



ASTRO-H

**ASTRO-H ALIGNMENT MEASUREMENT  
SYSTEM (CAMS)  
INSTRUMENTS AND DATA PROCESSING  
ASTH-SCT**

Version 0.92

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Version 0.91	August 24, 2015	<p>Added results of measurement of beta angles (Table 6).</p>
Version 0.92	Sep. 15, 2016	<p>Correction 1000/1024 to the offset measurements in Table 6 added. Commented in Appendix 2.</p> <p>Rotation sign changed in formulas (5)</p>



# 1 Introduction

## 1.1 Purpose

This document describes the instrument configuration and data processing of the ASTRO-H Alignment Measurement System also known as the Canadian Astro-H Metrology System (CAMS). CAMS will be used in post-processing hard x-ray imager (HXI) observations to improve the quality of images by correcting the positions of photon events depending on the measured distortion of the extendable optics bench (EOB) during observations. This document provides the scientific user with information related to the functions, specifications and capabilities of the hardware, and a basic understanding of the data products: how they are produced and what is included.

## 1.2 Applicable Documents

The following documents are applicable to this document.

- AD1. SE-801 NDG Canadian Astro-H Metrology System (CAMS) Users Manual (NDG010428) Rev8, 2015-06-19.
- AD2. SE-118 NDG CAMS-LD FM1 & FM2 Calibration Report (NDG012660) Rev2, Neptec Design Group, 2015-07-17.

## 1.3 Reference Documents

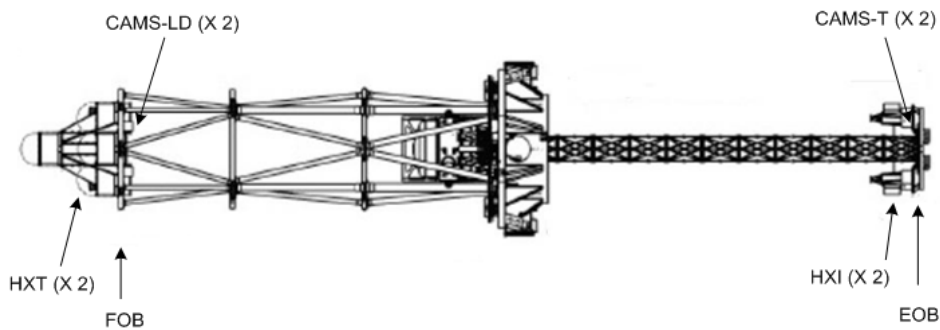
The following documents contain additional background information and were used to derive the requirements contained in this document.

- RD1. ASTRO-H Coordinates Definitions, ASTH-SCT-020, Version 0.2, Hans Krimm, December 2014.
- RD2. CAMS ICD, ICD-0S0054-AR.02N08.xls, Revision 8, January 2015.
- RD3. CAMS System Design Document, NDG011523, Revision 3, February 2014.
- RD4. ASTRO-H System Design, ASTH-100, Revision 14, May 22, 2012.
- RD5. S. Ueno, M. Ishida, T. Yuasa, “CAMS-LD and CAMS-T Electrical Interface Check and Mechanical Interface Check in January 2014”, JAXA, Presented at Canadian ASTRO-H Metrology System CDR, February 5-6 2014, Canada.
- RD6. Alignment parameters and calibration, Presentation slides, March 20, 2015.
- RD7. SE-110 NDG CAMS Performance Test Report (NDG011553) Rev4, 2015-07-17.

## 1.4 Overview of CAMS

The CAMS is a pair of laser-based position sensors that measure the relative displacement between ASTRO-H's fixed optics bench (FOB) and the hard X-ray imager (HXI) located at the focal plane of the telescope on the extendable optics bench (EOB).

The CAMS laser emitter and detector (CAMS-LD) are housed on the FOB alongside the mirror (lens) for the hard x-ray telescope (HXT) as shown in Figure 1. The HXI and the CAMS corner-cube retro-reflector (CAMS-T) are located at the end of the EOB. The CAMS system is capable of estimating three degrees of freedom for the relative motion between the EOB and the FOB. These are the lateral displacement (in a plane normal to the telescope's boresight), and the rotation about the boresight axis. As the corner-cube (focal plane) translates relative to the CAMS-LD (FOB) the position of the reflected light as measured by the CAMS image sensor translates by double the actual relative displacement. By measuring the relative displacement at two spatially distinct locations, the motion between the FOB and EOB can be resolved into a lateral translation and a rotation.



**Figure 1. Structural schematic of ASTRO-H showing the positions of the hard x-ray instruments and the CAMS units (from JAXA ISAS).**

The driving requirements of the CAMS\_LD and the CAMS-T are summarized in Table 1 [RD3].

**Table 1. Driving requirements of CAMS**

CAMS-LD	
Lifetime	3 years in LEO
Position resolution	240 $\mu\text{m}$ , 1-sigma
Field of view	+/- 13mm circular (includes 3mm deployment error)
Sampling rate	> 5 Hz
Mass	< 3.3 kg / module
Size	< 14.5 x 14.5 x 22.2 cm (not including mounting flange)
Power	< 5 W / module, Unstabilized (32V – 52V)
Data I/F	SpaceWire RMAP
CAMS-T	
Mass	< 0.5kg / module
Size	< 5 x 5 x 5 cm (not including mounting flange)

Both HXT/HXI telescopes will use CAMS data to correct their event positions. For each event recorded by an HXI, a position correction is applied based on the lateral shift and rotation of the EOB relative to the FOB estimated using data from both CAMS units. The specific algorithms used to perform this correction are presented in Section 5. A summary of the sequence of steps involved for each event correction are as follows:

1. An event is recorded by the HXI at a particular location and a particular timestamp
2. Measurements taken at 5 Hz by both CAMS units are used to estimate the relative shift in the focal plane and boresight rotation of the EOB
3. The CAMS estimated shifts are interpolated to give the estimated shift at the event timestamp
4. Depending on which HXI the event was recorded, the location of the event is adjusted based on the amount of the estimated shift.

## 2 CAMS Concept

The overall function of the CAMS laser metrology system is shown in Figure 2. For ASTRO-H to have the ability to accurately trace a photon event back to a coordinate in the celestial sphere, it relies on measurements from the HXI, CAMS, and the attitude determination system (represented by the star tracker in Figure 2). Details of the specific CAMS components are provided in the following sections.

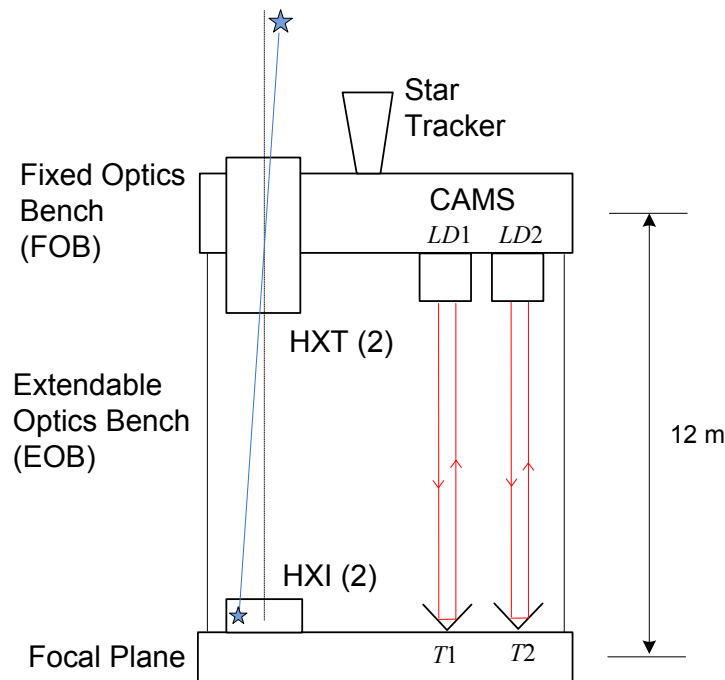


Figure 2. General schematic of relevant components for the CAMS metrology system.

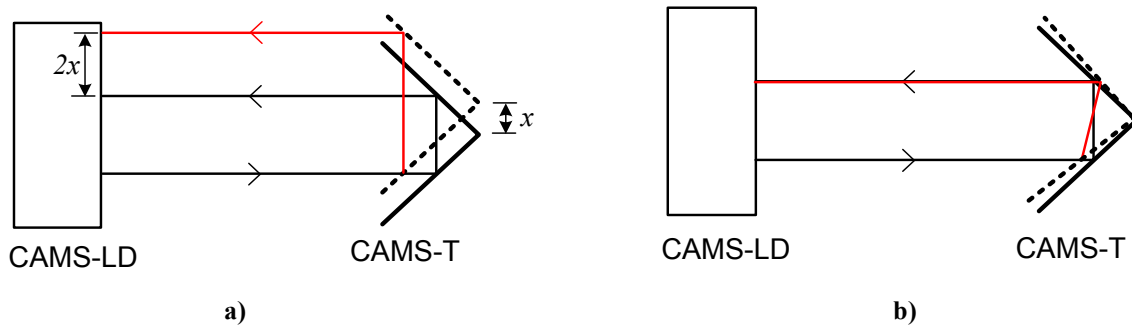


## 2.1 Design Concept

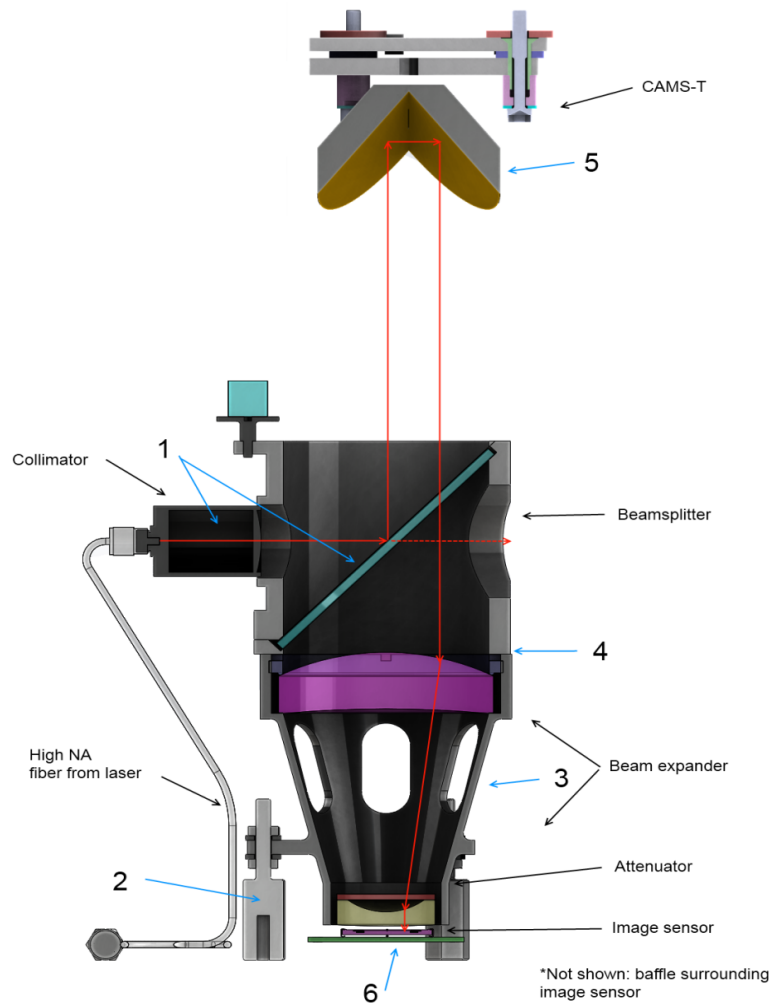
The design concept for CAMS operation is as follows [RD3]:

- a continuous wave (CW) laser signal is projected from the CAMS-LD module
- the laser beam is reflected back by the CAMS-T module, which is a corner-cube reflector (the path of the laser beam depends on precisely where on the corner cube the original incident light was reflected)
- an imaging sensor within the CAMS-LD module records the detected position of the reflected laser spot.

The corner-cube reflector, CAMS-T, is a passive component. It has two key optical features: it reflects all incoming light in a direction parallel to the incident light, and the reflected light does not depend on its orientation, which is demonstrated in Figure 3. The position of the laser as detected at the CAMS-LD depends on the lateral position of the reflector, and this is how the sensor measures lateral displacement. Specifically if CAMS-T is displaced by a distance,  $x$ , the reflected light will be displaced by double that distance,  $2x$ .



**Figure 3. CAMS operation with a corner cube reflector (CAMS-T); the black line is the nominal light path and the red line is the path after CAMS-T has been perturbed in a) translation and b) rotation.**



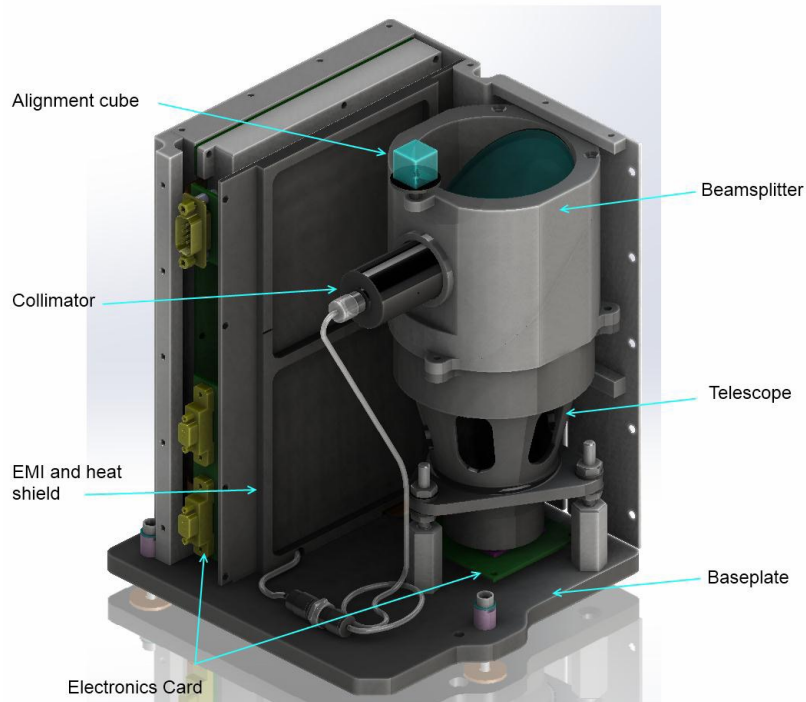
**Figure 4. CAMS optical system; the laser enters at the source through a collimator (1) and is reflected by the beamsplitter (1) towards the corner-cube (5), then passes through the optics (3) and received on the detector (6); mounting posts (2) and beamsplitter structure (4) are also shown (from Neptec).**

The various components of the CAMS optical system are shown in Figure 4. The laser source enters the system through a collimator orthogonal to the optical axis. A beamsplitter positioned at 45 degrees to the beam reflects a fraction of the incoming light and allows the other fraction to pass and get absorbed by CAMS enclosure. The light which reaches the CAMS-T corner-cube is reflected back, parallel to the incident light but offset laterally depending on the position of the corner-cube. This reflected light again encounters the beamsplitter, which reflects a fraction towards the source and allows the other fraction to pass through. The part that passes through is scaled by the beam expander and finally reaches the image sensor.

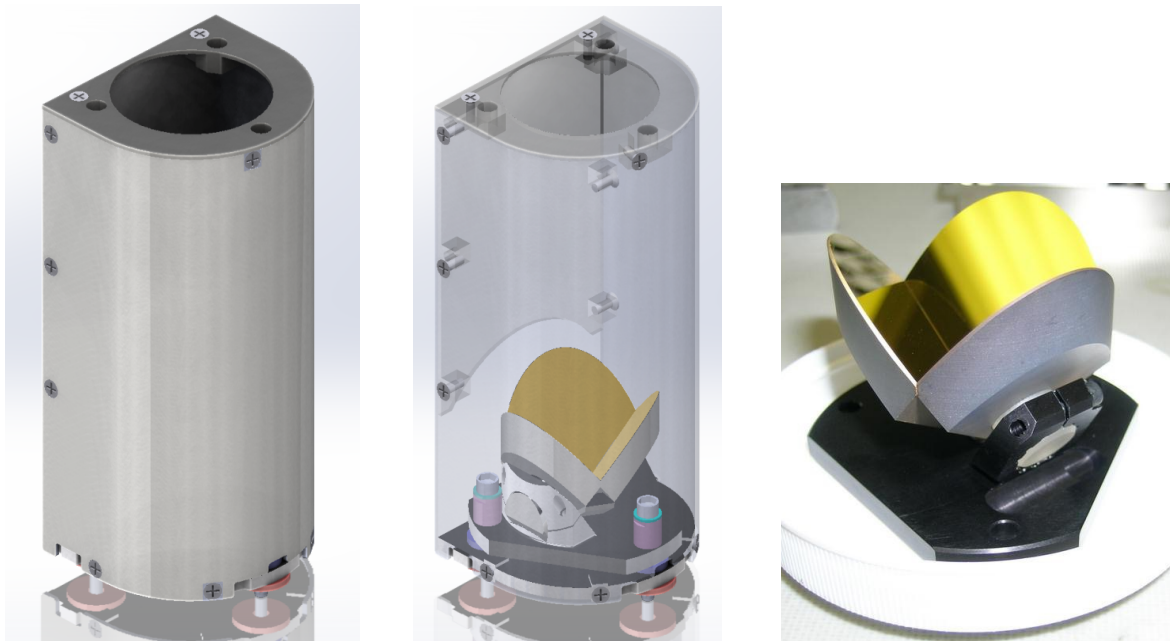
Generally, the correlation between the position of the CAMS-T and the center of the laser beam on the image sensor is non-linear. A math model takes into account the optical distortion, translation and scaling factor. This model is based on bivariate spline method. The model parameters are established during the unit level calibration. Detailed description of the unit level calibration can be found in [AD2].

## 2.2 CAMS-LD / CAMS-T

The main components of the CAMS-LD are shown in the 3-D CAD model in Figure 5. When installed there is a metal cover enclosing the unit which is not shown. The corner cube reflector of CAMS-T is shown in Figure 6. It will be mounted on the EOB within a baffle for shielding. It requires no power for its optics, however, it will require power for heating elements inside the baffle to regulate the temperature.



**Figure 5. 3-D CAD model of CAMS-LD.**



**Figure 6. CAMS-T corner cube reflector.**

### 2.2.1 Optical / Mechanical Components

A description of certain components of the CAMS-LD are given in Table 2.

**Table 2. Description of CAMS-LD components**

Component	Details
Laser	980 nm, 400 mW rated power
Telescope	Reduces image by factor of 4.87
Positive lens	70 mm diameter
Attenuator	Stack of an ND filter and a Narroband filter
Negative lens	32 mm diameter
CMOS Imager	1024x1024, 15 $\mu\text{m}$ pixel size

### 2.2.2 Nominal Resolution

The nominal resolution of the CAMS can be determined from the physical properties of the CAMS. The pixel size of the image sensor is 15  $\mu\text{m}$ , but for the CAMS position resolution the rest of the optics system must be considered. The CAMS-T reflector amplifies translational motion by a factor of 2, and the CAMS-LD telescope optics attenuates motion by a factor of 4.87. Therefore, 15  $\mu\text{m}$  at the image sensor corresponds to approximately 36  $\mu\text{m}$  translation of the CAMS-T.

$$\text{Resolution} = 15 \times 4.87 / 2 = 36.52 \mu\text{m} \quad (1)$$

The laser spot detected by the CAMS-LD is larger than the pixel size, and thus fills many pixels. This enables the centroiding algorithm to achieve sub-pixel accuracy. Therefore the theoretical resolution of the CAMS is better than the nominal resolution noted above. This sub-pixel resolution should be about 1/10<sup>th</sup> the nominal resolution, but because noise levels are expected to be greater than this maximum theoretical resolution, it is not useful to assign a specific value to the theoretical resolution. The numerical precision of the CAMS output is 0.977  $\mu\text{m}$  and will be discussed in more detail in Section 4.

To put in perspective for the HXT/HXI which has a theoretical resolution of 4.3 arc-seconds, the 36  $\mu\text{m}$  nominal resolution of the CAMS corresponds to 0.6 arc-seconds of the HXT.

