



HaloSat Analysis Guide

Version 1.6

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DOCUMENT TITLE: HaloSat Analysis Guide			
ISSUE	DATE	PAGES AFFECTED	DESCRIPTION
Version 1.0	Apr 2020	All	First version
Version 1.1	Jun 2020	Selected pages	Section 1.2: Fix caldb link, add link to the Halosat Archive document
Version 1.2	Feb 2021	Select Pages	Section 1.3 update the image; 2.3 add section of the background and bright sources
Version 1.3 and 1.4	Feb 2022	Select pages	Section 2.1 added the steps to rescreen the data starting from the unfiltered data, 2.2 added an example to filter unfiltered events with GTI, 2.3 added inflight calibration results
Version 1.5	Dec 2022	Select Pages	Section 2.3 describe the new background method; change the example to reflect the new background
Version 1.6	Apr 2023	Select pages	Section 2.3 add section on the data reprocessing

1 Data Overview

1.1 Introduction

HaloSat was designed to survey the distribution of hot gas in the Milky Way and constrain the mass and geometry of the Galactic halo (Kaaret et al 2019 ApJ 884 162k). The mission, led by the University of Iowa (UIowa, PI P. Kaaret), was deployed into circular low Earth orbit on July 13, 2018 and started science operations in October 2018. Originally approved for 12 months of science operations, HaloSat successfully collected science data from October 15, 2018, up to September 29, 2020, effectively doubling the mission life time. HaloSat reentered Earth's atmosphere on January 4, 2021 after nearly two and half year in orbit.

HaloSat is equipped with a non-focusing instrument, comprised of three co-aligned independent silicon drift detectors (SDD) with the following characteristics :

- Energy range: 0.4 -7.0 keV
- Field of View (FOV): 10 deg diameter full response, tapering to 14 deg zero response
- Energy Resolution: ~85 eV at 677 eV and ~137 eV at 5895 eV
- Grasp at 600 eV: 17.6 cm² deg² (Grasp = Telescope area x field of view)

To complete the sky survey, HaloSat divides the sky into 333 sky positions that are observed during mission operations. Additional observations are added to observe the dark Earth and other fields used for calibration. HaloSat's orbital period is about 90 minutes. The science instrument is turned on only during the night-side half of the orbit. During that time the science event data, instrument housekeeping data, orbital position information, and attitude information are collected. No science event data, housekeeping data, orbital position information, or attitude information are collected during the day-side half of the orbit. HaloSat's observation strategy is to follow two selected positions in the sky for 10 consecutive orbits, and to observe each of the positions for about 1300 seconds per orbit. At the end of the 10 orbits, the pattern is repeated for two other positions, and so on. In May 2019 the number of consecutive orbits in the observing pattern was increased to 16.

1.2 Data processing

The HaloSat data are processed at the UIowa using a Python-based software. The pipeline consists of three processing steps. In the first step, the telemetered housekeeping (hk) and science packets are organized into science and housekeeping databases where packets are sorted and bad packets discarded.

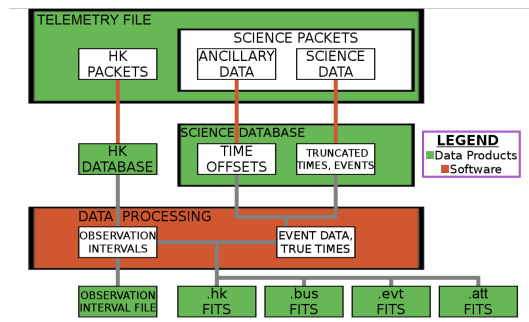


Fig 1 : First step of the pipeline processing

Time intervals when the instrument is operating are calculated as well as the information to derive the absolute time of the events based on the spacecraft GPS time. The outputs from these databases are the raw science and housekeeping data for each individual detector (numbered as SDD14, SDDD38 and SDD54) and attitude data written as FITS files (see Fig 1). This data is organized by pointing with no calibration applied. These “raw” data files are not part of the HEASARC archive.

In the second step, the calibration is applied to the science data files. Additional information is calculated and included in the housekeeping data files. The two-line elements (TLEs, from www.space-track.org) and the attitude are used within the HEASoft *prefilter* task to calculate rigidity, time since last South Atlantic Anomaly (SAA) and other orbital parameters and are added to the housekeeping file. Light curves are calculated from the science data in various bands (see Table 1) and are also added into the housekeeping file. The contents of the housekeeping file is in the appendix a (Table 5).

Table 1: Light Curve Band Definitions		
Name	PHA Band	Description
LC_OXYGEN	900-1400	Science, 0.45-0.73 keV
LC_SCI	900-2250	Science, 0.45-1.2 keV
LC_HARD	5600-12900	Background, 3-7 keV
LC_VLE	12900-16384	Large events, > 7 keV
LC_GAP1	600-750	Higher amplitude electronic noise, 0.30-0.38 keV
LC_ALL	0-16384	Total count rate
LC_ALSI	2250-3750	Instrumental Lines band, 1.2-2.0 keV
LC_UP	1400-2250	Band between LC_OXYGEN and LC_ALSI, 0.73-1.2 keV
LC_RESET	0-100	Band with reset pulses

The science data are calibrated for the gain, and events acquired when the instrument performance or other condition are not nominal are filtered out. The gain is applied to the pulse height analyzer

column (PHA) and the results are written in the Pulse Invariant (PI) column. The PI calculation is described in the document “[halosat_001_caldb_01](https://heasarc.gsfc.nasa.gov/docs/heasarc/caldb/halosat/docs/halosat_caldb_docs.html)”, available from the HaloSat caldb page (https://heasarc.gsfc.nasa.gov/docs/heasarc/caldb/halosat/docs/halosat_caldb_docs.html).

To exclude events collected when not in nominal condition, time intervals are derived from the hk file to include times of instrument specific nominal voltages, nominal temperature, SAA exclusion and other parameters. Table 2 lists all the parameters included in the events filtering together with the acceptable ranges.

The hk and the science FITS data files for each of the detectors obtained from this second step of processing are the “unfiltered” data and are included in the archive.

The last step creates the “cleaned” science files and the spectra. The “cleaned” science files are derived by filtering the data on time intervals obtained using the LC_HARD and LC_VLE columns in the hk file. These columns are binned by a factor of 8 (64 sec) and the Good Time Intervals (GTIs) are derived using the following expression for all but the brightest targets:

$$('LC_HARD' \leq 0.16) \& ('LC_VLE' \leq 0.75) .$$

These GTI are applied to the ‘unfiltered’ science data to obtain the “cleaned” data files. The spectra are derived by creating a histogram in PI of all events in the “cleaned” science file. The “cleaned” science and the spectral files for each of the detectors are part of the archive.

