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Lunar Orbiter Image Recovery Project (LOIRP) Lunar Orbiter (LO)

**LOIRP LO SOFTWARE INTERFACE SPECIFICATION**

January 24, 2018

Lunar Orbiter Image Recovery Project Lunar Orbiter

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ACRONYMS

|  |  |
| --- | --- |
| DSIF | Deep Space Instrumentation Facility |
| FM/VSB | Frequency Modulation / Vestigial Sideband Modulation |
| GRE | Ground Reconstruction Equipment |
| LOIRP | Lunar Orbiter Image Recovery Project |
| PDS | Planetary Data System |
| OMS | Optical Mechanical Scanner |
| SFOF | Space Flight Operations Center |
| SIS | Software Interface Specification |
| TBD | To Be Determined |
| V/H | Vertical over Horizontal or Image Motion Compensation for Lunar Orbiter Images |

GLOSSARY

|  |  |
| --- | --- |
| **TERM** | **DEFINITION** |
| Fiducial marks | Seen as “stitching” in an Lunar Orbiter framelet. Image information toward the edges of a framelet beyond the stitching is an image overlap to the adjacent framelet. |
| Framelet | Single 22 second scan of the 70mm film onboard the Lunar Orbiter Spacecraft |
| Frame | A single Lunar Orbiter photograph, whether medium or high resolution |
| FR-900 | 2” Instrumentation magnetic tape drive from Ampex that stored Lunar Orbiter images |
| Head clog | A buildup of oxide particles on the tape drive head that diminishes the signal from the tapes. |
| Line Scan Tube | A rotating phosophor coated drum used to create a 6.5 micron focused light beam to scan the Lunar Orbiter film |
| Optical Mechanical Scanner | The mechanical latching device in the Photographic Subsystem on Lunar Orbiter where the film is scanned via an optical beam output from the Line Scan Tube |
| Photographic Subsystem | The Lunar Orbiter cameras |
| Photo Video Chain | The Photographic Subsystem element that converts the light beam from the Optical Mechanical Scanner into an analog signal then fed into the communications system. |
| Pre detection | Radio Frequency information downlinked from Lunar Orbiter and written to tape before any ground processing |
| Read Out | The process of reading out Lunar Orbiter images |
| SO-243 | 70mm Aerographic film used to capture images of the lunar surface on Lunar Orbiter |
| SO-349 | 35mm TV recording film used to capture Lunar Orbiter images at the DSIF ground stations. Forms the basis of the GRE Film archive. |
| Subframe | A Lunar Orbiter High Resolution Frame separated into three parts designated H1, H2, and H3.  |
| Scan line | A single line of Lunar Orbiter image data, approximately 1205 microseconds long |
| Tape | Memorex or other brand 2” one hour analog tapes that hold the Lunar Orbiter Images. |

# INTRODUCTION

## Purpose and Scope

The purpose of this Data Product SIS is to provide users of the Lunar Orbiter Image Recovery Project (LOIRP) Lunar Orbiter (LO) data product with a detailed discription of of the LOIRP LO images and a discription of how this data set was generated, including data sources and destinations. The LOIRP LO data product was obtained from 1474 original DSIF ground station recordings on a Ampex FR-900 2” Instrumentation tape drive recorded in pre-detection format. This SIS is intended to provide enough information to enable users to read and understand the LOIRP LO data product. The users for whom this SIS is intended is the general planetary science community.

## Contents

This Data Product SIS describes how the LOIRP LO data product was acquired by the Lunar Orbiter Photographic System, and how it is processed, formatted, labeled, and uniquely identified. The document discusses standards used in generating the product and software that may be used to access the product. The data product structure and organization is described in sufficient detail to enable a user to read the product. Finally, an example of a product label is provided.

# Applicable Documents and Constraints

This Data Product SIS is responsive to the following LOIRP LO documents:

1. Data Management Plan - not apllicable
2. Project Archive Plan - not applicable.

This SIS is also consistent with the following Planetary Data System documents:

1. Planetary Data System Data Preparation Work­book, February 1, 1995, Version 3.1, JPL D-7669, Part 1.
2. Planetary Data System Data Standards Refer­ence, February 27, 2009, Version 3.8, JPL D-7669, Part 2.

The reader is referred to the following documents for additional information:

1. NASA Contract Number NAS 1-3800, Picture Data Systems Analysis, Lunar Orbiter, The Boeing Company, December 1964 [published early 1965] (Also known as NASA N67-37199).
2. TM-65-1012-6, Tape Recording of Lunar Orbiter Pictures, C. J. Byrne, Bellcomm Inc. July 6, 1965.
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8. NASA CR-847, Lunar Orbiter 1 Photography, The Boeing Company, August 1967.
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11. NASA CR-66437, Lunar Orbiter II Final Report, Mission Operational Performance, Volume III, The Boeing Company Aerospace Group---Space Division, Seattle Washington, April 24, 1967.
12. NASA CR-66438, Lunar Orbiter II Volume VI, Appendices, The Boeing Company, June 22, 1967.
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25. Dragg, J, Naugle, N; Photometric Reduction of Lunar Orbiter Video Tapes, SPIE 13th Technical Symposium, Washington, DC, August 1968.
26. Beeler, M, Michlovitz, K; Lunar Orbiter Photographic Data, NSSDC 69-05, National Space Science Data Center, Goddard Spaceflight Center, Greenbelt, MD, June 1969.
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This SIS is meant to be consistent with the contract negotiated between the Lunar Orbiter Image Recovery Project and the NASA Ames Solar System Exploration Research Virtual Institute (SSERVI) in which re­duced data records and documentation are explicitly defined as deliver­able products.

