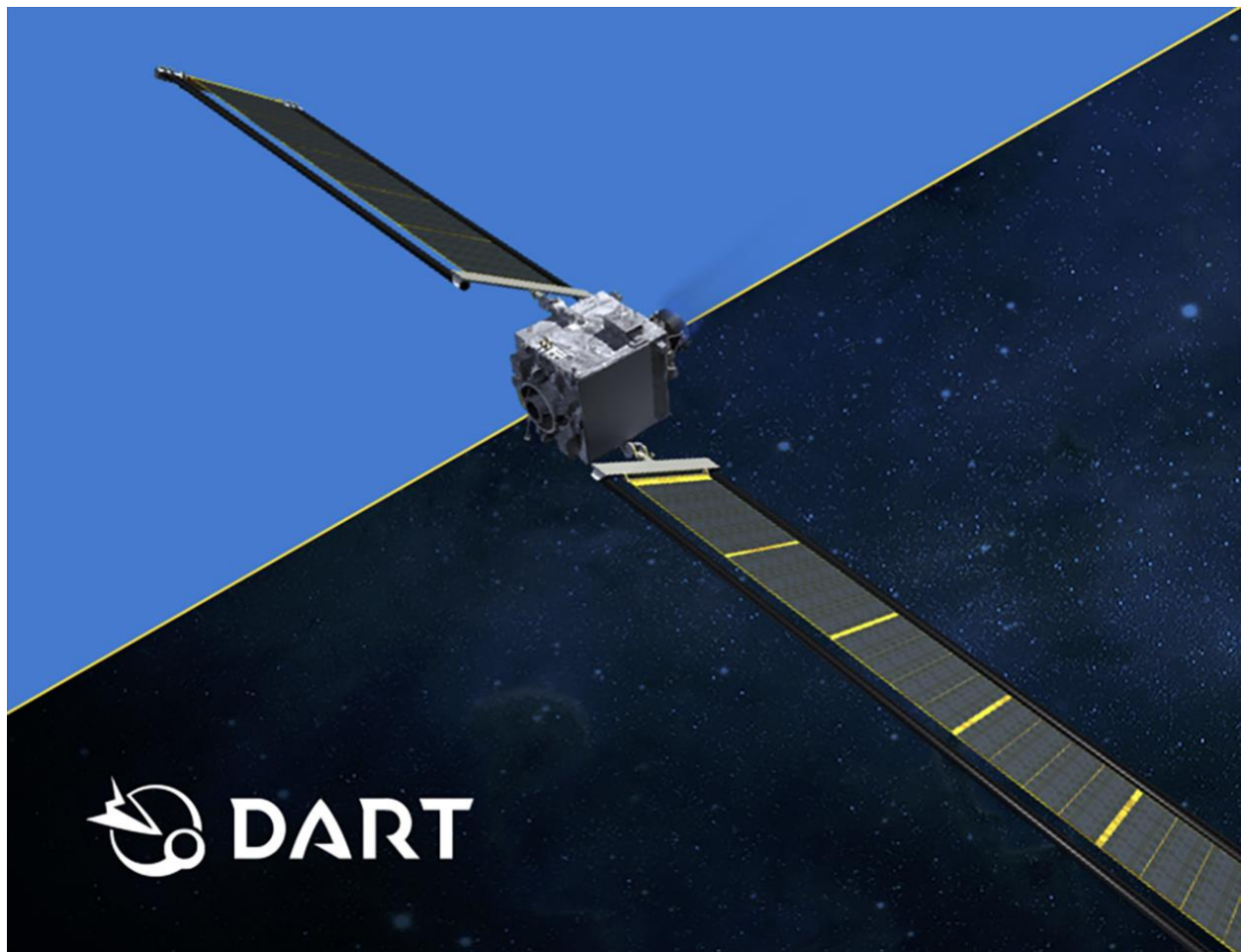


# Didymos Reconnaissance and Asteroid Camera for OpNav (DRACO) Calibration Pipeline Description



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## 1. Introduction

This document defines and describes how the DART Science Operations Center (SOC) will calibrate images taken by the Didymos Reconnaissance and Asteroid Camera for OpNav (DRACO). The pipeline will be implemented by the SOC. This document also enumerates the input files to the calibration pipeline and their required formats.

This document focuses on the procedure the SOC uses to produce calibrated images. This document does not discuss calibration activities or results. Instrument design and ground calibration topics are discussed in Fletcher et al. (2022; <https://doi.org/10.1117/12.2627873>). A publication by Ernst et al. will be submitted in 2023 and describe in detail the inflight performance and calibration of DRACO.