Table 2 : Unfiltered Data Cut			
Key Name	Lower Limit (>=)	Upper Limit (<=)	Description
IN_SAA	False	-----	Remove remaining data in SAA.
SDD_TEMP	-31.0	-29.0	Instrumental cut
MON_3P3V	3.20	3.30	Instrumental cut
MON_P5V	4.80	5.10	Instrumental cut
MON_M5V	-5.10	-4.80	Instrumental cut
SDDHVMON	-138.0	-133.0	Instrumental cut
SDD0	0.060	0.080	Instrumental cut
OFFSET	-----	0.25	Require pointing within 0.25 deg of source location.
NADIR_ANGLE	92.0	181.0	Require instrument pointing away from Earth limb.
LC_ALL	> 15	140	Remove times of too few counts and too high counts to avoid deadtime issues.
LC_GAP1	-----	< 1.0	Energetic noise removal.
TIME_DUR	8.0	-----	Require standard duration of hk time bins.

The Python-based software used to generate the “unfiltered” and “cleaned” data files is not part of the archive. However, the HEASoft software package has standard tasks that may be used to reproduce the creation of the Good Time Intervals (GTIs) from the housekeeping data and the spectrum from the event data. Specifically, *maketime* calculates GTI and *xselect/extractor* extracts a spectrum.

The raw data are not included in the archive; however, the events excluded from the unfiltered data files are all those that are not qualified for science analysis. The data processing pipeline occurs at UIowa and the data outputs are provided to the HEASARC for the final archive. File formats are provided in the Appendix of this document and /or in the ‘‘HaloSat Archive’’ description document (https://heasarc.gsfc.nasa.gov/docs/halosat/archive/halosat_archive.pdf)

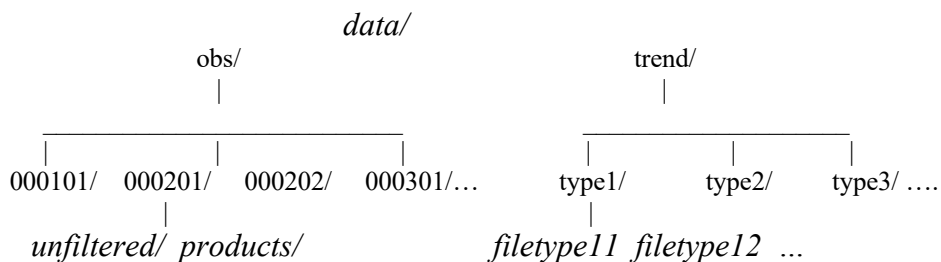
1.3 Archival data

The archive is organized by observation. An observation is defined as data acquired on one specific sky position observed in a time interval where individual files do not exceed 2 Gb. Data associated with an observation are labeled with a 6-digit sequence number, *YYYYZZ*, where:

- *YYYY* is the target number associated to a specific RA and Dec position. The target number has always 4 digits with a range of 0001 – 0999 for sky positions and 1001 – 1999 for dark earth observations. The value of 0000 is reserved for non-science observations.
- *ZZ* is a number used to create sequences in the same sky position to limit the size of individual files. If all data taken for a given sky position may be included in FITS files < 2GB, there will be a single data set for that sky position and *ZZ* will be 01.

The sequence number is used to name the directory containing the science and HK files and is also embedded in each filename.

The HaloSat archive is divided in two areas: the *obs/* directory and the *trend/* directory. The *obs/* directory contains the science data organized by sequence number, and the *trend/* directory contains data organized by data type. The structure of the data directory is as follows:



Each observation contains the files (listed in Table 3) output from the step 2 processing (unfiltered directory) and step 3 processing (products directory).

Table 3	
<i>unfiltered/</i>	
<i>hsYYYYZZ_s14.hk.gz</i>	Housekeeping and orbital information SDD 14
<i>hsYYYYZZ_s38.hk.gz</i>	Housekeeping and orbital information SDD 38
<i>hsYYYYZZ_s54.hk.gz</i>	Housekeeping and orbital information SDD 54
<i>hsYYYYZZ.att.gz</i>	Attitude data

hsYYYYZZ.cat.gz	Catalog of the files included in the observation
hsYYYYZZ_s14_uf.evt.gz	Unfiltered event file for the SDD 14 detector
hsYYYYZZ_s38_uf.evt.gz	Unfiltered event file for the SDD 38 detector
hsYYYYZZ_s54_uf.evt.gz	Unfiltered event file for the SDD 54 detector
<i>products/</i>	
hsYYYYZZ.log.pdf.gz	Log of the processing
hsYYYYZZ_s14_cl.evt.gz	Filtered event file for the SDD 14 detector
hsYYYYZZ_s38_cl.evt.gz	Filtered event file for the SDD 38 detector
hsYYYYZZ_s54_cl.evt.gz	Filtered event file for the SDD 54 detector
hsYYYYZZ_s14.pi.gz	Spectrum for the SDD 14 detector
hsYYYYZZ_s38.pi.gz	Spectrum for the SDD 38 detector
hsYYYYZZ_s54.pi.gz	Spectrum for the SDD 54 detector
hsYYYYZZ_sp.gif	Plot of the spectra

The HaloSat archive were first released in April 2020 including all observations of the first year of science operations. After mission operations, all data collected from October 15, 2018, up to September 29, 2020 were processed to produce the final archive released in February 2021. Figure 2 shows the pointing color-coded of the data in the final archive accordingly with the exposure obtained from the detector SDD14 (the exposure is similar in all three detectors).

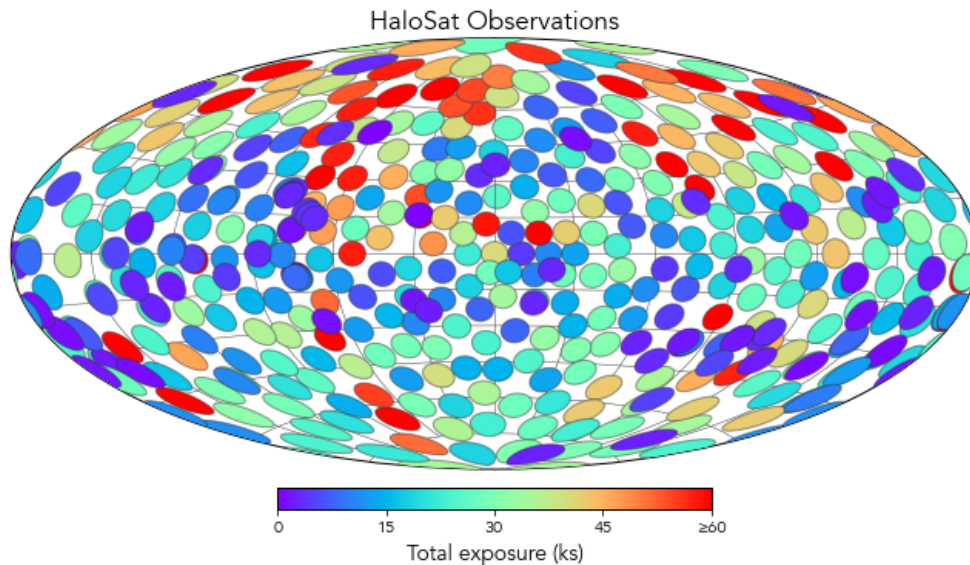


Fig 2: All HaloSat observations taken during the mission operation

2 Data Analysis

The event data in the public archive have been prepared with optimized filtering. However, users may further manipulate the data as necessary for their science goals. Using existing tools in HEASoft, users may select data and extract the resulting spectrum.

