Lucy
SOFTWARE INTERFACE SPECIFICATION
Radio Science Data Products

September 2024

SwRI® Project 22668

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Rev 0 Chg 1

Contract NNM16AA08C

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REVISION NOTICE

Revision Number	Change Number	Sections Affected	Change Description	Release Date
0	0	All	(DRAFT, R0)	12/10/2020
0	0	All	INITIAL RELEASE	07/2024
0	1	2.3.2.1, 2.3.3, 4.1	Deleted section 2.3.2.1 and added text to other sections.	pending PDS review

TBD/TBS RESOLUTION SCHEDULE

Location	Description	Planned Resolution Date

1. INTRODUCTION

1.1 Purpose and Scope

The purpose of this Software Interface Specification (SIS) is to provide the consumers of the *Lucy* Radio Science Investigation raw and calibrated data products with a detailed description of the data products, and how they were generated, including data sources and destinations. The document is intended to provide enough information to enable users to read and understand the data product. The users for whom this document is intended are the scientists who will analyze the data, including those associated with the project and those in the general planetary science community.

Raw data products described in this SIS are uncalibrated, uncorrected data products reassembled from spacecraft telemetry as acquired by the instrument. Calibrated data products described in the SIS are corrected and calibrated data products with values given in physically meaningful data units. The *Lucy* Science Operations Center located at the Southwest Research Institute, Boulder, Colorado produces these data products and distributes them to both the *Lucy* Science Team and the Planetary Data System (PDS). This SIS describes how the radio science data products are acquired, processed, formatted, labeled, and uniquely identified. The document discusses standards used in generating the product and software that may be used to access the products.

1.1 Contents

This Data Product SIS describes how the raw data products are acquired by the *Lucy* Mission and how the products are processed, formatted, labeled, and uniquely identified. This SIS also describes how the calibrated data products are derived from the raw data or other calibrated data products. The document discusses standards used in generating the products, and software that may be used to access the products. The raw and calibrated data product structure and organization is described in sufficient detail to enable a user to read the product. Processing is described at a high level, and full definitions of all metadata attributes are provided.

1.2 Applicable Documents

This SIS is meant to be consistent with the contract negotiated between the *Lucy* Project, the *Lucy* Radio Science Investigation Team and the *Lucy* Science Operations Center (SOC). Product label keywords/attributes may be added to future revisions of this SIS. Therefore, it is recommended that software designed to process products specified by this SIS should be robust to (new) unrecognized keywords. Similarly, entirely new products may be added over time.

This Data Product SIS is responsive to the following documents:

Table 1-1. List of Applicable Documents

Document ID	Title	Release Date	Revision
JPL D-7669, Part 2	Planetary Data System Standards Reference	June, 2023	1.20
n/a	Data Provider's Handbook, Archiving Guide to the PDS4 Data Standards	June, 223	1.20
n/a	Planetary Data System Common Dictionary Document	June, 2023	TBD
22702-DMAP-01	*Lucy* Data Management and Archive Plan		current revision unless revision is specified
22668.07-ST-ICD-01	*Lucy* Science Operations Center to Science Team ICD		current revision unless revision is specified
Lucy-SYS-ICD-0017	*Lucy* to MGSS ICD		current revision unless revision is specified

1.3 Relationship with Other Interfaces

This SIS could be affected by changes to the *Lucy* Data Management and Archive Plan (DMAP) or the *Lucy*-SBN Interface Control Document (ICD). Where possible, references are made to the DMAP or ICD rather than duplicating information in this document. This SIS may be revised by consent of the signatories.

Table 1-2. List of Interface Relationships

Name	Type	Owner
Lucy SOC Database Schema	Product	SOC
DSN Tracking Data (trk-234)	Product	SOC
DSN Media Calibration Data	Product	SOC
NAIF Small Forces Files	Product	SOC
Inst Pipeline Software	Software	SOC
Lucy SOC-SBN ICD	Document	SOC
Lucy DMAP	Document	Project

