

LEXI GROUND DATA PRODUCTS AND PROCESSING PIPELINE

(CALIBRATION AND MEASUREMENT ALGORITHMS DOCUMENT)

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Glossary of Abbreviations

BU

Boston University. [5](#), [24](#)

CAD

Computer Assisted Design. [15](#)

DCM

Direction Cosine Matrix. [16](#)

HV

High Voltage. [8](#)

LEXI

Lunar Environment heliospheric X-ray Imager. [5](#), [6](#), [9](#), [10](#), [15](#), [16](#), [19](#), [20](#), [24](#)

LSB

Least Significant Bit. [6](#), [8](#)

MET

Mission Elapsed Time. [6](#)

MSB

Most Significant Bit. [6](#), [8](#)

1 LEXI Overview

The [Lunar Environment heliospheric X-ray Imager \(LEXI\)](#) (Walsh et al., 2024; Kuntz et al., 2022) is a soft X-ray (0.1 - 2 keV) imager developed to provide wide field-of-view ($\sim 9.1^\circ \times 9.1^\circ$) images of the interaction between the solar wind and Earth's magnetosphere. The telescope operated for 6.5 days from the lunar surface on the Blue Ghost 1 lander from Mare Crisium. The project is led by [Boston University \(BU\)](#) and is a collaboration with NASA Goddard, Johns Hopkins University, the University of Leicester, and the University of Miami. [LEXI](#) is part of NASA's Lunar Science and Technology Program.

2 LEXI Data processing

In this section we discuss the details of **LEXI** data processing using codes written in Python programming language. The following sections give details of deriving each data product starting from the initial binary files which are received from the spacecraft. Table 3 shows the different data levels of the **LEXI** instrument and also lists out the type of output file corresponding to each data level. All the codes corresponding to the data processing steps are available on GitHub at the following link: [LEXI Data Processing](#)¹.

2.1 LEXI Data Format

Each packet sent by the instrument has 16 bytes. The table below defines the byte format with details of **Most Significant Bit (MSB)** and **Least Significant Bit (LSB)** for relevant data packets. Also note that all the data packets have ‘big-endianess’. **Mission Elapsed Time (MET)** is in milliseconds and represents the time elapsed since the instrument was turned on. In addition to the payload generated packet, Firefly adds a timestamp to each packet with 100 ms resolution or better which adds another 12 bytes of data. Tables 1 and 2 show the data format for science and housekeeping packets for **LEXI** respectively. A payload telemetry file is also provided by Firefly that has the following filename format :

`payload_mnemonic_sec_subsecs.dat`

where `sec` and `subsecs` are the seconds and subseconds since the Unix epoch (00:00:00 UTC on 1 January 1970). The `mnemonic` is the mnemonic of the instrument, ‘LEX’ for **LEXI**. The format of the timestamp written to the telemetry file is:

`<Identifier 0x54 0x53><8-byte double-precision timestamp in seconds>
<2-byte length of data><data>`

A new file is sent by the onboard payload manager component based on three limits.

1. Maximum file size, which for **LEXI** is 1 MB.
2. Maximum time between two writes to the data file. This value is set to 3 seconds.
3. Maximum length of time for which a file is kept open. This value is set to 300 seconds.

Once either of the three limits are met, the file is closed and a new file is opened. Assuming a new file is sent by spacecraft every time the file size reaches 1 MB, based on Tables 1 and 2, it takes around 2 minutes to fill up the 1 MB file (Defined in **BGM1 Payload Flight Software Interface Control Document (FSW ICD) Document: SPC_ENG_0056**). So the ground station receives a new binary file from the spacecraft around every 2 minutes. This binary file is the level 0 (LO) file (see Section 2.2 for more details). Figure 2 shows the data-pipeline flowchart for **LEXI** and lists out different data products.

2.2 Details of various data levels

2.2.1 Level 0 data

In the first step, the raw data is received from the spacecraft. A new binary file of size 1 MB is received every 2 minutes or so. These files constitute the Level 0 files (LO).

¹https://github.com/Lexi-BU/lexi_data_pipeline

Table 1: LEXI telemetry packets and data format

Telemetry Type	Data Format
Science Telemetry	Send 16-byte Science Telemetry packets for each event byte 0 : 0xFE Sync pattern byte 1 : 0x6B Sync pattern byte 2 : 0x28 Sync pattern byte 3 : 0x40 Sync pattern byte 4 : Time tag is 30 bits total across 4 bytes bit 7 : Telemetry Type = 0 bit 6 : 1 if commanded event bits 5-0 : MS 6-bits of MET byte 5 : Time tag bits 7-0 : middle 8-bits of MET byte 6 : Time tag (cont.) bits 7-0 : 8-bits of MET byte 7 : Time tag (cont.) bits 7-0 : LS 8-bits of MET (LSbit = 1 msec) byte 8 : ch1 MS byte data (0xDD) Each channel is 16bits byte 9 : ch1 LS byte data (0xDD) byte 10 : ch2 MS byte data (0xDD) byte 11 : ch2 LS byte data (0xDD) byte 12 : ch3 MS-byte data (0xDD) byte 13 : ch3 LS-byte data (0xDD) byte 14 : ch4 MS-byte data (0xDD) byte 15 : ch4 LS-byte data (0xDD)

2.2.2 Level 1a data

From each binary file, two files are generated, one corresponding to time series of four voltages recorded by the detector (called **SCI**). The other file contains the time series of housekeeping data (called **HK**). These are Level 1a files (**L1a**). For the details of how these files are generated, see Section 3. The list below lists out all the data stored in **SCI** and **HK** files.

- **SCI** file: The **L1a** science file containing time, voltages from the 4 channels.
 - **Date** : Time stamp of each observation in UTC
 - **TimeStamp** : Seconds since LEXI was turned on or was last reset
 - **IsCommanded** : Flag indicating if the event was commanded by the software or was an actual photon observation
 - **Channel1** : Voltage of the first channel in V (0 – 4.51V)

Table 2: LEXI telemetry packets and data format

Telemetry Type	Data Format
Housekeeping Telemetry	<p>Send 16-byte Housekeeping Telemetry packet - sent whenever High Voltage (HV) state changes or once every second (whichever comes first)</p> <p>byte 0 : 0xFE Sync pattern byte 1 : 0x6B Sync pattern byte 2 : 0x28 Sync pattern byte 3 : 0x40 Sync pattern byte 4 : Time tag is 30 bits total across 4 bytes bit 7 : Telemetry Type = 1 bit 6 : Unused bits 5-0 : MS 6-bits of MET</p> <p>byte 5 : Time tag bits 7-0 : upper middle 8-bits of MET</p> <p>byte 6 : Time tag (cont.) bits 7-0 : lower middle 8-bits of MET</p> <p>byte 7 : Time tag (cont.) bits 7-0 : LS 8-bits of MET (LSbit = 1 msec)</p> <p>byte 8 : HK Status points bits 7-4 HK ID, bits 3-0 MS nibble of data</p> <p>HK ID 0 : Pin Puller Temperature 1 : Optics Temperature 3 : HV Power Temperature 2 : LEXI Base Temperature 3 : HV Power Temperature 4 : +5.2V Current Monitor 5 : +10V Current Monitor 6 : +3.3V Current Monitor 7 : Anode Voltage Monitor 8 : +28V Current Monitor 9 - 13 : unused 14 : MCP HV after auto change 15 : MCP HV after manual change</p> <p>byte 9 : bits 7-0: LS byte of HK ADC data or MCP HV setting</p> <p>byte 10 : MSB of delta Event Count (since last HK packet)</p> <p>byte 11 : LSB of delta Event Count (since last HK packet)</p> <p>byte 12 : MSB of delta Dropped Event Count (due to threshold test since last HK packet)</p> <p>byte 13 : LSB of delta Dropped Event Count (due to threshold test, since last HK packet)</p> <p>byte 14 : MSB of delta Lost Event Count (due to FIFO overflow, since last HK packet)</p> <p>byte 15 : LSB of delta Lost Event Count (due to FIFO overflow, since last HK packet)</p>