### 1.1. Relevance to mission level 1 requirements

The Investigation Team will use calibrated DRACO images to meet DART Level 1 requirement 4B, “The DART project shall obtain data, in collaboration with ground-based observations and data from another spacecraft (if available), *to constrain the location and surface characteristics of the spacecraft impact site* and to allow the estimation of the dynamical changes in the Didymos system resulting from the DART impact and the coupling between the body rotation and the orbit” (emphasis added).

The calibrated images referred to in this document, which will be produced by the SOC for use by the Investigation Team, are distinct from the calibrated images used by SMART Nav processing onboard the spacecraft. In the latter case, an onboard calibration table developed by the SMART Nav team is subtracted from DRACO images prior to processing by SMART Nav. This document describes only the SOC calibration pipeline. The DRACO Software Interface Specifications (SIS) document provides additional information about the SMART Nav calibration table and when it is applied to images.

### 1.2. Responsibility and change authority

The DRACO Instrument Scientist (IS) or Deputy IS (hereafter referred to simply as IS) is responsible for making changes to this document. Requests for changes will be made to the IS, who will incorporate changes and publish an updated version.

## 2. Related documents

- DRACO Software Interface Specification (SIS)
- Fletcher et al., 2018. Design of the Didymos Reconnaissance and Asteroid Camera for OpNav (DRACO) on the double asteroid redirection test (DART). In *Space Telescopes and Instrumentation 2018: Optical, Infrared, and Millimeter Wave*, 10698, 602 – 612.
- Weaver et al., 2020. In-flight Performance and Calibration of the LONG Range Reconnaissance Imager (LORRI) for the New Horizons Mission. *Publications of the Astronomical Society of the Pacific*, 132(1009), p.035003.
- Fletcher et al., 2022. Didymos Reconnaissance and Asteroid Camera for OpNav (DRACO): design, fabrication, test, and operation. In *Space Telescopes and Instrumentation 2022: Optical, Infrared, and Millimeter Wave*, 12180, 113 – 138.

In the event of a conflict between the DRACO SIS and this document, the SIS takes precedence.

### **3. Calibration pipeline inputs**

#### **3.1. DRACO images**

DRACO images that enter the calibration pipeline will be 16-bit 1024x1024 fits files. They will have been 2x2 binned from a 2048x2048 window of the DRACO CMOS detector. Some of the downlinked DRACO images will have been windowed a second time to 512x512, but the DART Mission Operations Center (MOC) will have positioned these correctly within the original 1024x1024 frame. Keywords in the fits header describe the location of the first and second windows. The MOC will set the value of all pixels not in the 512x512 downlinked image to PXOUTWIN. For additional details on these images, see the DRACO SIS.

#### **3.2. Additional calibration pipeline inputs**

##### *3.2.1. On-board calibration table*

All DRACO images taken during SMART Nav tests and during the mission's Terminal and Final phases will have an onboard calibration table subtracted from them before downlink. The table improves SMART Nav performance by compensating for popcorn noise and hot pixels in global shutter images. The onboard calibration table is applied only to images in which the CALIB keyword = 'TRUE'. See DRACO SIS for additional information on the CALIB keyword.

Pixels in the onboard calibration table are in units of DN.

##### *3.2.2. Bad pixel map*

At most, the bad pixel map will include a handful of pixels that do not exhibit a good photoresponse. For purposes of the calibration pipeline, the bad pixel map is provided as its own file, although onboard the spacecraft the bad pixel map is packaged with the calibration table in a single file. As of November 2022, no bad pixels have been flagged in the bad pixel map.

Pixels in the bad pixel map are unitless.

##### *3.2.3. Bias frames*

In global shutter mode, a reset frame is subtracted onboard the spacecraft. This subtraction effectively removes the bias in global shutter. The pipeline retains a step for bias subtraction for global shutter images in case it is needed to correct for a residual offset in pixel value from zero that develops at some later time. As of November 2022, however, the bias frames for global shutter images are set to contain all zeros. The bias in rolling shutter mode is much larger than the bias in global shutter mode, and the bias frames for rolling shutter are derived from DRACO images taken in flight. Bias frames are produced using images with a lint (i.e., 87.467 microsecond) integration time, which is the shortest integration time that the detector can provide. A separate bias frame exists for each combination of shutter mode and gain state.

Pixels in the bias frames are in units of DN.

