# LETS PDS User's Guide

# 1 Overview

## 1.1 Purpose and Scope of Document

This User's Guide describes the data products in the Linear Energy Transfer Spectrometer (LETS) instrument data archive associated with NASA Commercial Lunar Payload Services Task Order 2AB (CLPS TO-2AB), also known as Peregrine Mission 1. The data products are described in sufficient detail to enable a user to read and understand the data. This document also briefly describes the Planetary Data System (PDS) archive bundle, the structure in which the data products, documentation, and supporting material are stored. This User's Guide is intended for the scientists who will analyze the data, including those associated with the project and those in the general planetary science community.

## 1.2 Applicable Documents

These publications or websites describe the Planetary Data System Standards used to produce the LETS archive. These documents are archived in the PDS system and are not found specifically in the LETS archive. These documents are revised approximately every six months with each new release of the PDS Information Model. Current and previous versions may be found at the links below.

1. Planetary Data System Standards Reference, https://pds.nasa.gov/datastandards/documents/sr/v1/StdRef_1.21.0.pdf
2. PDS4 Data Dictionary, https://pds.nasa.gov/datastandards/dictionaries/index-1.21.0.0.shtml
3. Planetary Data System (PDS) PDS4 Information Model Specification, https://pds.nasa.gov/datastandards/documents/im/v1/index_1L00.html
4. Data Providers' Handbook: Archiving Guide to the PDS4 Data Standards, https://pds.nasa.gov/datastandards/documents/dph/v1/PDS4_DataProvidersHandbook_1.21.0.pdf

While a publication specific to the LETS instrument does not exist as of this document's publication, the following references describe, in detail, the technology that the LETS instrument is built upon, the Timepix radiation detection system, and applications of the Timepix to radiation detection for human spaceflight operations.


5. M. Kroupa *et al., "*A semiconductor radiation imaging pixel detector for space radiation dosimetry,*" Life Sciences in Space Research,* vol. 6, pp. 69–78, Jul. 2015. doi:10.1016/j.lssr.2015.06.006.

6. N. Stoffle *et al.*, "Timepix-based radiation environment monitor measurements aboard the International Space Station," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 782, pp. 143–148, May 2015. doi:10.1016/j.nima.2015.02.016.

7. L. S. Pinsky and S. Pospisil, "Timepix-based detectors in mixed-field charged-particle radiation dosimetry applications,*" Radiation Measurements*, vol. 138, p. 106229, Nov. 2020. doi:10.1016/j.radmeas.2019.106229.

8. S. P. George *et al.*, "Very high energy calibration of silicon Timepix detectors," *Journal of Instrumentation*, vol. 13, no. 11, Nov. 2018. doi:10.1088/1748-0221/13/11/p11014.

9. D. Parcerisas et al., “ADMIRA Project: Teaching Particle Physics at high school with Timepix detectors,” *Physics Education*, vol. 57, no. 2, p. 025018, Jan. 2022. doi:10.1088/1361-6552/ac4143.
10. N. N. Stoffle et al., “HERA: A Timepix-based radiation detection system for exploration-class space missions,” *Life Sciences in Space Research*, vol. 39, pp. 59–66, Nov. 2023. doi:10.1016/j.lssr.2023.03.004.
11. X. Llopart, R. Ballabriga, M. Campbell, L. Tlustos, W. Wong, “Timepix, a 65k programmable pixel readout chip for arrival time, energy and/or photon counting measurements”, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 581, no. 1-2, 2007, pp. 485-494, ISSN 0168-9002, doi:10.1016/j.nima.2007.08.079.

# 2 Instrument Overview

## 2.1 What is LETS?

The LETS is a radiation detector designed to study the radiation environment in cislunar space and on the lunar surface. The objective of the LETS instrument is to measure the rate of incident radiation, both from galactic cosmic rays, and from any solar particle events, to characterize the radiation health hazards posed to astronauts in transit to—and on—the lunar surface. LETS is mounted on the top deck of the Peregrine Lunar Lander, above one of its landing legs, and faces the lunar sky in a nominal landing configuration. Figure 1 shows a schematic of LETS.