- Channel12 : Voltage of the second channel in V (0 – 4.51V)
- Channel13 : Voltage of the third channel in V (0 – 4.51V)
- Channel14 : Voltage of the fourth channel in V (0 – 4.51V)
- HK File: The L1 housekeeping file contains 22 columns of data:
 - Date: Time stamp of each observation in UTC
 - TimeStamp: Seconds since LEXI was turned on or was last reset
 - HK_ID: The housekeeping ID that indicates the type of data. This varies from 0 to 15. See Table 2 for the list of HK IDs.
 - PinPullerTemp: Pin Puller Temperature
 - OpticsTemp: Optics Temperature
 - LEXIbaseTemp: LEXI base Temperature
 - HVsupplyTemp: HV supply Temperature
 - V_Imon_5.2: Current corresponding to the 5V supply
 - V_Imon_10: Current corresponding to the 10V supply
 - V_Imon_3.3: Current corresponding to the 3.3V supply
 - AnodeVoltMon: Anode Voltage
 - V_Imon_28: Current corresponding to the 28V supply
 - ADC_Ground: ADC Ground Voltage
 - Cmd_count: Command Count, the number of commands sent to [LEXI](#)
 - Pinpuller_Armed: Status of the pin puller
 - Unused1: Unused
 - Unused2: Unused
 - HVmcpAuto: Status of the HV MCP (auto)
 - HVmcpMan: Status of the HV MCP (manual)
 - DeltaEvntCount: Number of events recorder
 - DeltaDroppedCount: Number of dropped events
 - DeltaLostEvntCount: Number of lost events

2.2.3 Level 1b data

The four voltages from L1a dataset are then corrected for zero-point offset. The details of this correction are discussed in Section 3.2.2. The modified data, along with the original data, is then saved to cdf files as Level 1b data. These files are also modified to have a maximum time length of 1 hour.

- The L1b files have the following columns:
 - Epoch: Time stamp of each observation in UTC
 - Epoch_unix: Time stamp of each observation in seconds since the Unix epoch (00:00:00 UTC on 1 January 1970)
 - TimeStamp: Seconds since LEXI was turned on or was last reset

- **IsCommanded**: Flag indicating if the event was commanded by the software or was an actual photon observation
- **Channel11**: Voltage of the first channel in V (0 – 4.51V)
- **Channel11_shifted**: Voltage of the first channel in V (0 – 4.51V) after zero-point offset correction
- **Channel12**: Voltage of the second channel in V (0 – 4.51V)
- **Channel12_shifted**: Voltage of the second channel in V (0 – 4.51V) after zero-point offset correction
- **Channel13**: Voltage of the third channel in V (0 – 4.51V)
- **Channel13_shifted**: Voltage of the third channel in V (0 – 4.51V) after zero-point offset correction
- **Channel14**: Voltage of the fourth channel in V (0 – 4.51V)
- **Channel14_shifted**: Voltage of the fourth channel in V (0 – 4.51V) after zero-point offset correction
- **x_volt**: The x position of the photon in voltage coordinates. This is dimensionless and is computed using Equation (1). The value is between 0 and 1.
- **y_volt**: The y position of the photon in voltage coordinates. This is dimensionless and is computed using Equation (2). The value is between 0 and 1.
- **x_volt_lin**: The x position of the photon after linear correction was applied to the x position. This is dimensionless.
- **y_volt_lin**: The y position of the photon after linear correction was applied to the y position. This is dimensionless.
- **x_mcp**: The x position of the photon in physical detector coordinates in cm.
- **y_mcp**: The y position of the photon in physical detector coordinates in cm.

2.2.4 Level 1c data

The L1b data is then further processed to compute the celestial coordinates of the detected photons. This involves transforming the detector coordinates to celestial coordinates using the pointing vector data as well as the relative orientation of the lander and **LEXI**. This coordinate transformation is quite involved and requires multiple intermediate steps. These steps are described in detail in Section 3.2.3. The transformed data is then saved to a CDF file as Level 1c data (L1c).

- The L1c files have the following columns:
 - **Epoch**: Time stamp of each observation in UTC
 - **Epoch_unix**: Time stamp of each observation in seconds since the Unix epoch (00:00:00 UTC on 1 January 1970)
 - **photon_x_mcp**: The x position of the photon in physical detector coordinates in cm. This is same as **x_mcp** in L1b.
 - **photon_y_mcp**: The y position of the photon in physical detector coordinates in cm. This is same as **y_mcp** in L1b.
 - **photon_RA**: The right ascension of the photon in celestial coordinates (J2000). Units are degrees.

- `photon_Dec`: The declination of the photon in celestial coordinates (J2000). Units are degrees.
- `photon_az`: The azimuthal angle of the photon in the local topocentric coordinate system. North is 0 degrees and increases clockwise. Units are degrees.
- `photon_el`: The elevation angle of the photon in the local topocentric coordinate system. 0 degrees is at the horizon and increases upwards. Units are degrees.

2.2.5 Level 2 data

The Level 2 data (L2) are the image data generated using the cleaned L1c data. This dataset contains several 2-D histograms (described below) and the associated metadata. The integration time for these images is 5 minutes. The details of how these images are generated are discussed in Section 3.3. The images are saved to a CDF file.

- The L2 files have the following datasets:
 - `epoch_start`: Start time of the integration periods in UTC.
 - `epoch_end`: End time of the integration periods in UTC.
 - `ra_bin`: The right ascension bin centers for the 2-D histogram. Units are degrees.
 - `dec_bin`: The declination bin centers for the 2-D histogram. Units are degrees.
 - `ra_bin_map`: The right ascension bin centers for the 2-D histogram expanded to match the dimensions of the 2-D histogram. Units are degrees.
 - `dec_bin_map`: The declination bin centers for the 2-D histogram expanded to match the dimensions of the 2-D histogram. Units are degrees.
 - `exposure_map`: The exposure map for the 2-D histogram. Units are seconds. This is the amount of time each pixel was exposed to the sky during the integration period.
 - `flat_field_maps`: The flat field map for the 2-D histogram. This is a dimensionless quantity that represents the relative sensitivity of each pixel.
 - `galactic_background_map`: The galactic background map for the 2-D histogram. This is the background count rate due to the Milky Way and other extragalactic sources. Units are counts per pixel.
 - `dark_background_map`: The dark background map for the 2-D histogram. This is the background count rate due to dark counts and other instrumental effects. Units are counts per pixel.
 - `total_background_map`: The total background map for the 2-D histogram. This is the sum of the galactic and dark background maps. Units are counts per pixel.
 - `lexi_hist`: The 2-D histogram of photon counts in RA and Dec coordinates. Units are counts per pixel. This is the raw counts as observed by LEXI. This does not have any background subtraction or flat fielding applied.
 - `lexi_histogram_background_corrected`: The 2-D histogram of photon counts in RA and Dec coordinates, after background subtraction have been applied. Units are counts per pixel per second.
 - `lexi_histogram_background_flatfield_corrected`: The 2-D histogram of photon counts in RA and Dec coordinates, after background subtraction and flat fielding have been applied. Units are counts per pixel per second. This is the final image product.

Table 3 lists out the data levels and their corresponding description and type of data file associated with each level.

Table 3: Data levels and their corresponding description and type of data file associated with each level.

