1 Overview

1.1 Purpose and Scope of Document

This User's Guide describes the data products in the Blue Ghost Mission 1 (BGM1) Lunar Magnetotelluric Sounder (LMS) archive in sufficient detail to enable a user to read and understand the data. It also 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 scientists who will analyze LMS data. This archive includes electric and magnetic field time-series data collected during BGM1.

1.2 Applicable Documents

These publications or websites describe the Planetary Data System Standards used to produce the LMS archive. These documents are archived in the PDS system and are not found specifically in the LMS archive. Current and previous versions may be found at the links below.

1. Planetary Data System Standards Reference, https://pds.nasa/gov/datastandards/documents/sr/current
2. PDS4 Data Dictionary, https://pds.nasa.gov/datastandards/documents/dd/current
3. Planetary Data System (PDS) PDS4 Information Model Specification, https://pds.nasa.gov/datastandards/documents/im/current
4. Data Providers' Handbook: Archiving Guide to the PDS4 Data Standards, https://pds.nasa.gov/datastandards/documents/dph/current

These papers describe in detail the LMS space-qualified prototype.

5. Grimm, et al. (2021) A Magnetotelluric instrument for probing the interiors of Europa and other worlds, *Advances in Space Research, 68*, 2022-2037. https://doi.org/10.1016/j.asr.2021.04.011

2 Instrument Overview

2.1 What is LMS?

The objective of the Lunar Magnetotelluric Sounder (LMS) is to determine the electrical conductivity of the interior at depths up to 1000 km to better constrain the Moon's internal temperature, composition, and evolution. Electrical conductivity is calculated from time-varying electric and magnetic fields measured at the lunar surface. The electrometer system (ELEC) uses four spring-launched Remote Electrodes (REs). The magnetometer system (MAG) uses a compact fluxgate sensor. All sensors are harnessed to a central Electronics Box (EBox) that includes five boards. See Grimm et al. (2021) for a relevant description.

2.2 How LMS Operates

LMS was designed to acquire MAG and ELEC science data semi-autonomously, generally on an alternating cadence of high (256 samples per second, or sps) and low (32 sps) rates. MAG science data (**Sci-Mag**) consist of three components of the magnetic field. ELEC science data comprise all six differential voltage measurements (**Sci-DiffE**) among the four REs for redundancy. The electric field in the direction between any two electrodes is the voltage difference divided by the distance between them. Reconstruction of orthogonal components of the electric field is described below. Single-ended electrode data (**Sci-SingE**) are used for assessing electrode data quality by their responses to a voltage bias sweep (**CAL-Bias**) conducted approximately every 12 hrs. During the bias sweep, ELEC data were not saved in science data, but in calibration data. However, during the bias sweep, MAG were acquired at the same data rate as immediately before the bias sweep was entered. Single-ended electrode data and instrument housekeeping (**HK-E** & **HK-Mag**) data were returned at 0.1 sps throughout all LMS operations. A separate Engineering mode was used to set some parameters such as acquisition cadence. However, other parameters such as bias updates could be implemented while in Science Mode.

LMS started with a commissioning phase (Table 1) and then transitioned into a science phase (Table 2) on 3/3/25 at 15:22 UTC. Table 1 shows the events of the commissioning phase, including launching of the remote electrodes, extension of the magnetometer mast, and the first bias sweep and bias voltage settings. ELEC and MAG data in the commissioning phase were all collected at 32 sps. Note that no MAG and ELEC data were collected in Engineering mode in the commissioning or science phase of LMS operations.

Table 1. Commissioning phase of data collection.

Time in UTC	UNIX Time	Event
3/2/2025 8:34	1740904440.00	BGM1 landed
3/3/2025 9:28	1740994100.00	LMS turned on in Engineering Mode
3/3/2025 9:29	1740994156.02	Mode changed to Science
3/3/2025 9:30	1740994220.98	Mode changed to Engineering
3/3/2025 9:54	1740995657.02	Mode changed to Science
3/3/2025 11:34	1741001677.70	RE1 Deployed and inflight for 4.63 sec.
3/3/2025 12:33	1741005236.64	RE2 Deployed and inflight for 5.06 sec.
3/3/2025 12:45	1741005915.36	RE3 Deployed and inflight for 5.69 sec.
3/3/2025 12:54	1741006469.55	RE4 Deployed and inflight for 5.44 sec.
3/3/2025 13:45	1741009527.02	Mast Deployed for 0.60 sec.
3/3/2025 13:50	1741009822.98	Mode changed to Engineering
3/3/2025 15:10	1741014657.02	Mode changed to Science
3/3/2025 15:10	1741014658.02	Sweep #1 Start
3/3/2025 15:18	1741015137.98	Sweep #1 End
3/3/2025 15:22	1741015339.98	Mode changed to Engineering
3/3/2025 15:25	1741015545.02	Mode changed to Science
3/3/2025 18:46	1741027606.00	Bias voltages changed
3/3/2025 18:49	1741027742.98	Mode changed to Engineering

