Gravity/Radio Science (G/RS) Investigation

PDS Archive

Software Interface Specification

Raw and Calibrated Data

Rev. 0.9

May 23, 2023

<ID>

Prepared by

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Europa Clipper

Gravity/Radio Science Investigation

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1 Introduction

This software interface specification (SIS) describes the format and content of the Europa Clipper Gravity/Radio Science (G/RS) Planetary Data System (PDS) data archive for Raw and Calibrated data products. It includes descriptions of the data products and associated metadata, and the archive format, content, and generation pipeline.

1.1 Document Change Log

Table 1: Document change log

Version	Change	Date	Affected portion
0.1	Initial draft	July 6, 2021	All
0.2	First revision after team review & PDS review	August 25, 2021	All
0.3	Table 16 updated	Sept 22, 2021	
0.4	Updated to use multi-mission data bundle	June 13, 2022	Sections 3,4,5
0.5	New format for Small Forces Files, separate ramp table into different product in calibrated bundle	August 4, 2022	Sections 3,4,5
0.9	Update from PDS Peer review conducted March/April 2023	May 15, 2023	All

1.2 TBD Items

Table 2 lists items that are not yet finalized.

Table 2: List of TBD items

Item	Section(s)	Page(s)
References/Guiding documents	2.3	
Table 7 DSN Locations DSS-23, 33, 53	2.6.3	
Any/all RED items		

1.3 Abbreviations

Table 3: Abbreviations and their meanings

Abbreviation	Meaning
AGC	Automated Gain Control
APC	Antenna Pointing and Control (DSN Subsystem) *—or—* Antenna Phase Center File (data file type)

Abbreviation	Meaning
APSS	Auxiliary Payload Sensor Subsystem
ASCII	American Standard Code for Information Interchange
ALB	Automated Link Build (DSN Subsystem)
BWG	Beam Waveguide (DSN Antenna)
CCSDS	Consultative Committee for Space Data Systems
CDR	Calibrated Data Record
CDSCC	Canberra Deep Space Communications Complex
CHDO	Compressed Header Data Object
CODMAC	Committee on Data Management, Archiving, and Computing
CR	Carriage Return
CSP	Control Statement Processor language
CSV	Comma Separated Value
DDA	DSN Downlink Array (DSN Subsystem)
DOM	Distributed Object Manager
DOY	Day of Year
DSCC	Deep Space Communications Complex
DSN	Deep Space Network
DSS	Deep Space Station
EDR	Experiment Data Record
EOP	Earth Orientation Parameters
ETX	Exciter-Transmitter Subsystem (DSN Subsystem)
FBA	FanBeam Antenna
FEI	File Exchange Interface
FOV	Field of View
FTP	File Transfer Protocol
FTS	Frequency and Timing Subsystem (DSN Subsystem)
GB	Gigabyte(s)
GDSCC	Goldstone Deep Space Communications Complex
GEO	PDS Geosciences Node (Washington University, St. Louis, Missouri)
GNSS	Global Navigation Satellite System (e.g. Global Positioning System)

Abbreviation	Meaning
G/RS	Gravity/Radio Science
GSFC	Goddard Space Flight Center (Greenbelt, MD)
HEF	High Efficiency (DSN Antenna)
HGA	High Gain Antenna
HK	Housekeeping
HSB	High-Speed Beam Waveguide (DSN Antenna)
HTML	Hypertext Markup Language
ICD	Interface Control Document
IF	Intermediate Frequency
IPT	Io Plasma Torus
IM	Information Model
ION	Ionosphere (in reference to Ionosphere calibration files)
ISO	International Standards Organization
IQ	In-phase and Quadrature
JPL	Jet Propulsion Laboratory (Pasadena, CA)
LF	Line Feed
LGA	Low Gain Antenna
LID	Logical Identifier
LIDVID	Versioned Logical Identifier
LNA	Low Noise Amplifier (DSN Subsystem)
LVO	Label Value Object
MB	Megabyte(s)
MD5	Message-Digest Algorithm 5
MDSCC	Madrid Deep Space Communications Complex
MGA	Medium Gain Antenna
MOS	Mission Operation System
NAIF	Navigation and Ancillary Information Facility (JPL)
NASA	National Aeronautics and Space Administration
NAV	Navigation
NMC	Network Monitoring and Control (DSN Subsystem)

Abbreviation	Meaning
NSSDCA	NASA Space Science Data Coordinated Archive
OLR	Open Loop Receiver (DSN Subsystem)
PDS	Planetary Data System
PDS4	Planetary Data System Version 4
PN	Pseudonoise (in reference to DSN ranging technique)
RA	Restricted ASCII
RAD	Radiometer
RDA	Raw Data Archive
RDEF	Raw Data Exchange Format
RF	Radio Frequency
RFS	Radio Frequency Subsystem
RS	Radio Science
RSS	Radio Science Subsystem
SCM	Spacecraft Mass File (data file)
SDS	Science Data System
SCT	Spacecraft Team
SFDU	Standard Formatted Data Unit
SFF	Small Forces Files
SIS	Software Interface Specification
SNR	Signal-to-Noise Ratio
SPC	Signal Processing Center (DSN Location)
SPS	Service Preparation Subsystem (DSN Subsystem)
SPICE	Spacecraft, Planet, Instrument, C-matrix, and Events (NAIF toolkit)
SPK	Spacecraft and Planetary ephemeris Kernel (NAIF data format)
SRA	Sequential Ranging Assembly (DSN Subsystem)
TBD	To Be Determined
TDM	Tracking Data Message (data format)
TNF	Tracking and Navigation File (TRK 2-34)
TRO	Troposphere (in reference to Troposphere calibration files)
TSAC	Tracking System Analytic Calibration (DSN Subsystem)

Abbreviation	Meaning
URN	Uniform Resource Name
UTC	Universal Time, Coordinated
VID	Version Identifier
WEA	Weather (in reference to DSN Weather files)
XML	eXtensible Markup Language

1.4 Glossary

Many of these definitions are taken from Appendix A of the PDS4 Concepts Document, pds.nasa.gov/pds4/doc/concepts. The reader is referred to that document for more information.

Archive – A place in which public records or historical documents are preserved; also the material preserved – often used in plural. The term may be capitalized when referring to all of PDS holdings – the PDS Archive.

Basic Product – The simplest product in PDS4; one or more data objects (and their description objects), which constitute (typically) a single observation, document, etc. The only PDS4 products that are *not* basic products are collection and bundle products.

Bundle Product – A list of related collections. For example, a bundle could list a collection of raw data obtained by an instrument during its mission lifetime, a collection of the calibration products associated with the instrument, and a collection of all documentation relevant to the first two collections.

Class – The set of attributes (including a name and identifier) which describes an item defined in the PDS Information Model. A class is generic – a template from which individual items may be constructed.

Collection Product – A list of closely related basic products of a single type (e.g. observational data, browse, documents, etc.). A collection is itself a product (because it is simply a list, with its label), but it is not a *basic* product.

Data Object – A generic term for an object that is described by a description object. Data objects include both digital and non-digital objects.

Description Object – An object that describes another object. As appropriate, it will have structural and descriptive components. In PDS4 a 'description object' is a digital object – a string of bits with a predefined structure.

Digital Object – An object which consists of real electronically stored (digital) data.

Identifier – A unique character string by which a product, object, or other entity may be identified and located. Identifiers can be global, in which case they are unique across all of PDS (and its federation partners). A local identifier must be unique within a label.

Label – The aggregation of one or more description objects such that the aggregation describes a single PDS product. In the PDS4 implementation, labels are constructed using XML.

Logical Identifier (**LID**) – An identifier which identifies the set of all versions of a product.

Versioned Logical Identifier (LIDVID) – The concatenation of a logical identifier with a version identifier, providing a unique identifier for each version of product.

Manifest - A list of contents.

Metadata – Data about data – for example, a 'description object' contains information (metadata) about an 'object.'

Object – A single instance of a class defined in the PDS Information Model.

PDS Information Model – The set of rules governing the structure and content of PDS metadata. While the Information Model (IM) has been implemented in XML for PDS4, the model itself is implementation independent.

Product – One or more tagged objects (digital, non-digital, or both) grouped together and having a single PDS-unique identifier. In the PDS4 implementation, the descriptions are combined into a single XML label. Although it may be possible to locate individual objects within PDS (and to find specific bit strings within digital objects), PDS4 defines 'products' to be the smallest granular unit of addressable data within its complete holdings.

Tagged Object – An entity categorized by the PDS Information Model, and described by a PDS label.

Registry – A data base that provides services for sharing content and metadata.

Repository – A place, room, or container where something is deposited or stored (often for safety).

XML – eXtensible Markup Language.

XML schema – The definition of an XML document, specifying required and optional XML elements, their order, and parent-child relationships.

2 Overview

2.1 Purpose and Scope

The purpose of this SIS document is to provide users of the Europa Clipper Gravity/Radio Science Raw and Calibrated data archive with a detailed description of the data products and how they are generated, along with a description of the PDS4 archive bundle, the structure in which the data products, documentation, and supporting material are stored. 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.

This SIS covers raw and calibrated data products, which have been generated by the G/RS team and are intended to be archived in the PDS. In particular, these products are primarily tracking data and calibration files from the NASA Deep Space Network (DSN). Raw data products include closed-loop tracking data as TRK 2-34 Tracking and Navigation Files (TNF), open-loop recordings as 0222-Science Open Loop Receiver (OLR) data, troposphere calibration files (TRO), ionosphere calibration files (ION), DSN weather files (WEA), Earth orientation parameters (EOP) files, and spacecraft telemetry information. Calibrated data products include processed open-loop data files (OLF) and processed uplink frequency profiles (ULF) as ramp tables. Of particular interest to users may be Tables 14, 15, 17 and 18, which highlight the naming convention and how to find files by a particular time period of interest.

2.2 SIS Contents

This SIS describes how the G/RS investigation acquires data, and how the data are processed, formatted, labeled, and uniquely identified. The document discusses standards used in generating the data products and software that may be used to access the products. The data structure and organization are described in sufficient detail to enable a user to read and understand the data.

Appendices include a description of the file naming conventions used in the G/RS data archive, and a list of cognizant persons involved in generating the archive.

2.3 Applicable Documents

[1] The PDS4 Data Provider's Handbook, Version 1.19.0, October 1, 2022.

[2] Planetary Data System Standards Reference, JPL D-7669, Part 2, Version 1.19.0, October 1, 2022.

[3] PDS4 Data Dictionary, Abridged, Version 1.19.0.0, September 19, 2022.

[4] Planetary Data System (PDS) PDS4 Information Model Specification, Version 1.19.0.0, September 19, 2022.

[5] Radio Science Documentation Bundle, Planetary Data System Geosciences Node. https://pds-geosciences.wustl.edu/radiosciencedocs/urn-nasa-pds-radiosci_documentation/

[6] Europa Clipper Science Data Management Plan, JPL D-92253, Revision C, August 6, 2021.

[7] DSN Telecommunications Link Design Handbook, DSN No. 810-005, Rev E. JPL D-19379. October 28, 2015. http://deepspace.jpl.nasa.gov/dsndocs/810-005/

[8] TRK 2-34 DSN Tracking System Data Archival Format, DSN No. 820-013, TRK-2-34, Rev N. JPL D-76488. November 7, 2013.

[9] 0222-Science Open Loop Data Interface, DSN No, 820-013, 0222-Science, Rev B. JPL D-76531. <tbd_release_date>

[10] TRK 2-23 Media Calibration Interface, DSN No. 820-013, TRK-2-23, Rev C. JPL D-16765. March 5, 2008.

[11] TRK 2-24 Tracking System Interfaces Weather Data Interface, DSN No. 820-013, TRK-2-24, Rev A. JPL D-16765. March 15, 2006.

[12] TRK-2-21 DSN Tracking System Earth Orientation Parameter Data Interface, DSN No. 820-013, TRK-2-21, Rev E. JPL D-76520. July 14, 2020.

[13] Multi-Mission Small Forces File (SFF) Software Interface Specification, Version 2 Release 2, JPL Mission Design and Navigation Section document, November 18, 2020.

[14] Mazarico, E., Buccino, D., Castillo-Rogez, J. *et al.* The Europa Clipper Gravity and Radio Science Investigation. *Space Sci Rev* **219**, 30 (2023). https://doi.org/10.1007/s11214-023-00972-0

[15] Buccino, Dustin, et al, G/RS Data Processing & Calibration Document, <tbd>

The PDS4 Documents [1] through [4] are subject to revision. The most recent versions may be found at http://pds.nasa.gov/pds4/doc/. The G/RS PDS4 products specified in this SIS have been designed based on the versions current at the time, which are those listed above.

References [8], [9], [10], [11], [12], and [13] are included either in the documents collection in this archive or the PDS Radio Science Documentation Bundle [5]: https://pds-geosciences.wustl.edu/radiosciencedocs/urn-nasa-pds-radiosci_documentation/

2.4 Audience

This document serves both as a Data Product SIS and an Archive SIS. It describes the format and content of G/RS data products in detail, and the structure and content of the archive in which the data products, documentation, and supporting material are stored. This SIS is intended to be used both by the investigation team to generate the archive, and by data users to understand the format and content of the archive. Typically, these individuals include scientists, data analysts, and software engineers.

2.5 Europa Clipper Mission

The overarching goal of NASA's Europa Clipper mission is to explore Europa to investigate its habitability. This goal traces to three mission objectives consisting of characterizing the ice shell and any subsurface water, including their heterogeneity, ocean properties, and the nature of surface–ice–ocean exchange; understanding the habitability of Europa's ocean through composition and chemistry; understanding the formation of surface features, including sites of recent or current activity, and characterizing high science-interest localities.

