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Lunar GNSS Receiver Experiment (LuGRE), Code 450.2

Lunar GNSS Receiver Experiment (LuGRE) Product Handbook

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Preface

The Lunar GNSS Receiver Experiment (LuGRE) is a joint NASA-Italian Space Agency (ASI) payload on the Firefly Blue Ghost Mission 1 (BGM1) with the goal to demonstrate GNSS-based positioning, navigation, and timing at the Moon. LuGRE was chosen by the NASA Commercial Lunar Payload Services (CLPS) program as one of ten payloads on its "19D" task order for delivery to the lunar surface in 2025.

The primary organizations involved include NASA via its Space Communication and Navigation (SCaN) Program; ASI, Qascom S.r.l., and Politecnico di Torino (PoliTo) via its Department of Electronics and Telecommunications. Qascom led development and testing of the payload system, including in-house development of the LuGRE GNSS receiver. PoliTo led ASI science activities as co-principal investigator (PI) with NASA.

The LuGRE payload consists of a weak-signal GNSS receiver, a high-gain L-band antenna, and a front-end assembly containing a low-noise amplifier and a radio-frequency filter. The receiver tracks GPS L1 C/A and L5, and Galileo E1 and E5a signals and returns pseudorange, carrier phase, and Doppler measurements to the ground. It also calculates least-squares point solutions and Kalman-filter based navigation solutions onboard. In addition, the receiver features the capability to record raw in-phase and quadrature (I/Q) baseband samples for downlink and ground processing.

LuGRE builds on the legacy of prior missions in the Space Service Volume (SSV) including the initial experiments by AMSAT-OSCAR 40 and others, the GOES-R series of geostationary weather satellites, and the NASA Magnetospheric Multiscale (MMS) mission, which operated on GPS-based navigation at nearly 50% of lunar distance. Further, LuGRE is one of the very first demonstrations of GNSS signal reception and navigation in the lunar environment and on the lunar surface, paving the way for operational use by future lunar and cislunar missions. LuGRE science data is released publicly for the benefit of the GNSS and space communities.

Change History Log

Revision	Effective Date	Description of Changes (Reference the CCR & CCB/ERB Approval Date)
Draft	October 13, 2025	First consolidated draft

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1 INTRODUCTION

1.1 Purpose

This document describes the public data products from the LuGRE mission, including Level-0, Level-1, and ancillary products. The description of each product contains the key details needed to understand and utilize the product, including the file contents, naming scheme, format, and any processing performed on the data.

1.2 Scope

The scope of this document is limited to the key details of the LuGRE public data products. It does not attempt to provide a comprehensive description of the mission, the payload, or the well-known fundamental concepts needed to apply the data. General information about the mission can be found in the Reference Documents listed in this section. Specific implementation details for certain products, such as the binary data format, are contained in the Applicable Documents, as noted in the text.

1.3 Related Documentation

1.3.1 Applicable Documents

[ICD] Qascom S.r.l, "LuGRE Receiver Interface Control Document", NIL-TN-QAS-024

[SDR] Institute of Navigation, "GNSS Software Defined Receiver Metadata Standard," https://sdr.ion.org/

1.3.2 Reference Documents

[NAVI] Joel J. K. Parker, Fabio Dovis, Lauren Konitzer, Nathan Esantsi, Benjamin Ashman, Alex Minetto, Andrea Nardin, Oliviero Vouch, Simone Zocca, Fabio Bernardi, Matilde Boschiero, Samuele Fantinato, Efer Miotti, Claudia Facchinetti, Mario Musmeci, and Giancarlo Varacalli, "GNSS Reception at the Moon: First Results of the Lunar GNSS Receiver Experiment (LuGRE)," NAVIGATION: Journal of the Institute of Navigation (submitted)

[GPS ICD] "NAVSTAR GPS Space Segment/Navigation User Segment Interfaces", IS-GPS-200, rev. N, 22 Aug. 2022, Space Systems Command (SSC).

[GAL ICD] "Galileo Open Service Signal-In-Space Interface Control Document", OS-SIS-ICD, Issue 2.1, Nov. 2023, European Union.