2.1 Screening

Additional screening based on specific times of the hk parameters can be achieved using generic HEASoft tasks. The screening involves four steps. For example to rescreen the unfiltered event using different LC_HARD and LC_VLE boundaries ($LC_HARD \leq 0.16$ && $LC_VLE \leq 0.6$) the steps are:

1) Build a lightcurve from the hk file for the LC_VLE and LC_HARD with 64 sec binning :

```
fcurve infile="hs002501_s14.hk.gz" gtifile="hs002501_s14_uf.evt.gz+2" outfile="hk_sel.hk"
timecol=TIME columns="lc_vle lc_hard" binsz=64 lowval=619477924.0 highval=645767891.0
binmode=mean
```

2) Select all time with good livetime :

```
fselect infile=hk_sel.hk outfile=hk_sel_lvgt1.hk expr="LIVETIME=>1"
```

3) Create gti for the new expression to be applied to the unfiltered data:

```
maketime infile="hk_sel_lvgt1.hk" outfile="hk_sel_lvgt1.gti" expr="LC_HARD <= 0.16 && LC_VLE <=
0.6" time=TIME compact=no preftr=0.5 postfr=0.5 premax=32 postmax=32
```

4) Apply the new gti using xselect as shown in the example 2 in the next section

2.2 Using xselect to extract a spectrum and a light curve

The HEASoft tasks *xselect/extractor* have been updated to include the HaloSat specifications and released with HEASoft version 6.27 (Mar 31, 2020). Below are two examples of how to derive a spectrum and a light curve using the cleaned event file *hs013201_s14_cl.evt.gz* (example 1) and how to derive a spectrum using an unfiltered data file *hs002501_s14_uf.evt.gz* with gti file, *hk_sel_lvgti.hk* (example 2), obtained using different LC_HARD and LC_VLE boundaries (see section 2.1).

Example 1 :

```
xselect
```

```
    ** XSELECT V2.4m **
```

```
> Enter session name >[xselect]
```

```
xselect:SUZAKU > read event hs002501_s14_cl.evt.gz
```

```
> Enter the Event file dir >[.]
Got new mission: HALOSAT
> Reset the mission ? >[yes]
```

```
Notes: XSELECT set up for HALOSAT
Time keyword is TIME in units of s
Default timing binsize = 16.000
```

```
Setting...
```

```
Energy keyword = PI with binning = 1
```

```
Getting Min and Max for Energy Column...
```

```
Got min and max for PI: 1 455
```

```
Got the minimum time resolution of the read data: 0.50000E-01
```

```
MJDREF = 5.1544000742870E+04 with TIMESYS = TT
```

```
Number of files read in: 1
```

```
***** Observation Catalogue *****
```

```
Data Directory is: /processing/halosat/xselect/
```

```
HK Directory is: /processing/halosat/xselect/
```

```
OBJECT      TELESCOP INSTRUME  OBJTYPE  DATAMODE  DATE-OBS      DATE-END
1 HaloSat J1748+0300 HALOSAT  SDD14    SCIENCE  PHOTON      2019-08-19T00:00:49 2020-
06-18T03:57:02
```

```
xselect:HALOSAT-SDD14 > extract curve
```

```
extractor v5.39 23 Jun 2021
```

```
Getting FITS WCS Keywords
```

```
Doing file: /processing/halosat/xselect/hs002501_s14_cl.evt.gz
```

```
100% completed
```

Total	Good	Bad:	Time	Phase	Grade	Cut
29950	29950	0	0	0	0	

```
=====
```

Grand Total	Good	Bad:	Time	Phase	Grade	Cut
29950	29950	0	0	0	0	

```
in 76544. seconds
```

```
Fits light curve has 29950 counts for 0.3913 counts/sec
```

```
xselect:HALOSAT-SDD14 > save curve mycurve_14
```

```
Wrote FITS light curve to file mycurve_14.lc
```

```
xselect:HALOSAT-SDD14 > extract spectrum
```

```
extractor v5.39 23 Jun 2021
```

```
Getting FITS WCS Keywords
```

```
Doing file: /processing/halosat/xselect/hs002501_s14_cl.evt.gz
```

```
100% completed
```

Total	Good	Bad:	Time	Phase	Grade	Cut
29950	29950	0	0	0	0	

```
=====
```

Grand Total	Good	Bad:	Time	Phase	Grade	Cut
29950	29950	0	0	0	0	

```
in 76544. seconds
```

```
Spectrum has 29950 counts for 0.3913 counts/sec
```

Keyword DATE-END has two values: '2020-06-18T03:39:58' and '2020-06-18T03:57:02'
 ... written the PHA data Extension
 xselect:HALOSAT-SDD14 > **save spectrum myspec_14**
 Wrote spectrum to myspec_14.pha
 xselect:HALOSAT-SDD14 >

Example 2 :

xselect

**** XSELECT V2.4m ****

> Enter session name >[xselect]
 xselect SUZAKU > **read event hs002501_s14_uf.evt.gz**
 > Enter the Event file dir >[.]
 Got new mission: HALOSAT
 > Reset the mission ? >[yes]

Notes: XSELECT set up for HALOSAT
 Time keyword is TIME in units of s
 Default timing binsize = 16.000

Setting...

Energy keyword = PI with binning = 1

Getting Min and Max for Energy Column...

