hical—The HiRISE Radiometric Calibration Software Developed within the ISIS3 Planetary Image Processing Suite

Chapter 27 of
Section C, Computer Programs
Book 7, Automated Data Processing and Computations

Techniques and Methods 7–C27

U.S. Department of the Interior
U.S. Geological Survey

Cover: Calibrated color HiRISE image of a fresh crater near Sirenum Fossae, Mars. The steep inner slopes of this relatively young ~1-km-diameter crater are carved by gullies and include possible recurring slope lineae on the equator-facing slopes. Fresh craters often have steep, active slopes, so the HiRISE team is monitoring this crater for changes over time. North is toward the right and illumination is from the top in this subframe of calibrated near-infrared, red, and blue-green channels. Color enhanced to show subtle variations.

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Contents

Figures

Tables

Conversion Factors

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
micrometer (µm)	0.00003937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
meter (m)	1.094	yard (yd)
	Area	
square meter (m^2)	0.0002471	acre
square centimeter (cm^2)	0.001076	square foot (ft^2)
square meter (m^2)	10.76	square foot (ft^2)
square centimeter (cm^2)	0.1550	square inch (ft^2)

Abbreviation

CCD	charge coupled device
CSV	comma separated values
DN	digital number
EDR	experiment data record
FPA	focal plane array
GDP	ground data processing
HiRISE	High Resolution Imaging Science Experiment
HiROC	HiRISE Operations Center
I/F	Irradiance to solar flux ratio
ISIS3	Integrated Software for Imagers and Spectrometers
MRO	Mars Reconnaissance Orbiter
NAIF	Navigation and Ancillary Information Facility
NASA	National Aeronautics and Space Administration
PVL	parameter value language
PDS	Planetary Data System
RDR	reduced data record
SNR	signal-to-noise ratio
SPICE	Spacecraft, Planet, Instrument, C-Matrix, and Events
TDI	time delay integration
USGS	U.S. Geological Survey

Module equation terms

GCN	GainChannelNormalize, normalize gain for binning/TDI
GFF	GainFlatField, multiplicative flat-field correction
GLD	GainLineDrift, time-based gain-line drift correction
GNL	GainNonLinearity, line-based nonlinearity gain correction
GNT	GainTemperature, temperature-dependent gain correction
GUC	GainUnitConversion, DN to scientific unit conversion
SED	ScanExposureDuration
ZBS	ZeroBufferSmooth, fill gaps in buffer data
ZBF	ZeroBufferFit, nonlinear fit to ZeroBufferSmooth results
ZD	ZeroDark, temperature-dependent dark current correction
ZRev	ZeroReverse, process reverse-clocked data

hical—The HiRISE Radiometric Calibration Software Developed Within the ISIS3 Planetary Image Processing Suite

By Kris J. Becker,[1] Moses P. Milazzo,[1] W. Alan Delamere,[2] Kenneth E. Herkenhoff,[1] Eric M. Eliason,[3] Patrick S. Russell,[4] Laszlo P. Keszthelyi,[1] and Alfred S. McEwen[3]

Introduction

This report summarizes the software and algorithms that are used to calibrate images returned by the High Resolution Imaging Science Experiment (HiRISE) camera onboard the Mars Reconnaissance Orbiter (MRO) spacecraft. The instrument design and data processing methods are summarized below, followed by a description of relevant calibration data and details of the calibration procedure. In this document, we describe the software that uses those coefficients and matrices to radiometrically calibrate HiRISE data. This software is included in version 3 of the Integrated Software for Imagers and Spectrometers (ISIS3) (Anderson and others, 2004), which is developed and maintained by the U.S. Geological Survey (USGS) Astrogeology Science Center in Flagstaff, Ariz., for the international planetary science community via funding from the National Aeronautics and Space Administration (NASA) (Keszthelyi and others, 2013, 2014). ISIS3 is freely available to the scientific community and can be obtained at http://isis.astrogeology.usgs.gov/index.html. Support for ISIS3 is provided at https://github.com/USGS-Astrogeology/ISIS3.

HiRISE

HiRISE is the largest camera (50-cm primary mirror) to leave Earth orbit and is part of the science payload onboard MRO. HiRISE has been observing Mars since 2006, and as of this writing it has acquired more than 40,000 observations of the Martian surface. McEwen and others (2007) described the instrument and its operating modes. Early results, including in-flight calibrations, were described in McEwen and others (2010). This report describes the procedures and software used to perform radiometric calibration of HiRISE observations using a highly specialized application developed within the ISIS3 image processing system called hical (https://isis.astrogeology.usgs.gov/Application/presentation/Tabbed/hical/hical.html).

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HiRISE Observation Structure

HiRISE Focal Plane Array

The HiRISE instrument is a "pushbroom" imaging system made up of 14 two-channel charge coupled devices (CCDs), each 2,048 pixels wide and with 128 lines for time delay integration (TDI), not counting extra pixels along the edges that are not used for imaging. Ten CCDs are laid side-by-side, with an overlap of 48 pixels on each side, for a total coverage of 20,264 pixels (fig. 1); these 10 CCDs are covered by a broadband red filter (labeled RED0-RED9). In front of and behind (in the down-track direction) the RED CCDs are four more overlapping CCDs, two each with filters for the near-infrared (IR10 and IR11) and blue-green (BG12 and BG13) spectral ranges. Thus, a full HiRISE observation is a 10-CCD-wide red-filter image with a 2-CCD-wide center swath in 3 colors. Each of the 14 CCDs is split into 2 channels, for a total of 28 channels. Each channel is stored as a Planetary Data System (PDS) experiment data record (EDR) image, which is converted to an ISIS3 image cube and processed by hical. Every channel has its own electronics and, thus, must be calibrated separately. Although each channel has been calibrated separately and requires special attention within the software, for the purposes of this manuscript, unless otherwise stated, discussion of calibration will be for a single generic CCD channel.

HiRISE Operating Modes

The HiRISE CCDs (but not individual channels within CCDs) may be turned on or off independently of each other and may have their binning modes and TDI commanded independently (McEwen and others, 2007). The possible binning modes are 1 × 1, 2 × 2, 3 × 3, 4 × 4, 8 × 8, or 16 × 16, but in practice only 1 ×1, 2 × 2, and 4 × 4 are used to image Mars. TDI is usually set to 128, 64, 32, or 8 lines and is used to control the time over which the signal is measured. In TDI 128, for example, photons from each ground point are collected through 128 CCD lines; thus, the integrated brightness is 128 times what it would be for a single line exposure whereas noise increases roughly as the square root of

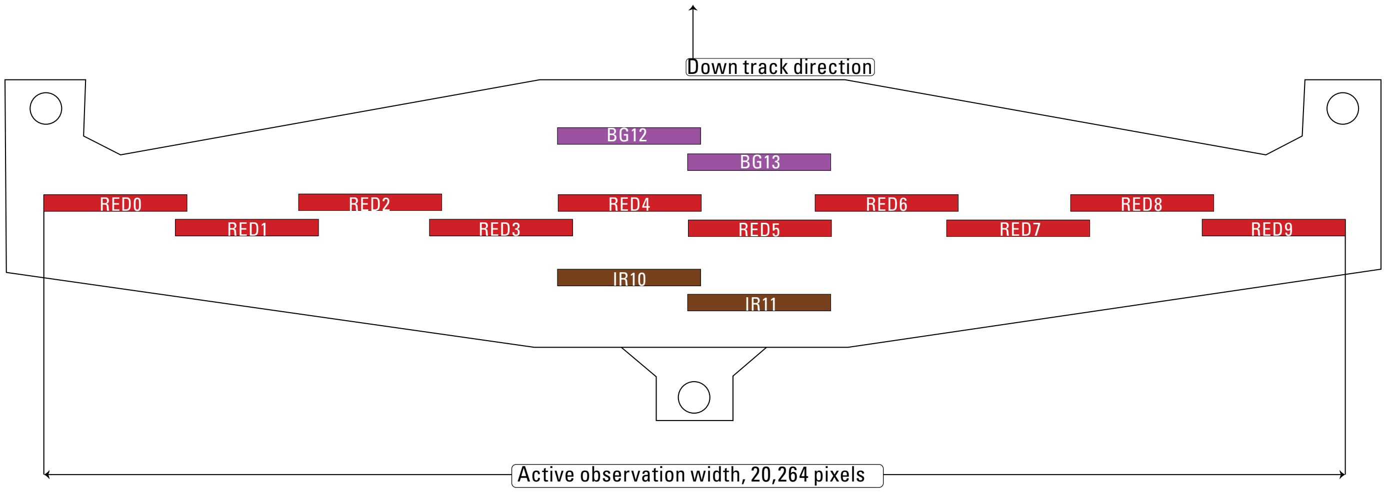

Figure 1. Schematic diagram of the HiRISE focal plane array. There are 10 red filter (RED) charge coupled devices (CCDs) with 48-pixel overlaps between the CCDs; 2 blue-green (BG) and 2 infrared (IR) CCDs, also with 48-pixel overlaps and with full-CCD-frame overlap with the corresponding RED CCDs.

Table 1. Imaging modes most commonly used by the HiRISE science team.

