STEREO/SECCHI Level-0 to Level-0.5 FITS Pipeline CMAD

V1.0 / 30 June 2021 – First release

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1. Introduction

The SECCHI ground system reads CCSDS packet files from the STEREO MOC (Level-0) and converts the image packets to FITS files (Level-0.5). Level-0.5 is defined as uncompressed image data with software-induced artifacts corrected. Units are uncorrected DN. Metadata (FITS headers) include all available instrument and spacecraft ancillary data to describe the context for the image. This "pipeline" is run daily at the NRL Payload Operations Center. The resulting files are distributed to NASA and partner institution archives.

1.1   Purpose

This section describes the steps for conversion from CCSDS packets to SECCHI Level-0.5 FITS files. The procedures applies equally to both the Science and Beacon images.

1.2   Content

The SECCHI pipeline utilizes IDL routines that are part of SolarSoft, which is a multi-mission software library written mainly in Interactive Data Language (IDL). Below we reference and provide brief descriptions of the IDL routines that identify the instrument-specific algorithms used to compute the Level-0.5 image and header values. Not listed are SolarSoft general routines (such as sunspice) that are used to repackage information.

1.3   Acronyms

APID   Application (packet) Identifier

CCSDS Consultative Committee for Space Data Systems

FSW   SECCHI Flight Software

GT   SECCHI Guide Telescope

HI   Heliospheric Imager (HI1 and HI2)

ITOS   Integrated Test and Operations System from the Hammers Company

SCIP   Sun-Centered Imaging Package (EUVI, COR1, COR2)

SEB   SECCHI Electronics Box

seq   Sequence image type

SSD   STEREO Science Center

1.4   References

1. Consultative Committee for Space Data Systems LOSSLESS DATA COMPRESSION INFORMATIONAL REPORT CCSDS 120.0-G-3 GREEN BOOK April 2013 https://public.ccsds.org/Pubs/120x0g3.pdf
2. White R., Postman M., Lattanzi M., 1992, in: Digitised Optical Sky Surveys, MacGillivray H., Thompson E. (eds.). Kluwer, Dordrecht, p. 167 https://www.stsci.edu/software/hcompress.html
3. Kiely and M. Klimesh, "The ICER Progressive Wavelet Image Compressor", IPN Progress Report 42-155 November 15, 2003, https://ipnpr.jpl.nasa.gov/progress_report/42-155/155J.pdf
4. ICER, https://en.wikipedia.org/wiki/ICER
5. Freeland, S. L. and B. N. Handy, 1998, "Data Analysis with the SolarSoft System", Solar Physics, 182, 497-500
6. SECCHI Image Header Database Tables IMG_SEB_HDR and IMG_SEB_HDR_EXT contain the values from the raw image header: http://sohowww.nascom.nasa.gov/solarsoft/stereo/secchi/doc/secchi_img_tables_def.html

7. SECCHI FSW Image Processing Codes:
   http://sohowww.nascom.nasa.gov/solarsoft/stereo/secchi/data/PT/IN/OTHER/cnvrt_ip.dat
8. SICM 07-0007 SECCHI FITS Header Keyword Definition:
   http://sohowww.nascom.nasa.gov/solarsoft/stereo/secchi/doc/FITS_keywords.pdf
9. Thompson, W. T., 2006, "Coordinate Systems for Solar Image Data", Astronomy and Astrophysics, 449, 791-803

2. Overview

Here is an outline of the steps to generate a SECCHI Level-0.5 image:

1. Combine packets into a raw image file
2. Generate FITS file from raw image file
   a. Separate image data from header metadata
   b. Decompress image data and apply compression related corrections
   c. Rectify image
   d. Compute metadata and populate FITS header

3. File Capture

Code: ITOS file_capture

SECCHI image packet data holds a stream of blocks generated from the onboard compressed image file. Each file includes an image header at the start of an image and trailer (copy of the header) at the end of the image (Table 1). During playback of the telemetry packet file from the SSC, the file_capture program extracts the data from the Block Data field in the CCSDS packets to form one file per image.

Table 1: Description of the SECCHI Image File Transport Packet Format

Position in Bytes	Size in Bits	Description
0	48	Primary Header
6	48	Instrument Time
12	16	1st Block Pointer: byte offset; 0 offset indicates next byte begins block; 0x7FF for no block starts
14	258*8	Block Data
varies	5	0
+0	11	Image Count (0x7FF indicates Fill Block)
+2	2	0=data; 1=header; 2=trailer
+0	14	Block Number (0:16383)
+2	16	Block Length (bytes of Block Data – 1)
+2	varies	Block Data

4. Convert Image File to Level-0.5 FITS

Code: secchi_reduce.pro

The top-level IDL routine scans the files written by file_capture and performs the pipeline processing to FITS. Such files are known as Level-0.5, because the full calibration to Level-1 has not been applied yet.