The mission will place a large, flagship-class spacecraft in orbit around Jupiter. Through a series of more than 40 flybys of Europa with closest approach altitudes varying from 25 km to 2700 km above the surface, the Europa Clipper spacecraft will investigate these objectives. A series of science instruments will collect data during each encounter: the Plasma Instrument for Magnetic

Sounding (PIMS), the Europa Clipper Magnetometer (ECM), the Mapping Imaging Spectrometer for Europa (MISE), the Europa Imaging System (EIS), the Radar for Europa Assessment and Sounding: Ocean to Near-surface (REASON), the Europa THermal Emission Imaging System (E-THEMIS), the MAss SPectrometer for Planetary EXploration/Europa (MASPEX), the Ultraviolet Spectrograph/Europa (UVS), the SUrface Dust Mass Analyzer (SUDA), and the Gravity/Radio Science (G/RS) Investigation.

Europa Clipper has a launch readiness date in October 2024 and will launch on a Mars-Earth Gravity Assist (MEGA) trajectory. Europa Clipper will arrive at Jupiter in April 2030. Upon arrival at Jupiter, the mission will execute a Ganymede gravity assist 11 hours before the Jupiter Orbit Insertion (JOI) main engine burn. After JOI, the spacecraft will execute several flybys of Ganymede and Callisto to setup for the Europa science tour.

The Europa science tour consists of two campaigns. Europa Campaign 1 will focus on the sunlit anti-Jovian hemisphere and Europa Campaign 2 will focus on the sunlit sub-Jovian hemisphere During each campaign, the spacecraft will be conducting repeat flybys of Europa on a regular cadence. The campaigns will be separated by a “switch flip” phase during which the spacecraft will conduct a sequence of Europa and Callisto flybys to setup the orbit.

2.6 G/RS Instrument Description

The G/RS investigation utilizes the X-band telecommunications capability of the Europa Clipper spacecraft in combination with the coherent radiometric tracking equipment at the Deep Space Network (DSN) to perform radio science experiments. The spacecraft part of the radio science instrument is described in Section 2.6.2 followed by a description of the DSN (ground) part of the instrument in Section 2.6.3.

For more information about the G/RS Investigation, refer to Mazarico et al 2023 [14].

2.6.1 Science Objectives

During close-in encounters, the G/RS investigation will measure the gravitational field and ionosphere of Europa by measuring the frequency of the radio signal.

The primary objective of the G/RS investigation is measuring the tidal Love number k_2, a diagnostic measure of the presence of a global subsurface ocean. Additional investigation focus objectives include:

- Investigate whether Europa is in hydrostatic equilibrium by improving measurements of the J2 and C22 gravity field coefficients, placing constraints on the deep interior
- Improve measurements of Europa’s rotational state, particularly pole position and longitude libration, to constrain coupled geochemical and physical models
- Improve Europa’s low degree (spherical harmonic degree < 10) gravitational field coefficients and conduct line-of-sight analysis to probe the near-surface.
- Characterize the spatial distribution of plasma in Europa’s ionosphere

Furthermore, radio tracking of Europa Clipper will improve the orbital position knowledge of the Galilean satellites and characterize the Laplace resonance.

In some encounters, the Europa Clipper spacecraft will be occulted by Europa itself, or fly through Europa’s ionosphere in-situ. During these times, the coherent radio signal can be interpreted to measure the column electron content of Europa’s ionosphere, and constrain models of Europa’s ionosphere. During the course of the mission, the spacecraft may also be able to sample the Io plasma torus with the radio system.

Other radio science experiments using this dataset are likely possible. Such experiments include reconstruction of the trajectory of Europa Clipper spacecraft, occultations of other bodies in the Jovian system, or gravity studies of other objects in the Jovian system.

2.6.2 Europa Clipper Telecommunications System

The Europa Clipper telecommunications system uses a Frontier Radio, designed by the Johns Hopkins Applied Physics Laboratory (APL), as the transponder. There are two redundant radios. The Frontier Radio on Europa Clipper is configured to receive uplink at X-band (7170 MHz) and downlink at both X-band (8424.5 MHz) and Ka-band (31860 MHz). The respective turnaround ratios (defined as the ratio of the uplink frequency over the downlink frequency) are 880/749 for the X-up/X-down link and 3328/749 for the X-up/Ka-down link. Under normal operating conditions, the radio can be configured to operate at either X-band or Ka-band, but not simultaneously.

A block diagram of the radio system is shown in Figure 1.

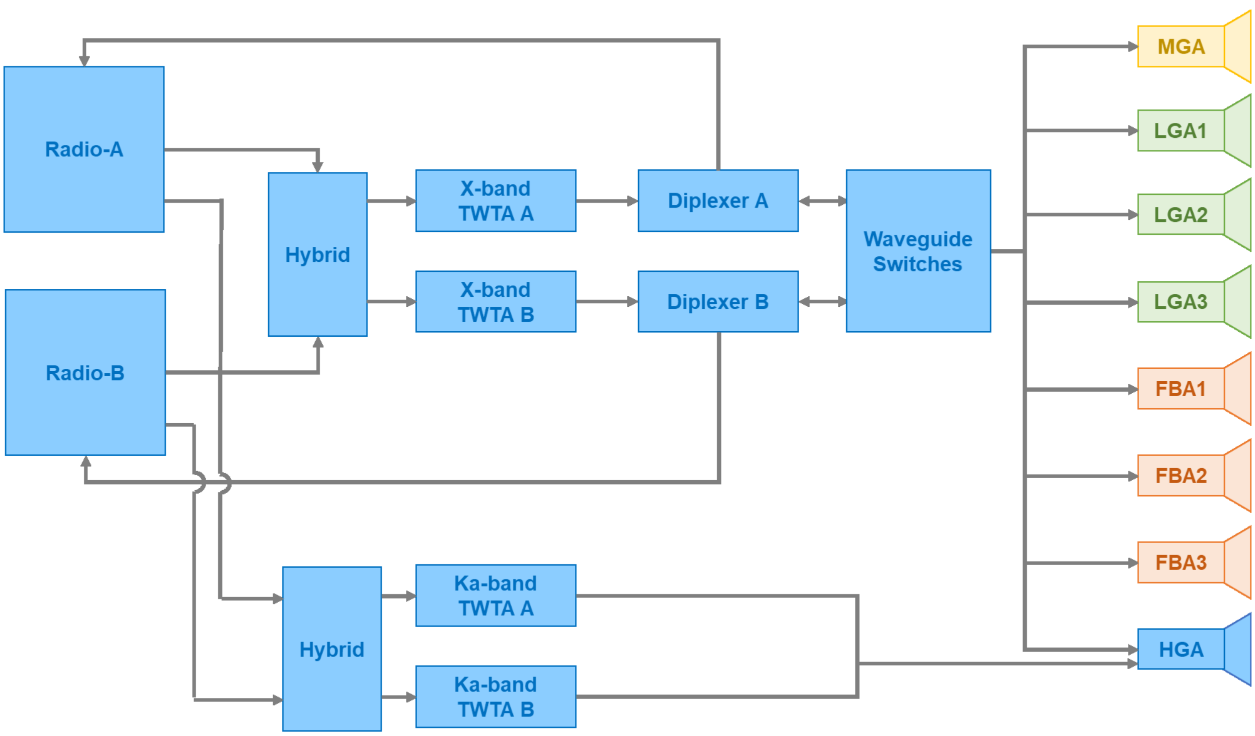

Figure 1: Europa Clipper telecommunications block diagram

The Frontier Radio transmits the X-band signal through a 20 Watt Traveling Wave Tube Amplifier (TWTA) and Ka-band through a 35 W TWTA, each of which amplifies the power for transmission. The signal goes through a diplexer and a series of switches until out the horn of the desired antenna. Europa Clipper has a set of eight antennas: a High Gain Antenna (HGA), a Medium Gain Antenna (MGA), three Low Gain Antennas (LGAs), and three FanBeam Antennas (FBAs). Only the HGA is capable of both X-band and Ka-band transmission; the MGA, LGAs, and FBAs are limited to X-band only. Figure 2 shows the placement of the radio antennas onboard the Europa Clipper spacecraft.

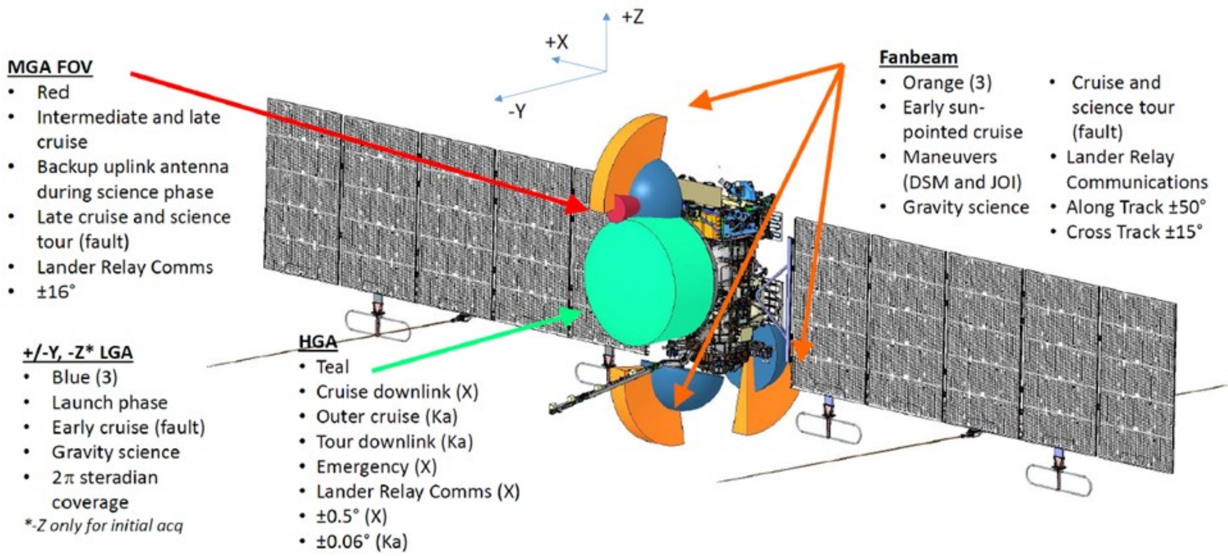

Figure 2: Europa Clipper spacecraft antenna locations and fields of view.

The table below describes the physical coordinates of the antennas. The coordinate system is the Europa Spacecraft bus frame, referred to as the "EUROPAM_SPACECRAFT" frame in SPICE Kernels.

Table 4: Pre-launch Europa Clipper antenna coordinates with respect to the HGA boresight phase center. The coordinates are derived from mechanical drawings of the spacecraft and are the best estimates of the antenna phase center pre-launch.

Antenna	Boresight Direction	X (millimeters)	Y (millimeters)	Z (millimeters)
HGA	-Y	0	0	0
MGA	-Y	0	-314	-560
LGA1	+Y	-454	0	-513
LGA2	-Y	-349	-229	-197
LGA3	-Z	0	0	-283
FBA1	-Y/+Z	390	-409	50
FBA2	-Y/-Z	-939	-495	856
FBA3	+Y/-Z	-1083	505	610

Europa Clipper is identified by the Deep Space Network using a spacecraft identification code shown in Table 5.

Table 5: Europa Clipper DSN mission name, abbreviation, and ID code

Mission Name	Abbreviation	Spacecraft ID
Europa	EURC	159

2.6.3 Deep Space Network

The DSN is the ground network that provides tracking and communications for Europa Clipper. A high-level description of the DSN from the perspective of radio science is described in this section; however, users should reference the current version of the official DSN Telecommunications Link Design Handbook [7] for the latest information.

2.6.3.1 Instrument Overview

Three Deep Space Communications Complexes (DSCCs) comprise the DSN. The Goldstone DSCC (GDSCC) is located near Barstow, CA; the Canberra DSCC (CDSCC) is located near Canberra, Australia; and the Madrid DSCC (MDSCC) is located near Madrid, Spain. The complexes are strategically placed roughly 120 degrees in longitude apart to give continuous coverage of a point in the sky as the Earth rotates. Each complex is equipped with several antennas, including one 70-meter antenna, a set of 34-m Beam Wave Guide (BWG) antennas, associated electronics, and operational systems.

Primary activity at each complex is transmission of commands to and reception of telemetry data from active spacecraft. Transmission and reception are possible in several radio-frequency bands, the most common being S-band (nominally a frequency of 2100-2300 MHz), X-band (7100-8500 MHz), and Ka-band (31800-32300 MHz). At X-band, transmitter output power is typically 20 kW, though 80 kW transmitters are available at some stations.

Ground stations have the ability to transmit coded and uncoded waveforms that can be echoed by distant spacecraft. Analysis of the received coding allows navigators to determine the distance to the spacecraft; analysis of Doppler shift on the carrier signal allows estimation of the line-of-sight spacecraft velocity. Range and Doppler measurements are used to calculate the spacecraft trajectory and to infer gravity fields of objects near the spacecraft.

Ground stations can record spacecraft signals that have propagated through or been scattered from target media. Measurements of signal parameters after wave interactions with surfaces, atmospheres, rings, and plasmas are used to infer physical and electrical properties of the target.

The DSN is managed by the Jet Propulsion Laboratory (JPL) of the California Institute of Technology for the U.S. National Aeronautics and Space Administration.

2.6.3.2 Subsystems

The Deep Space Communications Complexes (DSCCs) are an integral part of the Radio Science instrumentation, along with the spacecraft telecommunications and Radio Frequency Subsystem. Their system performance directly determines the degree of success of Radio Science investigations, and their system calibration determines the degree of accuracy in the results of the experiments. The following paragraphs describe the functions performed by the individual subsystems of a DSCC. This material has been adapted from DSN 810-005, Telecommunications Link Design Handbook [7].

