LONEOS Processing Details

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Abstract

This document describes how pairs of original 2.88°x1.44° Lowell Observatory Near Earth Object Survey (LONEOS) images without World Coordinate System (WCS) information, and containing pre-scan and/or over-scan columns, produced by each LONEOS telescope exposure, are converted to archivable images. This is accomplished by cropping out the original image pairs' (where both exist) pre-scan and/or over-scan columns and writing WCS information and other relevant keywords into the headers of the cropped images which are referred to herein as "augmented" images.

The LONEOS Archive described in this document contains all available images obtained using Lowell Observatory Imaging Software (LOIS[1]) versions 3.2.0.beta and 4.2.0 during the LONEOS project, *i.e.,* all images we received on hard disk drives (HHD) that were obtained between 2003/08/05 and 2008/03/01, inclusive. For details on the source of these images see loneos_data_acquisition.pdf.

Due to numerous issues with the original images and the lack of any useful documentation, many of the original images proved useless. As noted in loneos_augmented_images_validation.pdf, even the best images have poor whole-image astrometric solutions. Nevertheless, the archived augmented images are useful in searching for pre-discovery images of near-Earth objects (NEOs) because, if any are found, their coordinates can be refined by cropping out the area immediately around them and performing an astrometric solution on that region.

The archived images are not intended to be used to extract photometric information. Nevertheless, photometry has been obtained, using the same instrumentation as in the LONEOS (by others but not on any of the images in version 1.0 of this archive), and the results published. See[2] §§4.2 Photometry and 5 Caveats for additional details.

1. Introduction

The LONEOS Archive consists of three directories: …/data_augmented/, …/data_original/, and …/document/. The two data directories each have subdirectories ordered by LOIS version, and within each LOIS directory the images and their labels are organized by the date they were obtained. The …/document/ directory contains all the documents describing the archive's creation and contents, *e.g.*, the document you are now reading.

See loneos_archive_directory_structure.pdf for a more detailed description of the archive data structure.

2. Processing

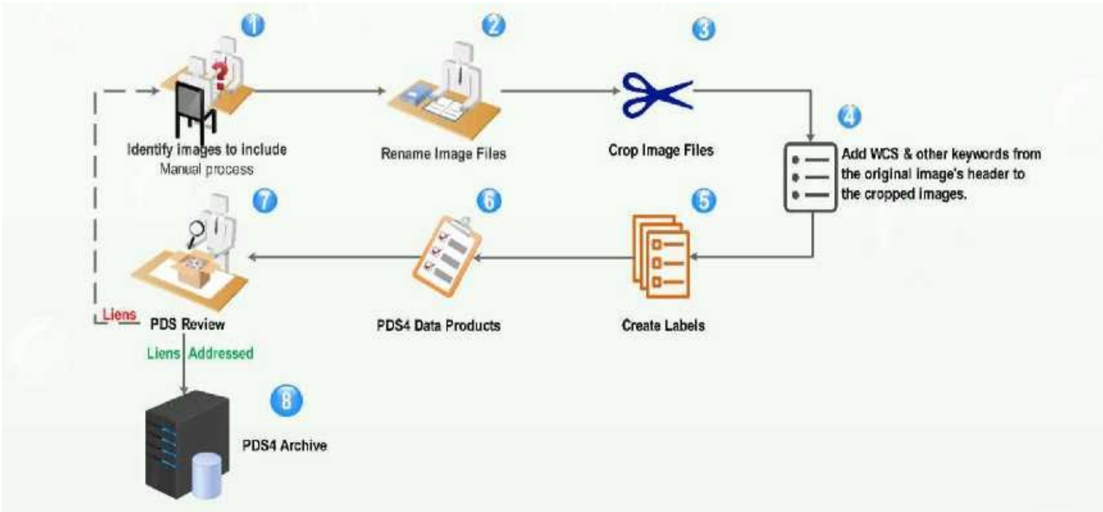
This section describes the steps performed to convert the original LONEOS image files into archived augmented images. These input images are referred to as the "original data". However, as explained in loneos_data_acquisition.pdf, some are more "original" than others. That is, FITS files obtained from Lowell Observatory hard disk drives (HDDs) are digital copies of the images written by the camera to a disk drive immediately following the exposure. A Tape Archive format (tar) or collection of compressed tar.gz images (if not corrupt) is essentially equivalent to this. However, the images received on magnetic tapes could not simply be read from them due to their poor condition. See loneos_data_acquisition.pdf for information on how these images were recovered. That document also describes what, if anything, was recovered from each tape *(e.g.,* entries for tapes 127 through 145, and numerous others, are missing because these tapes were not among those we received from JPL or from which nothing could be recovered).

Below is a flowchart describing how the LONEOS images from the "original, unmodified" LONEOS images,

[1] Lowell Observatory Imaging Software is used by all visual wavelength CCD cameras at the Lowell Observatory (B. Skiff, personal communication, 2022).

[2] Text in underlined blue are links to external documents hosted at permanent links (DOI - Digital object identification locations, if available), primarily refereed papers (although not all refereed papers have a DOI). Text in underlined green links to places within this document. Where I simply wish to show the source for the material cited, I provide the URL as it was when I accessed that information, or the PDF document's filename elsewhere in this archive (usually in this archive's …/document/ directory), just not as an active link. These pseudo-links are in dark orange and not underlined, as shown in footnote 3.

currently at Planetary Data System (PDS) Original LONEOS Dataset[3], were processed into PDS4 compliant data products.