Got min and max for PI: 1 455

Got the minimum time resolution of the read data: 0.50000E-01
 MJDREF = 5.1544000742870E+04 with TIMESYS = TT
 Number of files read in: 1

***** Observation Catalogue *****

Data Directory is: /processing/halosat/xselect/

HK Directory is: /processing/halosat/xselect/

OBJECT	TELESCOP	INSTRUME	OBJTYPE	DATAMODE	DATE-OBS	DATE-END
1 HaloSat	J1748+0300	HALOSAT	SDD14	SCIENCE	PHOTON	2019-08-18T21:11:27 2020-06-18T03:57:34

xselect:HALOSAT-SDD14 > **filter time file hk_sel_lvgt1.gti**
 xselect:HALOSAT-SDD14 > **extract spectrum**
 extractor v5.39 23 Jun 2021
 Getting FITS WCS Keywords
 Doing file: /processing/halosat/xselect/hs002501_s14_uf.evt.gz
 100% completed

Total	Good	Bad: Time	Phase	Grade	Cut
50784	28200	22584	0	0	0
=====					
Grand Total	Good	Bad: Time	Phase	Grade	Cut
50784	28200	22584	0	0	0

in 72480. seconds

```
Spectrum      has 28200 counts for 0.3891 counts/sec
... written the PHA data Extension
xselect:HALOSAT-SDD14 > save spectrum myspec2_14
Wrote spectrum to myspec2_14.pha
xselect:HALOSAT-SDD14 >
```

The spectrum may be analyzed within *xspec*. There is a single response and arf applicable to all the spectral files obtained for the three detectors. The responses are located in HEASARC caldb area: <https://heasarc.gsfc.nasa.gov/FTP/caldb/data/halosat/sdd/cpf/>
They are: [hs_sdd_all20180701v002.arf](#) [hs_sdd_avgnoise20180701v001.rmf](#)

There is an additional response [hs_sdd_diag20180701v001.rmf](#) that is applicable to the background modelling (see section 2.3). These responses were released on 2020-03-20 and 2023-05-01 (update for the arf) and are valid for data taken since the start of the mission (2018-07-01).

2.3 Spectral modelling and Inflight Calibration

HaloSat has a wide field of view, thus each spectrum contains emission from several background and foreground components in addition to the emission from the astrophysical object of interest. The HaloSat team has adopted the following spectral model components:

- 1) Astrophysical source
- 2) Diffuse cosmic X-ray background (CXB)
- 3) Local hot bubble emission (LHB)
- 4) Particle-induced detector background (PIDB)

The choice of model for the astrophysical sources depends on the target of interest (Kaaret, P. et al. 2019, ApJ, 844, 162). Many models are available for the CXB. It is important to note that point sources are present in HaloSat spectra, so the CXB normalization must be chosen to include point sources. It is possible to either take the LHB as fixed, using, e.g., the results of Liu et al. 2017, ApJ, 834, 33, or to fit the LHB. However, it should be noted that the strongest emission of the LHB lies below the HaloSat band.

The particle background is best modeled as two power laws. This is a new background model and it is fully discussed in the report “Halosat background Analysis” by Bluem J. et al. 2022 (<https://heasarc.gsfc.nasa.gov/docs/halosat/analysis/back20230501.pdf>).

The main (hard) background power law has a fixed power law index which value dependent on the detector and the hard cut applied to the data as shown in Table 4. This component contributes strongly across all energies.

Table 4 : Hard component Power Law index			
Hard rate Cut	D14 photon index	D54 photon index	D38 photon index
0.12 count/s	0.80+/- 0.08	0.75 +/- 0.08	0.73+/-0.07
0.16 count/s	0.69+/-0.06	0.65+/- 0.06	0.64 +/-0.07

The secondary (soft) power law is a steeper component that primarily contributes at the lowest energies and has a fixed photon index of 3.4 for each of the detectors. The normalizations of both

components are left free to fit and are not linked between the detectors. The 3.4 photon index power law component varies enough that at times it is not required. In these cases, the best fit gives a normalization that is consistent with zero.

These background components are used in combination with the diagonal HaloSat response matrix (hs_sdd_diag20180701v001.rmf).

This new method supersedes the previous described in the "Modeling the instrumental background in HaloSat"

(<https://heasarc.gsfc.nasa.gov/docs/halosat/analysis/back20210209.pdf>),

an analysis of the instrumental background for fields in the southern Galactic halo as used in Kaaret et al. (2020, Nature Astronomy, 4, 1072). The new method was motivated by the HaloSat study of the circumgalactic medium (Bluem et al. 2022 ApJ 936 72). The paper shows that by using the previous background model on the three high-statistics spectra, one for each DPU obtained stacking spectra from individual fields, the previous background model was insufficient with noticeable residuals in the 1.5-2.5 keV range as well as in the 0.4-0.5 keV range.

Because the HaloSat field of view is quite large, bright X-ray sources are sometime included within the field of view and contribute to the observed spectra. Bluem et al. (2020, ApJ, 902, 91) describing fitting the spectra of a field containing the X-ray binary Cygnus X-3. Data from MAXI (Monitor of All-sky X-ray Image) were used to generate light curves and spectra for Cyg X-3 for the times of the HaloSat observation. A model was fit to the MAXI spectrum to fix the spectral parameters and relative normalizations of the various components. The same model was included as an added component in the fit to the HaloSat spectrum with the overall normalization allowed to vary.

Inflight calibration

The X-ray data from CasA were used to calibrate the on-orbit energy scale calibration and the Crab data to investigate residuals around 1.8 keV. The note "Halosat Response Matrix modification" (<https://heasarc.gsfc.nasa.gov/docs/halosat/analysis/response20220128.pdf>) describes the analysis and results of these on orbit calibrations. It was found that the original data files suffer a small gain offset and need addition of an edge model around 1.8 in spectral fitting. Gain adjustment is no longer required for data processed with the version hsuf_20221026. Similarly, the edge has been included in the arf file hs_sdd_all20180701v002.arf and therefore not required in the spectral fitting.

Use of the previous data files and released responses can be handled in the spectral analysis with two steps. The first is to add a small gain offset adjustment of the response necessary for spectra with high statistics and/or fits with multiple components. The gain adjustment is different for each detector and is 0.0232 keV for DPU14, 0.0240 keV for DPU54, and 0.0239 keV for DPU38 respectively. The second is to add in the spectral fitting an edge model with a threshold energy of 1.839 keV and tau of 0.169 to account for the residual around 1.8 keV.

Data reprocessing and new arf

All Halosat data collected during the science operations from Oct 15, 2018 and Sep 29, 2020 have been reprocessed for the final archive in March 2023, processing version `hsuf_20221026`. The main changes in the reprocessing include:

- Fix an error in writing the spectra to correct channel offset. The gain shift is no longer necessary when fitting the spectra.
- Fix a bug in the creation of the housekeeping files that resulted in listing equal values for specific columns in specific time range. This bug did not affect the data selection nor the final spectra calculation.
- DATE-OBS and DATE-END are now reported in UTC in all headers of the FITS file.
- Correct the PDF files reporting the observation log for specific sequences that were unreadable.