Each DSCC includes a set of antennas, a Signal Processing Center (SPC), and communication links to JPL. The general configuration is illustrated below; antennas (Deep Space Stations, or DSS) are listed in the table.

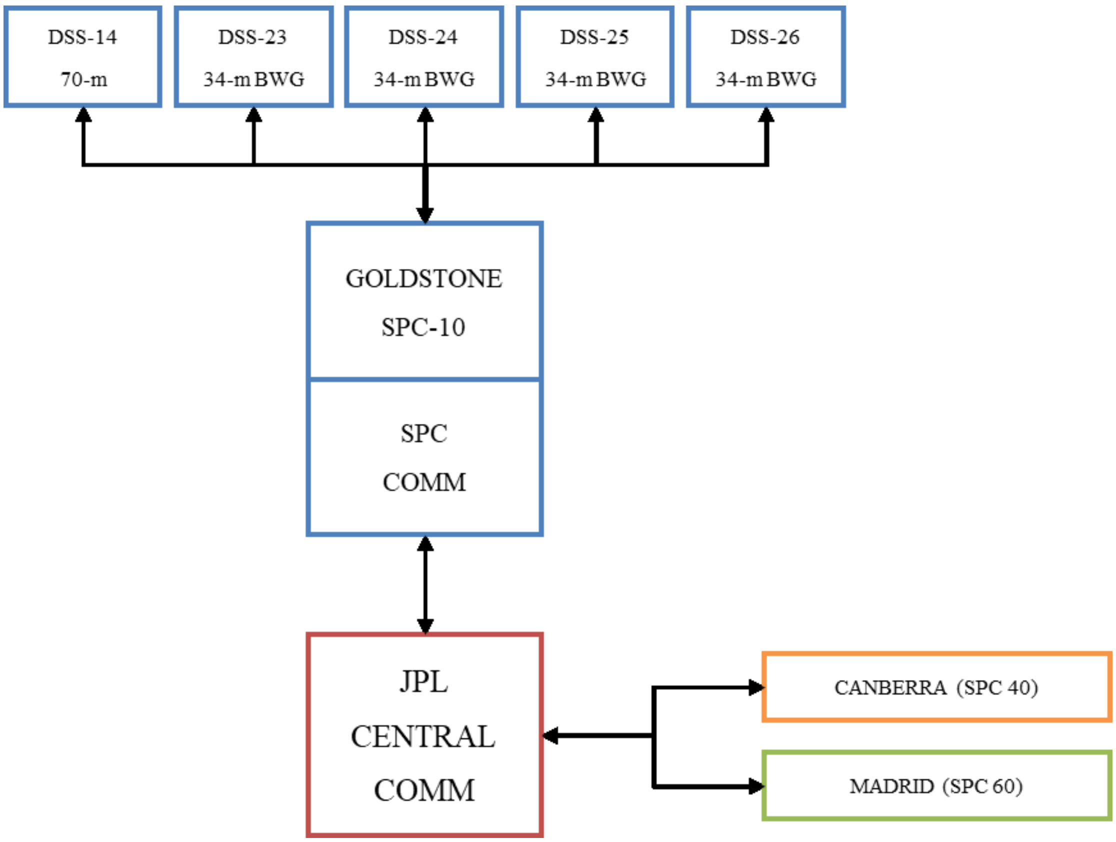

Figure 3: General configuration of the NASA Deep Space Network, showing the Goldstone Deep Space Communications Complex in detail. The remaining complexes are configured similarly.

Table 6: DSS distribution among complexes

Antenna Type	Goldstone SPC-10	Canberra SPC-40	Madrid SPC-60
34-meter BWG	DSS-23* DSS-24 DSS-25 DSS-26	DSS-33* DSS-34 DSS-35 DSS-36	DSS-53 DSS-54 DSS-55 DSS-56
70-meter	DSS-14	DSS-43	DSS-63
Developmental	DSS-13		

* Antennas in planning or construction phase as part of the DSN Aperture Enhancement Program (DAEP). DSS-23 planned completion October 2025; DSS-33 planned completion October 2027; DSS-53 planned completion January 2023

Subsystem interconnections at each DSCC are shown in the diagram below, and they are described in the sections that follow. The Network Monitor and Control (NMC) Subsystem is connected to all other subsystems.

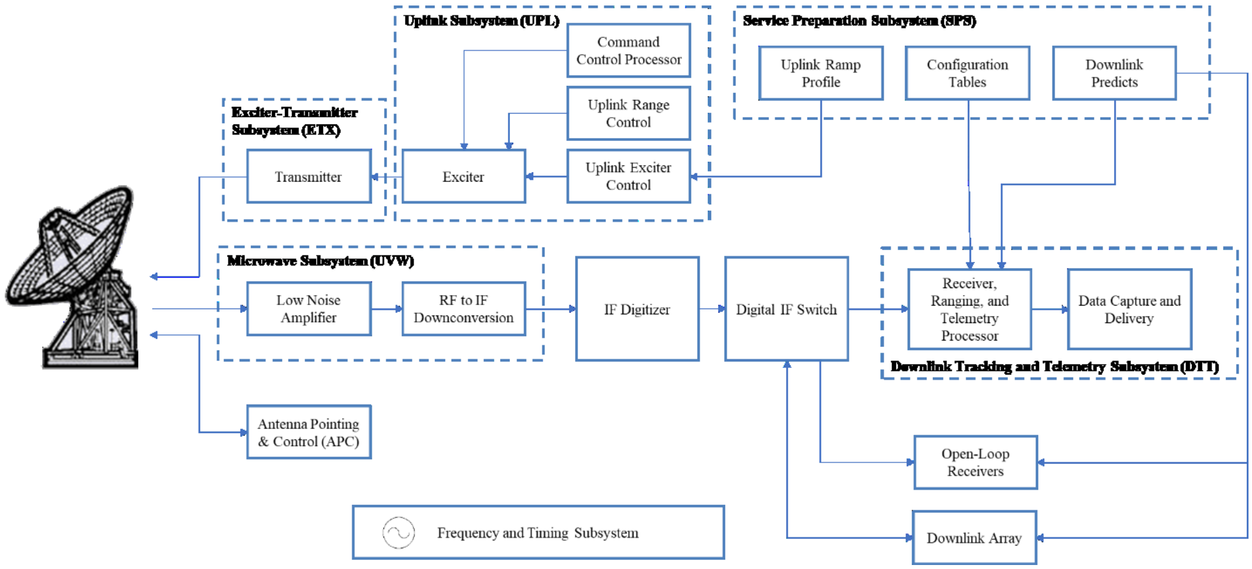

Figure 4: General configuration of a DSS

2.6.3.2.1 Service Preparation Subsystem

The Service Preparation Subsystem (SPS) is an integrated system to provide the required data products to execute a DSN tracking pass. The SPS ingests the DSN schedule, which is negotiated between projects 10-20 weeks in advance, the spacecraft ephemeris file from the project navigation team, a Sequence of Events (SOE), and configuration parameters. Configuration parameters include, but are not limited to, spacecraft best lock frequency, turnaround ratios, and telemetry modulation information. The SPS generates a Support Data Package (SDP) for each track, which is then transmitted to the DSN complex for execution.

2.6.3.2.2 Automated Link Build

The Automated Link Builder (ALB) – not pictured in Figure 4 – is a subsystem to provide automation to the DSN. The project and DSN operators provide a list of tracking requirements to the DSN SPS, and the ALB will automatically assign the required equipment from the SDP. DSN operators can manually override the ALB for complex tasks, or swap equipment as needed in order to resolve discrepancies in the link.

2.6.3.2.3 Network Monitor and Control Subsystem

The Network Monitor and Control Subsystem (NMC) provides all the interconnections between equipment in the DSN. The NMC receives real-time information from subsystems during their operation, allowing the operators access to that information. Control of most of subsystems, as well as the handling and displaying of any responses to control directives and configuration and status information received from each of the subsystems, is done through the NMC. The effect of this configuration is to centralize the control, display, and archiving functions necessary to operate a DSN antenna. Communication among the various subsystems is done using a Local Area Network (LAN) hooked up to each subsystem.

2.6.3.2.4 Antenna Mechanical Systems

Typically, Radio Science activities require support from either the 70-m and/or 34-m BWG antenna subnets. The antennas at each DSCC function as large-aperture collectors that, by double reflection, cause the incoming radio frequency (RF) energy to enter the feed horns. The large collecting surface of the antenna focuses the incoming energy onto a subreflector, which is adjustable in both axial and angular position. These adjustments are made to correct for gravitational deformation of the antenna as it moves between zenith and the horizon; the deformation can be as large as 5 cm. The subreflector adjustments optimize the channeling of energy from the primary reflector to the subreflector and then to the feed horns. The 70-m antennas have 'shaped' primary and secondary reflectors, with forms that are modified paraboloids. This customization allows more uniform illumination of one reflector by another. The BWG reflector shape is ellipsoidal.

On the 70-m antennas, the subreflector directs received energy from the antenna onto a dichroic plate, a device that reflects S-band energy to the S-band feed horn and passes X-band energy through to the X-band feed horn. In the 34-m BWG, a series of mirrors (approximately 2.5 meters in diameter) directs microwave energy from the subreflector region to a collection area at the base of the antenna – typically in a pedestal room. A retractable dichroic reflector separates S- and X-band on some BWG antennas or X- and Ka-band on others. RF energy to be transmitted into space by the horns is focused by the reflectors into narrow cylindrical beams, pointed with high precision (either to the dichroic plate or directly to the subreflector) by a series of drive motors and gear trains that can rotate the movable components and their support structures.

The different antennas can be pointed by several means. At X-band, two pointing modes commonly used during tracking passes are CONSCAN (canonical scan) and "blind pointing." With CONSCAN enabled and a closed loop receiver locked to a spacecraft signal, the system tracks the radio source by conically scanning around its position in the sky. Pointing angle adjustments are computed from signal strength information (feedback) supplied by the receiver. In this mode the Antenna Pointing Assembly (APA) generates a circular scan pattern that is sent to the Antenna Pointing & Control System (APC). The APC adds the scan pattern to the corrected pointing angle predicts. Software in the receiver-exciter controller computes the received signal level and sends it to the APA. The correlation of scan position with the received signal level variations allows the APA to compute offset changes. Thus, within the capability of the closed-loop control system, the scan center is pointed precisely at the apparent direction of the spacecraft signal source.

The Ka-band beamwidth of the DSN antennas are ~4x narrower than X-band. CONSCAN physically moves the antenna around the boresight, which at Ka-band will cause significant fluctuations in received power. In lieu of CONSCAN, Ka-band typically employs a "monopulse" pointing system. The monopulse system compares the phase and gain of the nominal Ka-band downlink with an "error channel" in a second receiver to determine elevation and cross-elevation corrections to the antenna pointing at the millidegree level. Unlike CONSCAN, monopulse does not require any antenna movement except for the corrections to apply. However, current implementation of the monopulse system requires routine calibration with a live spacecraft signal, called an "on-point phase calibration," where the antenna is manually moved by several millidegrees. With the known offset, the monopulse system can be calibrated.

During periods when excessive signal level dynamics or low received signal levels are expected (e.g., during an occultation experiment), CONSCAN and monopulse may be disabled under direction from the DSN operator or radio science operator. Under these conditions, blind pointing is used, and pointing angle adjustments are based on a predetermined Systematic Error Correction model.

Independent of the CONSCAN or monopulse state, subreflector motion in at least the z-axis may introduce phase variations into the received Radio Science data. For that reason, during certain experiments, the subreflector in the 70-m and 34-m HEFs may be frozen in the z-axis at a position (often based on elevation angle) selected to minimize phase change and signal degradation. This can be done via Operator Directives (ODs) initiated by the DSN operator.

Pointing angles for all antenna types are computed by the Service Preparation Subsystem (SPS) from an ephemeris provided by the flight project. Before each track, they are transferred to the APA, which transforms the direction cosines of the predicts into Azimuth and Elevation coordinates. The pointing predicts consist of time-tagged AZ-EL points at selected time intervals along with polynomial coefficients for interpolation between points.

The APC automatically interpolates the predict points, corrects the pointing predicts for refraction and subreflector position, and adds the proper systematic error correction and any manually entered antenna offsets. The APC then sends angular position commands for each axis at the rate of one per second. In the 70-m and 34-m HEF, rate commands are generated from the position commands at the servo controller and are subsequently used to steer the antenna.

When not using binary predicts (the routine mode for spacecraft tracking), the antennas can be pointed using "planetary mode" – a simpler mode that targets right ascension and declination values. A third pointing mode – sidereal – is available for tracking radio sources fixed with respect to the celestial frame.

Regardless of the pointing mode being used, a 70-m antenna has a special high-accuracy pointing capability called "precision'" mode. A pointing control loop derives the main AZ-EL pointing servo drive error signals from a two-axis autocollimator mounted on the Intermediate Reference Structure. The autocollimator projects a light beam to a precision mirror mounted on the Master Equatorial drive system, a much smaller structure, independent of the main antenna, which is exactly positioned in RA and DEC with shaft encoders. The autocollimator detects elevation/cross-elevation errors between the two reference surfaces by measuring the angular displacement of the reflected light beam. This error is compensated for in the antenna servo by moving the antenna in the appropriate AZ-EL direction. Pointing accuracies of 0.004 degrees (15 arc seconds) are possible in 'precision' mode. The "precision" mode is not available on 34-m antennas – nor is it needed, since their beamwidths are twice as large as on the 70-m antennas.