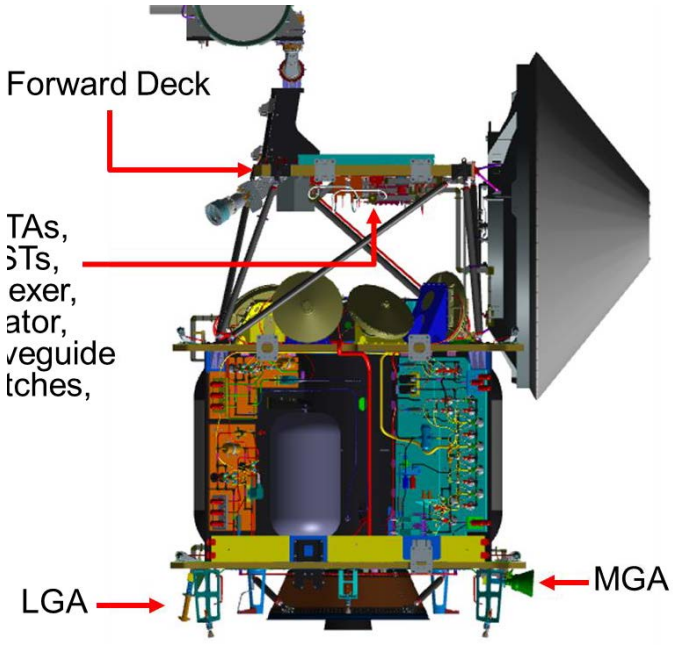
2. DATA PRODUCT CHARACTERISTICS AND ENVIRONMENT

2.1 Spacecraft and Telecommunications Systems Overview

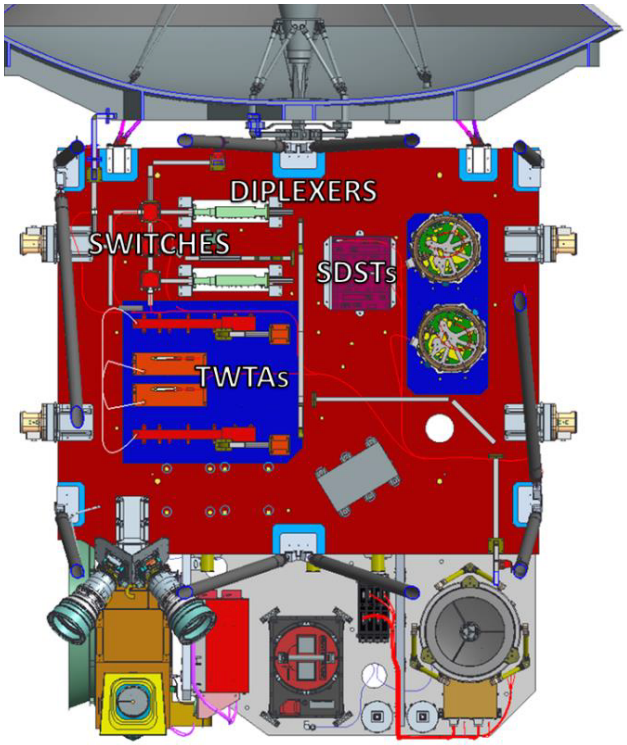
The Lucy mission will explore the 'Jupiter Trojans', a grouping of asteroids in the L4 and L5 Lagrange points around Jupiter. This unique region encompasses planetesimals that have been relatively untouched since the early history of the Solar System. By visiting six such bodies over five distinct encounters, Lucy will sample all Trojan taxonomic classes during its mission operations phase and provide critical insight into planetary formation of the Solar System. Lucy will encounter a Main Belt asteroid in 2025, and visit its first Trojan asteroid in 2027, and accomplish its remarkable succession of encounters by 2033, a feat made possible by an advantageous celestial geometry.

Lucy will include a small but high-value payload suite including "L'Ralph" (high resolution visible color and infrared mapping spectroscopy facility), "L'LORRI" (supplemental high-resolution imager to enable optical navigation), and "L'TES" (a thermal infrared spectrometer). A radio science investigation will also be conducted to further classify and characterize the Trojan targets. The following paragraphs give an overview of the spacecraft components that will be used by the radio science investigation.

Figure 2-1. Lucy spacecraft -Y-axis view



Fig



2.1.1 Spacecraft Telecommunications System

Lucy uses an X-band subsystem for deep space communications with the DSN.

2.1.1.1 X-Band

The X-band telecom subsystem is a high heritage design implementing redundant Small Deep Space Transponders (SDST), 25 W Travelling Wave Tube Amplifiers (TWTA), a 2-m direct feed parabolic dish high-gain antenna (HGA), a medium gain antenna (MGA), a low gain antenna (LGA), and an assemblage of switches, filters, and waveguide. The HGA is used in the mission for high-rate communications ranging from a minimum downlink rate of 8 kbps to 352.941 kbps. The HGA is pointed directly in the spacecraft body positive X direction while the MGA and LGA are pointed 3.5 degrees and 100 degrees off the positive X direction respectively. Continuous use of the HGA is restricted to SPE angles less than 45 degrees when the solar range is less than 1 AU and less than 60 degrees when the solar range is greater than 1 AU. Between those SPE angles, dependent on solar range, and SPE angle of 88.8 degrees the HGA can be operated in Burst Mode where the spacecraft slews to Earth point for 35 minutes at a time before slewing back to Sun point. The LGA is used for nominal mission communications outside the high data rate passes on the HGA and when SPE is greater than 88.8 degrees. The MGA antenna is the primary command path for safemode operations and has 2 configurations. For SPE less than 14 degrees the MGA will be used directly at sun point. For SPEs between 14 and 53 degrees the spacecraft points itself 21.5 degrees off the sun. The LGA is used for SPEs greater than 53 degrees. Lucy also has an HGA safemode option when SPE is less than 60 degrees but requires attitude knowledge and the ability for reaction wheel control. For navigation, the X-band telecom system also provides ranging, Doppler, and DDOR.