3/3/2025 18:55	1741028139.02	Mode changed to Science (From Commissioning to Science Phase)

Table 2 shows the events of the science phase including when ELEC and MAG data were acquired at high rate (green), when bias voltages were changed (light orange), when bias sweeps occurred (yellow), and when anomalous events occurred (purple and grey). Low-rate MAG data alone were acquired during intervals not explicitly noted.

Table 2. Science phase of data collection.

Time in UTC	UNIX Time	Event
3/3/2025 18:55	**1741028139.02**	**Mode changed to Science (From Commissioning to Science Phase)**
3/3/2025 18:55	1741028140.00	HF Mode Start
3/3/2025 21:19	1741036780.00	HF Mode End
3/4/2025 3:55	1741060538.02	Sweep #2 Start
3/4/2025 4:03	1741061018.98	Sweep #2 End
3/4/2025 6:44	1741070656.00	Bias voltages changed
3/4/2025 6:55	1741071340.00	HF Mode Start
3/4/2025 9:19	1741079980.00	HF Mode End
3/4/2025 15:55	1741103738.02	Sweep #3 Start
3/4/2025 16:03	1741104218.98	Sweep #3 End
3/4/2025 19:14	1741115676.00	Bias voltages changed
3/4/2025 18:55	1741114540.00	HF Mode Start
3/4/2025 21:19	1741123146.00	HF Mode End
3/4/2025 21:19	1741123146.00	LMS turned off
3/5/2025 0:37	1741135074.02	Turned on into Science mode
3/5/2025 0:40	1741135207.00	HF Mode Start
3/5/2025 3:04	1741143847.00	HF Mode End
3/5/2025 9:40	1741167605.02	Sweep #4 Start
3/5/2025 9:48	1741168085.98	Sweep #4 End
3/5/2025 12:40	1741178407.00	HF Mode Start
3/5/2025 15:04	1741187048.00	HF Mode End
3/5/2025 21:40	1741210806.02	Sweep #5 Start
3/5/2025 21:48	1741211286.98	Sweep #5 End
3/6/2025 0:40	1741221608.00	HF Mode Start
3/6/2025 3:04	1741230248.00	HF Mode End
3/6/2025 5:35	1741239355.98	LMS turned off
3/6/2025 12:27	1741264033.02	Turned on into Science mode
3/6/2025 12:30	1741264239.00	HF Mode Start
3/6/2025 12:50	1741265431.00	HF Mode End
3/6/2025 12:50	1741265431.00	LMS turned off
3/7/2025 18:59	1741373944.02	Turned on into Science mode
3/7/2025 19:02	1741374149.00	HF Mode Start

3/7/2025 21:00	1741381213.00	HF Mode End
3/7/2025 21:00	1741381212.00	Engineering mode. Acquisition changed to continuous high-rate.
3/7/2025 21:02	1741381354.02	Mode changed into Science
3/7/2025 21:02	1741381355.00	HF Mode Start
3/7/2025 21:34	1741383255.00	HF Mode End
3/7/2025 21:34	1741383260.00	HF Mode Start
3/8/2025 2:02	1741399353.00	HF Mode End
3/8/2025 2:02	1741399353.00	Sweep #6 Start
3/8/2025 2:10	1741399835.00	Sweep #6 End
3/8/2025 2:10	1741399835.00	HF Mode Start
3/8/2025 14:02	1741442553.00	HF Mode End
3/8/2025 14:02	1741442553.00	Sweep #7 Start
3/8/2025 14:10	1741443035.00	Sweep #7 End
3/8/2025 14:10	1741443035.00	HF Mode Start
3/8/2025 14:37	1741444661.00	HF Mode End
3/8/2025 14:37	1741444661.00	Engineering mode. ELEC data acquisition changed to 5 mins before and after a bias sweep.
3/8/2025 14:44	1741445062.02	Mode changed into Science
3/8/2025 14:49	1741445362.02	Sweep #8 Start
3/8/2025 14:57	1741445841.98	Sweep #8 End
3/8/2025 15:02	1741446143.00	HF Mode Start
3/9/2025 2:44	1741488265.00	HF Mode End
3/9/2025 2:49	1741488564.02	Sweep #9 Start
3/9/2025 2:57	1741489043.98	Sweep #9 End
3/9/2025 3:02	1741489345.00	HF Mode Start
3/9/2025 14:44	1741531465.00	HF Mode End
3/9/2025 14:49	1741531764.02	Sweep #10 Start
3/9/2025 14:57	1741532243.98	Sweep #10 End
3/9/2025 15:02	1741532545.00	HF Mode Start
3/10/2025 2:44	1741574667.00	HF Mode End
3/10/2025 2:49	1741574965.02	Sweep #11 Start
3/10/2025 2:57	1741575445.98	Sweep #11 End
3/10/2025 3:02	1741575747.00	HF Mode Start
3/10/2025 14:44	1741617867.00	HF Mode End
3/10/2025 14:49	1741618165.02	Sweep #12 Start
3/10/2025 14:57	1741618645.98	Sweep #12 End
3/10/2025 15:02	1741618947.00	HF Mode Start
3/10/2025 15:14	1741619644.00	HF Mode End
3/10/2025 15:14	1741619645.00	LMS turned off
3/12/2025 7:56	1741766181.02	Turned on into Science mode
3/12/2025 8:01	1741766461.02	Sweep #13 Start