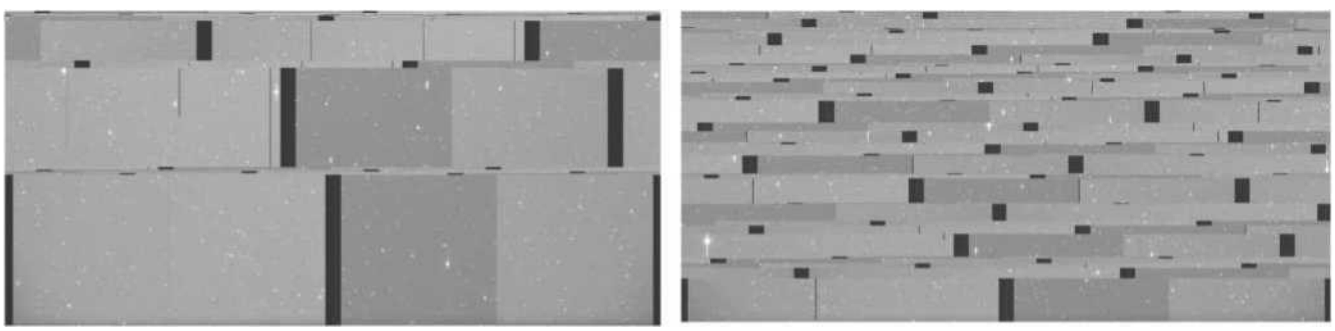
LONEOS Images Processing Flowchart

2.1 Processing Steps

1) Identify Images to Include

Much of the work described in this step was performed before the proposal that funded this work was submitted. The images from 2005-11-13 through 2008-03-01 are all those from the final LOIS version (4.2.0). Thus, these were chosen as the first images to process because it was assumed that they would all have identical header formats and hence be suitable for input to a processing pipeline. As I will document below, and in the descriptions for the other LOIS versions, this assumption proved false.

Another unanticipated step that proved necessary, and that must be done manually, is to visually examine every original image to detect, and remove, corrupt images such as the two examples shown below.



2) Rename Files using the PowerShell script Rename_LONEOS_Files.ps1

Due to limitations in Windows' operating system (OS) renaming files with filenames ending in .xxx is not straightforward as the OS assumes this is a filename "extension", *i.e.,* that it designates the file's type *(e.g.,* .docx for a Word file, .xlsx for an Excel file, *etc.).* This PowerShell script renames the original LONEOS image filename used in most years for files obtained from hard disk drives, *viz.,* YYMMDD_#.nnn, where YYMMDD is a two-digit Year, Month, and Day, # is 1 or 2, for the northern and southern images, output by the two-Charged Couple Device (CCD) camera, respectively, and nnn is the exposure number for the given date (a value between 001 and 999) to YYMMDD_#_nnn.fits

[3] https://sbnarchive.psi.edu/loneos/ The non-personal files from this location will be archived at Zenodo and cited here at which time, I assume, this Small Bodies Node (SBN) archive will be deleted.

3) Crop

Every LONEOS exposure obtained with the LONEOS-II camera[4] was saved to two 2.88°x1.44° files: the northern half of the image used a filename containing _1 and the southern half containing _2. Except for these filename differences, the keywords and their values in the headers for each of these north-south files are identical. The original plan was to merge these two 2.88°x1.44° files into a single 2.88°x2.88° image. However, it transpired that on many nights some, or all, _1 or _2 images were missing or corrupted and so could not be merged. Hence, no image pairs were merged.

On most nights the first 10 exposures, for both the _1 and _2 images are bias frames. However, many nights have no bias frames, or bias frames at both the beginning and end of the night, or bias frames at some random time during the night. The headers for the bias images differ from those of the exposures on the sky. Therefore, no changes are made to bias images or their headers and they were simply written to the archive's …/data_original/lois_4_2_0/YYMMDD directory as is.

However, the non-bias (sky) images cannot simply be archived in their original form because:

1. The images contain pre-scan and/or over-scan columns on the right and left (west and east) sides which lead to incorrect WCS values, *i.e.,* the RAs are incorrect. (See Appendix I.)

   To remove the pre-scan and/or over-scan columns, I cropped each sky image using ImageMagick[5], where the width and height of the crop rectangle and the x and y coordinates of the top left corner of the image must be specified. The command is then, *e.g.*:

   ```
   magick Merged_Image.fits -crop 4096x2050+201+0 Merged-Cropped_Image.fits
   ```

2. As with the original images, the cropped images' headers lack keywords required for a WCS image. In fact, the ImageMagick cropped images' headers lack any non-required keywords from the original images, containing only the following:

   ```
   SIMPLE  =                    T
   BITPIX  =                   16
   NAXIS   =                    2
   NAXIS1  =                 4096
   NAXIS2  =                 2050
   BSCALE  =                    1
   BZERO   =                32768
   DATAMAX =                65535
   DATAMIN =                    0
   HISTORY https://imagemagick.org
   END
   ```

4) Add WCS and Other Keywords

The following keywords must be added to the cropped image's header to produce an image with WCS information. For image 051113_1_011.fits, used as an example, the values of these keywords are:

```
CTYPE1   = 'RA---TAN'
CTYPE2   = 'DEC--TAN'
CRPIX1   =             2048.5
CRPIX2   =             1025.5
LONPOLE  =              180.0
LATPOLE  =                0.0
CRVAL1   =         321.124583 From keyword TELRA  = '21:24:29.9'
CRVAL2   =           8.571944 From keyword TELDEC = '+08:34:19' ± 0.72°
CD1_1    =           0.000703
CD1_2    =         -1.814E-06
CD2_1    =         -1.952E-06
CD2_2    =          -0.000703
```

Except for `CRVAL1` and `CRVAL2`, which are unique to each image-pair and can be obtained from either

[4] See loneos_project_description.pdf §3.b for a description of the two cameras used in the LONEOS program. Archive version 1.0 only contains images obtained with the LONEOS-II camera.