# Relationships with Other Interfaces

None

# Data Product Characteristics and Environment

## Instrument Overview

From August of 1966 through November of 1967 NASA sent five Lunar Orbiter (LO) spacecraft to the moon to perform a photoreconiasance of the Moon in preparation for the Apollo lunar landings. The LO spacecraft were the highest resolution images obtained from the Moon until the arrival and operation of the NASA Lunar Reconniasance Orbiter in 2009. The Lunar Orbiter Image Recovery Project Lunar Orbiter (LOIRP LO) archive has reproduced, from the original Deep Space Instrumentation Facility (DSIF) ground station tapes, images from all five LO missions. The tape data retains the original full dynamic range data as recorded on the spacecraft and transmitted to the DSIF stations [Byrne, 1965]. These images are of a higher dynamic range than existing 35 mm SO-349 film data sets from USGS and the Lunar and Planetary Data System archive. The LORIP LO data set is also free of artifacts from the SO-349 (Kodak T.V. Recording film process D-19) 35mm Ground Reconstruction Equipment (GRE) LO image data set acquired in parallel with the magnetic tapes of the LOIRP LO archive [Kodak, 1966]. Thus the LOIRP LO archive is closest to original data set for the LO images, using modern techniques applied to the original data as it was received at the DSIF stations in 1966-67 [Dragg and Naugle, 1968].

The Lunar Orbiter photo subsystem, used to obtain the visible light images from the five Lunar Orbiter spacecraft, exposed and processed film and converted the information contained on the film to an electrical signal for transmission to Earth. The camera system featured a dual lens optical system that simulaneously produced two images on 70mm SO-243 film [NASA CR-782, 1967]. High resolution photographs were obtained by using a 610mm (24 inch) focal length Pacific Optical Paxoramic lens at the same time that a medium resolution photographs were obtained by an 80mm (3 inch) focal length Schneider Xenotar lens. Both of these lenses operated at a fixed aperture of f/5.6 with controllable shutter speeds of 0.04, 0.02, and 0.01 second. A double courtained focal plane shutter was used with the high resolution lens and a between the lens shutter was used with the medium resolution lens. Volume limitations within the photo system container necessitated the use of a mirror in the optical path of the 610mm lens. This mirror resulted in the reversal of all high resolution photographs on the spacecraft film (from left to right across the flight path) with respect to the medium resolution photographs. A Society of Photographic Scientists and Engineers paper [Broome, and Moorman 1967] states that a .21 neutral density filter was added to the 610mm lens to achieve a balanced exposure after Lunar Orbiter 1. The optical format for the field of view for the high resolution image was 5 degrees by 20 degrees and 35 degrees for the medium resolution image. The 70mm film area exposed was 55x 219mm for a high resolution frame and 55 x 65mm for a medium resolution frame. A pre exposed 9 step gray scale edge mark pattern provides sensitometric control for ground data reduction. Also present on the film (except for LO I) is a pattern of pre exposed Reseau crosses [Elle, et al., 1967].

An auxillary optical system, which operated through the high resolution lens system, sampled the image of the lunar terrain and determined a velocity to height (V/H) ratio. This output was converted to an image motion compensation signal, which moved each camera pleten to compensate for image motion at the film plane. The V/H ratio also controls the space of shutter operations to provide the commanded overlap.

Each exposure commanded produced a medium resolution and a high resolution picture. The physical arrangement of the lens system prevented the placing of these two photographs on adjacent ares in the spacecraft film. The time of each exposure was exposed on the film in digital code by 20 timing lights [Note: the nature of this code and how to decode it is lost to time].

The exposed film was developed, fixed, and dried by the processor dryer. The eastman Kodak “Bimat” system processed the spacecraft film at a rate of 2.4 inches per minute and requires 3.4 minutes to fully process the latent image. The processing was accomplished by temporarily laminating the emulsion side of the Bimat film against the SO-243 film emulsion as it traveled around the processor drum. After leaving the processor drum, the film passed over a heated drum where any moisture in the film is removed and collected by a desiccant. Thereafter, the film could be read out and moreover was no longer susceptible to radiation damage. After processing the last photograph, the Bimat web was cut by a hot wire on command. The film could then be moved in either direction by command after Bimat clear. During priority readout the film moved in the forward direction, and during final readout it moved in the opposite direction.

The photographic data was converted by the readout system into electrical signals that were directly transmitted to the DSIF ground stations. This was accomplished by scanning the film with a high intensity light beam. Variations in light intensity, produced by variations in the density of the SO243 film were detected by a photomultiplier tube and converted into an analog voltage. The readout system elecronics added timing and syncrhonization pulses to the composite video signal. This resulted in a fully analog system where film density was directly converted into a density dependent variable voltage rather than discrete digital steps. The electrical signals were fed into a video amplifer and then to the spacecraft modulation system. In a unique circumstance (considering todays methodology), digital telemetry signals were fed into the modulator as discrete analog voltages as part of the video spectrum. The combined fully mixed analog/digital signals were then fed to a 2.295 GHz traveling wave tube for transmission to the DSIF stations.

