9. LORRI INSTRUMENT DESCRIPTION

9.1 Overview

The LOng Range Reconnaissance Imager (LORRI) is a narrow angle (FOV=0.29°), high resolution (IFOV=5 µrad), Ritchey-Chrétien telescope with a 20.8 cm diameter primary mirror, a focal length of 263 cm, and a three lens field-flattening assembly. A 1024 x 1024 pixel (optically active region), back-thinned, backside-illuminated CCD detector (model CCD 47-20 from E2V) is located at the telescope focal plane and is operated in standard frame-transfer mode. LORRI does not have any color filters; it provides panchromatic imaging over a wide bandpass extending approximately from 350 nm to 850 nm. The LORRI telescope has a monolithic silicon carbide structure, built by SSG Precision Optronics, Inc., is designed to maintain focus over the entire operating temperature range (-125 C to +40 C) without a focus adjustment mechanism. A detailed description of the design and fabrication of LORRI can be found in the paper by Conard, et al., "Design and fabrication of the New Horizons Long-Range Reconnaissance Imager" in SPIE proceedings 5906-49, 2005. A detailed discussion of the performance of LORRI, as measured during calibration testing before launch, can be found in the paper by Morgan et al., “Calibration of the New Horizons Long-Range Reconnaissance Image” in SPIE proceedings 5606-49, 2005.

LORRI is a supplemental instrument on New Horizons and is not needed to meet the baseline scientific objectives of the mission. Nevertheless, LORRI adds significant capabilities to New Horizons, including the highest available spatial resolution (50 m/pixel at the Pluto closest approach distance of 10,000 km) and redundancy for the primary optical imager, MVIC on Ralph.

The exposure time for LORRI is adjustable in 1 msec increments from 0 ms to 29,967 msec. However, exposure times will normally be limited to ≤ 150 msec to prevent image smear associated with spacecraft motion during observations. Initially, the shortest useful exposure time was expected to be ~40 msec owing to frame transfer smear associated with the transfer of charge from the active CCD region to the storage region, during which time the active region remains exposed to the image scene because LORRI has no shutter, but an improved frame transfer smear removal algorithm was developed that now permits exposure times as little as 1 msec. The LORRI exposure time can be commanded to a specific value, or LORRI can be operated in “auto-exposure” mode, in which the LORRI flight software sets the exposure time automatically based on the signal level in a previous image. In auto-exposure mode, the algorithm used to set the exposure time depends on several adjustable parameters that are stored in an onboard table. The optimal values for these table parameters vary with the type of scene being observed, which means that new table loads may be required prior to some observations. Although the LORRI auto-exposure mode worked well during ground testing, no decision has yet been made on whether it will be used in-flight during encounter observations.

LORRI can also be operated in “rebin” mode, in which case the signal in a 4 x 4 pixel region is summed on-chip to produce an active region that is effectively 256 x 256 pixels covering the entire 0.29° FOV. The main purpose of this mode is to provide high sensitivity acquisition of a Kuiper Belt object (KBO), which requires an exposure time of ~10 sec. Although LORRI rebin mode may never be used for science observations, the LORRI pipeline is still required to calibrate rebinned images.

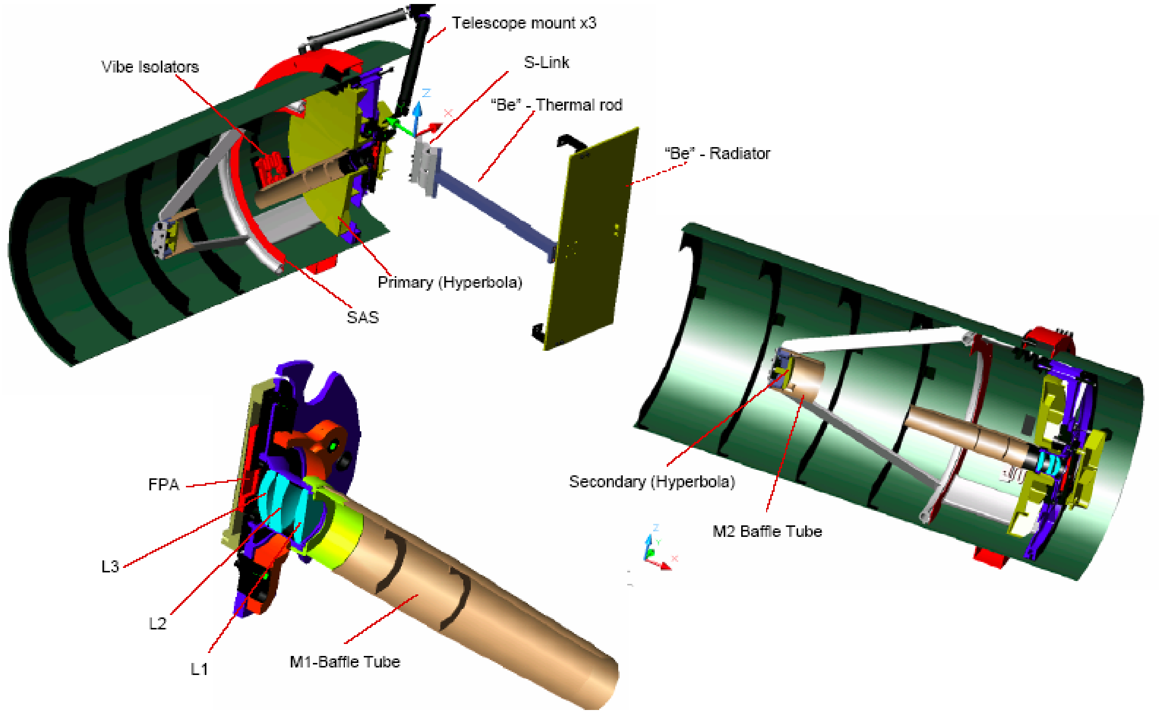


Figure 9-1:Cutaway Views of LORRI

9.2 Raw image Specifics

9.2.1 Data Format

The raw image data is organized in a FITS file. The primary header and data unit (HDU) is used to store the reconstructed image from telemetry. Additional data are stored in the extensions of the file. The two tables below contain a description of the layout for the extensions for raw data.

As described previously, LORRI operates in two binning modes: 1x1 and 4x4. For the 1x1 binning mode, the raw image dimensions are 1028x1024 where columns 0 through 1023 are the optically active region of the CCD and the remaining columns (1024-1027) are from optically inactive region (dark columns) of the CCD and represent a temperature-specific measurement of the bias value. For the 4x4 binning mode, the raw image dimensions are 257 x 256 where columns 0 through 255 are optically active and column 256 for the dark column.