[5] https://imagemagick.org

original 2.88°x1.44° image (_1 or _2) and entered as decimal degrees[6], the remaining WCS keywords and their values are the same for all images obtained with the same telescope, camera, and detectors. Some images have CRVAL1 and CRVAL2 in keywords OBSRA, OBSDEC or RA, DEC.

CTYPE1 and CTYPE2 indicate the coordinate type and projection. The first four characters, RA-- and DEC-, indicate equatorial coordinates and -TAN is used to signify a tangent projection, under the assumption that a CCD image can be closely approximated by such a projection and CRPIX1 and CRPIX2 are the pixel coordinates of the reference point to which the projection and the rotation refer (http://tdc-www.harvard.edu/wcstools/wcstools.wcs.html).

LONPOLE and LATPOLE give the rotation angle between the pixel axis and the physical coordinate axis in degrees (although the reserved FITS coordinate system keyword for LONPOLE is LONGPOLE[7])

CD1_1, CD1_2, CD2_1, CD2_2 are referred to as the "CD matrix" and are four values which describe the mapping of the celestial coordinate system to the FITS image x,y coordinate grid. Initially, I assumed no image rotation, since I had not seen any in the images I had examined to date, *i.e.*, CD1_2 = 0 and CD2_1 = 0. The other two, CD1_1 and CD2_2, are simply the plate scale, in degrees, along the x- and y-axes. The LONEOS camera's plate scale is 2.53 ± 0.04 "/px (± 1.6%), or 0.00070278°/px. To check these values, I solved a few images using Astrometry.net (https://nova.astrometry.net/upload) and used the average values from its solutions, as given in the example header above.

Thus, Python scripts create_hdr_nn.py and add_wcs_nn_m.py (where nn = 32 or 42 and m = _1 and _2), extract the TELRA and TELDEC (or their equivalents) from an original image together with keywords LOISVERS, OBSERVER, DATE, AIRMASS, OBJECT, EXPTIME, and UTCSTART, convert the TELRA and TELDEC to decimal degrees and write them ±0.72° (as CRVAL1 and CRVAL2) along with the other extracted keywords, to the cropped image's header to produce the final 2.88°x1.44° WCS image as outlined below for the LOIS 4.2.0 images. The names of the scripts to process the LOIS 3.2.0.beta data have the 42 replaced by 32. Because images on numerous nights have different headers with their own unique number of lines (aka "cards"), keywords, and values, there are multiple versions of create_hdr_nn.py and add_wcs_nn.py.

a) create_hdr_42.py

Input: Original FITS images, *e.g.,* 051113_#_nnn.fits, where # = 1, 2

Output: 051113_#_nnn.hdr, where # = 1, 2

051113_#_nnn.hdr is used as one of the input files required by add_wcs_42_1.py and add_wcs_42_2.py

b) add_wcs_42_1.py and add_wcs_42_2.py

Input: pairs of files like 051113_#_nnn.hdr and 051113_#_nnn.fits

Output: Images with embedded WCS (as 051113_#_nnn_wcs.fits), their header files (051113_#_nnn_wcs.hdr), and the Image Data Table (051113_#.tbl which contains the image "corners" required for each image's PDS4 Label)

See Appendix II for the LOIS 4.2.0 example night's (051113) original and augmented header.

5) Create Data Product Labels

create_label_42.py was used to create the Comma-Separated Values (*.csv) files from which the PDS4 Extensible Markup Language (*.xml) label files for nightly LONEOS WCS images were then created by the PDS/SBN.

Input: Table (*.tbl) and *wcs.hdr files (*e.g.*, 051113_#_nnn.wcs.hdr and 051113_#.tbl)

Output: *.csv (*e.g.*, 051113_#.csv) which contains one line for each image and the header required for the *.xml Label.

[6] TELRA, TELDEC are the position of the center of the merged _1, _2 images, assuming they were merged. But they were not merged, and so TELRA is the same for both images, hence 0.72° (half the N-S height of each image) must be added to the _1 image and 0.72° must be subtracted from the _2 image to correctly designate their center declinations.

[7] https://heasarc.gsfc.nasa.gov/docs/heasarc/ofwg/docs/general/wcs_keywords/node6.html

A similar code was used to create *.csv files for the original images.

6) PDS Data Products

The files created in steps 4 and 5 were delivered to the PDS/SBN for placement in the appropriate subdirectories in the top level loneos archive directory. For example, for 2005/11/13, all images with embedded WCS, *i.e.*, the "augmented" images (*e.g.*, 051113_1a_nnn.fits and 051113_2a_nnn.fits) were put into tar files (051113_1a.tar and 051113_2a.tar) and placed in subdirectory …/data_augmented/lois_4_2_0/051113/ and the *.csv files (*e.g.*, 051113_1a.csv and 051113_2a.csv), from which the PDS4 label files are created, in that same subdirectory.