In addition the arf file has been updated (`hs_sdd_all20180701v002.arf`) to include the edge at 1.8 keV and available in CALDB. When using this arf, it is no longer necessary to include an edge in the spectral fitting.

The document <https://heasarc.gsfc.nasa.gov/docs/halosat/analysis/reproc20230501.pdf> explains in detail the changes for the final data processing as well as the changes included in the arf.

Data processed with version earlier than `hsuf_20221026` require applying a gain shift in the spectral fitting. Using the previous arf version (`hs_sdd_all20180701v001.arf`) requires adding an edge in the spectral fitting independently of the data processing version.

Example of Spectral Fitting

The example shows the command files to use in *xspec*. The spectral modeling includes the source model and the background power laws model. The spectral files are for the latest reprocessing (`hsuf_20221026`) and uses the latest arf (`hs_sdd_all20180701v002.arf`) which accounts for the edge. The value of the column density (Tabs function) is derived using the method described by LaRocca et al. (2020 ApJ, 904, 54)

```
xspec > @load_h0199_s54.xcm
xspec> @halo_fit.xcm
xspec > fit
xspec> plot data delchi
```

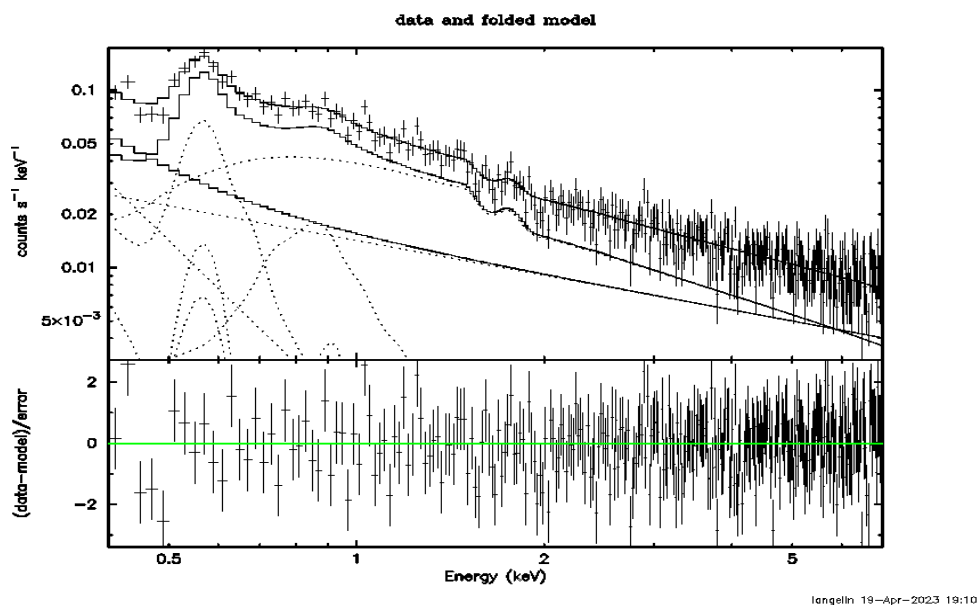


Figure 3: Data and the spectral components (upper panel); the goodness of the fit (lower panel)

where the command files contain the following settings:

load_h0199_s54.xcm

```
data hs019901_s54.pi
response hs_sdd_avgnoise20180701v001.rmf
arf hs_sdd_all20180701v002.arf
```

```
ign 0.0-0.4
ign 7.0-**
setplot rebin 3.0 30
plot ldata
```

```
cpd /xw
setplot energy
```

halo_fit.xcm

```
method leven 10 0.01
abund wilm
xsect vern
cosmo 70 0 0.73
xset delta 0.01
statistic cstat
systematic 0
```

```
model apec + TBabs*powerlaw + TBabs(apec + apec) + gaussian + gaussian
0.084 -1 0.008 0.008 64 64
```

1	-0.001	0	0	5	5
0	-0.01	-0.999	-0.999	10	10
0.4	-1	0	0	1e+20	1e+24
0.0148	-1	0	0	100000	1e+06
1.45	-1	-3	-2	9	10
0.38	-1	0	0	1e+20	1e+24
0.0148	-1	0	0	100000	1e+06
0.7623	0.01	0.008	0.008	64	64
0.3	-1	0	0	5	5
0	-0.01	-0.999	-0.999	10	10
0.183	0.01	0	0	1e+20	1e+24
0.147	-1	0.008	0.008	64	64
0.3	-1	0	0	5	5
0	-0.01	-0.999	-0.999	10	10
1.54	0.01	0	0	1e+20	1e+24
0.5634	-1	0	0	1e+06	1e+06
0.001	-1	0	0	10	20
0.03	-1	0	0	1e+20	1e+24
0.6531	-1	0	0	1e+06	1e+06
0.001	-1	0	0	10	20
0.0027	-1	0	0	1e+20	1e+24

response 2:1 hs_sdd_diag20180701v001.rmf

model 2:back powerlaw + powerlaw

0.65	-1	-3	-2	9	10
0.03	0.001	0	0	1e+20	1e+24
3.4	-1	-3	-2	9	10
0.02	0.001	0	0	1e+20	1e+24

3 Appendix A: HaloSat event and HK FITS file formats

a) Event File : EVENT, GTI and SCREENING extensions

The keywords and column names for the EVENT, GTI and screening extensions are listed in Table 4. The unfiltered files contain the EVENT and GTI extensions, and the cleaned files contain the EVENT, GTI and SCREENING extensions. The HDUCLAS2 keyword value distinguishes the EVENT and the GTI extensions associated with the unfiltered and cleaned files (see the setting below).

Table 4		
EVENT extension, Valid for unfiltered and cleaned files		
Keyword	Value	Comment
TTYPE1	'TIME '	/Time of events
TFORM1	'ID '	/data format of field
TUNIT1	's '	/physical unit of field
TTYPE2	'PHA '	/Pulse Height Analyzer
TFORM2	'II '	/ data format of field
TUNIT2	'chan '	/physical unit of field
TLMIN2	600	/minimum legal value of the column
TLMAX2	12900	/maximum legal value of the column
TTYPE3	'PI '	/Pulse Invariant
TFORM3	'II '	/ data format of field
TUNIT3	'chan '	/ physical unit of field
TLMIN3	1	/minimum legal value of the column
TLMAX3	455	/maximum legal value of the column
TNULL3	-1	/ null value
PI2ENE	0.02	/ PI conversion from chan to energy keV
EXTNAME	'EVENTS'	/ Binary table extension name
HDUCLASS	'OGIP'	/Format conforms to OGIP/GSFC standards
HDUCLAS1	'EVENTS'	/ First class level
HDUCLAS2	'string'	/ Second class level
TELESCOP	'HALOSAT'	/ Telescope (mission) name
INSTRUME	'SDDnn'	/ Instrument name
DATAMODE	'PHOTON'	/Instrument datamode
OBSERVER	'PHILIP KAARET'	/ Principal Investigator
OBS ID	'string'	/ Observation ID
OBJECT	'string'	/ Object/Target name
OBJTYPE	'string'	/ Object/Target type
EQUINOX	2000	/[yr] Equinox of celestial coord system
RADECSYS	'FK5'	/ Celestial coord system
RA NOM	0.0	/ [deg] R.A. of nominal aspect point [J2000]