FITS File Storage Location	Description
Primary HDU	Reconstructed image from telemetry
First Extension	histogram from image descriptor packet (ApID 0x611)
Second Extension	Instrument housekeeping from first 34 pixels
Third Extension	Matching image descriptor

Table 9-1 Raw FITS file extension layout (ApID => Packet Application ID)

9.2.2 Data Sources (High/Low Speed, CCSDS, ITF)

The LORRI high-rate data is delivered to the Instrument Interface card over a low-voltage differential signal (LVDS) interface and is then transferred to the SSR through the spacecraft high-speed PCI bus by the C&DH software. The image data is stored directly on the SSR and CCSDS (Consultative Committee for Space Data Systems) packets are generated by command to the C&DH software as is described in the table below. The ApID (packet Application Process IDentifier; also Application ID) from which the image originated is part of the filename, so this mapping may provide some assistance in decoding the filenames retrieved from the SOC.

ApID	MNEMONIC	Description
0x0601	LORRI_MEM_DMP	Memory Dump
0x0602	LORRI_MEM_CKSM	Memory Checksum
0x0603	LORRI_CMD_ECHO	Command Echo
0x0604	LORRI_ALARM	Alarm
0x0605	LORRI_STAT	Status
0x0606	LORRI_MON	Monitor Limits
0x0607	LORRI_BOOT	Boot Status
0x0608	LORRI_MAC_DMP	Macro Dump
0x0609	LORRI_MAC_CKSM	Macro Checksum
0x0610	LORRI_PARM	Parameters
0x0611	LORRI_IMG_DES	Image Descriptor

Table 9-2 Low Rate Instrument Telemetry Description

ApID	C&DH side	binning mode	compression type
0x630	1	1x1	lossless
0x631	1	1x1	packetized
0x632	1	1x1	lossy
0x633	1	4x4	lossless
0x634	1	4x4	packetized
0x635	1	4x4	lossy
0x636	2	1x1	lossless
0x637	2	1x1	packetized
0x638	2	1x1	lossy
0x639	2	4x4	lossless
0x63A	2	4x4	packetized
0x63B	2	4x4	lossy

Table 9-3 LORRI high-speed telemetry description

9.2.3 Definition of an "Observation"

Each LORRI image is an "observation."

9.2.4 Housekeeping Needed in Raw Image Files (for Calibration)

No special requirements other than pointing

9.2.5 Raw Science Data and/or Housekeeping Requirements

No special requirements

9.3 Calibrated Image Specifics

9.3.1 Algorithms for Pipeline Calibration Process

The calibration of LORRI images potentially involves all of the following steps:

1) Bias subtraction
2) Signal linearization
3) Charge transfer inefficiency (CTI) correction
4) Dark subtraction
5) Smear removal
6) Flat-fielding
7) Absolute calibration

Ground testing has demonstrated that the linearization, CTI, and dark subtraction steps will not be needed, so they are not described below. Nevertheless, the LORRI pipeline architecture will be maintained to allow these additional steps to be incorporated quickly, if in-flight data suggest they are needed.

The LORRI pipeline software consists of a series of IDL routines that implement the above processing steps. In general, the IDL routines have the following naming convention: ***lorri_function.pro***, where "function" refers to the specific task performed by that routine. (The "pro" extension will be omitted below when discussing specific routines.) Each routine typically has several command line arguments and keywords that specify the input and output files and, possibly, parameters for tailoring the routine for particular circumstances. The routines that perform the bias subtraction, the smear removal, and the flat-fielding are described below. No special routines are provided to perform the absolute calibration. Instead, the absolute calibration is performed using keywords provided in the FITS header, as described further in Section 9.3.1.4.

9.3.1.1 Bias Subtraction

If an image has an associated "dark" image (i.e., an image taken with the same exposure time but without any illumination), then the debiased image is simply the difference of those two images. This was usually the case during on-ground testing when images taken of a scene were immediately followed by images taken with the scene blocked (i.e., an obstruction was placed in the optical path to block the illumination). However, in-flight images may often be taken without accompanying darks either because of limitations on downlink bandwidth, or because a decision is made to take more target images at the expense of concurrent darks. In either case, the same pipeline routine will be used to debias the image (***lorri_debias***), but the algorithm employed is different in each case and different reference files are required.

If in-flight data indicate that bias images are stable over time, many bias images will be combined (after filtering out clearly discrepant pixels) to produce a "super-bias" image. Then the median value of the inactive region of the image (i.e., the median of a 1024 row by 4 column region) is subtracted from the super-bias image to produce a "delta-bias" image. The IDL procedure that produces the delta-bias image is called ***lorri_delta_bias***, but this routine is *not* part of the standard LORRI calibration pipeline; rather, it is an ancillary routine used to produce a calibration reference file.

The delta-bias image will exhibit the pixel-to-pixel variation in the bias and will oscillate about zero. The bias subtraction for any new image is then a two-step process:

1) The median signal level in the inactive region of the image is subtracted from each pixel's value to remove the overall bias level, and
2) The delta-bias image is subtracted from the image created in the previous step to remove the pixel-to-pixel variation and produce the final, debiased image.

Ground calibration testing showed that the overall bias level in step (1) above depends on the signal level in the last few columns of the active region of the CCD. The effect is produced by amplifier undershoot, which means that the bias level recorded by the pixels in the inactive region is smaller than the actual bias level. The magnitude of the effect depends on the signal level in the active region and on the column number in the inactive region and can be as large as ~12 DN. Thus, prior to computing the median signal in the inactive region (step 1 above), the intensities of all the pixels must be corrected for amplifier undershoot. This correction step is incorporated into the ***lorri_debias*** procedure.

If the in-flight bias images vary significantly in time, separate bias images (i.e., 0 ms exposures) must be taken for each science image obtained. In this case, the bias subtraction proceeds exactly as performed during ground calibration testing, with the bias removal achieved by simple subtraction of the bias image from the science image. There are several drawbacks to this approach: (1) more images must be taken, which affects the data volume that must be stored on the on-board solid-state recorder, (2) more data must be downlinked, which may not be possible because of limited downlink bandwidth and/or the cost associated with the extra Deep Space Network (DSN) support required, (3) the signal-to-noise ratio (SNR) may be degraded because the bias subtraction no longer involves a high SNR reference file, and (4) fewer science images can be obtained because they have been displaced in the observing timeline by extra bias images.

9.3.1.2 Smear Removal

LORRI does not have a shutter, so the target being observed illuminates the active region of the CCD whenever LORRI is pointed at the scene. In particular, the CCD continues to record the scene as the charge is transferred from the active portion to the storage area, and this results in a smearing of the observed scene. Fortunately, this smear can be removed to high accuracy using the correction algorithm described below.