3/12/2025 8:09	1741766941.98	Sweep #13 End
3/12/2025 8:14	1741767243.00	HF Mode Start
3/12/2025 19:56	1741809363.00	HF Mode End
3/12/2025 20:01	1741809661.02	Sweep #14 Start
3/12/2025 20:09	1741810141.98	Sweep #14 End
3/12/2025 20:14	1741810443.00	HF Mode Start
3/12/2025 23:14	1741821261.00	Bias voltages changed
3/13/2025 7:56	1741852563.00	HF Mode End
3/13/2025 8:01	1741852871.02	Sweep #15 Start
3/13/2025 8:09	1741853350.98	Sweep #15 End
3/13/2025 8:14	1741853652.00	HF Mode Start
3/13/2025 19:56	1741895772.00	HF Mode End
3/13/2025 20:01	1741896070.02	Sweep #16 Start
3/13/2025 20:09	1741896550.98	Sweep #16 End
3/13/2025 20:14	1741896852.00	HF Mode Start
3/14/2025 5:00	1741928400.00	Eclipse began
3/14/2025 6:18	1741933080.00	Eclipse Totality began
3/14/2025 7:56	1741938972.00	HF Mode End
3/14/2025 8:01	1741939273.02	Sweep #17 Start
3/14/2025 8:09	1741939752.98	Sweep #17 End
3/14/2025 8:14	1741940054.00	HF Mode Start
3/14/2025 8:34	1741941240.00	Eclipse Totality ended
3/14/2025 10:00	1741946400.00	Eclipse ended
3/14/2025 18:31	1741977119.00	HF Mode End
3/14/2025 18:31	1741977119.00	Engineering mode. Resumed alternating low- and high-rate cadence.
3/14/2025 18:35	1741977322.00	Mode changed into Science
3/14/2025 18:35	1741977322.00	HF Mode Start
3/14/2025 20:59	1741985962.00	HF Mode End
3/15/2025 3:35	1742009721.02	Sweep #18 Start
3/15/2025 3:43	1742010200.98	Sweep #18 End
3/15/2025 6:35	1742020522.00	HF Mode Start
3/15/2025 8:59	1742029164.00	HF Mode End
3/15/2025 15:35	1742052923.02	Sweep #19 Start
3/15/2025 15:43	1742053402.98	Sweep #19 End
3/15/2025 18:35	1742063724.00	HF Mode Start
3/15/2025 20:59	1742072364.00	HF Mode End
3/16/2025 3:35	1742096124.02	Sweep #20 Start
3/16/2025 3:43	1742096594.02	Sweep #20 End
3/16/2025 6:35	1742106924.00	HF Mode Start
3/16/2025 8:59	1742115565.00	HF Mode End
3/16/2025 15:35	1742139325.02	Sweep #21 Start

3/16/2025 15:43	1742139795.00	Sweep #21 End
3/16/2025 18:28	1742149695.00	Bias voltages changed
3/16/2025 18:35	1742150125.00	HF Mode Starts
3/16/2025 18:53	1742151212.00	HF Mode Stops
3/16/2025 18:53	1742151211.00	Engineering mode. Acquisition changed to continuous high-rate & no more sweeps.
3/16/2025 18:55	1742151322.02	Mode changed into Science
3/16/2025 18:55	1742151323.00	HF Mode Start
3/16/2025 19:37	1742153876.83	Sun touches the limb
3/16/2025 20:44	1742157886.04	Sun disappears behind the limb
3/16/2025 20:52	1742158331.00	HF Mode End
3/16/2025 20:52	1742158332.00	LMS turned off

3 Archive Organization

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

3.1 The LMS 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 BGM1 archive is organized into one bundle. The bundle's PDS Logical Identifier (LID) is "urn:nasa:pds:clps_to_19d_lms".

