LONEOS Processing Details

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Abstract

This document describes how Flexible Image Transport System (FITS[1]) images containing pre-scan and/or overscan columns, obtained with the Lowell Observatory Near-Earth Object Survey (LONEOS) telescope were converted to archivable images.

The archivable images were created by cropping out the original image's pre-scan and/or overscan columns and writing World Coordinate System (WCS) information, and other relevant keywords, into the headers of these cropped images which are referred to herein as "augmented" images. These original and augmented images, and their labels containing metadata on each image, were then delivered to the Planetary Data System's Small Bodies Node (PDS/SBN) to be archived as the LONEOS Archive V2.0.

The LONEOS Archive described in this document contains all archivable images[2] obtained during the LONEOS and Near-Earth Asteroid Photometric Survey (NEAPS) projects, *i.e.*, all archivable images we received that were obtained between 1998/02/26 and 2000/01/11 (LONEOS-I), 2000/02/04 and 2008/03/01 (LONEOS-II), and 2010/01/04 – 2011/06/16 (NEAPS), inclusive. For details on the sources of these images see loneos_data_acquisition.pdf[3].

Due to numerous issues with the original images many of them could not be converted to augmented images. And, as presented in loneos_augmented_images_validation.pdf, even the best augmented images have poor whole-image astrometric solutions. Nevertheless, the archived augmented images will be 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, published photometry has been obtained using some of these images. (See §4.2. Photometry.)

1. Introduction

LONEOS Archive V2.0 consists of three directories: …/data_augmented/, …/data_original/, and …/document/. The two data directories have subdirectories in chronological order grouped by their Lowell Observatory Imaging Software (LOIS) version, the software used to read out the CCD and write the image from each exposure to a hard disk drive (HDD). The separation by LOIS is due to each of the seven LOIS versions having its own image header structure and therefore requiring its own version of the scripts required to read them. The …/document/ directory contains all the documents describing the archive's creation and content, *e.g.*, the document you are now reading.

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

2. Processing

[1] A data file in FITS format (Wells, Greisen, and Harten, 1981; Ponz, Thompson, and Munoz, 1994) consists of a series of Header Data Units (HDUs), each containing two components: an ASCII text header and the binary data. The header contains a series of header keywords that describe the data in a particular HDU and the data component immediately follows the header. (https://fits.gsfc.nasa.gov/)

[2] An "archivable image" is one that was not corrupt and that had a date / time in its header. All dates herein are those for which I found images on the media received from the Lowell Observatory. However, this is only a subset of the images obtained in the LONEOS and NEAPS programs as indicated by the paucity of LONEOS images from 2002 and 2005, and Skiff, *et al's*. (2012) mention of NEAPS observations obtained between "2008 May through 2008 December" and the absence of such images in that date range among the images received.

[3] Text in underlined blue are links to external documents which have a Digital Object Identification (DOI), primarily refereed papers (although not all refereed papers have a DOI). Text in underlined green are links to places within this document. Where I simply wish to show the source for the material cited, I provide the URL (Uniform Resource Locator, also called a web address) 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 actual URL (because the PDS does not permit using non-permanent URLs, even to documents in the same PDS directory as the document containing the URL). These "pseudo-URLs" are in orange.

LONEOS Processing Details

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 HDDs are digital copies of the images written by the camera to a disk drive immediately following the exposure. A correctly created .tar or .tar.gz[4] file is essentially equivalent to this.

However, the files received on magnetic tapes could not simply be read from them due to their poor condition and, possibly, errors when the .tar or .tar.gz files were created on the tapes. See loneos_data_acquisition.pdf, §3, for information on how the FITS images on tapes were acquired and Table 2 therein for a summary of the FITS files found on those tapes. Appendix I, below, describes how these acquired "original data" files, from the Lowell Observatory HDDs and tapes were stored when they arrived at the Planetary Science Institute (PSI) and how the images were obtained from the tapes.

Below is a flowchart describing how the LONEOS images from the "original, unmodified" LONEOS images were processed into PDS4 compliant data products.

LONEOS Images Processing Flowchart

As discussed in more detail in Appendix II, 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 Python (.py) were used. Windows PowerShell (.ps1) and Linux and Windows batch scripts (.sh and .btm, respectively) were also used.

2.1 Processing Steps

1) Identify Images to Include

The available images had seven different LOIS versions (see Table 1 in Appendix II), the latest being from LOIS version 4.2.0. Thus, LOIS 4.2.0 images 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 this assumption proved false.

Another unanticipated step that proved necessary, and that had to be done manually, was to visually examine every original image to detect, and remove, corrupt images such as the example in Fig. 1. This was done using IrfanView 64 Thumbnails[5]. Fig. 1 gives an example of its display showing a corrupt image.

[4] "tar" stands for "tape archive" and is a file format used to archive, and losslessly compress multiple files and/or directories into a single .tar file. A compressed tar file is created using the Linux gzip (short for GNU Zip) command and typically appends ".gz" to the .tar extension, hence, creating a "*.tar.gz" file.

[5] https://www.irfanview.com/64bit.htm

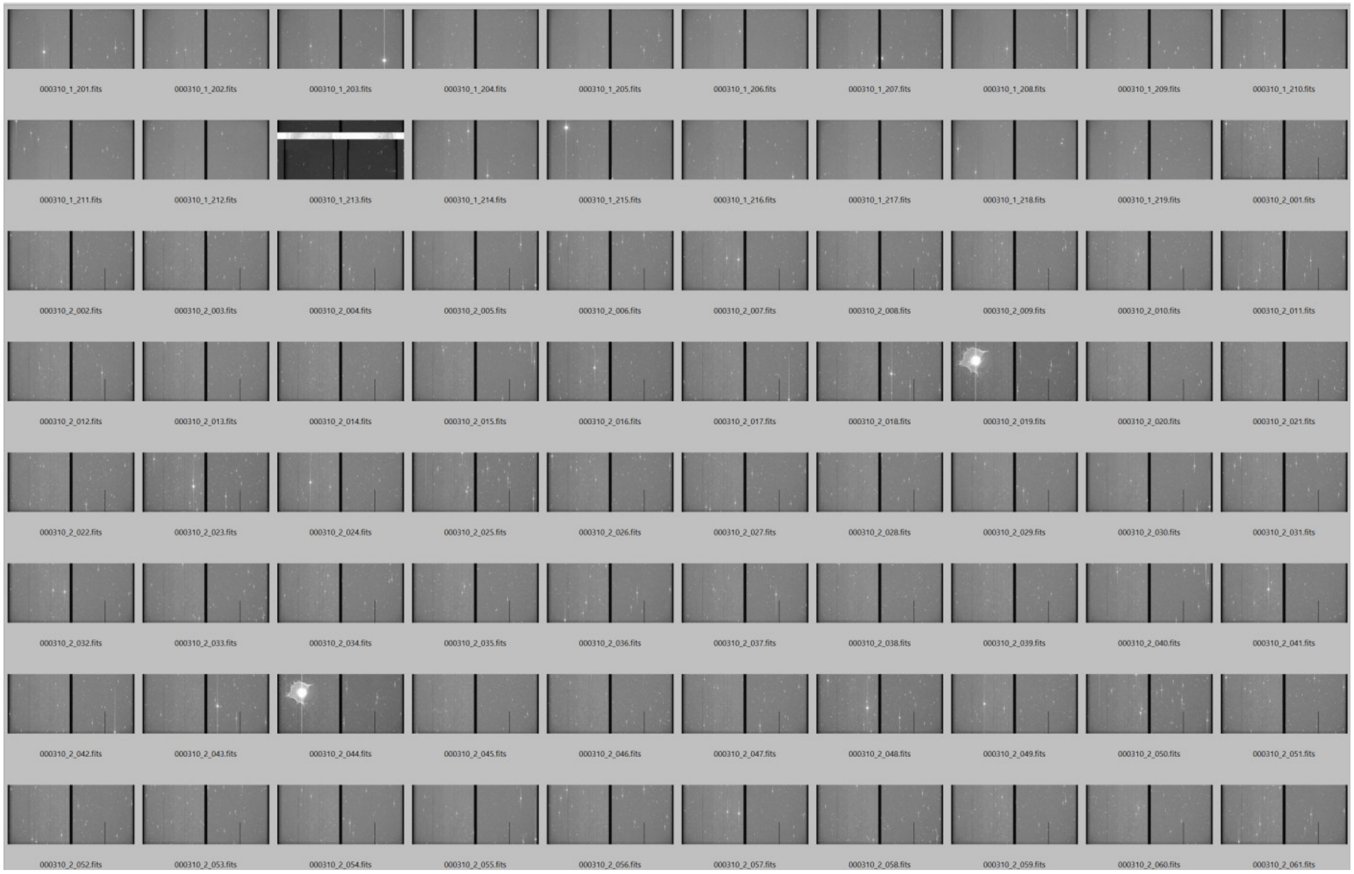


Fig. 1. IrfanView 64 Thumbnails display of 80 original images from night 000310.

Corrupt images were deleted before running the pipeline. However, despite this culling, the pipeline would still occasionally crash or output incorrect labels due to missing or incorrect keywords or their values in some night's images. More insidious were cases where poor-quality images, not detectable using IrfanView, made it through the pipeline. Examples of these include images that show trailed sources or double sources. If the image contained a bright enough star the trailed sources could be detected but images with double sources could only be detected when examined at a larger scale. Fig. 2 shows an example of double-source images.