When bright objects are observed, the readout smear makes the raw image difficult to use for analysis purposes. In the image of Jupiter below, the raw image is on the left and the calibrated image with readout smear (aka frame transfer smear) removed is on the right.

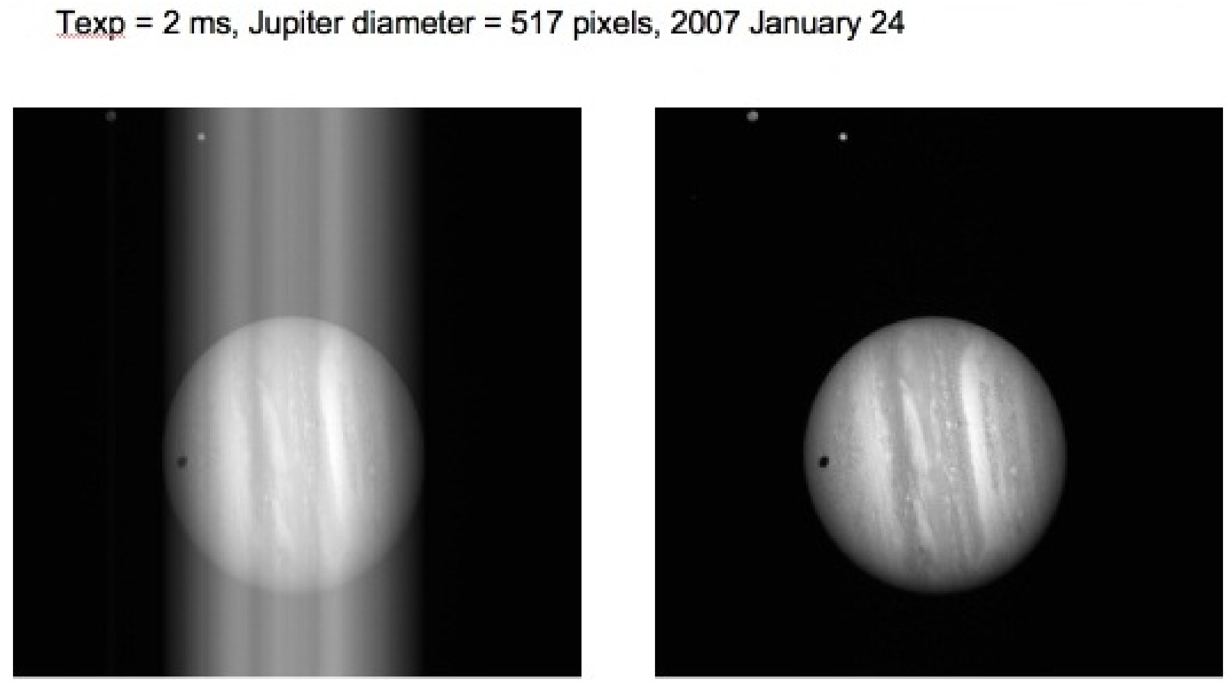

Texp = 2 ms, Jupiter diameter = 517 pixels, 2007 January 24

Figure 9-2:Demonstration of Smear Removal

The need for the readout smear removal arises from the operation of the frame transfer CCD used in LORRI, where first the image zone is flushed, then an exposure is taken, and finally the image is transferred into the storage zone. Hence a pixel of the raw image is exposed to the scene radiance from the corresponding geometrical element of the scene, but it is also exposed to the radiances of all the scene elements in the same image column during the image transfers. Thus the raw image is the superposition of the scene radiance and the signal acquired during frame transfers, which is called readout smear.

The readout smear is removed as follows. Let $P_{i,j}^{meas} = \text{measured image array in DN}$ where i, j are the column and row indices, respectively. Let the exposure time be written T_{exp}, with the transfer times for the frame scrub T_{f1} and the frame storage T_{f2} and with N the number of rows (which is 1024 for 1×1 images and 256 for 4x4). Let T_{favg} be the average of T_{f1} and T_{f2} to define the constant $A = \dfrac{T_{\exp}}{T_{\exp} - \dfrac{T_{favg}}{N}}$.

Finally we define the $N \times N$ constant matrix $\varepsilon_{k,j} = \begin{cases} T_{f1} / T_{favg} & \text{for k < j} \\ 1 & \text{for k = j} \\ T_{f2} / T_{favg} & \text{for k > j} \end{cases}$

with $k, j = 1, \ldots, N$, and we calculate the $N \times N$ matrix $\lambda_{i,j}^{(1)} * T_{\exp} = A \left[P_{i,j}^{meas} - \dfrac{A\, T_{favg} \sum_k P_{i,k}^{meas} \varepsilon_{k,j}}{N\left(T_{\exp} + A\, T_{favg}\right)} \right]$.

The desmeared image is then

$$P_{i,j}^{desmear} = A\left[P_{i,j}^{meas} - \frac{A\,T_{favg}\left[\sum_k P_{i,k}^{meas}\varepsilon_{k,j} + \frac{E_{i,j}}{A}\right]}{N\left(T_{\exp} + A\,T_{favg}\right)}\right]$$

with $\frac{E_{i,j}}{A} = T_{favg}\left[\sum_k \lambda_{i,k}^{(1)}\,\varepsilon_{k,j} - \frac{1}{N}\sum_l\sum_k \lambda_{i,k}^{(1)}\,\varepsilon_{k,l}\varepsilon_{l,j}\right]$. In-flight tests have verified desmear by this technique using observations of Jupiter obtained at exposure times as short as 1 ms.

The value for T_{favg} is dependent on the desired exposure time and has been determined empirically using in-flight data. The following Table 9-4 provides the appropriate values at different exposure times.

Desired Exposure Time (msec)	Value for T_{favg} (msec)
1	7.1
2	8.75
3	9.65
6	10.5
Nominal	10.7

Table 9-4 Value for Tfavg from Texp

It should be noted that when the raw data is saturated, the resulting readout smear correction will be inaccurate. The algorithm relies on an accurate accumulation of charge in all rows of each column and if the raw data is clipped for lack of dynamic range to capture that integrated signal, the effect of readout smear cannot be completely and properly removed.

This correction algorithm has been implemented in the IDL routine ***lorri_desmear***.

