MESSENGER Radio Science Raw Data Archive (PDS4)

Software Interface Specification (SIS)

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Document Change Log

PDS4 Rev	Revision Date	Author	Sections	Remarks
1.0	2022-03-09	Simpson and Verma	All	Wholesale revision of the PDS3 MESSENGER RS RDA EDR SIS to reflect different PDS4 structure, naming, etc.

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Acronyms and Abbreviations

ANT	Antenna Configuration
APL	JHU Applied Physics Laboratory
ASCII	American Standard Code for Information Interchange
AU	Astronomical Unit
CK	Camera Kernel (as in CK file)
CSV	Comma Separate Value file
DAT	extension on names of binary data files
DDOR	Delta-Differential One-way Range (file or directory)
DSCC	Deep Space Communications Complex
DSN	Deep Space Network
DSS	DSN station identifier
EDR	Experiment Data Record
EN	PDS Engineering Node
FK	Frames Kernel file
FOV	Field of view
G&C	Guidance and Control
ICD	Interface Control Document
IERS	International Earth Rotation and Reference Systems Service
IK	Instrument Kernel file
ION	Ionosphere Calibration File (or directory)
JHU	Johns Hopkins University
JPL	Jet Propulsion Laboratory
ksps	kilo samples per second
LID	logical identifier
LTF	Light Time File (or directory)
LSK	Leap Seconds Kernel file
MDM	Momentum Dump Maneuver
MESSENGER	MErcury Surface, Space ENvironment, GEochemistry, and Ranging
MESS	an abbreviated form of the MESSENGER acronym
Msps	Mega samples per second
MPD	Maneuver Performance Data (file or directory)
NAIF	Navigation and Ancillary Information Facility
NASA	National Aeronautics and Space Administration
NAV	Navigation Subsystem/Team
ODF	Orbit Data File (TRK-2-18 files) or directory
ODL	Object Description Language
PCK	Planetary Constants Kernel
PDF	Adobe Portable Document Format
PDS	Planetary Data System
PDS3	PDS Standards version 3
PDS4	PDS Standards version 4
PPI	PDS Planetary Plasma Interactions Node
RDA	Raw Data Archive
RS	Radio Science

RSD	Radio Science Documentation (bundle)
RSR	Radio Science Receiver (open loop data) file or directory
RSSG	Radio Science Systems Group (JPL)
RST	Radio Science Team
SCLK	Spacecraft Clock
SCET	Spacecraft Event Time
SFF	Small Forces File
SIS	Software Interface Specification
SOC	Science Operations Center
SPICE	Spacecraft Planet Instrument Camera-matrix Events
SPK	Spacecraft Planet Kernel file
TAB	extension on names of ASCII table files
TBD	To Be Determined
TRO	Troposphere Calibration Data (file or directory)
TNF	Tracking And Navigation File (TRK-2-34 data) or directory
TSAC	Tracking System Analytic Calibration
TXT	Text, extension on names of text files
UCLA	University of California, Los Angeles
UT1	Universal Time (principal form)
VLBI	Very Long Baseline Interferometer
WEA	DSN Weather data (file or directory)

Contents

1 Introduction

This Software Interface Specification (SIS) describes the format and content of the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) Radio Science (RS) Raw Data Archive (RDA). The MESSENGER RS RDA is the complete archive of raw data from investigations conducted using the radio link between the MESSENGER spacecraft and stations of the NASA Deep Space Network (DSN).

The MESSENGER RS RDA is a product of the MESSENGER Radio Science Team (RST), working in conjunction with the MESSENGER Science Operations Team and the NASA Planetary Data System (PDS). It is the deliverable raw data archive from the MESSENGER Project radio science investigations to PDS.

The data were originally delivered according to version 3 of the PDS Standards (PDS3). The PDS3 archive has been 'migrated' so that it is now compliant with version 4 of the Standards (PDS4). The migration was carried out so that users could take advantage of new capabilities and tools that are available under PDS4; but both versions of the archive remain accessible to users.