Data Levels		Description	File type
Level 0		Binary data set. Original file from the spacecraft.	.dat (binary)
Level 1	a	Data containing time , voltages from the 4 channels and 22 parameters corresponding to house-keeping.	.CSV, .CDF
	b	Data containing time and dewarped x, y spatial position of each photon in detector coordinate	.CDF
	c	Data containing time, dewarped x, y spatial position of each photon in detector coordinate, and celestial coordinates (RA, Dec, Az, El)	.CDF
Level 2		Level 2 data, images as generated by LEXI.	.CDF

LEXI - Data Flow Diagram

Version number: 0.04
Version date: 2025/09/14 12:00

- Legend**
- Level 0
 - Level 1a
 - Level 1b
 - Level 1c
 - Level 2

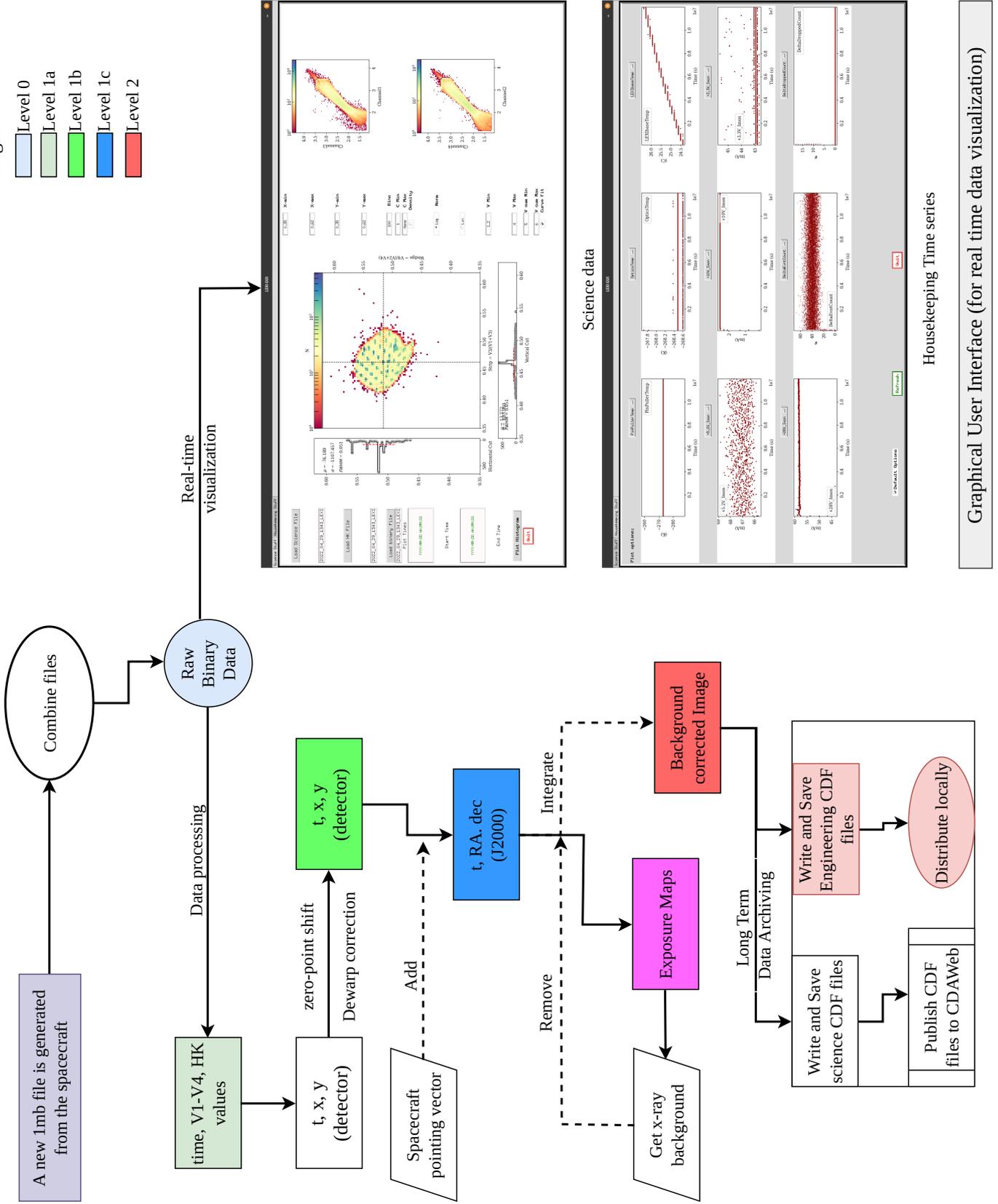


Figure 2: LEXI data-pipeline flowchart

3 LEXI Data Processing Algorithm

This section describes the algorithm used to process the data collected by the LEXI instrument in comprehensive detail. The algorithm is designed to convert raw data into scientifically useful products, including images and time series data. The processing steps are divided into different levels, each building upon the previous one to produce refined data products.

3.1 Level 0 Data

The Level 0 data is the raw binary data received from the LEXI instrument. This data is stored as it is received in a binary format.

3.2 Level 1 Data

The Level 1 data is derived from the Level 0 data and includes several key transformations for each sub-level dataset.

3.2.1 Level 1a Data

The L0 files are then processed using a python code that reads the binary files and extracts the data from each file and saves it to a CSV file in double precision format, which is the default format for all datasets. A combination of two sync patterns (5453 and FE6B2840) is used to read the binary file and convert it to CSV files. Tables 1 and 2 show the data format for each of the telemetry packets. The first sync pattern (5453) is used to locate the start of the packet. Immediately following this sync pattern are 8-bytes of time stamp data, which is then followed by the FE6B2840 sync pattern, which indicates the start of the data packet as generated by the instrument. Based on these two sync words the binary packets are parsed, and the data is extracted. The extracted data is then saved in two separate files, one for the science data and the other for the housekeeping data as described in the housekeeping data in Section 2.2.2.

3.2.2 Level 1b Data

The channel voltages computed in Level 1a have an intrinsic bias which we call zero-point offset. For each of the four voltage channels, zero-point offset is computed by making a very high resolution (small bin sizes) histogram of voltage and determining the index of the histogram bin with the maximum number of counts between the first and the central bin of the histogram. The voltage corresponding to this index is the zero-point offset and is subtracted from the relevant channel to get the new shifted voltage with a new name. For example, the voltage corresponding to Channel3 after shift is renamed to Channel3_shifted and so on. These offset corrected voltages are then used to compute the dimensionless x and y positions of each photon, in detector coordinate system, using the following equation (Martin et al., 1981):

$$x_{\text{volt}} = \text{Channel3}_{\text{shifted}} / (\text{Channel1}_{\text{shifted}} + \text{Channel3}_{\text{shifted}}) \quad (1)$$

$$y_{\text{volt}} = \text{Channel4}_{\text{shifted}} / (\text{Channel2}_{\text{shifted}} + \text{Channel4}_{\text{shifted}}) \quad (2)$$

Because of the artifacts introduced by the detector, these x_{volt} and y_{volt} positions are slightly distorted and thus must be corrected appropriately. The correction, also called dewarping, for each coordinate, is carried out by multiplying each point by a constant factor. This constant factor is the inverse of slopes of x_{volt} and y_{volt} which were computed empirically from an earlier experiment where the detector was covered with an aperture that had holes at regular intervals in a grid like pattern. When irradiated with x-rays, one would expect to see a straight line

of points in the detector plane. However, a slightly curved line was observed. The slopes of this line were used to compute the correction factors by fitting a straight line through them and computing its slope. The x_{volt} and y_{volt} values, are then linearly corrected to center them at (0,0). The resultant x and y positions are named $x_{\text{volt}_{\text{lin}}}$ and $y_{\text{volt}_{\text{lin}}}$ to indicate the linear transformation. The equation below shows the linear transformation applied to the x and y positions:

$$\mathbf{M}_{\text{inv}} = \begin{bmatrix} 0.98678 & 0.16204 \\ 0.11385 & 0.993497 \end{bmatrix}, \quad (3)$$