9.3.1.3 Flat-Fielding

Flat-fielding refers to the process of removing the pixel-to-pixel sensitivity variations in the image. An exposure obtained by illuminating the LORRI aperture uniformly with light is called a “flat-field” image. During ground calibration testing, flat-fields were obtained by using an “integrating sphere to provide uniform illumination. The light source was a xenon arc lamp with a spectrum similar to that of the sun. The absolute intensity of the input illumination was measured using a calibrated photodiode. For the panchromatic case, which is the one most relevant for flat-fielding LORRI images, the light from the xenon lamp was unfiltered. Flat-field images were also obtained by passing the light through bandpass filters centered at five different wavelengths spanning the range over which LORRI is sensitive, prior to injection into the reference sphere, in order to estimate the sensitivity of the flat-fields to the spectral distribution of the source. The spatial patterns in the flat-field images change fairly dramatically with wavelength. However, the variation in panchromatic flat-fields caused by differences in the spectral distribution of the illumination source should be much less significant. Indeed, panchromatic flat-field images produced using a tungsten lamp were virtually indistinguishable from those produced by the xenon lamp. Flat-fields were obtained at four different telescope temperatures (at standard laboratory room temperature, and at the lowest, nominal, and highest temperatures predicted for in-flight conditions), but no significant temperature variations in the flat-field images were detected.

The flat-field reference file used in the LORRI pipeline was produced by averaging 100 flat-field images taken at room temperature using the xenon arc lamp as the light source, debiasing and desmearing the average image as described earlier, and normalizing the intensities in the active region to a median value of 1. If “S” (units are DN) is an image of a target that has already been desmeared and debiased, and if “FF” is the reference flat-field image, then the flat-fielded (i.e., photometrically-corrected) target image (“C”; units are DN) is given by:

$$C = S/FF$$

The flat-fielding correction is implemented in the LORRI pipeline by the routine ***lorri_flatten***.

If in-flight measurements indicate that the LORRI flat-field characteristics are different than those measured during ground calibration tests, new reference flat-field images must be obtained. Although LORRI has two internal reference lamps (sometimes referred to as “cal lamps”), the illumination pattern is highly non-uniform and, thus, not very suitable as a secondary flat-field standard. Various test measurements will be performed during the early portion of the mission to determine if scattered sunlight can serve as a suitable secondary flat-field standard. If there is a Jupiter encounter, smeared images of Jupiter might also prove to be useful as a secondary flat-field standard. In any case, there will be an attempt to monitor the flat-field characteristics of LORRI over time, and the reference flat-field image used by the LORRI pipeline will be updated as necessary to maintain an accuracy better than 1% in the correction of the pixel-to-pixel sensitivity variation, except possibly near the center of the field where image ghosts may compromise the quality of the reference flat-field (see further discussion below).

During ground calibration tests, intensity artifacts caused by optical ghosts were observed near the center (roughly covering a 200 x 200 pixel region) of the flat-field images. Ray tracing of the optical system indicates that the intensity of the ghost image should be less than ~1% of the intensity produced by the direct illumination, but measurements indicated that ghost intensities have an amplitude of ~5-7% of the direct intensity for panchromatic illumination. The ghost intensity is scene-dependent with most (~80%) of the ghost signal arising from regions outside the nominal field-of-view of LORRI. There is a suspicion that at least some of the ghost signal is an artifact of the test conditions, and the reference flat-fields currently used by the pipeline do *not* include the ghost signal produced by the out-of-field light. Any flat-field data taken in-flight will be carefully scrutinized to search for any effects attributable to optical ghosts. Depending on those results, further modifications to the reference flat-fields may be required. There is also the possibility that different flat-field reference images may be required depending on the scene being imaged (i.e., a ghost subtraction step may be required prior to application of the flat-field correction under some circumstances).

9.3.1.4 Absolute Calibration (Conversion from corrected DN to physical units)

The calibration software pipeline does not perform the conversion from DN to physical units because that conversion requires knowledge of the spectral distribution(i.e. color) of the target. Instead, various LORRI FITS header keywords (“photometry” keywords) are provided that allow users to convert from

DN to physical units depending on the spectral type and spatial distribution (diffuse vs. point source) of the target.

Photometry keywords are provided for targets having spectral distributions similar to Pluto, Charon, Pholus, Jupiter, and the Sun. The units adopted for the radiance (aka "intensity") of diffuse targets are ergs/cm2/s/sr/Å. The units adopted for the irradiance (aka "flux") of point (i.e., unresolved) targets are ergs/cm2/s/Å. Tables providing the values for the photometry keywords at the time of launch are given below. The latest (i.e., current) values of the photometry keywords are provided in the header of the calibrated image FITS file for the image being analyzed.

The absolute calibration is achieved by specifying a keyword (RPLUTO) in the header of the calibrated image file that allows the user to convert a count rate ("C/TEXP" in DN/s/pixel, where "C" is the flat-fielded signal in a pixel and "TEXP" is the exposure time) for a resolved source into a radiance value ("I" in ergs/cm^2/s/sr/Å) at LORRI's pivot wavelength (specified by the FITS keyword PIVOT; see below), assuming that the spectrum of the target is identical to the globally-averaged spectrum of Pluto. The relevant formula is:

$$I = C/TEXP/RPLUTO$$

Similarly, the keyword RSOLAR allows the conversion of the count rate for a resolved source into a radiance value at the pivot wavelength assuming that the target has a solar-like spectral distribution:

$$I = C/TEXP/ RSOLAR$$

Finally, the keyword RPHOLUS allows the conversion of the count rate for a resolved source into a radiance value at the pivot wavelength assuming that the target has a spectral distribution identical to that of the centaur object 5145 Pholus, which may be a good analog for the reddest regions on Pluto:

$$I = C/TEXP/RPHOLUS$$

The current best estimates for these sensitivity keywords, based on ground calibration tests, are provided in the table below. In-flight calibration observations of photometric standard stars will be used to verify these values and to monitor them over time.

Keyword	**Value [(DN/s/pixel)/(ergs/cm^2/s/sr/Å)]**
RSOLAR	2.664×10^5
RPLUTO	2.575×10^5
RCHARON	2.630×10^5
RJUPITER	2.347×10^5
RPHOLUS	3.243×10^3

If users need conversions for other spectral distributions, they must derive those themselves using the LORRI spectral response function provided in the paper describing LORRI's in-flight calibration results.

The pivot wavelength (PIVOT) is given by:

$$PIVOT = \sqrt{\left(\frac{\int P\lambda d\lambda}{\int P d\lambda / \lambda}\right)}$$

where “P” is the LORRI system quantum efficiency (i.e., fraction of photons detected) at wavelength “ λ”. The current best estimate for the LORRI pivot wavelength is 6076 Å.