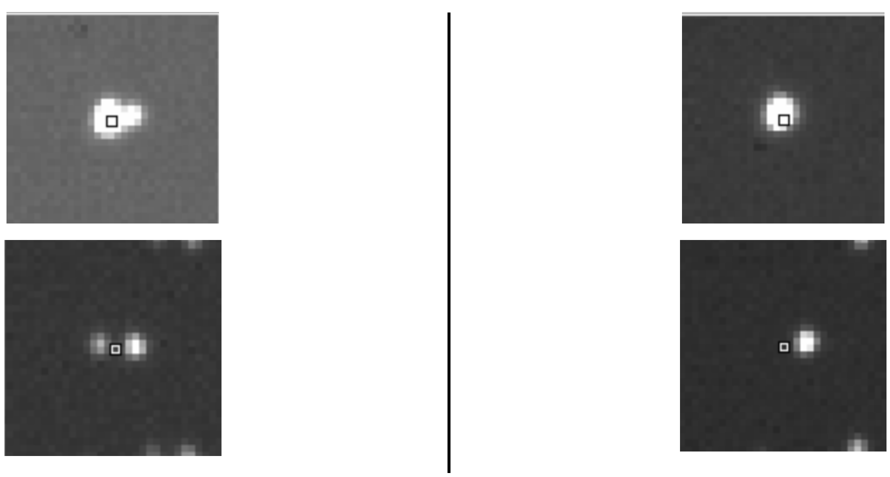


Fig. 2. 981015_013.fits (top) / 981015_022.fits (bottom) 981015_071.fits (top) / 981015_072.fits (bottom)

Fig. 2 shows images 981015_013.fits and 981015_022.fits appear double while 981015_071.fits 981015_022.fits, both of the same fields, are single. This is likely due to the telescope having been bumped or buffeted by wind during the exposure.

Table 1. Calibration Results for Images 981015_013.fits and 981015_071.fits

UT	01:56:37.00	UT	03:41:49.00
Center (RA, Dec):	(347.959, 9.460)	Center (RA, Dec):	(347.961, 9.451)
Center (RA, hms):	23h 11m 50.183s	Center (RA, hms):	23h 11m 50.626s
Center (Dec, dms):	+09° 27' 35.987"	Center (Dec, dms):	+09° 27’ 02.886”
Size:	1.63 x 3.22 deg	Size:	1.63 x 3.23 deg
Radius:	1.807 deg	Radius:	1.808 deg
Pixel scale:	2.8 arcsec/pixel	Pixel scale:	2.8 arcsec/pixel
Orientation:	Up is -179.9° E of N	Orientation:	Up is -180.0° E of N
981015_013.fits		981015_071.fits	

Table 1 shows the Astrometry.net calibrations for the same field - one with a double image (981015_013.fits) and then with a single image (981015_071.fits), *cf.*, Fig. 2. The images in Fig. 2 are from the LONEOS-I camera but this same issue was present in images obtained with the LONEOS-II camera.

There were also images with nominal exposure times but all of whose pixel values were essentially the same, perhaps due to a cloud, and in which few, if any, stars could be seen.

The NEAPS images were obtained for a different purpose than for the LONEOS-I and LONEOS-II programs. As its name (Near-Earth Asteroid Photometric Survey) implies, rather than image a large area of sky with each targeted field being imaged three or four times each night, it observed a small number of fields (one for each asteroid it was observing to obtain its lightcurve) many times during the night.

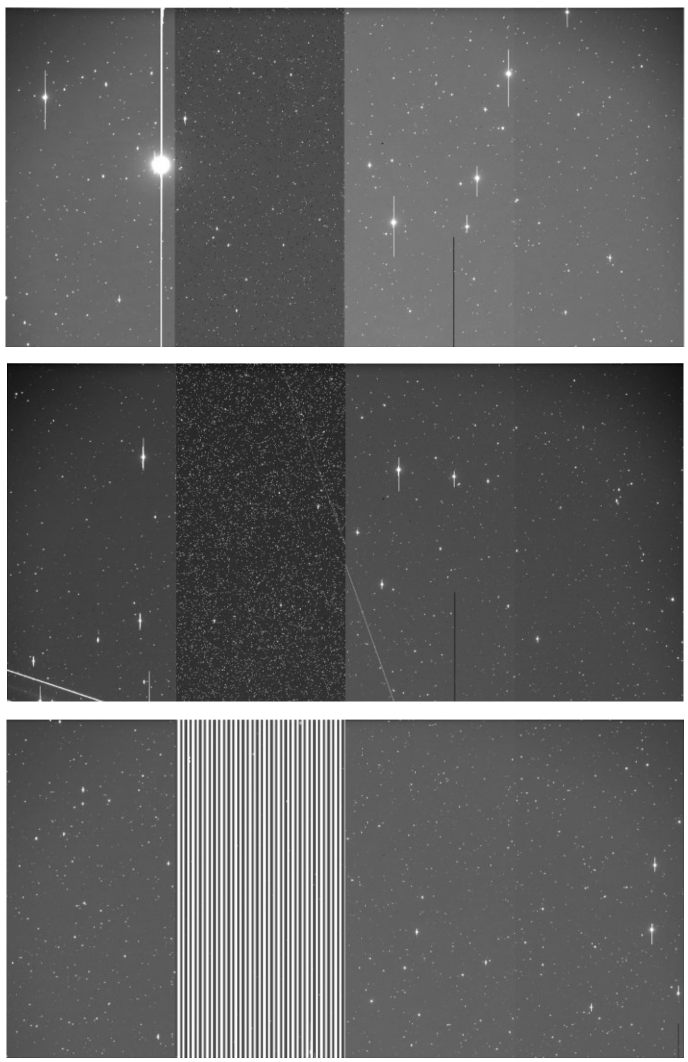


Fig. 3. Typical augmented images for nights 100601 (top), 100707 (middle), and 100715 (bottom).

The other major difference with the LONEOS programs was that, although NEAPS used the LONEOS-II camera and LOIS 4.2.0, the CCDs were degrading, as shown in Fig. 3. NEAPS images are available between 2010/01/04 – 2011/06/16 but, as can be seen in Fig. 3, beginning on 2010/06/01 band 2 (counting E to W, left-to-right in these images) is ratty, although perhaps still useable. However, the images degrade rapidly after this being barely useable by 2010/07/07 and by 2010/07/15 (the next available night) band 2 is useless. By 100715 the augmented image's columns 2050 through 3070 (band 2) in both the _1 and _2 CCDs are dead, where dead means they alternate between low values (the black columns, with values ~1,000) to saturated (the white columns, with values of 65,536). Nevertheless, the other three bands continue to be useful.

2) Rename Files using Python Script create_ccdfnames_xx.py or PowerShell script Rename_LONEOS_Files.ps1

Most utilities, functions, subroutines, and scripts running under the Linux, Unix, Mac, and Windows operating systems (OS) recognize a FITS file *via* its filename's extension, generally "fts" or "fits".

Images obtained using the LONEOS-I camera[6] between 1998/02/26 and 2000/01/11 were written to the camera's HDD using the format YYYYMMDDnnnnb.fits, *e.g.*, 199804250204b.fits, where nnnn was the night's exposure number, referred to in their headers as keyword CCDPICNO, meaning "running sequence number". The meaning of b is unknown. Unfortunately, these images' headers contain neither a filename nor a LOIS keyword. Hence, I assigned all LONEOS-I images the LOIS keyword value lois_none.

All the LONEOS-I images we received were on 38 tapes. 21 of these (the _C tapes) contained 9,132 images in the YYYYMMDDnnnnb.fits format with an additional 1,703 images in YYYYMMDDnnnnb.fits.gz format.

The filename for files with this format could trivially be renamed, *e.g.*, to 980425_204.fits However, available files using this filename format were the exception because all LONEOS-I images were received on tape and only a few could be directly read from the tapes (the _C tapes).

Most LONEOS-I images were extracted from the _CR tapes in the f-format[7] using the recovery method described in Appendix I.

The LONEOS-II two Charged-Couple Device (CCD) camera, used for files obtained in the LONEOS-II and NEAPS programs (2000/02/04 and 2008/03/01 and 2010/01/04 – 2011/06/16), wrote the images obtained to HDD using a format of YYMMDD_#.nnn, where YYMMDD is a two-digit Year, Month, and Day, # is 1 or 2 for an exposure's northern CCD and southern CCD images, and nnn is the exposure number for the given date (a value between 001 and 999).

Due to limitations in Windows' OS, renaming files with filenames ending in .xxx is not straightforward as the OS assumes the xxx 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.).* Hence, a PowerShell script renames the original LONEOS-II image filenames (*i.e.*, YYMMDD_#.nnn) to the YYMMDD_#_nnn.fits format used for this archive.

create_ccdfnames_xx.py writes recovered filenames and their CCDFNAMEs for ALL *.fits files in the executing directory to a file named rename_fimages.btm. There are variants of create_ccdfnames_xx.py for f-formatted images with headers having various numbers of lines and with single- and double-spaced headers.

rename_fimages.btm is a batch file with the recovered f-formatted filenames and the filenames constructed from their headers. There is one line for each f-formatted file in the executing directory. A typical line is:

```
REN f0000001.fits 000326_1_001.fits
```

Thus, when this Windows batch file is run it renames each f-formatted image in the executing directory to the YYMMDD_#_nnn.fits format used for this archive.

6 For additional details on the telescope and cameras see §3 in loneos_project_description.pdf

7 The format, *e.g.*, f123456789.fits, Datarecovery.com, Inc.® (DR) used for images it recovered from tapes that could not be read using normal tape-reading tools.

See footnote a to Appendix I for additional information on the types of source-specific (*i.e.*, HDD or tape) directories created for each night and on how the images for input into the pipelines were recovered from the tapes.

3) Crop

LONEOS exposures obtained with the LONEOS-I one-CCD camera[8] (*i.e.*, all images obtained between 1998/02/26 and 2000/01/11) were saved to a 1.63° x 3.22° FITS image. These original images, obtained in formats YYYYMMDDnnnnb.fits, *e.g.*, 199804250204b.fits, or as recovered f-formatted images, were renamed to the LONEOS Archive's standard YYMMDD_nnn.fits format as described in §2. See Fig. 4, a DS9[9] display of 980425_204.fits, for what one of these images looked like. Note the dark rows on the north edge and the dark columns on the east edge. These are overscan rows and columns. There is also slight vignetting in the NW and SW corners. No bias frames were found for LONEOS-I images.