3.2 LMS Collections

The LMS bundle includes the collections of data products, documents, and other products shown in Table 3.

Table 3. Collections in the LMS Bundle.

Collection Logical Identifier	Collection Type	Contents
urn:nasa:pds:clps_to_19d_lms:data_raw_diffe	Data	DiffE
urn:nasa:pds:clps_to_19d_lms:data_raw_mag	Data	Mag
urn:nasa:pds:clps_to_19d_lms:data_raw_singe	Data	SingE
urn:nasa:pds:clps_to_19d_lms:data_pproc_bias	Data	CAL-Bias
urn:nasa:pds:clps_to_19d_lms:data_pproc_hk	Data	HK-E HK-Mag
urn:nasa:pds:clps_to_19d_lms:data_pproc_diffe	Data	COM-DiffE SCI-DiffE
urn:nasa:pds:clps_to_19d_lms:data_pproc_mag	Data	COM-Mag SCI-Mag

urn:nasa:pds:clps_to_19d_lms:data_pproc_singe	Data	COM-SingE SCI-SingE
urn:nasa:pds: clps_to_19d_lms:data_cal_bias	Data	Cal-Bias
urn:nasa:pds: clps_to_19d_lms:data_cal_diffe	Data	SCI-DiffE
urn:nasa:pds: clps_to_19d_lms:data_cal_mag	Data	SCI-Mag
urn:nasa:pds:BGM1_LMS:document	Document	Documentation, including this User's Guide

3.3 LMS Data Organization

See Appendix 6.2 for a diagram of the full directory structure of the bundle.

3.4 LMS Product Identification and Naming

An LMS product consists of one digital object 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.

4 Data Products

BGM1 LMS data products in this bundle consist of raw, partially processed, and calibrated products. Table 4 shows a summary of the data product types. Table 5 defines the standard PDS processing levels.

Table 4. BGM1 LMS Product Types.

Product Name	PDS Processing Level	PDS4 collection, assuming prefix urn:nasa:pds:clps_to_19d_lms	Product Description	PDS4 Data Type
DiffE	Raw	data_raw_diffe	6 channels of differential ELEC data given in data number over all operations	csv
Mag	Raw	data_raw_mag	3-axis MAG values given in data number over all operations	csv
SingE	Raw	data_raw_singe	4 remote electrode single-ended values of ELEC data given in data number over all operations	csv
COM-DiffE	Partially processed	data_pproc_diffe	6 channels of differential ELEC data given in mV for commissioning phase	csv

Product Name	PDS Processing Level	PDS4 collection, assuming prefix urn:nasa:pds:clps_to_19d_lms	Product Description	PDS4 Data Type
COM-Mag	Partially processed	data_pproc_mag	3-axis MAG values given in nT in instrument coordinates for commissioning phase	csv
COM-SingE	Partially processed	data_pproc_singe	4 remote electrode single-ended values of ELEC data given in mV for commissioning phase	csv
CAL-Bias	Partially processed	data_pproc_bias	Provides 4 single-ended voltage measurements and the bias voltage for the entire bias sweep.	csv
HK-E	Partially processed	data_pproc_hk	Samples per second and bias sweep flag over all operations	csv
HK-Mag	Partially processed	data_pproc_hk	Temperatures on Mag board and Mag sensor over all operations	csv
SCI-DiffE	Partially processed	data_pproc_diffe	6 channels of differential ELEC data given in mV in instrument coordinates for science phase	csv
SCI-Mag	Partially processed	data_pproc_mag	3-axis MAG values given in nT in instrument coordinates for science phase	csv
SCI-SingE	Partially processed	data_pproc_singe	4 remote electrode single-ended values of ELEC data given in mV for science phase	csv
Cal-Bias	Calibrated	data_cal_bias	Provides an average and standard deviation of single-ended voltage for each RE as a function of the input bias voltage, and input current for the entire bias sweep.	csv
SCI-DiffE	Calibrated	data_cal_diffe	2 components of surface electric field in V/m in geographic coordinates for science phase	csv
SCI-Mag	Calibrated	data_cal_mag	3 components of magnetic field in nT in geographic coordinates for science phase	csv

Table 5. PDS Data Processing Level Definitions.