This SIS and the PDS4 archive that it describes have been peer reviewed by the NASA Planetary Data System (PDS) Planetary Plasma Interactions (PPI) Node and have been ingested into the PDS4 system. The document provides information to enable users to understand the files and their organization in the PDS4 archive. Those users are expected to be scientists and investigators who will process and analyze the data, including both those who have been associated with the MESSENGER Project and others.

The Johns Hopkins University Applied Physics Laboratory (APL) managed the MESSENGER mission and was responsible for delivering the RS data to the PDS Geosciences Node, where the data were originally posted for public use. Migration of the RS raw data was managed by the PDS Planetary Plasma Interactions (PPI) node at UCLA.

2 Data Overview

The MESSENGER RS RDA includes data and documentation generated by various elements of the NASA Deep Space Network (DSN), the MESSENGER Project, the RST, and others between October 2006 (before Venus Flyby 2) and April 2015 (end of flight operations). Data consist of observational data and supplementary data. Observational data are the raw measurements from one or more instruments or the results from processing those measurements. Supplementary data are useful for understanding, processing, or interpreting the observational data but are not usually considered to have science value of their own.

Observational data cover the time from October 2006 (two years into the cruise phase of the mission) until April 2015, when the spacecraft intentionally impacted the surface of Mercury. Coverage includes the Venus 2 Flyby and all of the subsequent Mercury orbital activities. The total volume of observational data is approximately 120 GB (Table 1). Supplementary data volume is small by comparison (Table 2).

Table 1 – Observational Product Types and Key Characteristics

Product Type	DDOR	ODF	RSR	TNF
First Data	2007-349	2007-155	2006-297	2007-155
Last Data	2015-116	2015-120	2015-119	2015-120
Number of Files	97	1525	2405	3924
Volume	298 kB	455 MB	59.4 GB	56.7 GB

Data are stored in files of various sizes and formats. The formats vary among product types; users should consult the appropriate data product SIS for details at the bit and byte level (see Tables 6 and 7). For the most part, this document provides an overview at the product and higher levels.

2.1 Observational Data

Tracking and Navigation Files (TNFs) originated in the closed-loop transmitting/receiving system of one or more NASA DSN stations, where phase-locked loops tracked the uplink (transmitted) and spacecraft (downlink) signals. Closed-loop data were efficient for characterizing slowly changing signals and were the input to operational navigation and orbit-determination processes and, eventually, to solutions for improved models of Mercury's gravity field. Closed loop receivers reported the amplitude and phase of uplink (when available) and downlink radio signals at a typical cadence of 10 measurements per second.

During the MESSENGER era, Orbit Data Files (ODFs) were derived from TNFs. They were smaller files that emphasized frequency (rather than phase) measurements, which could be incorporated directly into legacy orbit determination pipelines. In earlier times, ODFs were the primary output from the closed-loop system; their production was suspended in December 2017 as users took advantage of the higher intrinsic precision of TNFs.

For some observations receivers at two DSN complexes were used in a very-long baseline interferometry (VLBI) configuration. They captured the frequency/phase of the spacecraft signal relative to the frequency/phase of a quasar nearby in the antennas' fields of view. The differential phase over the two antenna baseline provided a measurement of motion of the spacecraft orthogonal to the line of sight. These data were captured in DDOR products at a rate of approximately one measurement every four minutes. Accuracies on the order of 10 nanoradians (1.5 km at 1 AU) can be achieved.

In the open-loop system, the signal was converted to a baseband frequency range, and the entire passband was sampled and recorded for later processing. Radio Science Receiver (RSR) records were the primary data type from the open-loop system. Open-loop data (because of their much higher rate and volume) were collected only when the signal was expected to be very dynamic—such as during a spacecraft maneuver or an occultation. For MESSENGER, RSR data were used primarily to determine the time of occultation so that Mercury's radius could be measured more precisely, especially in the southern hemisphere.