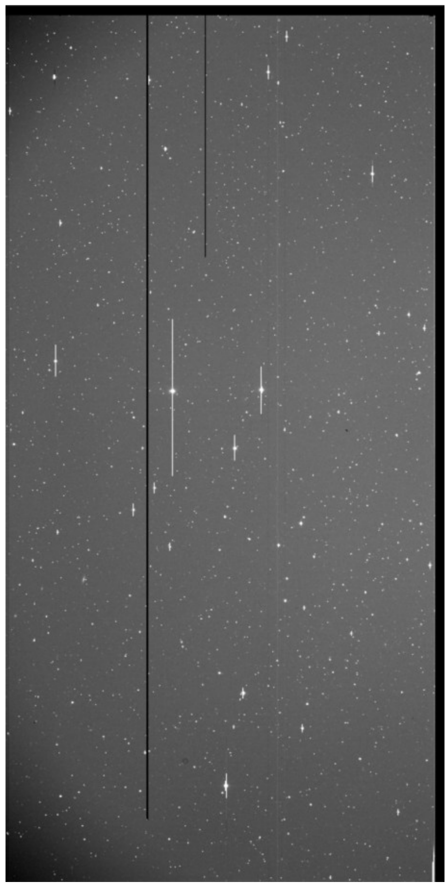


Fig. 4. DS9 display of 980425_204.fits
(North up, East to the right).

Every LONEOS and NEAPS (2000/02/04 and 2008/03/01 and 2010/01/04 – 2011/06/16) exposure obtained with the LONEOS-II two-CCD camera was saved to two 3.08°x1.44° files: the northern half of the image used a filename containing _1 and the southern half containing _2. These original images, obtained in formats YYMMDD_#.nnn, *e.g.*, 051113_1.014 and 051113_2.014, or as recovered f-formatted images, were renamed to the LONEOS Archive's standard YYMMDD_#_nnn.fits format as described in §2. See Fig. 5, a DS9 display of 051113_1_014.fits and 051113_2_014.fits, for what one of these exposure image pairs looked like.

[8] See loneos_project_description.pdf §3.b for a description of the two cameras used in the LONEOS program.

[9] SAOImage DS9 is an astronomical imaging and data visualization application. DS9 supports FITS images and is available from https://sites.google.com/cfa.harvard.edu/saoimageDS9 The latest version used in this work was v8.4.1

Note the dark rows on both the east and west edges. These are overscan columns. Also note that each image is divided into four rectangular east-to-west by north-to-south segments, a consequence of each CCD being read out using four different amplifiers, the vignetting in the corners, and the numerous defects, primarily dark full-height and partial-height columns. To see this better open the images in DS9, set Zoom → Invert Y, and vary the stretch.

Except for the _1 and _2 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 3.08°x1.44° files into a single 3.08°x3.08° 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.

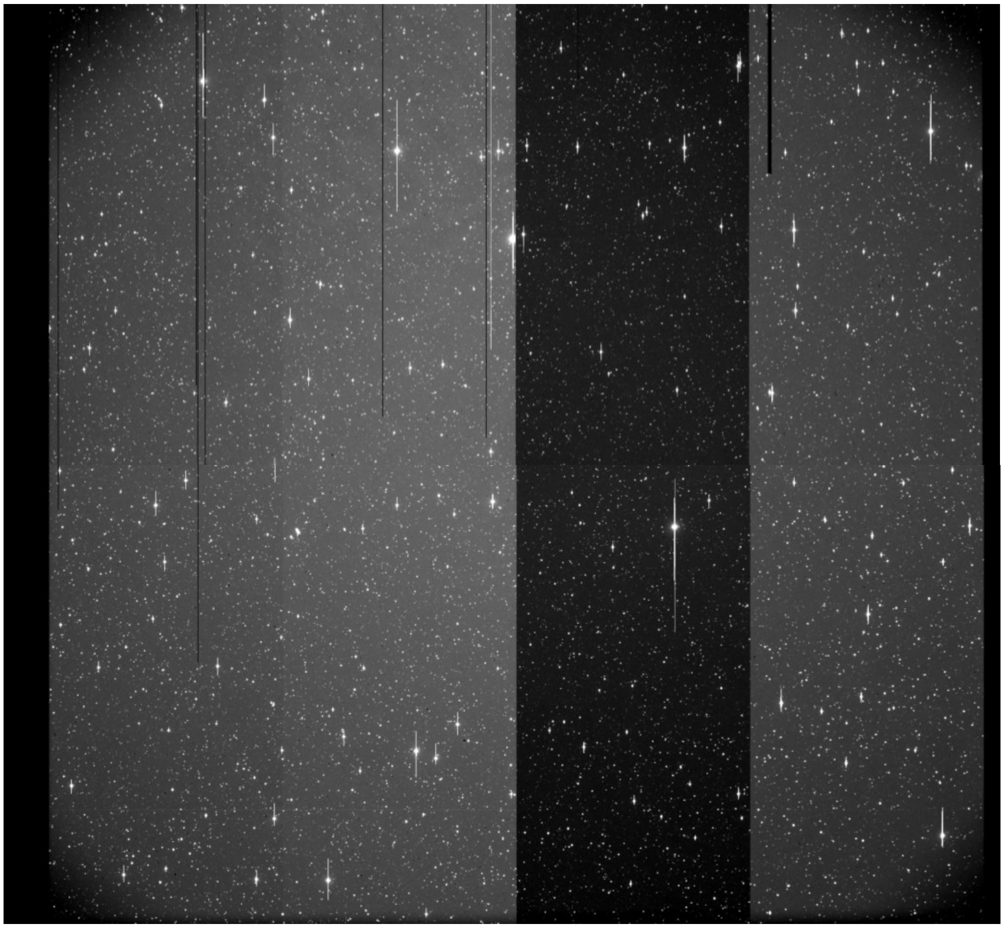


Fig. 5. DS9 display of 051113_1_014.fits (top) and 051113_2_014.fits (bottom). Both North up, East to the right.

On most nights the first 10 or so exposures 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_*/YYMMDD directory as is. (lois_none nights had no bias images.)

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

a. The images contain overscan columns which lead to incorrect WCS values, *i.e.,* the Astronomical Equatorial Right Ascensions (RAs) are incorrect. (See Appendix IV.)

To remove the overscan columns, I cropped each sky image using ImageMagick[10]**,** where the width and height of the crop rectangle and the x and y coordinates of the top left corner of the image must

[10] https://imagemagick.org

be specified. The commands are then, for the LONEOS-I camera's images:

```
magick Merged_Image.fits -crop 2046x4096+2+50 Merged-Cropped_Image.fits
```

which results in a 1.59°x3.19° augmented image.

and for the LONEOS-II camera's images:

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

which results in a 2.88°x1.44° augmented image.

b. 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 LONEOS-I (lois_none) images (values below from 199901130003b.fits = 990113_003.fits) the keyword and values are:

```
CTYPE1  = 'RA---TAN'
CTYPE2  = 'DEC--TAN'
CRPIX1  =             1258.400024
CRPIX2  =             2139.800049
LONPOLE =               180.0 Assigned in script add_wcs_none.py
LATPOLE =                 0.0 Assigned in script add_wcs_none.py
CRVAL1  =          200.953330 From 990113_003.fits header
CRVAL2  =           -9.472500 From 990113_003.fits header
CD1_1   =            1.000000 From 990113_003.fits header keyword PC001001
CD1_2   =           -0.000000 From 990113_003.fits header keyword PC001002
CD2_1   =            0.000000 From 990113_003.fits header keyword PC002001
CD2_2   =            1.000000 From 990113_003.fits header keyword PC002002
```

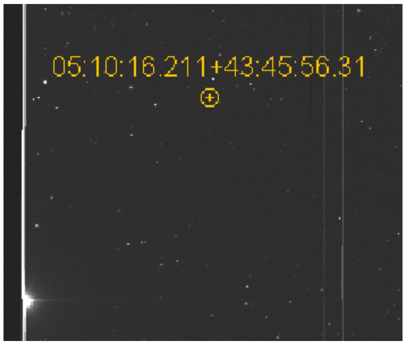
All the lois_none images (from 1998/02/26 through 2000/01/11) have WCS information, however, the WCS coordinates in these images are useless.

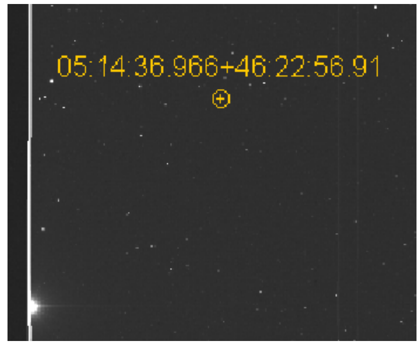
Fig. 6 is a portion of 199901130003b.fits using the header embedded (LONEOS-I) WCS coordinates and those from the image with WCS coordinates embedded by Astrometry.net comparing the coordinates of a random field star. The difference in the coordinates (Astrometry.net – LONEOS-I) is ΔRA = +04^{m}:20.75^{s} (+1.09°) and ΔDec = +2°37' (+2.62°). I found differences of this order for all the LONEOS-I camera (lois_none) images I examined.