#### 3.2.4. *Dark current frames*

In principle, the dark current level is expected to vary with shutter mode, gain state, and temperature, so multiple dark current frames are available to the DRACO calibration pipeline. The DRACO dark current is very low, and remained too low to measure separately from the bias for the duration of the mission. Therefore, every dark current frame contains all zeros.

Pixels in the dark current are in units of DN per second.

#### 3.2.5. *Flat field*

The flat field file is derived from a combination of ground calibration data and flight data. An initial flat field was produced using images taken on the ground with a 25-int (i.e., 2186.675 microsecond) integration time in rolling shutter mode with 1x gain. This initial flat field was refined using images of star clusters taken in rolling shutter mode with 30x gain. As of November 2022, all DRACO images have been calibrated using the refined flat field.

Pixels in the flat field image are unitless.

#### 3.2.6. *Radiometric lookup tables*

Radiometric calibration involves conversion of raw signals in engineering units (DN) to physical units. DART has no requirement to radiometrically calibrate DRACO images. However, radiometrically calibrated images provide useful information to the Investigation Team and the science community. DRACO images have been radiometrically calibrated on a best-effort basis.

The conversion from DN to physical units requires knowledge of the spectral properties of the source, the target, and the instrument. DRACO is a broadband imager. The “pivot” wavelength is one way to characterize the effective wavelength of a broadband optical instrument; see Weaver et al. (2020). The pivot wavelength of DRACO is 622 nm. This pivot-wavelength approach has been used by other cameras (e.g., LORRI; Weaver et al., 2020) and is commonly used among astronomers. The calibration pipeline uses different photometry keywords for different targets, as well as the solar flux at 622 nm.

The detector response depends on shutter mode and gain state. A separate lookup table exists for each combination of shutter mode and gain state used.

Each row in the radiometric lookup table maps a particular DN value to a number of electrons.

### **3.3. Required formats for calibration pipeline inputs**

The DRACO SIS lists the naming convention and file formats for calibration pipeline inputs. The names of all of these input files shall be arguments in the calibration pipeline to make it easier to change the input file when a new version (e.g., of the on-board calibration table) is delivered to the SOC. The name of each input file and the value of each scalar input used to calibrate a particular image shall be added to the fits header of the calibrated images; see section 4.5.

### 3.4. Production and sources of calibration pipeline inputs

Table 1 lists the parties responsible for producing each input to the calibration pipeline. The data producers are responsible for complying with the file format, naming conventions, and metadata requirements specified in the DRACO SIS.

**Table 1. Teams responsible for producing calibration pipeline inputs**

Pipeline input	Data source	Produced by	Number of deliveries
Onboard calibration tables	Ground-test data; in-flight data	SMART Nav team [Carolyn Sawyer]	Two (ground calibration, cruise)
Bias frames	Ground-test data; in-flight data.	DRACO team [Syau-Yun Hsieh & Andy Cheng]	Two (ground calibration, cruise)
Dark current frames	Ground-test data; in-flight data during commissioning (door closed)	DRACO team [Syau-Yun Hsieh & Andy Cheng]	One (ground calibration)
Flat field	Ground-test data only	DRACO team [Syau-Yun Hsieh, Andy Cheng, and Tony Farnham]	Two (ground calibration, cruise)
Radiometric look-up tables	Ground-test data; in-flight data	DRACO team [Syau-Yun Hsieh & Andy Cheng]	Two (ground calibration, cruise)
RDIDYMOS	Ground-test data; in-flight data	DRACO team [Syau-Yun Hsieh & Andy Cheng]	One (ground calibration)





## 4.2. Fits keywords queried by pipeline

The pipeline processes images taken in both global and rolling shutter modes. The steps in the pipeline are the same, but the particular files used to calibrate an image may vary depending on the shutter mode, gain state, and use of the onboard calibration table. The pipeline selects the bias files, dark current frames, and lookup tables that match the shutter mode and gain state of the image. A single flatfield file applies to all images. In order to choose which calibration inputs to use on a particular image, the pipeline parses the following keywords from the fits header of the DRACO image being calibrated.