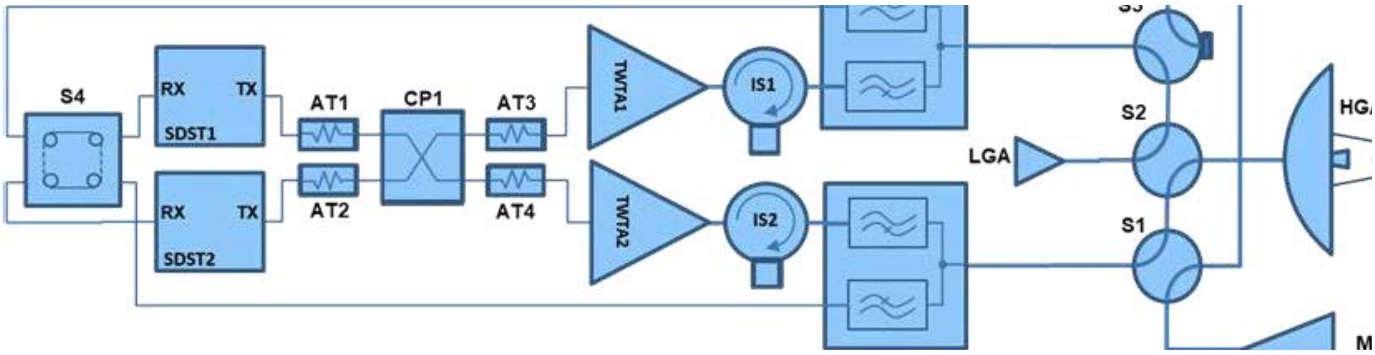
2.1.1.2 Performance

The uplink performance for all antennas is represented by the calculated total power thresholds for various uplink rates for a 1E-5 bit error rate with 3dB of uplink ranging suppression assuming a 34-m BWG station. Even for safe mode, Lucy does not require use of the 70-m DSN subnet. However, there are some critical mission phases where 70-m support may be considered as an option in the future.

The calculated total power thresholds for various downlink rates are calculated for 1E-6 bit error rate and a 34-m BWG station performance. During initial acquisition, the DSN tracking profile will be constructed with an off-point such that the receive power remains below -90 dBm.

Figure 2-3 Lucy Telecom Subsystem, is a block diagram that describes the Lucy telecom subsystem.

Figure 2-3. Lucy Telecom Subsystem



2.1.2 Lucy Spacecraft Telecom Parameters

This section defines the spacecraft telecom parameters that are required for DSN to configure and validate the network interfaces for operational support. The Lucy spacecraft utilizes the following parameters for communications:

Note that the Lucy project has been approved to use of the uplink and downlink X-band frequencies/channels assigned to the OSIRIS-REx and MAVEN projects. Since the uplink and downlink X-band frequencies/channels are shared between the three projects, the Lucy project will take responsibility for coordinating its operations with OSIRIS-REx and MAVEN operations to avoid potential mutual interference.

Table 2-1. Uplink Characteristics

UPLINK				
Frequency				
X-band uplink frequency **7188.499990 MHz**				
Transponder receiver bandwidth **20 Hz** Transponder tracking bandwidth **+/- 200 kHz**				
Transponder frequency turnaround ratio:				
X-Band **880/749**				
S/C Carrier threshold	**-157 dBm**			
S/C command threshold	**-129 dBm at 200 b/s** **-147 dBm at 7.8125 b/s**			
S/C Max receive power	**-70 dBm**			
Command				
Command Modulation	**PCM(NRZ-L)/PSK/PM**			
Subcarrier Frequency	**16 kHz**			
Subcarrier Waveform	**Sine wave**			
Command Rates				
	Command Rate (bps)	Mod Index (rad)	Mod Index (degrees)	Carrier Suppression (dB)
	7.8125	**0.94**	**53.85**	**2.04**
	15.625	**1.2**	**68.75**	**3.46**
	31.25	**1.5**	**85.94**	**5.82**
	62.5	**1.5**	**85.94**	**5.82**
	125	**1.5**	**85.94**	**5.82**
	250	**1.5**	**85.94**	**5.82**
	500	**1.5**	**85.94**	**5.82**
	1000	**1.5**	**85.94**	**5.82**
	2000	**1.5**	**85.94**	**5.82**
Uplink Command PLOP	**2**			
Uplink Inter-Modulation Type	**Idle Sequence**			
Idle Sequence:	**AA**			

