgary, 2500 University Dr. N.W., Calgary, Alberta T2N 1N4, Canada, ahildebr@ucalgary.ca [3]Leidos, 11955 Freedom Drive, Reston, VA. 20190, USA.

**Introduction:** First introduced in the 1980's, the matched-filter (MF) algorithm has significant advantages over more traditional methods for identifying moving objects in astronomical images. By shifting and stacking images according to a matched-filter hypothesis set, significant improvements in SNR can be realized.

Here, we describe the implementation of the SALTAD (Software and Algorithmic Testbed for Asteroid Detection) MF algorithm [1] in a workflow to reprocess imagery from the cryogenic phase of the WISE mission. SALTAD is based on the matched-filter formulation of Mohanty [2] and, although modified significantly since the original implementation, it is basically a two-step process. The first step consists of mean removal and clutter suppression while the second step runs an adaptive MF detection to enhance the signal of moving objects. For the MF detection, a set of hypothesis templates for all reasonable moving object positions, speeds, and directions is developed. The images in the set are then shifted and stacked according to each hypothesis and examined for moving objects.

*Wide-field Infrared Survey Explorer (WISE) mission.* The WISE space telescope collected imagery over the entire visible sky in four infrared passbands from Jan 7, 2010 until Aug 6, 2010 [3]. Originally designed for astronomical surveying WISE was additionally used to discover and characterize asteroids [4] and observed >100,000 Main Belt asteroids [e.g. 5].

Initial results from the use of SALTAD on WISE imagery indicate an increase in the number of detected moving objects when compared to the original WISE submissions to the MPC. With an effective single-frame source detection limit SNR of between 2 and 3, we identify a number of precovery objects and possibly new discoveries.

**Method:** The four WISE 1024x1024 sensors have effective plate scales of 2.757"/pixel in bands W1-W3 and 5.5"/pixel in band W4 [3]. With a spacecraft orbital period of 90 minutes and a sidereal field shift of 4 arc-minutes between subsequent orbits, repetitive sky coverage results in image sequences of nine or more frames over intervals of up to 24 hours within out test areas. To maximize detection efficiency, we decimate our 2° x 2° test search areas into 400 overlapping subfields of a minimum 0.2° x 0.2° in size. Such an arrangement means that, not only will SALTAD will always have between 5 and 9 frames available covering each subfield, but most objects will be detected (and inspected) in two to four subfields.

After selection of the search area, all data is retrieved from the IRSA servers and pre-processed to remove bad pixels. New plate solutions are then generated with SCAMP astrometric software [6] before being trimmed to a common area of overlap using SWarp [7]. SALTAD is run over the registered W3 (12.2μm) image sets within each. The results are then filtered by stacked-SNR to identify the most-likely objects to be manually inspected in bands W3 and W4 (22μm) (Figure 1.). After inspection, the object lists are sorted and correlated with WISE submissions to the MPC and with nearby objects identified by the MPC's MPCheck tool.

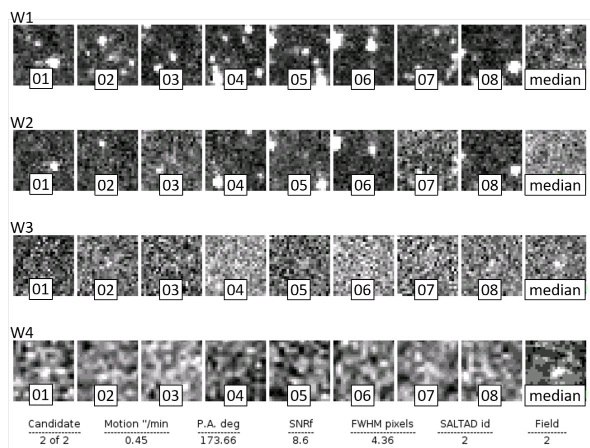


Figure 1. An example of a faint object as presented for inspection. This object is identified with a high-level of confidence as it is visible in not only the median "stack" frames, but also in all the individual W3 and W4 images (without any significant interfering background stars). Although the stacked SNR is 8.6, the single-frame SNR closer to 3.

The described workflow has been implemented in a combination of python and C++. The UI and QC scripts run on a remotely-controlled Raspberry Pi while with most of the work being done on a modest server. In our workflow, SALTAD is running on an NVIDIA gpu which results in typical compute times of about 2 minutes per subfield. Surprisingly, the current bottleneck is image retrieval and setup.