2.2 Supplementary Data

Supplementary data, which supported analysis of observational data and which were included in the MESSENGER RS RDA, came from several sources as shown in Table 2. Data sources included the MESSENGER Guidance and Control Team (G&C), Navigation Team (NAV), and Science Operations Center (SOC) and the DSN Tracking System Analytic Calibration (TSAC) Team.

Table 2 – Supplementary Data in the MESSENGER RS RDA

Type	Description	Data Source	# Files	Est Total Volume
ANT	Antenna configuration file — uplink and downlink antenna selections, based on spacecraft telemetry	SOC	1	206 kB
ION	Ionosphere (media) calibration files — historical and predicted Earth ionospheric conditions	TSAC	113	2.8 MB
LTF	Light Time File — radio propagation time from spacecraft to Earth and from Earth to spacecraft (vs. time)	NAV	318	975 MB
MDM	Momentum Dump Maneuver file — summary information on each angular momentum dump and orbit correction maneuver.	G&C	1	35 kB
MPD	Maneuver Performance Data — estimates of spacecraft mass and center of mass; moments of inertia; thruster locations, directions, and magnitudes; and propellant flow rate	G&C	26	81 kB
SFF	Small Forces File — details of thruster activity	G&C	25	2.7 MB
TRO	Troposphere (media) calibration files — historical and predicted Earth troposphere conditions	TSAC	96	15.1 MB
WEA	Meteorological conditions at each DSN complex (vs time)	TSAC	198	128 MB

Other supplementary data can be obtained from the JPL Navigation and Ancillary Information Facility (NAIF) and the International Earth Rotation and Reference Systems Service (IERS). NAIF provides ephemerides, attitude, and other 'kernels' in formats that are easily read into programs on a range of platforms using the NAIF Toolkit software. For more information see

http://naif.jpl.nasa.gov/naif software and documentation
http://naif.jpl.nasa.gov/pub/naif/generic_kernels files with generic data such as leap seconds, digital shape models, star catalogs, and planetary constants.
https://naif.jpl.nasa.gov/pub/naif/pds/data/mess-e_v_h-spice-6-v1.0/messsp_1000/ MESSENGER kernels (Table 3)

Table 3 – MESSENGER Kernels Archived by NAIF

Type	Description	# Files	Est Total Volume
CK	Spacecraft attitude, instrument pointing	367	39 GB
FK	Coordinate frame specifications	10	741 kB
IK	Instrument FOV, timing, geometry	21	675 kB
SCLK	Spacecraft clock conversion	13	1.55 MB
SPK	Spacecraft and planetary ephemerides	22	4.5 GB

The IERS web site (http://www.iers.org) provides information about Earth orientation and rotation.

MESSENGER RS analyses do not require the pointing angle for the high-gain (phased array) antenna or the low-gain antennas. The phase center of the low-gain antennas varies less than a centimeter over +/-90 degrees from its bore-sight. The angular dependence of the phase center of the high-gain antenna is not required because spacecraft attitude does not change during a DSN contact period when using either the fan beams or high-gain antennas.

2.3 Data Flow

Many RS files were delivered to servers at JPL from which they were transferred to APL, associated with labels, and placed into the RS directory at the APL Science Operations Center (SOC) where they were immediately accessible to the MESSENGER RS team. RSR data were collected by the JPL Radio Science Systems Group (RSSG) and transferred to the SOC.

Deliveries to PDS were organized as the observational and supplementary data became available. Each delivery was reviewed, validated, and forwarded to PDS for archiving about once every six months, according to the MESSENGER program schedule.

3 Archive Organization

3.1 Products, Collections, and Bundles

Raw data measurements were captured as digital data objects. A common example of a digital data object is a table, which may be either ASCII or binary. A DDOR or an RSR may be viewed as a binary table; WEA data are organized into ASCII tables. Accompanying each digital data object is a description object — ASCII text in an XML document that contains information about the digital data object's structure and content, such as the number of columns and rows in the table, maximum and minimum values, etc.