For LONEOS-II and NEAPS images, *i.e.*, all LOIS versions except lois_none, the values of these keywords (in this example, from 051113_1_011.fits) 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
```





LONEOS Header Embedded   Astrometry.net

Fig. 6. LONEOS header embedded WCS coordinates vs. Astrometry.net coordinates for 199901130003b.fits and their coordinates for a random field star. The bright star at the lower left is Capella and the bright area to its left is the overscan column.

Except for CRVAL1 and CRVAL2, which are unique to each LONEOS-II camera's image-pair and which can be obtained from either uncropped original 3.08°x1.44° image (_1 or _2) and entered as decimal degrees[11], the remaining WCS keywords and their values are the same for all image pairs. 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), *i.e.*, the center of the image.

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[12])

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-II 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_N.py and add_wcs_N_#.py (where N = an abbreviation of the image's LOIS, *i.e.*, 11, 132, 133, 20, 32, 42, and # = _1 or _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. Because images on numerous nights have different headers with their own unique number of (single- or double-spaced) lines (aka "cards"), keywords, and values, there are multiple versions of create_hdr_N.py and add_wcs_N.py.

[11] 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.

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

i) 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

ii) 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 V 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 augmented (*i.e.*, WCS) LONEOS 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.

A similar script 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 all LOIS versions.

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

As noted in §2.1.3, not every night has bias files; most have 10, others have a smaller or larger number, and some have none, or bias frames at both the beginning and end of the night, or bias frames at some random time during the night. The number of _1 and _2 files should always be the same, since for every exposure the LONEOS-II 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 or have a corrupt 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 (some nights had only _2 images but no nights had only _1 images) or 2) the images were present among the files we received but were corrupt or unusable for some reason (*e.g.*, lacking a necessary keyword, like the time of the exposure or the coordinates of where it pointed).

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 the LONEOS Images Processing Flowchart, above and Appendix II) 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 scripts, primarily those in Steps 4 and 5. For these reasons, each script'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 script that produced the incorrect output, writing a new script 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 script 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. Once all liens were addressed to the satisfaction of the panel and PDS personnel, the PDS4 LONEOS Archive V2.0 was finalized and released.

3. Validation

See loneos_augmented_images_validation.pdf

4. Conclusions

4.1. 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 - https://catch.astro.umd.edu/) 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 of them. If it was, then its coordinates could be measured, potentially extending its observational arc back to the end of the 1900s or early 2000s, hence, extending that object's discovery orbital arc by 15- to 30-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.

4.2. Photometry

Differential (lightcurves) and even some absolute photometry have been obtained from LONEOS-I (Miceli, *et al*. (2008) and NEAPS images (Koehn, *et a*l. 2014; Skiff, *et al*. (2012, 2019a, and 2019b). 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 primarily because Skiff, *et al*. and Koehn, *et al*. had flat field images available, which images in this archive 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 LONEOS-I 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 all non-lois_none images to allow for errors of this order in the archived positions of each image's corners.

lois_none images Dec centers should include at least a ±1° buffer but their RA buffer should be on the order of ±2.5°. See loneos_augmented_images_validation.pdf for more on the lois_none images. It is recommended that none of the presently archived lois_none images be used as input to CATCH. However, if one wishes to search a lois_image for a possible precovery image this can be done provided the image has its embedded WCS keywords replaced with those determined using Astrometry.net

Although many of the augmented non-lois_none 2.88°x1.44° images have issues, with care accurate positions for sources, even those near or adjacent to a dead column, can be extracted.

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 challenging. (One of the Archive V1.0 reviewers asked that it be emphasized that measuring photometry was strongly discouraged.)

The DATE keyword in the FITS image headers for the original LOIS 3.2.0.beta images are in YYYY-DD-MM format. However, they have the correct, YYYY-MM-DD, format in the .xml labels.

Many nights have missing images. This is due to a variety of reasons, *e.g.*, the image was not among those we received, was corrupt, was underexposed or overexposed such that no stars could be seen, was trailed, *etc*.

Issues presented in §2.1.1 mean that some of the images in the archive are likely to have trailed or double images or brighter than nominal limiting magnitudes.

6. References

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Wells, D.C., Greisen, E.W., Harten, R.H., 1981. FITS - a Flexible Image Transport System. Astronomy and Astrophysics Supplement, Vol. 44, p. 363. Bibscript: 1981A&AS...44..363W https://articles.adsabs.harvard.edu/pdf/1981A%26AS...44..363W

LONEOS Processing Details

Appendix I. The "Original, Unmodified, LONEOS Data"[a]

Directory	Size	Contents
DataRecovery	**4.27 TB**	**The files recovered from the tapes. (See Table 2 in loneos_data_acquisition.pdf)**
/000000_CR	266 MB	15 images from 1997/10/27 to 1998/02/26
/000001_C	27.5 GB	205 images from 1998/04/25
/000002_CR	764 MB	22 images from 1998/05/25
/000003_C	3.02 GB	187 images from 1998/06/22
/000004_C	2.92 GB	180 images from 1998/07/02
/000005_C	382 MB	23 images from 1998/07/31
/000006_CR	34.6 GB	136 images from 1998/08/26 & 16GB 000006.img
/000007_CR	14.5 GB	298 images from 1998/09/18 + 5GB 000007.img
/000008_CR	52.5 GB	251 images from 1998/09/26 + 24GB 000008.img
/000009_CR	42.1 GB	317 images from 1998/10/11 + 18GB 000009.img
/000010_CR	50.9 GB	155 images from 1998/10/15 + 24GB 000010.img
/000011_CR	24.2 GB	1,492 images from 1998/10/15 to 1998/10/19
/000012_CR	48.4 GB	1,473 images (f49042076.fits) from 1998/11/14-20
/000013_CR	53.0 GB	1,488 images (f0000003.fits) from 1998/11/23 to 1998/12/01 + 24GB 000013.img
/000014_C	8.24 MB	1 image from 1998/12/09 + 4MB 000014.img
/000015_CR	51.9 GB	1,485 images (f0000040.fits) from 1998/12/09 to 1998/12/17
/000016_CR	49.5 GB	1,496 images (f0000002.fits) from 1998/12/23 to 1998/12/30
/000017_CR	48.1 GB	1,466 images (f0000002.fits) from 1999/01/02 to 1999/01/09
/000018_CR	53.9 GB	1,486 images (f0000429.fits) from 1999/01/13 to 1999/01/22
/000019_CR	50.7 GB	1,468 images (f0000146.fits) from 1999/01/30 to 1999/02/12
/000025_CR	4.19 GB	86 images (f0000049.fits) from 1999/05/13
/000026_C	2.90 GB	176 images from 1999/05/24
/000027_C	19.8 GB	214 images from 1999/06/13
/000028_C	26.8 GB	161 images from 1999/06/30
/000029_C	28.3 GB	252 images from 1999/08/07 + 24GB 000029.img
/000030_C	24.6 GB	24 images from 1999/09/06 + 24GB 000030.img
/000031_C	24.3 GB	21 images from 1999/09/21 + 24GB 000031.img
/000032_C	51.5 GB	1,484 images (f0000063.fits) from 1999/09/30 to 1999/10/04
/000033_C	29.6 GB	328 images from 1999/10/06 + 24GB 000033.img
/000034_C	29.2 GB	326 images from 1999/10/13 + 24GB 000034.img
/000035_C	47.9 GB	326 images from 1999/10/25 + 24GB 000035.img.repaired with 1,461 images
/000036_C	48.5 GB	1,489 images from 1999/10/28-11/01 + 24GB 000036.img
/000037_C	32.4 GB	337 .gz images from 1999/11/04 + 29GB 0000376.img
/000038_C	65.7 GB	2,550 "images" from 1999/11/14-17, 1999/11/19-26 +33GB 000038.img
/000039_C	975 MB	59 images from 1999/12/07 +1 ASCII file
/000040_C	65.7 GB	2,009 .fits images from 1999/12/07-17 +33GB 000040.img +49 ASCII files
/000041_CR	93.8 GB	2,028 .fits images from 1999/12/21 - 2000/01/05 +31GB 000041.img
/000042_C	46.7 GB	1,432 .fits images from 2000/01/07-11 +23GB 000042.img
/000043_CR	68.7 GB	2,026 images from 2000/01/04-25 +33GB 000043.img & recovered
/000044_CR	69.2 GB	2,030 images from 2000/01/26-03/04 +33GB 000044.img & recovered
/000045_CR	36.9 GB	2,020 images from 2000/01/29-03/12 +33GB recovered directory
/000046_CR	36.6 GB	2,027 images from 2000/03/13-26 in dir recovered
/000047_CR	29.0 GB	1,302 images from 2000/03/26-27 & 5 from 2001/01/02 in 21GB dir recovered +1 ASCII file
/000048_CR	67.0 GB	2,026 images from 2000/03/26-2000/04/04 in 33GB .img & dir recovered
/000049_CR	66.4 GB	2,001 images from 2000/04/04-2000/04/08 in 33GB .img & dir recovered
/000050_CR	33.1 GB	2,001 images from 2000/04/09-2000/04/13 in dirs 1, 2, 3, 4, and 5
/000051_CR	33.6 GB	2,026 images from 2000/04/14-2000/04/27 in 33GB dir recovered
/000052_CR	9.90 GB	579 images from 2000/04/27-2000/04/30 in 9.5GB dir recovered
/000053_CR	19.3 GB	1,168 images from 2000/05/01-2000/05/04 in 19GB dir recovered
/000054_CR	25.4 GB	1,544 images from 2000/05/05 in 25GB dir recovered
/000055_C	33.5 GB	16 images from 2000/05/11 +33GB .img file with dates from 2000/05/11-17