### 2.2.3 Data Flow

The CAMS-LD data processing is described in [AD1], Section 2.3.2.

## 3 Operations

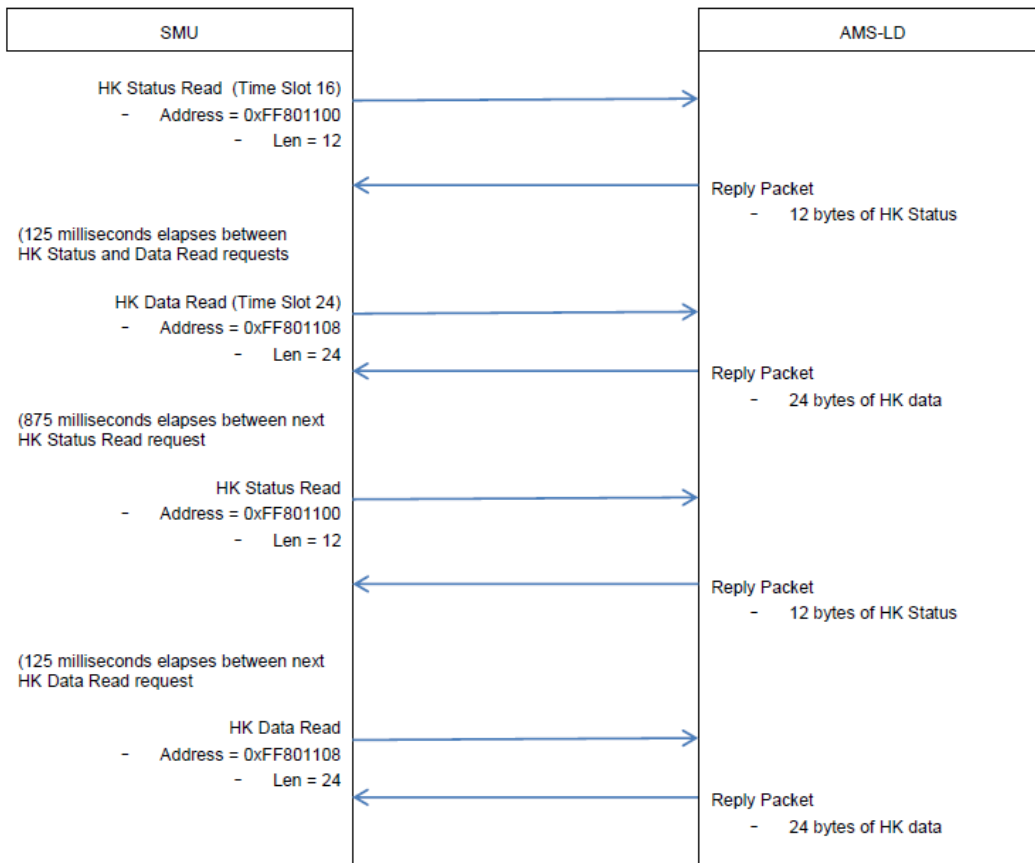
Under normal operation, each CAMS provides a position measurement at 5 Hz. The specific format of the output data is described in [AD1]. It is also possible to use CAMS in Image Readout Mode, where the raw image obtained by the image sensor is transmitted instead of the laser position. This Image Readout Mode is intended to be a diagnostic tool and is not a part of regular CAMS operation.

In the case that one of the CAMS is not functioning properly, corrections can still be applied to HXI observations; however the ability to estimate the twist angle of the EOB relative to the FOB is lost. An alternative algorithm should be used in this case and is discussed in Section 5.4.

## 4 Data Description

### 4.1 Timing

Although the CAMS performs position measurements at 5 Hz, the communication between the CAMS and the spacecraft's satellite management unit (SMU) occurs at a frequency of 1 Hz. Therefore each data package transmitted from CAMS to SMU consists of 5 sequential positions. The timing of this data transfer is described in [AD1], Section 8. The figure below is an excerpt from [AD1, rev.8] presented for convenience here, the reader should consult the latest revision of the [AD1] document for up to date information.



**Figure 7. HK status and data read – traffic diagram.**

At a rate of 64Hz, a Time Code (a.k.a. Tick) will be sent to the AMS-LD [AD1, section 5.8]. The FPGA will use the Time Code information for time stamping the HK Data.

## 4.2 Telemetry

The CAMS housekeeping (HK) data has two parts, HK Status and HK Data. The content of HK Data is described in [AD1], Section 5.7. The text below is an excerpt form [AD1, rev.8] presented for convenience here, the reader should consult the latest revision of the [AD1] document for up to date information.

**Table 3. HK Data description.**

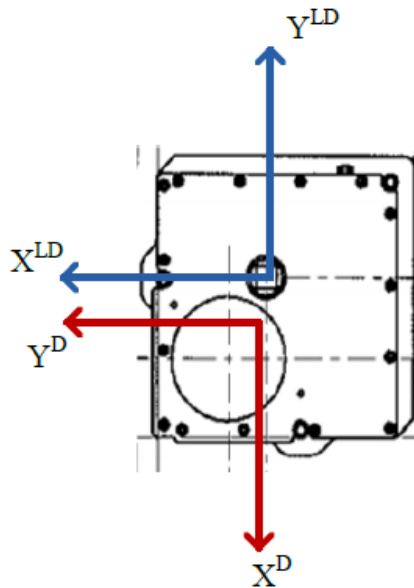
DATA Name	Bit #	
Xn	15:0	X position of AMS-T, 16 bits signed. If equal to 0x7FFF, no data was sampled. Populated by DSP when the data valid bit is set. If not, FPGA calculated centroid (no calibration applied) in 16 bits fixed-point format [fx10.6]
Yn	31:16	Y position of AMS-T, 16 bits signed. If equal to 0x7FFF, no data was sampled. Populated by DSP when the data valid bit is set. If not, FPGA calculated centroid (no calibration applied) in 16 bits fixed-point format [fx10.6]
Flags	31:30	31: Image Saturation bit. If set to '1', image is saturated  30: Data valid. If set to '1', the X and Y position data has been processed by the DSP.
TimeXnYn	6 bits	Timestamp for measurement "n". This is based on the SpaceWire time distribution information and its value represents 64 <sup>th</sup> of seconds. E.g. a value of 12 means that the sample was taken at $T_0 + 12 \times 1/64^{\text{th}} = T_0 + 0.1875$ seconds where $T_0$ is an integer number of seconds

The integer values returned from both X and Y coordinate are encoded as described in Table 3 HK Data “Xn” and “Yn” Measurement Bit fields. The values are 16bit signed integers representing the retro reflector displacement in millimeter units multiplied by 1024. In other words the fractional portion of the measurement is encoded with 10bits for a resolution of 1/1024 of mm, or 0.977 μm.

**Table 4. HK Data “Xn” and “Yn” Measurement Bit fields**

Bit field		
15	14:10	9:0
Sign	Rational Value in mm	Fractional

The X & Y orientation used for HK Data is the CAMS LD as measured on the alignment cube. The coordinate system is shown on Figure 5-1. “LD” denotes the CAMS LD coordinate system while “D” denotes the detector coordinate system, which is rotated with respect to the CAMS LD coordinate system. Raw detector images are oriented with respect to the detector coordinate system.



**Figure 8. X & Y Orientation of detector (XD, YD) (CAMS-LD top view)**

Note, the telemetry values reported by CAMS are in “LD” coordinate system. The “D” is the physical coordinate system for the CMOS detector itself and ONLY used for raw image capture in the debugging mode. Normal telemetry does not include image captures.

**Table 5. HK Status Description.**

DSP Allocated Bits		
DSP State	-	Bit mapping is as follows:
	0	DSP Up
	2:1	Acq/Cal Bank No ( 0, 1, 2, or 3)
	3	Unlocked (1 – unlocked, 0 – locked) This status, when set, is used to indicate that the DSP has the codes to unlock an EEPROM bank when a write access is requested.
	4	Program Done (1 – Completed programming data to an EEPROM, 0 - inactive) This status is used to indicate that programming was completed.
	7:5	Unused
EEPROM Errors	-	Bit mapping is as follows:
	8	EEPROM Bank 0 invalid (1 – invalid CRC, 0 – valid CRC) Set by the DSP when it detects that the bank's CRC is