2 LEVEL 0 PRODUCTS

2.1 TLM_ACQ, TLM_NAV, TLM_RAW

2.1.1 Description

The TLM_ACQ, TLM_NAV, and TLM_RAW products contain unprocessed telemetry messages from the LuGRE receiver. No post-processing is applied to the telemetry. The messages included are:

- ACQ – contains information on acquired satellites, Doppler, and correlators
- RAW – contains pseudorange, Doppler, carrier phase, C/N_0
- NAV – contains least-squares position, velocity, and time (PVT) solutions in the Earth-fixed frame (ECEF)

This product is provided in both ASCII text and binary formats.

2.1.2 Filename Format

`TLM_ACQ_`*`YYYYMMDD_HHMMSS_DUR_P_OP#_#.EXT`*
`TLM_NAV_`*`YYYYMMDD_HHMMSS_DUR_P_OP#_#.EXT`*
`TLM_RAW_`*`YYYYMMDD_HHMMSS_DUR_P_OP#_#.EXT`*

Fields:

`YYYYMMDD_HHMMSS`	Timestamp of start of associated LuGRE operation
`DUR`	Nominal duration of operation, to nearest hour (e.g. 01H)
`P`	Mission phase: C = commissioning T = transit L = low lunar orbit S = lunar surface
`OP#_#`	LuGRE operation number (e.g., OP1_0, OP77_1)
`EXT`	File extension: .txt (ASCII text) or .bin (binary)

2.1.3 File Content Format

ASCII text format: Time-ordered sequence of messages as freeform text, with each field identified. See [ICD] for details of each field.

Binary format: Defined in [ICD].

2.1.4 Cadence and Timespan

The data cadence is 1 Hz. The timespan is the duration of the real-time processing (RTP) mode execution for each operation.

2.2 TLM_CLK

2.2.1 Description

The TLM_CLK products contain unprocessed telemetry data from the LuGRE receiver related to the receiver's estimate of its own clock bias and bias rate relative to the telemetry timestamps. The files contain selected data fields extracted from proprietary receiver Kalman filter messages. No post-processing is applied to the data beyond extraction of the relevant fields from the raw telemetry.

This product is provided in .csv text format only.

2.2.2 Filename Format

`TLM_CLK_`*`YYYYMMDD_HHMMSS_DUR_P_OP#_#`*`.csv`

Fields:

`YYYYMMDD_HHMMSS`	Timestamp of start of associated LuGRE operation
`DUR`	Nominal duration of operation, to nearest hour (e.g. 01H)
`P`	Mission phase: C = commissioning T = transit L = low lunar orbit S = lunar surface
`OP#_#`	LuGRE operation number (e.g., OP1_0, OP77_1)

2.2.3 File Content Format

Comma-Separated Value text format: Time-ordered series of data

Each file contains 3 columns of data for the operation described in the filename. The contents of each column are described with the following headers:

- Receiver Time [s] – telemetry timestamp
  - Units: seconds of GPS time
- Clock Bias [m] – receiver clock bias estimated by the onboard extended Kalman filter
  - Units: meters
- ClockDrift [m/s] – receiver clock bias rate estimated by the onboard extended Kalman filter
  - Units: meters/second

2.2.4 Cadence and Timespan

The data cadence is 1 Hz, aligned with the same timestamps as the TLM_RAW messages. The timespan is the duration of the RTP mode execution for each operation.

2.3 TLM_EPH

2.3.1 Description

The TLM_EPH products contain unprocessed telemetry data from the LuGRE receiver related to the broadcast ephemeris messages decoded by the receiver. The files contain selected data fields extracted from proprietary receiver log messages. No post-processing is applied to the data beyond extraction of the relevant fields from the raw telemetry.

This product is provided in .csv text format only.

2.3.2 Filename Format

`TLM_EPH_`*`YYYYMMDD_HHMMSS_DUR_P_OP#_#`*`.csv`

Fields:

`YYYYMMDD_HHMMSS`	Timestamp of start of associated LuGRE operation
`DUR`	Nominal duration of operation, to nearest hour (e.g. 01H)
`P`	Mission phase: C = commissioning T = transit L = low lunar orbit S = lunar surface
`OP#_#`	LuGRE operation number (e.g., OP1_0, OP77_1)

2.3.3 File Content Format

Comma-Separated Value text format: Time-ordered series of data

Each file contains 8 columns of data for the operation described in the filename. The contents of the first 3 columns contain the timestamp of the telemetry and describe the signal and satellite from which the broadcast message was demodulated:

- rxTime – telemetry timestamp
  - Units: seconds of GPS time
- signal – signal identifier
  - Same convention as described for TLM_ACQ and TLM_RAW (see [ICD])
- svId – satellite vehicle identifier (PRN)
  - Same convention as described for TLM_ACQ and TLM_RAW (see [ICD])

The remaining 5 columns contain selected information from the demodulated broadcast message, following the conventions of the GPS and Galileo ICDs; see [GPS ICD] and [GAL ICD]:

- Toe – time of ephemeris: this field is demodulated from SIS navigation message and it is the reference time of the ephemeris parameters
- Toc – time of clock: this field is demodulated from the SIS navigation message and it is the reference time of the satellite clock correction parameters

- iodNav – issue of data for the Galileo ephemeris and satellite clock parameters. Every time a new set of Galileo ephemeris and satellite clock parameters are broadcasted from SIS the Issue of Data changes value. This Issue of Data is the proof that the receiver has demodulated many sets of Galileo ephemeris and satellite clock parameters during the mission operations
- iodE – issue of data for the GPS ephemeris. Every time a new set of GPS ephemeris parameters are broadcasted from SIS the Issue of Data changes value. This Issue of Data is the proof that the receiver has demodulated many sets of GPS ephemeris during the mission operations
- iodC – issue of data for the GPS satellite clock parameters. Every time a new set of GPS satellite clock parameters are broadcasted from SIS the Issue of Data changes value. This Issue of Data is the proof that the receiver has demodulated many sets of GPS satellite clock parameters during the mission operations

2.3.4 Cadence and Timespan

The data cadence is variable; messages are produced upon successful demodulation of the broadcast message for the indicated signal. For example, the entry combining *signalId = 2 and svId = 24* is repeated 15 times from rxTime = 1426198893 to rxTime = 1426199039 and even after that. These logs prove the successful demodulation of the live SIS navigation message for both GPS and Galileo signals.
The internal logic of the LuGRE receiver decides whether to refresh the current satellites' ephemeris parameters based on a proprietary algorithm developed by Qascom. Thus, every line on this telemetry file refers to a time in which the receiver updated part of the full set of ephemerides (i.e., orbital parameters, satellite clock corrections, other parameters from SiS ICD), that will be used for the next upcoming PVT solutions.

2.4 IQS_L1, IQS_L5

2.4.1 Description

The IQS_L1 and IQS_L5 products contain raw in-phase and quadrature (I/Q) samples recorded by the LuGRE receiver. These samples were captured during specific operations using the receiver's sample capture (SC) mode. Each SC operation had configurable parameters, including bands (L1/E1, L5/E5a, or both), capture duration (200ms to 2000ms), quantization depth (4–8 bits), and sample rate (4–8 Msamples/s for L1/E1, 24 Msamples/s for L5/E5a). The exact configuration of each SC operation is described in the OPTABLE ancillary product.

Each IQS product is accompanied by an SDR metadata file in XML format.

2.4.2 Filename Format

`IQS_`*`BAND_YYYYMMDD_HHMMSS_DUR_P_OP#_#`*`.bin`
`IQS_`*`BAND_YYYYMMDD_HHMMSS_DUR_P_OP#_#`*`.sdrx`

Fields:

`BAND`	Capture band: "L1" for L1/E1 or "L5" for L5/E5a
`YYYYMMDD_HHMMSS`	Timestamp of start of I/Q sample capture
`DUR`	Capture duration, in milliseconds
`P`	Mission phase: C = commissioning T = transit L = low lunar orbit S = lunar surface
`OP#_#`	LuGRE operation number (e.g., OP1_0, OP77_1)

2.4.3 File Content Format

The binary format is described in [ICD]. Each binary file is associated with an XML file containing the metadata in the ION SDR format.

The SDR metadata file format is described by the GNSS Software Defined Receiver Metadata Standard [SDR]. More specifically, the information is grouped into different classes, most importantly:

- **File** class: which describes the file itself, its name and datetime of creation
- **Session** class: which describes the collection campaign for which the file is a part of
- **System** class: provides information about the equipment used to collect data, including the receiver and the antenna
- **Lane** class: further contains other nested classes to allow the flexibility to describe any way in which the data could be formatted within the file. As a whole, it contains all information needed to correctly decode the binary file, including all fields that are contained in the header of the file

2.4.4 Cadence and Timespan

The cadence and timespan of each file is dependent on the configuration used for the relevant SC operation. The OPTABLE product contains this information.