/55_56_58_59_recovered_only	133 GB	8,086 f-formatted images from 2000-05-11 to 2000-06-07 (in dirs 1-17)
/000056_C	33.3 GB	13 images from 2000/05/22 +33GB .img file with dates from 2000/05/22-25
000057_ERR	Empty	
/000058_C	33.7 GB	25 images from 2000/05/30 +33MB .img file with dates from 2000/05/30-06/03

LONEOS Processing Details

Directory	Size	Contents
/000059_C	33.3 GB	10 images from 2000/06/04 +33MB .img file with dates from 2000/06/04-07
/000066_CR	14.7 GB	894 images from 2000/09/22-25 in 15GB dir recovered
/000067_CR	36.1 GB	171 images from 2000/09/04-10 in 3GB dir recovered +33GB .img file with dates from 2000/09/04-10
/000068_CR	6.20 GB	374 images from 2000/09/22-25 in 6GB dir recovered
/000069_CR	43.8 GB	645 images from 2000/09/26-29 in 11GB dir recovered +33GB corrupt .img file
/000070_CR	Empty	(Actually, one 512 byte .img file)
/000071_CR	66.6 GB	2,017 images from 2000/10/03-18 in 33GB dir recovered +33GB .img file with same dates
/000072_CR	36.1 GB	1,092 images from 2000/10/26-11/14 in 18GB dir recovered +18GB .img file with same dates
/000073_ERR – /000075_ERR	Empty	
/000076_CR	20.0 GB	1,214 images from 2000/11/25-30 in 20GB dir recovered
/000077_CR	65.0 GB	1,926 images from 2000/11/30-12/17 in 32GB dir recovered +33GB .img file with same dates
/000078_CR	53.7 GB	1,253 images from 2000/12/18 in 21GB dir recovered +33GB .img file with same dates
/000079_CR	43.1 GB	1,137 images from 2000/12/22-24 in 19GB dir recovered +24GB .img file with same dates
/000080_CR	66.3 GB	2,004 images all from 2000/12/24 in 33GB dir recovered +33GB .img file with same dates
/000081_CR	56.7 GB	1,391 images +55 from 2000/12/27-29 in 24GB dir recovered
/000082_CR	38.5 GB	290 images +11 from 2000/12/30-31 in 5GB dir recovered
/000083_CR	42.0 GB	508 images from 2001/01/02-04 in 8GB dir recovered
/000084_CR	66.6 GB	2,016 images from 2001/01/04-21 in 33GB dir recovered
/000085_CR	45.0 GB	671 images from 2001/01/26-02/12 in 11GB dir recovered
/000086_ERR	Empty	
/000087_C	33.4 GB	10 .fits BIAS images from 2001/02/21 +33GB .img file
/87_thru_103_recovered_only	307 GB	18,727 images from 2001/02/21-06/17 (in dirs 1 - 38)
/000088_C	33.5 GB	17 images from 2001/03/13 +33GB .img file with dates from 2001/03/13-18
/000089_ERR	Empty	
/000090_C	33.4 GB	10 BIAS images from 2001/03/23 +33GB .img file with dates from 2001/03/23-25
/000091_C	29.4 GB	10 images from 2001/03/25 +29GB .img file with dates from 2001/03/25-29
/000092_C	33.6 GB	23 images from 2001/03/29 +29GB .img file with dates from 2001/03/29-31
/000093_C	33.1 GB	1 image from 2001/04/01 +33GB .img file with dates from 2001/04/01-15
/000094_C	32.6 GB	1 image from 2001/04/16 +33GB .img file with dates from 2001/04/16-25
/000095_C	25.4 GB	1 image from 2001/04/25 +25GB .img file with dates from 2001/04/25-29
/000096_ERR	Empty	
/000097_C	32.9 GB	14 images from 2001/05/15 +32GB .img file with dates from 2001/05/15-23
/000098_C	33.1 GB	14 images from 2001/05/23 +32GB .img file with dates from 2001/05/23-26
/000099_C	33.3 GB	10 BIAS images from 2001/05/27 +33GB .img file with dates from 2001/05/27-06/01
/000100	118 MB	7 images from 2001/06/02
/000101	5.57 GB	1 image from 2001/06/11 +5.6GB .img file with dates from 2001/06/11
/000102_ERR	Empty	
/000103	168 MB	10 BIAS images from 2001/06/14
/000104_CR	7.47 GB	452 images from 2001/06/14-06/17 in 7.4GB dir 1 Including ~27 BIAS frames
/000105	16.8 MB	1 image from 2001/06/19
/0000106	353 MB	21 images from 2001/07/17
/000106_ERR	Empty	
/0000107	101 MB	6 BIAS images from 2001/07/21
/000108_CR	33.3 GB	2,012 images from 2001/07/27-08/18 in 33GB dir recovered
/000109_ERR	Empty	
/000110_CR	29.0 GB	1,754 images from 2001/08/23-08/24 in 29GB dir recovered
/000111	Empty	
/000112_ERR – /000114_ERR	Empty	
/000115_CR	319 MB	6 BIAS images from 2001/09/18 in 100MB dir recovered, et al.
/000116_ERR	Empty	
/000117	764 MB	22 readable images from 2001/09/24 +382MB .img file with same dates
/117_to_146_recovered_only	67.9 GB	4,281 images from 2001/09/24-2002/06/11 (in dirs 1- 9)

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Directory	Size	Contents
/000118	32.6 GB	2 images from 2001/10/12 +33GB .img file with dates from 2001/10/12-2002/03/02
/000119_ERR	Empty	1,214 images from 2000/11/25-30 in 20GB dir recovered
/000120	459 MB	14 images from 2001/10/19 +229MB .img file with same dates
/000121	163 MB	4 images from 2001/10/23 +96MB .img file with 6 images from same date
/000122_ERR	Empty	
/000123_ERR	Empty	
/000124	9.71 GB	15 images from 2001/11/15 +9.4GB .img file with same dates
/000125	192 MB	13 images from 2001/11/16 +96MB .img file with same files
/000126	9.33 GB	10 images from 2001/11/20 +9.2GB .img file with same dates
/000127_ERR – /000145_ERR	Empty	
/000146_C	2.89 GB	A collection of mostly personal directories. No image files. Only the 93 log files (macro.log.19990113 – macro.log.19990628) will be archived.
/000147_CR	27.1 GB	1,646 images from 2002/06/13-2002/07/06 in dirs 1, 2, ... 4
/000148_ERR	Empty	
/000149_C	4.64 GB	A collection of mostly personal directories, plus, a 2.4GB .img file containing the same directories. No image files. No files from this tape will be archived.
/000150_ERR – /000156_ERR	Empty	
/000157_CR	46.7 GB	2,845 images from 2002/12/09-2002/12/28 in dirs 1, 2, ... 12
/000158_CR	60.9 GB	1,566 images from 2002/12/31-2003/01/05 in dirs 1, 2, ... 4 +35GB .img file with same dates
/000159_CR	41.8 GB	1,004 images from 2003/01/05-2003/01/26 in recovered dirs 1, 2, ... 3 +25GB .img file with same dates Crashed EmEditor
/000160_CR	7.11 GB	433 images, incl scores of BIAS files, from 2003/01/26-2003/01/31 in recovered dirs 1, 2, ... 7
/000161_CR	14.2 GB	848 images from 2003/02/01-2003/02/06 in recovered dirs 1, 2 LOISVERS 2.0.0.beta
/000162_CR	77.8 GB	1,822 images from 2003/02/07-2003/02/22 in recovered dirs 1, 2 ... 4 LOISVERS 2.0.0.beta
/000163_CR	42.1 GB	1,040 images from 2003/02/22-2003/03/08 in recovered dirs 1, 2 ... 5 LOISVERS 2.0.0.beta
/000164_CR	61.8 GB	1,571 images from 2003/03/09-2003/03/27 in recovered dirs 1, 2 ... 8 LOISVERS 2.0.0.beta
/000164CR	25.8 GB	Same as 000164_CR sans .img file?
/000165_CR	48.9 GB	2,958 images from 2003/03/27-2003/03/31 in recovered dirs 1, 2 ... 6 LOISVERS 2.0.0.beta
/000166_CR	48.9 GB	2,958 images from 2003/04/01-2003/04/05 in recovered dirs 1, 2 ... 6 LOISVERS 2.0.0.beta
/000167_CR	48.9 GB	2,958 images from 2003/04/07-2003/04/14 in recovered dirs 1, 2 ... 6 LOISVERS 2.0.0.beta
/000168_CR	48.8 GB	2,958 images from 2003/04/15-2003/04/25 in recovered dirs 1, 2 ... 6 LOISVERS 2.0.0.beta
/000169_CR	48.8 GB	2,958 images from 2003/04/26-2003/05/01 in recovered dirs 1, 2 ... 6 LOISVERS 2.0.0.beta
/000170_CR	48.7 GB	2,958 images from 2003/05/05-2003/05/17 in recovered dirs 1, 2 ... 6 LOISVERS 2.0.0.beta
/000171_CR	90.2 GB	2,696 images from 2003/05/20-2003/05/27 in recovered dirs 1, 2 ... 6 LOISVERS 2.0.0.beta
Existing1	**1.46 TB**	**Files copied from the Lowell Observatory's post-program HDD-2 and -3 (See Table 1 in loneos_data_acquisition.pdf)**
/2000	36.7 GB	2000 - month 03
/2003	1.36 TB	2003 - months 04-12
/2004a	904 GB	See Combined 2004, below
/2010a	63.2 GB	2010 - month 08; NEAPS
Existing2	**1.77 TB**	**Files copied from the Lowell Observatory's post-program HDD-2 and -3 (See Table 1 in loneos_data_acquisition.pdf)**
/2004	241 GB	See Combined 2004, below
/2004_RAID	492 GB	See Combined 2004, below
/2010	942 GB	2010 - months 01, 03-10; NEAPS
/2011	876 GB	2011 - months 02-06 NEAPS

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Directory	Size	Contents
Existing3	**2.67 TB**	**Files copied from the Lowell Observatory's post-program HDD-1 (See Table 1 in loneos_data_acquisition.pdf)**
/2005-backup	296 GB	2005 - months 11-12
/2006-backup	1.29 TB	2006 - months 01-10, 12
/2007-backup	994 GB	2007 - months 01-12
/2008-backup	124 GB	2008 - months 01-03
Total:	**10.17 TB**	
Combined 2004	**1.60 TB**	**From directories /2004a on HDD-1 and /2004 and /2004_RAID on HDD-2**
/01	211 GB	Existing1\2004a 17 nights: 01/04 – 01/31
/02	81.3 GB	Existing1\2004a 9 nights: 02/02 – 02/16
/03	131 GB	Existing1\2004a 17 nights: 03/06 – 03/31
/04	139 GB	Existing1\2004a 13 nights: 04/10 – 04/26
/05	170 GB	Existing1\2004a 21 nights: 05/01 – 05/31
/06	172 GB	Existing1\2004a 21 nights: 06/01 – 06/25
/07	79.8 GB	Existing2\2004_RAID 12 nights: 07/01 – 07/30
/08	89.9 GB	Existing2\2004_RAID 10 nights: 08/08 – 08/30
/09	186 GB	Existing2\2004_RAID 16 nights: 09/03 – 09/30
/10	136 GB	Existing2\2004_RAID 12 nights: 10/01 – 10/15
/11	6.42 GB	Existing2\2004 1 night: 11/30
/12	235 GB	Existing2\2004 18 nights: 12/01 – 12/26

[a] Appendix I contains the directory listing of the LONEOS data received from the Lowell Observatory on HDDs and the files extracted by Datarecovery.com, Inc.® (DR) from the magnetic tapes received via the Jet Propulsion Laboratory (JPL) as they were copied onto HDDs at the Planetary Science Institute (PSI) by PDS/SBN member Jesse Stone.

Unfortunately, despite this award's Statement of Work task stating: "*This document*[13] *will describe exactly what original data was obtained and this unmodified original data will be archived under this award*.", the PDS/SBN refused to allow this unmodified original data to be archived at the PDS/SBN. Consequently, after I finish working on the PDS/SBN's LONEOS Archive V2.0 I will attempt to archive the non-personal files, *i.e.*, all those except some directories in 146_C and 149_C, from this original, unmodified dataset (*i.e.*, this Appendix I) at Zenodo. If I succeed in doing this, I will request that the PDS/SBN allow me to update this document to include the Digital Object Identifier (DOI) for this data product once the Zenodo archive has been created.

See loneos_data_acquisition.pdf for how these files were obtained, below for how those obtained on tape were extracted from the tapes by DR, and §2.1.2, above, for how they were renamed for use by the pipelines.