The high intensity light beam for film density readout was derived from a light source generated from a line scan tube. The line scan tube was similar to a cathode ray tube that generated a light beam from a source of electrons beamed at the tube. The line formed was focused to a 5.5 micron diameter spot on the spacecraft film by a lens system. The line scan tube rotated in order to avoid hot spots on the cathod itself. However, due to how the line scan tube was mounted, thermal variations from end to end created slight variations in beam intensity which in turn was reflected in slight variations in tone. This created what was termed a “W” pattern [Dragg&Naugle 1971]. The spot sweeped a 2.67 horizontal dimension of the spacecraft film. This was repeated 286 times per milimeter of flim. This was repeated ~17,400 times to produce a single “framelet”. The W pattern is clearly seen in vintage LO images. After scanning an entire framelet the film was advanced by 2.54 mm +/-0.005 mm and the scan processed repeated in the opposite direction. Approximately 29 framelets made up a LO medium resolution image and 98 framelets for a high resolution image. This varies slightly (+ 1 or 2 framelets) depending on whether or not the edge of a medium or high resolution image overlaps by less than a full framelet width.

The LO images were broken in to two primary products from an environmental perspective. LO I, II, and III orbiters had a low inclination orbit with a periselene below 50 km on the lunar near side for Apollo landing site photography. Additional global imagery was taken at various altitudes of the ellipitical orbit on the far side of the moon. The LO IV and V missions were in elliptical polar orbits, with LO IV dedicated to global photography and LO V doing this duty while also flying in a low periselene of ~100 km to fill in some gaps in Apollo landing site photography. Images from all five missions were captured from the LOIRP LO effort and constitutes a new addition to the LO pantheon of images for the planetary science community. No effort was taken to recover telemetry or other data from the mission.

It must be stressed that in the modern sense of a science mission, Lunar Orbiter’s products are not a strict science product. The Lunar Orbiter mission was one of photoreconnaisance, to find Apollo landing sites. Thus the mission and the Photographic system were optimized for this task. Numerous systematic errors such as the lack of calibration in the y Axis [Brown, 1967, and Morgan, 1971], unknown lens flare light levels, fogging due to radiation, and local uncertainties in albedo, and the uncertainties related to image blur related to the accuracy of the V/M sensor [Kodak, 1966]. The LO SO-243 photographic image is also not spectrally calibrated. The sensitivity of the film has a characteristic log sensitivity between 1.1-1.65 to a film density of 1.0 from 400-700 nanometers. [Kodak, 1966]. This curve was developed for the D-19 developer process but the Kodak literature states that it is essentially the same for the Bimat process. Some of the systematic errors can be removed with processing (y axis errors, albedo errors, and image blur) with the LOIRP LO archive as the overall dynamic range is higher, which allows for a better reconstruction of the brightness distribution of the tribar charts. This also allows for refinement in ground resolution due to the relationship between tri-bar resolution and minimum resolvable crater size [Kodak 1966, Boeing 1965].

On the images the tri-bar charts are located at the end of each framelet, and are the equivalent of standard resolution charts in terrestrial photography. There are charts in the direction of travel of the spacecraft as well as ones orthogonal, and at a 45 degree angle. These charts, along with the gray step charts and linearity bars, allows for maximal accuracy in our reconstructions as well as additional processing that is beyond the scope of our project. These are known more commonly in photography as Resolving Power Bar Charts and are described in this manner in a separate Boeing document [Boeing 1965]. This document details the tri-bar/resolving power bar charts as well as describes the linearity bars (white rectangles at the bottom of each framelet) that allow for accurate vertical/horizontal reconstruction of an LO framelet. The edge data, as it is called in Lunar Orbiter documentation, provide a wealth of information for properly reconstructing and analyzing LO images. The two documents referencing the edge data charts will be provided in the document folder of the LOIRP LO archive.

The principal difference between the LOIRP LO archive and the archives that preceeded it is related to the original purpose as a photoreconnaisance mission. The 35mm SO-349 film used to create the GRE record. The GRE film density recorded was intentionally restricted in order to maintain a high signal to noise ratio for interpretation by human experts of lunar features. Of the nine steps of the Gray Step chart pre-exposed at the end of every framelet, any density below 0.3 (corresponding the Gray Step 1 and part of 2) and any density above 1.3 (partial clip of step 8 and full clip of step 9) were clipped (SO 243 film density). This corresponded to film densities of below 0.4 and above 1.8 for the SO-349 film. This is a density reversal due to the fact that the SO-243 on the spacecraft is a negative image and the SO-349 GRE film is a positive image (a negative of a negative image) [Kodak, 1966]. In practical terms this gives a dynamic range of the GRE film of ~250 to 1 (~8 bits), while the LOIRP LO archive achieves the full 1000 to 1 dynamic range of the SO 243 film (~10 bits), 4x improvement in dynamic range.

## Data Product Overview

The LOIRP LO archive was recovered from magnetic tapes made at the three DSIF ground stations (Woomera, Madrid, Goldstone) during the five missions. The FM/VSB modulated signal recorded on the Ampex FR-900 instrumentation tapes recovered by the LOIRP project was played back from each tape. All five missions were played back, a total of 1474 tapes. All tapes from each ground station (Madrid, Goldstone, and Woomera) were played on the primary FR-900A-1 located at the McMoons facility at NASA Ames. Note: as described previously, the LOIRP LO archive measures lunar surface brightness only indirectly. Studious use of the references [Kodak 1966, Boeing 1965, Elleetal 1967, Dragg&Naugle 1968] is required in order to do more stringent science image processing to remove systematic errors in the images.