ANCILLARY PRODUCTS

2.5 OPTABLE

2.5.1 Description

The OPTABLE product defines the list of successful payload operations (OPs) executed during the mission. Each record corresponds to one operation and contains a minimal set of metadata describing its temporal references, operational configuration, and data capture settings. The product is intended as a reference for both mission analysis and post-processing, providing a structured overview of when and how payload activities were carried out.

The fields include:

- **Identifiers and mission context** (OP ID, phase, initial altitude).
- **Temporal references** (reference start time, RTP and SC time intervals).
- **Operational configuration** (mode and captured frequency bands).
- **Configuration parameters** (bit depth, sampling frequency, and duration for each band).

Details of each field are described in the File Content Format section.

2.5.2 Filename format

`OPTABLE.csv`

2.5.3 File Content Format

The file is in comma-separated values (CSV) format, encoded in plain text.

- **File extension:** .csv
- **Encoding:** UTF-8
- **Field separator:** comma (,)
- **Decimal separator:** dot (.)
- **Header row:** present (the first row defines the column names)
- **Missing values:** represented as empty fields (blank)

2.5.3.1 Example

```
2_0,T,25.25,2025/01/16 01:28:59,SC-RTP,2025/01/16 01:36:04,2025/01/16
02:23:58,2025/01/16 01:31:16.762,L1/E1,4.0,8.0,400.0,,,
```

This row corresponds to:

- **OP ID**: 2_0
- **Phase**: T (Transit)
- **Initial Altitude**: 25.25 RE
- **Reference OP start time**: 2025/01/16 01:28:59 UTC
- **Mode**: SC-RTP
- **RTP interval**: 2025/01/16 01:36:04 to 2025/01/16 02:23:58 UTC
- **SC start time**: 2025/01/16 01:31:16.762 UTC

- **SC band**: L1/E1
- **SC parameters (L1/E1)**: 4-bit depth, 8 Msps sampling frequency, 400 ms duration
- **SC parameters (L5/E5a)**: not populated in this row (fields left empty)

The following paragraphs define the structure of the OPTABLE and specify the information associated with each payload operation. Each field is documented with its meaning, expected format, and, where applicable, the set of possible values. Fields are presented in the order they appear in OPTABLE.

2.5.3.2 OP ID

A unique identifier for each payload operation. The identifier combines a progressive number with a suffix (e.g., 1_0, 2_0). The LuGRE operations were identified by a sequential numeric ID based on the pre-flight plan, including placeholders for backup and secondary opportunities; thus the as-executed sequence is not continuously numbered. New operations inserted into the baseline plan (as opposed to simply delaying until the next planned operation) were marked as "OPn_1", where n is the previously executed sequential ID. This field allows unambiguous reference to specific operations in analysis and documentation.

2.5.3.3 Phase

Indicates the mission phase during which the payload operation took place.
Possible values are:

- **C** – Commissioning phase
- **T** – Transfer/Transit phase
- **L** – Lunar orbit phase
- **S** – Lunar surface phase

This field helps group and filter operations according to the mission timeline.

2.5.3.4 Initial Altitude (RE)

The initial altitude of the spacecraft at the start of the payload operation, expressed in Earth radii (RE). Altitude measurements are referenced to the Earth geoid at the start time of each operation, where 1 RE is equal to 6378.137 km. This field provides the geometric context of the operation, useful for linking performance and trends to spacecraft distance from Earth.

2.5.3.5 Reference OP start time (yyyy/mm/dd hh:mm:ss UTC)

The nominal or planned start time of the payload operation in Coordinated Universal Time (UTC). This timestamp is a reference to the beginning of payload operation (payload startup and boot) and may not coincide with the actual start of individual RTP or SC segments or telemetry. This field matches the filename of the TLM products described in Sections 2.1, 2.2, and 2.3.

2.5.3.6 Mode

Specifies the operational configuration used during the payload operation.
Possible values include:

- **RTP** – RTP only
- **SC** – SC only
- **SC-RTP** – SC followed by subsequent RTP

- **RTP-SC** – RTP followed by subsequent SC

This parameter indicates whether the payload collected data in real time (i.e., GNSS observables, state estimation solutions), stored in-phase/quadrature signal samples, or both.

2.5.3.7 RTP_start (yyyy/mm/dd hh:mm:ss UTC)

The actual start time of the RTP segment in UTC.
It defines when the onboard payload began real-time operation for this OP.