[Usage as of April 2013, when the calibration parameters described herein were derived. TDI is not a parameter in imaging mode selection because it is chosen based on expected scene brightness]

Imaging Mode	Center RED BIN	Outer RED BIN	Color BIN	Number of Observations
Bin1A	1	1	2	22,500
Bin2A	2	2	2	13,121
Bin2	2	2	4	3,553
Bin1	1	1	4	3,293
Bin1-2A	1	2	2	2,032

integration time. The result is to improve the signal-to-noise ratio (SNR) by about a factor of 10. Binning also provides SNR improvements and is useful for increasing image coverage within the constraints of data volume that can be stored onboard the spacecraft and returned to Earth. TDI and binning are set for each image such that either the entire scene or a specific subregion of interest is not over- or underexposed. An observation may have any combination of CCDs with different BIN and TDI settings, but the HiRISE science and targeting teams almost exclusively use a few modes that meet most science and technical requirements (table 1). Therefore, the development of calibration software focused on the imaging modes shown in table 1.

HiRISE Ground Data Processing System

The HiRISE data are passed from the MRO spacecraft to the NASA Deep Space Network to the MRO operations center at the Jet Propulsion Laboratory, before arriving at the HiRISE Operations Center (HiROC) on the campus of the University of Arizona. At HiROC, the raw telemetry data are converted to scientifically usable data such as EDRs and reduced data records (RDRs) (fig. 2) that are archived and delivered to the PDS (https://hirise-pds.lpl.arizona.edu/PDS/). Beyond the EDR generation phase, this software pipeline makes extensive use of the USGS ISIS3 system. The hical application that is the subject of this report runs within the HiCal Pipeline segment. Prior to hical, the ISIS3 HiRISE ingestion application, hi2isis, must be applied to the EDRs to create ISIS3 image cubes. To create scientifically useful products, for example, the HiStitch Pipeline must be run on the output from hical to combine the two channels in each CCD image; then, these CCD images are either stitched to create unprojected products, or they are geometrically reprojected and then combined (mosaicked) into full images. Radiometric mismatches between image channels are normalized prior to the stitching or mosaicking (Eliason and others, 2009). ISIS3 in general, and hical specifically, utilizes components of NASA's Navigation and Ancillary Information Facility (NAIF) data and software to account for Sun, spacecraft, and target positions, all necessary for accurate radiometric corrections (Acton, 1996). For comparison with other Mars datasets, HiRISE data are usually converted to the ratio of the measured irradiance to the flux (I/F) from a perfectly reflecting Lambertian surface illuminated normally at the same distance from the Sun (Danielson and others, 1981). As the ratio of the radiance from a real planetary surface to the radiance of an ideal surface reflecting an exact solar spectrum, I/F is widely used in planetary science to characterize the reflectance properties of the surface, from which compositional and physical characteristics may be constrained.

ISIS3

Since 1971, the USGS Astrogeology Science Center has developed cartographic and scientific software systems used to process image data from almost all NASA planetary missions and many international ones. The software has evolved with advances in computing technology. The current version, ISIS3, provides cartographic support for more than 70 remote sensing instruments including HiRISE. ISIS3 has been integrated into several active NASA space mission instrument ground data processing (GDP) systems (Becker and others, 2013). HiRISE was one of the early ISIS3 adopters and had a large influence in design and development considerations for the system. ISIS3 is the first version of ISIS to adopt an object-oriented programming approach and is written in the C++ language.

ISIS3 File Format

An ISIS3 image cube (fig. 3) is a three-dimensional array (with axes of samples, lines, and bands) that includes a label (attached or detached) and binary pixel data. In the image data region, the sample and line dimensions typically represent spatial information whereas the band dimension represents spectral or other information. The label contains the metadata that describe the image data. ISIS3 image labels may also describe ancillary data stored in the image file as binary tables. HiRISE ISIS files contain key calibration information in these tables.

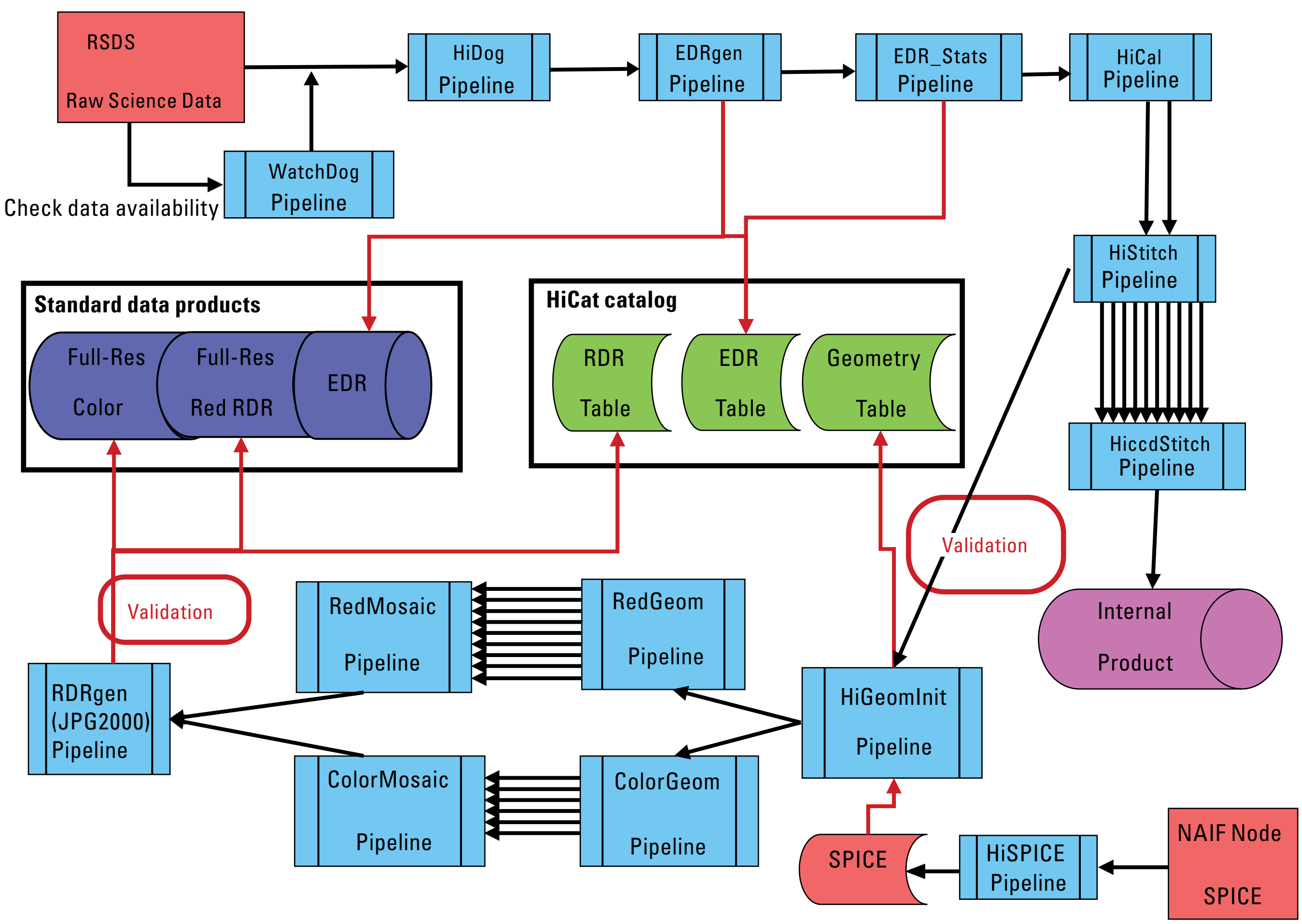

Figure 2. Schematic diagram of the HiRISE ground data processing system pipeline (Becker and others, 2013). HiRISE calibration performed by hical is the processing box in the upper right corner. JPL RSDS, Jet Propulsion Laboratory Raw Science Data Server; EDR, experiment data record; RDR, reduced data record; res, resolution; NAIF, Navigation and Ancillary Information Facility; SPICE, Spacecraft, Planet, Instrument, C-Matrix, and Events.