§2. Processing describes what is meant by "original data" in this documentation. In brief, the only truly "original data" are the FITS images written to the LONEOS's HDDs by its cameras. Copies of those to other HDDs, either as individual files or via a .tar archive file should be as good as the original. Directories Existing1, Existing2, and Existing3 contain files of this type[14]. Because data from 2004 was received in three different directories on HDD-1 (/2004a) and HDD-2 (/2004 and 2004_RAID), I copied these to directory Combined 2004 and removed duplicate files while doing so. This is why the size of Combined 2004 is 37 GB smaller than the sum of Existing1/2004a, Existing2/2004, and Existing2/2004_RAID.

The only other year's images received on more than one HDD was 2010. For this year, 6 nights are in Existing1 and 86 nights in Existing2, with no duplicates.

The situation is more complicated for nights whose files were received on tape because, as discussed in loneos_data_acquisition.pdf, they could not be read using normal tape reading utilities. Instead, they were

[13] loneos_data_acquisition.pdf.

[14] In loneos_data_acquisition.pdf HDDs HDD-1, HDD-2, and HDD-3 received from the Lowell Observatory were copied to these three directories (Existing1, Existing2, and Existing3).

extracted from the tapes by DR as described below.

The files obtained from tape include the LONEOS-I images, *i.e.*, those obtained between 1998/02/26 and 2000/01/11 (with no LOIS version, and therefore called lois_none) all of which were obtained with the one-CCD camera and received on tapes 000_CR through 042_CR and those LONEOS-II images obtained between 2000/01/04 and 2003/05/27 (LOIS versions 1.1, 1.3.2.2.beta, 1.3.3.0, and 2.0.0.beta) and available from tapes 043_CR through 171_CR. And, as shown in Table 1, with the exception of 2003, most of the images from these years were only available from the tapes.

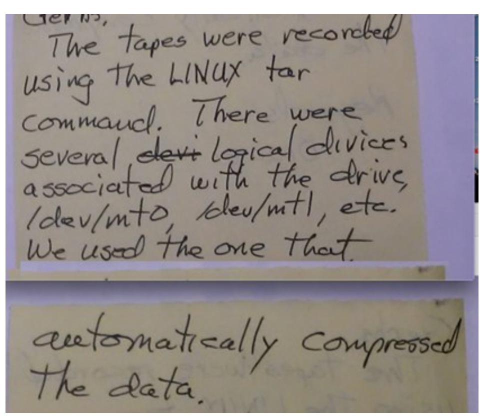
Table 1. Number of Images from 1998 Through 2003 Obtained from HDD and/or Tape[a].

Year	LOIS	HDD	Tape
1998	none		10,980
1999	none		15,298
2000	none/1.1	2,238	45,842
2001	1.1		26,383
2002	1.3.2.2.beta, 1.3.3.0, 2.0.0.beta		5,825
2003	2.0.0.beta	44,222	27,924

[a] The total number of images in the archive for these years is considerably less than the sum of the HDD and Tape values in this table because many of those recovered from tape (and a few from the HDDs) were duplicates, corrupt, and/or were missing a date and/or time in their headers.

The LONEOS-I camera wrote the lois_none images (one image per exposure) to a Lowell Observatory HDD using the format YYYYMMDDnnnnb.fits, *e.g.*, 199804250204b.fits. Hence, because these files ended with the .fits extension, the normal Windows terminal command could be used to rename them, *i.e.*, 199804250204b.fits was renamed to 980425_204.fits

However, although these images were written to HDD at the telescope as they were obtained, all the LONEOS-I (lois_none) and LONEOS-II images from 2000 through 2002 (LOIS versions 1.1, 1.3.2.2.beta, 1.3.3.0, and some 2.0.0.beta) we received were on the magnetic tapes. And only a small fraction of the files from those tapes could be directly read from them. That fraction was in the format YYYYMMDDnnnnb.fits And, while a small fraction of files could be directly read from the tapes in the format described here, most of the files on the tapes were written to them "… *using the LINUX tar command* …" according to the following handwritten note found with the tapes:



Notice that the version of the LINUX tar command used to write the LONEOS tapes' tar files: "… *automatically compressed the data* …".

LONEOS Processing Details

When shown this note, Ben Carmitchel, the Datarecovery.com, Inc.® (DR) Chief Executive Officer (CEO) and leader of the team at DR working on recovering the FITS images written to the LONEOS tapes told us: "*That is an interesting note. Tar can be tricky to work with depending on the flavor of Linux and version of tar. The data on the tapes seems to just have thousands of compressed images dumped to them with usually no folder structure at all. The result will be folders named after the tapes, full of raw fits images.*

I do not think that some of the backups were done properly, because I am successfully extracting data that looks more like a mirror of part of a hard disk. These images are in the worst shape because they appear fragmented."

And, in a later email message Ben wrote: "*We read the tapes using an in-house utility similar to the Linux DD command. Each tape was stored as a* [.img] *file. The reason we did this, was because end-of-data markers would not allow the normal tar command to restore the backup. The tapes were also in poor condition and so we had to read them while ignoring errors.*

Once in an [.img] *image format, we were able to extract the data from tapes where the tar metadata was not corrupt; however, if it was corrupt, we ran another program to essentially comb though the raw compressed data looking for FITS file markers. The files were then named according to where they were found in the image*[15]*. Fortunately, the fits files themselves contain their own metadata (time, date, location).*"

Note that although .img files are saved to the tape directories (see Appendix I's Content column) and which DR's Ben Carmitchel described as being: "… *raw images of the tapes (when obtainable)*: *Since we had to scan every bit of every tape, I thought we'd might as well save a copy just in case it was needed later. Since the tapes were written in tar format, you could simply rename the extension .tar and extract with a program like winrar; however, you won't get all of the data that way since the end-of-data markers are premature."* This means that by renaming the *.img file to *.tar and untaring it you can see which images were included in the backup but many of them will not be readable because they have faulty end-of-data markers.

DR was able to recover many of these images with corrupt tar metadata using their "… *program to essentially comb though the raw compressed data looking for FITS file markers …"* but, nevertheless, a few percent of these recovered f-formatted FITS files were corrupt. And that was recognized only when I attempted to process them.

The LONEOS-I (LOIS version lois_none) images were the last I processed because they were obtained with a different camera than those for the other LOIS versions, *i.e*., the LONEOS-I camera, rather than the LONEOS-II camera.

There are a total of 26,269 processable lois_none images from 126 nights:

1998 10 months with 53 nights,
1999 9 months with 67 nights, and
2000 1 month with 6 nights.

980226 - 981115 have double-spaced headers and 981116-000111 have single-spaced headers.

lois_none nights 980425, 980622, 980702, 980731, 980826, 980827, and 980828 were processed differently from the other lois_none images because their start_date and stop_date formats (YYYYMMDDTHH:MM:SS) differed from that of other LOIS versions (YYYY-MM-DDTHH:MM:SS).

Table 2 presents a log of the lois_none images processed. This is the lois_none portion of the Excel images processed workbook (LONEOS_Images_Processed.xlsx) but omitting, for each night processed, information describing any issues with processing that night's images.

[15] This is the origin of the f-formatted images.

Table 2. Dates and Number of lois_none Images Processed.

Night	Processed	Images		Night	Processed	Images		Night	Processed	Images
980226	25/01/14	4		981216	25/01/30	315		991022	25/02/04	108
980425	25/01/13	204		981217	25/01/30	258		991023	25/02/04	278
980525	25/01/15	22		981223	25/01/30	67		991025	25/02/04	68
980622	25/01/13	167		981224	25/01/30	336		991028	25/02/04	346
980702	25/01/13	180		981226	25/01/30	59		991029	25/02/04	312
980731	25/01/13	15		981227	25/01/30	180		991030	25/02/04	324
980826	25/01/13	134		981228	25/01/30	76		991031	25/02/04	264
980827	25/01/13	238		981230	25/01/30	41		991101	25/02/04	216
980828	25/01/13	182		990102	25/01/30	14		991103	25/02/04	2
980829	25/01/10	53		990105	25/01/30	267		991104	25/02/04	336
980830	25/01/13	226		990106	25/01/31	226		991114	25/02/04	325
980909	25/01/14	33		990107	25/01/31	229		991115	25/02/04	341
980913	25/01/14	121		990108	25/01/31	260		991119	25/02/04	330
980918	25/01/14	293		990109	25/01/31	167		991120	25/02/04	90
980926	25/01/14	134		990110	25/01/31	6		991121	25/02/04	341
981001	25/01/16	263		990113	25/01/30	336		991123	25/02/04	72
981002	25/01/16	152		990114	25/01/31	322		991125	25/02/04	192
981003	25/01/16	100		990115	25/01/31	321		991126	25/02/04	144
981011	25/01/16	317		990117	25/01/31	250		991207	25/02/05	240
981012	25/01/24	274		990122	25/01/31	225		991208	25/02/05	358
981013	25/01/24	78		990130	25/01/31	162		991209	25/02/05	336
981014	25/01/24	287		990131	25/01/31	139		991213	25/02/05	267
981015	25/01/27	134		990201	25/02/03	316		991214	25/02/05	282
981016	25/01/27	234		990202	25/02/03	312		991216	25/02/05	359
981017	25/01/27	306		990204	25/02/03	150		991217	25/02/05	136
981018	25/01/27	277		990207	25/02/03	39		991221	25/02/05	366
981019	25/01/27	294		990211	25/02/03	141		991223	25/02/05	84
981020	25/01/27	178		990212	25/02/03	182		991228	25/02/05	342
981114	25/01/27	32		990513	25/02/03	85		991230	25/02/05	342
981115	25/01/27	296		990524	25/02/03	168		991231	25/02/05	273
981116	25/01/28	282		990613	25/02/03	213		000104	25/02/05	347
981117	25/01/29	161		990630	25/02/03	150		000105	25/02/05	89
981118	25/01/29	246		990807	25/02/03	252		000107	25/02/05	240
981119	25/01/29	283		990906	25/02/03	17		000108	25/02/05	192
981120	25/01/29	110		990921	25/02/03	16		000110	25/02/05	309
981123	25/01/29	264		990930	25/02/03	287		000111	25/02/05	182
981124	25/01/29	228		991001	25/02/04	304				
981125	25/01/29	293		991002	25/02/04	300				
981126	25/01/29	329		991003	25/02/04	305				
981130	25/01/29	54		991004	25/02/04	257				
981201	25/01/29	206		991006	25/02/04	328				
981209	25/01/29	202		991013	25/02/04	326				
981211	25/01/30	231		991019	25/02/04	94				
981214	25/01/30	265		991020	25/02/04	124				
981215	25/01/30	156		991021	25/02/04	280				