2.6.3.2.5 Exciter-Transmitter Subsystem

The Exciter-Transmitter Subsystem (ETX) provides the uplink signal generation and amplification to transmit a signal to a spacecraft. The exciter generates a frequency reference using the Frequency and Timing Subsystem (FTS). The reference frequency can either be "ramped" or "unramped." A "ramped" frequency reference is an uplink frequency profile that varies as a function of time to forward-compensate the predicted Doppler shift to the spacecraft. By ramping the uplink, the spacecraft transponder should receive a nearly-constant frequency. An "unramped" frequency reference transmits to the spacecraft at a constant frequency, typically the best lock frequency. The exciter then mixes this reference frequency with range modulation from the Uplink Range Controller and command modulation from the Command Control Processor. This reference frequency is then sent to the transmitter for amplification.

The diplexer in the signal path between the transmitter and the feed horn is used for all antennas (used for simultaneous transmission and reception). The diplexer may be configured such that it is out of the received signal path (in listen-only or bypass mode) in order to improve the signal-to-noise ratio in the receiver system, if necessary.

The Transmitter accepts the S-band, X-band, or Ka-band frequency exciter signal from the exciter and amplifies it to the required transmit output level. The amplified signal is routed via the diplexer through the feed horn to the antenna and then focused and beamed to the spacecraft.

Transmitter powers and capabilities vary by uplink band and uplink station. Typical power output of an X-band transmitter is 18 kW, though powers up to 80 kW at X-band are available.

2.6.3.2.6 Antenna Microwave Subsystem

70-m Antennas: Each 70-m antenna has three feed cones installed in a structure at the center of the main reflector. The feeds are positioned 120 degrees apart on a circle. Selection of the feed is made by rotation of the subreflector. A dichroic mirror assembly, half on the S-band cone and half on the X-band cone, permits simultaneous use of the S- and X-band frequencies. The third cone is devoted to research, development, and more specialized work.

The Antenna Microwave Subsystem accepts the received S- and X-band signals at the feed horn and transmits them through polarizer plates to an orthomode transducer. The polarizer plates are adjusted so that the signals are directed to a pair of redundant amplifiers for each frequency, thus allowing simultaneous reception of signals in two orthogonal polarizations. For S-band and X-band, these are High Electron Mobility Transistors (HEMT).

34-m BWG Antennas: These antennas use feeds and low-noise amplifiers (LNA) in the pedestal room, which can be switched in and out as needed. LNAs are HEMTs at both X-band and Ka-band. Typically, the following modes are available:

1. Downlink non-diplexed path (RCP or LCP) to LNA-1, with uplink in the opposite circular polarization
2. Downlink non-diplexed path (RCP or LCP) to LNA-2, with uplink in the opposite circular polarization
3. Downlink diplexed path (RCP or LCP) to LNA-1, with uplink in the same circular polarization
4. Downlink diplexed path (RCP or LCP) to LNA-2, with uplink in the same circular polarization

For BWG antennas with dual-band capabilities (e.g., DSS 25) and dual LNAs, each of the above four modes can be used in a single-frequency or dual-frequency configuration. Thus, for antennas with the most complete capabilities, there are sixteen possible ways to receive at a single frequency (2 polarizations, 2 waveguide path choices, 2 LNAs, and 2 bands).

Directly after the low-noise amplification is performed, a downconversion from received radio frequency (RF) to an intermediate frequency (IF) is performed. The IF is between 0-600 MHz. The RF to IF conversion is a fixed value for a given band. The IF is then sent from the DSN antenna to the Signal Processing Center (SPC) at the complex.

The LNA and downconversion are performed within a cooled cryostat to reduce noise.

2.6.3.2.7 DSN Common Platform

The Common Platform provides the IF digitization and distribution among the various DSN receiver assets. After the SPC receives the incoming IF from the station, the IF is then digitized by the IF Digitizer (IFD). The IFD can be configured with Automatic Gain Control (AGC) enabled or disabled, though by default it is enabled. The digitized IF signal is then distributed to the various receivers via the Digital IF Switch. There are two redundant Digital IF switches per complex.

2.6.3.2.8 Downlink, Tracking, and Telemetry Subsystem

The Tracking Subsystem primary functions are to acquire and maintain communications with the spacecraft and to generate and format radiometric data containing Doppler and range. The Radio Metric Data Conditioning Team (RMDCT) at JPL produces a Tracking and Navigation Service File (TNF), which contains Doppler and ranging data.

The Block V Receivers are the current-generation receiver used at the DSN. A set of receivers are available per DSN complex. The ALB assigns a compatible receiver to the spacecraft's link. The receiver is configured to receive the digital IF from the tracking antenna through the digital IF switch.

The closed-loop receivers provide the capability for rapid acquisition of a spacecraft signal and telemetry lockup. In order to accomplish acquisition within a short time, the receivers are driven by a downlink frequency prediction file (DLF) to search for, acquire, and track the downlink automatically. Rapid acquisition precludes manual tuning though that remains as a backup capability. The subsystem utilizes Fast Fourier Transform (FFT) analyzers for rapid acquisition. The receiver starts acquisition at times given by the project's sequence of events or manually via operator directives. The receivers send performance and status data, displays, and event messages to the DSN operator and the NMC.

The loop bandwidth (B_L) will be configured such that the expected phase changes can be accommodated while maintaining the best possible loop SNR. Nominal carrier tracking loop at X-band is 3-8 Hz.

The Sequential Ranging Assembly (SRA) measures the round-trip light time (RTLT) of a radio signal traveling from a ground tracking station to a spacecraft and back. From the RTLT, phase, and Doppler data, the spacecraft range can be determined. A coded signal is modulated on an uplink carrier and transmitted to the spacecraft where it is detected and transmitted back to the ground station. As a result, the signal received at the tracking station is delayed by its round trip through space and shifted in frequency by the Doppler Effect due to the relative motion between the spacecraft and the tracking station on Earth.

The Pseudonoise (PN) Ranging System works in a similar manner as the SRA. The same PN code that was transmitted is correlated with the received ranging tones, and from the PN code delay the range to the spacecraft can be determined.

2.6.3.2.9 Open Loop Receivers

The Open Loop Receiver (OLR) supports radio science, Very Long Baseline Interferometry (VLBI), Delta Differential One-Way Ranging (DDOR), and engineering customers of the DSN. The OLR downconverts and records the raw antenna voltages of the received signal as In-phase and Quadrature (IQ) samples for further signal processing by the data user. For Radio Science applications, the radio science investigator or representative instrument operations team is responsible for configuration and operation of the OLR to record the data desired for processing.

Eight OLRs are installed at each complex. Six OLRs are reserved by the ALB as "green" OLRs, and two OLRs are reserved for opportunistic use by end-users as "blue" OLRs. "Green" OLRs must be configured in the link by the station operator and will automatically execute a command "script" loaded in advance by the OLR operator.

The OLR is configured either in real-time by the operator or via a command "script". The operator tunes the OLR's center frequency to either a constant Frequency Override (FRO) or a downlink frequency profile that is a function of time with a Downlink Frequency "Predict" file (DLF). The OLR receives the Intermediate Frequency (IF) signal from the DSN antenna selected through the digital IF switch. The Realtime Signal Processor (RSP) synthesizes the IF into 6.25 MHz channels. The OLR server processor selects the channel in which the "predict" is located. The OLR server processor uses a digital numerically-controlled oscillator (NCO) to center the signal on the "predict". The OLR filters and decimates these data to user-specified bandwidths and bit rates. Bandwidths between 200 Hz and 32 MHz are available at sample bit rates of 1 to 16 bits.

2.6.3.2.10 DSN Downlink Array

The DSN Downlink Array (DDA) provides the capability to array several DSN antennas at the same complex together to improve the received signal strength. The DDA is a digital, open-loop architecture array system. The DDA combines the IF signal from multiple stations and redistributes the arrayed IF to the rest of the receivers.

2.6.3.2.11 Frequency and Timing Subsystem

The Frequency and Timing Subsystem (FTS) provides all frequency and timing references required by the other DSCC subsystems. At each DSN complex, a single atomic frequency standard serves as the source for all coherent, precision station frequencies and provides the reference for the station's master clock. A hydrogen maser atomic frequency reference is used as the prime reference. Backups consisting of both hydrogen maser and cesium standards are available in case of a failure or instability in the prime frequency reference.

The clock at each complex is synchronized to the United States Naval Observatory realization of Universal Time, Coordinated (UTC) using the Global Positioning System (GPS) satellite network. Time offsets are measured routinely and forwarded to the DSN time analysts. Frequency and time performance and offset reports are recorded daily by the time analysts.

2.6.3.3 DSN Calibration

Calibrations of hardware systems are carried out periodically by DSN personnel; these ensure that systems operate at required performance levels – for example, that antenna patterns, receiver gain, propagation delays, and Doppler uncertainties meet specifications. Nominal performance specifications are shown in DSN 810-005 [7].

Prior to each tracking pass, station operators perform a series of calibrations to ensure that systems meet specifications for that operational period. Included in these calibrations is measurement of receiver system temperature and ranging delay in the configuration to be employed during the pass. Results of these calibrations are recorded in Controller's Logs for each pass and in the TRK-2-34 data file.

2.6.3.4 Station Locations

Station locations are documented in detail in DSN 810-005, Module 301: "Coverage and Geometry" [7]. Cartesian coordinates are copied here for reference along with the respective velocities at each DSN complex.

Table 7: Cartesian coordinates for DSN stations in ITRF93 Reference Frame, Epoch 2003.0

Antenna		Cartesian Coordinates		
DSS ID	**Description**	**X (m)**	**Y (m)**	**Z (m)**
DSS-13	34-m R&D	–2351112.659	–4655530.636	3660912.728
DSS-14	70-m	–2353621.420	–4641341.472	3677052.318
DSS-23 [2]	34-m BWG	TBD	TBD	TBD
DSS-24	34-m BWG	–2354906.711	–4646840.095	3669242.325
DSS-25	34-m BWG	–2355022.014	–4646953.204	3669040.567
DSS-26	34-m BWG	–2354890.797	–4647166.328	3668871.755
DSS-33 [2]	34-m BWG	TBD	TBD	TBD
DSS-34 [1]	34-m BWG	–4461147.093	2682439.239	–3674393.133
DSS-35 [1]	34-m BWG	−4461273.090	2682568.925	−3674152.093
DSS-36 [1]	34-m BWG	–446168.415	2682814.657	–3674083.901
DSS-43	70-m	–4460894.917	2682361.507	–3674748.152
DSS-53 [2]	34-m BWG	4849339.965	-360658.246	4114747.290
DSS-54	34-m BWG	4849434.488	–360723.8999	4114618.835
DSS-55	34-m BWG	4849525.256	–360606.0932	4114495.084
DSS-63	70-m	4849092.518	–360180.3480	4115109.251

Table 8: Site velocities for DSN stations

Complex	X (m/year)	Y (m/year)	Z (m/year)
Goldstone (1x & 2x)	-0.0180	0.0065	-0.0038
Canberra (3x & 4x)	-0.0335	-0.0041	0.0392
Madrid (5x & 6x)	-0.0100	0.0242	0.0156

2.6.4 Measured Parameters

2.6.4.1 Doppler

The Doppler effect is caused by the relative motion between a transmitter and receiver. The frequency received at the ground station will differ from the frequency as transmitted by the spacecraft. In the case of one-way Doppler (non-coherent), the spacecraft transmits a signal that is received at a DSN station. The downlink carrier phase is then measured and recorded as the received frequency. The Doppler measurement is then constructed as the difference between the transmitted and received frequency. In the case of two-way Doppler (coherent), the DSN station transmits a signal, and the uplink carrier phase is then measured and recorded as the transmitted frequency. The spacecraft receives the signal, which is then multiplied by the turn-around ratio and re-transmitted back to the DSN station. The DSN station then measures and records the downlink carrier phase. The Doppler measurement is then constructed as the difference between

[1] Coordinates are estimated to 3-cm accuracy.

[2] Coordinates are estimated to 3-meter accuracy.

transmitted frequency and received frequency divided by the turn-around ratio. A three-way Doppler measurement can be constructed in the same manner as a two-way measurement using a different DSN station for transmission and reception.

2.6.4.2 Range

The Sequential (SRA) and Pseudonoise (PN) Ranging techniques are a direct measurement of the round-trip light-time between the DSN station and the spacecraft. A signal is coded on the uplink transmission from a DSN station and given a time stamp, which is then received back at Earth some time later and also time stamped. The received time minus transmit time is then a measurement of the round-trip light-time, or range, to the spacecraft. Ranging can be conducted in two-way or three-way modes.

During Europa encounters, ranging data will *not be acquired*. Ranging data will be acquired during DSN tracking outside of the Europa encounters.

2.6.5 Operational Modes

Both the DSN and Europa Clipper’s telecommunications system can be configured in different modes for the desired link type.

2.6.5.1 Europa Clipper Configuration

During nominal flybys of Europa, the Europa Clipper spacecraft will point the instrument deck nadir to Europa’s surface for simplified operations. To maintain a telecom link to Earth, the spacecraft will use the low-gain and fan-beam antennas. This has two consequences for the operations of telecommunications equipment onboard the spacecraft. First, the signal-to-noise ratio will be low, and the radio will broadcast only a carrier signal for Doppler measurements. Second, the motion of the Europa spacecraft relative to Earth will frequently require one or multiple antenna swaps onboard the spacecraft. During antenna swaps, a brief loss of signal occurs.

2.6.5.2 Closed-Loop Receiver AGC Loop

The closed-loop receiver AGC loop can be configured to one of three settings: narrow, medium, or wide. Ordinarily, it is configured so that expected signal amplitude changes are accommodated with minimum distortion. The loop bandwidth is ordinarily configured so that expected phase changes can be accommodated while maintaining the best possible loop SNR. The loop bandwidth is nominally 10 Hz, but can be changed depending on real-time operational considerations. The carrier loop bandwidth used for any given Doppler measurement is specified in the TRK 2-34 file’s Downlink Carrier Phase Compressed Header Data Object (CHDO).