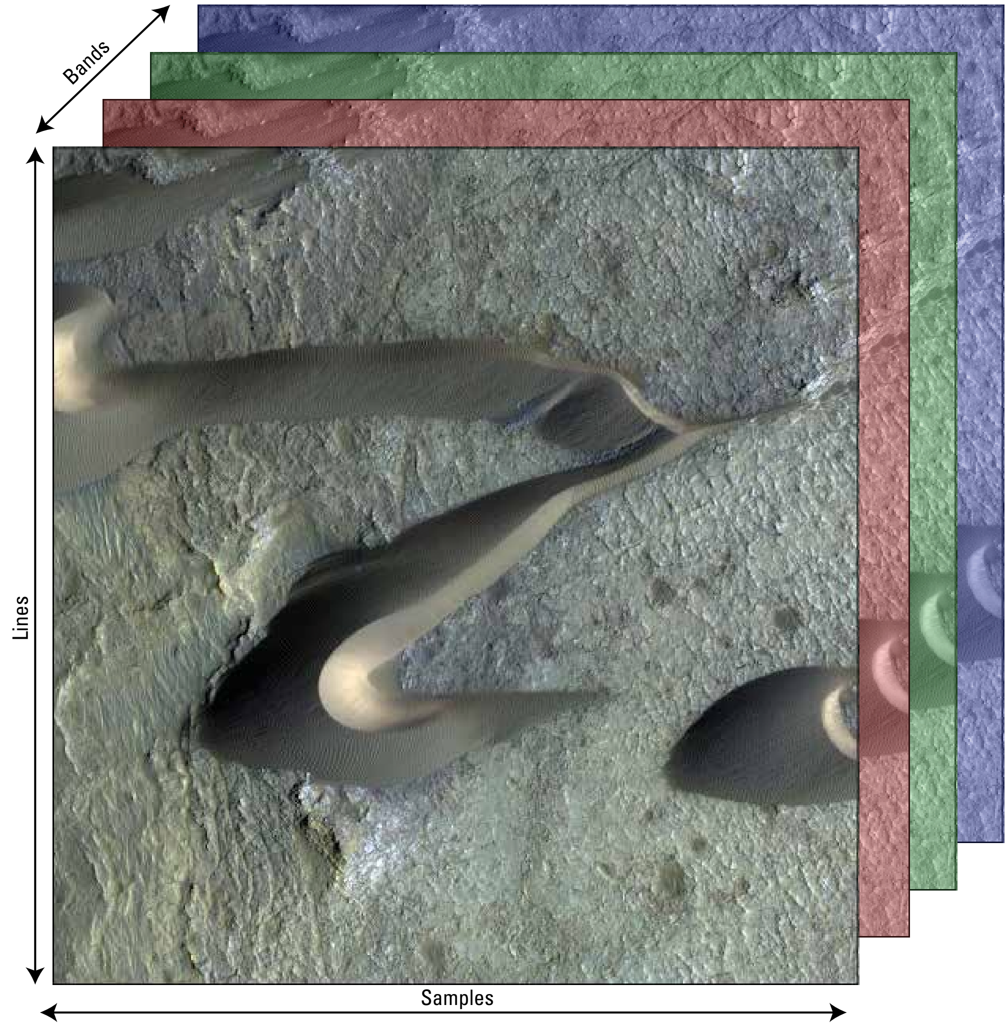

Figure 3. Diagram showing layout of an ISIS3 cube's image data. Samples and lines provide the spatial dimensions whereas bands provide the color or spectral dimension.

hical

The ISIS3 software tool hical applies radiometric calibration to HiRISE images. The hical program performs radiometric calibration at the channel level (that is, half a HiRISE CCD or individual EDR file from the PDS). This software corrects for instrument offset (bias), dark current, offset and dark current drift with time, time-dependent gain, whole-channel gain, and flat field and applies a conversion to radiance, I/F, or digital number per microsecond (DN/µs) (HiRISE Mars RDRs are released in I/F). A series of configurable calibration modules are used in hical, allowing updated calibration parameters to be applied without modifying the software. The parameters for each model are defined in a structured parameter value language (PVL) configuration file. The parameters for each hical module are fully described in appendix 1 ("hical Processing Modules").

Each hical processing module has a profile group (a fundamental PVL structure) contained in the hical configuration file that records the name of each hical calibration module invoked and the keyword/value entries for each parameter used in the module. Some of these parameters refer to numerical values, processing flags, or external ancillary files that are used by the module. HiRISE cube labels also contain some keywords that describe the commanded mode for the CCD and (or) channel.

Many of the module parameters refer to files located in the ISIS3 HiRISE ancillary data directory. The names of the calibration files indicate the CCD and (or) channel number with which they are associated. Module parameters in the hical configuration can be constructed by substituting parts of keyword value specifications that are surrounded by braces. For example, the ZeroDark module contains the keyword DarkCurrent. This keyword refers to a file name that is made up of the TDI and BIN keyword mapping values found in each HiRISE ISIS3 cube file label. The file name is of the form B_TDI{TDI}_BIN{BIN}_hical_????.csv where {TDI} is replaced with the value of the TDI keyword, {BIN} is replaced with the value of the BIN file label keyword, and the "????" refers to the version number of the file. An example of a DarkCurrent filename parameter is B_TDI128_BIN1_hical_0021.csv. Combinations of the keyword substitutions and application are fully described in appendix 2.

HiRISE Calibration Data

Other calibration data used in the hical application are stored in structured binary objects in the HiRISE ISIS3 image cube file. Key ancillary data, stored as reported by the instrument, are contained within each HiRISE channel EDR provided by the PDS. Once the image is converted to ISIS3 cube format, the data are stored in ISIS3 binary tables. Three primary tables are used in the HiRISE calibration processing, named HiRISE Calibration Image, HiRISE Calibration Ancillary, and HiRISE Ancillary. Figure 4 shows the locations of these ancillary data sources in the PDS EDR image file format.

- *HiRISE Calibration Image table*.—Contains image data useful for calibration. These data are acquired immediately before the Mars image observation from three distinct sources: reverse-clocked pixels, masked pixels, and ramp lines. Reverse-clocked pixels contain 20 lines of nominal zero (offset) data. There is some serial register dark current but this is negligible at the shorter line times. Masked pixels contain 20/BIN lines of data from behind an aluminum mask. The masked pixels should contain both serial and parallel dark current. Ramp lines contain 8, 32, 64, or 128 TDI lines that include signal from the reverse and forward clocking. For a uniform scene, the peak amplitude of the ramp lines should be two times the image area DN.

- *HiRISE Calibration Ancillary table.*—These data are also acquired concurrent with the calibration image, before the Mars image. This table contains two types of calibration data. Buffer pixels are the 12 pixels at the start of each line of the image. Dark pixels are the 16 pixels at the end of each line under an aluminum mask.

- *HiRISE Ancillary table*.—These data are acquired for each Mars image line. This table contains the same data as the HiRISE Calibration Ancillary table; the buffer-pixel and dark-pixel data contained here are for each image line and will equal the total number of Mars image lines.

A detailed description of these special calibration data sources is as follows:

- *Pre-Observation Lines*.—For each sample, data are acquired immediately before the Mars image observation lines from three distinct calibration sources:

  - Reverse-clocked pixels contain 20 lines of nominally zero (offset) value, acquired while the CCD transfers charge in the direction opposite to the normal imaging mode, to clear the CCD in preparation for imaging. Some serial register dark current contributes to the reverse-clocked pixels but this is negligible at line times typical of science operations (less than 100 microseconds [μs]).

  - Charge generated in the active area of the CCD is transferred, one line at a time, through 20 lines of pixels behind an aluminum mask to the serial register. The masked pixels record only thermal electrons generated from serial and parallel dark current and offset. Because the mask is opaque, no electrons are generated from photon interactions with the CCD materials. The physical size of each masked pixel is slightly larger than an image pixel (by a factor of 1.157), thus, the masked pixels accumulate slightly more dark current than the image pixels.

  - Finally, there are 8, 32, 64, or 128 ramp lines (equal to the TDI setting used to acquire the image). These include initial signal from the reverse and forward clocking through the CCD; the ramp lines include signal from the target, dark current, and offset. Ramp lines are first clocked for TDI lines "backward" through the CCD during reverse clocking and then by TDI lines "forward" through the CCD following the switch to forward clocking. Thus, for a flat target and no dark current or offset, the last ramp line would have twice the signal of the image line immediately following. This is represented by the gradient in the ramp section in figure 4.

- *Pre-Image Samples*.—The buffer pixels comprise 12 samples read out of the serial register before each image line. These buffer pixels only contain serial dark current and offset.

- *Post-Image Samples*.—The dark pixels comprise the 16 pixels at the end of each line of the CCD. These pixels are masked from exposure by an aluminum coating deposited onto the CCD. These pixels, similar to the masked pixels, should only contain serial and parallel dark current and offset values. There is some evidence for photon or electronic leakage through or around this part of the mask, so the dark pixels are generally not used in the calibration routines.