The Ampex FR-900 tape drives, obtained from retired NASA JPL archivist Nancy Evans had not been operated for any signficant length of time since the 1980’s and thus required extensive refurbishment. This refurbishment was accomplished by the LOIRP team, led by retired Ampex personnel and with a lot of support from other retirees and others with extensive experience with Ampex hardware. Due to advances in technology since that era, the team was able to bring the drive back into original specifications with a signficantly more stable signal system. In the 1960’s this system’s electronics were based on germanium transistors that were extremely temperature sensitive. These were all replaced with silicon parts. The critical part of the drive, among other critical parts, were the heads. These magnetic heads that actually read the tape also had their electronics replaced with modern silicon transistors and thus the system operated quite reliability after an extensive learning period [Wingo and Cowing, 2009, Wingo, et al., 2010, Wingo and Byrne, 2011, Wingo, et. al, 2012, Wingo, et al. 2013, Epps and Wingo, 2014, Harper, et al., 2017].

The output of the FR-900 when a tape was playing was fed into a demodulator that converted the RF signals from the drive to a video output signal virtually identical to the one produced from the readout electronics on the spacecraft. The demodulator discarded the digital telemetry and provide an output identical to that described in the literature [Kodak, 1966]. The signal level was from -0.5 to 5 volts, which was fed into a 16 bit Alazar Tek A/D capture board on a MacIntosh [2,1] computer running Windows Vista. This file was a continuous recording for the length of a tape. Exceptions to this were when the tape recorder would have a head clog (material build up on the head from the tape blocking the magnetic flux signal). The heads would be cleaned and then the tape backed up to guarantee no loss of data and restarted. These files with a .atb extension are our highest level data product, but not delivered to the PDS. After a days recording was finished, a Skycorp developed program would take the raw files and process them, This process began by aligning the individual video lines (800 lines/sec), shifted the black level to 0 volts and white level to 5.0 volts, and aligned each individual scan lines to line up with each other over the 17,400 lines of a framelet. Since the scanning was 5x over the nyquist sample rate an averaging program was used to average the resulting 16 bit words to create the proper relationship between the horizontal and vertical aspects of the framelets. The program also “sliced” the framelets into individual files that were stored on the computer.

Taxonomically the LOIRP LO archive images conform to the organization first used during the missions [Beeler and Michlovitz, 1969]. These were later further broken down into the taxonomy as shown in table 1.

Table 1, Lunar Orbiter Image Taxonomy

|  |  |  |  |
| --- | --- | --- | --- |
| **Lunar Orbiter** | **Naming Format** | **Medium Exposure** | **High Res Exposure** |
| Lunar Orbiter I | FRAME\_1xxx\_Res | FRAME\_1xxx\_M | FRAME\_1xxx\_H1, \_H2, \_H3 |
| Lunar Orbiter II | FRAME\_2xxx\_Res | FRAME\_2xxx\_M | FRAME\_2xxx\_H1, \_H2, \_H3 |
| Lunar Orbiter III | FRAME\_3xxx\_Res | FRAME\_3xxx\_M | FRAME\_3xxx\_H1, \_H2, \_H3 |
| Lunar Orbiter IV | FRAME\_4xxx\_Res | FRAME\_4xxx\_M | FRAME\_4xxx\_H1, \_H2, \_H3 |
| Lunar Orbiter V | FRAME\_5xxx\_Res | FRAME\_5xxx\_M | FRAME\_5xxx\_H1, \_H2, \_H3 |

For the purposes of the deliverable to the PDS, the raw data files and the individual framelet files were not delivered. Only full medium and high resolution frames/subframes were delivered. These files may be provided in a future release or will be stored at the NASA Ames public site.

The files as they are stored are organized as follows:

The data products submitted are mosaicked lunar surface images from the 1966/7 Lunar Orbiter missions. They’re all 16 bit IBM PC Byte order images that are organized by Orbiter number, frame number, and resolution indicator as listed in Table 1. Each Data Set ID covers one Orbiter and all images from that Orbiter.

## Data Processing

### Data Processing Level

Per JPL D-7669, Part 2 (Planetary Data Systems Standards Reference Version 3.8, the LOIRP data set data processing level is LEVEL 3. Caveat: Since the Lunar Orbiters were flown well before the development of this data processing level taxonomy, none of the levels exactly match the data. LEVEL 3 is the closest, even though the physical units for radiance are only indirectly available. Each framelet in each frame has a multiplicity of calibration marks, the one most specifically applicable is the gray scale chart. The gray scale chart is a function of the film density of the SO-243 70mm film which was the medium of recording of the intensity or radiance of the light from the Moon. The relationship between film density and radiance is described in detail in references [Kodak 1966, Boeing 1965, Elleetal 1967, Dragg&Naugle 1968, Applied Scientific, 1972]. No resampling of this data occurred.

### Data Product Generation

The Alazartech ATS9462 data capture card acquired the -0.5-+5 volt analog output of the Skycorp developed demodulator as a series of 16 bit words at a 5 MHz capture rate. It captured the video signal output of the demodulator as the tape played. This ideally (head clogs or tape imperfections would sometimes interrupt the tape play and the capture had to be rewound and restarted) ran for most of an hour recording LO images line by line, called a scan line.

A scan line was comprised of a blanking period (containing the synch pulse and front porch [black level]), an overscan period that corresponds to the overlap between framelets, the scan period where the unique data for each line was presented, and a further overlap period and back porch [end of line black level]. Each scan line was 1250 +/- 12 sec. For the purpose of this document the most important subunit is the jitter and rise time of the synch pulse. The jitter (alignment from one line to the next) time [Kodak, 1966] was ~0.4 sec from line to line and ~0.6 sec over the 22 second framelet time. At a 5 MHz scan rate that is between 2-3 sample periods. Each synch pulse rise time was ~1.8 sec minimum.