DEC NOM	0.0	/ [deg] Dec. of nominal aspect point [J2000]
RA OBJ	0.0	/ [deg] Object Right ascension [J2000]
DEC OBJ	0.0	/ [deg] Object Declination [J2000]
TIMESYS	'TT'	/ Reference Time System
MJDREFI	51544	/[d] MJD reference day (2000-01-01T00:00:00)
MJDREFF	7.4287037037037E-04	/[d] MJD reference (fraction of day)
TIMEREF	'LOCAL'	/Reference Frame
TASSIGN	'SATELLITE'	/Time assigned by clock
TIMEUNIT	's'	/Time unit for timing header keyword
TIMEDEL	0.05	/[s] Data time resolution
TIMEZERO	0.0	/[s] Time Zero
TIMEPIXR	1	/Bin time beginning=0 middle=0.5 end=1
TIERELA	1.0E-8	/[s/s] relative errors expressed as rate
TIERABSO	1.0	/[s] timing precision in seconds
TSTART	xxxxxxx.xxx	/[s] Observation Start Time
TSTOP	yyyyyyy.yyy	/[s] Observation Stop Time
TELAPSE	nnnnn.nnn	/[s] Stop – Start
ONTIME	value	/[s] Observation time on target
EXPOSURE	value	/[s] exposure
DATE-OBS	'yyyy-mm-ddThh:mm:ss'	/Start date of observations
DATE-END	'yyyy-mm-ddThh:mm:ss'	/End date of observations
CLOCKAPP	T	/ Clock correction applied ? (F/T)
DEADAPP	F	/ Has deadtime been applied to data? (F/T)
ORIGIN	'UNIVERSITY OF IOWA'	/ Origin of fits file
PROCVER	'hsuf_YYYYMMDD_hsc1_YYYYMMDD'	/Processing script version number
SOFTVER	'Hea_ddmmyyyy_Vxxxx'	/ Software version
CALDBVER	'hsYYYYMMDD'	/CALDB index version used
TLM2FITS	'db_YYYYMMDD'	/Telemetry converter FITS version
CREATOR	'string'	/ Software creator of the file
DATE	'yyyy-mm-ddThh:mm:ss'	/File creation date
CHECKSUM	value	/ data unit checksum updated date
DATASUM	value	/ HDU checksum updated date

GTI extension valid for unfiltered and cleaned files

Keyword	Value	Comment
TTYPE1	'START '	/Start time
TFORM1	'ID '	/ data format of field
TUNIT1	's '	/physical unit of field
TTYPE1	'STOP '	/Stop time
TFORM1	'ID '	/ data format of field
TUNIT1	's '	/physical unit of field
EXTNAME	'GTI'	/ Binary table extension name
HDUCLASS	'OGIP'	/Format conforms to OGIP/GSFC standards

HUCLAS1	'GTI'	/ First class level
HUCLAS2	'string'	/ Second class level
TELESCOP	'HALOSAT'	/ Telescope (mission) name
INSTRUME	'SDDnn'	/Instrument name
OBSERVER	'PHILIP KAARET'	/ Principal Investigator
OBS_ID	'string'	/ Observation ID
OBJECT	'string'	/ Object/Target name
OBJTYPE	'string'	/ Object/Target type
EQUINOX	2000	/[yr] Equinox of celestial coord system
RADECSYS	'FK5'	/ Celestial coord system
RA_NOM	0.0	/ [deg] R.A. of nominal aspect point [J2000]
DEC_NOM	0.0	/ [deg] Dec. of nominal aspect point [J2000]
RA_OBJ	0.0	/ [deg] Object Right ascension [J2000]
DEC_OBJ	0.0	/ [deg] Object Declination [J2000]
TIMESYS	'TT'	/ Reference Time System
MJDREFI	51544	/[d] MJD reference day (2000-01-01T00:00:00)
MJDREFF	7.4287037037037E-04	/[d] MJD reference (fraction of day)
TIMEREF	'LOCAL'	/Reference Frame
TASSIGN	'SATELLITE'	/Time assigned by clock
TIMEUNIT	's'	/Time unit for timing header keyword
TIMEZERO	0.0	/[s] Time Zero
TSTART	xxxxxxx.xxx	/[s] Observation start time
TSTOP	yyyyyyy.yyy	/[s] Observation stop time
DATE-OBS	'yyyy-mm-ddThh:mm:ss'	/Start date of observations
DATE-END	'yyyy-mm-ddThh:mm:ss'	/End date of observations
CLOCKAPP	T	/ Clock correction applied ? (F/T)
ORIGIN	'UNIVERSITY OF IOWA'	/ Origin of fits file
PROCVER	'hsuf_YYYYMMDD_hscf_YYYYMMDD'	/Processing script version number
SOFTVER	'Hea ddmmyyyy Vxxxx'	/ Software version
CALDBVER	'hsYYYYMMDD'	/CALDB index version used
TLM2FITS	'db_YYYYMMDD'	/Telemetry converter FITS version
CREATOR	'db_hsuf'	/Software creator of the file
DATE	'yyyy-mm-ddThh:mm:ss'	/File creation date
CHECKSUM	'value'	/ data unit checksum updated date
DATASUM	'value'	/ HDU checksum updated date
SCREENING extension valid for cleaned file		
Keyword	Value	Comment
TTYPE1	'EXTENSION '	/Name of extension to apply screening
TFORM1	'20A '	/ data format of field
TTYPE2	'EXPRESSION '	/Expression
TFORM2	'600A '	/ data format of field

EXTNAME	'SCREENING'	/ Binary table extension name
TELESCOP	'HALOSAT'	/ Telescope (mission) name
INSTRUME	'SDDnn'	/Instrument name
OBSERVER	'PHILIP KAARET'	/ Principal Investigator
OBS ID	'string'	/ Observation ID
OBJECT	'string'	/ Object/Target name
OBJTYPE	'string'	/ Object/Target type
ORIGIN	'UNIVERSITY OF IOWA'	/ Origin of fits file
PROCVER	'hsuf_YYYYMMDD_hsc1_YYYYMMDD'	/Processing script version number
SOFTVER	'Hea ddmmyyyy_Vxxxx'	/ Software version
CALDBVER	'hsYYYYMMDD'	/CALDB index version used
TLM2FITS	'db_YYYYMMDD'	/Telemetry converter FITS version
CREATOR	'db_hsuf_hsc1'	/Software creator of the file
DATE	'yyyy-mm-ddThh:mm:ss'	/File creation date
CHECKSUM	'value'	/ data unit checksum updated date
DATASUM	'value'	/ HDU checksum updated date

The TLMIN and TLMAX associated to the PI and PHA columns define the lower and upper channel for the spectrum. The lower and upper channels are positive integer numbers. The TNULL keyword contains the value associated to non-valid channel numbers.