Table 2-2. Downlink Characteristics

Downlink

Frequency
Frequency channel **36.6562**
X-Band downlink frequency
Two-way coherent downlink **8445.767679 MHz**
One-way non-coherent (aux osc) **8445.772484 MHz**
Telemetry
Telemetry modulation
On subcarrier **PCM/PSK/PM**
Direct modulation **Residual BPSK**
Telemetry coding **RS + Conv 7, 1/2**
Turbo 1/2
Turbo 1/6
Telemetry subcarrier frequency: **25 kHz (10 to 2,000 bps)**
281.25 kHz (8,000 to 20,000 bps)

Subcarrier waveform **Square wave**
Telemetry data rates:
Low subcarrier **20 - 12000 sym/s**
High subcarrier **48K - 600K sym/s**
Direct modulation (residual carrier) **705882 sym/s Residual BPSK**

Table 2-3. Ranging Characteristics

RANGING			
Waveform	**Sinewave**		
Maximum ranging frequency	**1 MHz**		
Range channel bandwidth	**1.4 MHz**		
Ranging Modulation Index	Mod Index (rad)	Mod Index (degrees)	Carrier Suppression (dB)
Uplink	**1.1**	**64.7**	**3.0**
Downlink	**0.3**	**17.8**	**0.2**

Table 2-4. Lucy Spacecraft Antenna Characteristics

S/C Antenna	Frequency Band	Gain (dBic)		Circuit/Path Loss (dB)		EIRP (dBm)	S/C Transmitter Output Power	Antenna Polarization	
		S/C Receive	S/C Transmit	S/C Receive	S/C Transmit			Uplink	Downlink
High Gain Antenna (HGA)	X-Band	41.7	43.4	1.8	0.8	86.9	27.3	RHCP	RHCP
Medium Gain Antenna (MGA)	X-Band	17.7	18.1	2.0	1.0	61.4	27.3	RHCP	RHCP
Low Gain Antenna (LGA)	X-Band	8.5	8.8	2.2	1.1	52.0	27.3	RHCP	RHCP

The Lucy telecom system information was excerpted from DSN-Lucy Mission Operations Interface Control Document (OICD), Released, July 20, 2021.

2.1.3 Lucy Small Deep Space Transponder

The SDST is a communications terminal providing a link between the Lucy spacecraft and the NASA Deep Space Network (DSN)

- Receives, demodulates, and transfers vehicle commands from Earth via an RF uplink to C&DH for processing
- Modulates spacecraft health/status and science data from C&DH onto a RF carrier or subcarrier for RF downlink to Earth
- Provides a RF navigational aide (ranging/Doppler)
- Two-way turnaround ranging or differential one-way ranging (DOR)
- Two-way Doppler for Radio Science around encounters and Navigation
- Redundancy: Block redundant units (i.e. primary and backup)

Design Heritage

- Developed by General Dynamics in cooperation with JPL in the late 90's
  - Deep Space 1, Spitzer Space Telescope, Mars Odyssey, MRO, MER, Phoenix
- Upgraded for MSL & Juno programs (aka GBIII), same design used on MAVEN
  - Upgraded ASICs
  - MAVEN procured Build-To-Print of GBIII X/X configuration
  - OSIRIS-REx/Insight/Mars 2020 (Group Buy IIIa) baseline is Build-To-Print of GBIII X/X configuration as well
  - Piece part substitutions due to obsolescence shortages or PCB rejection
- Total operating hours to date exceeds 900,000 hours

Transponder information excerpted from Lucy Subsystem CDR, Telecommunication Subsystem, C1 – Small Deep Space Transponder, July 17-18, 2019.

2.1.3.1 Lucy SDST Key Transmitter Specifications

Heritage GBIII design encompasses Lucy functional requirements

- *Receive and Decode X-Band Uplink Commands*
  - X-band (749f1) RF Input of -60 to -156 dBm
  - Supports 7.8125 to 4000 bps

- Transmit Downlink Telemetry and Ranging
  - X-band (880f1) RF Output power of +13 dBm
  - Coherent and Non-Coherent
  - 7 ½ Convolutional encoding
  - Differential One-Way Ranging (DOR)
  - Subcarrier or Direct Carrier
  - Modulation Index 0 to 135 degrees
  - Supports BPSK or QPSK Modulation

- 2-Way Doppler
- 1553 Monitor and Control Interface
- LVDS Telemetry and Command interfaces
- Size
  - Volume is 3500 cm^3 (=11.53cm x 18.08 cm x 16.64 cm)
  - Unit is mounted in “loaf of bread configuration”

- Weight
  - 3.3 kg specified maximum

- Power
  - State 1 (RX Only, DOR off) 11.9W nominal, 13.1W max
  - State 2 (RX + X-band Exciter, DOR on) 15.7 W nominal, 17.3W max

Transmitter specifications were excerpted from Lucy Subsystem CDR, Telecommunication Subsystem, C1 – Small Deep Space Transponder, July 17-18, 2019.