One or more digital data objects in a file accompanied by their concatenated description objects in a second file is a 'product'. The first file type is often called the 'data' and the second is called the 'label'. An aggregation of related products is a 'collection', and an aggregation of related collections is a 'bundle'.

3.2 Products, Collections, and Bundles in the MESSENGER RS RDA

The MESSENGER RS RDA is one bundle comprising five collections, each of which may have from a few to several thousand products (Figure 1). In the MESSENGER RS RDA there are four collections of observational products and one collection of supplementary products, which includes eight types of data products.

RS documents, such as this file ,belong to a MESSENGER RS document collection in the MESSENGER mission bundle. Context products, which provide information on the mission, spacecraft, RS instrument, etc., are hosted and maintained by the PDS Engineering Node.

3.3 Logical and Version Identifiers

Each bundle, collection, and product in PDS4 is uniquely identified by a 'logical identifier' (LID) and a version identifier (VID); the combination is known as a versioned logical identifier (LIDVID). Bundle LIDs are constructed using four fields — *e.g.*, *urn:nasa:pds:mess-rs-raw* for the MESSENGER RS RDA. Collection LIDs have a fifth field appended — *e.g.*, *urn:nasa:pds:mess-rs-raw:data-tnf* for the collection of MESSENGER TNFs. Product LIDs have a sixth field— *e.g.*, *urn:nasa:pds:mess-rs-raw:data-tnf:071550900sc236dss63_tnf*. Note that a single colon ":" separates fields in a LID. The VID has two fields — major and minor version numbers separated by a single period — *e.g.*, *2.0*. The VID is appended to the LID by a double colon "::". VIDs may be applied to bundle, collection, and product LIDs. The product LIDVID *urn:nasa:pds:mess-rs-raw:data-tnf:071550900sc236dss63_tnf::2.0* identifies the second version (0^{th}, or original, sub-version) of the TNF product *071550900sc236dss63_tnf.* Note that the LIDVID is a unique *logical* identifier; it does not necessarily imply a physical storage location, such as in a computer directory or folder (although they are often closely related).