NOTE:

HDUCLAS2 has different settings in the unfiltered and filtered data files. The values are:

- Unfiltered EVENT extension set to 'ALL'; Filtered EVENT extension 'ACCEPTED'
- Unfiltered GTI extension set to 'ALL'; Filtered GTI extension 'STANDARD'

PROCVER has different settings in the unfiltered and filtered data files. The values are:

- In EVENT and GTI extensions of the unfiltered file is set to 'hsuf_YYYYMMDD'
- In EVENT and GTI extensions of the cleaned file set to 'hsuf_YYYYMMDD_hsc1_YYYYMMDD'

b) Instrument housekeeping

The housekeeping file contains the keywords and columns of the instrument housekeeping and the orbital information parameters derived by prefilter.

Table 5		
Event extension		
Keyword	Value	Comment
TTYPE1	'TIME '	/Time
TFORM1	'1D '	/ data format of field
TUNIT1	's '	/physical unit of field

TTYPER2	'SDD_TEMP '	/[deg_C] Temperature readout for Si chip
TFORM2	'1D '	/ data format of field
TTYPER3	'TEC_PWN '	/Value duty cycle of the TEC
TFORM3	'1D '	/ data format of field
TTYPER4	'ADC_TEMP '	/[deg_C] Temperature readout ADC
TFORM4	'1D '	/ data format of field
TTYPER5	'LRS_PCNT '	/Low rate science packet
TFORM5	'1D '	/ data format of field
TTYPER6	'SDDHVSET'	/ Voltage DAC on set line
TFORM6	'1D '	/ data format of field
TUNIT6	'V '	/ physical unit of field
TTYPER7	'FLEXICNT'	/ FLEXI counter
TFORM7	'1D '	/ data format of field
TTYPER8	'SDD1'	/ reset pulse threshold
TFORM8	'1D '	/ data format of field
TUNIT8	'V '	/ physical unit of field
TTYPER9	'MON_3P3V'	/ Voltage Monitor on 3.3V line
TFORM9	'1D '	/ data format of field
TUNIT9	'V '	/ physical unit of field
TTYPER10	'MON_M5V'	/ Voltage Monitor on -5V line
TFORM10	'1D '	/ data format of field
TUNIT10	'V '	/ physical unit of field
TTYPER11	'MON_P5V'	/ Voltage Monitor on +5V line
TFORM11	'1D '	/ data format of field
TUNIT11	'V '	/ physical unit of field
TTYPER12	'SDD0'	/ event detection threshold
TFORM12	'1D '	/ data format of field
TUNIT12	'V '	/ physical unit of field
TTYPER13	'DAC_TEMP '	/[deg_C]Temperature of the DAC
TFORM13	'1D '	/ data format of field
TTYPER14	'BPL_TEMP '	/[deg_C]Temperature sensor of baseplate
TFORM14	'1D '	/ data format of field
TTYPER15	'HSK_PCNT '	/Housekeeping packet counter
TFORM15	'1D '	/ data format of field
TTYPER16	'SDDHVMON'	/ Voltage DAC on monitor line
TFORM16	'1D '	/ data format of field
TUNIT16	'V '	/ physical unit of field
TTYPER17	'DPU_TEMP '	/[deg_C]Temperature DPU band
TFORM17	'1D '	/ data format of field
TTYPER18	'RA'	/ Right Ascension of the pointing
TFORM18	1D	/ data format of field
TUNIT18	'deg'	/ physical unit of field
TTYPER19	'DEC'	/ Declination of the pointing
TFORM19	1D	/ data format of field

TUNIT19	'deg'	/ physical unit of field
TTYPER20	'SAT_LAT'	/Satellite Latitude
TFORM20	'1D'	/format of field
TUNIT20	'deg'	/ physical units of field
TTYPER21	'SAT_LON'	/Satellite Longitude
TFORM21	'1D'	/format of field
TUNIT21	'deg'	/ physical units of field
TTYPER22	'NADIR_ANGLE'	/Angular distance from pointing to Nadir
TFORM22	'1D'	/format of field
TUNIT22	'deg'	/ physical units of field
TTYPER23	'OFFSET'	/Offset
TFORM23	'1D'	/format of field
TUNIT23	'deg'	/ physical units of field
TTYPER24	'LC_GAP1'	/Averaged 8s Count Rate in LC_GAP1 band
TFORM24	'1D'	/format of field
TUNIT24	'count/s'	/ physical units of field
TTYPER25	'LC_SCI'	/Averaged 8s Count Rate in LC_SCI band
TFORM25	'1D'	/format of field
TUNIT25	'count/s'	/ physical units of field
TTYPER26	'LC_ALL'	/Averaged 8s Total Count Rate
TFORM26	'1D'	/format of field
TUNIT26	'count/s'	/ physical units of field
TTYPER27	'LC_HARD'	/Averaged 8s Count Rate in LC_HARD band
TFORM27	'1D'	/format of field
TUNIT27	'count/s'	/ physical units of field
TTYPER28	'LC_VLE'	/Averaged 8s Count Rate in LC_VLE band
TFORM28	'1D'	/format of field
TUNIT28	'count/s'	/ physical units of field
TTYPER29	'LC_OXYGEN'	/Averaged 8s Count Rate in LC_OXYGEN band
TFORM29	'1D'	/format of field
TUNIT29	'count/s'	/ physical units of field
TTYPER30	'LC_RESET'	/Averaged 8s Count Rate in LC_RESET band
TFORM30	'1D'	/format of field
TUNIT30	'count/s'	/ physical units of field
TTYPER31	'LC_ALSI'	/Averaged 8s Count Rate in LC_ALSI band
TFORM31	'1D'	/format of field
TUNIT31	'count/s'	/ physical units of field
TTYPER32	'LC_UP'	/Averaged 8s Count Rate in LC_UP band
TFORM32	'1D'	/format of field
TUNIT32	'count/s'	/ physical units of field
TTYPER33	'IN_SAA'	/Satellite in SAA?
TFORM33	'L'	/format of field
TTYPER34	'SAT_ALT'	/Satellite Altitude
TFORM34	'1D'	/format of field