2.2 Data Product Overview

The Lucy Radio Science Investigation will use or produce:

1. DSN Tracking Data – These products are the spacecraft radiometric tracking information provided to the mission by the Deep Space Network (DSN) in the standard trk-2-34 format.
2. DSN Media Calibration Files – These products are the Lucy mission dependent media calibration data products provided to the mission by the DSN in standard trk-2-23 format. Specifically, the files archived by the Lucy mission are the ionosphere calibration files.

3. Spacecraft Small Forces Files - These provide the cumulative delta-V effect of attitude thruster firings over one or more specified intervals of time. In some cases, it also provides an estimate of the cumulative spacecraft mass loss due to the use of propellant in those attitude thrusters.
4. Sky Frequency Calibrated Data Products – The products are residual frequency files produced from the tracking (trk-2-34) data products.

2.3 Data Processing

The Lucy Science Operations Center (SOC) located is responsible for all Lucy science data processing. However, the Lucy tracking, and media calibration are provided to the SOC through the Navigation Operations Center (NOC). The NOC receives these files directly from the Deep Space Network (DSN). The Mission Operations Center (MOC) receives the small forces files from NAIF, and pushes these files to the SOC. Once files have been received by the SOC, they are stored in the SOC data repository for use by the science and operations teams.

The Radio Science Investigation Team retrieves the radio science data products from the SOC data repository and processes the tracking data through a pipeline to produce calibrated TNF Closed Loop Doppler files containing sky frequency, impact parameter, observed and calibrated Doppler shift in frequency and Differential Doppler.

2.3.1 Data Processing Level

Lucy Radio Science Subsystem (RSS) data products comply with NASA processing level standards as shown in Table 2-5. Data Processing Levels. RSS data products are derived from the previous level product.

Table 2-5. Data Processing Levels

Lucy Archive Data Product	PDS4 Processing Level	Description
N/A	Telemetry	An encoded byte stream used to transfer data from one or more instruments to temporary storage where the raw instrument data will be extracted. PDS does not archive telemetry data.
Raw Data Product (SOC documentation refers to this as Uncalibrated Data Product)	Raw	Original data from an instrument. If compression, reformatting, packetization, or other translation has been applied to facilitate data transmission or storage, those processes will be reversed so that the archived data are in a PDS approved archive format. For Lucy these are the DSN tracking and media calibration data products, as well as the NAIF small forces files.
	Partially Processed	Data that have been processed beyond the raw stage, but which have not yet reached calibrated status.
Calibrated Data Product	Calibrated	Data converted to physical units, which makes values independent of the instrument. For Lucy these are the radio science sky frequency products.
	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.

2.3.2 Data Product Generation

The generation of the tracking data, media calibration data, and small forces files are not discussed in this SIS, as they are produced outside of the Lucy SOC environment. Full descriptions of the tracking and media calibration products can be found in the PDS Radio Science Documentation bundle found at urn:nasa:pds:radiosci.documentation. A full description of the small forces files can be found in the Small Forces File SIS located in the Lucy radio science documentation collection, urn:nasa:pds:lucy.rss:document.

2.3.3 Data Flow

The MOC and NOC provide RSS files to the SOC as described in Section 2.3. Once files have been received by the SOC, they are stored in the SOC data repository for use by the science and operations teams, and processed through the archive pipeline to create PDS labels and bundles.

2.3.4 Labeling and Identification

All radio science products consist of a PDS4-compliant detached XML label that describes the content and format of the associated data files. These labels describe the content and format of the associated data product. Labels and products are associated by file name with the label having the same name as the data product except that the label file has an .xml extension. Labels are constructed with the PDS4 Product Class, Product_Observational sub-class. The Product_Observational sub-class describes a set of information objects produced by an observing system. A representative hierarchical description of the contents of Product_Observational is presented below. Note that not all classes are represented in every label.

Product_Observational
- Identification_Area - attributes that identify and name an object.
  - Logical_Identifier - name/location of file
  - Version_ID - version of product
  - Title - Name of file
  - Information_model_version - version of PDS4 information model used to create product
  - Product_Class - attribute provides the name of the product class (Product_Observational)
  - Modification_History - attributes describing changes in data product
- Observation_Area - attributes that provide information about the circumstances under which the data were collected.
  - Time_Coordinates - time attributes of data product
  - Primary_Results_Summary - high-level description of the types of products included in the collection or bundle
  - Investigation_Area - mission, observing campaign or other coordinated, large-scale data collection attributes
  - Observing_System - observing system (instrument) attributes
  - Target_Identification - observation target attributes
  - Discipline _Dictionaries – discipline specific attributes collected by specific discipline areas.
  - Mission_Area - mission specific attributes needed to describe data product
- File_Area_Observational - describes a primary data file and one or more tagged_data_objects contained within.
  - File - identifies the file that contains one or more data objects as described below.
    - Header – contains any attached file header information.
    - Table_Binary/Character/Delimited – contains classes that define binary or text type tables.
    - Array_* - contains classes that describe a number or 2D or 3D arrays, typically images or spectra.
- File_Area_Supplemental - describes a supplemental data file and one or more tagged_data_objects contained within.
  - File - identifies the file that contains one or more data objects as described below.
    - Table_Binary/Character/Delimited – contains classes that define binary or text type tables.
    - Array_* - contains classes that describe a number or 2D or 3D arrays, typically images or spectra.
    - Parseable_Byte_Stream – contains classes used to describe parseable data objects.
    - Encoded_*- contains classes used to describe encoded objects.