A machine learning algorithm, developed by Skycorp was used to create a running average of the rise time of the synch pulse (average of 300 lines) and this was used to establish the left edge of a framelet. Statistically, this average was less than the jitter time between lines in the original specification. Thus the line to line aligment was less than 3 sample periods (600 nanoseconds at 5 megasamples/sec) over the length of a framelet. This process eliminated the skew that was inherent in the capture process. Skew is the inaccuracy of the overall line width (+/- 12 sec) which in practice was always a positive number. Thus the skew and the line to line jitter was erased to better than the original specification. This can be determined by future researchers by measuring the jitter in the resolution bar charts at the end of each framelet that are parallel to the long axis of a framelet.

The machine learning algorithm also reversed the negative image produced on the spacecraft as photographic film to set the black level (0 volts +/- 0.001 volt) to a 16 bit word value of 0. The white level then was allowed to float to its natural maximum of 5 volts (+ 32,768 decimel or HEX 7F). The least signficant bit was always set to zero, thus a 15 bit number was produced. This is overscan as well as the true dynamic range of the film was 1000 to 1 or ~ 10 bits. One additional step was to average samples to obtain a proper framelet vertical and horizontal relationship. Over a ~1105 microsecond scan line period, this averaging was approximately 8 to 1. This was accomplished with no loss of fidelity as the overscan in the line scan direction was over 20 to 1 (the total bandwidth of the transmitted video data was ~230 KHz) [Boeing 1965]. This reduced the file size to a much more manageable size.

The skew and alignment algorithms are destructive, as are the averaging algorithm in that the blanking period and synch pulses were discarded as each line was written into a 714 x 16500 16 bit array. Thus it is impossible to completely recover the original raw data. This should not be an issue as the scan line alignment is better than the original specification and the averaging algorithm still retained the data to more than a Nyquist sample rate of the original data. Discussions are underway with NASA to preserve the original tapes for posterity and future research. One other algorithm was used. This was the “slicer” algorithm that separated the individual framelets from the larger raw data file. This was required in order to produce framelet files that could then be organized into an image. This process did no further processing of the image and the 714 x 16500 word array was written to a framelet file that was then further processed. It should be noted that for all five orbiters this resulted in ~107,000 individual files.

The next step in the process was to visually inspect at the end of the day, every framelet file. This was to detect problems with the data capture process, whether from FR-900 tape drive, tape, or capture errors. Later, the first step in the formal process was to rename the slicer generated file name with a file name that corresponded to the LO and framelet number, which is part of the edge data at the end of every framelet. This is the first step in the process to allow for proper bookkeeping against the existing data sets at USGS and LPI for the number of framelets per medium or high resolution frame.

A laborious process of building a spreadsheet with the beginning and ending framelet number for all of the images in the LPI and USGS archives was undertaken, allowing the LOIRP LO archive team to verify that we had all of the framelets for each frame, or to note, as was common, the loss of the first few framelets of a medium image due to tape change issues noted elsewhere in this submittal. The framelet numbered files were then also validated against the tape run record that was generated in real time while the tapes were run at the LOIRP project to make sure that the automated process did not miss any framelet files. These actions provided a two step validation process to make sure that all captured framelets were obtained and fed into the next step of the process. It should be noted here that there was no data source in existence to allow a direct correlation between the numbers on the tape canisters and the LO images. An indirect method was discovered that allowed us to more accurately cross correlate between tape numbers and images in the LO documentation for the five orbiters. Each tape had a sequence number attached to it and this allowed us and will allows future researchers to disentangle the relationship between the magnetic tape derived images and the GRE film. The relationship between sequence numbers is in NASA contract reports [Boeing, 1967D, Boeing, 1967F, Boeing, 1967H, Boeing, 1967I, and Boeing, 1967J] (See documents folder for reference documents. for LO missions 1-5 respectively. Additional information was gleaned from Boeing 1968C and Boeing 1968E from LO 4-5 respectively. This multiple cross checking system provided the means to ensure that every possible framelet was captured and accounted for as the slicer generated file renaming process was quasi-manual, requiring human intervention to determine framelet number from visual file inspection and then entering this number into an scripting program that would then properly rename the file. With ~110,000 files, all manually renamed, this multiple level cross checking was required for accuracy.

For the framelet files, the first step in image processing was to run a program in Visual Basic, developed by LO science veteran Charles Byrne to remove the “W” pattern from the files. This is a fully reversable process. The information regarding the program will be provided in the extras folder. After framelet processing the framelets were all organized into folders related to their specific frame or subframe number, then another script called an autoassembler then placed the framelets in their proper order by framelet number. This process used the fiducial marks as an alignment reference between adjacent framelets as this is the area of overlap between framelets. For a limited number of images where the autoassembler did not properly assemble the framelets, a manual process was used for framelet alignment. All alignment verification and manual alignments was done in Photoshop software. After alignment verification the resulting images were saved with layers removed (each framelet was an indivdiual layer) as a .raw file. Afterwards a script was run to change the file suffix from .raw to .img for PDS compliance. The process for saving the file with layers removed was a destructive process, meaning it is irreversable for the PDS delivered files. As at the framelet level it is not possible to create PDS compliant files as corner coordinate information is not available.