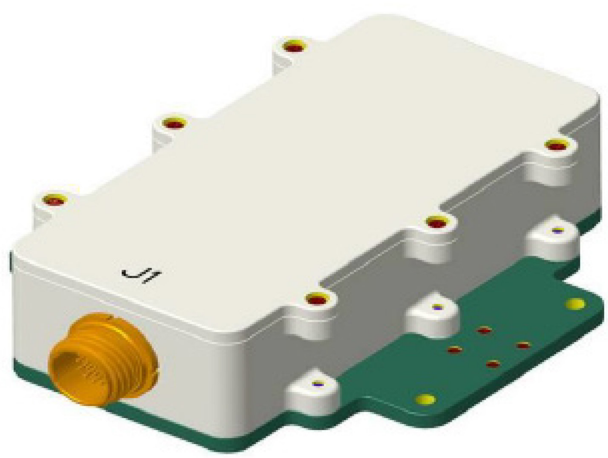


**Figure 1. Linear Energy Transfer Spectrometer (LETS) Model**

LETS uses a solid-state silicon Timepix sensor to detect incident radiation. The Timepix is a pixelated semiconductor sensor connected to a signal processing Application Specific Integrated Circuit. The Timepix chip is 1.4-by-1.4 cm with an array of 256-by-256 silicon pixels covering a total area of 2 $cm^2$. Each pixel is 55-by-55 μm and 500 μm thick. The Timepix can process a wide range of incident particle types and energies, ranging from 5 keV photons to 2 GeV heavy ions. The Timepix sensor is connected to an electronics processing chain on the LETS board that consists of a preamplifier, discriminator, and counter. A timer is used to measure the time each individual pixel sensor is over its threshold detection value, and this value is proportional to the energy deposited in each respective pixel. LETS is also equipped with heaters, a heater control board, a 28 V DC-to-DC converter, and an electromagnetic interference filter. See references [5,6,7,8,9,10,11] for a full description of the technology underpinning the LETS instrument (including the Timepix detector).

## 2.2 How LETS Operates

As stated previously, the LETS instrument relies on a Timepix detector for radiation detection. The radiation environment is surveyed via a silicon semiconductor sensor volume attached to the top surface of a Timepix detector as shown in Figure 2. Each pixel of the Timepix is bump-bonded to the sensor volume, and a reverse-bias voltage is applied to deplete the sensor volume of free charge carriers. When charged particles traverse the sensor volume, electron-hole pairs are generated via ionization. The subsequent redistribution of electrons and holes leads to signal acquisition in nearby Timepix pixels. The signal acquisition time profile in each pixel is used to determine particulate energy deposition via the time-over-threshold method. Let the signal profile for pixel $i$ be denoted $V_i(t)$. For some predefined threshold $V_0$, the duration $\Delta t_{TOT} = t_{TOT,1} - t_{TOT,0}$ over which the signal is greater than the threshold, $V_i\left(t \in [t_{TOT,0}, t_{TOT,1})\right) > V_0$, is used to determine the energy deposited in pixel $i$, $\mathcal{E}_i$, via a proportionality argument. The collection of pixel-by-pixel energy deposition data is compiled into Timepix *frames*, like the example shown in Figure 3. These frames are essentially snapshots of the incident radiation environment over some measurement period $\Delta t_{acq}$. Timepix frames display energy deposition on a pixel-by-pixel basis and clearly display particle tracks or "clusters" as charged particles traverse the sensor volume. The acquisition period for a single frame, or "shutter time", is adjusted dynamically by the Timepix to reduce particle track overlap and maximize data collection. The number of frames collected during a measurement period depends on the shutter time, which depends on the intensity of the local radiation environment. The energy deposition and position information encapsulated by each frame can be used to compute absorbed dose in silicon, linear energy transfer (LET), incident particle directionality, and estimates of particle identification and energy [5].

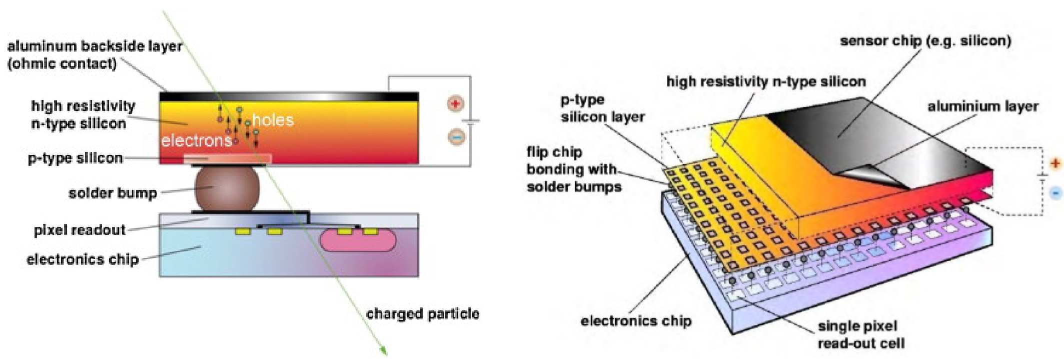


Figure 2: Timepix assembly schematic (single pixel and full view). [5]