2.5.3.8 RTP_end (yyyy/mm/dd hh:mm:ss UTC)

The actual end time of the RTP segment in UTC.
Together with RTP_start, it defines the duration of the RTP phase. This timestamp is only present if RTP was actually performed; otherwise, the field remains empty.

2.5.3.9 SC_Start (yyyy/mm/dd hh:mm:ss.fff UTC)

The actual start time of the SC segment in UTC. It is obtained from the header of IQS data packets generated by the payload in SC mode. This timestamp is only present if a sample capture was performed; otherwise, the field remains empty. This field matches the filename of the IQS products described in Section 2.4, to seconds precision.

2.5.3.10 SC_bands

The frequency band(s) that were captured during the SC phase.
Possible values are:

- **L1/E1** – GPS L1 / Galileo E1 band
- **L5/E5a** – GPS L5 / Galileo E5a band
- **L1/E1 + L5/E5a** – GPS L1/L5 / Galileo E1/E5a band

This field is key to determining which navigation signals were recorded during SC segments. Depending on the specific settings for the SC mode, different front-end filters resulted in different spectral behaviour of the collected samples. In general, one filter (filter A) was used for dual-frequency sample captures, and also in the OP78_0 single-frequency capture. Most single-frequency captures used filter B. See [NAVI] for details.

2.5.3.11 L1/E1 SC bit depth (bit/sample)

Indicates the number of bits per sample used by the ADC when acquiring data in the L1/E1 band. Higher values correspond to greater dynamic range but also larger data volumes.

2.5.3.12 L1/E1 SC sampling frequency (Msps)

The sampling frequency, expressed in mega-samples per second (Msps), for the L1/E1 acquisition. This parameter defines the resolution and bandwidth of the captured signal batches.

2.5.3.13 L1/E1 SC duration (ms)

The acquisition duration in milliseconds for the L1/E1 band.
This value specifies how long the payload recorded in-phase/quadrature samples in this band.

2.5.3.14 L5/E5a bit depth (bit/sample)

Indicates the number of bits per sample used during the acquisition in the L5/E5a band.
As with L1/E1, higher bit depth increases precision at the expense of data size.

2.5.3.15 L5/E5a SC sampling frequency (Msps)

Sampling frequency, in Msps, for the acquisition in the L5/E5a band.
This parameter defines the resolution and bandwidth of the captured signal batches.

2.5.3.16 L5/E5a SC duration (ms)

Duration of the raw data capture in milliseconds for the L5/E5a band.
This value specifies how long the payload recorded in-phase/quadrature samples in this band.

2.5.4 Notes

- The operational mode (**Mode**) is the main driver determining which fields are filled in:
    - For RTP operations, only RTP timestamps are populated.
    - For SC-RTP operations, both RTP and SC-related fields are filled.
- The columns remain empty when no SC was performed in that band.
- All timestamps follow the UTC format (yyyy/mm/dd hh:mm:ss UTC).
- Operation 78_1 was performed using a Receiver B. All others were performed using Receiver A. As a result, some data series may exhibit different behaviors and characteristics compared to the other operations.

Appendix A Abbreviations and Acronyms

ASCII	American Standard Code for Information Interchange
ASI	Italian Space Agency (Agenzia Spaziale Italiana)
BGM1	Blue Ghost Mission 1
CLPS	Commercial Lunar Payload Services
CSV	comma-separated values
ECEF	Earth-centered, Earth-fixed reference frame
I/Q	in-phase and quadrature
GNSS	global navigation satellite system
GPS	Global Positioning System
GSFC	Goddard Space Flight Center
HGA	high-gain antenna
LuGRE	Lunar GNSS Receiver Experiment
MMS	Magnetospheric Multiscale
NGLR	Next-Generation Lunar Retroreflector
PoliTo	Politecnico di Torino
PI	principal investigator
PRN	pseudo-random noise
PVT	position, velocity, and time
RE	Earth radius (radii)
RTP	real-time processing (LuGRE receiver mode)
SC	sample capture (LuGRE receiver mode)
SDR	software-defined radio
SCaN	Space Communications and Navigation
SSV	Space Service Volume
TBD	To be determined
TBR	To be revised
TBS	To be scheduled
UTC	Coordinated Universal Time
XML	Extensible Markup Language