Information in the preceding paragraphs was distilled from the PDS4 Information Model provided by PDS. Additional information on product labels can be found at https://pds.nasa.gov/pds4/about/index.shtml.

2.3.4.1 Product Naming

Each of the radio science data products have a unique naming convention. The conventions are listed below.

The naming convention for the tracking data products (trk-2-34) products are as follows:
sc_YYYY_DOY_HHMMSS_YYYY_DOY_HHMMSS_DS.ext

Example: lucy_2023_247_163512_2023_248_015001_14.tnf

Where:
Sc = Spacexraft name; lucy
YYYY_DOY_HHMMSS = File start time in year_day of year_hour minute second
YYYY_DOY_HHMMSS = File end time in year_day of year_hour minute second
DS = Deep Space Network antenna number.
Ext = file extension; .tnf for data file, .xml for PDS4 label

The naming convention for the ionosphere media calibration data products are as follows:
gimcal_sc_YYYYmon_vlbi/dopr_YYYY_MM_DD.ext
Example: gimcal_49_2023sep_vlbi_2023_10_16

Where:
gimcal = always gimcal
gc = spacecraft number, for Lucy always 49
YYYYmon = year and month of file coverage
vlbi/dopr = file type, vlbi = Delta Differenced One-way Ranging; dopr = Doppler and range data
YYYY_MM_DD= delivery date of file
ext= file extension, .csp for data file, .xml for PDS4 label

The naming convention for the small forces file data products are as follows:
SSS_r/p_yymmdd1_yymmdd2_vxx.ext
Example: lcy_r_230925_230926_v05.sff

Where
SSS = spacecraft id: lcy
r/p = either r for reconstructed or p for predicted
yymmdd1 = the start time year, month, and day of the file
yymmdd2 = the end time year, month, and day of the file
vxx = the version number of the file
ext = the file extension: .sff for the data file, .xml for the PDS4 label

The naming convention for the Sky Frequency data products are as follows:

SggrrrrLxx_fff_yydddhhmm_vv.eee
with
S = spacecraft; L = Lucy
gg = ground station number; 25 = DSN25, Goldstone complex
rrrr = receiver system; TNFX = Trac-2-34 two-way single X-band
Lxx = processing level; L02 = calibrated processing Level-2
fff = data type; DPX = two-way Doppler X-band
yy = year; 22 = 2022
ddd = Day of year; 082 = DOY082
hh = hour
mm = minute; hhmm = start of tracking
vv = software version number
eee = file type extension; TAB = tabulated data file
XML = PDS label file for the respective TAB file

2.4 Standards Used in Generating Data Products

2.4.1 PDS Standards

All data products described in this SIS conform to PDS4 standards as described in the PDS Standards document noted in the Applicable Documents section of this SIS. Prior to public release, all data products will have passed both a data product format PDS peer review and a data product production pipeline PDS peer review to ensure compliance with applicable standards.

2.4.2 Time Standards

Time Standards used by the Lucy mission conform to PDS time standards.

2.4.3 Coordinate Systems

All coordinate systems used by the *Lucy* mission conform to IAU standards. A complete discussion of the coordinate systems and how they are deployed in the mission can be found in the document "***Lucy* Mission Coordinate System Plan"** found in the mission bundle documents collection.

A summary of the Lucy Mission coordinate system process is as follows. The Lucy project will establish a task force to define coordinate systems for each target. The coordinate systems will be reviewed and validated by PDS prior to data delivery, as outlined in the PDS Policy on Acceptable Body-Fixed Coordinate Systems (PDS Mission Proposer's Archiving Guide v4-r5, 21 Sept. 2016). In parallel, the Lucy team will engage the International Astronomical Union (IAU) Working Group on Cartographic Coordinates and Rotational Elements (WGCCRE) coordinate system standards for an official approval of the proposed coordinate systems. Based on our experience, IAU may take several months to approve a coordinate system, and therefore the Lucy team will proceed with PDS delivery using the coordinate systems agreed upon by the project and the PDS. Once final approval by IAU is achieved, the Lucy project will redeliver georeferenced data to PDS, as needed. Upon PDS validation of all the coordinate systems for each Trojan asteroid, all archive instrument products will be updated with the accepted coordinate system for delivery to the PDS 4.5 months after last data downlink for each flyby (with the exception of Eurybates and Polymele). PDS will also review the science content of flyby deliverables. Derived products will be produced with the approved coordinate system or updated with this information when it becomes available.