The first step in the process is to separate the header and trailer blocks from the image data, using unblockSciFile.cpp. The source raw image files are saved to an "attic" subdirectory for storage.

4.1 Convert Compressed Data to Uncompressed Data Array

The type of compression used is determined from the header that came down with the image (IP_00_19). Depending on the compression scheme used, the appropriate program is spawned to decompress the image, and the resulting decompressed image is read into IDL.

4.1.1 Lossless Compression

Code: ricerecon64.c

For a lossless compression we use the Rice data compression algorithm, developed by J. Rice of JPL in the 1960s-1970s. It uses various variable length codes in each packet of an image to develop a lossless compression. It is defined in CCSDS document Ref[1].

For lossy compression we use one of two techniques, ICER and Hcompress, both wavelet-based.

4.1.2 Lossy Icer Compression

Code: idecomp.c

The ICER algorithm uses a progressive wavelet-based algorithm to encode progressively smaller partitions of the image until the desired compression is achieved for each partition. See Ref[3] and Ref[4]. For SECCHI, twelve pre-set ICER configurations are used, labelled consecutively from ICER0 to ICER11, with the following resulting compressed sizes:

ICER compression scheme	Compressed size (bytes)
ICER0	2000000
ICER1	1000000
ICER2	800000
ICER3	600000
ICER4	400000
ICER5	300000
ICER6	200000
ICER7	100000
ICER8	50000
ICER9	20000
ICER10	10000
ICER11	5000

The resulting amount of compression for any given ICER selection depends on the original image size. For example, a 2048×2048 image with two bytes per pixel that was compressed using ICER4 would have a compression ratio close to 21.

The ICER compression scheme works better the fewer bits are used. One of the IP functions is to check the dynamic range of the data (one of 7 operator-specified thresholds, usually ICER_A=10485) to see if the data should be truncated to improve the compression performance. If this test is performed and the data is divided by 2 (truncated), then this is indicated in the IP log in the header. If detected, the image is multiplied by 2 (up to 2x) to reflect the pre-compression data level. The amount of correction is stored in the FITS header in the keyword DIV2CORR, and information about the correction is added as a HISTORY record. (scc_icerdiv2.pro)

4.1.3   Lossy Hcompress Compression

Code: hdecomp.c (hd64)

Hcompress uses a parameter, specified in the image commanding, to eliminate the wavelet frequencies starting with the highest (that contain the noise) and progressively more if desired. In contrast, the size of the compressed image is specified for ICER compression. The Hcompress algorithm was developed by the Space Telescope Science Institute to compress images in the Hubble data archive. It uses the Haar wavelet transform, generalized to 2D, and then applies a user-specified factor to remove noise. See Ref[2]. Early in the mission it was determined that Hcompress did not provide sufficient compression to meet the science requirements, so Icer is used almost exclusively for SECCHI lossy compression.

There is an additional compression scheme that is "header only"; in this case there is no image data. For images that are summed onboard, only a header is returned.

4.2   Merge HI Low Word Image And High Word Image.

Code: secchi_hi_low_merge.pro

For the two Heliospheric Imager instruments HI-1 and HI-2, 32-bit summed images are first separated onboard into two 16-bit high and low word images. Each image is then compressed separately, and sent down separately in the telemetry. The high and low word parts of the image must then be recombined into a single image before writing to a FITS file.

4.3   Rectify Image Before Writing FITS File

Code: secchi_rectify.pro

The orientation of the solar image on the CCD detector differs from telescope to telescope. To correct for this, the images are put through a process known as rectification, where each image is reoriented so that solar north is nominally at the top, and the west limb is nominally to the right. Rectification is done by rotations by an integer number times 90 degrees, and/or transposition of the axes. As such, no interpolation is applied to the data—the pixels are simply reordered, with the new axes X_1,Y_1 being related in a simple fashion to the original axes X_0,Y_0. In IDL, rectification is performed via the ROTATE function, in which the direction parameter has the following meanings:

Direction	Transpose?	Rotation Counterclockwise	X_1	Y_1
0	No	None	X_0	Y_0
1	No	90˚	$-Y_0$	X_0
2	No	180˚	$-X_0$	$-Y_0$
3	No	270˚	Y_0	$-X_0$
4	Yes	None	Y_0	X_0
5	Yes	90˚	$-X_0$	Y_0
6	Yes	180˚	$-Y_0$	$-X_0$
7	Yes	270˚	X_0	$-Y_0$

The direction parameters used for the SECCHI are as follows, depending on whether or not the data were taken before or after solar conjunction in 2015:

Telescope	Pre-conjunction		Post-conjunction	
	Ahead	Behind	Ahead	Behind
COR1	3	1	1	3
COR2	1	3	3	1
EUVI	6	3	4	1
HI1	0	2	2	0
HI2	0	2	2	0

When the spacecraft pass Earth in 2023, the direction parameters will revert to their pre-conjunction values.

No change is made to how rectification is applied to the images in response to short-term spacecraft maneuvers such as rolls made for calibration or special observations.