$$\hat{\mathbf{b}} = \begin{bmatrix} 0.5529 \\ 0.5596 \end{bmatrix}, \quad (4)$$

$$\begin{bmatrix} x_{\text{volt}_{\text{lin}}} \\ y_{\text{volt}_{\text{lin}}} \end{bmatrix} = \mathbf{M}_{\text{inv}} \begin{bmatrix} x_{\text{volt}} \\ y_{\text{volt}} \end{bmatrix} - \hat{\mathbf{b}} \quad (5)$$

where, \mathbf{M}_{inv} is the inverse of the matrix that contains the slopes of the linearly corrected x and y positions, and $\hat{\mathbf{b}}$ is a vector that contains the offsets for the x and y positions. The $x_{\text{volt}_{\text{lin}}}$ and $y_{\text{volt}_{\text{lin}}}$ positions are now dimensionless and centered at (0,0). The next step is to convert these positions to physical coordinates in centimeters (cm). The conversion is done by multiplying the $x_{\text{volt}_{\text{lin}}}$ and $y_{\text{volt}_{\text{lin}}}$ positions by the physical size of the detector in cm. The physical size of the detector is approximately 90 cm. The final x and y positions in physical coordinates are named x_{mcp} and y_{mcp} respectively. The equations for these conversions are:

$$x_{\text{mcp}} = x_{\text{volt}_{\text{lin}}} \times r_{\text{detector}} \quad (6)$$

$$y_{\text{mcp}} = y_{\text{volt}_{\text{lin}}} \times r_{\text{detector}} \quad (7)$$

The Level 1b data is saved in both CSV and CDF formats for further analysis.

3.2.3 Level 1c Data

This section describes the Level 1c data processing, as well as define the several conventions for coordinate frames and angles used to describe the pointing of LEXI. Section 3.2.3.1 details how we analyzed the Computer Assisted Design (CAD) model in order to estimate LEXI's roll angle about the boresight. Section 3.2.3.2 describes how to perform various transformations at a given point in time, which is useful for transforming the LEXI detector data into various frames including J2000.

3.2.3.1 Pointing from CAD Model

Let \mathcal{F}_b be the reference frame fixed to the lander body, and \mathcal{F}_d be the reference frame fixed to the LEXI detector. At any point in time, we wish to write the rotation matrix \mathbf{R}^{db} :

$$\mathbf{v}_d = \mathbf{R}^{db} \mathbf{v}_b \quad (8)$$

that maps an arbitrary vector \mathbf{v}_b expressed in \mathcal{F}_b into the corresponding vector \mathbf{v}_d expressed in \mathcal{F}_d . Note that $\mathbf{R}^{bd} = \mathbf{R}^{dbT}$. The matrix \mathbf{R}^{db} is a function of three variables:

$$\mathbf{R}^{db} = f(\theta_1(t), \theta_2(t), \theta_3) \quad (9)$$

The angles θ_1 and θ_2 are explicitly time-dependent, and can be thought of as either the Az-El or the RA-DEC angles, but that distinction is not important for the present discussion. The angles θ_1 and θ_2 define the direction of the detector boresight, and the angle θ_3 defines the "roll" of the detector's horizontal and vertical axes about the boresight. Note that θ_3 does not vary in time, because the gimbal has no actuation about the boresight; the value of θ_3 is

determined by the mechanical design of the detector plate relative to the gimbal. The purpose of this section is to describe how to measure θ_3 from the LEXI CAD model.

The reference frames are defined by their unit basis vectors, $\mathcal{F}_b = \{\hat{\mathbf{b}}_1, \hat{\mathbf{b}}_2, \hat{\mathbf{b}}_3\}$ and $\mathcal{F}_d = \{\hat{\mathbf{d}}_1, \hat{\mathbf{d}}_2, \hat{\mathbf{d}}_3\}$. The matrix \mathbf{R}^{db} is a **Direction Cosine Matrix (DCM)**, which means that each element R_{ij} of \mathbf{R}^{db} is the direction cosine between $\hat{\mathbf{d}}_i$ and $\hat{\mathbf{b}}_j$. Thus, the first step is to use CAD software to measure the angle between the unit basis vectors. As shown in Figure 3, the frame \mathcal{F}_b is defined using the same convention that FireFly uses for the Lander Body Frame, where $\hat{\mathbf{b}}_1$ points towards zenith out the top deck, $\hat{\mathbf{b}}_2$ points towards north during a nominal landing, and $\hat{\mathbf{b}}_3$ points west during a nominal landing. The detector frame \mathcal{F}_d is defined with $\hat{\mathbf{d}}_1$ and $\hat{\mathbf{d}}_2$ aligned with LEXI detector's convention (X goes positive to the right in an image, Y goes positive down in an image), and $\hat{\mathbf{d}}_3$ is parallel to the boresight with positive direction going from detector to observation target.

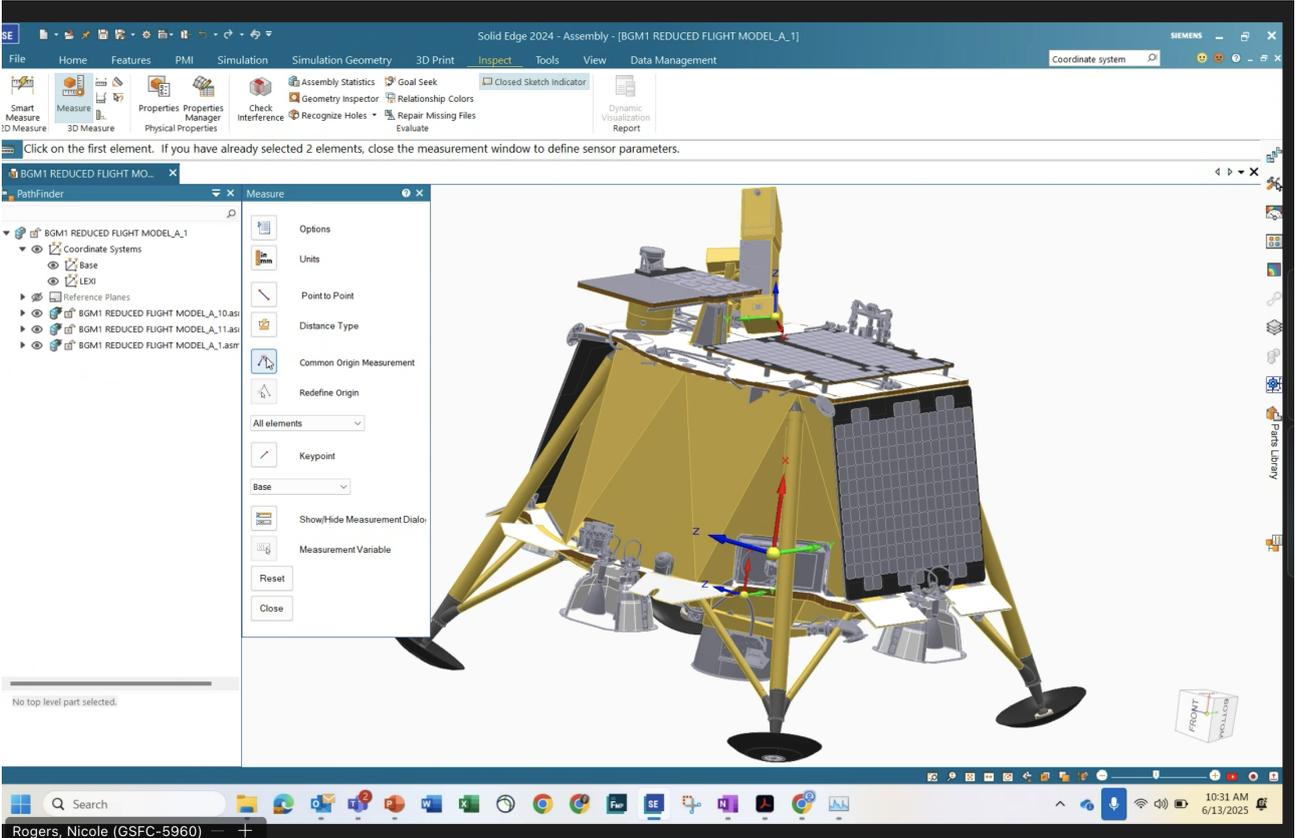


Figure 3: LEXI and BGM1 CAD models with detector frame and lander body frames defined.