The LONEOS-II images were obtained with a different camera than used during the LONEOS-I phase of the survey and were written using LOIS versions 1.1 through 4.2.0. Hence, as described toward the end of §2.1.2, their default image name format was different: YYMMDD_#.nnn, instead of YYYYMMDDnnnnb.fits. Besides the lack of a .fits extension, the main difference is the addition of _# to the filename. This was necessary because the LONEOS-II camera used two CCDs, each covering the same RA range but with their centers separated in Declination (Dec) by 1.44°. Consequently, each LONEOS-II exposure produced two, rather than one, FITS file, and these were distinguished by an _1 for the northern image and _2 for the southern.

These file-naming differences did not change DR's extraction process other than that the as-written individual images were in the YYMMDD_#.nnn format rather than the YYYYMMDDnnnnb.fits format, but the same f-format for images from tar files with corrupt tar metadata.

DR delivered the files extracted from the tapes in five types of directories, *e.g.*, 025_CR, 026_C, *_recovered_only, 057_ERR, and 100[16]. The, representative, content of these tape directories are described below.

025_CR contains 86 f-formatted files (f0000049 through f2889456) in subdirectory /recovered and, in its root directory, 87 FITS images (199905130002b.fits through 199905130088b.fits), a 122-byte "log" (no extension) text file which contains:

> "SCSI Media Changer Move Media Command 2.0
> Copyright 1996 Automated Network Technologies LLC
> All Rights Reserved Worldwide",

a 22.6 KB text file "log.990512" with 334 lines, and a 1.40 GB 000025.img file. This is one of the .img files DR's Ben Carmitchel described as being: "… *raw images of the tapes (when obtainable)."* Renaming 000025.img to 000025.tar and untaring it shows that it contains the same 87 FITS files that are present in the root directory. in general, the /recovered subdirectories each hold ≤500 files although, for this tape, there are no subdirectories.

As can be seen in Appendix I, 60 other tapes also contain an .img file.

026_C types (there are 38 of these) have files that could be read directly from the tape, *e.g*., on 026_C, 199905240001b.fits through 199905240176b.fits However, some tapes, like 146_C and 149_C, have no FITS files. On tape 146_C, the project backed up their Linux profiles (koehn, pjh, and taylor), the local directory, and a logs directory with entries for 93 nights between 1999/01/13 and 1999/06/28, inclusive. An example of a portion of one of the log files is given in Appendix III. Only the log files will be archived. Tape 149_C contains only personal and system directories (koehn, local, and pjh) and a 2.40 GB .img file (000149.img) that contains those same three directories. Hence, no files from this tape will be archived.

There are 3 *_recovered_only directories (/55_56_58_59_recovered_only, /87_through_103_recovered_only, and /117_to_103_recovered_only). These directories contain the images recovered from the tapes in the directory's filename. For example, /55_56_58_59_recovered_only contains the f-formatted images from tapes _055, _056, _058, and _059 in 17 subdirectories (1, 2, … 17). Each subdirectory except the last contains 500 f-formatted images and the last contains <500 f-formatted images (86 in this case). That is, the *_recovered_only directories are functionally equivalent to, but used by DR instead of, directories _055_CR, _056_CR, _058_CR, and _059_CR. And directories _055_C, _056_C, _058_C, and _059_C contain the images that could be directly read from the tape. For example, directory _055_C contains 16 images 000511_1.143 through 000511_1.158 plus an .img (.tar) file with those same 16 images in that format, while directory /55_56_58_59_recovered_only contains 8,086 images from f0000001.fits (000511_1.143) to f278279912.fits (000607_2.009).

057_ERR. There are 44 _ERR directories. These are tapes that were either empty or from which nothing could be recovered.

100-type directories (there are 13). They contain between 1 and 23 images. For example, tape directory 100 contains 7 images: 010602_2.154 through 010602_2.160

[16] Except for Appendix I, I have dropped the leading 000 for the tape names. They are retained in the appendix because that is how they were received from DR and therefore are the "original data" from the tapes.

Appendix II. The LONEOS Pipelines

Table 1. LOIS Versions.

LOISVER	Date Range[a]	LOISVER	Date Range
none	1998/02/26 to 2000/01/11 (125[b]) T	2.0.0.beta	2002/12/09 to 2003/07/09 (98[f]) T, HDD
1.1	2000/02/04 to 2002/03/02 (154[c]) T	3.2.0.beta	2003/08/05 to 2004/12/26 (226[g]) HDD
1.3.2.2.beta	2002/06/08 to 2002/06/20 (9[d]) T	4.2.0	2005/11/13 to 2008/03/01 (299[h]) HDD
1.3.3.0	2002/07/06 (1[e]) T	4.2.0	2010/01/04 to 2011/06/16 (133[i]) HDD

[a] T = Obtained from Tapes, HDD = Obtained from Hard Disk Drives. (nnn) = number of nights.

[b] 125 nights and 26,278 images, none of whose headers have a LOISVERS keyword or equivalent.

[c] 154 nights (000204-020302) with 53,811 images plus four nights (000225, 000226, 000229, 000303) with ~694 images but with no RA, DEC in their headers and which are not included in the Archive.

[d] 9 nights with 3,447 images.

[e] 1 night (020706) with 214 images.

[f] 50 nights from tape (021209 to 030515, less 030414, 030425, 030426, 030501 and 030505) with 21,292 images and 48 nights with 23,434 images from HDD (above plus 030517-030709, 030406, 030519, and 030630) for a total of 98 nights with 44,726 images.

[g] 136,207 images

[h] 156,144 images (not including NEAPS images)

[i] 133 nights and 112,830 images from the NEAPS program.

Table 2 presents a list of the scripts that form the pipeline, and which were run in the order given in the table. The details in this table are intended to give an impression of the various parts of the pipeline and how they interacted. These specific scripts are for the first pipeline version used (in mid-2023) to process images with LOIS version 4.2.0.

The need for multiple pipeline versions was because image header keywords changed their names, value formats, and their positions in the header not only from one LOIS version to another (as anticipated) but also within the same LOIS version and even from one image to another within the same night. Most of these anomalous header issues were discovered by observing incorrect entries in some or all of a night's labels. And this was first realized only after those labels had been sent to the PDS/SBN.

A consequence of this was that several of each pipeline's scripts, generally those involving the headers and/or labels, needed to be modified for every variant header version. And because the header structure of a given image was not known until its header was read (normally using create_hdr_xx.py) it was unknown what version of the label and WCS scripts to run until the output of that script could be examined. In practice, this meant that a best guess was made as to the likely header format of the images for a given night and the pipeline with the appropriate scripts for that header were then run. And, provided all images for that night had the same header format, if this guess was right then correct augmented images and labels were created.

These scripts were called from 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 scripts whose filenames have an xx since each LOIS version has its own peculiarities. For example, some headers were single-spaced and others double-spaced, many had the same keyword required for processing on different lines and/or with a different name, for most nights that had them bias images were the first 10-to-20 images but other nights had them as the last images or two sets – one at the beginning and another elsewhere, and headers could change their format in the middle of a night. The scripts, and the directories from which they run, are described below. All scripts are called from create_pds_files_xx.sh

Each LONEOS-I (lois_none) pipeline contained 10 scripts (because each exposure produced only one image) while the LONEOS-II and NEAPS pipelines contained 12 scripts. Each version of the pipeline contained ~3,000 lines, including comments. There were ~17 such pipelines, so ~50,000 lines, although far fewer unique lines.

Table 2. Scripts Forming the LOIS 4.2.0 Pipeline.

Script	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 script is called. "No. Lines" is the number of script 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 script is run.

"Location" is the directory from which that script is, and must be, run, \wd stands for "working directory", and _1a, _2a for the northern and southern images from each exposure[17].

I wrote: "There were ~17 such pipelines …" because I lost count of how many versions I created. This was due to some of the issues, *e.g.*, nights with bias images at the beginning and elsewhere, or with headers that changed their format during the night, not appearing until long after the results were submitted to the PDS/SBN and then failing validation. To save these images required modifying the pipeline that failed to properly process them.

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 script 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.

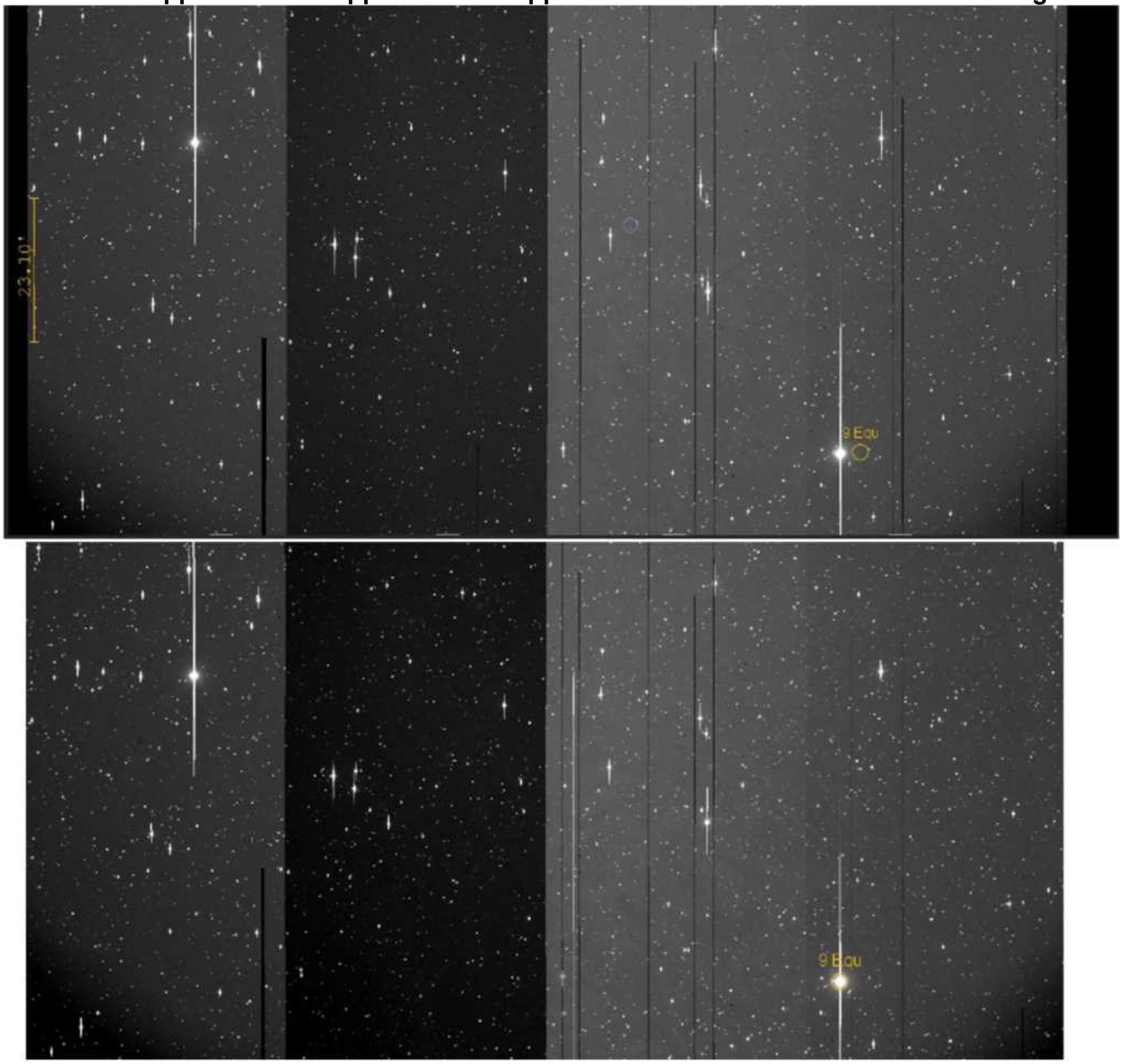
At the conclusion of the project, the source script, with associated documentation sufficient to enable use of the script, for software developed for this program (including that created pre-award) will be made publicly available via the planetary science section of GitHub because the PDS does not allow software source script 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 scripts 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.

[17] The northern and southern images needed to be processed differently because their Declination centers differed by 1.44°.

Appendix III. macro.log.19990113