The same was done with the original source images from which the augmented images were created and the nightly bias images (if any), and both their labels, except that they are placed in directory: …/data_original/lois_4_2_0/051113/. These consist of 051113_#.csv, 051113_#.tar, 051113_#_bias.csv, and 051113_#_bias.tar, where # = 1 or 2.

This completed delivery to the PDS/SBN of the original and augmented images and their labels for LOIS versions 3.2.0.beta and 4.2.0.

However, the actual archive the user will see is not that described above. For nights like 051113, which has ten _1 and ten _2 bias images, the PDS/SBN unpacks the *.tar bias files into ten _1 and ten _2 bias images of the form 051113_1_nnn_bias.fits and 051113_2_nnn_bias.fits and converts each line in the *.csv files into a corresponding *.xml label file of the form 051113_1_nnn_bias.xml and 051113_2_nnn_bias.xml, where nnn = 001 through 010 and the 448 pairs of original image files of the form 051113_#_nnn.fits, with # = 1 or 2 and nnn = 011 through 458 and their corresponding label files 051113_#_nnn.xml

The same procedure is used for the 448 _1a and 448 _2a augmented images of the form 051113_#a.nnn.fits, with # = 1 or 2 and nnn = 011 through 458 and their corresponding label files 051113_#a.nnn.xml

Not every night has bias files; most have 10, others have a smaller or larger number, and some have none. The number of _1 and _2 files should always be the same, since for every exposure the camera wrote the northern CCD's output to filenames containing an _1 and the southern CCD's output to filenames containing an _2. However, this is not the case. Some nights are missing a number of _1 and/or _2 images and so the number of _1 and _2 images differ. And if the numbers of _1 and _2 images are the same that does not necessarily mean that each has the same set of nnn. Reasons for the differing numbers of _1 and _2 images are: 1) the missing images were not among the set of files we received from the Lowell Observatory or 2) the images were present among the files we received but were corrupt.

The only thing you can be confident of is that there is always a one-to-one correspondence between the original and augmented images and their labels because the latter were created from the former.

Steps 1 through 6 are the "pipeline" (see Appendix III) through which the original images were run to convert them to archived "augmented" images and their labels. However, this is hardly a completely automated operation given that each night's images must be manually checked for corrupt images, there are multiple LOIS versions, and there are variations in the headers within all the LOIS versions. That is, this pipeline has many frequent and unexpected "leaks". Consequently, there are several versions for some of the codes, primarily those in Steps 4 and 5. For these reasons, each code's version is identified by including the LOIS version in its filename and an attempt was made for each version to deal with all known header variations within that LOIS version.

Nevertheless, images on some nights fail to process, *i.e.*, they do not output correct files, or they produce the expected files but some entries in the headers of the augmented images are incorrect. Identifying these anomalies is generally fairly straightforward, however, fixing them is not, as this invariably involves modifying the code that produced the incorrect output, writing new code to address the issue, or manually editing the output file (if it was a label file and the total number of lines needing to be corrected is reasonably small). Unless the issue was common to multiple files, modifying the code that produced the incorrect output was not usually done as this could, and did, have unintended consequences which then had to be dealt with.

7) PDS Review

These data products, and the documentation describing them, were reviewed by an external review panel which provided feedback in the form of liens. Satisfying some of these liens required rerunning all or portions of the pipeline. Once all liens are addressed to the satisfaction of the panel and PDS personnel the LONEOS PDS4 Archive is finalized and released to the public.

3. Validation

See loneos_augmented_images_validation.pdf

4. Conclusions

1. Astrometry

The primary purpose of archiving the LONEOS images was to make them available to be searched for pre-discovery observations of recently-discovered NEOs that are predicted to have been present in the area covered by one or more of these archived images on a given date and time. The PDS's Comet-Asteroid Telescopic Catalog Hub (CATCH) is a moving-target search tool that was designed to do this.

If the recently-discovered NEO passed through one or more LONEOS images, then those images can be examined to see whether that NEO was detected in any. If it was, then its coordinates could be measured, potentially extending its observational arc back to the early 2000s, hence, extending that object's discovery orbital arc by 15- to 20-years.

Finally, by using a matched filter algorithm it will be possible to identify moving sources 0.5 to 0.7 mag fainter than those identified in the original survey.

See Appendix II in loneos_augmented_images_validation.pdf for additional information.

2. Photometry

Differential (lightcurves) and even some absolute photometry have been obtained from LONEOS images (Koehn, *et a*l. 2014; Skiff, *et al*. (2012, 2019a, and 2019b), although not those images in Archive V1.0. For example, Skiff, *et al*. (2012), page 112, state: "… *nearly all our fields had plenty of photometric reference stars irrespective of exposure time, and reductions directly to Sloan r' were made without intermediary observations of standard fields*." However, this was possible only because Skiff, *et al*. and Koehn, *et al*. had flat field images available, which the Archive V1.0 images do not.

LONEOS images can also be used to study other transient astronomical phenomena, *e.g.*, novae, supernovae, variable stars, *etc*., *e.g.*, as done by Miceli, *et al*. (2008) using images obtained with the same LONEOS telescope but an earlier version of the camera used to obtain the Archive V1.0 images.