For unresolved sources (e.g., stars), the absolutely calibrated flux (also called “irradiance”) at the pivot wavelength can be determined using keywords that are defined analogously to the photometry keywords discussed above for resolved sources. In the case of a source having a spectral distribution identical to that of a globally-averaged Pluto spectrum, the observed count rate integrated over the LORRI PSF (“CINT/TEXP” in DN/s, where CINT is the total number of flat-field corrected counts integrated over the image and “TEXP” is the exposure time) can be related to the flux (“F” in ergs/cm^2/s/Å) by:

F = CINT/TEXP/PPLUTO

Similarly, the flux at the pivot wavelength for a target having the same spectral distribution as the sun is given by:

F = CINT/TEXP/PSOLAR

And the flux at the pivot wavelength for a target having the same spectral distribution as 5145 Pholus is given by:

F = CINT/TEXP/PPHOLUS

The current best estimates for these sensitivity keywords, based on ground calibration tests, are provided in the table below. In-flight calibration observations of photometric standard stars will be used to verify these values and to monitor them over time.

Keyword	**Value [(DN/s)/(ergs/cm^2/s/Å)]**
PSOLAR	1.066×10^{16}
PPLUTO	1.030×10^{16}
PCHARON	1.052×10^{16}
PJUPITER	9.386×10^{16}
PPHOLUS	1.297×10^{16}

Synthetic photometry techniques can be used to convert the fluxes derived in the manner described above to fluxes at other wavelengths, and then into standard *UBVRI* magnitudes in the Landolt (1992) photometric system, which is essentially identical to the Johnson *UBV* system combined with the Kron-

Cousins *RI* system. The results described in the LORRI calibration paper can be used to derive fluxes for targets whose spectral distributions do not match the three cases discussed above.

We provide below some examples showing how to convert from engineering units to physical units, for both diffuse and point targets.

Consider a diffuse target whose spectrum is similar to that of Pluto. You should then use the RPLUTO photometry keyword in the header of the calibrated image file to convert a count rate ("C/TEXP" in DN/s/pixel, where "C" is the flat-fielded signal in a pixel and "TEXP" is the exposure time) into a radiance value ("I" in ergs/cm2/s/sr/Å) at LORRI's "pivot" wavelength (specified by the FITS keyword PIVOT for the formal definition of the pivot wavelength):

I = C/TEXP/RPLUTO

Similarly, the photometry keywords RSOLAR, RCHARON, RJUPITER, and RPHOLUS should be used to convert count rates into radiance values at the pivot wavelength assuming that the target has, respectively, solar-like, Charon-like, Jupiter-like, or Pholus-like spectral distributions.

For LORRI, the pivot wavelength is 6076.2 Å, and we don't expect this to change, at least not significantly. Since the solar flux (F_solar) at a heliocentric distance of 1 AU at the pivot wavelength is 176 erg/cm2/s/Å, the value for the radiance can be converted to I/F (where pi*F = F_solar) using:

I/F = pi * I * r^2 / F_solar

where "r" is the target's heliocentric distance in AU.

For unresolved targets (e.g., stars), the absolutely calibrated flux (also called the "irradiance") at the pivot wavelength can be determined using keywords that are defined analogously to the photometry keywords discussed above for resolved targets. In the case of a target having a spectral distribution identical to that of a globally-averaged Pluto spectrum, the observed count rate integrated over the LORRI PSF ("CINT/TEXP" in DN/s, where CINT is the total number of flat-field corrected counts integrated over the image and "TEXP" is the exposure time) can be related to the flux ("F" in ergs/cm2/s/Å; not to be confused with "F" in I/F) by:

F = CINT/TEXP/PPLUTO

When observing point targets, it is more common to convert the absolute flux to a magnitude in a standard photometric system. The following equation can be used to transform a measured value of the irradiance (aka "flux") of an unresolved target to a magnitude in the standard V band:

V = -2.5 log S + PHOTZPT + CC + BC

where "V" is the visual magnitude in the Johnson photometric system, PHOTZPT is the "stellar photometry keyword", which is the "zero point" of the LORRI instrumental magnitude system, "S" is the integrated net signal rate from the target in DN/s, "CC" is the color correction (i.e., correction for the spectral distribution of the target), and "BC" is the aperture correction (in case the flux is not integrated over the entire stellar image; a careful analysis of the flux versus aperture size for a bright star in the field can then be used to determine the value of BC for the aperture selected for the photometry).

In-flight photometry of stars in the open galactic cluster M7 yield the following:

PHOTZPT = 18.94

Spectral Type	CC
O, B, A stars	-0.06
F, G stars	0
K stars	+0.4
M stars	+0.6
Pluto	-0.037
Charon	-0.014
Jupiter	-0.138
Pholus	+0.213

Table 9-5 Color correction coefficient for various targets

The following reference flux information is provided for convenience and was gathered from several sources. The UBV are in the Johnson system, RI are in the Landolt-Kron-Cousins system, and JHK_sK are in the UKIRT system.

The fluxes for Vega are from the model STScI absolutely-calibrated spectrum. At near-IR wavelengths, the model underestimates the actual Vega flux by about 5-6% owing to the excess flux from the Vega dust disk. Note also that Vega has U=B=V=0.03 (i.e., not 0).

Band	Center (Å)	Vega Flux (ergs/cm2/s/Å)
U	3600	3.05×10^{-9}
B	4400	6.74×10^{-9}
V	5500	3.54×10^{-9}
R	6500	2.11×10^{-9}
I	8000	1.12×10^{-9}
J	12200	3.18×10^{-10}
H	16540	1.11×10^{-10}
K_s	21570	4.10×10^{-11}
K	21790	3.97×10^{-11}

Table 9-6 Fluxes for Vega

9.3.1.5 Pointing Information

Pointing information for the LORRI boresight (center of the LORRI field-of-view, which is pixel [511,511]) is included in the FITS header in both the raw and the calibrated image files. An example of this information follows:

SPCBLRA = 233.4199004768138 / [degrees] Boresight RA, EME J2000

SPCBLDEC= -17.96897170490819 / [degrees] Boresight DEC, EME J2000

SPCEMEN = 283.935414259362 / [degrees] EME J2k North Clk Angle, CW from UP

9.3.1.6 Conversion of instrument housekeeping items to engineering units

The LORRI-specific housekeeping items reported in the raw FITS file are in units of counts or DN. To make these values more useful for data analysis, they have been converted to engineering units (volts, amps, degrees Celsius) and reported at the tail end of the header of the primary HDU of the calibrated FITS file. Because the contents of the raw header are duplicated in the calibrated file, a different set of tag names are used for the values that have been converted to engineering units. The new tags are reported after the comment that reads “LORRI Level 2 Calibrated telemetry items”.

9.3.2 Instrument Characterization

There are several characteristics of the instrument that are related to the radiometric calibration of LORRI that will be useful when analyzing the calibrated image data. They are the quantum efficiency and spectral responsivity, each as a function of wavelength. There are tables for each of these in the calibration directory for the PDS archive, but a graph for each is reproduced in the figures below.