2.6.5.3 Coherent vs Non-Coherent Operation

The frequency of the signal transmitted from the spacecraft can generally be controlled in two ways – by locking to a signal received from a ground station or by locking to an on-board oscillator. These are known as the coherent (or 'two-way') and non-coherent ('one-way') modes, respectively. Mode selection is made at the spacecraft, based on commands received from the ground. When operating in the coherent mode, the transponder carrier frequency is derived from the received uplink carrier frequency with a 'turn-around ratio'. In the non-coherent mode, the downlink carrier frequency is derived from the spacecraft on-board crystal-controlled oscillator. Either closed-loop or open-loop receivers (or both) can be used with either spacecraft frequency reference mode. Reception in two-way mode is usually preferred for routine tracking and is the nominal mode for the G/RS data collection. Occasionally, the spacecraft operates coherently while two ground stations receive the 'downlink' signal; this is sometimes known as the 'three-way' mode.

2.6.6 Operational Considerations

On rare occasions, the spacecraft may enter safe mode to protect itself from anomalous circumstances. During these times, radio science data may be collected but with a possible derogation in data quality or gaps due to telecommunications equipment being reconfigured onboard the spacecraft.

2.6.7 System Calibration

A brief overview of calibration is given here. For more complete information, refer to the Calibration document [15].

2.6.7.1 DSN Calibrations

System-level or hardware calibrations are performed routinely by DSN personnel and before each pass during "pre-cal", or pre-calibration. For a brief description of this calibration, refer to section 2.6.3.3, DSN Calibration.

2.6.7.2 Propagation Calibrations

Earth's troposphere and ionosphere cause delays and phase changes on the transmitted and received signals. These must be corrected by using derived troposphere and ionosphere models. The DSN typically provides calibration files for tracking parameters in CSP (Control Statement Processor) format often referred to as CSP cards (see DSN 810-013, TRK-2-23 [10] for more details). CSP cards effectively give the mapped zenith delay, in meters, of either Earth's troposphere or ionosphere as a function of time using polynomials. A mapping function can be used to transform the zenith delay to the appropriate station elevation angle the measurements are taken at. These corrections apply both to ranging measurements and Doppler measurements. Troposphere CSP cards are derived from surface meteorology (temperature, pressure, humidity, etc.). Ionosphere CSP cards are derived from measurements of the ionosphere using Earth-based systems such as Global Positioning Satellites (GPS).

The two other primary sources of propagation noise are solar plasma and the Io Plasma Torus (IPT). A phase delay on the radio signal occurs when it encounters electrons along the propagation path. In general, solar plasma cannot be modeled and is considered a noise source in the measurement. Solar plasma noise increases when the Sun-Earth-Probe angle is small. The magnitude of solar plasma noise is well documented:

Asmar, S. W., Armstrong, J. W., Iess, L., & Tortora, P. (2005). Spacecraft Doppler tracking: Noise budget and accuracy achievable in precision radio science observations. *Radio Science*, *40*(2).

Iess, L., Di Benedetto, M., James, N., Mercolino, M., Simone, L., & Tortora, P. (2014). Astra: Interdisciplinary study on enhancement of the end-to-end accuracy for spacecraft tracking techniques. *Acta Astronautica*, *94*(2), 699-707.

The IPT is a donut-shaped region of charged particles trapped in Jupiter's magnetosphere. When the signal propagates through the IPT, a systematic effect is introduced onto the radio link that must be modeled. Evaluations of IPT models are given in the calibrated data product bundle; however, the data user can also refer to publications on the IPT, such as:

Bagenal, F. (1994). Empirical model of the Io plasma torus: Voyager measurements. *Journal of Geophysical Research: Space Physics*, *99*(A6), 11043-11062.

Phipps, P. H., & Withers, P. (2017). Radio occultations of the Io plasma torus by Juno are feasible. *Journal of Geophysical Research: Space Physics*, *122*(2), 1731-1750.

2.6.7.3 Spacecraft Calibrations

Several considerations should be made to calibrate instrumental effects onboard the spacecraft. Because the Gravity/Radio Science investigation relies on using the low-gain and fan-beam antennas (Section 2.6.2), often at large off-point angles, the effect of the antenna phase center offset and antenna phase pattern should be accounted for.

During Europa encounters, the spacecraft points the remote sensing instruments nadir to the surface of Europa. Thus, during encounters, the phase center of the antenna moves with respect to the line-of-sight to Earth, imparting a Doppler shift caused by the movement of the antenna phase center relative to the spacecraft center of mass. Scientific analysis should account for this relative motion. During most Europa encounters, the spacecraft antenna will also be swapped to improve signal-to-noise ratio. The swap will introduce a new phase center offset which must be accounted for in any analysis.

Furthermore, for the same reason, the line-of-sight to Earth moves with respect to the antenna boresight vector during Europa encounters. The antenna phase, similar to the antenna gain, differs as a function of antenna clock/cone angle. Antenna phase patterns are difficult to measure on the ground, but in-flight calibrations are planned during instrument checkout during cruise.

An additional consideration is the spacecraft transponder delay. The transponder delay of the Frontier radio is estimated to be <66 nanoseconds from ground measurements.

Data products are provided in the Raw data archive and calibration techniques are reported in the Calibration document [15] for users to consider these effects.

3 Data Products

3.1 Data Product Overview

Gravity/Radio Science data products are routinely produced by the DSN for tracking and navigation of spacecraft and a selection of spacecraft-related telemetry products used for calibration and data processing. These data products are summarized in Table 9.

Primary data products in the Raw bundle are the open-loop recordings (OLR) and closed-loop tracking data in the Tracking and Navigation File (TNF), both in binary format. Ancillary data include ionosphere calibration files (ION), Small Forces Files (SFF), Antenna Time History (APC), Spacecraft Mass History (SCM) data. Multi-mission troposphere calibration files (TRO), DSN weather data (WEA), Earth Orientation Parameters (EOP). Ancillary data are all in ASCII format and provided in the multi-mission archive at the PDS Geosciences Node:

https://pds-geosciences.wustl.edu/radiosciencedocs/urn-nasa-pds-jpl_dsn_mmm/

The Calibrated data bundle includes Doppler observables extracted from the open-loop tracking data in Tracking Data Message (TDM) format alongside the uplink frequency profile from the DSN. All data in the Calibrated bundle are in ASCII format.

Table 9: Raw and calibrated data product summary

Bundle	**Delivery Frequency**	**Data Types**
Raw	Every 6 months	0222-Science Open-Loop Tracking Data TRK-2-34 Closed-Loop Tracking Data TRK-2-23 Troposphere Media Calibration Files TRK-2-23 Ionosphere Media Calibration Files TRK-2-24 DSN Weather Data TRK-2-21 Earth Orientation Parameters Spacecraft Small Forces Files Spacecraft Antenna Time History File Spacecraft Mass History
Calibrated	Every 6 months	Tracking Data Message Open-Loop Doppler Observables Transmit Frequency Ramp Data

Higher level data products generated for scientific analysis by the G/RS team will also be archived and are described in the derived data product SIS.

3.2 Data Processing

This section describes the processing of Gravity/Radio Science data products, their structure and organization, and their labeling for the Raw and Calibrated data products.

3.2.1 Data Processing Levels

Data processing levels mentioned in this SIS refer to the PDS4 processing level described in Table 10.

Table 10: Data processing level definitions

PDS4 processing level	PDS4 processing level description	CODMAC Level (used in PDS3)
Telemetry	Telemetry data with instrument data embedded. PDS does not archive telemetry data.	1
Raw	Original data from an instrument. 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 call EDRs (Experimental Data Records).	2
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).	3
Calibrated	Data converted to physical units, which makes values independent of the instrument.	4
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+

All Gravity/Radio Science data products described in this SIS are considered Raw and Partially Processed/Calibrated data products.

3.2.2 Raw Data Product Generation

DSN open-loop tracking data are recorded by the DSN Open-Loop Receiver. The Europa Gravity/Radio Science Instrument Operations Team (IOT) configures the receiver to record data. After the recording is complete, the data are copied from the DSN complex to the JPL Radio Science Linux cluster at the Jet Propulsion Laboratory and distributed to the Gravity/Radio Science team.

DSN closed-loop tracking data (Doppler and Range measurements) are generated in near-real time (once every second) by the Downlink Tracking and Telemetry (DTT) Subsystem of the DSCC as the spacecraft is actively communicating with the ground. Tracking data are sent to the Tracking Data Delivery Subsystem (TDSS), which distributes tracking data in TRK 2-34 format to the Radiometric Data Conditioning (RMDC) Team. Tracking data are finally delivered via an FTP server to the Gravity/Radio Science team. All Doppler and range tracking data delivered to the Gravity/Radio Science team by the DSN are archived.

DSN weather, troposphere, and ionosphere calibration files are generated by the Tracking System Analytic Calibration (TSAC) group and delivered via FTP server to the Gravity/Radio Science team.

Small Forces Files are generated by the Guidance, Navigation, & Control (GNC) and Navigation (NAV) teams and delivered to the Europa Clipper project data storage. The G/RS IOT acquires the Small Forces Files and distributes them to the Gravity/Radio Science Team.

The Antenna Time History files are derived from the spacecraft predicted sequence of events file created by the Europa Clipper Planning, Coordination, & Execution Operations (PCE) team. The G/RS team processes this file into a time-history of spacecraft antenna use.

The Spacecraft Mass History files are derived from information given by the Europa Clipper GNC and Propulsion teams. The G/RS team concatenates this information into the Spacecraft Mass History file.

Table 11 describes each file type, size, generation frequency, and source.

Table 11: Gravity/Radio Science Raw data products overview

File	Abbrev.	File Type	Generation Frequency	Update Frequency	File Size	Source
Open Loop Receiver File (0222-Science)	OLR	Binary	Per-pass	Real-time	~20 MB/hour (1 kHz bandwidth)	G/RS IOT
Tracking and Navigation File (TRK 2-34)	TNF	Binary	Per-pass	Real-time	5 MB/hour (single-frequency)	RMDC
Ionosphere Calibration File (TRK 2-23)	ION	ASCII	Monthly	Weekly	28 kB/month	TSAC
Troposphere Calibration File (TRK 2-23)	TRO	ASCII	Monthly	Weekly	160 kB/month	TSAC
DSN Weather File (TRK 2-24)	WEA	ASCII	Yearly	Daily	1.1 MB/year	TSAC
Earth Orientation Parameter File (TRK-2-21)	EOP	ASCII	Daily	Daily	~1.5 MB	TSAC
Small Forces File	SFF	ASCII	Per-orbit	Per-orbit	TBD	GNC/NAV
Antenna Time History	APC	ASCII	Per-orbit	Per-orbit	TBD	G/RS
Spacecraft Mass History	SCM	ASCII	Per-orbit	Per-orbit	TBD	G/RS

3.2.3 Calibrated Data Product Generation

Calibrated data products contain Doppler frequency observables derived from the open-loop recordings (OLR) in the Raw bundle plus the uplink frequency profile derived from the closed-loop data (TNF). Calibrated data products are produced by the G/RS team and delivered to the PDS on the same cadence as the Raw data.

Doppler observables are extracted from the 0222-Science OLR data through signal analysis techniques such as a Fast Fourier Transforms (FFT), spectral optimization of FFTs, Doppler-rate compensated FFTs, or a phase-locked loop (PLL). The Doppler observables are converted from OLR-recorded baseband to received RF frequency. Calibrations are applied to account for the Earth troposphere and Earth ionosphere, using the TRK-2-23 calibration files. Depending on the geometry of the flyby, additional calibrations are applied to account for the IPT or antenna phase pattern. Only calibrations for the instrumental or propagation effects are applied; calibrations or corrections for dynamical effects are *not applied* (such examples are antenna phase center, spacecraft dynamical effects, center of mass, etc.).

The uplink frequency profile is extracted from the TRK-2-34 TNF data through a simple tabular lookup from the Ramp table (see Section 5.1.1.2). Calibrations to the uplink frequency profile are *not applied* since the corrections are applied to the downlink observable instead. The extracted uplink frequency profile in the calibrated dataset is *identical* to the values in the TRK-2-34 TNF data files, but in an ASCII format instead of binary.

The Calibrated data are then combined into a Consultative Committee for Space Data Systems (CCSDS) 503.0-B-1 Tracking Data Message (TDM) format. Both the uncalibrated Doppler frequency observables and calibrated Doppler frequency observables are archived.

Table 12: Gravity/Radio Science Processed & Calibrated data products

File	Abbrev.	File Type	Generation Frequency	Update Frequency	File Size	Source
Processed Open Loop Data (CCSDS 503.0-B-1 Tracking Data Message)	TDM	ASCII	Per-pass	Per-pass	~2 MB/pass	G/RS
Calibrated Processed Open Loop Data (CCSDS 503.0-B-1 Tracking Data Message)	TDM	ASCII	Per-pass	Per-pass	~2 MB/pass	G/RS
Uplink Frequency Ramp Tables (CCSDS 503.0-B-1 Tracking Data Message)	TDM	ASCII	Per-pass	Per-pass	~2 MB/pass	G/RS

3.2.4 Data Flow

This section describes only those portions of the Europa Clipper data flow that are directly connected to G/RS data archiving. Figure 5 displays the data flow for raw and calibrated data products.