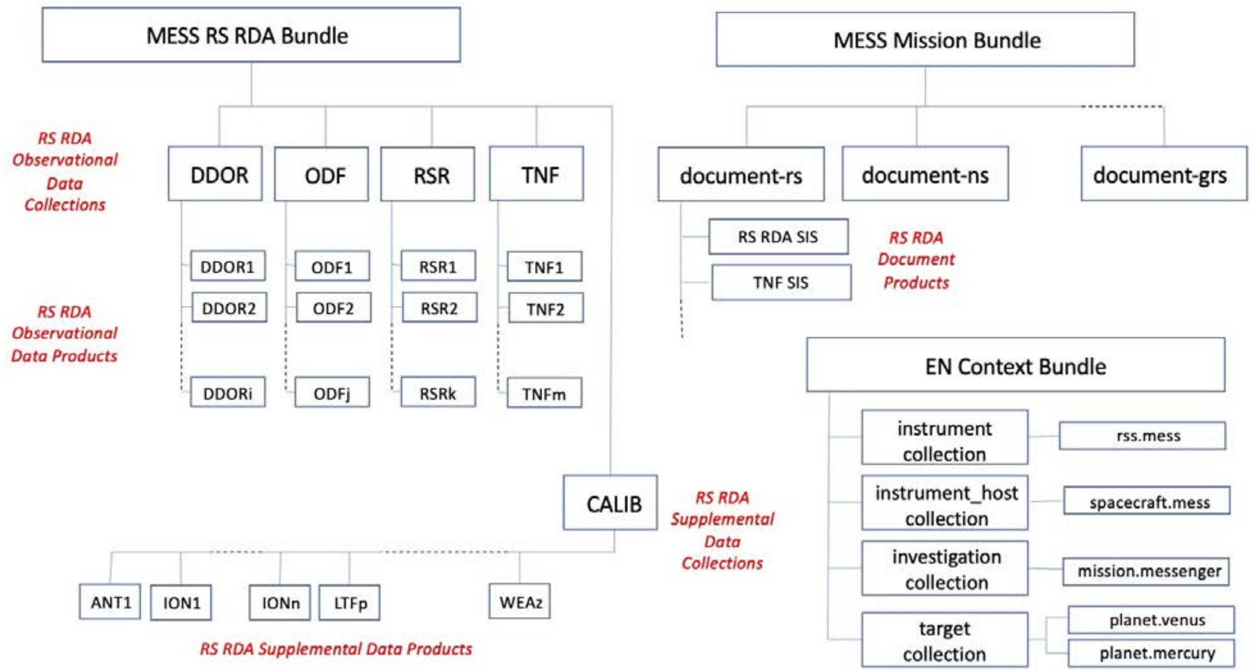

Figure 1. The MESSENGER RS RDA contains four collections of observational data — DDOR, ODF, RSR, and TNF (upper left) — and one collection of supplementary data (shown here in the lower left as CALIB), which contains about 800 files of eight different types — ANT, ION, LTF, MDM, MPD, SFF, TRO, and WEA. Many MESSENGER RS RDA labels reference context products in the Engineering Node (EN) Context bundle (lower right). Finally, MESSENGER RS RDA documents are members of an RS document collection in the MESSENGER Mission bundle (upper right).

3.4 Archive Physical Structure

The physical structure of the archive follows the logical organization of the bundles and collections. There are 'data' and 'calib' directories under the root. Each observational data collection is located in a separate subdirectory, and all of the calibration products are located in the 'calib' directory, which has subdirectories ‘ant’, ‘ltf’, ‘mdm’, etc. In cases where the number of products within an observational data collection is large, the files may be separated into subsubdirectories according to year.

3.5 LID and File Name Construction

3.5.1 Bundle and Collection LIDs

The MESSENGER RS RDA is a single bundle; the bundle's LID is *urn:nasa:pds:mess-rs-raw*. The collections under the bundle have the LIDs shown in the first six rows of Table 4.

The MESSENGER RS RDA references products in several context collections; thus "xxx" in Table 4 represents "investigation", "instrument_host", "instrument", and "target" (see also Figure 1). Note that the document collection (last row in Table 4) does not belong to the MESSENGER RS RDA; it is a member of the MESSENGER Mission bundle (Figure 1).

Table 4 — Collection LIDs for MESSENGER Radio Science Data		
Collection	**Type**	**Collection LID**
DDOR	Data	*urn:nasa:pds:mess-rs-raw:data-ddor*
ODF	Data	*urn:nasa:pds:mess-rs-raw:data-odf*
RSR	Data	*urn:nasa:pds:mess-rs-raw:data-rsr*
TNF	Data	*urn:nasa:pds:mess-rs-raw:data-tnf*
CALIB	Calibration	*urn:nasa:pds:mess-rs-raw:data-calib*
Context	Context	*urn:nasa:pds:context:xxx*
Document	Document	*urn:nasa:pds:messenger:document-rs*

3.5.2 Product LIDs and File Names

Product identifiers (the sixth field in the product LID) are constructed using rules that vary slightly among product types. The extension ".dat" is appended to the product identifier, which is also the base file name, to form the name of a binary data file. When the data file is an ASCII table with fixed width fields, the extension is ".tab"; when the data file is an ASCII table with variable width fields, the extension is ".csv"; when the data file is ASCII text, the extension is ".txt"; and when the data file is a PDF/A-formatted document, the extension is ".pdf". In each case labels use the base name of the data file and the extension ".xml".

Context products are labels only — XML documents labeling physical or conceptual objects, which have no digital component (for example, the MESSENGER mission and spacecraft and the target Mercury). Details and examples are shown below.