When powered on, LETS is nominally configured to collect data at either a 1-minute or 1-hour cadence. During each measurement period, frames are collected and processed, with the data analysis products binned for delivery in their respective telemetry packets. For each frame, a cluster identification algorithm is applied to isolate individual ion tracks under the assumption that the acquisition time adjustment is maintaining sufficient track separation. Analysis of each cluster provides per-track (i.e. per-ion) dose and linear energy transfer information which is then included in the aggregated science telemetry message. At the end of each measurement period, LETS transmits two telemetry messages to ground, one science message and one engineering message. The engineering message contains information primarily related to instrument health and operation while the science message contains all science observations (particle counts, absorbed doses, absorbed dose rates, LET bin counts, and detector livetime) over the measurement period $\Delta t_{acq}$. Because LETS is equipped with an efficient onboard processing unit, partially processed data can be included in telemetry and data rates are relatively low.

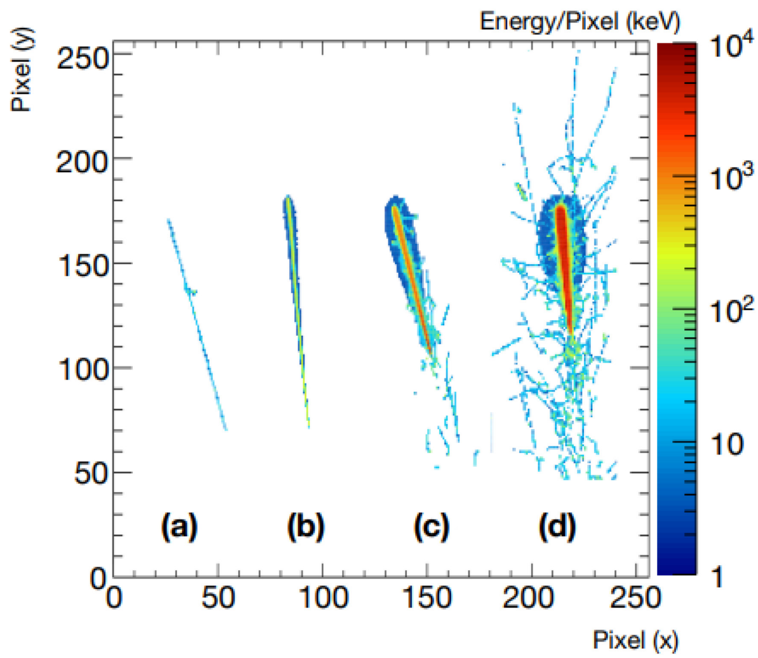


Figure 3: Example of Timepix frame data. Tracks show an increase in LET from (a) to (d). [6]

# 3 Archive Organization

This section describes the organization of the LETS archive according to the PDS4 Information Model.

## 3.1 The LETS Bundle

The highest level of organization for a PDS archive is the bundle. A bundle is a set of one or more related collections which may be of different types. A collection is a set of one or more related basic products which are typically all of the same type. Bundles and collections are logical structures, not necessarily tied to any physical directory structure or organization. The complete LETS archive is organized into one bundle. The bundle's PDS Logical Identifier (LID) is "urn:nasa:pds:clps_to_2ab_lets".

## 3.2 LETS Collections

The LETS bundle includes the collections of data products, documents, and other products shown in Table 1.

**Table 1. Collections in the LETS Bundle**

| Collection Logical Identifier | Collection Type | Contents | File |
|---|---|---|---|
| clps_to_2ab_lets:data_raw | Data | Livetime<br>Integration time<br>Maximum sensor gap<br>$p$ counts per energy bin<br>$\alpha$ counts per energy bin<br>C/N/O counts per energy bin<br>$\gamma$ counts per energy bin<br>$e^-$ counts<br>Heavy ion counts<br>Nuclear interaction counts<br>Unknown incident particle counts | timing.csv<br>timing.csv<br>timing.csv<br>proton_counts.csv<br>alpha_counts.csv<br>cno_counts.csv<br>gamma_counts.csv<br>electron_counts.csv<br>heavy_counts.csv<br>nuclear_counts.csv<br>unknown_counts.csv |

| | | | |
|---|---|---|---|
| | | Particle counts per LET bin | let.csv |
| clps_to_2ab_lets:data_derived | Data | Absorbed dose rate<br>Absorbed dose rate error<br>Cumulative absorbed dose<br>Cumulative absorbed dose rate error<br>Angle-restricted absorbed dose rate<br>Angle-restricted absorbed dose rate error<br>Angle-restricted cumulative absorbed dose<br>Angle-restricted cumulative absorbed dose error<br>LET flux distribution<br>LET flux distribution error | dose.csv<br>dose.csv<br>dose.csv<br>dose.csv<br>dose.csv<br>dose.csv<br>dose.csv<br>dose.csv<br>let_flux.csv<br>let_flux.csv |
| clps_to_2ab_lets:document | Document | User’s Guide | users_guide.docx |
| clps_to_2ab_lets:data_supplemental | Data | List of LETS commands performed<br>Deep-Space Network contacts<br>Operational vehicle-supplied current and instrument status data | lets_commands.csv<br>network_contact_periods.csv<br>operations.csv |