**Table 2. Fits keywords queried by pipeline.**

Keyword	Brief description	Use in pipeline
CALIB	Indicates whether the onboard calibration table was applied to the image. Options are ON or OFF.	Determines whether the onboard calibration table needs to be added back to the image.
IMGMOD	Indicates whether the image was taken using rolling shutter or global shutter mode. Options are ROLLING or GLOBAL.	Used to select calibration inputs that match the mode of the image.
GAIN	The gain state of the detector when the image was taken. Options are 1x, 2x, 10x, 30x, though not all gain states may be used in practice.	Used to select calibration inputs that match the gain state of the image.
DETTEMP1	Temperature of the DRACO detector, in degrees Celsius.	Used to select calibration files for dark current subtraction.
EXPTIME	Integration time of the image, in seconds	Used in dark current subtraction and radiometric calibration
TRUNC	Indicates whether the most-significant bit or least-significant bit was kept during truncation. Options are MSB or LSB.	Used to determine how to apply radiometric look-up table
VIRTROWS	Value used for a DRACO parameter that enables extended exposure times	Used to identify test pattern images.
CALFILE	Name of file uploaded for SMART Nav onboard calibration table.	Used to ensure that the correct onboard calibration table is used for each image.
OBSTYPE	Short description of observation type	Used to ensure that bias, dark current, and functional test images are not calibrated.
TARGET	The target of the observations, e.g., Didymos or Dimorphos.	Used to select the appropriate photometric keyword for a given image. Only applicable (for the purposes of the pipeline) for resolved images.
PHDIST	Heliocentric distance of Didymos	Used as the heliocentric distance in the I/F calculation

### 4.3. Checks prior to image calibration

The DRACO pipeline performs a few checks before calibrating the images. These checks ensure that the fits keywords in the image header have scientifically useful values and contain reliable image data or are intentionally left blank. These checks are represented by the three gray boxes between “raw image MOC” and “add SOC headers” in Figure 1.

The pipeline determines whether the image was affected by a detector reconfiguration. As described in the DRACO SIS, images taken around the time of detector reconfiguration have invalid metadata and image data. The pipeline identifies these images by comparing the values for IMGMOD, GAIN, EXPTIME, and TRUNC in each image to the commanded values of those parameters. If any of the keyword values do not match the commanded values, then the image was affected by detector reconfiguration and should not be used by an end user. The pipeline sets BADIMAGE = ‘TRUE’ in the header of the affected raw images so that users can easily identify them. During some DRACO observations, image pixels were affected by detector reconfiguration even when the header information appears correct. These images also have BADIMAGE = ‘TRUE’ in the header. Raw images flagged as BADIMAGE = ‘TRUE’ and test patterns are processed to the “raw image SOC” stage in Figure 1, but they are not calibrated. No corresponding calibrated image exists for these raw images.

The pipeline determines whether an image is a test pattern and, if so, updates the TSTPTTRN keyword to correctly identify which type of test pattern the image shows. Raw images flagged as test patterns are processed to the “raw image SOC” stage in Figure 1, but they are not calibrated. No corresponding calibrated image exists for these raw images.

In addition, the DRACO pipeline checks the OBSTYPE keyword to determine whether the images were taken to satisfy ‘DARK’ or ‘BIAS’ observations. Images from these latter two observations types are used to create calibration files, and hence are only processed to the ‘raw image SOC’ stage. No corresponding calibrated image exists for these raw images.

### 4.4. Description of calibration pipeline steps

4.4.1. *Add back the on-board calibration table, if it was applied.*

If CALIB = ‘OFF’, skip this step.

If CALIB = ‘ON’, parse CALFILE to determine the name of the onboard calibration table applied to the image. Add that calibration table back to the DRACO image. The pixel values in the onboard calibration table are in units of DN.

`output1 = raw_soc_image + onboard cal table`

*output1 is in units of DN.*

#### 4.4.2. Subtract a bias frame.

Select the bias frame set with the **same shutter mode** and **same gain state** as the image being calibrated and subtract the bias. The pixels in the bias frames are in units of DN.

$$\text{output2} = \text{output1} - \text{bias}$$

*output2 is in units of DN.*

#### 4.4.3. Subtract a dark current frame.

Select the dark current frame with the **same shutter mode** and **same gain state** and **TESTTEMP closest to the DETTEMP1 of the image** being calibrated. The pixels in the dark current frame are in units of DN sec<sup>-1</sup>.

$$\text{output3} = \text{output2} - (\text{dark current frame}) * \text{EXPTIME}$$

*output3 is in units of DN.*

As noted in section 3.2.4, the dark current frames contain zeros because the dark current is so low that it has not been able to be measured. Thus, the pixel values in output3 are identical to the pixel values in output2.

#### 4.4.4. Divide by a flat field.

A single flat field will be used to calibrate all DRACO images. The pixels in the flat field are dimensionless.

$$\text{output4} = \text{output3} / \text{flat field}$$

*output4 is in units of DN.*

#### 4.4.5. Convert to electrons.

The DRACO detector is sufficiently non-linear that a look-up table will be used to convert from DN to electrons. Select the lookup table with the **same shutter mode** and **same gain state** as the image being calibrated.