Based on the measured angles within CAD, the DCM of \mathbf{R}^{db} was found to be:

$$\mathbf{R}^{db} = \begin{bmatrix} \cos(180 - 55.36) & \cos(38.17) & \cos(75.96) \\ \cos(180 - 76.31) & \cos(116.02) & \cos(29.89) \\ \cos(180 - 142.0) & \cos(64.19) & \cos(64.19) \end{bmatrix} \quad (10)$$

$$= \begin{bmatrix} -0.56841826 & 0.78618058 & 0.24259923 \\ -0.23666858 & -0.43868486 & 0.86698374 \\ 0.78801075 & 0.43538823 & 0.43538823 \end{bmatrix} \quad (11)$$

where all the angles above are in degrees, and the terms having the 180 inside the cosine were to account for the correct sign, since the various CAD programs were inconsistent in how they measured angles between vectors. Note that another interpretation of the DCM is as a collection of column vectors of one set of basis vectors expressed in the other frame, namely:

$$\mathbf{R}^{db} = \begin{bmatrix} \hat{\mathbf{b}}_1^d & \hat{\mathbf{b}}_2^d & \hat{\mathbf{b}}_3^d \end{bmatrix} \quad (12)$$

where the superscript on a basis vector denotes the frame \mathcal{F} in which it is expressed. The understanding in Equation (12) allowed us to check the sign of the individual terms R_{ij} to decide whether the 180 needed to be added to Equation (10). The Figures 4 to 6 give convenient visual verification of the sign needed in the components in Equation (12).

We can double-check that the numerical values given in Equation (10) represent a valid rotation matrix in a couple of ways. One property of a rotation matrix is that the norm of the columns and rows should equal 1. Performing this calculation results in:

$$\text{Norms along rows} = [1.00001681 \quad 1.00005861 \quad 1.00004338] \quad (13)$$

$$\text{Norms along columns} = [1.00003614 \quad 1.00004361 \quad 1.00003905] \quad (14)$$

which are sufficiently close to 1. Another check is that any rotation matrix is orthogonal, and thus $\mathbf{R}^{-1} = \mathbf{R}^T$, which we can check with

$$\mathbf{R}^{-1} - \mathbf{R}^T = \begin{bmatrix} 1.30566263\text{e-}05 & 2.77672763\text{e-}05 & -7.39737298\text{e-}05 \\ -3.87599546\text{e-}05 & 8.35426602\text{e-}05 & -4.61712640\text{e-}05 \\ 1.76195339\text{e-}05 & -8.53548825\text{e-}05 & -1.92275805\text{e-}05 \end{bmatrix} \quad (15)$$

which is sufficiently close to zero. We therefore can have confidence that \mathbf{R}^{db} given above is a valid rotation matrix.

We can also visually check that \mathbf{R}^{db} is correct by doing a visual inspection of the \mathcal{F}_d basis vectors after being transformed with \mathbf{R}^{bd} into \mathcal{F}_b and comparing the illustrations of the frames in the CAD drawings. From Figures 4 to 6 below, the 3D plot on the left shows the predicted \mathcal{F}_d relative to \mathcal{F}_b given the \mathbf{R}^{bd} computed in Equation (10), and the right half of each figure shows the CAD view of the lander in the matching orientation; visual inspection allows us to confirm (within the accuracy allowed by this sanity check) that the frames are oriented in the proper direction.

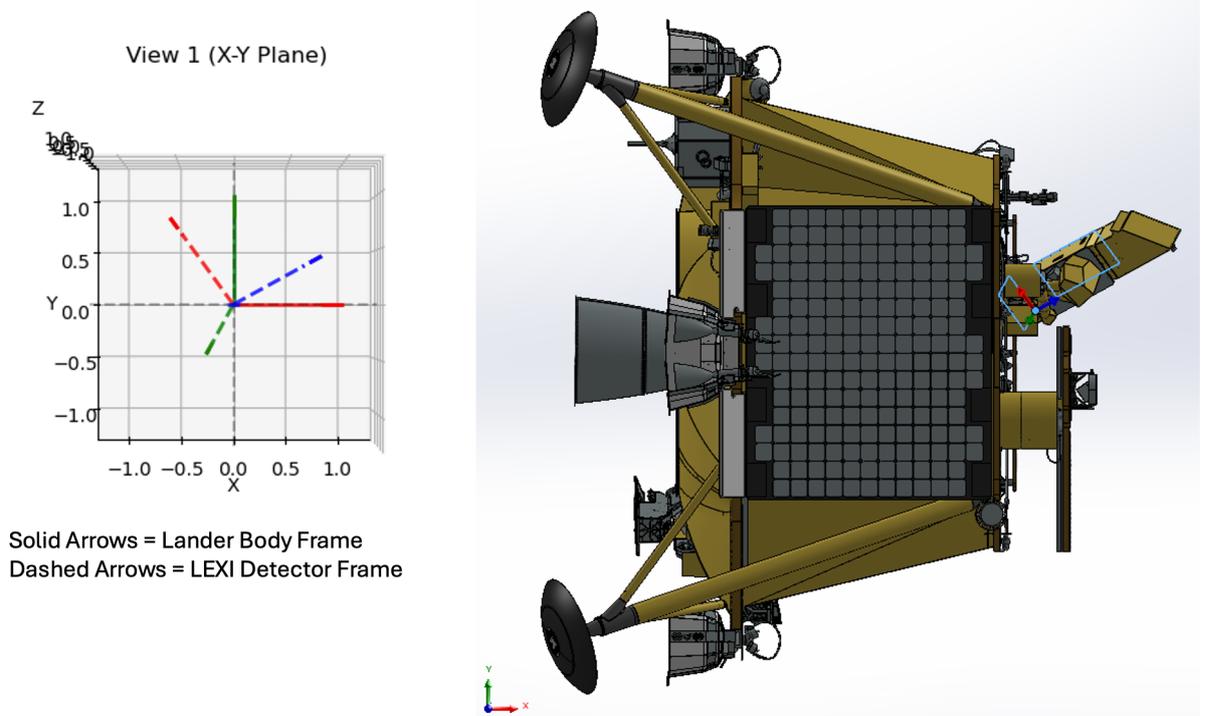


Figure 4: View of Lander X-Y frame with check of rotated basis vectors.

The final step is to compute the roll angle θ_3 from the DCM \mathbf{R}^{db} . Let the sequence of rotations implied by Equation (9) be given by the intrinsic 1-2-3 Euler angle sequence:

$$\mathbf{R}^{db} = \mathbf{R}_3(\theta_3)\mathbf{R}_2(\theta_2)\mathbf{R}_1(\theta_1) \quad (16)$$