## 3.3 LETS Data Organization

The LETS PDS bundle is organized into four collections, and these collections manifest as subdirectories of the clps_to_2ab_lets bundle. These collections are data_raw, data_derived, data_supplemental, and document. The data_raw collection consists of raw data. The data_derived collection consists of data derived from a combination of one or more raw or calibrated data products[1]. The terms “raw” and “derived” are defined in Table 3. The data_supplemental collection consists of data that relate to the operational timeline of the instrument, such as commanding sessions, instrument uptime, and communication contact periods. The document collection consists of documentation, including this User’s Guide. See Appendix 6.2 for a diagram of the full directory structure of the bundle.

## 3.4 LETS Product Identification and Naming

A LETS product consists of one digital object (such as a series of numerical data) in one file, accompanied by a PDS label file. The PDS label provides identification and other metadata for the data file. In addition to data products, the archive includes document products, which also have PDS labels. Finally, the collections and the bundle are considered products in PDS, and therefore have their own labels as well. LETS data products have self-explanatory names and are all in comma-separated-value (CSV) format. LETS data product labels are identically named with an *.xml extension replacing a *.csv extension.

# 4 Data Products

LETS data products in this bundle consist of raw and derived products. Table 2 shows a summary of the data product types. Table 3 defines the standard PDS processing levels.

[1] The LETS data archive does not include any calibrated data products because the LETS on-board processing unit handles the calibration and conversion of raw data (counts) to physically meaningful quantities (dose, LET) internally. Intermediate values are discarded for memory and telemetry reasons.

**Table 2. Peregrine Mission 1 (TO2AB) LETS Product Types (bundle = urn:nasa:pds:clps_to_2ab_lets)**

| Product Name | PDS Processing Level | PDS4 Collection | Product Description |
|---|---|---|---|
| alpha_counts | Raw | data_raw | Alpha particle counts binned by energy as a function of time. |
| cno_counts | Raw | data_raw | Carbon, nitrogen, and oxygen ion counts binned by energy as a function of time. |
| electron_counts | Raw | data_raw | Electron counts as a function of time. |
| engineering | Raw | data_raw | Component voltages, currents, and temperatures as a function of time. |
| gamma_counts | Raw | data_raw | Gamma counts binned by energy as a function of time. |
| heavy_counts | Raw | data_raw | Heavy ion counts as a function of time. |
| let | Raw | data_raw | LET bin counts as a function of time. |
| nuclear_counts | Raw | data_raw | Nuclear interaction counts as a function of time. |
| proton_counts | Raw | data_raw | Proton counts binned by energy as a function of time. |
| timing | Raw | data_raw | Timing statistics. |
| unknown_counts | Raw | data_raw | Energy deposition by unknown incident particle types as a function of time. |
| dose | Derived | data_derived | Absorbed dose rates and cumulative absorbed doses as a function of time. |
| let_flux | Derived | data_derived | LET flux spectrum binned in LET as a function of time. |
| users_guide | N/A | document | LETS PDS User's Guide. |
| lets_commands | Raw | data_supplemental | Ordered list of LETS commands performed. |
| network_contact_periods | Raw | data_supplemental | Ordered list of Deep-Space Network contact periods. |
| ontime | Raw | data_supplemental | Time-series of vehicle-supplied current to LETS heater and LETS instrument; includes field-effect transistor on/off times. |

**Table 3. PDS Data Processing Level Definitions**

| PDS4 processing level | PDS4 processing level description |
|---|---|
| **Raw** | Original archive format. Often called EDRs (Experimental Data Records) data from an experiment. If compression, reformatting, packetization, or other translation has been applied to facilitate data transmission or storage, those processes are reversed so that the archived data are in a PDS approved format). |
| **Partially Processed** | Data that have been processed beyond the raw stage but which have not yet reached calibrated status. These and more |

| | |
|---|---|
| | highly processed products are often called RDRs (Reduced Data Records). |
| **Calibrated** | Data converted to physical units, which makes values independent of the experiment. |
| **Derived** | Results that have been distilled from one or more calibrated data products (for example, maps, gravity or magnetic fields, or ring particle size distributions). Supplementary data, such as calibration tables or tables of viewing geometry, used to interpret observational data should also be classified as 'derived' data if not easily matched to one of the other three categories. |

## 4.1 Raw Data Products

All types of files that contain raw data are systematically listed and described below by filename.