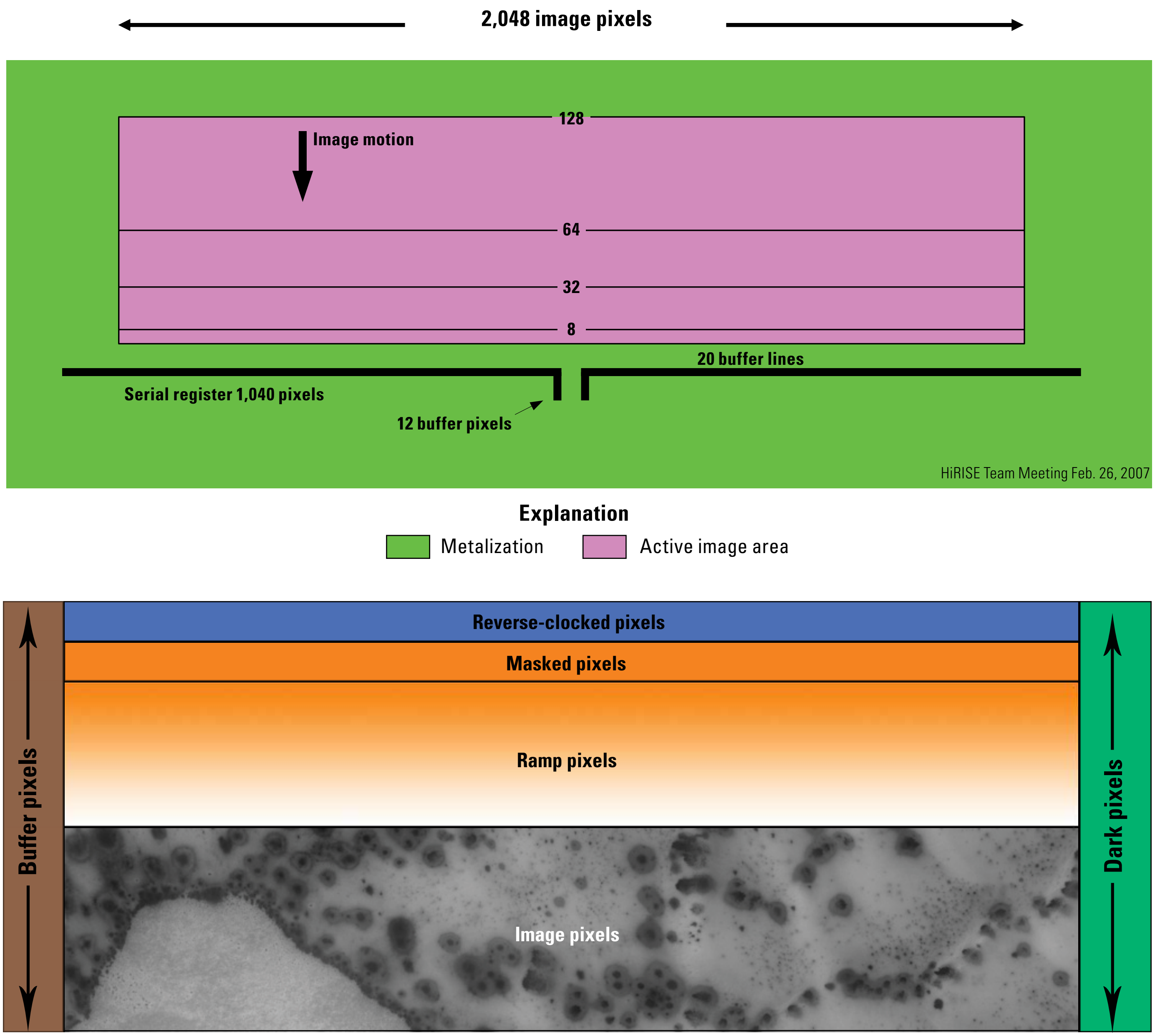

Figure 4. Schematic diagrams of the layout of each HiRISE charge coupled device (CCD) and resulting image. *Top*, CCD diagram, showing how charge accumulated in the active area is transferred through the masked buffer lines to the serial register. *Bottom*, Structure of the raw HiRISE image channel as delivered to the Planetary Data System. The first 20 lines are reverse-clocked lines. The next 20 are the masked lines, followed by 128/BIN ramp lines, and finally the imaging area lines. The first 12 samples are buffer pixels which are physically on the serial register rather than the CCD, followed by imaging area samples (or various calibration pixels for the first lines, as described in the HiRISE Calibration Image table above), and finally the dark pixel samples.

HiRISE Calibration Steps

The calibration is carried out by a series of software modules that provide various contributions to the calibration processing steps. Providing the calibration as a series of modules allows a user to process a HiRISE image through any stage of the calibration pipeline for testing and analysis purposes. The parameters that govern the behavior of these modules are contained in the program configuration file specified by the hical CONF parameter. The default parameters are automatically selected using the ISIS3 MRO ancillary data that accompany the ISIS3 release and would normally not need to be explicitly provided by the user. Each of the calibration modules has its own unique set of user-configurable PVL keyword/value entries that govern its behavior.

The general form of the HiRISE calibration equation is

$$oDN = \frac{iDN - ZBF - ZRev - ZD}{GLD * GCN * GNL * GFF * GNT} * GUC \quad (1)$$

where

iDN is the input raw pixel value, and

oDN is the calibrated output pixel value in 16-bit DN per microsecond, I/F, or calibrated radiance (in watts per square meter per steradian), depending on the user's choice of gain unit conversion (*GUC*).

The remaining terms are described in table 2 and the following text. Depending on the needs of a particular observation, some multiplicative module terms may be set to unity by the hical software or by the user so that there is effectively no operation performed by that module.

Zero-level Corrections

There is a simple voltage bias or "offset," which may depend on many factors. This is not a single value but is a pattern that is dependent on how the various electronics are configured for the operating mode of the CCD. We also correct for dark current, which is primarily a function of temperature. However, we do not directly measure CCD temperatures during the observation so we must use indirect temperatures and other data to account for the increase in dark current with time as the instrument heats up. Further complicating these corrections is that noise and gaps can appear in the data being used to calibrate the image. Various steps are taken to limit the effect of these issues with the data, but there are limits to what can be done because there are only a few pixels of some of these calibration data.

ZeroBufferSmooth (ZBS) and ZeroBufferFit (ZBF).—A large scatter in the buffer pixels must be smoothed before they are used to correct for offset. Samples 5 through 11 (samples 1–4 were found to be unreliable owing to noise) of the buffer pixels are averaged (smoothed) into a single column (ZeroBufferSmooth), filtered with a 201-line lowpass boxfilter, filtered again with a second 201-line lowpass boxfilter, and fit with a spline to interpolate through any missing buffer pixels while exactly fitting the existing filtered buffer pixels (ZeroBufferFit) (fig. 5).

Table 2. hical processing modules and their purposes.

[TDI, time delay integration; DN, digital number]

Module name	Purpose	Equation term
Zero-level corrections		
ZeroBufferSmooth	Fill gaps in buffer data	ZBS
ZeroBufferFit	Nonlinear fit to ZeroBufferSmooth results	*ZBF*
ZeroReverse	Process reverse-clocked data	*ZRev*
ZeroDark	Temperature-dependent dark current correction	*ZD*
Gain corrections		
GainLineDrift	Time-based gain-line drift correction	*GLD*
GainNonLinearity	Line-based nonlinearity gain correction	*GNL*
GainChannelNormalize	Normalize gain for binning/TDI	*GCN*
GainFlatField	Multiplicative flat-field correction	*GFF*
GainTemperature	Temperature-dependent gain correction	*GNT*
GainUnitConversion	DN to scientific unit conversion	*GUC*

ZeroReverse (ZRev).—Fixed-pattern noise is partly corrected by subtracting the average reverse-clocked pixels. Lines 2 through 19 of the reverse pixels are checked for the number of invalid pixels and compared with a threshold value (lines 1 and 20 are not useful owing to spurious electronic noise). If the number of invalid pixels is too large, or the standard deviation of the reverse samples is too large, then a constant value derived by averaging reverse pixels from a large number of Mars science images is used in place of the in-image reverse pixels. An additional configuration file, named ReverseClockStatistics.0001.conf (as an example, the number 0001 reflects the version number of the coefficients), contains statistical profiles for each CCD channel. The RevStdDevTrigger parameter sets the limit on the standard deviation and, if exceeded, the value of RevMeanTrigger is used instead. Otherwise, the 20 reverse lines are averaged, and a single line of 1,024/BIN samples is used.

ZeroDark (ZD).—The dark current subtraction consists of a correction based on images taken while the spacecraft was in eclipse as well as data from the dark pixels acquired with the tens of thousands of Mars surface images. The temperature-dependent correction to the dark current is based on a reference focal plane array (FPA) temperature of 21 degrees Celsius (°C) (294 kelvins [K]) and the average of the two FPA temperature measurements (FPA_POSITIVE_Y_TEMPERATURE and FPA_NEGATIVE_Y_TEMPERATURE [Eliason and others, 2012]) taken just before image acquisition. The temperature correction is a linear fit to correct for the FPA temperature of the image relative to the reference temperature. The dark current subtraction equation is:

$$ZD_s = B_s * \left(SED * 10^{-6} * BIN^2 * \left(\frac{20.0 * 103.0}{89.0} + TDI \right) \right) * \frac{D_t}{D_R}, \tag{2}$$

where

- ZD_s is the dark current in DNs per second at each sample s,
- B_s is the modeled dark current from the ***B***-matrix at each sample s,
- SED is the *ScanExposureDuration* in microseconds retrieved from the image label, the factor of 10^{-6} converts it to seconds,
- BIN is the binning mode,
- TDI is the time delay integration, and
- D_t and D_R are dark current model rates calculated at the focal plane array (FPA) and reference (21 °C) temperatures, respectively.

The ***B***-matrix is the algebraic equivalent from the equation of a line: $y = mx + b$, where m includes all multiplicative factors and b includes all additive factors required to implement the calibration. In this application, the equation is far more complex and involves nonlinear terms. The dark current rate D_t is a computed value in nanoamperes per square centimeter (nA/cm^2):

$$D_t = R * p^2 * 2.55 * 10^7 * (t)^{3/2} * e^{-\frac{E_g * Q}{2 * k * t}}, \tag{3}$$

where

- t is FPA temperature in kelvins (K),
- R is the dark rate (set to 2.0 nA/cm^2),
- p is pixel size (12 micrometers [µm]),
- e is Euler's number,
- E_g is $1.1557 - \frac{7.021 * 10^{-4} * t^2}{1{,}108 + t}$,
- Q is the elementary charge in coulombs, 1.6×10^{-19} C, and
- k is the Boltzmann constant, 1.38×10^{-23} joules per kelvin (J/K).