5. Caveats

Due to the issues discussed herein and in loneos_augmented_images_validation.pdf, the search areas specified in any searches should, conservatively, add about ±6 arcminutes in RA and Dec to allow for errors of this magnitude in the archived positions of each image's corners.

Although the augmented 2.88°x1.44° images have significant issues, with care accurate positions for sources, even those near or adjacent to a dead column, can be extracted; however, automating processing of these images may be challenging.

While differential photometry is clearly possible using these images, due to the lack of calibration images, other than bias frames, extracting useful absolute photometric data from the images archived here will be difficult.

Note that the DATE keyword in the FITS image headers for the LOIS 3.3.0.beta images are in YYYY-DD-MM format. However, they have the correct, YYYY-MM-DD format, in the .xml labels.

6. References

Koehn, B. W., Bowell, E.G., Skiff, B.A., Sanborn, J.J., and two colleagues, 2014. Lowell Observatory Near-Earth Asteroid Photometric Survey (NEAPS) - 2009 January through 2009 June. The Minor Planet Bulletin (ISSN 1052-8091). Bulletin of the Minor Planets Section of the Association of Lunar and Planetary Observers, Vol. 41, No. 4, pp. 286-300. Bibcode: 2014MPBu...41..286K https://articles.adsabs.harvard.edu/full/2014MPBu...41..286K

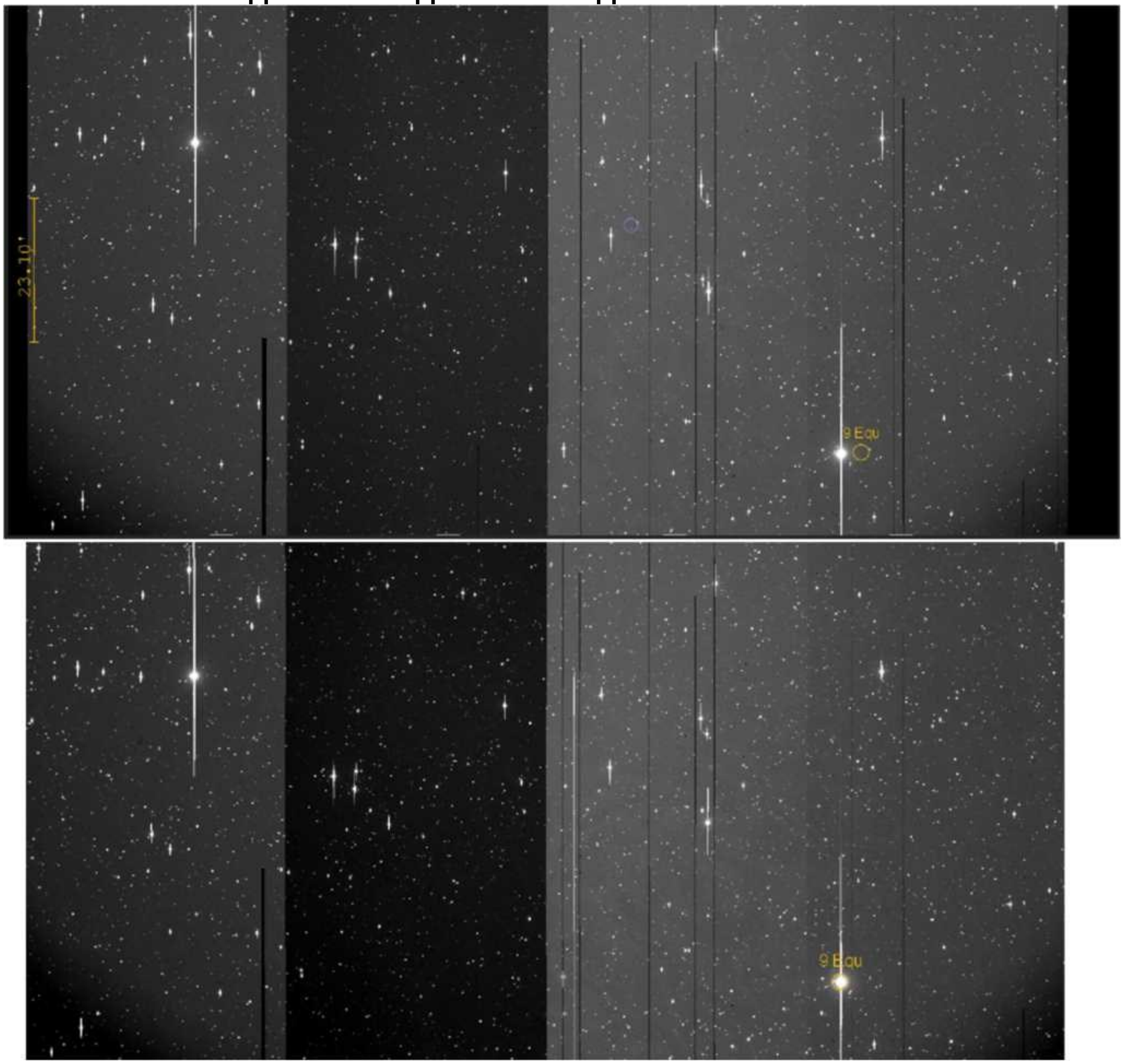
Miceli, A., Rest, A., Stubbs, C.W., Hawley, S.L., and five colleagues, 2008. Evidence for Distinct Components of the Galactic Stellar Halo from 838 RR Lyrae Stars Discovered in the LONEOS-I Survey. *Ap. J.* **678**:865-887. https://iopscience.iop.org/article/10.1086/533484/pdf