PDS4 processing level	PDS4 processing level description
Raw	Original 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 archive format. Often called EDRs (Experimental Data Records).
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

data_raw_diffe – contains 2,451 files in csv format, each containing 30 minutes or less of data. Each file has a naming prefix of DiffE_ following by the Unix Time in seconds followed by "_" and the fractional number of seconds and has a csv extension. Each file consists of 7 columns where the first column is Unix time in seconds, the second column is the voltage between Remote Electrode 1 (RE1) and RE2, the third column is the voltage between RE3 and RE4, the fourth column is the voltage between RE1 and RE3, the fifth column is the voltage between RE2 and RE3, the sixth column is the voltage between RE1 and RE4, and the seventh column is the voltage between RE2 and RE4. All voltages are given in data numbers (DN; 0-65,535).

data_raw_mag – contains 2,593 files in csv format, each containing 30 minutes or less of data. Each file has a naming prefix of Mag_ following by the Unix Time in seconds followed by "_" and the factional number of seconds and has a csv extension. Each file consists of 4 columns where the first column is Unix time in seconds, the second column is the magnetic field measurement made in the Mag-X direction, the third column is the magnetic field measurement made in the Mag-Y direction, the fourth column is the magnetic field measurement made in the Mag-Z direction, the fifth column is the sps, and the sixth column is the range. All magnetic field measurements are given in data numbers (DN).

data_raw_singe – contains single-ended voltages from the lander ground to each remote electrode It contains 2,593 files in csv format, each containing 30 minutes or less of data. Each file has a naming prefix of SingE_ following by the Unix Time in seconds

followed by "_" and the factional number of seconds and has a csv extension. Each file consists of 5 columns where the: first column is Unix time in seconds, second column is the voltage between Remote Electrode RE1 and the lander, third column is the voltage between RE2 and the lander, fourth column is the voltage between RE3 and the lander, fifth column is the voltage between RE4 and the lander. All voltages are given in data numbers (DN).

4.2 Partially Processed Data Products

data_pproc_diffe/COM – contains differential voltage measurements between 6 pairs of the 4 remote electrodes for the commissioning (COM) phase of LMS. Only one file is needed as it contains all the data from 3/3/25 in which the commissioning phase was executed. The dataset consists of 32 sps DiffE measurements in csv format. Header values are given as the first row in and display time and the number of millivolts between all the combinations of remote electrodes.

Equation 1 gives the translation from DN to voltage in the usual offset and scaling format. Table 6 gives these factors for each of the six differential channels.

$$V_j\,(\mathrm{mV}) = s_j\,(\mathrm{DN_j} - o_j) \qquad \text{(Eq. 1)}$$

Table 6. LMS ELEC Scale Factors and Offsets for differential voltage.

Channel	Electrode Pairs	Scale Factor s_j, mV / DN	Offset o_j, DN
0	1-2	0.193	32619.8
1	3-4	0.193	32854.3
2	1-3	0.523	32573.2
3	2-3	0.524	32619.0
4	1-4	0.132	32223.7
5	2-4	0.131	32395.4

Although this step produces calibrated mV, these data are only partially processed because they are not yet converted to electric field using the recovered electrode positions.

data_pproc_diffe/SCI – contains differential voltage measurements between 6 pairs of the 4 remote electrodes for the science (SCI) phase of LMS operations. Each calendar day has three csv files at 1, 32, and 256 sps. The naming conventions has the prefix of "lms_DiffE_", followed by the date "YYYYMMDD", and then with a suffix of indicating the sampling rate (1, 32, or 256 sps) "_sps".

Note that all data were collected at 256 sps and then downsampled to 32 or 1 sps using an 8^{th}-order Chebyshev Type I IIR filter. Header values are given as the first row in and display time and the number of millivolts between all the combinations of remote electrodes. Conversion from raw partially processed data follows the previous section.

data_pproc_mag/COM – contains three-axis magnetic field measurements for the commissioning (COM) phase of the BGM1. Only two datasets at 32 and 1 sps in csv format are archived as they contain all the data from 3/3/25 in which LMS commissioning was

started and completed. The dataset was acquired at 32 sps and were downsampled to 1 sps using 8th-order Chebyshev Type I IIR filters. Header values are given as the first row in and display time and units of nanoTeslas along each axis of the magnetometer.