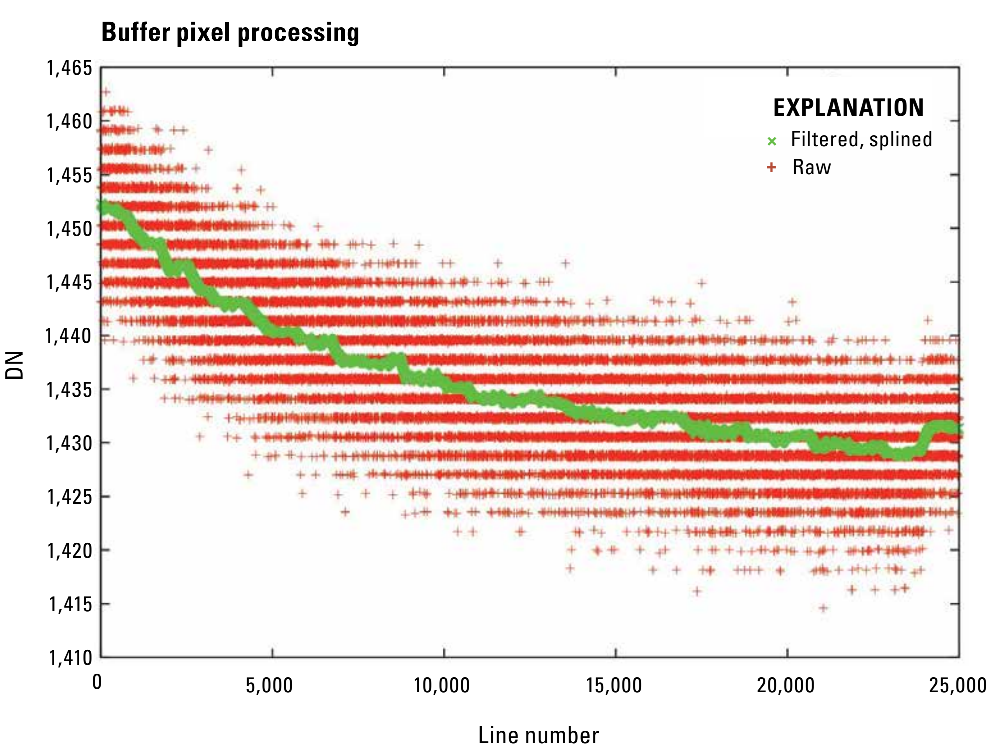

Figure 5. Plot showing filtering, smoothing, and fitting of buffer samples for each line of a calibration image. Raw data are plotted with red + symbols. Their quantization is an effect of the compression from 12 to 8 bits. Filtered and splined data are plotted with green x symbols. The filtered, smoothed, and fitted points are used in the calibration routines. DN, digital number.

Gain Corrections

GainLineDrift (GLD).—Gain-line drift models the change in gain over time. This module corrects this effect using the following equation:

$$GLD = C_1 + C_2 * LT + C_3 * e^{LT*C_4}, \tag{4}$$

where

LT is the linetime (total exposure time for a given line), and

$C_{\{1,2,3,4\}}$ are the coefficients derived by the HiRISE calibration team and archived with the ISIS3 software as calibration data.

GainNonLinearity (GNL).—Scene brightness affects the detector response in a nonlinear way, which we characterize with the gain factor, GainNonLinearity; binning mode provides a way to characterize the increase in gain with signal level. The GainNonLinearity module in hical uses the nonlinearity coefficients that are derived as a function of binning mode. These coefficients are used in the following equations to correct for nonlinearity of the detector response (signal-dependent gain):

$$GNL = 1 - (C_G * L_a), \tag{5}$$

where

C_G is the nonlinearity gain coefficient, and

L_a is the average of the line of the image being processed.

GainChannelNormalize (GCN).—This correction provides a factor for normalizing each HiRISE channel to the appropriate reference channel (RED5_1, IR11_1, and BG13_1 were chosen because they are in the middle of the array and they overlap). The GainChannelNormalize module uses the BIN-, TDI-, CCD-, and channel-dependent coefficients derived by the HiRISE calibration team and applies them using the following equation:

$$GCN = \frac{(128 * GCN_c)}{TDI * BIN^2}, \tag{6}$$

where

GCN_c is the normalization coefficient derived by the HiRISE calibration team and archived with the ISIS3 calibration data. Division by $TDI * BIN^2$ is the normalization to $BIN = 1$ and $TDI = 128$.

GainFlatField (GFF).—Flat-field corrections are produced for each TDI setting, binning factor, and CCD as the average of response for all samples in the CCD line detector. The flat-field values for each pixel in the CCD line detectors are read from a CSV (comma separated values) file, and the average is computed for the given observation parameters.

GainTemperature (GNT).—HiRISE gain is affected by the temperature of the focal plane assembly. The temperature-dependent gain is corrected using the following equation:

$$GNT = 1 - (T_g * (\overline{FPA} - 21)), \tag{7}$$

where

T_g is a correction factor derived by the HiRISE calibration team and archived with the ISIS3 calibration data, and

$\overline{FPA}$ is the average of the two FPA temperatures as described in the *ZD* module discussion above.

The reference temperature, 21 °C, was used by the HiRISE calibration team during correction derivation. Note that the HiRISE calibration team found an additive (dark current) as well as a multiplicative (gain) dependence on instrument (FPA) temperature, so that two modules (*ZD* and *GNT*) include temperature corrections.

GainUnitConversion (GUC).—The HiRISE instrument converts scene radiance to image DN. This absolute radiometric performance of the instrument can be expressed in a "calibration factor," with units of DN per second per watt per square meter per steradian. The calibration factor is used to convert image DN to (1) the radiance of the scene at each pixel and (2) the quantity I/F.

Calibration Accuracy

Table 3 summarizes the calibration accuracy as applied by hical to well-exposed HiRISE science images (Milazzo and others, 2015). Accuracy requirements were included in the original HiRISE mission requirements. Examples of hical calibration processing results are shown in figure 6*A* and *B*.

Table 3. Radiometric calibration requirements and accuracy results.

[%, percent]

Calibration	Accuracy requirement	Accuracy result
Relative (pixel-to-pixel)	1%	<0.05%
Absolute	20%	[1]≤20%
Signal-to-Noise Ratio	[2]100:1	>150:1

[1]Preliminary estimate

[2]At top of atmosphere

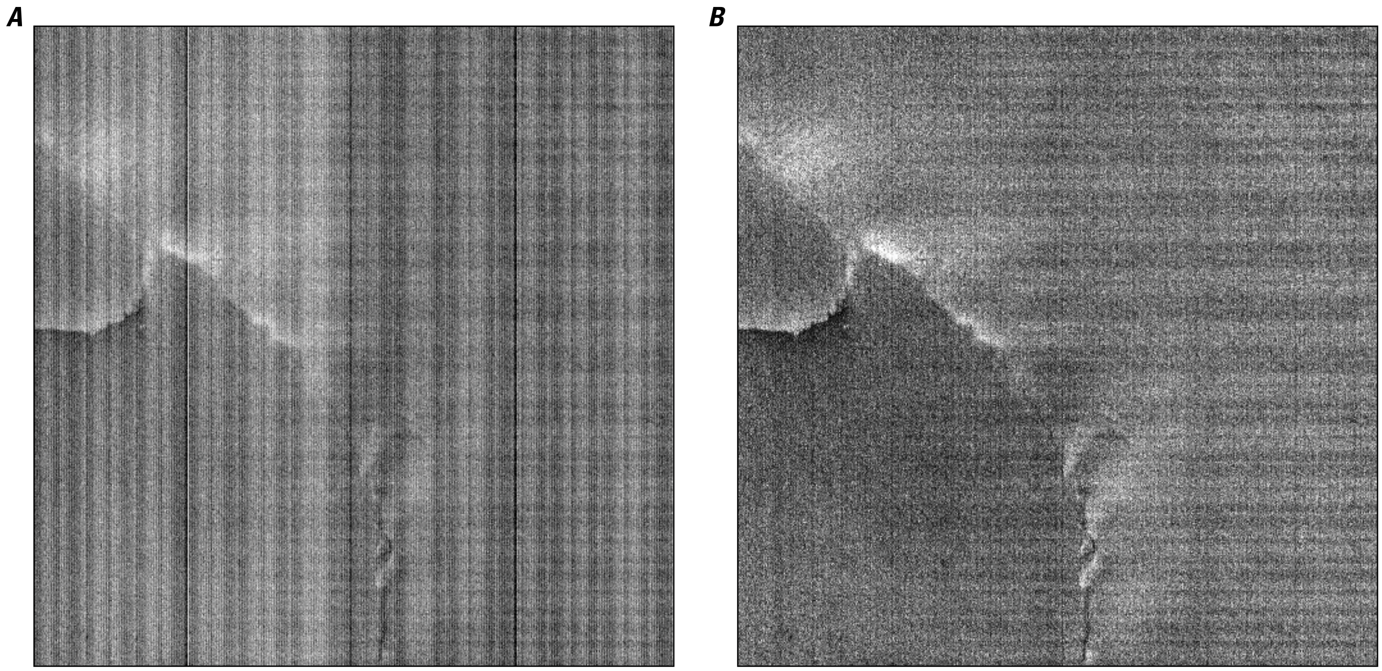

Figure 6. Cropped portion of HiRISE image ESP_015936_2640, charge coupled device (CCD) RED5, channel 1. This image was taken in relatively low light, where calibration artifacts are more obvious relative to surface signal. *A*, Image before calibration showing several artifacts, including instrument readout ringing (dark columns followed by bright columns) and alternating high and low column averages. *B*, Image after calibration showing substantial reduction of systematic artifacts but columnar patterns of alternating light and dark are not entirely removed. Note that hical does not remove any random noise.

Summary and Conclusions

We have described the HiRISE instrument radiometric calibration software written using the USGS ISIS3 planetary image processing system. In describing the software, we have presented the corrections and described their application using the hical software program.

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Appendix 1. hical Processing Modules

General descriptions of the module processing steps and configuration file parameters for the modules are provided below. These modules each have parameters that are specific to their function. The 10 different modules used in the hical application are ZeroBufferSmooth, ZeroBufferFit, ZeroReverse, ZeroDark, GainLineDrift, GainNonLinearity, GainChannelNormalize, GainFlatField, GainTemperature, and GainUnitConversion. Note that each module contains a name and a module keyword parameter that is always the module name (for example, ZeroBufferSmooth). Name and module keywords are excluded from each module description below owing to the redundant nature of the keywords and for brevity, except where they are set to something other than the module name.