[particle type]_counts:

This data product contains the number of energetic particles detected by the LETS instrument over each measurement period, binned by kinetic energy. LETS identifies particle types by analyzing properties of the particle track signatures collected by the Timepix chip. Let $C_{ji}(t)$ denote the number of $j$-type particle counts as a function of time $t$ in kinetic energy bin $i$. Since the number of energy bins is different for different incident particle types, assume there are $N$ energy bins for $j$-type particles. The energy bin edges (in MeV) are denoted by $E_0$, $E_1$, …, $E_N$. The $j$-type particle tally in energy bin $i$ is incremented by one if the energy $E$ of the incident $j$-type particle is between the low and high energy bin edges associated with bin $i$, i.e., $E_i < E \leq E_{i+1}$. This data product is organized in ASCII CSV format and contains four fields: Timestamp, Low Energy, High Energy, and Particle Counts. An example of the data structure is shown in

Table 4. Note that the timestamp remains constant until all energy bins for a single timestamp are displayed, and then the timestamp is incremented.

Table 5 denotes all particle types $j$ alongside their associated energy bin edges.

**Table 4. Format of [particle_type]_counts.csv Data Products**

| Timestamp | Low Energy | High Energy | Particle Counts |
|---|---|---|---|
| $t_0$ | $E_0$ | $E_1$ | $C_{j0}(t_0)$ |
| $t_0$ | $E_1$ | $E_2$ | $C_{j1}(t_0)$ |
| ⋮ | ⋮ | ⋮ | ⋮ |
| $t_0$ | $E_{N-1}$ | $E_N$ | $C_{jN-1}(t_0)$ |
| $t_1$ | $E_0$ | $E_1$ | $C_{j0}(t_1)$ |
| ⋮ | ⋮ | ⋮ | ⋮ |
| $t_k$ | $E_{N-1}$ | $E_N$ | $C_{jN-1}(t_k)$ |

**Table 5. Summary of [particle_type]_counts Data Products and Energy Bin Edges**

| Data Product | Particle Type(s) | Energy Bin Edges [MeV] | Symbol |
|---|---|---|---|
| alpha_counts | alpha particle | 0, 20, 40, 60, 80, 100, ∞ | $j = \alpha$ |

| | | | |
|---|---|---|---|
| cno_counts | carbon, nitrogen, and oxygen ions | 0, 100, 117, 138, 161, 189, 221, 260, 305, 358, 419, 492, 577, 676, 793, 930, 1091, 1279, 1500, ∞ | $j = C/N/O$ |
| electron_counts | electrons | 0, ∞ | $j = e^-$ |
| gamma_counts | photons | 0.005, 0.008, 0.01, 0.012, 0.015, 0.018, 0.02, 0.022, 0.024, 0.026, 0.028, 0.030, 0.035, ∞ | $j = \gamma$ |
| heavy_counts | heavy ions (excluding CNO, $\alpha$, $p$) | 0, ∞ | $j = H$ |
| nuclear_counts | nuclear interactions | 0, ∞ | $j = n$ |
| proton_counts | protons | 5, 8.9, 16.2, 20.0, 30.0, 47.0, 52.0, 78.0, 85.0, 116.0, 123.0, 161.0, 195.0, 243.0, 274.0, 339.0, 385.0, 427.0, 602.0, 701.0, 1000.0, ∞ | $j = p$ |
| unknown_counts | energy depositions from unknown source | 0, ∞ | $j = u$ |

engineering

This data product documents voltage, current, and temperature data pertaining to several LETS hardware components for each measurement period. This data product is organized in ASCII CSV format and contains 31 fields: Timestamp, Voltage;1.2 volt bus, Voltage;1.8 volt bus, Voltage;2.2 volt bus, Voltage;3.3 volt bus, Voltage;5.0 volt bus, Voltage;12 volt bus, HSU1 Voltage;12 volt bus, HSU2 Voltage;12 volt bus, HSU3 Voltage;12 volt bus, Voltage;Timepix DAC, Voltage;HV DAC, Voltage;Test Pulse, Voltage: HV Measured, Current;1.2 volt bus, Current;1.8 volt bus, Current;2.2 volt bus, Current;3.3 volt bus, Current;5.0 volt bus, Current;12 volt bus, HSU1 Current;12 volt bus, HSU2 Current;12 volt bus, HSU3 Current;12 volt bus, Temperature;HPU Timepix Carrier Board, Temperature;HPU Processing Board, Temperature;HPU Chassis, Temperature;HPU Chassis Reference, Temperature;Chassis, Temperature;Chassis Reference, Temperature;Timepix Carrier, and Temperature;HSU Board. All voltages are in mV, all currents are in mA, and all temperatures are in daK (dekakelvin). This data is primarily useful for troubleshooting potential anomalies in the resulting data set and not any explicit scientific purpose.