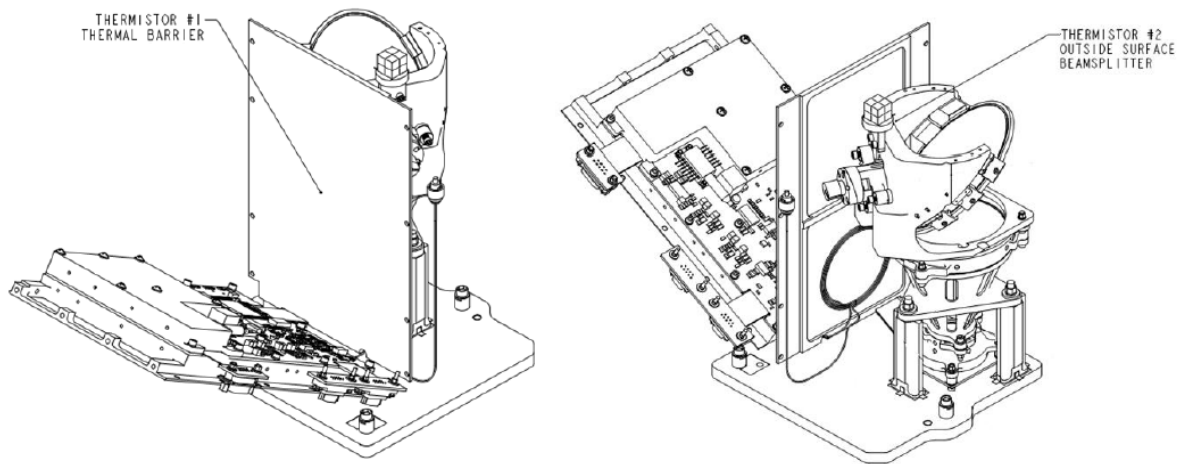
		invalid.
	9	EEPROM Bank 1 invalid (1 – invalid CRC, 0 – valid CRC) Set by the DSP when it detects that the bank's CRC is invalid.
	10	EEPROM Bank 2 invalid (1 – invalid CRC, 0 – valid CRC) Set by the DSP when it detects that the bank's CRC is invalid.
	11	EEPROM Bank 3 invalid (1 – invalid CRC, 0 – valid CRC) Set by the DSP when it detects that the bank's CRC is invalid.
	12	Acq/Cal Table Bank 0 invalid (1 – invalid CRC, 0 – valid CRC) Set by the DSP when it detects that the CRC of either table is invalid.
	13	Acq/Cal Table Bank 1 invalid (1 – invalid CRC, 0 – valid CRC) Set by the DSP when it detects that the CRC of either table is invalid.
	14	Acq/Cal Table Bank 2 invalid (1 – invalid CRC, 0 – valid CRC) Set by the DSP when it detects that the CRC of either table is invalid.
	15	Acq/Cal Table Bank 3 invalid (1 – invalid CRC, 0 – valid CRC) Set by the DSP when it detects that the CRC of either table is invalid.
	21:16	Unused
Quality	31:22	Beam quality factor
<b>FPGA Allocated Bits</b>		
FPGA Status	-	Bit mapping is as follows:
	32	Sampling (1 - AMS-LD is taking measurements, 0 = idle)
	33	Snapshot Image Ready (1 – image is available, 0 – empty)
	34	DSP Soft reset (1 - DSP soft reset; 0 - no DSP soft reset) Indicates that the DSP was reset due to a DSP_RESET command or firmware reboot
	35	Mailbox is Ready (1 – data is available, 0 – empty, will return 0x00ldbeaf)
	36	Time-Code Generation Flag (1 – AMS-LD is generating time-codes internally at 64Hz, 0 – AMS-LD is using external time-codes)
	38:37	EEPROM Bank No (0, 1, 2 or 3)
	39	Indicate that the command FIFO is ready to receive a command.
CAMS Error FIFO Overflow	40	Indicates that the Error FIFO has overflown. Cleared on CLEAR_ERROR command.
CAMS Error		Bit mapping is as follows:
	41	Error
	49:42	Error FIFO. This field will be flushed when the CLEAR_ERROR command is received; filled with 0 when the internal error status FIFO is empty, or filled with the next data extracted from the error status FIFO.
	51:50	Unused
HK Status and Data Generation Counter	53:52	Incremented by the FPGA whenever the CAMS-LD generates the HK status.
HK Status Read Counter	55:54	Incremented by the FPGA whenever an HK Status read

		packet is received.
HK Data Read Counter	57:56	Incremented by the FPGA whenever an HK Data read packet is received.
Command Received Counter	61:58	Incremented by the FPGA whenever a command is received meeting the following criteria: <ul style="list-style-type: none"> <li>• Operation ID is valid for the FPGA or the DSP and</li> <li>• Command arguments are in range</li> </ul>
Command Rejection Counter	63:62	Incremented by the FPGA whenever a command is received meeting the following criteria: <ul style="list-style-type: none"> <li>• Operation ID is invalid for the FPGA and the DSP or</li> <li>• Command arguments are out of range</li> </ul>
Laser Intensity	71:64	The DSP reads the laser intensity from the FPGA and transforms the value as follows: If bits 31:21 $\neq$ 0 then Laser Intensity field = 0x80 else Laser Intensity field = int2mulaw(bits 20:8) This field is only valid if the CAMS is sampling (ie: status bit 32 is set to '1') See Appendix for sample code for int2mulaw implementation.
Laser Current	79:72	The DSP reads the laser current from the ADC via the FPGA and transforms the 12 bit value from the ADC into an 8 bit value that covers the full operating range as follows: Laser Current field = (ADC Value – 1400) / 5 This field can be used to monitor changes in the laser driver circuitry efficiency over time. It does not provide current value readings in mA.
Thermistor 1	87:80	The values are 8bit signed integers representing the temperature in Celsius units multiplied by 2.
Thermistor 2	95:88	Populated by the DSP. Refer to section 11 for details on their location within the CAMS-LD.

Note, the laser intensity is a relative measurement used to monitor anomalies. In the Table above,  $\neq$  means  $\neq$ . The int2mulaw code is attached in appendix C of the latest user's manual [AD1]. The laser intensity is the sum of all pixels counts (10 bits digital value each) on the detector and is calculated using a 32 bits value. Due to housekeeping format limitation, only 8 bits can be used to represent this laser intensity. This is performed by the DSP using a  $\mu$ -law algorithm (see [http://en.wikipedia.org/wiki/%CE%9C-law\\_algorithm](http://en.wikipedia.org/wiki/%CE%9C-law_algorithm) ).

The laser current is a relative measurement used to monitor anomalies. It shouldn't exceed  $\frac{3}{4}$  of the range during normal operation.

The location of thermistor 1 and thermistor 2 for the CAMS-LD units "as shipped" is shown in the figure below.



**Figure 9. Baseline Position of Thermistor1 and Thermistor2 inside CAMS-LD for units**

## 5 Data Processing

There are four measurements provided by CAMS during each sample, i.e. the  $x$  and  $y$  translation of both CAMS-T positions:  $x_1, y_1, x_2, y_2$ . The data processing of these four measurements entails two basic steps:

1. Estimating the relative translation and rotation between the FOB and EOB,
2. Correcting raw HXI observations.

An overview of the data processing for ASTRO-H and the HXI are given in Figure 10. The only step that involves CAMS data is the transformation of HXI observations from the RAW to ACT coordinate frames. A description of the relevant coordinate frames will be presented in the next section followed by details of the CAMS data processing algorithms.

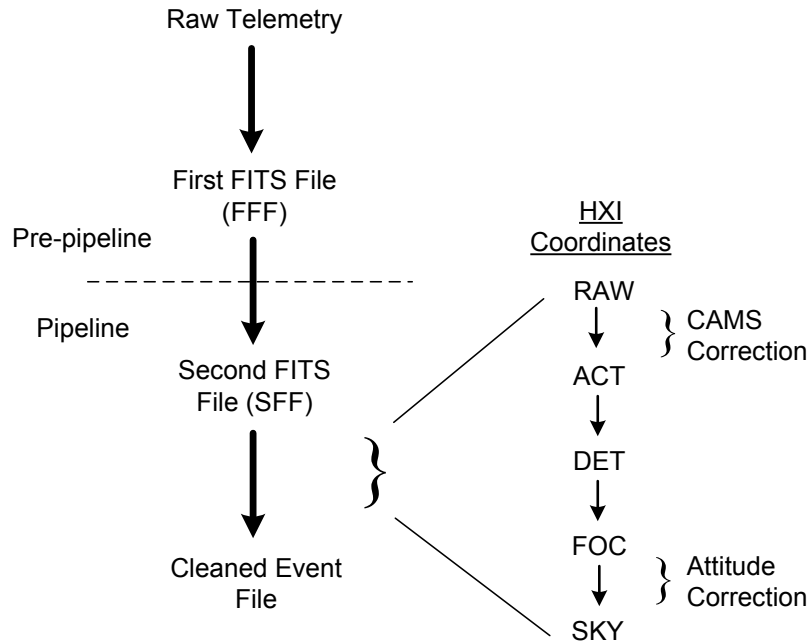


Figure 10. High-level data processing for ASTRO-H science data.

## 5.1 Coordinate Frames

The orientation of the spacecraft body-frame, denoted by SAT, is shown in Figure 11 along with the main spacecraft structure [RD3, RD4]. Figure 12 shows the location and orientation of the coordinate frames for both CAMS and HXI units. The CAMS measurements are reported in the CAMS 1 and 2 reference frames. The orientations of these local coordinate frames are defined by orientation of each alignment cube, but their origins are located in a geometrical center of each unit's FOV. The conversion of the CAMS readings into the satellite reference frame is discussed in Section 5.2.

A set of CAMS alignment parameters is expected to be determined via survey data after the installation to the spacecraft and alignment (shimming) of the CAMS units (Table 6). These parameters are required for determining the transformation from CAMS coordinates to the satellite coordinate system. The coordinate data for HXI detectors are also presented in the same table.

It is important to determine what reading of CAMS corresponds to a nominal (unshifted) position of the CAMS-T. Defining the location of this initial CAMS reading is non-trivial because the ASTRO-H s/c will not be tested in the deployed configuration on the ground before launch. Therefore, it is impossible to directly measure the CAMS readings when the CAMS-T is at 12 meters away and the EOB is undisturbed. As delivered to JAXA, CAMS reports displacement values with zero reading in the geometrical center of the FOV to which a bias offset has to be added based on calibration [AD2]. Note, the reported in [AD2] offset values are not useful for the s/c level calibration.

Instead, the method of determining the offset values is based on the spacecraft level CAMS alignment. When s/c level alignment is performed, CAMS units are shimmed such that each aligned unit have its laser beam propagating along the  $-z$ -axis of the satellite (perpendicular to the top plate) with the accuracy better than 10 arcseconds [RD5]. When aligned, the CAMS reported values are noted at a non-disturbed CAMS-T positions located at lower and middle plates and extrapolated to the EOB position at 12 m and include a correction for zero gravity [RD6] (values in [RD6] are given in pixel values and converted to mm of CAMS readings, see Appendix 2 for details). These reported values  $(x_{1,2}, y_{1,2})$  will be used as a measure of the calibration offset between the CAMS readings and the nominal positions of the CAMS-T.

**Table 6. CAMS installation parameters**

Description	Notation	Survey Values <sup>1</sup>	Nominal Values <sup>1</sup>
Spacecraft coordinates of the center of the CAMS-T1 unit	$\mathbf{r}_{C1}^{SAT}(x_{C1}, y_{C1}, z_{C1})$	N/A	(300,480,-5723)
CAMS-LD1 Alignment cube rotation angle about its z axis, deg	$\beta_{C1}$	-0.674	0
CAMS1 Reported values at zero EOB displacement	$\mathbf{r}_1^{CAMS1}(x_1, y_1)$	(-0.254,1.133)	(0,0)
Spacecraft coordinates of the center of the CAMS-T2 unit	$\mathbf{r}_{C2}^{SAT}(x_{C2}, y_{C2}, z_{C2})$	N/A	(-300,480,-5723)
CAMS-LD2 Alignment cube rotation angle about its z axis, deg	$\beta_{C2}$	+0.155	0
CAMS2 Reported values at zero EOB displacement	$\mathbf{r}_2^{CAMS2}(x_2, y_2)$	(0.879,2.246)	(0,0)
HXI-1 Reference frame origin in SAT coordinate frame	$\mathbf{r}_{H1}^{SAT}(x_{H1}, y_{H1}, z_{H1})$	N/A	(465,195,-5491)
HXI-1 Reference frame rotation, deg	$\beta_{H1}$	N/A	22.5
HXI-2 Reference frame origin in SAT coordinate frame	$\mathbf{r}_{H2}^{SAT}(x_{H2}, y_{H2}, z_{H2})$	N/A	(-465,195,-5491)
HXI-2 Reference frame rotation, deg	$\beta_{H2}$	N/A	-22.5

<sup>1</sup> – Coordinate values are displayed in mm. When survey data are N/A or TBD the nominal values should be used.