3.5.2.1 Observational Products

TNF LIDs have the form

urn:nasa:pds:mess-rs-raw:data-tnf:yydddhhmmsc236dssnn_tnf

where '*yydddhhmm*' is the data start year, day of year, hour, and minute and "*dssnn*" is the DSN number of the primary receiving antenna (in rare cases, the value "*dssall*" may appear). The DSN spacecraft identifier for MESSENGER is "*sc236*", which will be invariant throughout the MESSENGER RS RDA. The corresponding TNF file name template and an example are, respectively,

yydddhhmmsc236dssnn_tnf.dat
071550900sc236dss63_tnf.dat

ODF LIDs are derived from file names (reverse of the TNF procedure); the ODF file names usually have the form

mess_rs_yyddd_eee[_tts]_odf.dat

where '*yyddd*' is the data start year and day of year and '*eee*' is the stop day of year. ODFs can span multiple days and contain data from several DSN antennas. '*tts*' is an optional component of the file name which gives the integration time (seconds) per data point. An example of this type of file name is

mess_rs_12188_191_10s_odf.dat

The corresponding ODF LID is derived from the file name by dropping the extension "*.dat*"; the LID then has the form

urn:nasa:pds:mess-rs-raw:data-odf:mess_rs_yyddd_eee[_tts]_odf

However, there is variability in ODF file names (and, therefore, in the LIDs). Below is a (non-exhaustive) list of file name templates that are variations on the standard form. In each case the product identifier (field 6 in the LID) is the file name less the extension "*.dat*".

mess_rs_yyddd_hhmm_odf.dat
mess_rs_yyddd_eee_nav_odf.dat
mess_rs_yyddd_hhmm_1per1_odf.dat
mess_rs_yyddd_hhmm_1p1_odf.dat
mess_rs_yydddhhmm_ss_odf.dat
mess_rs_yydddhhmm_ss_ttodf.dat
mess_rs_yydddhhmm_ss_tt_odf.dat
mess_rs_yyddd_hhmm_10p1_odf.dat

where '*hhmm*' is the data start hour and minute, '*ss*' is the DSN receiving antenna number, and the notation '*xpy*' gives the integration time as the number of samples '*x*' in '*y*' seconds. Most integration times are 10 or 60 seconds. When the integration time is absent from the LID or file name, its value can be taken to be 60 seconds.

DDOR LIDs have the form

urn:nasa:pds:mess-rs-raw:data-ddor:yydddhhmmsc236dssnn_ddor

where '*yydddhhmm*' is the data start time year, day of year, hour, and minute and "*dssnn*" is the DSN number of the primary receiving antenna. Each DDOR observation requiresdtwo DSN antennas; only one appears as '*dssnn*'. The file name template and an example DDOR file name are, respectively,

yydddhhmmsc236dssnn_ddor.dat
110381405sc236dss26_ddor.dat

RSR LIDs have the form:

urn:nasa:pds:mess-rs-raw:data-rsr:yyyydddhhmm_ccc_rsr where '*yydddhhmm*' is the data start time year, day of year, hour, and minute and '*ccc*' is the RSR identifier and subchannel. During MESSENGER, each DSN complex had at least four RSRs, each with multiple subchannels, allowing a wide choice of frequency bands, sample rates, and sample resolutions. The file name template and an example RSR file name are, respectively,

yyyydddhhmm_ccc_rsr.dat
20062971548_2a1_rsr.dat

3.5.2.2 Supplementary Products in the MESSENGER RS RDA

All MESSENGER RS RDA supplementary data are in the calibration collection, which has LID

urn:nasa;pds:mess-rs-raw:calib

There is one ANT file in the calibration collection. It is an ASCII table with fixed width fields. Its LID and file name are, respectively,