Each module's parameters are contained within a parameter value language (PVL) group structure called a "Profile" in the hical configuration file. Profile groups are also containers for other parameters that are loaded into the content of a module at runtime based upon one or more keywords contained in the HiRISE image label. The construction of special runtime values is specified using the Application Control Parameters OptionKeywords and ProfileOptions described below. A one-to-one correspondence in these keywords is created by reading the keywords from the HiRISE image label named in the OptionKeywords parameter and replacing the contents of keyword values containing curly braces (that is, DarkCurrent = "$mro/calibration/matrices/B_TDI{TDI}_BIN{BIN}_hical_????.csv" where {TDI} and {BIN} are replaced with the value from the image label). This creates runtime conditions for modules based upon the type and conditions of the image being calibrated in hical.

Note that all module (PVL) group descriptions are profiles. Not all PVL group profiles are modules. Multiple profiles can be loaded to fully define a set of module parameters. The order of potential profiles that are loaded, in addition to the one requested directly within the hical application, is specified by the ProfileOptions keyword. (See appendix 2 for an example hical configuration file.)

Table 1.1. Application control parameters.

Parameter	Description
Program	Keyword is set to the name of the application and can be used to create unique filenames.
Name	Name of the current profile. This keyword is required and is present in the Object keyword section as well as in all other profile groups. This uniquely identifies the final profile.
DefaultProfile	Names the default profile that is loaded when none are specifically called for in the application. It can be any profile but is generally the hical object profile.
PropagateTables	Specifies the behavior of table propagation of the FROM file to the TO file when the file is completed. When FALSE all table objects in the FROM file are removed in the TO file, which effectively prevents hical from being able to run again. However, because of debugging capabilities, one may want to select which calibration modules are run. Setting this to TRUE will propagate all table objects in the FROM file to the TO file so that hical can be run again to apply other modules.
LabelGroups	Keyword identifies which groups in the FROM ISIS3 cube label are included in profiles. This allows any label keyword in the ISIS3 label to become available for profiling and filename generation.
OptionKeywords	Keyword selects other keywords in the configuration file or the FROM label groups as defined in the LabelGroups keyword. This list is used to specify additional profiles that can be loaded (via ProfileOptions) and variable substitution within file names (such as ***B***-, ***G***-, and ***A***- matrix files).
ProfileOptions	Keyword contains the load hierarchy pattern of modules/profiles that are evaluated each time a module is invoked. All values in this keyword are an additional potential module that will be loaded into the existing module keyword definition set if it exists in the configuration file (provided by CONF). The values enclosed in {} are presumed to be an existing keyword in the current state of the module keyword set. If the keyword exists, its value is used to search for an additional module that will be loaded into the current module keyword list. If it doesn't exist, it is ignored.
FpaReferenceTemperature	Specifies the reference temperature, in degrees Celsius, used to normalize temperature-dependent radiometric calibration variables. It is specified here because it is used in several modules.
Debug::SkipModule	Special keyword to provide the ability to completely bypass processing of a module. If this configuration keyword resolves to TRUE in any module configuration profile, then the module is not invoked, and the resulting contribution is set to unity so that it does not contribute to the calibration process. This is very useful for debugging and seeing how each module contributes to the calibration processing. Set PropagateTables to TRUE to perform subsequent runs of hical.

Table 1.1. —Continued

Parameter	Description
OPATH	Keyword is the value of the OPATH parameter entered when the program is executed. It can be used to specify a path where log files are written when that option is invoked. If the user did not specify a value for this keyword, the current path is supplied by default.
DumpModuleFile	Special keyword to provide the ability to dump data from each module. Each module implements a data dump that will be written to this file. The file name can be made up of a combination of any label or configuration keyword. The example provided in the configuration file section uses the ProductId and the name of the module with a .log extension. This keyword can be included in individual module groups or at the top level, which will effectively dump all modules. Note that the GainUnitConversion module is excluded from this feature as its data are contained entirely in the history report.
DumpHistoryFile	Special keyword to provide the ability to dump the module history from each module. Each module maintains a processing history that will be written to this file. The file name can be made up of a combination of any label or configuration keyword. The example provided in the configuration file section uses the ProductId and the name of the program with a .log extension.

Table 1.2. ZeroBufferSmooth (*ZBS*) module parameters.

Parameter	Description
ZeroBufferSmoothFirstSample	Specifies the first (0-based indexed) buffer pixels sample to start the average.
ZeroBufferSmoothLastSample	Specifies the last (0-based indexed) buffer pixels sample to end the average.
ZeroBufferSmoothFilterWidth	Specifies the width of the filter to smooth and fill gaps in the resulting buffer-pixel averages. [Default: 201]
ZeroBufferSmoothFilterIterations	Specifies the number of sequential filters to apply to the averaged buffer pixels before finally filling with a spline. [Default: 2]

Table 1.3. ZeroBufferFit (*ZBF*) module parameters.

Parameter	Description
ZeroBufferFitSkipFit	Turns on/off the nonlinear fitting process described above. When missing or set to TRUE, the result of the ZeroBufferSmooth module is used. If FALSE, the ZeroBufferFit fitting is applied using the parameters provided. [Default: TRUE, meaning it is currently not used]
ZeroBufferFitOnFailUseLinear	Selects the behavior of the data produced by the ZeroBufferFit module when the nonlinear fitting process has failed (typically owing to non-convergence). If set to TRUE, a linear fit to the latter half of the ZeroBufferSmooth (buffer-pixel) data is computed. If FALSE or nonexistent, the result of the ZeroBufferSmooth module is used as is.
ZeroBufferFitMinimumLines	Minimum number lines required to apply the nonlinear fit processing. The actual number of lines used is the total lines less trim lines/summing. If there are not enough lines, then the result of the ZeroBufferSmooth module (filtered buffer-pixel data) is simply passed through as is. This results in the same behavior when the ZeroBufferFitSkipFit parameter is invoked.
MaximumIterations	Maximum number of iterations to allow the equation to converge.
MaximumLog	Constrains the last term in the equation such that the exponent will not cause an overflow.
AbsoluteError	Specifies the absolute maximum error to determine convergence.
RelativeError	Specifies the relative maximum error to determine convergence.
GaussFilterWidth	Optionally filters the data used to fit the nonlinear equation before fitting. This controls the width of the filter. [Default: 17]
GaussFilterIterations	Controls the number of times the fit buffer is filtered prior to nonlinear fitting. Set this to 0 to turn off this processing and use the data as is. Note this is in addition to the filtering done in the ZeroBufferSmooth module. [Default: 1]

Table 1.4. ZeroReverse (*ZRev*) module parameters.

[LIS, low instrument saturation; HIS, high instrument saturation; NUL, null]

	Parameter	Description
	ZeroReverseFirstLine	Specifies the first line of the reverse-clocked region in the input FROM file “HiRISE Ancillary Image” table data to average for dark current correction.
	ZeroReverseLastLine	Specifies the last line in the reverse-clocked region in the input FROM file “HiRISE Ancillary Image” table data to average for dark current correction.
ReverseClockStatistics	Name	Names each image profile. The name is a combination of FILTER (for example, RED, BG, IR), CCD (1–13) followed by an underscore and the channel number (0, 1) followed by another underscore and the summing mode (0–8). Example: RED0_1_1.
ReverseClockStatistics	RevMeanTrigger	Maximum mean value of the reverse-clocked data region. Means that exceed this value will instead use this value as the offset correction value for all samples.
ReverseClockStatistics	RevStdDevTrigger	Maximum standard deviation value of the reverse-clocked data region. Standard deviations that exceed this value will instead cause the RevMeanTrigger value to be used as the offset constant for all samples.
	RevLisTolerance	Maximum number of LIS special pixels that can exist in the reverse-clocked calibration data region. If more LIS pixels exist in this region, then the RevMeanTrigger value is used in lieu of the processed reverse-clocked data. This value provides the default (1) for all HiRISE images which can be changed/overridden in subsequently loaded profiles (such as the one loaded in the ReverseClockStatistics file).
	RevHisTolerance	Maximum number of HIS special pixels that can exist in the reverse-clocked calibration data region. If more HIS pixels exist in this region, then the RevMeanTrigger value is used in lieu of the processed reverse-clocked data. this value provides the default (1) for all HiRISE images which can be changed/overridden in subsequently loaded profiles (such as the one loaded in the ReverseClockStatistics file).
	RevNulTolerance	Maximum number of NUL special pixels that can exist in the reverse-clocked calibration data region. If more NUL pixels exist in this region, then the RevMeanTrigger value is used in lieu of the processed reverse-clocked data. This value provides the default (1) for all HiRISE images which can be changed/overridden in subsequently loaded profiles (such as the one loaded in the ReverseClockStatistics file).

Table 1.5. ZeroDark (*ZD*) module parameters.

Parameter	Description
DarkCurrent	***B***-matrix as generated from the residuals left from the previous calibration steps performed on (some) dark frame (night-side) calibration imaging.
DarkSlope	Specifies the file pattern containing the slope component (m) of the temperature profile in the above “$y = mx + b$” equation.
DarkIntercept	Specifies the file pattern containing the intercept (b) component of the temperature profile in the above “$y = mx + b$” equation.
ZeroDarkFilterWidth	Width of the smooth filter component for the temperature profile applied after the data has been expanded or contracted to fit the binning mode of the image.
ZeroDarkFilterIterations	Specifies the number of sequential filters of width ZeroDarkFilterWidth to apply to the resulting temperature profile after expanding or contracting of the data. [Default: 1]

Table 1.6. GainLineDrift (*GLD*) module parameters.