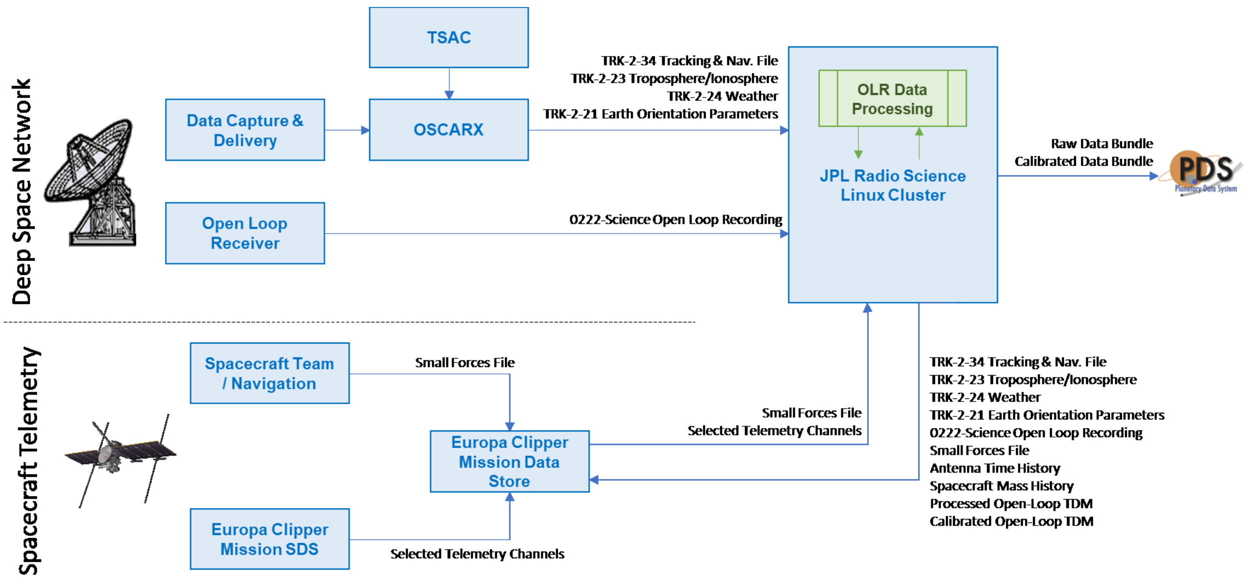

Figure 5: Gravity/Radio Science Raw and Calibrated data flow

The G/RS team receives the TRK-2-34 Tracking and Navigation File from the DSN Data Capture and Delivery Subsystem via the OSCARX FTP server. TRK-2-23 Troposphere and Ionosphere Calibration files, TRK-2-24 DSN Weather data files, and TRK-2-21 Earth Orientation Parameters are also received through the OSCARX FTP server via the Tracking System Analytic Calibration (TSAC) Subsystem. The G/RS IOT collects the 0222-Science Open Loop Receiver data from the DSN OLR system. Processing and calibration of OLR data is done by the G/RS team. Spacecraft-telemetry related products are provided to the G/RS team via the Europa Clipper mission Science Data System (SDS) data distribution system.

The G/RS team performs minimal reformatting of the TRK 2-34 Tracking and Navigation File for delivery to PDS (see Section 5.1.1.2).

The G/RS team processes and calibrates the 0222-Science Open-Loop Recordings as described in Section 3.2.2.

All science data products are delivered back to the Europa Clipper mSDS data distribution system for project distribution.

Once in PDS-compliant format, the G/RS archivist generates XML labels, assembles the data and documentation into archive bundles, and delivers the bundles to the PDS Geosciences Node. Deliveries take place according to the release schedule agreed upon by the Europa Clipper project and PDS as specified in the Science Data Management Plan [6]. The Geosciences Node validates the bundles and makes them available to the public online.

Multi-mission data (TRK-2-23 Troposphere Calibration files, TRK-2-24 DSN Weather data files, and TRK-2-21 Earth Orientation Parameters files) are archived by the PDS Radio Science Sub-Node (RSSN) with the PDS Geosciences Node at:

https://pds-geosciences.wustl.edu/radiosciencedocs/urn-nasa-pds-jpl_dsn_mmm/

3.3 Standards Used in Generating Data Products

G/RS products and labels comply with PDS standards, including the PDS4 data model, as specified in applicable documents [1], [3] and [4].

3.3.1 Time Standards

All data products in the raw and calibrated archive use the UTC (Universal Time Coordinated) standard time format.

3.3.2 Coordinate Systems

The data products contained in this archive are not dependent on the definition of a coordinate system.

Coordinates for the DSN stations are provided in ITRF93 and coordinates for the spacecraft antenna locations are provided in the spacecraft-fixed reference frame. See Section 2.6 for more details.

3.3.3 Data Storage Conventions

G/RS products are stored in either binary or ASCII format depending on the data product: 0222-Science Open-Loop Recordings and TRK 2-34 Tracking and Navigation Files are stored as uncompressed binary data files with integer, complex, floating point, and string data in most-significant byte first order (i.e., big-endian byte order). All other data products are stored as ASCII text.

3.4 Applicable Software

Software for parsing, reducing, and analyzing G/RS data have been developed at several institutions. Because such software must typically operate at the bit-level and is written for a narrow range of platforms, it is not suitable for general distribution and is institutionally proprietary. No software is included with this archival data set. Several options are available to scientific users of this type of data:

> ***MONTE*****—**The Jet Propulsion Laboratory's Mission Design and Navigation Section (MDNAV) develops the Mission Analysis, Operations, and Navigation Toolkit Environment (MONTE). MONTE is an astrodynamics computing platform with capabilities for mission design and statistical orbit determination from tracking data. The public can get information about MONTE and request a license, if desired, from: https://montepy.jpl.nasa.gov/

> ***SPICE*****—**The SPICE toolkit is a publicly available set of software tools that allow for geometric calculations from spacecraft. It is generally useful for analyzing data that are derived from these tracking data and is available on the NAIF node of PDS: http://naif.jpl.nasa.gov/naif/toolkit.html.

3.5 Backups and duplicates

The Geosciences Node keeps two copies of each archive product. One copy is the primary online archive copy, another is a backup copy. Once the archive products are fully validated and approved for inclusion in the archive, a third copy of the archive is sent to the NASA Space Science Data Coordinated Archive (NSSDCA) for long-term preservation in a NASA-approved deep-storage facility. The Geosciences Node may maintain additional copies of the archive products, either on or off-site as deemed necessary.

4 Archive Organization, Identifiers and Naming Conventions

This section describes the basic organization of the Gravity/Radio Science Raw and Calibrated data archives under the PDS4 Information Model (IM) (Applicable Documents [1] and [4]), including the naming conventions used for the bundle, collection, and product unique identifiers.

4.1 Logical Identifiers

Every product in the PDS is assigned an identifier that allows it to be uniquely identified across the system. This identifier is referred to as a Logical Identifier or LID. A LIDVID (Versioned Logical Identifier) includes product version information, and allows different versions of a specific product to be referenced uniquely. A product's LID and VID are defined as separate attributes in the product label. LIDs and VIDs are assigned by the data provider and approved by the PDS. LIDs are formed according to the conventions described in sections 4.1.1 and 4.1.2. The uniqueness of a product's LIDVID may be verified using the PDS Registry and Harvest tools. LIDs follow the convention defined in the Science Data Management Plan [6].

4.1.1 LID Formation

LIDs take the form of a Uniform Resource Name (URN). LIDs are restricted to ASCII lower case letters, digits, dash, underscore, and period. Colons are also used, but only to separate prescribed components of the LID. Dash, underscore, or period are used as separators within one of these prescribed components. LIDs are limited in length to 255 characters.

Europa Clipper Gravity/Radio Science LIDs are formed according to the following conventions:

- Bundle LIDs are formed by appending a bundle specific ID to the base ID:

  urn:nasa:pds:<bundle ID>

  Where the <bundle ID> is defined as: <mission ID>.<instrument ID>.<processing level>. The Europa Clipper mission identifier is "clipper," and the Gravity/Radio Science instrument identifier is "rss":

  Example:

  urn:nasa:pds:clipper.rss.raw defines the bundle of raw G/RS data

  The bundle ID must be unique across all products archived with the PDS.

- Collection LIDs are formed by appending a collection specific ID to the collection's parent bundle LID:

  urn:nasa:pds: <bundle ID>:<collection ID>

  Where <collection ID> is defined as: data.<processing level>.<data type>

  Example:

  urn:nasa:pds:clipper.rss.raw:data.trk234_trknav defines the TRK-2-34 data collection

  Since the collection LID is based on the bundle LID, which is unique across PDS, the only additional condition is that the collection ID must be unique across the bundle. Collection IDs correspond to the collection type (e.g., "browse", "data", "document", etc.). Additional descriptive information may be appended to the collection type (e.g., "data-raw", "data-calibrated", etc.) to ensure that multiple collections of the same type within a single bundle have unique LIDs.

- Basic product LIDs are formed by appending a product specific ID to the product's parent collection LID:

  urn:nasa:pds: <bundle ID>:<collection ID>:<product ID>

  Where <product ID> is defined as: <filename>

  Example:

  urn:nasa:pds:clipper.rss.raw:data.0222science_olr: rss008e01_2031030T0300_x25x25001knjpl_olr010.dat defines a 0222-Science OLR data product in orbit 8, Europa Encounter #1, with a start time of 2031-10-30 03:00 UTC

  Since the product LID is based on the collection LID, which is unique across PDS, the only additional condition is that the product ID must be unique across the collection. Often the product LID is set to be the same as the data file name without the extension. See Section 4.4 for examples of data product LIDs.

4.1.2 VID Formation

Product Version IDs consist of major and minor components (mmn), where "mm" represents the major version and "n" the minor version. Both components of the VID are integer values. The major component is initialized to a value of "1", and the minor component is initialized to a value of "0". The minor component resets to "0" when the major component is incremented. The PDS Standards Reference [1] specifies rules for incrementing major and minor components.

4.1.3 File Naming Convention

Europa Clipper G/RS files are named per the following convention in Table 14 and Table 15, and follow the file name convention defined in the Science Data Management Plan [6]:

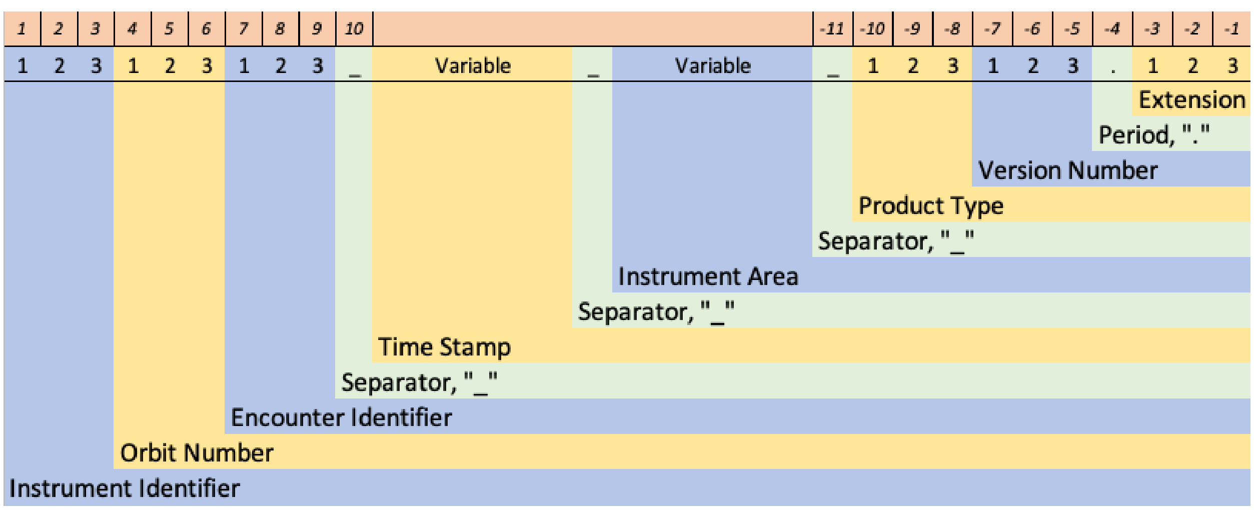

Figure 6: Europa Clipper file naming convention (from [6]).

The definitions specific to G/RS data products are shown in Table 13.

Table 13: G/RS file naming convention overview

Identifier	Length	Definition for G/RS Products
Instrument Identifier	3	Set to RSS for all G/RS data products
Orbit Number	3	Identifies the 3-digit orbit number defined by the MOS. 000 indicates cruise 999 indicates not applicable if a product spans multiple orbits, the first applicable orbit number will be used
Encounter Identifier	3	3-character definition for the encounter defined by the MOS. Example: E01 = Europa #01, G01 = Ganymede #01. XXX indicates not applicable if a product spans multiple encounters, the first applicable encounter will be used
Separator	1	_
Time Stamp	12	Start time of data file: YYYYDOYTHHMM YYYY = 4 digit year DOY = 3 digit day of year T = static separator HH = hour of day MM = minute of hour
Separator	1	_
Instrument Area		uUUdDDttttPPPP u = uplink band (set to N if not applicable, m if multiple) UU = uplink station (set to NN if not applicable, mm if multiple) d = downlink band (set to N if not applicable, m if multiple) DD = downlink station (set to NN if not applicable, mm if multiple) tttt = time resolution applicable only for OLR, TNF, and TDM data types if OLR: tttt is an indicator of the recording bandwidth (*0200* indicates 200 Hz, *001K* indicates 1 kHz, *004K* indicates 4 kHz, etc *continued →*

Identifier	Length	Definition for G/RS Products
		if TNF or TDM: `tttt` is an indicator of the count-time (0001 indicates 1 second count-time, 0005 indicates 5 second count time, etc.) if any other data type: `tttt` is set to `NNNN` `pppp` = Producer identification (Examples include: *NJPL* = produced by JPL/DSN; *RMDC* = produced by JPL/RMDC; *TSAC* = produced by JPL/TSAC; *332K* = produced by JPL radio science; *EGRS* = produced by Europa Clipper G/RS team); *ENAV* = produced by the Europa Clipper navigation team
Separator	1	_
Product Type	3	One of the following for raw data products: `OLR` = 0222-Science Open Loop Data `TNF` = TRK-2-34 Tracking and Navigation File `ION` = TRK-2-23 Ionosphere Calibration File `APC` = Antenna Time History File `SCM` = Spacecraft Mass History File One of the following for calibrated data products: `OBS` = Processed Open-Loop Doppler Observables `CAL` = Calibrated Open-Loop Doppler Observables `UPL` = Uplink Frequency Ramp Tables
Version Number		`mmn` `mm` = Major version `n` = minor version
Period	1	.
Extension	3	File extension `XML` = PDS label `TXT` = plain-text file `TAB` = table (plain-text) `CSV` = comma-separated value (plain-text) `DAT` = binary data file `CXML` = eXtensible Markup Language `TDM` = tracking data message (plain-text)

In the tables below, examples are given for each file type.