let

This data product contains the linear energy transfer (LET) bin counts per measurement period, binned by incident particle LET. LETS measures the *unrestricted* LET, or the total energy lost by a charged particle due to electronic collisions in a material (in LETS's case, silicon) per unit path length. This data product is organized in ASCII CSV format and contains four fields: Timestamp, Low LET, High LET, and LET Bin Counts. Let $N_n(t)$ represent the number of instances during a measurement period $t$ in which LET $L$ in the range $L_n < L \leq L_{n+1}$ was observed by LETS due to an incident particle slowing down (depositing energy over some distance) in the Timepix chip. Here, $L_n$ represents the lower edge of the $n$th LET bin in keV μm$^{-1}$. There are 147 LET bin edges (keV μm$^{-1}$). 145 LET bin edges are generated via the formula

$$L_n = 10^{x_n} \text{ \{keV μm}^{-1}\},$$

where $x_n$ are 145 linearly spaced values between -1 and 3 (excluding 3) to produce LET bin edges between 0.1 keV μm$^{-1}$ and 1000 keV μm$^{-1}$ (excluding 1000 keV μm$^{-1}$). The final two LET bin edges are 0 (for underflow) and ∞ (for overflow). Table 6 shows the format of the LET data product. Note that the timestamp remains constant until all LET bins for a single timestamp are displayed, and then the timestamp is incremented.

**Table 6. Format of let.csv Data Product**

| Timestamp | Low LET | High LET | LET Bin Counts |
|---|---|---|---|
| $t_0$ | 0.0 | 0.1 | 3 |

| | | | |
|---|---|---|---|
| $t_0$ | 0.1 | 0.106512 | 5 |
| ⋮ | ⋮ | ⋮ | ⋮ |
| $t_0$ | 938.8641 | ∞ | 0 |
| $t_1$ | 0.0 | 0.1 | 2 |
| ⋮ | ⋮ | ⋮ | ⋮ |
| $t_k$ | 938.8641 | ∞ | 2 |

timing

This data product contains the timing statistics associated with each measurement period. This data product is organized in ASCII CSV format and contains four fields: Timestamp, Livetime, Integration Time, and Maximum Sensor Gap. The livetime is the duration (in milliseconds) that the detector was actively measuring the radiation environment during the latest measurement period. The integration time is the sum of all "shutter times", or durations over which frame data was being collected (in milliseconds), during the latest measurement period. The maximum sensor gap is the longest continuous duration (in seconds) during which the detector *was not* measuring the radiation environment. Table 7 shows the format of this data product.

**Table 7. Format of timing.csv Data Product**

| Timestamp | Livetime | Integration Time | Maximum Sensor Gap |
|---|---|---|---|
| $t_0$ | $\tau_0$ | $\Delta t_{int,0}$ | $\Delta t_{gap,0}$ |
| $t_1$ | $\tau_1$ | $\Delta t_{int,1}$ | $\Delta t_{gap,1}$ |
| ⋮ | ⋮ | ⋮ | ⋮ |
| $t_k$ | $\tau_k$ | $\Delta t_{int,k}$ | $\Delta t_{gap,k}$ |

lets_commands

This data product contains an ordered list of commands sent to the LETS instrument over the course of the mission. This data product is organized in ASCII CSV format and contains five fields: LETS Command Index, LETS Command, Start Timestamp, End Timestamp, and Status. The LETS command index is simply an index associated with each command sent to LETS during the course of the mission in chronological order starting from zero. The LETS command is the name of the command sent. The start timestamp is the timestamp (UTC) for when the command was sent and the end timestamp is the timestamp (UTC) for when the command's status was returned. Status is the command's status after returning, which takes on a value of "success", "failure", or "unknown". "Success" means that the command was sent, accepted by the instrument, and a message indicating that the command-induced process was completed is returned. "Failure" means that the command was sent and rejected by the instrument or the command-induced process was not completed. "Unknown" means that the command was sent but a status message was never returned. Table 8. Format of lets_commands.csv Data ProductTable 8 shows the format of this data product.