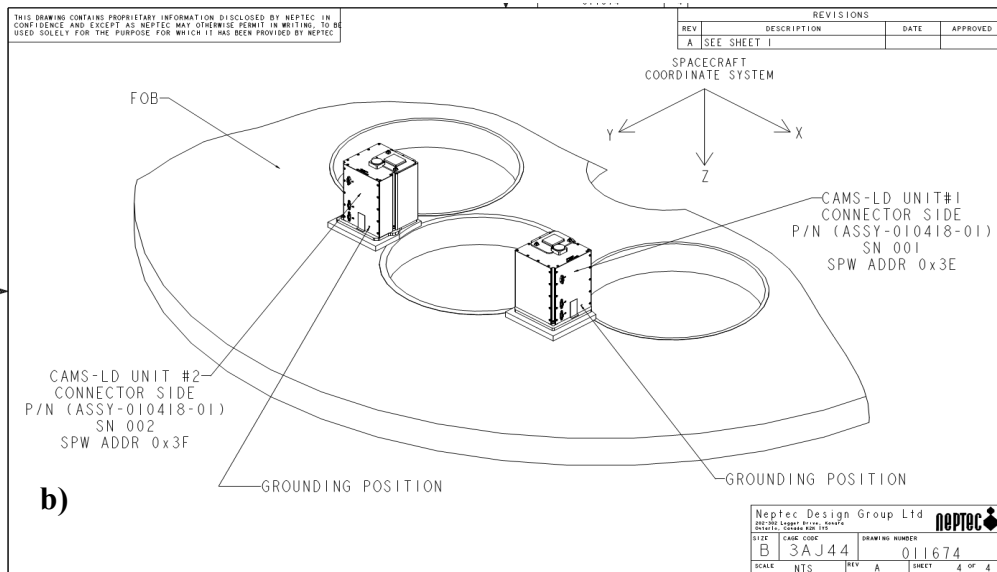
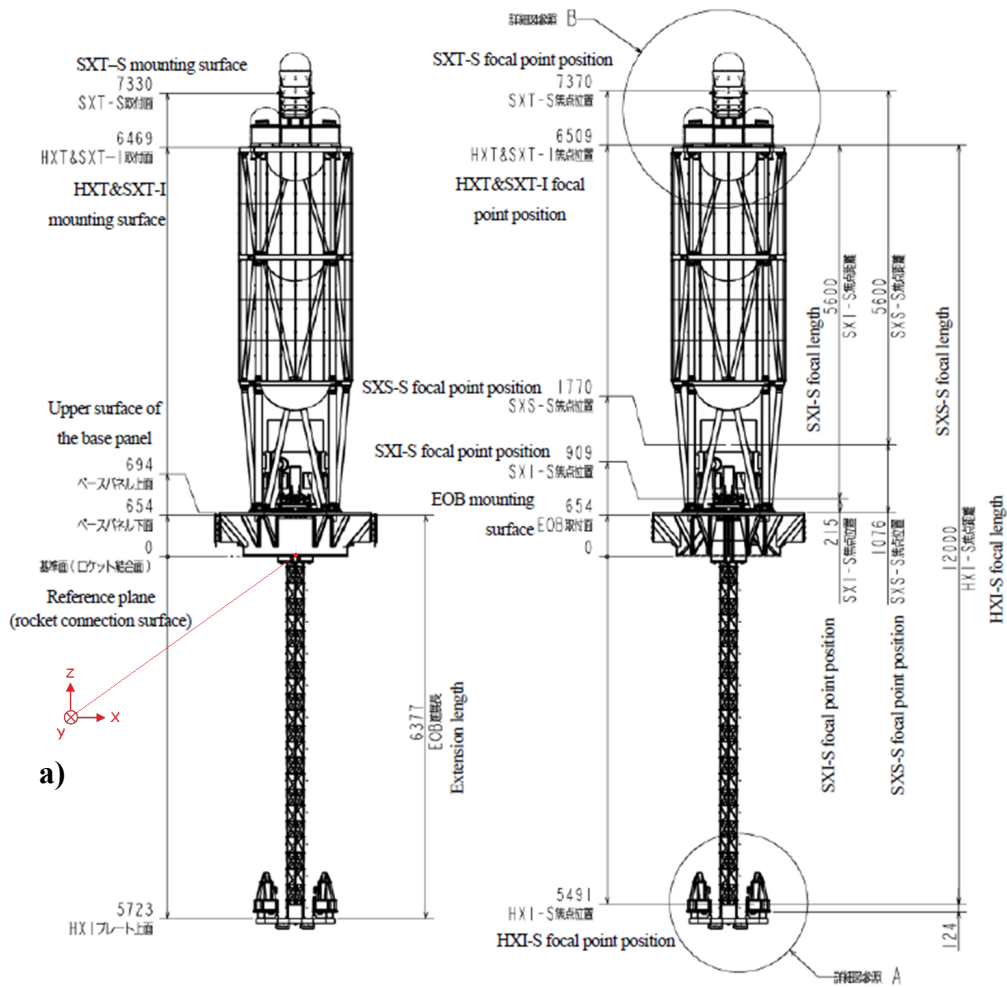
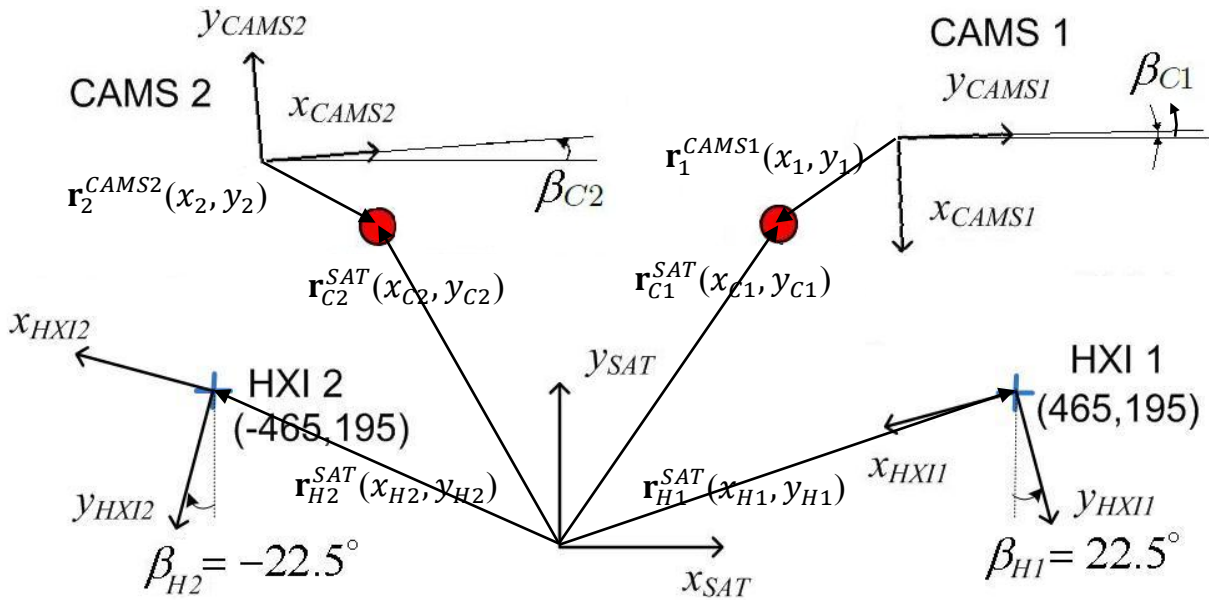


Figure 11. ASTRO-H spacecraft structure showing the location of the reference plane ( $z=0$ ) and distances to its different parts [RD4] (a) and location and orientation of two CAMS units on the top plate of ASTRO-H (b) and orientation of the spacecraft coordinate frame (SAT) [RD2].

As per confirmation in [RD6] there will be no survey data on the locations of the CAMS-T units  $\mathbf{r}_{C1,2}^{SAT}(x_{C1,2}, y_{C1,2}, z_{C1,2})$  and HXI detectors  $\mathbf{r}_{H1,2}^{SAT}(x_{H1,2}, y_{H1,2}, z_{H1,2})$ , therefore the nominal values (as designed) for the locations of these units will be used.

Two other frames related to the HXI, which are relevant to the data processing, are the RAW and ACT coordinate frames, shown in Figure 13. The RAW coordinate frame is the base sensor frame attached to the HXI. The raw positions of photon events observed by the imager are expressed in RAW coordinates, and as such, the RAW frame translates and rotates along with the HXI detectors mounted on EOB. The ACT coordinate frame (ACT is short for active) is a virtual coordinate frame representing the ideal (or nominal) location of the HXI, or the location of the HXI when all deformations of the EOB are zero. In the case of zero EOB deformation, the ACT, RAW and HXI frames all have the same orientation but their origins are offset as shown in Figure 13.