Table 14: G/RS Raw data product naming convention examples

Data Product Type	Naming Convention
Open Loop Receiver File	RSS008E01_2031030T0300_X25X25001KNJPL_OLR010.DAT
Tracking and Navigation File	RSS008E01_2031030T0230_X25X250001NJPL_TNF010.DAT
Ionosphere Calibration File	RSS008E01_2031001T0100_NMMNMMNNNNTSAC_ION010.TXT
Small Forces File	RSS008E01_2031022T0310_NNNNNNNNNNENAV_SFF010.TXT
Antenna Time History	RSS008E01_2029273T1200_NNNNNNNNNNEGRS_APC010.CSV
Spacecraft Mass History	RSS008E01_2029273T1200_NNNNNNNNNNEGRS_SCM010.CSV

Table 15: G/RS Calibrated data product naming convention examples

Data Product Type	Naming Convention
Processed Open Loop Data	RSS008E01_2031030T0300_X25X250060332K_OBS010.TDM
Calibrated Open Loop Data	RSS008E01_2031030T0300_X25X250060332K_CAL010.TDM
Uplink Frequency Ramp Table	RSS008E01_2031030T0300_X25NNNNNNN332K_UPL010.TDM

4.2 Bundles

The highest level of organization for a PDS archive is the bundle. A bundle is a set of one or more related collections that may be of different types. A collection is a set of one or more related basic products that are all of the same type. Bundles and collections are logical structures, not necessarily tied to any physical directory structure or organization.

The complete archive is organized into the bundles described in Table 16. This SIS addresses only the Raw and Calibrated Data Bundles.

Table 16: G/RS Bundles

Bundle Logical Identifier	PDS4 Processing Level	Description
`urn:nasa:pds:clipper.rss.raw`	Raw	G/RS Raw Data Bundle
`urn:nasa:pds:clipper.rss.calibrated`	Calibrated	G/RS Calibrated Data Bundle
`urn:nasa:pds:clipper.rss.derived`	Derived	G/RS Derived Data Bundle

4.3 Collections

Collections consist of basic products all of the same type. The Raw Data Bundle contains the collections listed in Table 17 and the Calibrated Data Bundle contains the collections listed in Table 18. Please note this table includes both primary data and documents, provided by the G/RS team, and secondary data and documents, provided elsewhere on the PDS.

Table 17: Collections in the G/RS Raw Data Bundle

Collection Logical Identifier	Collection Type	Description
`urn:nasa:pds:clipper.rss.raw:data.0222science_olr`	Data	Open Loop Receiver File
`urn:nasa:pds:clipper.rss.raw:data.trk234_trknav`	Data	Tracking and Navigation File
`urn:nasa:pds:clipper.rss.raw:data.trk223_mediacal`	Data	Ionosphere Calibration Files
`urn:nasa:pds:clipper.rss.raw:data.nav_sff`	Data	Small Forces File
`urn:nasa:pds:clipper.rss.raw:data.sc_ant_hist`	Data	Antenna Time History
`urn:nasa:pds:clipper.rss.raw:data.sc_mass_hist`	Data	Spacecraft Mass History
`urn:nasa:pds:jpl.dsn.mmm:tro`	Secondary Data	Troposphere Calibration Files
`urn:nasa:pds:jpl.dsn.mmm:wea`	Secondary Data	DSN Weather File
`urn:nasa:pds:jpl.dsn.mmm:eop`	Secondary Data	Earth Orientation Parameter File

Collection Logical Identifier	Collection Type	Description
`urn:nasa:pds:clipper.rss.raw:document`	Documents	Documentation in support of the G/RS raw data
`urn:nasa:pds:radiosci.documentation:dsn.trk-2-23`	Secondary Documents	Documentation for TRK-2-23 format
`urn:nasa:pds:radiosci.documentation:dsn.trk-2-24`	Secondary Documents	Documentation for TRK-2-24 format
`urn:nasa:pds:radiosci.documentation:dsn.trk-2-34`	Secondary Documents	Documentation for TRK-2-34 format
`urn:nasa:pds:radiosci.documentation:dsn.0222-science`	Secondary Documents	Documentation for 0222_Science format
`urn:nasa:pds:clipper.rss.calibrated:document:ccsds_tdm_sis`	Secondary Documents	Documentation for Tracking Data Message format

Secondary collections may be found in the multi-mission radio science bundle on the PDS Geosciences Node:

https://pds-geosciences.wustl.edu/radiosciencedocs/urn-nasa-pds-jpl_dsn_mmm/

Table 18: Collections in the G/RS Calibrated Data Bundle

Collection Logical Identifier	Collection Type	Description
`urn:nasa:pds:clipper.rss.calibrated:data.olr_tdm_obs`	Data	Processed Open Loop Data
`urn:nasa:pds:clipper.rss.calibrated:data.olr_tdm_cal`	Data	Calibrated Open Loop Data
`urn:nasa:pds:clipper.rss.calibrated:data.upl_tdm_ramp`	Data	Uplink Frequency Ramp Tables
`urn:nasa:pds:clipper.rss.calibrated:document`	Documents	Documentation in support of the G/RS calibrated data

4.4 Products

A PDS product consists of one or more data objects and an accompanying PDS label file. PDS labels provide identification and description information for labeled objects. The PDS label includes a Logical Identifier (LID) by which any PDS labeled product is uniquely identified throughout all PDS archives. PDS4 labels are XML-formatted ASCII files.

The tables below give examples of LIDs for data products in the G/RS collections.

4.4.1 Raw Data Collection

The following table gives examples of LIDs for raw data. The LID for a raw data product is formed by appending the file name, without its extension, to the collection LID.

Table 19: Examples of Raw Data LIDs

Data Product Type	Example LID
Open Loop Receiver File	`urn:nasa:pds:clipper.rss.raw:data.0222science_olr:` `rss008e01_2031030T0300_x25x25001knjpl_olr`
Tracking and Navigation File	`urn:nasa:pds:clipper.rss.raw:data.trk234_trknav:` `rss008e01_2031030T0230_x25x250001njpl_tnf`
Ionosphere Calibration File	`urn:nasa:pds:clipper.rss.raw:data.trk223_mediacal:` `rss008e01_2031001T0100_nmmnmmnnnntasc_ion`
Small Forces File	`urn:nasa:pds:clipper.rss.raw:dat.nav_sff:` `rss008e01_2031022T0310_nnnnnnnnnnenav_sff`
Antenna Time History	`urn:nasa:pds:clipper.rss.raw:dat.sc_ant_hist:` `rss001e01_2029273T1200_nnnnnnnnnnegrs_apc`
Spacecraft Mass History	`urn:nasa:pds:clipper.rss.raw:data.sc_mass_hist:` `rss001e01_2029273T1200_nnnnnnnnnnegrs_scm`

4.4.2 Calibrated Data Collection

The following table gives examples of LIDs for calibrated data. The LID for a calibrated data product is formed by appending the file name, without its extension, to the collection LID.

Table 20: Examples of Calibrated Data LIDs

Data Product Type	Example LID
Processed Open Loop Data	`urn:nasa:pds:clipper.rss.calibrated:data.olr_tdm_obs:` `rss008e01_2031030T0300_x25x250060332k_obs`
Calibrated Open Loop Data	`urn:nasa:pds:clipper.rss.calibrated:data.olr_tdm_cal:` `rss008e01_2031030T0300_x25x250060332k_cal`
Uplink Frequency Ramp Tables	`urn:nasa:pds:clipper.rss.calibrated:data.olr_tdm_cal:` `rss008e01_2031030T0300_x25x250060332k_upl`

4.5 Europa Clipper Document Bundle and Collections

Documents are also considered products by PDS, and have LIDs, VIDs and PDS4 labels just as data products do. The Europa Clipper archives include a Europa Clipper Document Bundle, which consists of collections of documents relevant to the mission itself and all the science experiments. The G/RS Team is responsible for the G/RS document collection in this bundle.

Table 21: Collections in the G/RS Document Bundle

Collection Logical Identifer	Description
`urn:nasa:pds:clipper.rss.raw:document`	Documentation bundle for the Clipper G/RS raw data
`urn:nasa:pds:clipper.rss.calibrated:document`	Documentation bundle for the Clipper G/RS calibrated data

Documents in the Europa Clipper Document Collections are assigned LIDs based on file names such that they are unique identifiers. Further documentation on various radio science data may be found in the PDS Radio Science Documentation Bundle, available at:

https://pds-geosciences.wustl.edu/radiosciencedocs/urn-nasa-pds-radiosci_documentation/

5 Archive Product Formats

Data that comprise the G/RS data archives are formatted in accordance with PDS specifications (see Applicable Documents [1], [3] and [4]). This section provides details on the formats used for each of the products included in the archive.

5.1 Data Product Formats

This section describes the format and record structure of each of the data file types.

5.1.1 Raw Data File Data Structure

5.1.1.1 0222-Science Open Loop Receiver File

Full documentation of the 0222-Science OLR files are provided in the PDS Radio Science Documentation Bundle, available at:

https://pds-geosciences.wustl.edu/radiosciencedocs/urn-nasa-pds-radiosci_documentation/

This is an official DSN document with the name "0222 Science Open Loop Data Interface". This document is one of several in the DSN 820-013 collection. A summary of the contents is given here. Due to the complexity of the file, the detailed 0222-Science format is not given in this SIS; users should refer to the document itself for file definition.

0222-Science OLR files are binary files in the Raw Data Exchange Format (RDEF) format. The RDEF is composed of individual records concatenated together to form the entire file. Each record contains exactly 1 second of open-loop data with a header as shown in the figure below.

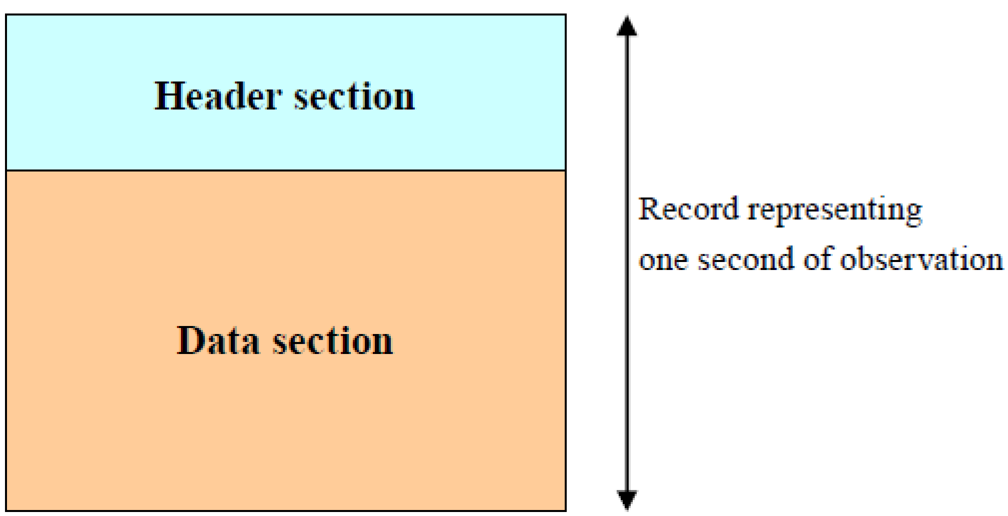

Figure 7: RDEF record format

Each header section of an RDEF is the same length (176 bytes). The length of a data section is variable and depends on the recording bandwidth of the open-loop data. The data section contains only the In-phase and Quadrature (IQ) components of the open-loop recording.

Using the data section, the data user can extract frequency estimates. Timestamps, baseband tuning frequencies, and other ancillary data are in the header section, allowing the data user to produce the sky-level frequency observables from the 0222-Science data files alone.

5.1.1.2 TRK 2-34 Tracking and Navigation File

Full documentation of the TRK 2-34 file are provided in the PDS Radio Science Documentation Bundle, available at:

https://pds-geosciences.wustl.edu/radiosciencedocs/urn-nasa-pds-radiosci_documentation/

This is an official DSN document with the name "TRK 2-34 DSN Tracking System Data Archival Format". This document is one of several in the DSN 820-013 collection. A summary of the contents is given here. Due to the complexity of the file, the detailed TRK 2-34 format is not given in this SIS; users should refer to the document itself for file definition.

TRK 2-34 files are binary files in a Standard Formatted Data Unit (SFDU) format. There are 18 possible record types in a TRK 2-34 file, distinguished by a unique Format Code in the Primary CHDO.