**Results:** Within an area of 12 square degrees, 274 moving objects were identified with a high-level of confidence (YES), with a further 63 identified as being uncertain (MAYBE). 213 of the YES objects are already known to the MPC. Of these, 197 had been identified by the WISE team in 2010 and 8 were WISE discoveries. 31 of the indentified objects are precoveries ranging from 1-7 years before discovery. Remaining are 61 unidentified moving objects. Some of these are possibly precoveries with poorly constrained orbits, but, many are likely to be discoveries.

Even with these high numbers, we are currently missing known objects in the field due to timing issues. Between 10 and 20 percent of the known WISE reported objects are not detected because they start or end outside of an image set. Designing a solution, however, is a balance between subfield size and limiting magnitude (which is enhanced by increasing the number of overlapping images). To explore the faintness limit of SALTAD on the WISE data, this loss was accepted. Figure 2 shows the results from one of the 4 square degree test fields.

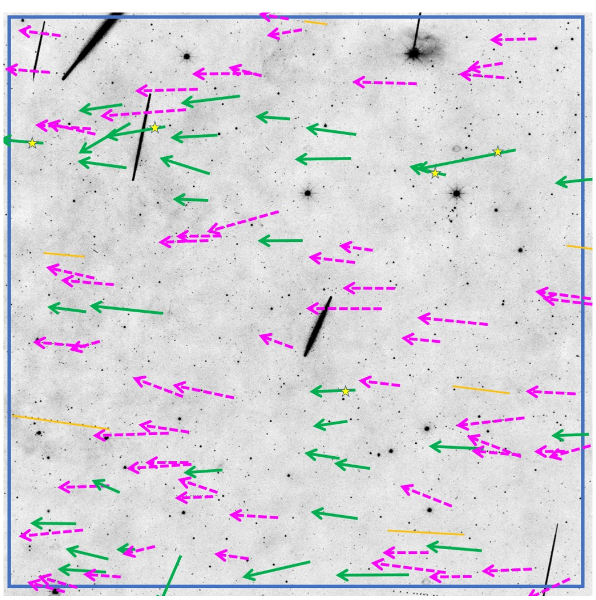

Figure 2. An example of the results from a 2x2 test area. Green (solid) arrows indicate detections with no WISE counterpart. Magenta (dashed) arrows indicate objects with both a SALTAD detection and a WISE counterpart. Orange (solid) lines show the missed detections. Stars indicate the most-likely new objects in the field.

Practically speaking, the stacked-SNR limit for confirmation of a moving object in our test areas is about 7. With image sets of between 5 and 9 frames, this corresponds to a single-frame SNR limit of between 2.3 and 3.1. Although there may be real detections at stack-SNRs of less than 7 (in band 3), it is impossible for the human operator to confirm the object based on the individual frames in which they appear. However, an unusual aspect of the WISE imagery is the availability of simultaneous band 4 data. Particularly if an asteroid is in the outer part of the belt it may have a stronger stack in band 4 than band 3 thus confirming a detection that would be equivocal with band 3 data alone. Also note that known objects may be located with stack SNRs <7.

As WISE images only in the IR, we rely on MPC magnitudes to gauge the SALTAD search limiting magnitude. Of the 213 confirmed objects, the faintest has a V magnitude of 22.7. This compares to 22.2 for the WISE objects in the test areas, but this isn't surprising as the original processing pipeline was constrained to source extraction at relatively high SNR's to limit the false detection rate so that available inspection resources could keep up with the data flow from WISE.

**Discussion:** The results show that significant gains can be made by using a matched-filter asteroid detection workflow. SALTAD has been used to process satellite imagery without significant modifications and has been shown to detect moving objects at SNRs of between 2 and 3. With confident detections nearly 30% greater than the number of objects known in the test areas, this workflow can be used effectively for asteroid discovery at the data SNR limits. In addition to discovery, the potential for precoveries has been demonstrated. The 31 precoveries within the test areas extend our knowledge of the orbits of these objects by up to 7 years. Although the numbers from these tests are promising, there remains room for improvement. Working with larger subfields is expected to yield up to 20% more real detections. Further work is currently being done to reprocess additional areas and to adapt the code to other datasets.

**References:** [1] Gural P. S., Larsen J. A. and Gleason A. E. (2005) *The Astronomical Journal, 130,* 1951–1960. [2] Mohanty N. C. (1981) *IEEE Transactions on Pattern Analysis and Machine Intelligence, 3,* 606. [3] Wright E. L. et al. (2010) *The Astronomical Journal, 140,* 1868–1881. [4] Mainzer A. et al. (2011) ApJ, 731, 53. [5] Masiero, J.R. et al. (2011) ApJ, 741, 68 [6] Bertin E. (2006) *ASP Conf. Ser.,* 351, 112. [7] Bertin E. (2002) *ASP Conf. Ser.*, 281, 228.

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