```
The observer is S. M. Hermann
The date is Wed Jan 13 01:18:04 GMT 1999
Clouds:
Seeing:
  Time/Date MST    In (T,Hum,DewP) Out (T,Hum,DewP)     Wind      Barom
18:14:01_01/12/99   37.3  1% -53.3    36.1 40% 14.3        0 mph  22.83 in
The observer is S. M. Hermann
The date is Wed Jan 13 01:19:12 GMT 1999
Clouds:
Seeing:
  Time/Date MST    In (T,Hum,DewP) Out (T,Hum,DewP)     Wind      Barom
18:14:01_01/12/99   37.3  1% -53.3    36.1 40% 14.3        0 mph  22.83 in
NFILTER 1
FILTER1 open
OFFSET1 0.0
region 2058 west, pass 1, /pallas/d2/990113/199901130006b.fits Wed Jan 13 01:44:19 GMT 1999
region 2058 east, pass 1, /pallas/d2/990113/199901130007b.fits Wed Jan 13 01:46:09 GMT 1999
region 2059 west, pass 1, /pallas/d2/990113/199901130008b.fits Wed Jan 13 01:47:59 GMT 1999
region 2059 east, pass 1, /pallas/d2/990113/199901130009b.fits Wed Jan 13 01:49:50 GMT 1999
region 2060 west, pass 1, /pallas/d2/990113/199901130010b.fits Wed Jan 13 01:51:40 GMT 1999
region 2060 east, pass 1, /pallas/d2/990113/199901130011b.fits Wed Jan 13 01:53:30 GMT 1999
region 2171 west, pass 1, /pallas/d2/990113/199901130012b.fits Wed Jan 13 01:55:19 GMT 1999
region 2171 east, pass 1, /pallas/d2/990113/199901130013b.fits Wed Jan 13 01:57:09 GMT 1999
region 2172 west, pass 1, /pallas/d2/990113/199901130014b.fits Wed Jan 13 01:58:59 GMT 1999
region 2172 east, pass 1, /pallas/d2/990113/199901130015b.fits Wed Jan 13 02:00:49 GMT 1999
region 2173 west, pass 1, /pallas/d2/990113/199901130016b.fits Wed Jan 13 02:02:39 GMT 1999
region 2173 east, pass 1, /pallas/d2/990113/199901130017b.fits Wed Jan 13 02:04:28 GMT 1999
region 2058 west, pass 2, /pallas/d2/990113/199901130018b.fits Wed Jan 13 02:06:18 GMT 1999
region 2058 east, pass 2, /pallas/d2/990113/199901130019b.fits Wed Jan 13 02:08:09 GMT 1999
region 2059 west, pass 2, /pallas/d2/990113/199901130020b.fits Wed Jan 13 02:09:59 GMT 1999
region 2059 east, pass 2, /pallas/d2/990113/199901130021b.fits Wed Jan 13 02:11:49 GMT 1999
region 2060 west, pass 2, /pallas/d2/990113/199901130022b.fits Wed Jan 13 02:13:38 GMT 1999
region 2060 east, pass 2, /pallas/d2/990113/199901130023b.fits Wed Jan 13 02:15:28 GMT 1999
region 2171 west, pass 2, /pallas/d2/990113/199901130024b.fits Wed Jan 13 02:17:18 GMT 1999
region 2171 east, pass 2, /pallas/d2/990113/199901130025b.fits Wed Jan 13 02:19:08 GMT 1999
region 2172 west, pass 2, /pallas/d2/990113/199901130026b.fits Wed Jan 13 02:20:58 GMT 1999
region 2172 east, pass 2, /pallas/d2/990113/199901130027b.fits Wed Jan 13 02:22:48 GMT 1999
region 2173 west, pass 2, /pallas/d2/990113/199901130028b.fits Wed Jan 13 02:24:38 GMT 1999
region 2173 east, pass 2, /pallas/d2/990113/199901130029b.fits Wed Jan 13 02:26:28 GMT 1999
region 2058 west, pass 3, /pallas/d2/990113/199901130030b.fits Wed Jan 13 02:28:18 GMT 1999
region 2058 east, pass 3, /pallas/d2/990113/199901130031b.fits Wed Jan 13 02:30:08 GMT 1999
region 2059 west, pass 3, /pallas/d2/990113/199901130032b.fits Wed Jan 13 02:35:16 GMT 1999
region 2059 east, pass 3, /pallas/d2/990113/199901130033b.fits Wed Jan 13 02:37:06 GMT 1999
region 2060 west, pass 3, /pallas/d2/990113/199901130034b.fits Wed Jan 13 02:38:55 GMT 1999
region 2060 east, pass 3, /pallas/d2/990113/199901130035b.fits Wed Jan 13 02:40:45 GMT 1999
region 2171 west, pass 3, /pallas/d2/990113/199901130036b.fits Wed Jan 13 02:42:35 GMT 1999
region 2171 east, pass 3, /pallas/d2/990113/199901130037b.fits Wed Jan 13 02:44:25 GMT 1999
region 2172 west, pass 3, /pallas/d2/990113/199901130038b.fits Wed Jan 13 02:46:15 GMT 1999
region 2172 east, pass 3, /pallas/d2/990113/199901130039b.fits Wed Jan 13 02:48:05 GMT 1999
region 2173 west, pass 3, /pallas/d2/990113/199901130040b.fits Wed Jan 13 02:49:56 GMT 1999
region 2173 east, pass 3, /pallas/d2/990113/199901130041b.fits Wed Jan 13 02:51:45 GMT 1999
region 2058 east, pass 3, /pallas/d2/990113/199901130042b.fits Wed Jan 13 02:54:58 GMT 1999
region 1514 west, pass 1, /pallas/d2/990113/199901130043b.fits Wed Jan 13 03:02:49 GMT 1999
region 1514 east, pass 1, /pallas/d2/990113/199901130044b.fits Wed Jan 13 03:04:39 GMT 1999
region 1513 west, pass 1, /pallas/d2/990113/199901130045b.fits Wed Jan 13 03:06:30 GMT 1999
region 1513 east, pass 1, /pallas/d2/990113/199901130046b.fits Wed Jan 13 03:08:19 GMT 1999
region 1512 west, pass 1, /pallas/d2/990113/199901130047b.fits Wed Jan 13 03:10:09 GMT 1999
region 1512 east, pass 1, /pallas/d2/990113/199901130048b.fits Wed Jan 13 03:12:00 GMT 1999
region 1511 west, pass 1, /pallas/d2/990113/199901130049b.fits Wed Jan 13 03:13:49 GMT 1999
region 1511 east, pass 1, /pallas/d2/990113/199901130050b.fits Wed Jan 13 03:15:39 GMT 1999
region 1406 west, pass 1, /pallas/d2/990113/199901130051b.fits Wed Jan 13 03:17:30 GMT 1999
region 1406 east, pass 1, /pallas/d2/990113/199901130052b.fits Wed Jan 13 03:19:19 GMT 1999
region 1405 west, pass 1, /pallas/d2/990113/199901130053b.fits Wed Jan 13 03:21:10 GMT 1999
region 1405 east, pass 1, /pallas/d2/990113/199901130054b.fits Wed Jan 13 03:22:59 GMT 1999
region 1404 west, pass 1, /pallas/d2/990113/199901130055b.fits Wed Jan 13 03:24:49 GMT 1999
region 1404 east, pass 1, /pallas/d2/990113/199901130056b.fits Wed Jan 13 03:26:39 GMT 1999
region 1403 west, pass 1, /pallas/d2/990113/199901130057b.fits Wed Jan 13 03:28:28 GMT 1999
```

Appendix IV. Cropped vs. Uncropped Astrometric Fits for a LONEOS-II Image



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	3.08 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 V. 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
```