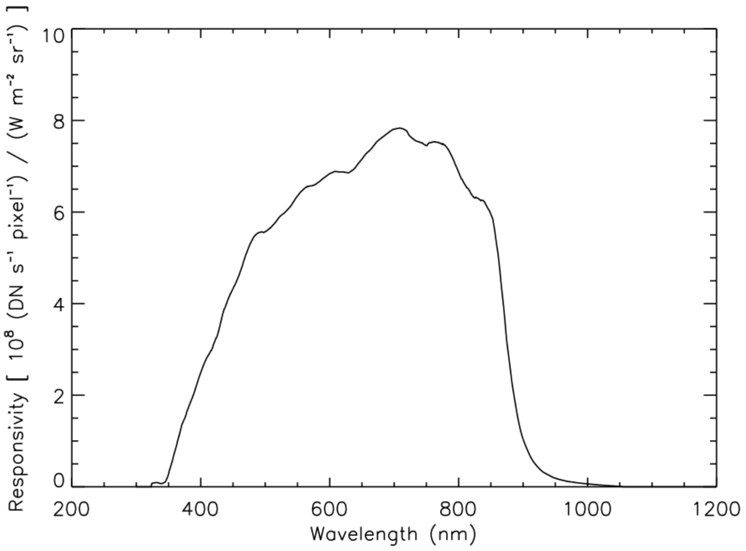


Figure 9-3 LORRI Spectral Response vs Wavelength

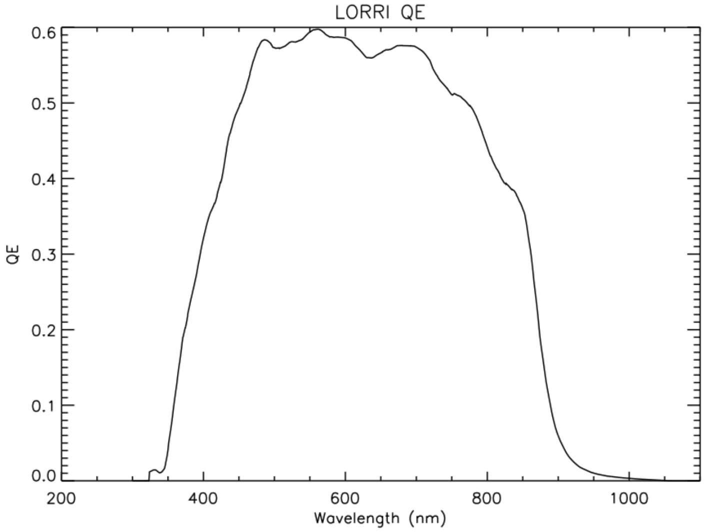
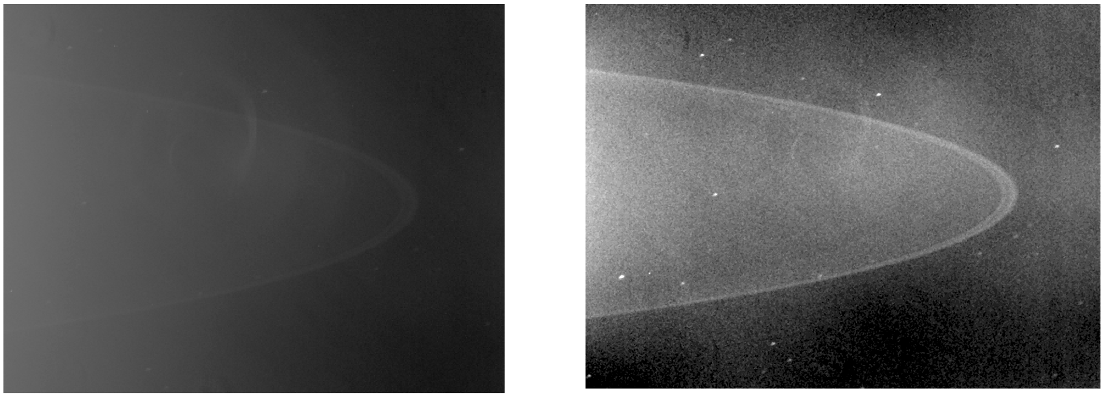


Figure 9-4 LORRI Quantum Efficiency vs Wavelength

9.3.3 *Special Processing*

After the data have been calibrated, additional processing steps are likely to be required. Obvious examples of this are ghost removal and stray light processing. At present, there have been no algorithms developed for public release because they are highly scene dependent. Individual images must be analyzed to understand the structure of the effects to determine an appropriate method for its removal. In the example below, a cutout from a calibrated image is presented to illustrate the effect of stray light from Jupiter’s disk, which is just out of the field of view. The circular structure is an example of the ghost pattern. The image on the right demonstrates the processed version of that image. The gradient from the stray light has been removed, as well as the majority of the effects of the ghost.

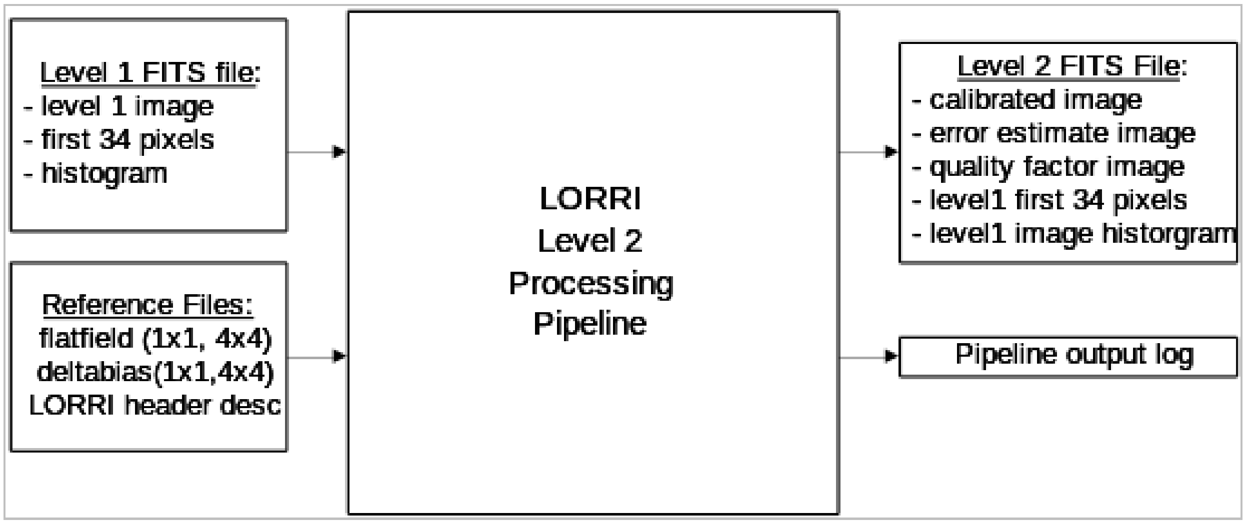


Calibrated Image (MET=003460092) with stray light and ghost effects

Image after special processing to remove ghost and stray light

Figure 9-5 Example of Special Processing of Calibrated Data

9.3.4 Dataflow Block Diagram



9.3.5 Data Format

The calibrated image data is organized in a FITS file. The primary header and data unit (HDU) is used to store the calibrated image that results from the calibration pipeline. The first extension is the error estimate image, followed by the second extension containing the data quality image. The table below contains a description of the layout for the extensions for calibrated data.