As described in the DRACO SIS, the DRACO detector is actually two independent detectors. Separate conversions apply to pixels in the two halves of the detector. The pipeline must track the row numbers in the image to correctly choose the conversion for any given row. One conversion applies to rows 0 – 511 (detector A) and the second conversion applies to rows 512 – 1023 (detector B). The radiometric lookup tables start counting at row 0. Note, however, the DRACO instrument kernel has a 1-based index and so starts counting at row 1.

The lookup table contains only integer DN values. To apply the look-up table, the pipeline linearly interpolates between the integer DN values in the look-up table. The formula for applying the look-up table depends on whether the truncation mode was most-significant bit

(TRUNC = ‘MSB’) or least-significant bit (TRUNC = ‘LSB’). The majority of DRACO images were taken with the MSB truncation mode.

IF TRUNC = ‘MSB’, then

$$x = [\text{output4}]/2$$

$$\text{output5} = [\text{electrons corresponding to } x \text{ DN in the lookup table}] * 4$$

IF TRUNC = ‘LSB’, then

$$x = [\text{output4}]/4$$

$$\text{output5} = [\text{electrons corresponding to } x \text{ DN in the lookup table}] * 4$$

*output5 is in units of electrons.*

This step of the pipeline also flags saturated pixels. A fully saturated pixel in a raw DRACO image has a DN of 4094. This value is the maximum DN because of the way DRACO images are binned onboard the spacecraft. DRACO images on the spacecraft begin as 11-bit unbinned images, so 2047 is the maximum DN value in an unbinned pixel. The pixels are then 2x2 binned: the DN in four pixels is summed and divided by two to get a 12-bit image. So, four saturated unbinned pixels (DN = 2047) works out to a single 4094 pixel after binning. The pipeline changes the value of pixels with DN = 4094 to SATPXVAL = +1E09.

However, in practice the maximum DN value that can be reliably calibrated is less than 4094. If the DN value in a pixel exceeds the maximum DN value in the corresponding radiometric lookup table (Table 3), but the DN is less than 4094, the pipeline flags that pixel as saturated and changes the value of that pixel to OORADLUT = +1E08.

**Table 3. DN Cutoffs\* for Radiometric Lookup Tables**

Lookup Table	Unbinned pixels		Binned pixels TRUNC = ‘MSB’	
	Rows 0 – 511	Rows 512 – 1023	Rows 0 – 511	Rows 512 – 1023
draco_lookup_GLOBAL_1x_20220222.csv	1750	1650	3500	3300
draco_lookup_GLOBAL_2x_20211028.csv	1779	1720	3558	3440
draco_lookup_GLOBAL_10x_20211028.csv	1480	1500	2960	3000
draco_lookup_ROLLING_1x_20211028.csv	1750	1670	3500	3340
draco_lookup_ROLLING_2x_20211028.csv	1830	1730	3660	3460
draco_lookup_ROLLING_10x_20211028.csv	1800	1700	3600	3400
draco_lookup_ROLLING_30x_20211028.csv	1820	1740	3640	3480

\*The DN cutoff applies to the DN value of output4, not to the DN value of the raw image. The cutoffs in Table 3 are relevant to images that have had a bias subtracted, dark current corrected, flat field applied, and were truncated using MSB mode.

In rolling shutter mode, pixels with little signal have a (typically small) negative DN value after the bias has been subtracted due to noise in the detector. The lookup tables do not extend to negative DN values. For rolling shutter images, the pipeline assigns negative pixels the negative of the electron value that they would have been assigned, had they been positive.

In global shutter mode, the onboard reset frame subtraction bottoms out at 0 DN, so global shutter images never have negative DN values, and the lookup table for global shutter images cannot be mirrored across zero in the same way as the rolling shutter lookup tables. Instead, the pipeline, for global shutter images only, sets pixels with a DN value of *exactly* 0 to 0 electrons. If the DN is even slightly above 0 (e.g., 0.01 DN), then the corresponding radiometric lookup table is used to compute the number of electrons.

#### 4.4.6. *Convert to radiance.*

This step yields the radiance at the DRACO pivot wavelength, 622 nm, for an object the color of Didymos. The images of the greatest value to the mission will be images of Didymos and Dimorphos, and because of this the DRACO pipeline uses a single photometric conversion for all DRACO images. Radiance is derived using the conversion constant in the keyword, RDIDYMOS, in the fits header. Corrections to this constant may be derived for objects with different colors (e.g., Jupiter) to improve the calibration of those objects.