Skiff, B.A., Bowell, E., Koehn, B.W., Sanborn, J.J, and two colleagues, 2012. Lowell Observatory Near-Earth Asteroid Photometric Survey (NEAPS) - 2008 May through 2008 December. The Minor Planet Bulletin (ISSN 1052-8091). Bulletin of the Minor Planets Section of the Association of Lunar and Planetary Observers, Vol. 39, No. 3, p. 111-130. Bibcode: 2012MPBu...39..111S https://articles.adsabs.harvard.edu/full/2012MPBu...39..111S

Skiff, B.A., McLelland, K.P., Sanborn, J.J., Pravec, P., and one colleagues, 2019a. Lowell Observatory Near-Earth Asteroid Photometric Survey (NEAPS): Paper 3. The Minor Planet Bulletin (ISSN 1052-8091). Bulletin of the Minor Planets Section of the Association of Lunar and Planetary Observers, Vol. 46, No. 3, pp. 238-265. Bibcode: 2019MPBu...46..238S https://articles.adsabs.harvard.edu/full/2019MPBu...46..238S

Skiff, B.A., McLelland, K.P., Sanborn, J.J., Pravec, P., and one colleagues, 2019b. Lowell Observatory Near-Earth Asteroid Photometric Survey (NEAPS): Paper 4. The Minor Planet Bulletin (ISSN 1052-8091). Bulletin of the Minor Planets Section of the Association of Lunar and Planetary Observers, Vol. 46, No. 4, pp. 458-503. Bibcode: 2019MPBu...46..458S https://articles.adsabs.harvard.edu/full/2019MPBu...46..458S

Appendix I. Cropped vs. Uncropped Astrometric Fits



Astrometry.net fits to uncropped (top) and cropped (bottom) versions of 051113_011.fits

Astrometry.net (AN) Solutions for 051113_011.fits

Solution	Cropped	Uncropped
Center (RA):	21h 24m 21.625s	21h 24m 18.565s
Center Dec):	+08° 34' 18.404"	+08° 34' 21.460"
Size:	2.88 x 2.88 deg	3.07 x 2.88 deg

9 Equ

ICRS coord. (ep=J2000):	21 21 04.826	+07 21 16.22
AN Cropped coord.	21 21 05.8	+07 21 30.0
AN Uncropped cord.	21 21 12.7	+07 21 30.4

The AN uncropped RA is 6.9s (104”) east of the cropped image’s fit RA while the fit Decs differ by <1”. The absolute agreement of the cropped position with the ICRS position is ~15” in both RA and Dec. 9 Equ’s proper motion (43.287, -17.670 mas/yr) over ~6 years is negligible, so this difference is disappointingly large.