For 1x1 binning mode, the calibrated image dimensions are 1024x1024, and for 4x4 mode, the dimensions are 256x256 pixels. In both situations, these pixels correspond to the optically active pixels from the raw image mentioned previously.

FITS File Storage Location	Description
Primary HDU	Calibrated image
First Extension	Error image
Second Extension	Data Quality Image

Table 9-7 Calibrated FITS file extension layout

9.3.6 Extra FITS Extensions (planes) and Their Definitions

LORRI calibrated FITS files have 3 extensions. The debiased, desmeared LORRI image is written into the primary HDU as a 2-dimensional, 32-bit real image. The unit for each data value is photometrically-corrected DN. The estimated errors in these corrected DN values are stored as a 2-dimensional, 16-bit real image in the first extension. A data quality image is stored in the second extension as a 2-dimensional, 16-bit integer image.

The error in the photometrically-corrected signal is estimated from:

$$\sigma = \frac{\sqrt{(P_{meas}/g) + (RN)^2 + (fP_{meas})^2}}{FF}$$

where “σ” is the 1-sigma error in the corrected signal for a particular pixel (DN), “P_{meas}” is the observed signal in that pixel (DN, after bias subtraction but before smear removal), “g” is the electronics gain (22 e/DN), “RN” is the electronics noise (1.3 DN), “f” is the estimated error in the reference flat-field image (0.005), and “FF” is the value of the reference flat-field image at the relevant pixel. The above formula neglects any noise contributed by the bias and smear removal steps, but those errors are generally expected to be small compared to the other sources of error.

The data quality image is used to flag pixels that have known artifacts and may need special consideration when performing scientific analysis. The pixel value in the quality flag image represents the sum of all quality flags present for that pixel. This pixel value can also be described as the result of the bitwise ‘OR’ of each quality flag value. The list of data quality values and their descriptions are listed in the table below:

Quality Flag Value	Bit position in 2-byte word	Description
0	n/a	Good pixel
1	0	Defect in reference deltabias image (set if 0 or NaN)
2	1	Defect in reference flatfield image (set if 0 or NaN)
4	2	Permanent CCD defect; pixel>0 in dead_ground_NxN.fit map
8	3	Hot Pixel identified; pixel>0 in hot_ground_NxN.fit map
16	4	Saturated pixel in raw data (A/D value of 4095)
32	5	Missing raw data (assume fill value of 0)
64 and higher	6-15	unused at present

Table 9-8 Quality flag value descriptions

9.3.7 Scientific Units

Following the convention adopted by the New Horizons Principal Investigator, the unit used for calibrated data product are “photometrically-corrected DN”. The procedure given above must be completed to obtain absolutely calibrated data products. The units adopted for the radiance (aka “intensity”) of diffuse targets are ergs/cm^2/s/sr/Å. The units adopted for irradiance (aka “flux”) of point (i.e. unresolved) targets are ergs/cm^2/s/Å. Wavelengths are quoted in angstrom units.

9.3.8 Additional FITS and PDS Keywords Added

Listed below are the keywords and sample values for those keywords that have been added to the FITS header and are stored with the primary HDU of the output calibrated image FITS file.

```
COMMENT ********************************************************
COMMENT *** LORRI Level 2 software name and version info      ***
COMMENT ********************************************************
L2_SWNAM= 'lorri_level2_pipeline' /Level 2 calibration software
L2_SWVER= 'untagged'           /software version tag
COMMENT ********************************************************
COMMENT *** LORRI Level 2 software logic flow control flags   ***
COMMENT ********************************************************
IMGSUBTR= 'OMIT    '           / image subtraction step
BIASCORR= 'PERFORM '           / bias subtraction step
SLINCORR= 'OMIT    '           / signal linearization step
CTICORR = 'OMIT    '           / charge transfer inefficiency step
DARKCORR= 'OMIT    '           / dark subtraction step
```

```
SMEARCOR= 'PERFORM '           / smear removal step
FLATCORR= 'PERFORM '           / flat-fielding step
GEOMCORR= 'OMIT    '           / geometric correction step
ABSCCORR= 'PERFORM '           / absolute calibration step
COMPERR = 'PERFORM '           / compute error estimate
COMPQUAL= 'PERFORM '           / compute quality flags
COMMENT *********************************************************
COMMENT *** LORRI Level 2 Reference Filename                  ***
COMMENT *********************************************************
REFDEBIA= 'sap_006_combined_100img_1x1.fit' / debias image filename
REFFLAT = 'cflat_grnd_SFA_20050309_v2.fit' / flat field image filename
REFDEAD = 'dead_ground_1x1_synthetic.fit' / dead pixel image filename
REFHOT  = 'hot_ground_1x1_synthetic.fit' / hot pixel image filename
REFSUBIM= '        '           / subtraction image filename
COMMENT *********************************************************
COMMENT *** LORRI Level 2 Absolute Calibration Parameters     ***
COMMENT *********************************************************
PIVOT   =        6076.20019531 / LORRI pivot wavelength. units=angstroms
RSOLAR  =        266400.000000 / Conv to radiance for solar source
RPLUTO  =        257500.000000 / Conv to radiance for pluto source
RPHOLUS =        324300.000000 / Conv to radiance for 5145 pholus source
RCHARON =        263000.000000 / Conv to radiance for charon source
RJUPITER=        234700.000000 / Conv to radiance for jupiter source
PPLUTO  =    1.03000005170E+16 / Conv to irradiance for pluto source
PSOLAR  =    1.06600003807E+16 / Conv to irradiance for solar source
PPHOLUS =    1.29700002225E+16 / Conv to irradiance for 5145 pholus source
PCHARON =    1.05199994793E+16 / Conv to irradiance for charon source
PJUPITER=    9.38600033786E+15 / Conv to irradiance for jupiter source
PHOTZPT =        18.9400000000 / Zero point for visual magnitude, V
COMMENT *********************************************************
COMMENT *** LORRI Level 2 Calibrated telemetry items          ***
COMMENT *********************************************************
EPU_P5VO=        5.04305504857 / EPU +5 voltage. units=Volts
EPU_P5CU=       0.143143000000 / EPU +5 current. units=Amps
FPU_P15V=        15.0005851594 / FPU +15 voltage. units=Volts
FPU_P15C=      0.0493827000000 / FPU +15 current. units=Amps
```

```
FPU_P6_V=        6.05666080780 / FPU +6 voltage. units=Volts
FPU_P6_C=       0.152152000000 / FPU +6 current. units=Amps
FPU_HTRC=        0.00000000000 / FPU heater current. units=Amps
EPU_25PV=        2.50943456804 / EPU +2.5 voltage. units=Volts
RINGTEMP=       -66.8836898878 / Intermediate ring temp. units=celsius
MFOOTTMP=       -61.8964797242 / Mounting foot-top temp. units=celsius
M2MNTTMP=       -66.8836898878 / M2 mirror mount temp. units=celsius
RADTEMP =       -88.9564863168 / Radiator temp. units=celsius
BAFATEMP=       -62.9653774259 / Baffle-aft temp. units=celsius
BAFFTEMP=       -70.8007466057 / Baffle-forward temp. units=celsius
M1SUPTMP=       -67.2398321861 / M1 mirror support temp. units=celsius
M1MIRTMP=       -66.5275372052 / M1 mirror temp. units=celsius
CCDTEMP =       -79.5485000000 / CCD temperature. units=celsius
M1VFTEMP=       -66.0128183000 / M1 V/F temperature. units=celsius
M2VFTEMP=       -66.3287025000 / M2 V/F temperature. units=celsius
FPUBTEMP=        29.5499120000 / FPU board V/F temp. units=celsius
STEMPCVR= 'ENABLE  '           / Temperature conversion enable
SCLMP2PE= 'OFF     '           / Cal lamp 2 power enable
SCLMP1PE= 'OFF     '           / Cal lamp 2 power enable
SSOURCE = 'CCD     '           / Image source
SFORMAT = '1X1     '           / Image format
SEXPMODE= 'MANUAL  '           / Exposure mode
PDUNAME = 'Level 2 LORRI image' /
```