2.4.4 Data Storage Conventions

All radio science data products are stored as either binary or text tables. ASCII or UTF-8 text file generally, line endings are line-feed. Line endings are specified in the PDS4 .xml label that accompanies all data files.

2.5 Data Validation

The SOC has a comprehensive Verification and Validation (V&V) Plan for all software used at or developed by the SOC. All software is configuration controlled and any changes made follow the SOC Configuration Control Plan, which includes substantive testing of changes. During day-to-day production of raw data products from telemetry, check sums and spot checks are used to validate that software is producing data products correctly. In addition to software verification and validation, each *Lucy* data product has been peer reviewed for both PDS data format acceptability and scientific usefulness. No changes are expected to data formats after peer review. The SOC – SBN Configuration Control Plan governs any changes, should they be needed.

When data are prepared for submission to the PDS, both the Radio Science Investigation Team and SOC Teams will use PDS / mission-provided automated validation tools for conformance to the PDS4 standards. Validation of the science data contained within the radio science data products will, however, occur as a manual inspection by the Radio Science Investigation Team and the *Lucy* science team.

3. DETAILED DATA PRODUCT SPECIFICATIONS

3.1 Data Products Structure and Organization

The *Lucy* archive is organized into bundles for each instrument/detector, bundles for each discipline specific set of higher-order data products, and a mission bundle with mission-wide documentation, context and schema information. Each PDS bundle also contains a document collection, to provide the appropriate ancillary information to properly interpret and use the data. Radio science data products are structured as ASCII tabular data and are organized by data type and mission phase.

The radio science bundle structure is as follows:

Table 3-1. Radio science bundle and collection structure

Bundle	*Collection*	*LID*
Radio Science	data_*_sff	urn:nasa:pds:lucy.rss:data_*_sff
	data_*_skyfreq	urn:nasa:pds:lucy.rss:data_*_skyfreq
	data_*_trk234	urn:nasa:pds:lucy.rss:data_*_trk234
	data_*_ion	urn:nasa:pds:lucy.rss:data_*_ion
	document	urn:nasa:pds:lucy.rss:document

In each case the * indicates replacement by the mission phase. Possible mission phases include ega 1-3, cruise 1-7, Didymos, Dinkinesh, Donaldjohanson, Eurybates-Polymele, Leucus, Orus, or Patroclus-Menoetius.

3.2 Data Format Descriptions

The following sections describe in detail the formats of the radio science data products.

3.2.1 DSN Tracking (trk-2-34) and Media Calibration (ion) Data Product Format

The DSN Tracking and Navigation Files (trk-2-34) are natively formatted as a binary collection of approximately 18 different data record types. Not all data record types are present in each file. Each of the data record types can be described in a PDS4 .XML label as a PDS4 Table_Binary object. The difficulty in labeling the natively formatted trk-2-34 files is that data records are not sorted by type, meaning that in a worst-case scenario, the PDS .XML label would be required to have a Table_Binary specification for each data record in the trk-2-34 file, resulting in an XML label file that is hundreds of times larger in size than the data file. To remedy this unwieldy labeling result, the original trk-2-34 files (formatted according to urn:nasa:pds:radiosci.documentation:dsn.trk-2-34:2021-06-03), have been sorted by time and data record type. The resulting files conform to the PDS DSN TRK-2-34 for PDS4 Archiving Interface Document.

Media calibration files are unchanged from receipt at the SOC and are in the format described by urn:nasa:pds:radiosci.documentation:dsn.trk-2-23:2008-03-05.

All other DSN files are mission independent and can be found in the mission independent DSN files bundle archived at the PDS Geoscience Node (https://pds-geosciences.wustl.edu/radiosciencedocs/urn-nasa-pdsjpl_dsn_mmm/). The DSN SIS documents are not mission specific, they are applicable to all DSN produced data products.

3.2.2 Small Forces File Data Product Format

The Lucy navigation team also uses Navigation and Ancillary Information Facility (NAIF) produced Small Forces Files (SFF). These files record the cumulative delta-v effect of attitude thruster firings over a specified time period(s). An estimate of mass loss due to fuel usage may also be included. In some cases, the SFFs may have overlapping time frames. The file that is produced later in time will incorporate any updated SPICE kernels. It is recommended to always use the latest version of data.

The Small Forces Files are formatted natively as character files with a KEYWORD=VALUE header structure followed by data records in a comma separated variable structure. The full format is described in the Small Forces File Software Interface Specification (located in the Lucy radio science bundle document collection).