Raw DN are converted to magnetic field using Equations 2 and 3 and Table 7. The MAG sensor model comprises offsets, scaling, and cross-talk (orthogonality) between each of the three components

$$\begin{bmatrix} B_1 \\ B_2 \\ B_3 \end{bmatrix} = \begin{bmatrix} 1 & a_{12} & a_{13} \\ a_{21} & 1 & a_{23} \\ a_{31} & a_{32} & 1 \end{bmatrix} \begin{bmatrix} s_1(c_1 - o_1) \\ s_2(c_2 - o_2) \\ s_3(c_3 - o_3) \end{bmatrix} \quad \text{(Eq. 2)}$$

where 1=x, 2=y, 3=z, in the sensor coordinate system. The measured offsets for LMS MAG are o_1 = –2731, o_2 = 5110, o_3 = 3954 DN. The scale factors s_1, s_2, s_3 depend on the gain range (Table 7).

Table 7. LMS MAG scale factors in two gain ranges that are automatically implemented depending on the measured field.

MAG Range	Physical Range (nT)	Nominal Scale Factor (nT/DN)	X Scale Factor measured s_1 (nT/DN)	Y Scale Factor measured s_2 (nT/DN)	Z Scale Factor measured s_3 (nT/DN)
1	±2048	0.0625	0.06192	0.06226	0.06074
0	±512	0.015625	0.015458	0.015530	0.015157

And the measured cross-talk matrix is

$$A = \begin{bmatrix} \mathbf{1} & \boldsymbol{a_{12}} & \boldsymbol{a_{13}} \\ \boldsymbol{a_{21}} & \mathbf{1} & \boldsymbol{a_{23}} \\ \boldsymbol{a_{31}} & \boldsymbol{a_{32}} & \mathbf{1} \end{bmatrix} = \begin{bmatrix} 0.999996 & 0.000108 & 0.002738 \\ 0.000108 & 0.999908 & 0.013546 \\ 0.002738 & 0.013546 & 0.999904 \end{bmatrix} \quad \text{(Eq. 3)}$$

Although this step produces calibrated nT, these data are only partially processed because they are still in instrument coordinates. Also note that the lunar static field at the landing site was small enough that MAG could operate at its highest sensitivity (Range 0) throughout LMS operations after sensor deployment. Prior to deployment, the significant lander magnetic field triggered operation at lower sensitivity, MAG range 1.

data_pproc_mag/SCI – contains three-axis magnetic field measurements for the science (SCI) phase of the BGM1. Each calendar day contains three files sampled at 256, 32, and 1 sps in csv format. The data were acquired at 256 or 32 sps and were downsampled using 8th-order Chebyshev Type I IIR filters. Header values are given as the first row in and display time and the number of nanoTeslas along each axis of the magnetometer. Equations 2 and 3 and Table 7 were again used to convert from DN to magnetic field.

data_pproc_singe/COM – contains single-ended voltage measurements of the 4 remote electrodes for the commission (COM) phase of the BGM1. Only one file is needed as it contains all the data from 3/3/25 in which the commissioning phase of LMS operations was started and completed. The dataset consists of 0.1 sps data in csv format. Header values are given as the first row in and display time and the number of millivolts of all the remote electrodes.

data_pproc_singe/SCI – contains single-ended voltage measurements of the 4 remote electrodes for the SCI phase of the BGM1. Only one dataset is needed as it contains all the data from SCI phase. The dataset consists of 0.1 sps data in csv format. Header values are given as the first row in and display time and the number of millivolts of all the remote electrodes.

Eq 4 and Table 8 to convert from DN to voltage:

$$V_i(mV) = s_i(DN_i - o) \quad \text{(Eq. 4)}$$

Table 8. LMS ELEC Scale Factors and Offsets for single-ended voltages

Remote Electrode	Scale Factor s_j, mV / DN	Offset o_j, DN
1	104.115	1037.11
2	103.700	1037.50
3	104.429	1042.40
4	104.747	1039.60

data_pproc_hk/HK-Mag – contains one dataset that lasts throughout LMS operations (both SCI and COM) with a sampling rate of 0.1 sps and is in csv format. The columns are labeled and represent time and MAG magnetometer sensor temperature and electronics board temperature. These data could be used to better calibrate the MAG for temperature. However, as *Grimm et al.* (2021) such temperature variations are small.

data_pproc_hk/HK-E – contains one dataset that lasts throughout LMS operations (both SCI and COM) with a sampling rate of 0.1 sps and is in csv format. The columns are labeled and represent time and the sampling mode of the ELEC system and a flag for the bias sweep (where 1 is when a bias sweep is occurring). This data could be used for situational awareness.

data_pproc_bias – contains 21 files for each bias sweep conducted over BM1. The naming convention has a prefix of "Bias_Sweep_" followed by the Unix time in seconds and decimal seconds after the underscore. The files then end with a suffix of "_Sweep_#", where # is the number of sweeps from 1 to 21. The data were sampled every 10 seconds, and the bias voltage was swept from ~35 V to -35 V, with each step lasting 30 seconds. **Table 9** gives the 15 precise voltage sweeps voltages over the bias sweep. Note, originally there were 16 steps in to bias sweep, but the last one was incorrectly programmed in and is excluded from all data.