[CSV, comma separated values; CCD, charge coupled device]

Parameter	Description
LineGainDrift	Specifies the file pattern containing the four line correction parameters ($C_{1;}$ $C_{2;}$ $C_{3;}$ C_4) of the gain/line equation as described above.
LineGainDriftColumnHeader	Specifies whether the LineGainDrift file contains a header line to skip. It is a TRUE/FALSE Boolean value. It is needed here to notify the generic CSV parser a column header exists but is not used to resolve the extraction of values from the file.
LineGainDriftRowName	Specifies the desired row header name contained in the LineGainDrift file from which to extract the applicable four parameters. This must be specified to select a specific given row. Its presence in the configuration file implies a row header exists in the first column of the LineGainDrift file. The value of this parameter is typically specified in the configuration files as a pattern combination of the CCD and channel of the image being calibrated.

Table 1.7. GainNonLinearity (*GNL*) module parameters.

[CCD, charge coupled device]

Parameter	Description
NonLinearityGain	File pattern containing the *GNL* parameter in equation 5.
NonLinearityGainRowName	Specifies the name of the row in the NonLinearityGain file to extract the coefficient from. The existence of this parameter implies the first column in this file contains a named header for each row. The value of this parameter is typically specified in the configuration files as a pattern combination of the CCD and channel of the image being calibrated.

Table 1.8. GainChannelNormalize (*GCN*) module parameters.

[CCD, charge coupled device]

Parameter	Description
Gains	File pattern of the ***G***-matrix containing the GCN_c parameter in equation 6.
GainsRowName	Specifies the name of the row in the Gains file from which to extract the GCN_c parameter. Its existence implies a row header exists in the first column of the file. Its value is a function of the binning mode of the image being calibrated.
GainsColumnName	Specifies the name of the column in the Gains file from which to extract the GCN_c parameter. Its existence implies a column header exists in the first row of the file. Its value is a combination of the CCD and channel of the image being calibrated.

Table 1.9. GainFlatField (*GFF*) module parameters.

[CCD, charge coupled device]

Parameter	Description
Flats	File pattern of the ***A***-matrix containing the per-sample flat-field correction parameter.
FlatsColumnName	Specifies the name of the column in the Flats file from which to extract the flat-field parameter. Its existence implies a column header exists in the first row of the file. Its value is a combination of the CCD and channel of the image being calibrated.

Table 1.10. GainTemperature (*GNT*) module parameters.

[FPA, focal plane array; CCD, charge coupled device]

Parameter	Description
FPAGain	File pattern of the FPA factor for the temperature-dependent gain coefficient.
FPAGainColumnName	Specifies the column name pattern of the desired parameter in the FPAGain file. The value of this parameter is typically specified in the configuration file as a pattern combination of the CCD and channel of the image being calibrated.
FPAGainRowName	Specifies the desired row header name contained in the FPAGain file from which to extract the applicable parameter. This must be specified to select a specific given row. Its presence in the configuration file implies a row header exists in the first column of the FPAGain file. The value of this parameter is typically specified in the configuration file as a pattern for the binning/summing node of the image being calibrated.

Table 1.11. GainUnitConversion (*GUC*) module parameters.

[BG, blue-green filter; RED, red filter; IR, infrared filter; I/F, irradiance to solar flux; TDI, time delay integration]

Parameter	Description
GainUnitConversionBinFactor	Specifies the factor that takes into account binning of the image data. [Default: 1.0]
FilterGainCorrection	Specifies the filter-dependent gain correction factor. Note that these values are found in the BG, RED, and IR profiles and hical relies on the profile options to load the proper parameter at runtime.
IoverFbasetemperature	Base temperature I/F conversion factor that is filter dependent. This parameter is found in the filter-dependent profiles BG, RED, and IR and relies on the profile options to load the proper parameter in at runtime.
QEpercentincreaseperC	Measurement of quantum efficiency increase per 1 °C assuming linear with temperature. This parameter is found in the filter-dependent profiles BG, RED, and IR and relies on the profile options to load the proper parameter in at runtime.
AbsGain_TDI128	Normalization of absolute gain to TDI 128. All other TDIs are scaled by this parameter. This parameter is found in the filter-dependent profiles BG, RED, and IR and relies on the profile options to load the proper parameter in at runtime.