Table 22: Record types contained in a TRK 2-34 file

Format Code	Secondary CHDO Type	Description	SFDU Length (bytes)
0	Uplink	Uplink Carrier Phase	162
1	Downlink	Downlink Carrier Phase	358
2	Uplink	Uplink Sequential Ranging Phase	194
3	Downlink	Downlink Sequential Ranging Phase	304
4	Uplink	Uplink PN Ranging Phase	276
5	Downlink	Downlink PN Ranging Phase	388
6	Derived	Doppler Count	200
7	Derived	Sequential Range	330
8	Derived	Angles	178
9	Derived	Ramp Frequency	124
10	Interferometric	VLBI	204
11	Derived	DRVID	182
12	Filtered	Smoothed Noise	164
13	Filtered	Allan Deviation	160
14	Derived	PN Range	348
15	Derived	Tone Range	194
16	Derived	Carrier Frequency Observable	182 + 18*n
17	Derived	Total Count Phase Observable	194 + 22*n

Each SFDU is organized as illustrated in Figure 8. Only one of the 18 possible content blocks (the last element in the tree) shown will appear in any given SFDU. Only its parent Secondary CHDO will appear before it in the SFDU.

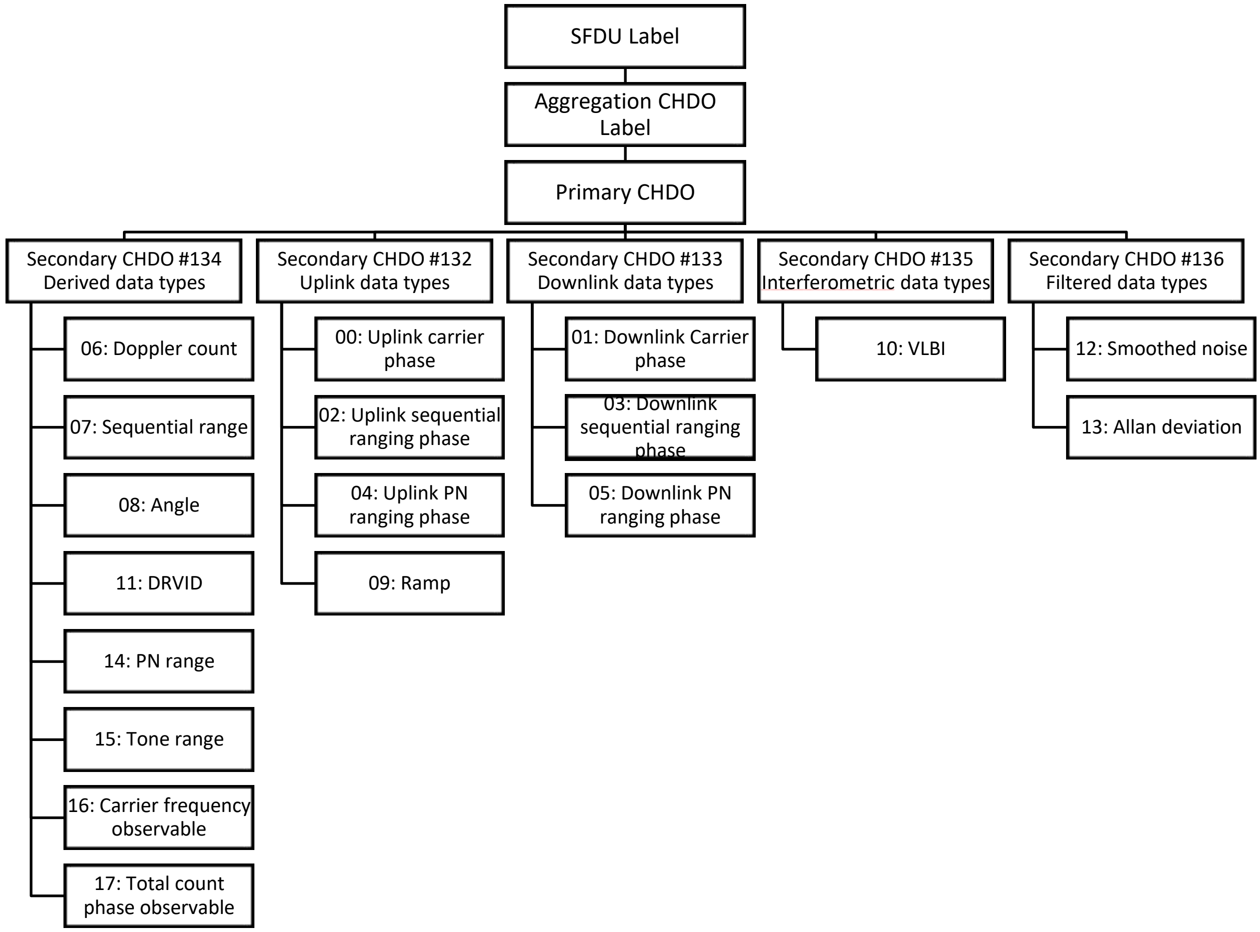

Figure 8: TRK 2-34 SFDU format

A typical TRK 2-34 file should contain the following data types:

- Uplink carrier phase (Format code 00)
- Downlink carrier phase (Format code 01)
- Ramp (Format code 09)
- Doppler count (Format code 06)
- Carrier frequency observable (Format code 16)
- Total count phase observable (Format code 17)

Note that Format codes 16 and 17 can be variable in length. For most Europa Clipper passes, these are fixed with one observation (n=1) per SFDU. Additional data types may be present depending on the configuration of the DSN during the tracking pass.

The G/RS team performs minimal reformatting of the TRK 2-34 Tracking and Navigation File for delivery to PDS. For archival purposes, the TRK 2-34 file is re-grouped such that common-type SFDUs are together and are not necessarily in time-ascending order. For example, all Format Code 00 (uplink carrier phase) are grouped together at the start of the file, followed by all Format Code 01 (downlink carrier phase), etc. Note that each file will only contain the SFDU data types that are generated for that particular pass, e.g. not every TRK 2-34 file will contain every data type. The regrouped TRK-2-34 are fully compliant with the original TRK-2-34 data specification.

Parsing a TRK-2-34 file can be complex. To aid in the parsing of this file, the PDS4 transform tool may be of interest and can be found on the PDS Engineering Node website.

5.1.1.3 TRK 2-23 Media Calibration Interface File

Troposphere and Ionosphere files are plain-text ASCII stream files containing adjustments that should be made to the tracking data. These calibrations are provided as CSP (Control Statement Processor) "cards." Each file is updated every several days and spans one-month, including both reconstruction and prediction if the release data is in the middle of the month. The file format and how to read CSP cards are described in the DSN documentation "TRK 2-23 Media Calibration Interface" [10], and a copy is provided in the PDS Radio Science Documentation Bundle, available at:

https://pds-geosciences.wustl.edu/radiosciencedocs/urn-nasa-pds-radiosci_documentation/

These files are labeled as *Product_Ancillary* files [3], [4]. Multiple tracking data files may be calibrated by a single TRK 2-23 file.

5.1.1.4 TRK-2-24 DSN Weather File

DSN Weather files are plain-text ASCII tables and are generated in near-real time from station monitoring data. Meteorology points are stored in the table every hour. One file is produced per year and continually updated every few days. The full file format is described in "TRK 2-24 DSN Tracking System Interfaces: Weather Data Interface" [11], and a copy is provided in the PDS Radio Science Documentation Bundle, available at:

https://pds-geosciences.wustl.edu/radiosciencedocs/urn-nasa-pds-radiosci_documentation/

. DSN weather files are not explicitly required to calibrate data within the archive. They may be used for diagnostics on the radio science data or for the data user to compute their own Earth troposphere calibrations.

5.1.1.5 TRK-2-21 Earth Orientation Parameters File

Earth Orientation Parameters (EOP) files contain information required to compute the precise rotation and timing of Earth. The EOP file contains universal time and polar motion conversions. EOP files are plain-text ASCII files with a header and data section. The data section is in a Fortran namelist format, which is a simple comma-separated value format. The format of the EOP files are described by the "DSN Tracking System Interfaces: Earth Orientation Parameter Data Interface" from the DSN 820-013 series of documents. A copy of this document is provided in the PDS Radio Science Documentation Bundle, available at:

https://pds-geosciences.wustl.edu/radiosciencedocs/urn-nasa-pds-radiosci_documentation/

5.1.1.6 Small Forces File

Small Forces Files (SFF) contain data on each time thrusters were fired by the spacecraft. Firing thrusters imposes a velocity change in the spacecraft's trajectory, causing detectable changes in the Doppler observables. These are sometimes useful in certain applications, for example, orbit reconstruction. By mission design, there are no thruster firings around closest approach, so the non-gravitational force imparted by the thrusters does not bias the gravity solutions.

Nonetheless, these data are included as a standard product and are useful in orbit reconstruction analysis. The user should read the accompanying SIS for the SFF data (included in the documentation bundle) for detailed interpretation. The data in the Small Forces Files are reconstructed small forces, i.e., the velocity change in the files is the best-estimate based on navigation tracking data and onboard telemetry channels.

5.1.1.7 Antenna Time History File

The Antenna Time History file (also called the APC file) is an ASCII plain-text data file in Comma Separated Value (CSV) format specified in Table 23. The file gives the currently active spacecraft antenna as a function of time. Each time the spacecraft RF path changes to use a given antenna, a new entry is created in the file. The currently active antenna can be assumed to be that value until the next timestamp in the file.

The file contains a new line for each entry with a carriage-return line-feed (CR-LF) between lines. Each entry contains two fields separated by a comma, the first is the applicable timestamp and the second is the current active antenna. For a list of valid antennas, see the instrumentation portion of this document (Section 2.6).

Table 23: Spacecraft antenna time history file format

Field Number	Description	Number Format	Start Byte	End Byte
1	Timestamp *System: UTC Spacecraft Event Time* *Format: YYYY-DDDTHH:MM:SS.###* *YYYY = 4-digit year* *DDD = 3-digit day of year* *T = separator* *HH = hour of day (24 hour)* *MM = minute* *SS = second* *### = fractions of second*	String	1	22
2	Active Antenna *One of the following:* *HGA, MGA, LGA1, LGA2, LGA3, FBA1, FBA2, FBA3*	String	23	31

5.1.1.8 Spacecraft Mass History File

The Spacecraft Mass History file (also called the SCM file) is an ASCII plain-text data file in Comma Separated Value (CSV) format specified in Table 24. The file gives the total spacecraft mass in kilograms as a function of time. Each time the mass of the spacecraft is known to change significantly (e.g., during a large engine maneuver that expels propellant mass from the spacecraft), the file is incremented with an additional value. The spacecraft's mass can be assumed to be that value until the next timestamp in the file.

The file contains a new line for each entry with a carriage-return line-feed (CR-LF) between lines. Each entry contains two fields separated by a comma, the first is the applicable timestamp and the second is the new spacecraft mass at that timestamp.

Table 24: Spacecraft mass history file format

Field Number	Description	Number Format	Start Byte	End Byte
1	Timestamp *System: UTC Spacecraft Event Time* *Format: YYYY-DDDTHH:MM:SS.###* *YYYY = 4-digit year* *DDD = 3-digit day of year* *T = separator* *HH = hour of day (24 hour)* *MM = minute* *SS = second* *### = fractions of second*	String	1	22
2	Total Spacecraft Mass, in kilograms	Float	23	33

5.1.2 Calibrated Data Files Data Structure

The primary data for the Europa Clipper Gravity/Radio Science investigation will come from open-loop data. The calibrated data product bundle will contain the processed and calibrated Doppler observables extracted from the open-loop data files (0222-Science).

5.1.2.1 Tracking Data Message Format

Processed and calibrated Doppler observables from open-loop data files are archived under the CCSDS Tracking Data Message (TDM) format. Each file conforms to the 503.0-B-1 standard (November 2007), a copy of the document is provided in the calibrated document collection.

Generically, a TDM is a plain-text ASCII file that is separated into a header section, followed by the body. The body section is composed of several segments, each of which contain a metadata section and a data section. A TDM can have multiple segments with a plethora of different data types (e.g., ramps, one-way Doppler, two-way Doppler, three-way Doppler, range, phase, VLBI, Differenced Doppler, Angles, etc).

For Europa Clipper Gravity/Radio Science, only the Ramp frequency table and sequential Doppler types are used.

Two TDMs are produced and archived for each DSN tracking pass during closest approach to Europa. The first contains the extracted Doppler observables from the open-loop data and ramp data extracted from the closed-loop data. The second contains the same data, but calibrated for all known propagation effects. These files are archived into two respective collections as described in Section 4.3.

5.2 Document Product Formats

Documents in this archive are provided as PDF/A (www.pdfa.org/download/pdfa-in-a-nutshell) or as plain ASCII text if no special formatting is required.

5.3 PDS Labels

Each G/RS product is accompanied by a PDS4 label. PDS4 labels are ASCII text files written in the eXtensible Markup Language (XML). Product labels are detached from the files they describe (with the exception of the Product_Bundle label). There is one label for every product. A product, however, may consist of one or more data objects. The data objects of a given product may all reside in a single file, or they may be stored in multiple files, in which case the PDS4 label points to all the files. A PDS4 label file usually has the same name as the data product it describes, but always with the extension ".xml".

Documents are also considered to be products; they have PDS4 labels just as other products do.

For the Europa Clipper mission, the structure and content of PDS labels will conform to the PDS common schema and Schematron files based upon the PDS Information Model [4]. By use of an XML editor, the schema and Schematron files may be used to validate the structure and content of the product labels. In brief, the schema is the XML model that PDS4 labels must follow, and the Schematron files are a set of validation rules that are applied to PDS4 labels.

The PDS common schema and Schematron files documents are produced, managed, and supplied to Europa Clipper by the PDS. In addition to these documents, the Europa Clipper mission has produced additional XML schemas and Schematron files, that govern the products in this archive. These documents contain attribute and parameter definitions specific to the Europa Clipper mission. A list of the XML documents associated with this archive is provided at http://pds.nasa.gov/pds4/schema/released/.

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Appendix A Support staff and cognizant persons

Table 25: Archive support staff

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