Table 9. External bias voltage for each electrode.

Sweep Increment Relative Time (sec)	Applied Bias Voltage (V)			
	Re1	Re2	Re3	Re4
0-30	35.0266	34.8974	34.8535	34.8949
30-60	30.3429	30.241	30.1692	30.3164
60-90	25.6957	25.576	25.5814	25.6226
90-120	20.9754	20.9109	20.9019	20.9656

120-150	16.3282	16.2276	16.2407	16.2349
150-180	11.6627	11.5625	11.6162	11.6516
180-210	7.01557	6.9703	6.93671	6.99466
210-240	2.29523	2.28698	2.29388	2.30088
240-270	-2.35194	-2.35988	-2.33059	-2.35609
270-300	-7.054	-7.0614	-7.02847	-7.04986
300-330	-11.7377	-11.7083	-11.6896	-11.7437
330-360	-16.4032	-16.3552	-16.3508	-16.3454
360-390	-21.087	-21.0384	-21.0304	-21.0391
390-420	-25.7524	-25.7947	-25.6548	-25.7146
420-450	-30.4361	-30.2775	-30.2793	-30.4268

The data files contain headers for each column. They are described here in greater detail. Column 1 is the Unix time in second. Column 2-7 give the year, month, day, hour, minute and second of the measurement. Column 8-11 gives the measured voltages of each single-ended RE measurement in volts. Column 12-15 gives the applied bias voltage in volts for each RE measurement as shown in **Table 9**.

4.3 Calibrated Data Products

data_cal_bias – contains 22 files, 21 files for each bias sweep conducted over BM1, and 1 file for the bias setting of each RE over the entire mission. The naming convention of the 21 files is the same as the partially_processed dataset.

The data files contain headers for each column. They are described here in greater detail. Column 1 is the Unix time in second. Column 2-7 give the year, month, day, hour, minute and second of the measurement. Column 8-11 gives the averaged measured voltages of each single-ended RE measurement in volts. This is an average of the three voltage measurements made during the 30 seconds of time when the applied bias voltage remained the same. Column 12-15 gives the standard deviation of the three averaged voltage measurements. Columns 16-19 provides the applied bias voltage in volts for each RE measurement as shown in **Table 9**. Columns 20-23 provides the derived bias current in nanoamps (nA).

The bias current values were established from calibrations performed on the flight model electrodes. Each electrode was connected to ground using a known resistance. This resistance then forms a voltage divider with the internal bias resistor which is then measured by the electrode input. During a bias sweep, the electrode output was recorded, and the bias offset voltage determined as a function of bias step from the voltage divider output and using the known values of the bias and external resistors. The bias current is then determined by dividing the measured bias offset voltage by the internal bias resistor of 44 megaohms.

The last file in this directory is LMS_Bias_Settings.csv. The data files contain headers for each column. They are described here in greater detail. Column 1 is the Unix time in second. Column 2-7 give the year, month, day, hour, minute and second of the measurement. Columns 8-11 contain the bias current setting for each electrode.

data_cal_diffe/SCI – contains geographic (E,N) components of the electric-field time series for the science (SCI) phase of LMS operations. Each calendar day has csv files at 1, 32, and 256 sps. Note that all data were collected at 256 sps and then downsampled to 32 or 1 sps using an 8th-order Chebyshev Type I IIR filter. Header values are given as the first and display time and V/m for the two horizontal axes.

Conversion of partially processed electric potentials to calibrated electric fields required (1) determination of electrode positions from imaging, (2) assignment of electrode differentials to the E-field calculation, (3) calculation of the scaling+rotation matrix to convert those differentials to surface electric fields in the east and north directions.

The BG1 lander included several cameras intended to capture RE deployments. Table 9 gives the recovered RE positions with estimated errors and comments. These positions relative to the individual launchers were translated to a common origin at RE3 (Table 10). The six differential voltages among the four electrodes provide five different geometric configurations for projection to orthogonal axes using three or four electrodes (the two remaining geometries were rejected because their directions are nearly parallel or degenerate). The primary four-electrode configuration was determined to have the smallest geometric error on the recovered electric field (2.2% east, 3.4% north) and was selected for final processing and archiving.