Appendix 2. Main Configuration File

We include an example of the main hical configuration file below. The parameters and options are described in appendix 1 and in the main text. This file may contain comments in two forms ("#" for single-line comments or "/*…*/" for multi-line comments). The rest of the file contains configuration options for hical that are accessible through the top-level object, "Object = Hical", which is required.

```
#  HiRISE Calibration Matrices configuration file
#  See documentation for the hical application on the content
and form of
#  this file.
Object = Hical

  Program = "hical"

  Name          = "HiMatrices"
  DefaultProfile = "HiMatrices"

/* If you want to rerun hical, you must set PropagateTables to
True. Use */
/* this in conjunction with Debug::SkipModule = True option
for each module. */
  PropagateTables = False

/* Define label groups that are loaded for each profile
reference */
/* Note all keywords in these groups become available to all
profiles. */
/* Thus, you can use them in the OptionKeywords and
ProfileOptions keywords */
/* to create very specialized profiles for special needs. */
/* Specify the FPA reference temperature. It is used in several
modules so */
/* it is specified at the top level */

  LabelGroups = ("Dimensions", "Instrument", "Archive")

/* These keywords are used in ProfileOptions mapping. Note
that order and */
/* case matter!  WARNING:  You can easily break file lookups
if these keys */
/* are deleted or modified improperly!!! */
  OptionKeywords = ("FILTER", "CCD", "CHANNEL",
"TDI", "BIN", "ProductId",
                 "Program", "Module", "OPATH", "CalOptions")

/* Additional profile combinations and order load hierarchy.
These keywords */
/* are defined when the LabelGroups are loaded. */
/* Kris Becker & Eric Eliason updated 24 October 2008 */
/* ProfileOptions value added: {Module}_{CalOptions} */
  ProfileOptions = ("{FILTER}", "TDI{TDI}", "BIN{BIN}",
"TDI{TDI}/BIN{BIN}",
                 "{FILTER}{CCD}_{CHANNEL}",
                 "{FILTER}{CCD}_{CHANNEL}/TDI{TDI}/
BIN{BIN}", "Debug",
                 "{Module}_{CalOptions}")

/* Specify the FPA reference temperature. It is used in several
modules so */
/* it is specified at the top level */
  FpaReferenceTemperature = 21.0

  /* This profile contains parameters pertinent to processing the
buffer */
  /* pixels for subsequent using in the down-line offset correc-
tion, ZeroBufferFit module */
  Group = Profile
    Name = ZeroBufferSmooth
    Module = ZeroBufferSmooth
    ZeroBufferSmoothFirstSample = 5
    ZeroBufferSmoothLastSample = 11

    ZeroBufferSmoothFilterWidth = 201
    ZeroBufferSmoothFilterIterations = 2
  End_Group

/* This profile contains parameters pertinent to processing the
down-line offset correction */
/* We do not use this by default because a functional fit misses
important bumps and wiggles */
/* in the buffer pixels, which are required to remove similar
noise from the image area. */

  Group = Profile
    Name = ZeroBufferFit
    Module = ZeroBufferFit

  /* Uncomment to turn off nonlinear fitting of ZeroBuffer-
Smooth data and pass it through */
    ZeroBufferFitSkipFit = True

  /* Uncomment to use linear fitting of ZeroBufferSmooth data
when nonlinear fitting fails */
  /* Default is to pass through filtered ZeroBufferSmooth data
*/
  /* ZeroBufferFitOnFailUseLinear = True */

  /* Minimum number of good lines (NLines - (TrimLines/
Summing)) to fit */
    ZeroBufferFitMinimumLines = 250

  /* Maximum number of iterations for the algorithm to con-
verge and */
```

```
  /* other limits */
    MaximumIterations = 100
    MaximumLog        = 709.0

  /*  Convergence parameters for Levenberg-Marquardt algorithm */
  /*  Equation is solved when |dx_i| < AbsoluteError + RelativeError * |x_i| */
  /*    where dx is the last step and x is the current step for each i-th */
  /*    value */
    AbsoluteError = 1.0E-4
    RelativeError = 1.0E-4

  /* Filtering of the guestimate buffer */
    GuessFilterWidth = 17
    GuessFilterIterations = 1

  #   DumpModuleFile = "{ProductId}_{Module}.log"
  End_Group

/* This profile contains parameters pertinent to processing the offset in the columns */
  Group = Profile
    Name = ZeroReverse
    Module = ZeroReverse

/* Set calibration parameters for hiclean operations. Indices are all 0-based */
    ZeroReverseFirstLine = 1
    ZeroReverseLastLine  = 19


/* Reverse Clock trigger Statistics profiles */
    ReverseClockStatistics = "$mro/calibration/matrices/ReverseClockStatistics.????.conf"
    RevLisTolerance = 1
    RevHisTolerance = 1
    RevNulTolerance = 1
  End_Group

/*  Skip reverse clock if the ReverseReadoutNoise is too large */
/*  Profile added by Kris Becker & Eric Eliason, 25 October 2008 */
  Group = Profile
    Name = Zz_ReverseReadoutNoise
    Debug::SkipModule = True
  End_Group

/* This profile contains parameters pertinent to processing dark current. */
/* Required label keywords:  Summing, TDI, FpaPositiveYTemperature, */
/*                          and FpaNegativeYTemperature, Lines */
/* Also needs LineTime which is computed. */
  Group = Profile
    Name = ZeroDark
    Module = ZeroDark

/* Define the B matrix file reference */
/* As of version 0020, 9 March 2010, we will be using the following names and formats */
/* We are calling this the DarkCurrent now. The filename will stay the same (with a .csv extension) */
    DarkCurrent = "$mro/calibration/matrices/B_TDI{TDI}_BIN{BIN}_hical_????.csv"
    DarkCurrentColumnName = "{CCD}/{CHANNEL}"

/* The slope and intercepts to the temperature-dependent correction to the dark current are given below. */
    DarkSlope = "$mro/calibration/matrices/B_Temperature_Slope_hical_????.csv"
    DarkSlopeColumnName = "CH{CHANNEL}_TDI{TDI}"

    DarkIntercept = "$mro/calibration/matrices/B_Temperature_Intercept_hical_????.csv"
    DarkInterceptColumnName = "CH{CHANNEL}_TDI{TDI}"

    /* Do filtering? */
    ZeroDarkFilterWidth      = 3
    ZeroDarkFilterIterations = 1
  End_Group

/* This profile contains parameters pertinent to processing the nonlinear gain correction */
  Group = Profile
    Name = GainNonLinearity
    Module = GainNonLinearity

/* Define the nonlinearity correction coefficients */
    NonLinearityGain = "$mro/calibration/matrices/Gain_NonLinearity_BIN{BIN}_hical_????.csv"
    NonLinearityGainRowName  = "{CCD}_{CHANNEL}"
  End_Group


/* This profile contains parameters pertinent to processing down-line gain correction. */
/* Required label keywords: CpmmNumber, ChannelNumber, Lines */
/* This module has been reactivated as of 29 January 2010 */
  Group = Profile
    Name = GainLineDrift
    Module = GainLineDrift

    SkipLines          = 1
/* Added "_hicalbeta" to filename as of 2 April 2008. This is consistent with */
/* naming convention used for the beta version of hical. */
```

```
    GainLineCoefficients = "$mro/calibration/matrices/line_correct_{BIN}_hical_????.csv"

/* As of version 0020, 9 March 2010, these are more correctly called the LineGainDrift correction*/
    LineGainDrift = "$mro/calibration/matrices/Line_Gain_Drift_BIN{BIN}_hical_????.csv"
    LineGainDriftColumnHeader = True
    LineGainDriftRowName = "{CCD}/{CHANNEL}"
  End_Group

/* This profile contains parameters pertinent to processing gain correction. */
/* Required label keywords: CpmmNumber, ChannelNumber, Lines */
  Group = Profile
    Name = GainChannelNormalize
    Module = GainChannelNormalize

/* Define the G-matrix file reference */
/* As of version 0020, 9 March 2010, these coefficients have been renamed to Gains. */
    Gains = "$mro/calibration/matrices/Gains_hical_????.csv"
    GainsRowName = "{BIN}"
    GainsColumnName = "{CCD}/{CHANNEL}"
  End_Group

/* This profile contains parameters pertinent to processing gain correction. */
/* Required label keywords: CpmmNumber, ChannelNumber, TDI, Lines */
  Group = Profile
    Name = GainFlatField
    Module = GainFlatField

/* Define the A-matrix file reference */
/* As of version 0020, 9 March 2010, These have the same filename with a .csv extension.*/
/* As of version 0020, 9 March 2010, These coefficients are now called Flats. */
    Flats = "$mro/calibration/matrices/A_TDI{TDI}_BIN{BIN}_hical_????.csv"
    FlatsColumnName = "{CCD}/{CHANNEL}"
  End_Group

/* This profile contains parameters pertinent to processing */
/* temperature-dependent gain correction. Formerly in GainFlatField module. */
/* Required label keywords: CpmmNumber, ChannelNumber, Samples */
  Group = Profile
    Name = GainTemperature
    Module = GainTemperature

/* Define temperature-dependent gain correction CSV file */
    FpaTemperatureFactorSkipLines = 4
    FpaTemperatureFactorHeader = True
    FpaTemperatureFactorFile = "$mro/calibration/matrices/FpaTemperatureGain_BIN{BIN}.????.csv"

/* As of version 0020, 9 March 2010, This is now called the FPAGain. */
    FPAGain = "$mro/calibration/matrices/Temperature_Gain_????.csv"
    FPAGainColumnName = "{CCD}/{CHANNEL}"
    FPAGainRowName = "{BIN}"

  End_Group
/* This profile contains parameters pertinent to processing I/F conversion. */
/*  Required label keywords: ScanExposureDuration */
  Group = Profile
    Name = GainUnitConversion
    Module = GainUnitConversion

/* I/F correction for TDI/BIN - currently set at 1.0 for all TDI/BIN */
/* combinations. */
    GainUnitConversionBinFactor = 1.0
  End_Group

/* Here are the filter profiles. All keywords that pertain to a filter set */
/* should be specified here. FilterGainCorrection are I/F corrections in */
/* units of DN/s. */
/* Added CalFact, CCD QE, Temperature dependence correction 28 April 2010 */
  Group = Profile
    Name = RED
    FilterGainCorrection = 157702564.0
    IoverFbasetemperature = 18.9
    QEpercentincreaseperC = 0.0005704
    AbsGain_TDI128 = 6.376583
  End_Group

  Group = Profile
    Name = IR
    FilterGainCorrection = 56464791.0
    IoverFbasetemperature = 18.9
    QEpercentincreaseperC = 0.002696
    AbsGain_TDI128 = 6.989840
  End_Group

  Group = Profile
    Name = BG
    FilterGainCorrection = 115074166.0
    IoverFbasetemperature = 18.9
    QEpercentincreaseperC = 0.00002295
    AbsGain_TDI128 = 6.997557
  End_Group
```

```
  Group = Profile
    Name = IR10_1
#   LastGoodLine = 3100
  End_Group


  Group = Profile
    Name = Debug

/** Current disables writing to label history owing to bug in
keyword formatter in ISIS3 **/
/* The bug has the following error signature: */
/*       terminate called after throwing an instance of 'std::out_
of_range'  */
/*         what():  basic_string::substr                        */
/*        Abort                                              */
/* You must set this to false when this occurs as a workaround
and use the */
/* DumpHistoryFile parameter to see the parameter history. */
    LogParameterHistory = False

/* Uncomment this line to write parameter history to the Pro-
ductId log */
   DumpHistoryFile = "{OPATH}/{ProductId}.{Program}.log"

/* Uncomment this line to dump Module data for every mod-
ule when using Debug */
/* profiling. */
#    DumpModuleFile = "{OPATH}/{ProductId}_{Module}.
log"
  End_Group

End_Object
```

Appendix 3. Absolute Radiometric Calibration

For a hypothetical Lambertian Mars surface illuminated by the Sun at 1.5 astronomical units (au), the calibration factor for conversion to the irradiance to solar flux ratio (I/F), C_{Mars}, is defined as:

$$C_{\mathrm{Mars}} = \frac{S_{\mathrm{Mars}} \int_0^\infty F_{1.5}(\lambda) M^n(\lambda) T_f(\lambda) Q(\lambda) d\lambda / \pi}{\int_0^\infty I_{\mathrm{Mars}}(\lambda) M^n(\lambda) T_f(\lambda) Q(\lambda) d\lambda}, \tag{3.1}$$

where

S_{Mars} is the signal in digital number (DN) that would be produced in a HiRISE image by direct observation of this hypothetical Mars surface,

λ is the wavelength of light,

I_{Mars} is the scene spectral radiance,

$F_{1.5}$ is the solar spectral irradiance at 1.5 au,

M^n is the spectral reflectance of the mirrors (n = 5 is the number of mirrors in HiRISE),

T_f is the filter transmission, and

Q is the spectral quantum efficiency of the charge coupled device (CCD).

Neither S_{Mars} nor I_{Mars} are known. However, they can be determined using calibration observations of an integrating sphere with known properties and the measured radiometric response of the instrument, because these quantities allow derivation of the wavelength-independent absolute gain, G, of the analog-to-digital converter (in DN per electron). The signal produced by the calibrated integrating sphere, S_{sphere}, can be expressed as

$$S_{\mathrm{sphere}} = GA\Omega \int_0^\infty I_{\mathrm{sphere}}(\lambda) M^n(\lambda) T_f(\lambda) Q(\lambda) d\lambda, \tag{3.2}$$

where A is the instrument aperture,

Ω is the solid angle subtended by each HiRISE pixel, and

I_{sphere} is the calibrated spectral radiance of the integrating sphere.

Solving for G,

$$G = \frac{S_{\mathrm{sphere}}}{A\Omega} \left[\int_0^\infty I_{\mathrm{sphere}}(\lambda) M^n(\lambda) T_f(\lambda) Q(\lambda) d\lambda \right]^{-1}. \tag{3.3}$$

Because G is independent of the source spectrum to first order, once it is determined using integrating sphere data, it can be applied to calibration of sources with different spectra, and it is used here to define the I_{Mars} and S_{Mars} terms:

$$S_{\mathrm{Mars}} = \frac{G}{\pi} \int_0^\infty R_{\mathrm{Mars}}(\lambda) F_{1.5}(\lambda) M^n(\lambda) T_f(\lambda) Q(\lambda) d\lambda, \tag{3.4}$$

and

$$I_{\mathrm{Mars}}(\lambda) = \frac{R_{\mathrm{Mars}}(\lambda) F_{1.5}(\lambda)}{\pi}, \tag{3.5}$$

where

R_{Mars} is the spectral reflectance of Mars, which varies across the planet.

Equations 3.4 and 3.5 are then substituted into equation 3.1 to obtain the Mars-appropriate calibration factor, C_{Mars}. The I/F of a pixel is computed using this factor and the distance from the Sun, *d*, in astronomical units:

$$\left[\frac{I}{F}\right]_{\text{image}} = \frac{S_{\text{image}}}{(C_{\text{Mars}}(1.5/d)^2)}, \tag{3.6}$$

where

S_{image} is the signal in DN in a HiRISE image pixel.h

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