One thing that was not done was non linearity adjustments within a single framelet in regards to line to line scan non linearities. In a 1973 NASA contractor document CR-128581, [AppliedScientific\_1973] an analysis of the line to line non linearity was undertaken. From one line to another the step specification was 6.5 microns with an allowed jitter of +0.4 microns line to line [Kodak 1966]. The CR-128581 study indicated that a measured variance of 18 microns over 100 scan lines (350 microns). This indicates a 5.1% line to line non linearity. The Kodak specification for line to line non linearity is 6.2%, thus the non linearity is within specification, though immensely annoying, resulting in noticable mis matches in the overall lengths of each framelets scan. These are random in nature as well with no syncronization, thus can appear along any number of lines within a framelet. They do appear to be quasi periodic and thus could be removed with an advanced image processing algorithm. This was not funded by NASA for the LOIRP effort. Unfortunately this cannot be repaired in the assembled images as the individual framelets are lost in the process. A secondary delivery to NASA Ames of the framelet files would allow researchers to develop algorithms to remove the line scan non linearity and thus provide a superior product for further research.

### Data Flow

Each data product within a Data Set is made up of around 29 “framelets” or strips of image that are recorded end to end on one of 1474 2” analog instrumentation (Ampex FR-900 tape drive) magnetic tapes from the original 1966/7 Lunar Orbiter missions. The Lunar Orbiter Image Recovery Project ran, recorded, and digitized all of these tapes and their data from 2008-2013, resulting in ~107,000 framelet files. These framelets were then manually numbered, catalogued, color corrected, skew corrected and organized by the image that they create when assembled from 2013-2015. From there each framelet from an image is run through a program created specifically for this project that assembles it into a Photoshop .raw image which is then ready to be manually edited and exposure corrected.

Since the LOIRP LO archive was recovered from tape there is variance between its content and other available archives. Table 2 gives an indication of the percentage completeness of the capture vs NASA SP 242, “Guide to Lunar Orbiter Photographs” document.

Table 2. LOIRP Images Captured as a Percentage of the “Official” NASA SP242 Record

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Orbiter** | **LOIRP Data** | **NASA SP242** | **LOIRP Percentage** | **Include 'Not Read Out'** | **LOIRP Percentage** |
|  | Medium | High | Medium | High | Medium | High | Medium | High |  |  |
|  |  |  |  |  |  |  |  |  |  |  |
| **LOI** | 162 | 19 | 204 | 15 | 78% | 113% | 0 | 192 | 78% | 8%\* |
| **LOII** | 206 | 209 | 208 | 209 | 99% | 100% | 3 | 2 | 98% | 99% |
| **LOIII** | 148 | 167 | 157 | 173 | 94% | 97% | 54 | 38 | 70% | 79% |
| **LOIV** | 133 | 140 | 125 | 141 | 106% | 99% | 47 | 31 | 77% | 81% |
| **LOV** | 208 | 211 | 210 | 209 | 99% | 100% | 1 | 2 | 99% | 101% |
| **Totals** | 855 | 745 | 904 | 747 | 95% | 102% | 105 | 265 | 84% | 73% |
| **Overall** | 857 | 745 | 904 | 747 |  |  | 1012 | 1012 |  | 87% |

 |

\* The 8% is due to nomenclature. All high resolution frames after the failure of the V/H sensor were read out and were present on the tapes. However, due to the inability to correct in software for V/H failure, the LOIRP project only captured two smeared high resolution frames for historical interest.

For the size of the data product for each LO mission, refer to table 3.

Table 3. Contents and size of the Lunar Orbiter digitized from magnetic tape archive.

|  |  |  |
| --- | --- | --- |
| **Archive Items HR and MR Frames** | **Number** | **Volume (GB)** |
| LO I | 179 | 129.99 |
| LO II | 415 | 524.9 |
| LO III | 315 | 373.91 |
| LO IV | 273 | 341.49 |
| LO V | 419 | 551.32 |

Table 4 provides information on each individual LO mission.

Table 4. Lunar Orbiter Camera Operational Characteristics.

Photographic Lunar Lunar Lunar Lunar Lunar

Parameters Orbiter I Orbiter II Orbiter III Orbiter IV Orbiter V

----------------- --------- --------- --------- --------- ----------

Launch Date 8/10/66 11/6/66 2/5/67 5/4/67 8/1/67

Periselene\* (km) 40 50 55 2706 99

Aposelene\* (km) 1817 1853 1847 6114 6028

Inclination\* (deg) 12 12 21 85.5 85

Period\* (h) 3.5 3.5 3.5 12 8.5

Photo Acquisition 8/18-29/66 11/18-25/66 2/15-23/67 5/11-26/67 8/6-18/67

Highest ground

resolution (m)

-Periselene 8 1 1 58 2

-Aposelene 275 33 32 134 125

\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_

After [Hansen, 1970]; \*Lowest values.

Each DATA\_SET\_ID covers the images from one entire orbiter and on average each orbiter mission took images over the course of a couple of weeks. Each individual data product or image is on average 700 MB and the total estimated volume of every image from every Orbiter is about 2TB of data. The images submitted to the PDS from the Lunar Orbiter Image Recovery Project were produced from April 2016 to April 2017, however the data used to create these mosaicked images were run and digitized from 2008-2013 and catalogued from 2014-2015. The framelets will be stored at the NASA Ames SSERVI public website for those wishing to go behind the image files. The raw capture files will be privately curated by Skycorp for archiving on the Internet at some future time. It is the desire of the LOIRP LO project to provide the framelet level product and the raw product to the PDS and community at some future time.