`output6 = output5 / EXPTIME / RDIDYMOS`  
*output6 is in units of  $W m^{-2} nm^{-1} sr^{-1}$ .*

Some radiance images may contain negative pixel values because the conversion to electrons retains negative pixel values. The pipeline retains these negative values to better represent the noise in the dark sky background for those who do aperture photometry.

Images whose processing ends with radiance will have `_rad_` added to their filename.

#### 4.4.7. *Convert to I/F (Terminal and Final phases only).*

Images taken during the mission's Terminal and Final phases will be converted to I/F. The pipeline uses the target's heliocentric distance in AU,  $r$ , and the solar flux at 622 nm (i.e., at the DRACO pivot wavelength), `F_SUN622`. The pipeline uses  $F\_SUN622 = 1.6784 W m^{-2} nm^{-1}$ . `PHDIST` is the heliocentric distance of Didymos, and this single value is used for both Didymos and Dimorphos because the difference in heliocentric distance between the two is negligible.

`output7 = output6 * pi * PHDIST2 / F_SUN622`  
*output7 is dimensionless.*

If a pixel has a negative value after the conversion to I/F, the pipeline changes the value of that pixel to `IOVRFLAG = -1E08`. A negative value in the I/F image indicates that there was not enough signal in the pixel to obtain a reliable I/F measurement, and replacing the negative value with `-1E08` alerts users to this fact.

Images processed all the way through I/F will have `_iof_` added to their filename.

Should a user desire a radiance image, instead of I/F, the user can compute the radiance image (output6) from output7 by reversing the calculation and using the values in the PHDIST and F\_SUN622 keywords.

*4.4.8. Change the values of bad pixels to -1E09.*

The SMART Nav team sets the values of pixels in the bad pixel map uploaded to the spacecraft to 4095. The pipeline will identify pixels in raw images with DN = 4095 and change the values of those pixels in the calibrated images to BADMASKV = -1E09. To date, no bad pixels have been flagged by the bad pixel map, so no pixels in a calibrated image will have this value.

*4.4.9. Change the values of out-of-window pixels to -1E10 and missing pixels to +1E10.*

The final step will change the values of pixels whose original values were PXOUTWIN (i.e., pixels that were not part of the downlinked 512x512 image) or MISPXVAL (pixels that were missing). The pipeline will also update the values of both keywords in the fits header to match the values in the calibrated images.

**4.5. Fits keywords added or modified by calibration pipeline**

In order to track what was done in the calibration process, the pipeline will modify or add the keywords listed below to the fits header of the calibrated images. For description of these keywords, see the DRACO SIS. As noted in section 4.3, images affected by detector reconfiguration and test patterns are not calibrated.

- ACQ\_JDAT
- ACQ\_UTC
- ACQTM
- ACQTM\_ET
- ACQTMSET
- ACQTMSOC
- BADIMAGE
- BADMASKV
- BIAS\_SUB
- BOREDEC
- BORERA
- CALFILE
- CELN\_CLK
- COR\_UTC
- DARK\_SUB
- ECLN\_CLK
- F\_SUN622
- FLATFILE
- FSWNAM
- FSWVER
- IFOV
- IOVERF
- IOVRFLAG
- LINEREAD
- LUPTABLE
- MPHASE
- MXPXVAL
- OBSTYPE
- ONBRDCAL
- OORADLUT
- PHDIST
- PIVOTWL
- PIXDELAY
- PPPCLK
- PSCRNG
- PSELON
- PSPHASE
- PSSOLLAT
- PSSOLLON
- PSUBLAT
- PSUBLON
- PXARCS
- PXMRAD
- PXOUTWIN
- RADIANCE
- RDIDYMOS
- REFBIAS
- REFDARK1
- REFDARK2
- REFFLAT
- SATPXVAL
- SCLKNAME
- SCLKPATI
- SECTAR
- SHDIST
- SMERSINX
- SMERSINY
- SMERSINZ
- SOCQUATA
- SOCQUATX
- SOCQUATY
- SOCQUATZ
- SPPCLK
- SSCRNG
- SSELON
- SSPHASE
- SSSOLLAT
- SSSOLON
- SSUBLAT
- SSUBLON
- SUN\_CLK
- TARGET
- TSTPTTRN
- WIN2XEND
- WIN2YEND