9.3.8.1 Reading FITS file contents using IDL

The main method for accessing the various extensions and headers from the FITS file within IDL rely on a third-party library known as the Goddard Astron library. From within IDL, one can load the primary HDU from a fits file using the following command:

```
IDL> calimg=readfits('lor_0035015237_0x630_sci_1.fit', hdr )
IDL> help, calimg
CALIMG          FLOAT     = Array[1024, 1024]
```

The return value of this function (“calimg”) is a two dimensional array containing the image data from the primary HDU and its type depends on the data that is read from the file. In the case of raw data, it will be a 16-bit integer array and for calibrated data, it will be a 32-bit floating-point array. The first argument in the call to readfits() is the name of the FITS file to be read. The second argument is an ASCII string variable that will contain the FITS header for the primary HDU upon completion of the function.

The same function may be used in order to read any of the extensions listed in the files. For example, to read the data quality image from the calibrated FITS file, one would use a statement such as:

```
IDL> quality=readfits('lor_0035015237_0x630_sci_1.fit',  hdr2, exten_no=2)
IDL> help, quality
QUALITY         UINT      = Array[1024, 1024]
```

In this example, the ASCII string variable "hdr2" contains the FITS header associated only with the second extension and has no portion of the header from the primary HDU.

9.3.9 Hardware/OS Development Platform

The pipeline software was developed in a variety of environments with the commonality of unix-style operating systems. There are no dependencies on the endian properties of the environment.

9.3.10 Language(s) Used

IDL

9.3.11 Third Party Libraries Required

There are two third party IDL libraries that are needed by the calibration pipeline software:

1) Goddard Astron library, which contains routines needed to read and write FITS files, the format used by the raw data files. Because this library is provided by the SOC for use by many instruments, we will not be delivering this library, but will rely on the version provided to us.
2) IDLUSR, a collection of useful IDL routines made available for public release at APL. Information about this library can be found at http://fermi.jhuapl.edu/s1r/idl/idl.html

9.3.12 Calibration Files Needed (with Quantities)

There are currently five categories of reference files needed to perform the calibration process. The reference image categories are the delta-bias, flat-field, dead pixel, hot pixel and desmear e-matrix. Because the LORRI instrument can produce images in either 1024 x 1024 mode or 256 x 256 mode, there are two varieties of each of these images. The filenames associated with these images will be obvious by inspection, although no formal file naming convention has been adopted.

There are two ASCII description files in the calibration directory that don't qualify as calibration files but are related to the operation of the pipeline. The first is a configuration file that details all of the configuration parameters for the pipeline ("default_config.txt"). The other file is a description of the housekeeping items that are stored in the first 34 pixels (51 bytes) of the raw image data ("binary_lorri_image_hdr.txt"). These values can be used to validate the FITS header tags that were produced by associating the high-speed image data with the low-speed telemetry values. The values in the first 34 pixels are guaranteed to be correctly associated with a particular image (provided the were not compressed in a lossy fashion) because the LORRI ASE put them in place prior the transfer of the image data to the SSR. As such, they represent a valuable check of the telemetry processing performed on the ground after receipt.

The following is a table of the types of files in the calibration directory:

Description	***Quantity***	***1x1 filesize***	***4x4 filesize***
delta bias	2	~ 8 MiB	~0.5MiB
flat field	1	~ 8 MiB	~0.5MiB
hot pixel map	1	~ 8 MiB	~0.5MiB
dead pixel map	1	~ 8 MiB	~0.5MiB
desmear e-matrix	1	~ 8 MiB	~0.5MiB
pipeline configuration file	1	~5KiB	
LORRI header description	1	~4KiB	

9.3.13 Memory Required

~ 100 MiB

9.3.14 Temporary File System Space Needed

None

9.3.15 Predicted Size of Output File(s)

Image dimensions	*Binning*	*binmode*	*Expected File Size*
1024 x 1024	1x1	0	~ 10.5 MiB
256 x 256	4x4	1	~ 700 KiB

9.3.16 Predicted Execution time

Less than 30 seconds per image.

9.3.17 Contact/Support Person(s)

Raw data support: Howard Taylor, John Hayes, and Hal Weaver

Calibrated data support: Howard Taylor and Hal Weaver

9.3.18 Maintenance Schedule (Code/Data Updates, Documentation)

As in-flight calibration data are collected and analyzed, certain aspects of the calibration pipeline will require updates, either in the form of updated reference files, or updated code for bug fixes or future improvements.

9.4 References

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