TUNIT34	'km'	/ physical units of field
TTYPER35	'ELV'	/angle between pointing and earth limb
TFORM35	'1D'	/format of field
TUNIT35	'deg'	/ physical units of field
TTYPER36	'BR_EARTH'	/angle between pointing and bright earth
TFORM36	'1D'	/format of field
TUNIT36	'deg'	/ physical units of field
TTYPER37	'FOV_FLAG'	/0=sky ; 1=dark earth; 2 bright earth
TFORM37	'I'	/format of field
TNULL37	-999	/ tnull value
TTYPER38	'SUNSHINE'	/1= in sunshine ; 0=not
TFORM38	'I'	/format of field
TNULL38	-999	/ tnull value
TTYPER39	'SUN_ANGLE'	/angle between pointing vector and sun vector
TFORM39	'1D'	/format of field
TUNIT39	'deg'	/ physical units of field
TTYPER40	'MOON_ANGLE'	/angle between pointing vector and moon vector
TFORM40	'1D'	/format of field
TUNIT40	'deg'	/ physical units of field
TTYPER41	'RAM_ANGLE'	/angle between pointing and velocity vectors
TFORM41	'1D'	/format of field
TUNIT41	'deg'	/ physical units of field
TTYPER42	'ANG_DIST'	/angular distance of pointing from nominal
TFORM42	'1D'	/format of field
TUNIT42	'deg'	/ physical units of field
TTYPER43	'COR_ASCA'	/magnetic cut-off rigidity (ASCA map)
TFORM43	'1D'	/format of field
TUNIT43	'GeV/c'	/ physical units of field
TTYPER44	'COR_SAX'	/magnetic cut-off rigidity (IGRFmap)
TFORM44	'1D'	/format of field
TUNIT44	'GeV/c'	/ physical units of field
TTYPER45	'MCILWAIN_L'	/McIlwain L parameter (SAX)
TFORM45	'1D'	/format of field
TTYPER46	'SAA'	/1=in ; 0=not
TFORM46	'I'	/format of field
TNULL46	-999	/ tnull value
TTYPER47	'SAA_TIME'	/time since entering/exiting SAA
TFORM47	'1D'	/format of field
TUNIT47	's'	/ physical units of field
TTYPER48	'RAP'	/ Right Ascension by prefilter
TFORM48	1D	/ data format of field
TUNIT48	'deg'	/ physical unit of field
TTYPER49	'DECP'	/ Declination by prefilter
TFORM49	1D	/ data format of field

TUNIT49	'deg'	/ physical unit of field
TTYPE50	'SAT_LATP'	/Satellite Latitude by prefilter
TFORM50	'1D'	/format of field
TUNIT50	'deg'	/ physical units of field
TTYPE51	'SAT_LONP'	/Satellite Longitude by prefilter
TFORM51	'1D'	/format of field
TUNIT51	'deg'	/ physical units of field
TTYPE52	'POSITION'	/Prefilter ECI Position satellite {X,Y,Z}
TFORM52	'3E'	/format of field
TUNIT52	'km'	/ physical units of field
TTYPE53	'VELOCITY'	/Prefilter ECI velocity satellite {vX,vY,vZ}
TFORM53	'3E'	/format of field
TUNIT53	'km/s'	/ physical units of field
TTYPE54	'ROLL'	/pointing roll angle
TFORM54	'1D'	/format of field
TUNIT54	'deg'	/ physical units of field
TTYPE55	'SUN_RA'	/ Right Ascension of Sun
TFORM55	1D	/ data format of field
TUNIT55	'deg'	/ physical unit of field
TTYPE56	'SUN_DEC'	/ Declination of Sun
TFORM56	1D	/ data format of field
TUNIT56	'deg'	/ physical unit of field
HDUCLASS	'OGIP'	/Format conforms to OGIP/GSFC standards
HDUCLAS1	'TEMPORALDATA'	/ First class level
HDUCLAS2	'HK'	/ Second class level
TELESCOP	'HALOSAT'	/ Telescope (mission) name
INSTRUME	'SDDnn'	/Instrument name
OBSERVER	'PHILIP KAARET'	/ Principal Investigator
OBS_ID	'string'	/ Observation ID
OBJECT	'string'	/ Object/Target name
OBJTYPE	'string'	/ Object/Target type
EQUINOX	2000	/[yr] Equinox of celestial coord system
RADECSYS	'FK5'	/ Celestial coord system
RA_NOM	0.0	/ [deg] R.A. of nominal aspect point [J2000]
DEC_NOM	0.0	/ [deg] Dec. of nominal aspect point [J2000]
RA_OBJ	0.0	/ [deg] Object Right ascension [J2000]
DEC_OBJ	0.0	/ [deg] Object Declination [J2000]
TIMESYS	'TT'	/ Reference Time System
MJDREFI	51544	/[d] MJD reference day (2000-01-01T00:00:00)
MJDREFF	7.4287037037037E-04	/[d] MJD reference (fraction of day)
TIMEREF	'LOCAL'	/Reference Frame
TASSIGN	'SATELLITE'	/Time assigned by clock
TIMEUNIT	's'	/Time unit for timing header keyword

TIMEDEL	8.0	/[s] Data time resolution
TIMEZERO	0.0	/[s] Time Zero
TIERRELA	1.0E-8	/[s/s] relative errors expressed as rate
TIERABSO	1.0	/[s] timing precision in seconds
TSTART	xxxxxxx.xxx	/[s] Observation Start Time
TSTOP	yyyyyyy.yyy	/[s] Observation Stop Time
DATE-OBS	'yyyy-mm ddThh:mm:ss'	/Start date of observations
DATE-END	'yyyy-mm ddThh:mm:ss'	/End date of observations
CLOCKAPP	T	/ Clock correction applied ? (F/T)
ORIGIN	'UNIVERSITY OF IOWA'	/ Origin of fits file
PROCVER	'hsuf_YYYYMMDD_hscf_YYYYMMDD'	/Processing script version number
SOFTVER	'Hea ddmmmyyyy Vxxxx'	/ Software version
CALDBVER	'hsYYYYMMDD'	/CALDB index version used
TLM2FITS	'db_YYYYMMDD'	/Telemetry converter FITS version
CREATOR	'db_hscf'	/Software creator of the file
DATE	'yyyy-mm-ddThh:mm:ss'	/File creation date
CHECKSUM	'value'	/ data unit checksum updated date
DATASUM	'value'	/ HDU checksum updated date