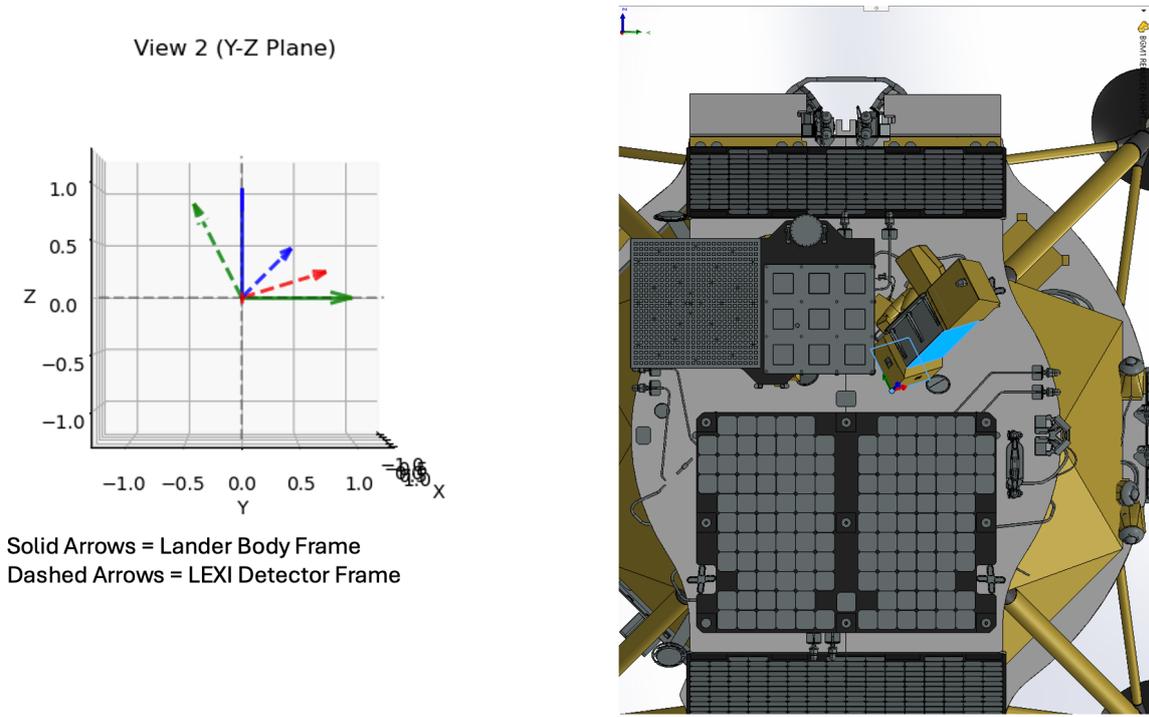


Figure 5: View of Lander Y-Z frame with check of rotated basis vectors.

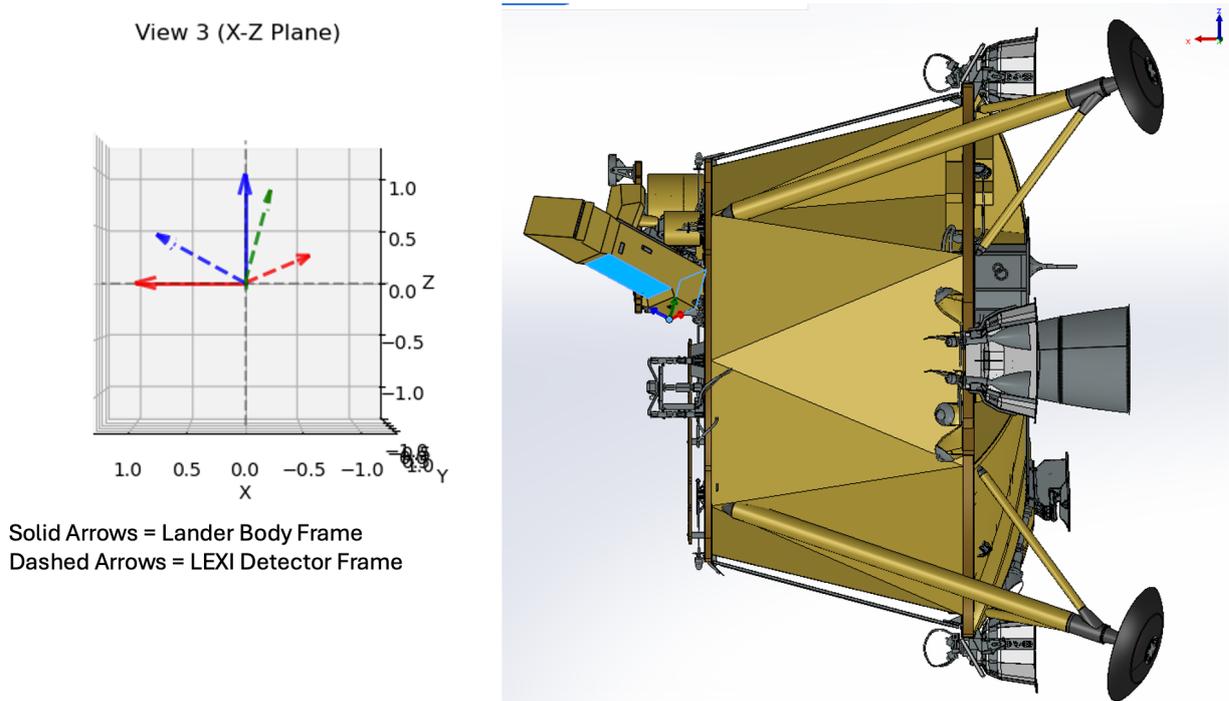


Figure 6: View of Lander X-Z frame with check of rotated basis vectors.

where θ_3 is the roll angle we wish to find. The equation for this 1-2-3 sequence is :

$$\mathbf{R}^{db} = \begin{bmatrix} c_3 c_2 & c_3 s_2 s_1 + s_3 c_1 & -c_3 s_2 c_1 + s_3 s_1 \\ -s_3 c_2 & -s_3 s_2 s_1 + c_3 c_1 & s_3 s_2 c_1 + c_3 s_1 \\ s_2 & -c_2 s_1 & c_2 c_1 \end{bmatrix} \quad (17)$$

where $c_1 = \cos \theta_1$, $s_1 = \sin \theta_1$, etc. We can solve for θ_3 using:

$$\theta_3 = \text{atan2}(-R_{2,1}, R_{1,1}) \quad (18)$$

which, given the numerical values for \mathbf{R}^{db} above, give $\theta_3 = 157.3949^\circ$.

3.2.3.2 Pointing over Time

A few more steps are required to compute the correct \mathbf{R}^{db} given the RA and DEC angles measured at a given time. That works out to be:

$$\mathbf{R}^{db} = \mathbf{R}_3(\theta_3)\mathbf{R}_2(\theta_2)\mathbf{R}_1(\theta_1) \quad (19)$$

where θ_3 is the value given just above, and θ_1 and θ_2 are computed from the actual boresight RA (α) and DEC (δ) angles. Given the RA and DEC angles expressed in the J2000 frame (or ITRF frame, since they are nearly identical for our purposes), the boresight vector expressed in \mathcal{F}_{J2000} is:

$$\mathbf{v}_{J2000} = \begin{bmatrix} \cos \delta \cos \alpha \\ \cos \delta \sin \alpha \\ \sin \delta \end{bmatrix} \quad (20)$$

This vector is then expressed in the actual lander body frame (i.e. reflecting how the real lander was oriented on the surface according to post-landed telemetry) with:

$$\mathbf{v}_{\text{BODYACT}} = \mathbf{R}^{\text{BODYACT} \leftarrow J2000} \mathbf{v}_{J2000} \quad (21)$$

where $\mathbf{R}^{\text{BODYACT} \leftarrow J2000}$ is provided in the quaternion data files based on the post-touchdown telemetry and FreeFlyer simulation. Then, we can compute the angles θ_1 and θ_2 using:

$$\theta_1 = \text{atan2}(-v_y, v_z) \quad (22)$$

$$\theta_2 = \text{asin}(v_x) \quad (23)$$

where $\mathbf{v}_{\text{BODYACT}} = (v_x, v_y, v_z)$. Note that θ_1 is positive for right-hand rotations about the x -axis, per the definition in Equation (19), which explains why the negative sign appears on $-v_y$ in Equation (22). When discussing these pointing results, it is handy to use the ‘‘Azimuth’’

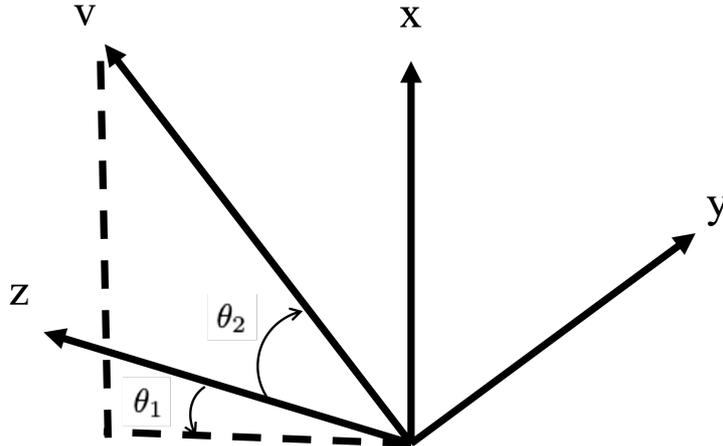


Figure 7: Illustration of conventions used to define θ_1 and θ_2 .

and ‘‘Elevation’’ angles in the local topocentric frame (i.e. BODY-NOMINAL frame), in which case θ_2 is Elevation and $270 - \theta_1$ is Azimuth, where we use the standard azimuth convention of zero degrees pointed to north and a positive angle measured clock-wise.