**Table 8. Format of lets_commands.csv Data Product**

| LETS Command Index | LETS Command | Start Timestamp | End Timestamp | Status |
|---|---|---|---|---|
| 0 | LETS-01_Activation | $t_{0,i}$ | $t_{0,f}$ | success |
| 1 | LETS-14_Functional_Test | $t_{1,i}$ | $t_{1,f}$ | success |
| ⋮ | ⋮ | ⋮ | ⋮ | ⋮ |
| 15 | LETS-16 | $t_{15,i}$ | $t_{15,f}$ | success |

network_contact_periods

This data product contains an ordered list of Deep-Space Network contact periods that were available over the course of Peregrine Mission 1. This data product is organized in ASCII CSV format and contains three fields: Contact Period Index, Start Timestamp, and End Timestamp. The contact period index is an index associated with each block of available time during which the Peregrine Lunar Lander was expected to be connected to the Deep-Space Network. The index values are in chronological order starting from one. The start timestamp and end timestamp indicate when the period begins and ends, respectively (in UTC). This product is useful for explaining gaps in collected time-series data. Table 9 shows the format of this data product.

**Table 9. Format of network_contact_periods.csv Data Product**

| Contact Period Index | Start Timestamp | End Timestamp |
|---|---|---|
| 1 | $t_{1,i}$ | $t_{1,f}$ |
| 2 | $t_{2,i}$ | $t_{2,f}$ |
| ⋮ | ⋮ | ⋮ |
| 22 | $t_{22,i}$ | $t_{22,f}$ |

ontime

This data product contains time-series data on when the LETS heaters and the LETS instrument itself were powered on or powered off. This data product is organized in ASCII CSV format and contains three fields: Timestamp, LETS Heater Enabled FET, and LETS Enabled FET. The LETS heater field-effect transistor (FET) and LETS FET fields each contain a time series of zeros and ones that indicate whether the heater/LETS instrument is turned on (1) or turned off (0) at any timestamp. Table 10 shows the format of this data product.

**Table 10. Format of ontime.csv Data Product**

| Timestamp | LETS Heater Enabled FET | LETS Enabled FET |
|---|---|---|
| $t_0$ | 1 | 0 |
| $t_1$ | 1 | 0 |
| ⋮ | ⋮ | ⋮ |
| $t_k$ | 1 | 1 |

## 4.2 Derived Data Products

dose

This data product contains absorbed dose (in silicon) data for each measurement period. This data product is organized in ASCII CSV format and contains nine fields: Timestamp, Absorbed Dose Rate, Cumulative Absorbed Dose, Angle-Restricted Absorbed Dose Rate, and Angle-Restricted Cumulative Absorbed Dose. The absorbed dose rate, $\dot{D}(t)$, is defined as the total amount of energy deposited $\mathcal{E}$ in the sensor volume per unit mass of the sensor volume $m$ per measurement duration $\Delta t_{acq}$, i.e.,

$$\dot{D}(t) = \frac{\mathcal{E}}{m\Delta t_{acq}}.$$

Note that $\mathcal{E}$ is the total energy deposited $\mathcal{E}_i$ over all pixels $i$ during measurement period $\Delta t_{acq}$,

$$\mathcal{E} = \sum_i \mathcal{E}_i.$$

The cumulative absorbed dose is simply the sum of all absorbed dose rates multiplied by their respective acquisition times from time $t_0$ to time $t$,

$$D(t) = \sum_k^{t_k=t} \dot{D}(t_k)\Delta t_{acq,k}.$$

The Timepix chip can estimate the incident angle of incoming energetic particles. Particles that deposit energy in the sensor volume with incident angles greater than 45° with respect to the normal vector of the detecting face of LETS also contribute to the “angle-restricted” dose and dose rate (a useful filtering tool for longer-track particle lengths). Beyond this difference, the angle-restricted varieties of absorbed dose are defined similarly to the unrestricted varieties. All doses are expressed in mGy and dose rates are expressed in mGy/min. Doses should be interpreted as dose *in water* at room temperature and standard pressure conditions.