Appendix II. LOIS 4.2.0 example night's (051113) Original and Augmented Headers

051113_1_011.fits 112-line original header:

```
SIMPLE  =                    T / file does conform to FITS standard
BITPIX  =                   16 / number of bits per data pixel
NAXIS   =                    2 / number of axis
NAXIS1  =                 4376 / length of data axis 1
NAXIS2  =                 2050 / length of data axis 2
BZERO   =         3.276800E+04 / zero point
BSCALE  =         1.000000E+00 / data scaled by value
BUNIT   = 'ADU     '           / pixel units(ADU,electrons)
CTYPE1  = 'Linear Unbinned ADC Pixels' / Axis Type for NAXIS1
CRPIX1  =         1.000000E+00 / Locataion of Reference Point along axis 1
CRVAL1  =         1.000000E+00 / Coordinate value at reference point for axis 1
CRDELT1 =         1.000000E+00 / Coordinate increment at reference point
CROTA1  =         0.000000E+00 / Rotation from stated coordinate type
CFINT1  =         1.000000E+00 / The data fill values for NAXIS 1
CTYPE2  = 'Linear Unbinned ADC Pixels' / Axis Type for NAXIS2
CRPIX2  =         1.000000E+00 / Locataion of Reference Point along axis 2
CRVAL2  =         1.000000E+00 / Coordinate value at reference point for axis 2
CRDELT2 =         1.000000E+00 / Coordinate increment at reference point
CROTA2  =         0.000000E+00 / Rotation from stated coordinate type
CFINT2  =         1.000000E+00 / The data fill values for NAXIS 2
LOISVERS= '4.2.0   '           / LOIS Version
LCAMMOD = 'loneos  '           / LOIS Camera module
LTELMOD = 'telloneos'          / LOIS telescope module
LINSTMOD= 'none    '           / LOIS instrument module
OBSERVER= 'M. E. Van Ness'     / observer(s)
OBSAFFIL= 'Lowell Observatory' / observer(s) affiliation
OBSERVAT= 'Lowell Observatory' / observatory
ALTITUDE=         2.200000E+03 / altitude in meters
LATITUDE=         3.509593E+01 / latitude, degrees
LONGITUD=        -1.115367E+02 / east longitude, degrees
DATUM   = 'WGS84   '           / The coordinate system for longitude and latitud
DATE    = '2005-11-13T01:35:30' / UT Date of File creation
DETECTOR= 'Loneos 4096x4096 Mosaic CCD' / CCD Detector Name
CAMMODE = 'Single  '           / CCD exposure mode
DETSIZE = '4096x4100'          / Detector Size in pixels(e.g. 2048x1024)
PIXSIZE =         1.350000E+01 / Pixel Size in Microns
PIXSCAL =         2.531430E+00 / Pixel Scale in arcs per pixel
PIXTIME =         0.000000E+00 / Pixel Readout time in microsec
DETTEMP =        -9.478600E+01 / CCD Temp in Deg C
SETTEMP =        -1.100532E+02 / CCD Temp Set Value in Deg C
CTTEMP  =        -1.102000E+02 / Cold Tip Temp value in Deg C
TELESCOP= 'TELLONEOS'          / Telescope name
LST-OBS = '21:38:27'           / Local Sideral Time of exposure start
TELRA   = '21:24:29.9'         / TCS right ascension(hh:mm:ss)
TELDEC  = '+08:34:19'          / TCS declination (dd:mm:ss)
OBSRA   = '21:24:28.795'       / requested right ascension(hh:mm:ss)
OBSDEC  = '+08:34:13.2'        / requested declination (dd:mm:ss)
EQUINOX =         2.000000E+03 / equinox of OBSRA and OBSDEC
AIRMASS =         1.120000E+00 / airmass
TELFOCUS=        -5.627000E+03 / telescope focus position
HA      =         0.000000E+00 / hour angle
ZA      =         0.000000E+00 / zenith angle
CREATOR = 'LOIS    '           / File Creation task or process(ie LOIS)
FILENAME= '051113_1.011'       / Original Camera Disk File Name
DATASRC = 'Instrument'         / Data source
INTERLCE=                    F / Image interlaced(true) or deinterlaced(false)
TRIGGER = 'SOFTWARE'           / Either Hardware or Software trigger to start ex
IMAGEID =                    1 / Image Identification Number
OBSERNO =                   11 / Image Count for Observing Session
OBJNAME = 'No Target'          / Target Object Name
OBJECT  = ' Region 3009 '      / Object Name
OBSTYPE = 'OBJECT  '           / object, flat, bias, etc.
DATE-OBS= '2005-11-13T01:35:31.01' / UT date(yyyy-mm-dd) of observation
```

LONEOS Processing Details

```
TIMESRC = 'NTP Time Server'    / Indicates the manner in which time was set e.g.
TIMEQUAL= 'NTP: max_error=335007 est_error=35433' / Time Quality Value
GPSSTATE= 'Trak 8821 Status Value' / Current GPS status String
EXPTIME =        4.500000E+01 / Actual integration time, seconds
UTCSTART= '01:35:31.01'       / universal time (start of exposure)
UTCEND  = '01:36:28'          / universal time (end of readout)
NUMAMP  =                   4 / Number of readout amplifiers for image
PRESCAN =                  50 / Number of prescan columns per amplifier
POSTSCAN=                  20 / Number of postscan columns per amplifier
POSTCLK =                   0 / Number of postclocked rows
SUBARNO =                   1 / Number of subarrays in observation
SUBARSER=                   1 / Subarray sequence number
AAMP_01 =                   1 / Amplifier 01 - 1 if used, 0 if not used
AAMP_02 =                   1 / Amplifier 02 - 1 if used, 0 if not used
AAMP_03 =                   1 / Amplifier 03 - 1 if used, 0 if not used
AAMP_04 =                   1 / Amplifier 04 - 1 if used, 0 if not used
AGAIN_01=        0.000000E+00 / Gain for amplifier 01
ARDNS_01=        0.000000E+00 / Read Noise for amplifier 01
AORGX_01=                   1 / X pos. of first physical pixel read by amp 01
AENDX_01=                1024 / X pos. of last physical pixel read by amp 01
ADELX_01=                   1 / Binning factor for amp 01 in X direction
AORGY_01=                   1 / Y pos. of 1st physical pixel read by amp 01
AENDY_01=                4100 / Y pos. of Last physical pixel read by amp 01
ADELY_01=                   1 / Binning factor for amp 01 in Y direction
AGAIN_02=        0.000000E+00 / Gain for amplifier 02
ARDNS_02=        0.000000E+00 / Read Noise for amplifier 02
AORGX_02=                4096 / X pos. of first physical pixel read by amp 02
AENDX_02=                1025 / X pos. of last physical pixel read by amp 02
ADELX_02=                  -1 / Binning factor for amp 02 in X direction
AORGY_02=                   1 / Y pos. of 1st physical pixel read by amp 02
AENDY_02=                4100 / Y pos. of Last physical pixel read by amp 02
ADELY_02=                   1 / Binning factor for amp 02 in Y direction
AGAIN_03=        0.000000E+00 / Gain for amplifier 03
ARDNS_03=        0.000000E+00 / Read Noise for amplifier 03
AORGX_03=                   1 / X pos. of first physical pixel read by amp 03
AENDX_03=                1024 / X pos. of last physical pixel read by amp 03
ADELX_03=                   1 / Binning factor for amp 03 in X direction
AORGY_03=                   1 / Y pos. of 1st physical pixel read by amp 03
AENDY_03=                4100 / Y pos. of Last physical pixel read by amp 03
ADELY_03=                   1 / Binning factor for amp 03 in Y direction
AGAIN_04=        0.000000E+00 / Gain for amplifier 04
ARDNS_04=        0.000000E+00 / Read Noise for amplifier 04
AORGX_04=                   1 / X pos. of first physical pixel read by amp 04
AENDX_04=                1024 / X pos. of last physical pixel read by amp 04
ADELX_04=                   1 / Binning factor for amp 04 in X direction
AORGY_04=                   1 / Y pos. of 1st physical pixel read by amp 04
AENDY_04=                4100 / Y pos. of Last physical pixel read by amp 04
ADELY_04=                   1 / Binning factor for amp 04 in Y direction
END
```