3.2.3 Sky Frequency Data Product Format

The Sky Frequency Data Product is a calibrated translated two-way TNF Closed Loop Doppler file containing sky frequency, predicted sky-frequency, frequency residuals, distance and received signal power.

The format description is the following:

Column	description
1	Sample number
2	UTC time; The UTC receiver date and time (t_r) of this measurement, in the format CCYY-MM-DDTHH:MM:SS.sss
3	Fractions of Day of Year (DOY); The day-of-year (and fraction) corresponding to UTC TIME (column 2) where 1.00000000 is at 0h on 1 January of the current year. Format F12.8
4	Ephemeris second (s); Seconds from 12h 1 January 2000 TDB corresponding to UTC TIME (column 2); includes leap seconds, if any. Format F16.6
5	Distance (km); the geometric distance of the spacecraft from the center of mass of the reference body when the spacecraft transmitted the photon which was received on Earth at UTC TIME. Format F16.6
6	Not used in closed-loop mode; set to 0000-00-00T00:00:00.000
7	Not used in closed-loop mode; set to -999999999.999999
8	Not used in closed-loop mode; set to -99999.999999

9	Received X-band antenna frequency (sky-frequency) (Hertz); Frequency of the signal at the terminals of the receiving antenna structure at UTC TIME (t_r). Format F17.6 Set to -999999999.999999 for missing or corrupted data.
10	Predicted X-band frequency (Hertz) Based on the reconstructed orbit file or SPICE kernels. Expected frequency of the signal at the terminals of the receiving antenna structure at UTC TIME in column 2 . The calculation includes geometrical effects (relative positions and motions of ground station and spacecraft, including Earth rotation and light time adjustments) and a model-based correction for one- or two-way (as appropriate) propagation through the Earths neutral atmosphere. Format F17.6
11	Correction for Earth atmosphere propagation (Hertz); Correction term for the propagation of the signal in the Earth atmosphere, based on meteorological data observed at the ground station site (MET-files); Format F9.6
12	Residual calibrated X-band frequency shift (Hertz); Value in column 9 minus value in column 10; Format F12.6
13	Received signal power level (dB); Signal level from AGC in decibel (dB). This value is set to -999.9 if it is not available. Format F6.1
14	Not used in single frequency radio mode; set to -999.999999
15	Not used in closed-loop mode; set to -99999.999999
16	Not used in closed-loop mode; set to-999.9
17	Not used in closed-loop mode; set to -999.9

3.3 Label and Header Descriptions

All radio science data products are produced with PDS4 compliant detached XML labels. Examples of these labels can be found in the mission bundle, document collection.

4. APPLICABLE SOFTWARE

The sky frequency Data Product file is formatted in ASCII and can be read using any available editor.

PDS4 XML labels can be opened using most XML aware text editors.

PDS4 utility programs such as the PDS4 Viewer and other IDL- and Python based PDS4 readers are available through the PDS Tool Registry (https://pds.jpl.nasa.gov/tools/toolregistry/)

4.1 Utility Programs

There are no utility programs to use with these products.

4.2 Applicable PDS Software Tools

The PDS supplies a number of software tools that can be used in conjunction with PDS data products. Please refer to the PDS4 software website (http://pds.nasa.gov/pds4/software/index.shtml) for additional information on these tools.

5. APPENDICES

5.1 ACRONYM LIST

Table 5-1: **Acronym List**

Acronym	Definition
DMAP	Data Management and Archive Plan
DPI	Deputy Principal Investigator
ICD	Interface Control Document
LDAT	*Lucy* Data Archive Team
LEISA	Linear Etalon Imaging Spectral Array
L'LORRI	*Lucy* Long Range Reconnaissance Imager
L'Ralph	Instrument comprised of LEISA and MVIC
L'TES	*Lucy* Thermal Emission Spectrometer
MGSS	Multi-Mission Ground System and Services
MOC	Mission Operations Center
MVIC	Multi-spectral Visible Imaging Camera
NAIF	Navigation and Ancillary Information Facility
NAV	Navigation
NOC	Navigation Operations Center
NSSDCA	National Space Science Data Coordinated Archive
OPS	Operations
PDS	Planetary Data System
PI	Principal Investigator
SBN	Small Bodies Node
SC	Spacecraft

SIS	Software Interface Specification
SOC	Science Operations Center
SPICE	Data sets that are called kernel files and stand for: • **S**pacecraft trajectory, given as a function of time (SPK kernels). • **P**lanet, satellite, comet, asteroid, associated physical, and cartographic constants (PCK kernels). • **I**nstrument information, including internal timing and other geometric information (IK kernels). • **C** matrix, time-tagged orientation data of mounted structures and instruments (CK kernels). • **E**vents for the spacecraft and ground data system, both planned and unplanned (EK kernels).
ST	Science Team
SwRI	Southwest Research Institute
TTCAM	Terminal Tracking Camera
TBD	To Be Determined