Thus, we now know the roll angle θ_3 from earlier (which is constant), and θ_1 and θ_2 can be found at any point in time from the boresight RA-DEC pointing history data, and we can compute \mathbf{R}^{db} using Equation (19). If we want to rotate LEXI images between the detector frame to the J2000 frame (and vice versa), that is done with:

$$\mathbf{R}^{d \leftarrow J2000} = \mathbf{R}^{db} \mathbf{R}^{\text{BODYACT} \leftarrow J2000} \quad (24)$$

or the transpose of the above, noting that the “b” in \mathbf{R}^{db} is treated as the “actual” lander body (versus the “nominal” lander body). When we compute these angles near the time of sunset, we get approximately $\theta_1 = -0.007^\circ$, and $\theta_2 = 29.003^\circ$, which makes sense for LEXI pointed westward in a default configuration.

If we wish to find the angle between the LEXI boresight and the local horizontal, ϕ , we can use the following procedure. Let the LEXI boresight in the detector frame \mathcal{F}_d be $\mathbf{v}_d = [0, 0, 1]^T$. Then this boresight vector can be expressed in the “Body Nominal” frame (equivalent to a local topocentric frame) with

$$\mathbf{v}_{\text{BODYNOM}} = \mathbf{R}^{\text{BODYNOM} \leftarrow J2000} \mathbf{R}^{J2000 \leftarrow \text{BODYACT}} \mathbf{R}^{bd} \mathbf{v}_d \quad (25)$$

where \mathbf{R}^{bd} comes from evaluating the transpose of Equation (17), given θ_1 from Equation (22), θ_2 from Equation (23), and $\theta_3 = 157.3949^\circ$. Recognizing that the x component is the vertical component of $\mathbf{v}_{\text{BODYNOM}}$, we find ϕ with:

$$\phi = \text{asin}(\mathbf{v}_{\text{BODYNOM}}[0]) \quad (26)$$

which works out to be a nearly constant value of around $\phi = 24.825^\circ$ for the time span at sunset when the gimbal was stationary. Comparing this value with $\theta_2 = 29.003^\circ$, these two values are in agreement, because the actual lander body was tilted 4.197° from local vertical in a direction that was less than 1° from due west. In other words, as a sanity check, starting from the as-landed orientation, the boresight direction needs to be tilted up by approximately 4.2° to reach the local horizontal, then another 24.8° to reach $^\circ$ to reach the final value of 29° , thus completing the sanity check.

3.3 Level 2 Data

This section describes the Level 2 data processing, which involves creating images from the Level 1c data. The Level 2 data products include images and the associated metadata needed to generate and interpret the images. See Section 2.2.5 for a list of items in the Level 2 data products.

3.3.1 Generating the RA and Dec Bins

The first step in generating images is to create the RA and Dec bins. Since LEXI’s field of view is circular of 9.1° , and we chose an RA and Dec resolution of 0.1° , we need to have 91 bins in both RA and Dec. The center of the field of view is computed based on the 5-minute averaged RA and Dec angles from the look direction data. This value is then used to create the RA and Dec bins of 4.55° on either side of the center. This process generates the `ra_bin` and `dec_bin` arrays that are used to create the images. For ease of generation of images, we also create a meshgrid of the RA and Dec bins called `ra_bin_map` and `dec_bin_map` for each axis.

3.3.2 Generating the Exposure Map

The next step is to create the exposure map. In the celestial coordinate, the detector moves either because of the gimbal motion or the movement of the moon itself. In order to accurately assess the amount of time each ra-dec bin was observed, we need to create an exposure map that accounts for these motions. This is done by computing the time spent in each ra-dec bin over the course of the observation (during the 5-minute integration window) using the look direction data. The exposure map is then saved as a 2D array called `exposure_map`. Figure 8 shows a sample exposure map generated from the look direction data. The black dot in the center of the map indicates the center of the field of view located at (RA, Dec) = (15.50, 14.12)

degrees. Most of the pixels in the exposure map have a value of 300 seconds, which is the total integration time. The pixels with lower values indicate the areas that were not observed for the full duration of the observation due to the gimbal/lunar motion.

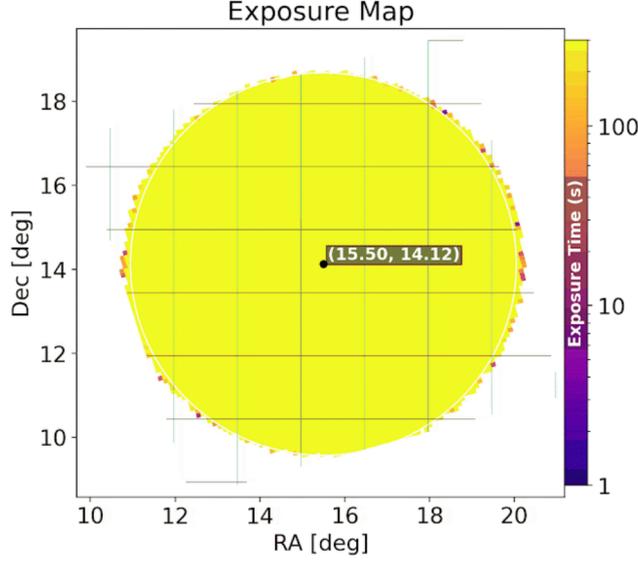


Figure 8: Sample exposure map generated from the look direction data.

3.3.3 Generating the Flat Field Map

The next step is to create the flat field map. The flat field map is used to correct for the non-uniform response of the detector. We rely on the data collected during the ground testing of LEXI MCP. This data was collected by recording the total photons detected by the MCP over a period of 7 days under no external illumination. The data was then binned into a 2D histogram of 91x91 bins, which corresponds to the RA and Dec bins. This histogram was then normalized using the mode of the histogram to create the flat field map. Figure 9 shows a sample flat field map generated from the ground testing data. The flat field map shows the non-uniform response of the detector, with the top left edge showing a slightly higher response compared to the rest of the detector. The flat field map is then saved as a 2D array called `flat_field_map`. A separate flat field map is generated for each integration window to account for any spatial variation in the detector response.