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} = \begin{bmatrix} -0.0201 & +0.0024 \\ -0.0007 & +0.0186 \end{bmatrix} \begin{bmatrix} v_{12} \\ v_{34} \end{bmatrix} \quad \text{(Eq. 5)}$$

where x = East, y = North, and z (not used here) = Up. The close agreement of this matrix to the approximation $E_x = -v_{12}/52$ and $E_y = v_{34}/52$ indicates that the electrode deployments were nearly along the geographic axes with end-to-end separations of ~52 m.

data_cal_mag/SCI – contains geographic (E,N,U) components of the magnetic-field time series for the science (SCI) phase of LMS operations. To do this, we use the -Y axis of the magnetometer for east, the +X axis of the magnetometer for north, and the +Z axis of the magnetometer for Up (Table 11). These files have a prefix of "lms_MAG_", then the calendar date in YYYYMMDD, and then the sampling rate. Each calendar day has csv files at 1, 32, and 256 sps, again with downsampling from 256 sps using an 8th-order Chebyshev Type I IIR filter. Header values are given in the first row as display time and nanoTeslas for each of the three axes.

Conversion of partially processed to calibrated magnetometer data required (1) removal of spacecraft artifacts and (2) rotation from instrument to geographic coordinates. Close inspection of the magnetometer data during mast deployment revealed that the magnetic field levelled off to a constant value before the mast reached maximum extension. This confirms that the mast placed the sensor effectively out of the lander's static magnetic field. A variety of time-variable artifacts – principally step offsets associated with radio operations – were removed by a combination of simple algorithms and visual inspection. Because MAG is aligned with spacecraft-body axes and the landed orientation was very nearly aligned with geographic axes, coordinate transformations are nearly simple exchanges of axes (Table 11). In reality the lander azimuth 0.05° east of north was

neglected as being trivially small. The tilt of 4.2° of the Blue Ghost lander to the west was corrected as a clockwise rotation around the geographic +y axis and was corrected for.

Table 9. LMS deployed RE positions from the launcher of each electrode. Errors are ± 1σ.

RE	Easting, m	Northing, m	Total Distance, m	Comments
1 (West)	-24.6 ± 0.3	-0.7 ± 0.1	24.6 ± 0.3	Multiple images, clearly visible on surface.
2 (East)	+24.4 ± 1.1	+1.0 ± 0.5	24.4 ± 1.0	In crater, position assigned to center with 2-σ error equal to crater radius
3 (North)	+2.7 ± 0.4	+25.0 ± 1.3	25.1 ± 1.5	Multiple possibilities + smudged image. Position and 1-σ as-signed from mean and std dev of two most likely candidates.
4 (South)	-4.0 ± 1.0	-25.4 ± 0.5	25.7 ± 0.5	Visible on far wall of crater but with uncalibrated camera.

Table 10. LMS RE locations as relative to the RE3 launcher.

RE	Easting, m	Northing, m
1 (West)	-24.8 ± 0.3	-0.8 ± 0.1
2 (East)	+24.8 ± 1.0	+0.9 ± 0.4
3 (North)	+2.7 ± 0.4	+25.0 ± 1.5
4 (South)	-4.0 ± 1.0	-27.8 ± 0.5

Table 11. Approximate Relations Between MAG, Lander, and Geographic Coordinates.

Geographic	East (x)	North (y)	Up (z)
Lander	-z	+y	+x
MAG	-y	+x	+z

4.4 Derived Data Products

Spectral analysis of time-series data at any Level requires correction for the frequency-dependent gain and phase response of the measurement system. LMS MAG is essentially unity gain and zero phase over the entire measured bandwidth. The gain and phase of ELEC (Table 13) were constructed from the averages of all six electrode pairs (standard deviations increasing from zero at 0 Hz to 2.6% in gain and 2.2° in phase at 128 Hz).

Table 13. ELEC spectral response.

Frequency, Hz	Gain	Phase (deg)
0	1.00	0.0
1	1.00	-0.3
2	1.00	-1.0
5	1.00	-3.2
10	1.01	-7.3

20	1.04	-15.1
30	1.09	-22.8
50	1.20	-38.4
75	1.35	-53.9
100	1.49	-68.4
128	1.60	-82.4

None provided.

5 Tools

None provided.

6 Appendices

6.1 Acronyms

BGM1 – Blue Ghost Mission 1
COM – Commissioning Phase
DiffE – Differential Electric Field measurement
HF – High Frequency mode.
LMS – Lunar Magnetotelluric Sounder
MAG – Magnetometer sensor
PDS – Planetary Data System
RE – Remote Electrode
SCI – Science Phase
SingE – Single-end Electric Field measurement
sps – samples per second