**Figure 12. CAMS and HXI coordinate frames as viewed looking from the FOB towards the EOB: the nominal (as designed) location of each instrument is given in mm as a (x,y) coordinate pair in the SAT coordinate frame, except CAMS readings which are in CAMS local coordinate frames. Red circles represent the center of CAMS-T1,2 in undisturbed EOB location. The CAMS 1,2 frame origins are the centers of their field of view.**

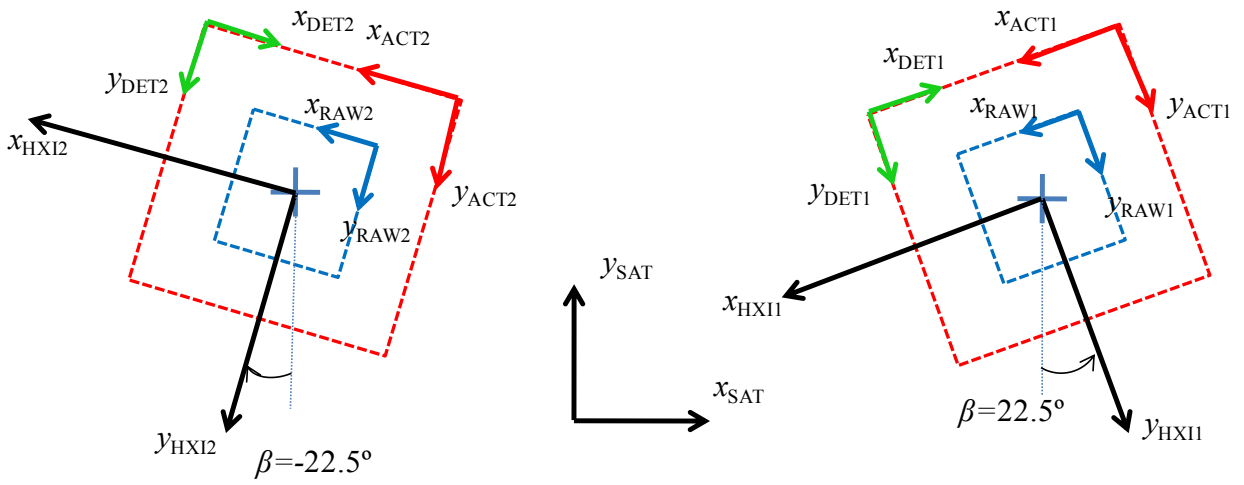


Figure 13. RAW, ACT and DET coordinate frames for HXI 1 and HXI 2.

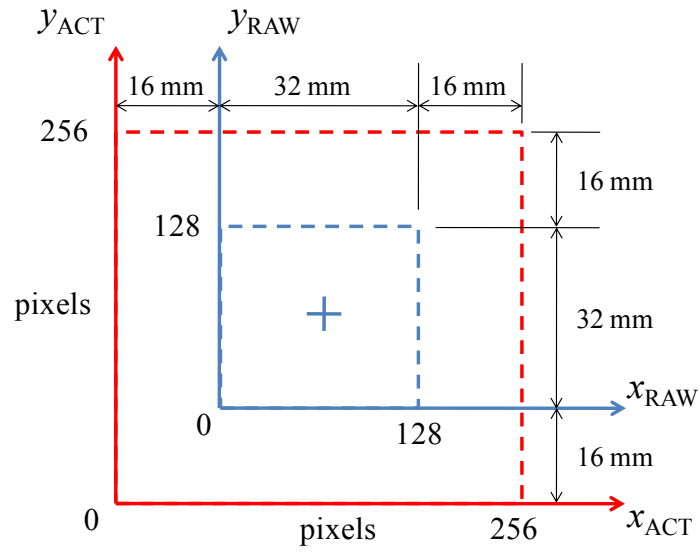
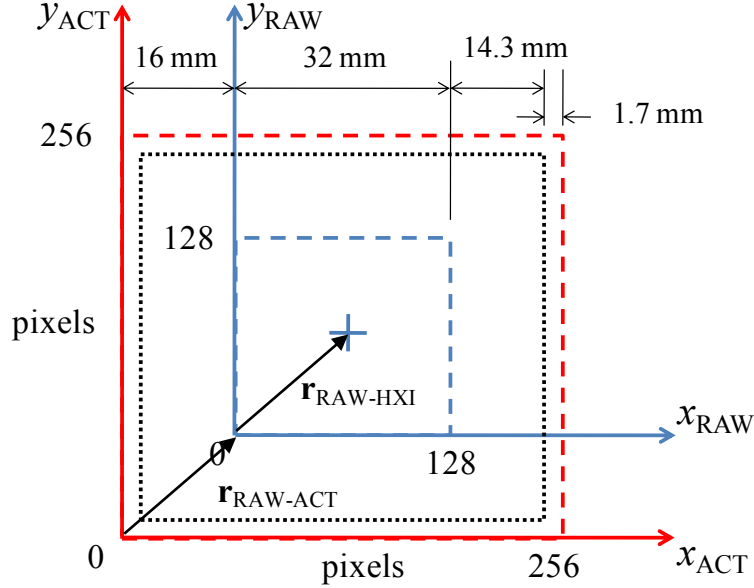


Figure 14. Size and relative location of RAW and ACT coordinate systems.





**Figure 15. Maximum footprint of events reconstructed with CAMS data. Vector  $\mathbf{r}_{\text{RAW-ACT}}$  is the origin of RAW reference in ACT reference. Vector  $\mathbf{r}_{\text{RAW-HXI}}$  is the origin of HXI reference in RAW reference. Both vectors are defined in a non-disturbed nominal condition.**

The reason that the RAW frame is offset from the HXI frame is based on the Goddard Space Flight Center (GSFC) convention that the origin of the coordinate system should be located at the edge of actual detector and not in the center. Therefore the blue box in Figure 13 represents the outline of the detector of the HXI and the full range of RAW coordinates. The ACT coordinates have a larger range to accommodate the events captured in RAW coordinates that after the CAMS correction fall outside the original RAW range. In other words, an event originally observed near the edge of the RAW coordinates may end up outside the RAW boundary when adjusted for EOB motion.

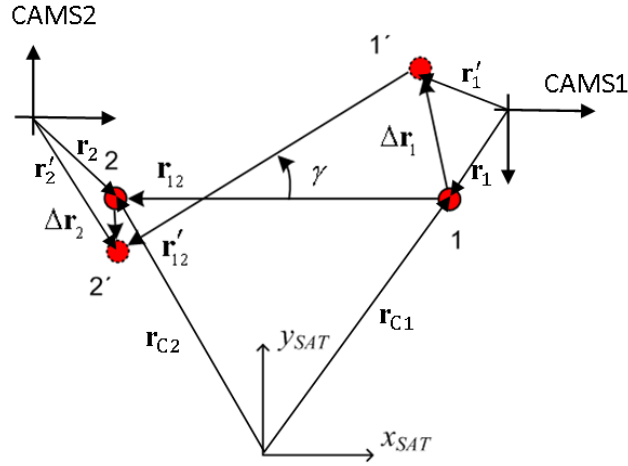
## 5.2 Relative Displacement between the FOB and EOB

For step 1, the four CAMS measurements are used to estimate three parameters representing the three significant relative motion degrees of freedom—the 2-D planar translation, and the rotation about an axis parallel to the boresight. The proposed data processing algorithm begins by estimating the twist angle,  $\gamma$ , followed by the planar displacement. Although the CAMS measurements are planar, they will be represented as a 3-D position vectors with a zero value in the z-direction, i.e.  $\mathbf{r}_1^{\text{CAMS1}} = [x_1 \ y_1 \ 0]^T$  and  $\mathbf{r}_2^{\text{CAMS2}} = [x_2 \ y_2 \ 0]^T$  in each local CAMS coordinate frame (denoted as a superscript). The measurement vectors and the twist angle are shown in Figure 16, along with the original position of the reflected laser beams 1 and 2, and the displaced position denoted with a prime superscript. The position vectors from one laser beam location to the other,  $\mathbf{r}_{12}$  and  $\mathbf{r}'_{12}$  are combined with a dot product to calculate the twist angle,  $\gamma$ .

$$\gamma = \cos^{-1} \left( \frac{\mathbf{r}_{12} \cdot \mathbf{r}'_{12}}{|\mathbf{r}_{12}| |\mathbf{r}'_{12}|} \right) \quad (1)$$

To determine the sign of the twist angle,  $\gamma$  the cross product of  $\mathbf{r}_{12}$  and  $\mathbf{r}'_{12}$  is used.

$$\text{sign}(\gamma) = \text{sign}(\mathbf{r}_{12} \times \mathbf{r}'_{12}) \quad (2)$$



**Figure 16. Estimation of roll angle,  $\gamma$ , using the planar displacement of two CAMS-T, 1 and 2.**

The previous equations assume that the position vectors  $\mathbf{r}_{12}$  and  $\mathbf{r}'_{12}$  are known and expressed relative to a common reference frame. To calculate  $\mathbf{r}_{12}$  and  $\mathbf{r}'_{12}$  the location of each CAMS-T unit,  $\mathbf{r}_{C1}$  and  $\mathbf{r}_{C2}$  must be known (see Table 6) and the CAMS measurements,  $\mathbf{r}_1$  and  $\mathbf{r}_2$ , must be expressed in a common reference, not the individual unit frames shown in Figure 12.

$$\begin{aligned} \mathbf{r}_{12} &= \mathbf{r}_{C2} - \mathbf{r}_{C1} \\ \mathbf{r}'_{12} &= \mathbf{r}_{C2} + \mathbf{r}_2'^{SAT2} - \mathbf{r}_2^{SAT2} - (\mathbf{r}_{C1} + \mathbf{r}_1'^{SAT1} - \mathbf{r}_1^{SAT1}) \\ \Delta \mathbf{r}_1 &= \mathbf{r}'_1 - \mathbf{r}_1 \\ \Delta \mathbf{r}_2 &= \mathbf{r}'_2 - \mathbf{r}_2 \end{aligned} \quad (3)$$

It is assumed here that the original reference orientation of EOB is the non-disturbed nominal orientation, where the targets are located at nominal coordinates. The shifted reading of CAMS has to take into account a bias ( $\mathbf{r}_{1,2}^{CAMS1,2}$ ) measured at s/c calibration (Table 6). A simple rotation would be necessary to express the CAMS measurements in a common frame such as the SAT frame.

$$\begin{aligned} \mathbf{r}_1^{SAT} &= R_{CAMS1}^{SAT} \mathbf{r}_1^{CAMS1} \\ \mathbf{r}_2^{SAT} &= R_{CAMS2}^{SAT} \mathbf{r}_2^{CAMS2} \end{aligned} \quad (4)$$

For the orientation of the frames in Figure 12, the following rotations could be used:

$$\begin{aligned}
R_{CAMS1}^{SAT} &= R_z\left(-\frac{\pi}{2} + \beta_{c1}\right) \\
R_{CAMS2}^{SAT} &= R_z(\beta_{c2})
\end{aligned} \tag{5}$$

where  $R_z(\theta)$  is a 3-D rotation matrix for a rotation of an angle  $\theta$  about the z-axis. The specific rotation matrices for rotations about Cartesian axes are given in Appendix 1. The superscript notation applied to vectors indicates the specific reference frame the vector is expressed in. In most cases throughout this document the superscript will be omitted as the frame will be implied or generic.