### File Labeling and Naming Conventions

Each product is identifed by LO#, frame number and resolution identifier to ensure that images that share the same frame number are uniquely catalogued. This is assigned according to the original Lunar Orbiter cataloguing system, with a slight modification to how HR photographic frames are handled, consistent with the lunar and planetary laboratory taxonomy developed post NASA SP-242. On average each mosaicked image is made up of 29 framelets, however when a high resolution image was taken by the space craft it was made up of around 97 framelets and was broken down into three distinct images to handle the size. Each of these subframes has its own modifier: H1, H2, H3.

Each “frame number” refers to the order the images were taken in and the specific site the LO spacecraft photographed; Due to the imaging system design, each frame number has 2 different resolution images which are refered to as medium and high resolution frames Each image has these resolutions attached to its name. For example:

Frame 3215 has FRAME\_3215\_M.IMG (Medium Resolution Image for LO3, image 215)

 FRAME\_3215\_H

 FRAME\_3215\_H1.IMG (High Resolution Subframe 1 for LO3, image 215)

 FRAME\_3215\_H2.IMG (High Resolution Subframe 2 for LO3, image 215)

 FRAME\_3215\_H3.IMG (High Resolution Subframe 3 for LO3, image 215)

And each product has that information within its name.

Each image also has a unique label, however all H1, H2, and H3 subframe image labels have identical metadata other than refering to the proper subframe image, as the original Lunar Orbiter data for the images views the high resolution images as one complete image.

## Standards Used in Generating Data Products

### PDS Standards

The LOIRP LO archive data product complies with Planetary Data System standards for file formats and labels, as specified in the PDS Standards Reference [4].

### Time Standards

All times used for images are in the GMT time format.

### Coordinate Systems

There is some uncertainty regarding which coordinate system was in place for the Lunar Orbiter missions as formal taxonomy was not accurate pre mission. Our best estimate is that the Positional Reference System (1969) was used.

### Data Storage Conventions

All images are 16 bit, IBM PC byte order and must be opened as such or the image will NOT appear correctly.

## Data Validation

All framelets that make up the finished mosaicked frame or subframe are exact digital copies of the framelet data from the magnetic tapes and are contrast and exposure corrected based on the Gray Step chart, linearity bars, and other calibration markings in each framelet, then assembled. Once assembled they are checked visually and manually corrected framelet by framelet for any alignment issues. For the purpose of accuracy’s sake we did no visual modifications or corrections beyond adjusting framelet location and alignment, so the framelets are completely intact and as accurate as possible. However, due to defects in some tapes due to age, not all of the pixels were recovered on a small percentage of the framelets causing some visual static in some of the images.

# Detailed Data Product Specifications

## Data Product Structure and Organization

Each image frame or subframe label starts with the word “FRAME\_” then includes the Lunar Orbiter number that its from, followed by the image number itself, followed by the resolution identifier. High Resolution image subframes are denoted with an H1,H2, or H3, and are all part of one large image despite being broken into thirds. Medium Resolution images are denoted with an M.

## Data Format

Each file is a variable length image with a fixed height of 16500 pixels and are an IBM PC byte order image. This corresponds directly with the digitization process described in section 4.3.2. Each pixel in the image corresponds to the film density of the 70mm SO243 film on the Lunar Orbiter.

## Labels and Headers

The data from the Lunar Orbiter Image Recovery Project is organized by frame number and then resolution. For example, Frame 3215 has 4 images refered to as ‘subframes’: 3215\_H1, 3215\_H2, 3215\_H3 and 3215\_M. Each subframe starts with the word “FRAME\_” then includes the Lunar Orbiter number that its from, followed by the image number itself, followed by the resolution identifier. High Resolution images are denoted with an H, and are all part of one large image despite being broken into thirds. Medium Resolution images are denoted with an M. Each of these subframes can be found along with their labels underneath a folder with the image number as its name:

FRAME\_3215

 FRAME\_3125\_H1.IMG

 FRAME\_3125\_H1.LBL

 FRAME\_3125\_H2.IMG

 FRAME\_3125\_H2.LBL

 FRAME\_3125\_H3.IMG

 FRAME\_3125\_H3.LBL

 FRAME\_3125\_M.IMG

 FRAME\_3125\_M.LBL

**Archive Label Example:**

PDS\_VERSION\_ID = PDS3

/\* FILE CHARACTERISTICS \*/

RECORD\_TYPE = FIXED\_LENGTH

RECORD\_BYTES = 16500

FILE\_RECORDS = 19992

INTERCHANGE\_FORMAT = BINARY

/\* POINTERS TO DATA OBJECTS \*/

^IMAGE = "FRAME\_3006\_H1.IMG"

/\* IDENTIFICATION DATA ELEMENTS \*/

DATA\_SET\_ID = "LO3-L-80MMFLC/24INCHFLC-5-MIDR-V1.0"

PRODUCT\_ID = "Frame\_3006\_H1"

PRODUCT\_VERSION\_ID = "V1.0"

SOURCE\_PRODUCT\_ID = "3006H"

PRODUCT\_TYPE = MIDR

MISSION\_NAME = "LUNAR ORBITER 3"

SPACECRAFT\_NAME = "LUNAR ORBITER 3"

INSTRUMENT\_HOST\_NAME = "LUNAR ORBITER 3"

INSTRUMENT\_NAME = "24 INCH FOCAL LENGTH CAMERA"

INSTRUMENT\_ID = "24INCHFLC"

LAUNCH\_DATE = 1967-02-05

MISSION\_START\_DATE = 1967-02-05

MISSION\_STOP\_DATE = 1967-10-09

SPACECRAFT\_CLOCK\_START\_COUNT = "N/A"

SPACECRAFT\_CLOCK\_STOP\_COUNT = "N/A"

TARGET\_NAME = "MOON"