Rectification is not applied to calibration images (see 4.5.1).

4.4   Populate FITS Header

Code: make_scc_hdr.pro

The FITS header is populated from the raw image header in the telemetry, combined with derivations of values from ground tables and the housekeeping database. The pointing parameters are derived from the spacecraft attitude history SPICE files (via the SunSPICE package in SolarSoft), modified by individual telescope offsets in yaw, pitch, and roll. These are initial values, and only coarse offsets from the spacecraft are recorded. In particular, the SPICE yaw and pitch values are ignored if less than 0.1˚, because the spacecraft-provided jitter values are unreliable. Instead, the pointing values are updated later in the program. Each telescope's platescale (CDELTi) is a constant calibration parameter modified by the amount of binning applied to the image. The method used for determining the CRPIXi and CRVALi values differs by telescope:

EUVI: The CRPIXi values are set to the calculated location of Sun center in each image, with the CRVALi values set to zero.

COR1,**COR2**: The CRPIXi values are set to constant values representing the center of the occulter, and the CRVALi values are set to the calculated pointing values at those positions.

HI1,**HI2**: The CRPIXi values are set to the center of the image (e.g. 512.5,512.5), and the CRVALi values are set to the calculated pointing values at those positions.

Pointing values are specified in two coordinate systems within the FITS headers. The primary set of keywords (CRPIX1, CRVAL1, etc.) specify Helioprojective Projective Cartesian coordinates (see Ref[9]). A parallel set of keywords ending in the letter "A" (CRPIX1A, CRVAL1A, etc.) specify celestial coordinates in the Right Ascension, Declination system.

See Ref[8] for a complete list of SECCHI FITS keyword definitions.

4.4.1   Extended Header For Images Summed Onboard (both HI and SCIP)

Code: make_scc_ext_tbl.pro

When the image downloaded from the spacecraft is actually a combination of images summed onboard, an ASCII table extension is added to the FITS file giving information about the individual exposures making up the summed image. The information in this table comes from the header-only files generated for each exposure.

4.4.2   Exposure Duration

For the SCIP instruments, the exposure duration (EXPTIME) is recorded in the MEB (since all SCIP telescopes have shutters) and sent down in the image header. In some cases, the SCIP exposure duration is estimated to be the commanded value, if the measured value is out of family from the commanded value; this is noted as a comment in the FITS header.

Since the HI telescopes do not have a shutter, the exposure duration is computed onboard using the camera clear and readout interrupts.

For images that are summed onboard, the exposure duration from the header-only images for each image in the sum are added together. If for some reason not all of the images in the sum have a corresponding header, then the exposure duration is estimated as the duration of the last image times the number of images in the sum.

4.4.3   Cosmic Ray Report

For HI summed images there is the option (usually implemented) to scrub cosmic rays from each exposure before it is summed. The HI Cosmic Ray Scrub has two algorithms to remove cosmic rays from HI images. The first is a two-image scrub where the current image is compared with the previous image on a pixel by pixel basis. If the current image pixel is greater than previous pixel plus the photon noise of the pixel, the pixel is replaced with the previous pixel. The three-image scrub takes the median value of the current, previous and oldest image. Each HI telescope saves the previous two 2048x2048-pixel images to compare with the current image. The number of pixels so modified is recorded in the first N pixels of the image returned, replacing the data in those pixels. These are then totaled and reported in the COSMICS keyword of the FITS header; the number for each individual frame is reported in the extended header.

4.4.4   Apply Fine Pointing Correction (SCIP)

Code: euvi_point.pro, cor1_point.pro, cor2_point.pro

For the SECCHI telescopes, the initial coarse pointing values in the header are revised based on telemetry from the Guide Telescope. Each telescope has its own pointing calibration routine, provided by the individual telescope teams, but the basic methodology is the same. Spacecraft roll information is taken from the SPICE attitude history files, while the difference in the guide telescope signal is used to determine the change in yaw and pitch from nominal when combined with the roll information. The SunSPICE package in SolarSoft is used to convert Heliocentric Projective Cartesian sun-pointed coordinates into the celestial Right Ascension, Declination system. Correction for EUVI also takes into account Fine Pointing System offsets in the image header. The EUVI pointing is known to drift over time, so a correction is also applied for this.

4.4.5   Apply HI Fine Pointing Correction and Geometric Calibration

Code: hi_point_v2.pro

For the summed HI images, a pointing vector offset and roll is determined for each exposure in the sum, and then the offsets are averaged before being applied to the FITS header pointing keywords. The HI telescopes have additional corrections and header additions for geometric distortion. These are described in more detail in the HI calibration section.

4.5   Write FITS File

Code: writefits.pro

Images and metadata in the header are saved in FITS format. If there is an extended header, it is appended.

4.5.1   Calibration Images

Images that are tagged with SEB_PROG=DARK, LED, CONT (with the exception of HI DARK) are written to a different location in the archive.