Once the twist angle,  $\gamma$ , is determined, the planar displacement of the EOB can be estimated using the centroid position of the two CAMS-T1,2 locations. Specifically, the displacement,  $\Delta \mathbf{r}$ , is the difference between a vector pointing to the centroid of the original CAMS-T1,2 locations,  $\mathbf{r}_{c/m}$ , after it has been rotated by the twist angle,  $\gamma$ , and a vector to the centroid of the displaced CAMS-T1,2 locations,  $\mathbf{r}'_{c/m}$ . This step is shown graphically in Figure 17.

$$\Delta \mathbf{r} = \begin{bmatrix} \Delta x \\ \Delta y \\ 0 \end{bmatrix} = \mathbf{r}'_{c/m} - R_z(\gamma)\mathbf{r}_{c/m} \tag{6}$$

A vector pointing to the centroid of any two vectors,  $\mathbf{r}_1$  and  $\mathbf{r}_2$ , can be found using the following relationship:

$$\mathbf{r}_{c/m} = \mathbf{r}_1 + \frac{1}{2}(\mathbf{r}_2 - \mathbf{r}_1) \tag{7}$$

It should be noted that Eq. **Error! Reference source not found.** gives a displacement that is dependent on the choice of location of the twist-angle axis. The position vectors to the centroids,  $\mathbf{r}_{c/m}$  and  $\mathbf{r}'_{c/m}$ , originate from the focal plane intersection of the twist-angle axis. In Figure 17 the twist axis is assumed to pass through the origin of the SAT coordinate frame; however, any axis may be chosen for the twist-angle as long as it is normal to the focal plane.



to RAW origin in nominal condition is  $\mathbf{r}_{ORAW} = \mathbf{r}_{HXI} - R_{ACT}^{SAT} \mathbf{r}_{RAW-HXI}^{ACT}$ , where  $\mathbf{r}_{HXI}$  is defined in Table 6 and Figure 12,  $\mathbf{r}_{RAW-HXI}^{ACT}$  is as per Figure 15.

The coordinate rotation matrices are:

$$\begin{aligned} R_{RAW}^{ACT} &= R_z(\square) \\ R_{SAT}^{ACT} &= R_z(\pi + \beta_H) \\ R_{ACT}^{SAT} &= R_z(-\pi - \beta_H) \end{aligned} \quad (9)$$

The vectors used in this equation are displayed in Figure 18. There is a constant shift vector between coordinate frames  $\mathbf{r}_{ACT-RAW}$  shown in Figure 15 expressed in ACT reference frame.

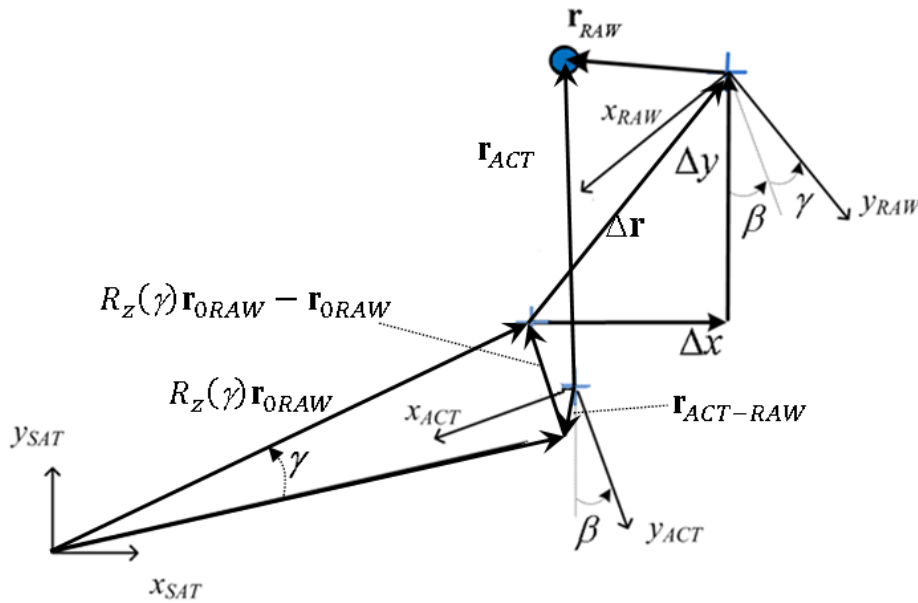


Figure 18. 2D-transformation from RAW to ACT coordinates.

If the HXI axis at  $\mathbf{r}_{ORAW}$  is chosen as the  $\gamma$  rotation axis the position vector  $\mathbf{r}_{ORAW}$  is zero and the equation simplifies to:

$$\mathbf{r}_{ACT} = \mathbf{r}_{ACT-RAW} + R_{RAW}^{ACT} \mathbf{r}_{RAW} + R_{SAT}^{ACT} \Delta \mathbf{r} \quad (10)$$

or,

$$\mathbf{r}_{ACT} = \mathbf{r}_{ACT-RAW} + R_z(\square) \mathbf{r}_{RAW} + R_z(\pi + \beta) \Delta \mathbf{r} \quad (11)$$

Note, however, that in this case the  $\Delta \mathbf{r}$  has to be calculated in (11) in the HXI reference frame, thus  $\mathbf{r}_{c/m}$  is a vector connecting the center of mass with the origin of HXI reference frame. It is easy to see that such a change of  $\mathbf{r}_{c/m}$  vector after substitution to (6) will lead to the same result as (8) where the  $\Delta \mathbf{r}$  is in a satellite reference frame. This means that it does not make a difference

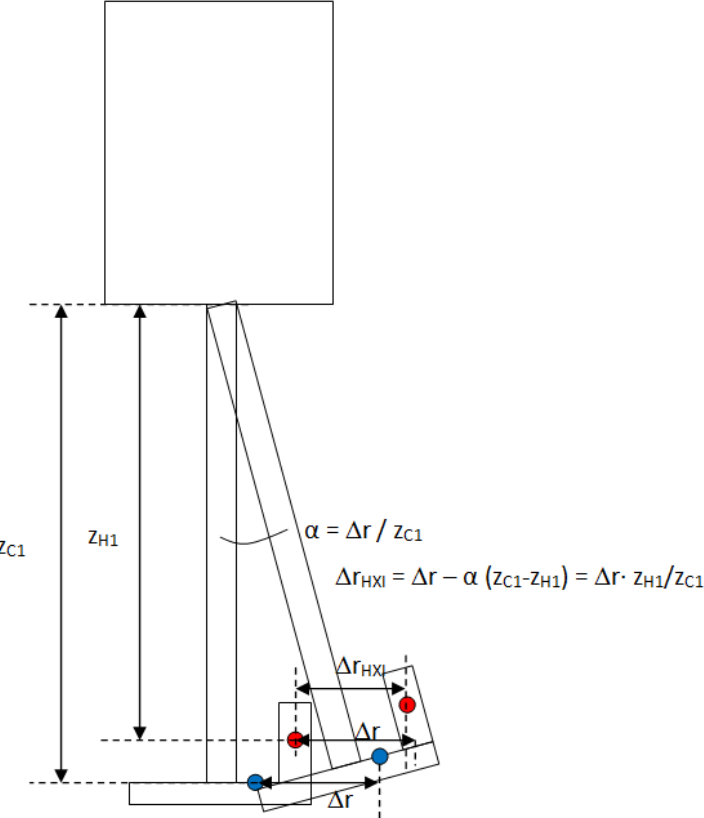
for the end result at this point what part of motion is counted as a rotation and what part is counted as a lateral shift since using both reference frames produce the same total result.

This however, becomes not accurate when the difference in z coordinates is considered for the HXI plate (where CAMS measures the motion) and the HXI detectors. Since the HXI detectors are elevated 232 mm above the HXI plate the lateral displacement measured by CAMS has to be factored. Indeed, the higher HXI detectors are located the smaller the motion is if it is caused by bending of the EOB (Figure 19). This however is not true for the twist angle of the EOB. The rotation associated with twist is still preserved without an extra factor. This consideration means that calculating the HXI detector displacement  $\Delta \mathbf{r}$  in the reference frame centered in the physical axis of the rotation becomes important. In this case the expression (6) becomes:

$$\Delta \mathbf{r} = \begin{bmatrix} \Delta x \\ \Delta y \\ 0 \end{bmatrix} = \frac{z_{H1}}{z_{C1}} (\mathbf{r}'_{c/m} - R_z(\gamma) \mathbf{r}_{c/m}) \tag{12}$$

Where  $z_{H1}$  and  $z_{C1}$  are z-coordinates shown in Table 6 (although both are negative values, the ratio is a positive value) and all vectors are expressed in the satellite reference frame. The expression (12) has to be used with expressions (8) and (9) to determin the  $\mathbf{r}_{ACT}$  coordinates.

It is easy to see that the change in the coordinate frame as it is done in (10-11) does not render the same result anymore and should not be used.



**Figure 19. Consideration for the z-coordinate of the HXI detectors:  $\Delta r$  is the measured EOB displacement and  $\Delta r_{\text{HXI}}$  is the displacement of the HXI detector. The blue circle corresponds to location of CAMS-T1 and the red circle corresponds to location of the HXII.**

## 5.4 CAMS Failure Operation

Provisional algorithms to process the CAMS data in the event of a failure by either unit are necessary. These algorithms would be used when measurements from one of the CAMS units are unavailable or deemed unreliable. A quality factor for each CAMS measurement is assessed onboard the CAMS unit and transmitted along with the measurement. The quality factor can be used to flag dubious measurements that should be omitted from the subsequent data processing sequences.

The failure-case algorithm would be the same regardless of which CAMS unit fails, once the CAMS measurements have been transformed into SAT coordinates using Eq. (4-5). When only one CAMS unit is available, only the two displacement variables are measured. One would need to make an assumption to proceed further.