**Table 11. Format of dose.csv Data Product**

| Timestamp | Absorbed Dose Rate | Cumulative Absorbed Dose | Angle-Restricted Absorbed Dose Rate | Angle-Restricted Cumulative Absorbed Dose |
|---|---|---|---|---|
| $t_0$ | $\dot{D}(t_0)$ | $D(t_0)$ | $\dot{D_{45}}(t_0)$ | $D_{45}(t_0)$ |
| $t_1$ | $\dot{D}(t_1)$ | $D(t_1)$ | $\dot{D_{45}}(t_1)$ | $D_{45}(t_1)$ |
| ⋮ | ⋮ | ⋮ | ⋮ | ⋮ |
| $t_k$ | $\dot{D}(t_k)$ | $D(t_k)$ | $\dot{D_{45}}(t_k)$ | $D_{45}(t_k)$ |

let_flux

The LET flux spectrum is computed via

$$\phi_n(t) = \frac{N_n(t)}{\Delta L_n \Delta A \Delta \Omega \tau},$$

where $N_n(t)$ is the LET bin count in LET bin $L_n < L \leq L_{n+1}$ at timestamp $t$, where $\Delta L_n$ is the associated LET bin width ($\Delta L_n = L_{n+1} - L_n$), $\Delta A \Delta \Omega$ = 13.34 cm$^2$ sr is the LETS geometry factor, and $\tau$ is the detector livetime during the measurement duration associated with timestamp $t$. The associated uncertainty is computed via

$$\sigma(\phi_n(t)) = \frac{\sqrt{N_n(t)}}{\Delta L_n \Delta A \Delta \Omega \tau}.$$

Table 12 shows the format of this data product.

**Table 12. Format of let_flux.csv Data Product**

| Timestamp | Low LET | High LET | LET Flux | LET Flux Error |
|---|---|---|---|---|
| $t_0$ | 0.0 | 0.1 | $\phi_0(t_0)$ | $\sigma(\phi_0(t_0))$ |
| $t_0$ | 0.1 | 0.106512 | $\phi_1(t_0)$ | $\sigma(\phi_1(t_0))$ |
| ⋮ | ⋮ | ⋮ | ⋮ | ⋮ |
| $t_0$ | 938.8641 | ∞ | $\phi_{145}(t_0)$ | $\sigma(\phi_{145}(t_0))$ |
| $t_1$ | 0.0 | 0.1 | $\phi_0(t_1)$ | $\sigma(\phi_1(t_0))$ |
| ⋮ | ⋮ | ⋮ | ⋮ | ⋮ |
| $t_k$ | 938.8641 | ∞ | $\phi_{145}(t_k)$ | $\sigma(\phi_{145}(t_k))$ |

# 5 Tools

All data products are organized in CSV format. Many programs are capable of reading from and displaying CSV data, including…

- Any scripting language with graphing capabilities (Python, MATLAB, C++, etc.)
- Root
- Excel

- PDS4Viewer (https://sbnwiki.astro.umd.edu/wiki/PDS4_Viewer)

# 6 Appendices

## 6.1 Acronyms

**Table 13. Acronyms**

| | |
|---|---|
| LETS | **L**inear **E**nergy **T**ransfer **S**pectrometer |
| PDS | **P**lanetary **D**ata **S**ystem |
| CLPS | **C**ommercial **L**unar **P**ayload **S**ervices |
| TO2-AB | **T**ask **O**rder **2** - **A**stro**b**otic |
| CSV | **C**omma-**S**eparated-**V**alue(s) |

## 6.2 Bundle Directory Structure

```
/---clps_to_2ab_lets
  |  bundle_clps_to_2ab_lets.xml
  |  readme.txt
  |
  +---data_derived
  |      collection_data_derived_inventory.csv
  |      collection_data_derived_inventory.xml
  |      dose.csv
  |      dose.xml
  |      let_flux.csv
  |      let_flux.xml
  |
  +---data_raw
  |      alpha_counts.csv
  |      alpha_counts.xml
  |      cno_counts.csv
  |      cno_counts.xml
  |      collection_data_raw_inventory.csv
  |      collection_data_raw_inventory.xml
  |      electron_counts.csv
  |      electron_counts.xml
  |      engineering.csv
  |      engineering.xml
  |      gamma_counts.csv
  |      gamma_counts.xml
  |      heavy_counts.csv
  |      heavy_counts.xml
  |      let.csv
  |      let.xml
  |      nuclear_counts.csv
  |      nuclear_counts.xml
  |      proton_counts.csv
  |      proton_counts.xml
  |      timing.csv
  |      timing.xml
  |      unknown_counts.csv
  |      unknown_counts.xml
  |
  +---data_supplemental
```

```
|       collection_data_supplemental_inventory.csv
|       collection_data_supplemental_inventory.xml
|       lets_commands.csv
|       lets_commands.xml
|       network_contact_periods.csv
|       network_contact_periods.xml
|       ontime.csv
|       ontime.xml
|
\---document
        collection_document_inventory.csv
        collection_document_inventory.xml
        users_guide.docx
        users_guide.xml
```