3.3.4 Generating the Background Maps

The LEXI images are affected by two types of background: galactic background and the dark background. The dark background is the background generated by the detector and the surrounding elements under no illumination. This background was measured during the ground testing of LEXI MCP. The process of generating the dark background map is similar to the process of generating the flat field map. The dark background map is then saved as a 2D array called `dark_background_map`. The galactic background is the background generated by the diffuse emission from the galaxy. This background is measured by using the ROSAT all-sky survey data (?). For a given look direction, the galactic background is extracted from the ROSAT data by averaging the counts in the corresponding RA and Dec bins. This is then scaled to the LEXI energy range using a conversion factor derived from the ROSAT data. This data is then binned into a 2D histogram of 91x91 bins, which corresponds to the RA and Dec bins. This histogram is then saved as a 2D array called `galactic_background_map`. A separate galactic background map is generated for each integration window to account for the

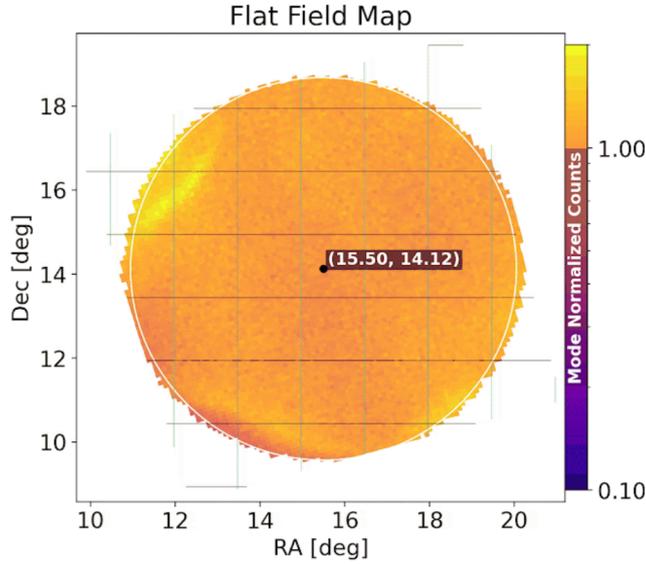


Figure 9: Sample flat field map generated from the ground testing data.

variation in the galactic background at different locations in the sky. This data is saved as `galactic_background_map`.

Total background map is the sum of the dark background map and the galactic background map. This total background map is then saved as a 2D array called `total_background_map`. The units of the background map are in counts per pixel. Figure 10 shows a sample background map. The background map shows the combined background emission from the galaxy and the detector.

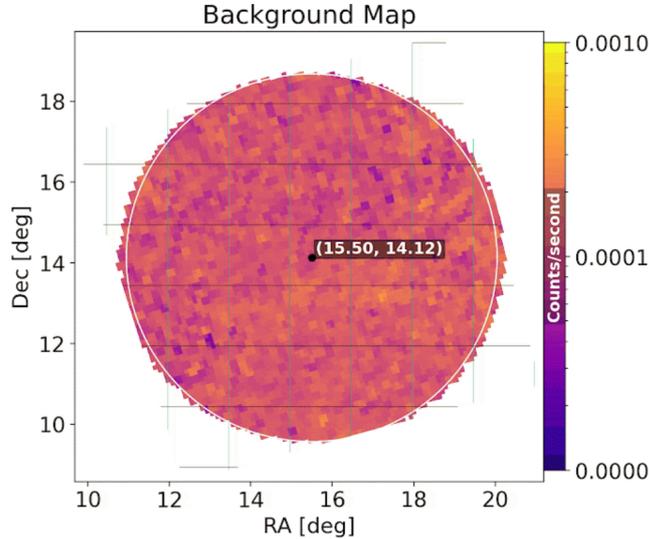


Figure 10: Sample background map generated from the ground testing data.

3.3.5 Generating the LEXI Histograms

The next step is to create the LEXI histograms. The LEXI histograms are created by binning the photon events from the Level 1c data into the RA and Dec bins created in Section 3.3.1. The photon events are first filtered to only include events that fall within the field of view of LEXI. This is done by computing the angular distance between the photon event and the center of the field of view using the look direction data. If the angular distance is less than or equal to 4.55° , then the event is included in the histogram. The filtered photon events are then

binned into a 2D histogram of 91x91 bins, which corresponds to the RA and Dec bins. This is the raw histogram of the LEXI data before any corrections are applied. The raw histogram is then corrected for exposure map to account for the varying exposure time across the field of view. This is done by dividing the raw histogram by the exposure map created in Section 3.3.2. The resultant histogram is then saved as a 2D array called `lexi_hist` and has the units of counts per pixel per second. The raw histogram is then corrected for the background (both dark and galactic) to account for the background emission. This is done by subtracting the total background map created in Section 3.3.4 from the exposure corrected histogram. The resultant histogram is then saved as a 2D array called `lexi_histogram_background_corrected`. The final step is to apply the flat field correction to account for the non-uniform response of the detector. This is done by dividing the background corrected histogram by the mode normalized flat field map created in Section 3.3.3. The resultant histogram is the final LEXI histogram that is corrected for exposure, background, and flat field. This histogram is then saved as a 2D array called `lexi_histogram_background_flatfield_corrected`. The units of the final histogram are in counts per pixel per second. Figure 11 shows the three stages of the LEXI histogram: (from left to right) raw, background corrected, and flat field corrected.

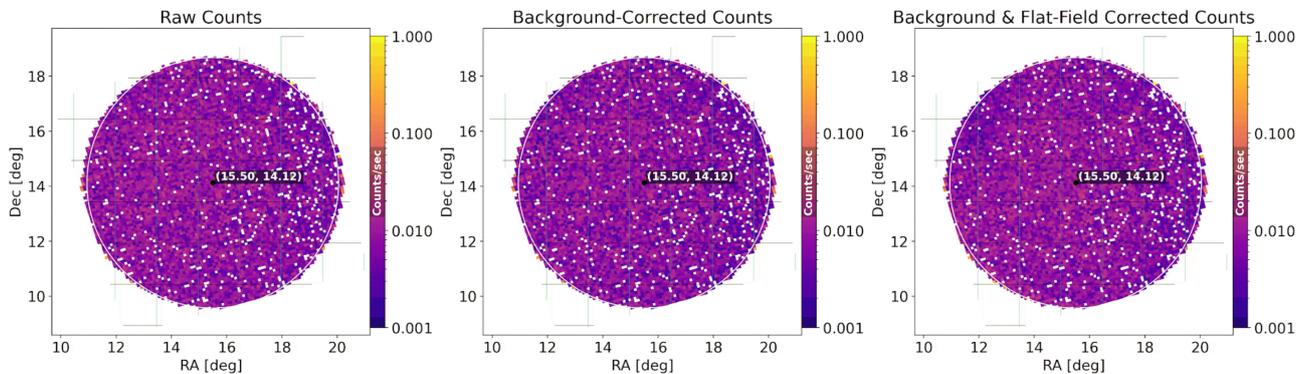


Figure 11: Sample LEXI histogram generated from the Level 1c data.

4 Lexi data storage and archiving

4.1 Data Storage and Archiving

The raw and calibrated data will be archived in the Coordinated Data Analysis Web (CDAWeb). Initial coordination has been made with the SPDF CDAWeb archive. These are publicly accessible archives. Analysis software is publicly available through GitHub ([LEXI data analysis tools](#))¹.

A backup copy of all data and analysis tools are being stored at BU in non-volatile digital storage facilities at the following location: `spt1-data.bu.edu` which is being hosted using an FTP server and can be accessed anonymously.

4.2 Availability and Timing

All data will be made publicly available within 6 months of the time when data is transferred to the [LEXI](#) team by the spacecraft.

4.3 Software Analysis Tools

Analysis tools will be developed and made public to the community. Python tools will inject the Level 1 and 2 data to allow users to specify their own time integration periods, pixel shape and size, and background subtraction. The tools will be based on the existing Python libraries. The tool will have the capability to convert the CDF/CSV file to png file. Software tools will be made available with the release of science data products.

The library will be open to community contribution through GitHub pull requests. The [LEXI](#) team software administrator will maintain oversight and evaluate proposed modifications to implementation to the final tools.

4.4 Acceptance Plan

The software and pipeline has been tested using known inputs. Simulated X-ray images produced through MHD numerical modeling will be fed into the pipeline for cleaning and processing. The final data products will be compared with the known inputs for verification.

¹https://github.com/Lexi-BU/lexi_data_analysis

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