If the assumption is that the majority of that displacement is a translational displacement, then the measured values can be associated with it. In this case,  $\Delta x$  and  $\Delta y$ , can be estimated and the ability to assess the twist angle,  $\gamma$ , is lost. Assuming that the unknown twist angle is zero,  $\gamma = 0$ , the displacement variables  $\Delta x$  and  $\Delta y$  can be calculated directly from the single CAMS measurement,  $\Delta \mathbf{r} = \Delta \mathbf{r}_i$ , where  $i$  represents the unit, either 1 or 2, that is functioning normally. Therefore, Eqs. **Error! Reference source not found.** to **Error! Reference source not found.** and Eq. (12) can be replaced by:

$$\begin{bmatrix} \Delta x \\ \Delta y \\ 0 \end{bmatrix} = \frac{z_{H1}}{z_{C1}} \begin{bmatrix} \Delta x_i \\ \Delta y_i \\ 0 \end{bmatrix} \quad (13)$$

This assumes that  $\Delta \mathbf{r}_i$  is expressed in the SAT coordinate frame.

Other assumptions may be considered, such as, (a) that the majority of displacement is of rotational (twist) nature, or (b) there may be some known ratio between these two motions (rotational and translational) that can be introduced. Deciding on one of these assumptions would require referring to either model of EOB displacements or its measurement statistics throughout some part of the mission. Analyzing on validity of these assumptions goes beyond the purpose of this document.

## 6 CAMS Thermal Correction

Before CAMS data are applied for correction of HXI measurements, it is important to ensure that an adequate correction of thermal pointing drifts is applied to the CAMS data themselves. This correction is meant to cancel out the main portion of the laser beam displacement caused by

temperature variation of the CAMS. Currently, on-ground unit level tests determined linear thermal drift coefficients for correcting the CAMS internal contribution [AD2]. A contribution to thermally induced laser pointing drift caused by the top plate bending could only be determined through on-orbit calibration of CAMS.

There are two ways to implement such a correction: through on-board processing and through ground processing. The CAMS on-board software does include such a correction for CAMS internal errors. This correction can be updated (coefficients and thermistors used) through the calibration table upload. If required, the onboard thermal correction can also be zeroed such that CAMS produces uncorrected data by uploading zero correction coefficients via calibration table upload.

Note, the onboard correction benefits from higher resolution temperature data obtained from CAMS thermal sensors (16 bit) while only 8 bit temperature reading (0.5 deg resolution) can be downloaded via telemetry. Therefore, if thermal correction is done on the ground it may be somewhat less accurate. The reduction in accuracy can be estimated using thermal sensitivity of the CAMS-LD units (<36  $\mu\text{m}/\text{deg C}$ ) to be in the range of 18  $\mu\text{m}$  of displacement. This value is small as compared to CAMS requirement (240  $\mu\text{m}$ ) therefore the reduction in accuracy can be acceptable.

Currently, on-ground thermal correction is selected as a baseline approach.

Note, according to [AD1], the thermistor values are 8bit signed integers representing the temperature in Celsius units multiplied by 2. Ground processing software has to multiply these values by a factor of 0.5 to get the deg C values.

The temperature corrected CAMS readings can be calculated using the following expression [RD7]:

$$\begin{aligned} x_{Corrected1,2} &= x_{CAMS1,2} - \alpha_{x1,2}^{CAMS} (T_{CAMS1,2} - T_{Calibration1,2}) \\ y_{Corrected1,2} &= y_{CAMS1,2} - \alpha_{y1,2}^{CAMS} (T_{CAMS1,2} - T_{Calibration1,2}) \end{aligned} \quad (14)$$

Where for each CAMS unit 1 and 2,  $x_{CAMS}$  and  $y_{CAMS}$  are CAMS readings in x and y,  $\alpha_x^{CAMS}$  and  $\alpha_y^{CAMS}$  CAMS thermal coefficients obtained via unit level thermal tests,  $T_{CAMS}$  is the temperature of optical assembly within CAMS reported by CAMS telemetry,  $T_{Calibration}$  is the temperature of the CAMS optics during the ground calibration of the unit. In this case, only one temperature sensor needs to be used for the CAMS correction.

Table 7 lists the calibration values required for the thermal correction. The actual values are to be used whenever available; when not available or TBD the nominal values should be used.

**Table 7. Thermal correction parameters for CAMS**

Description	Notation	Actual	Nominal
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		Values <sup>1</sup>	Values
CAMS1 thermal coefficient in x, mm/degC	$\alpha_{x1}^{CAMS}$	-0.021	0
CAMS1 thermal coefficient in y, mm/degC	$\alpha_{y1}^{CAMS}$	0.0262	0
CAMS1 ground calibration temperature, degC	$T_{Calibration1}$	22.8	22
CAMS2 thermal coefficient in x, mm/degC	$\alpha_{x2}^{CAMS}$	-0.0199	0
CAMS2 thermal coefficient in y, mm/degC	$\alpha_{y2}^{CAMS}$	0.0364	0
CAMS2 ground calibration temperature, degC	$T_{Calibration2}$	23.1	22
Temperature sensor used for correction CAMS1		Thermistor2	
Temperature sensor used for correction CAMS2		Thermistor2	

<sup>1</sup> – The values shown are as per [AD2] & [RD7].

## 7 CAMS Data Processing Summary

In summary, the following Table presents the steps how the CAMS data should be processed and applied throughout the data processing.

**Table 8. CAMS data processing flow**

Step	Description	Input data	Output data	Expressions / Reference
1	CAMS data temperature correction	CAMS telemetry: displacements and temperatures; Calibration data Table 7.	Temperature corrected displacements in CAMS coordinates	Section 6; Exp. (14); Table 7
2	Calculating CAMS displacements relative to default position in SAT coordinates	Temperature corrected CAMS displacements; Calibration data Table 6.	CAMS displacements in SAT coordinates	Section 5.2; Exp. (3)-(5); Table 6
3	EOB twist angle calculation	CAMS displacements in SAT coordinates	EOB twist angle	Section 5.2; Exp. (1),(2); Table 6
4	Calculating CAMS reported center of mass translation at a level of HXI detectors	CAMS displacements in SAT coordinates; EOB twist angle; Calibration Table 6.	Center of mass translation at a level of HXI detectors	Section 5.2, 5.3; Exp. (12), (7)
5	Converting HXI-1,2 readings from RAW frame to ACT frame	Translation and twist data, Calibration data (Table 6). HXI-1,2 RAW data	HXI-1,2 ACT data	Section 5.3; Exp. (8), (9)

# Appendix 1 – Rotation Matrices

The following rotation matrices are for single-axis rotations about the 3 principal Cartesian coordinate axes:

$$R_x(\phi) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \phi & -\sin \phi \\ 0 & \sin \phi & \cos \phi \end{bmatrix}, \quad R_y(\psi) = \begin{bmatrix} \cos \psi & 0 & \sin \psi \\ 0 & 1 & 0 \\ -\sin \psi & 0 & \cos \psi \end{bmatrix}, \quad R_z(\theta) = \begin{bmatrix} \cos \theta & -\sin \theta & 0 \\ \sin \theta & \cos \theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

## Appendix 2 – CAMS-T Nominal Coordinates

Nominal coordinates were measured in sensor (denoted as D, in pixels) and CAMS (denoted as LD, in mm) coordinate frames in [RD6] for CAMS-T engineering models located at 1.6 and 3.4 meters from CAMS-LD (middle and lower plates of ASTRO-H). These values were used to calculate the expected CAMS-T nominal coordinates at 12 m distance in D coordinate frame in pixels. This value is introduced in [RD6]. It also takes into account zero-gravity correction. The Tables below show the calculation of nominal coordinates in millimeters (LD reference frame). Here the red cells present the output results and blue cells represent measured values. The XLDC and YLDC are calculated coordinates in mm based on the Ratio, XD and YD measured in px and center of FOV coordinates (D frame). The center of FOV coordinates in px X0D and Y0D are used as fitting parameters to match the calculated values with the measured values in mm. Then, based on FOV center coordinates, ratio and determined px values at 12 m the values in mm at 12 m were calculated.

It should be noted that this calculation is based on readings reported by CAMS. As per [AD1] there is a correction factor of 1000/1024 that has to be applied to obtain real values in millimeters. When this factor is applied the final nominal coordinates are calculated and reported in Table 6.

### CAMS1

Distance, m	XD, px	YD, px	XLD,mm	YLD, mm	XLDC, mm	YLDC, mm	X0D, px	Y0D, px	Ratio, um/px
1.6	543.1	534.6	-0.398	1.274	-0.2941032	1.2460977	577.165	542.64	36.58
3.4	540.2	533.4	-0.234	1.324	-0.3379992	1.3521797			

measured values				
Include zero gravity correction				
12	545.5	535.5		

calculated with ratio	
based on measured px	
-0.2611812	1.1583057

FOV Center on Sensor

### CAMS2

Distance, m	XD, px	YD, px	XLD,mm	YLD, mm	XLDC, mm	YLDC, mm	X0D, px	Y0D, px	Ratio, um/px
1.6	560.2	546.9	0.877	2.123	0.9216331	2.229551	621.15	521.705	36.58
3.4	564.4	547.5	0.988	2.182	0.9435811	2.075915			

measured values		
Include zero gravity correction		
12	558.4	546.4

calculated with ratio	
based on measured px	
0.9033431	2.295395

FOV Center on Sensor

## **Appendix 3 - Acronyms and Definitions**

**AMS** – Alignment Measurement System

**CAMS** – Canadian ASTRO-H Metrology System

**CAMS-LD** – CAMS Laser / Detector unit

**CAMS-T** – CAMS Target unit; corner-cube retro-reflector

**DSP** – Digital Signal Processor

**EEPROM** – Electrical Erasable Programmable Read-Only Memory

**EOB** – Extendable Optical Bench

**FOB** – Fixed Optical Bench

**FOV** – Field of View

**FPGA** – Field Programmable Gate Array

**HK** – Housekeeping

**HXI** – Hard X-Ray Imager

**HXT** – Hard X-Ray Telescope

**SMU** – Satellite Management Unit; the ASTRO-H onboard controller, which handles telecommand distribution and housekeeping telemetry collection.