051113_1a_011.fits 31-line augmented header:

```
SIMPLE  =                    T
BITPIX  =                   16
NAXIS   =                    2
NAXIS1  =                 4096
NAXIS2  =                 2050
BSCALE  =                    1
BZERO   =                32768
DATAMAX =                65535
DATAMIN =                    0
LOISVERS= '4.2.0   '
OBSERVER= 'M. E. Van Ness'
DATE    = '2005-11-13T01:35:30'
CTYPE1  = 'RA---TAN'
CTYPE2  = 'DEC--TAN'
CRPIX1  =               2048.5
CRPIX2  =               1025.5
AIRMASS =                 1.12
FILENAME= '051113_1a_011.fits'
OBJECT  = 'Region 3009'
EXPTIME =                 45.0
UTCSTART= '01:35:31.01'
LONPOLE =                180.0
LATPOLE =                  0.0
CRVAL1  =           321.124583
CRVAL2  =             9.291944
CD1_1   =             0.000703
CD1_2   =           -1.814E-06
CD2_1   =           -1.952E-06
CD2_2   =            -0.000703
HISTORY https://imagemagick.org
END
```

Appendix III. The LONEOS Pipeline

Below is a list of the codes that form the pipeline and which were run in the order shown. The details in the table below are intended to give an impression of the various parts of the pipeline and how they interacted and is for the version used in mid-2023.

Because the purpose of this pipeline was to process highly variable input within a short timeframe (well under 12-months) and it was developed by one individual, its documentation is minimal, incomplete, and likely invalid in places and version control was essentially nonexistent.

These codes were called from a bash script create_pds_files_xx.sh, where xx is the LOIS version. This script was run from a Windows Subsystem for Linux version 2 (WSL2) virtual Ubuntu version 20.04.6 terminal under a montage38 environment obtained from http://montage.ipac.caltech.edu/ and links therein.

There are various versions for each of the codes whose filenames have an xx since each LOIS version has its own peculiarities. The codes, and the directories from which they run, are described below. All codes are called from create_pds_files_xx.sh

Code	Called in Line	No. Lines	Step	Location
create_pds_files_xx.sh	N/A	723	0	D:\LONEOS\wd
Rename_LONEOS_Files.ps1	216	7	1	D:\LONEOS\wd
create_bias_hdr_42.py	271	95	1	D:
create_bias_label_42.py	289	249	1	D:
create_hdr_xx.py	386	121	1	D:\LONEOS\wd
step_2.btm	488	49	2	D:\LONEOS\wd
step_3.btm	504	56	3	D:\LONEOS\wd
add_wcs_42_1.py	556	350	4	D:\LONEOS\wd_1a\
add_wcs_42_2.py	562	350	4	D:\LONEOS\wd_2a\
create_label_42.py	611	376	5	D:\LONEOS\wd_1a\
create_label_42.py	622		5	D:\LONEOS\wd_2a\
step_6-7.btm	138	682	6-7	D:\LONEOS\wd

"Called in Line" is the line in create_pds_files_xx.sh from which the indicated code is called. "No. Lines" is the number of code lines, including comments, in the script on that line. Both "Called in Line" and "No. Lines" values are approximate as they vary when comment lines are added or removed, or minor changes are made for other LOIS versions other than 4.2.0 used here as an example.

"Step" is the step within the pipeline from which that code is run.

"Location" is the directory from which that script is, and must be, run and wd stands for "working directory".

When create_pds_files_xx.sh is run, all images to be processed are in D:\LONEOS\wd_1. As the pipeline runs, files are written to and read from the subdirectories in \wd. Then, after the last step, which packages the output to be sent to the PDS/SBN and places it in the appropriate output directories (described in loneos_archive_directory_structure.pdf), any remaining files created by the pipeline in those \wd subdirectories are deleted which makes the directories available for processing the next night's images.

The line numbers under the "Called in Line" column are approximate as the code for the various LOIS versions (xx) differ by a few lines from version to version.

All processing performed under this project was done using Windows PCs running Microsoft Windows 11 Pro x64. Where a Windows program was unavailable, or not as efficient, a Linux version was used running Ubuntu under Microsoft Windows Subsystem for Linux (WSL2) and both Windows and Linux versions of PowerShell and Python were used.

At the conclusion of the project, all source code, with associated documentation sufficient to enable use of the code, for software developed for this program (including that created pre-award) will be made publicly available via the planetary science section of GitHub because the PDS does not allow software source code to be archived. However, NASA requires that software developed under its support be deposited in the planetary science section of GitHub (https://github.com/NASA-Planetary-Science). Thus, if you wish to see the source codes referred to in the table above you will need to go to this (still to be created at the time of this writing) GitHub depository.