START\_TIME = 1967-02-15T10:00:43.11

STOP\_TIME = "UNK"

/\* DESCRIPTIVE DATA ELEMENTS \*/

IMAGE\_NUMBER = ("300616421", "300616430",

 "300616710", "300616720")

LO:FRAME\_NUMBER = 3006

LO:TAPE\_NUMBER = "M\_3001"

LO:TAPE\_SCAN\_CREATION\_DATE = 2012-07-02

LO:TAPE\_SCAN\_RESOLUTION = 8.0e7 <b/s>

SPACECRAFT\_ALTITUDE = 59.72 <km>

LO:SC\_POSITION\_MEAN\_ALTITUDE\_RATE = -0.0684 <km/s>

SUB\_SPACECRAFT\_LATITUDE = 3.03 <deg>

SUB\_SPACECRAFT\_LONGITUDE = 34.42 <deg>

LO:SC\_ORIENTATION\_TILT\_ANGLE = 1.51 <deg>

LO:SC\_ORIENTATION\_TILT\_AZIMUTH = 282.71 <deg>

LO:SC\_ORIENTATION\_SWING\_ANGLE = 82.01 <deg>

LO:SC\_ORIENTATION\_NORTH\_DEV\_ANGLE = 339.31 <deg>

SOLAR\_AZIMUTH = 92.27 <deg>

INCIDENCE\_ANGLE = 76.57 <deg>

EMISSION\_ANGLE = 1.56 <deg>

PHASE\_ANGLE = 75.03 <deg>

LO:PHOTO\_ILLUMINATION\_ALPHA\_ANGLE = 1.54 <deg>

LO:PRINCIPAL\_POINT\_LATITUDE = 3.04 <deg>

LO:PRINCIPAL\_POINT\_LONGITUDE = 34.37 <deg>

FOOTPRINT\_POINT\_LATITUDE = (3.34, 2.68, 2.74, 3.41)

FOOTPRINT\_POINT\_LONGITUDE = (34.58, 34.33, 34.16, 34.41)

LO:AB\_SIDE\_LENGTH = 21.4 <km>

LO:BC\_SIDE\_LENGTH = 5.4 <km>

LO:CD\_SIDE\_LENGTH = 21.5 <km>

LO:DA\_SIDE\_LENGTH = 5.4 <km>

LO:SIDE\_LENGTH\_TILT\_DISTANCE = 16.10 <km>

PRODUCER\_INSTITUTION\_NAME = "SKYCORPINC"

PRODUCT\_CREATION\_TIME = 2016-08-04T10:59:00.00

NOTE = "LO3 CONSTRUCTED FRAME 006.

 HIGH RESOLUTION 1 OF 3."

/\* DATA OBJECT DEFINITIONS \*/

OBJECT = IMAGE

 LINES = 16500

 LINE\_SAMPLES = 19992

 SAMPLE\_TYPE = LSB\_UNSIGNED\_INTEGER

 SAMPLE\_BITS = 16

END\_OBJECT = IMAGE

END

The DATA\_SET\_ID changes slightly with each Lunar Orbiter:

LO1: "LO1-L-80MMFLC/24INCHFLC-5-MIDR-V1.0"

LO2: "LO2-L-80MMFLC/24INCHFLC -5-MIDR-V1.0"

LO3: "LO3-L-80MMFLC/24INCHFLC -5-MIDR-V1.0"

LO4: "LO4-L-80MMFLC/24INCHFLC -5-MIDR-V1.0"

LO5: "LO5-L-80MMFLC/24INCHFLC -5-MIDR-V1.0"

# Applicable Software

## Utility Programs

These images may be opened with Photoshop, or any other program capable of reading a “.raw” file. The only requirement would be that once the image is downloaded from the PDS, the file extension “.IMG” would have to be changed to “.raw” to be read by those programs. Labels may be read outside of NASAView with any text edit application such as TextEdit or Text Wrangler.

## Applicable PDS Software Tools

PDS-labeled images and tables can be viewed with the program NASAView, developed by the PDS and available for a variety of computer platforms from the PDS web site https://pds.nasa.gov/tools/nasa-view.shtml. There is no charge for NASAView.

## Software Distribution and Update Procedures

Not Applicable

Table . Processing Levels for Science Data Sets

| NASA | CODMAC | Description |
| --- | --- | --- |
| Packet data | Raw - Level 1 | Telemetry data stream as received at the ground station, with science and engineering data embedded. |
| Level-0 | Edited - Level 2 | Instrument science data (e.g., raw voltages, counts) at full resolution, time ordered, with duplicates and transmission errors removed. |
| Level 1-A | Calibrated - Level 3 | Level 0 data that have been located in space and may have been transformed (e.g., calibrated, rearranged) in a reversible manner and packaged with needed ancillary and auxiliary data (e.g., radiances with the calibration equations applied). |
| Level 1-B | Resampled - Level 4 | Irreversibly transformed (e.g., resampled, remapped, calibrated) values of the instrument measurements (e.g., radiances, magnetic field strength). |
| Level 1-C | Derived - Level 5 | Level 1A or 1B data that have been resampled and mapped onto uniform space-time grids. The data are calibrated (i.e., radiometrically corrected) and may have addi­tional corrections applied (e.g., terrain correction). |
| Level 2 | Derived - Level 5 | Geophysical parameters, generally derived from Level 1 data, and located in space and time commensurate with instrument location, pointing, and sampling. |
| Level 3 | Derived - Level 5 | Geophysical parameters mapped onto uniform space-time grids. |