urn:nasa;pds:mess-rs-raw:calib:mess_rs_ant
mess_rs_ant.tab

ION files are ASCII card images archived as text files. ION LIDs have the form

urn:nasa:pds:mess-rs-raw:calib:mess_rs_yyyyddd_eee_dp_ion

where '*yyyy*' is the ION data start year, '*ddd*' is the start day of year, and '*eee*' is the stop day of year (which may be in the next year). '*dp*' indicates that the file contains calibration data for Doppler measurements; if the '*dp*' is replaced by '*vl*', the file is to be used with VLBI (DDOR) data. Corresponding ION file name templates and example file names are, respectively,

mess_rs_yyyyddd_eee_dp_ion.txt
mess_rs_2007335_001_dp_ion.txt

mess_rs_yyyyddd_eee_vl_ion.txt
mess_rs_2007337_365_vl_ion.txt

LTF files are ASCII tables with fixed width fields. LTF LIDs have the form

urn:nasa:pds:mess-rs-raw:calib:mess_rs_yyyyddd_zzzzeee_ltf

where '*yyyy*' is the LTF data start year, '*ddd*' is the start day of year, 'zzzz' is the stop year, and '*eee*' is the stop day of year. The corresponding LTF file name template and an example file name are, respectively,

mess_rs_yyyyddd_zzzzeee_ltf.tab
mess_rs_2007335_2008001_ltf.tab

There is one MDM file in the calibration collection. It is an ASCII table with variable width fields delimited by commas. Its LID and file name are, respectively,

urn:nasa;pds:mess-rs-raw:calib:mess_rs_mdm
mess_rs_mdm.csv

MPD files are ASCII files; each has several tables with differently formatted fixed width fields. MPD LIDs have the form

urn:nasa:pds:mess-rs-raw:calib:mess_rs_yyyyddd_zzzzeee_mpd

where '*yyyy*' is the MPD data start year, '*ddd*' is the start day of year, 'zzzz' is the stop year, and '*eee*' is the stop day of year. The corresponding MPD file name template and an example file name are, respectively,

mess_rs_yyyyddd_zzzzeee_mpd.tab
mess_rs_2007290_2007290_mpd.tab

SFF files are ASCII tables with fixed width fields. SFF LIDs have the form

urn:nasa:pds:mess-rs-raw:calib:mess_rs_yyyyddd_zzzzeee_sff

where '*yyyy*' is the SFF data start year, '*ddd*' is the start day of year, '*zzzz*' is the stop year, and '*eee*' is the stop day of year. The corresponding SFF file name template and an example file name are, respectively,

mess_rs_yyyyddd_zzzzeee_sff.tab
mess_rs_2008079_2008079_sff.tab

TRO files are ASCII card images archived as text files. TRO LIDs have the form

urn:nasa:pds:mess-rs-raw:calib:mess_rs_yyyyddd_zzzzeee_tro

where '*yyyy*' is the TRO data start year, '*ddd*' is the start day of year, *'zzzz'* is the stop year, and '*eee*' is the stop day of year. The corresponding TRO file name template and an example file name are, respectively,

mess_rs_yyyyddd_zzzzeee_tro.txt
mess_rs_2008061_2008092_tro.txt

WEA files are ASCII files; each file contains multiple tables with similarly formatted fixed width fields. WEA LIDs have the form

urn:nasa:pds:mess-rs-raw:calib:mess_rs_yyyyddd_eee_ss_wea where '*yyyy*' is the WEA data start year, '*ddd*' is the start day of year, '*eee*' is the stop day of year (which may be in the next year), and '*ss*' is the identifier for the DSN complex where the WEA data were collected (10, 40, or 60). The corresponding WEA file name template and an example file name are, respectively,

mess_rs_yyyyddd_eee_ss_wea.tab
mess_rs_2007001_365_10_wea.tab

3.5.2.3 Other Supplementary Products

Other supplementary products of possible interest to users of the MESSENGER RS RDA are available through the PDS NAIF and the IERS web sites. See Section 2.2 for more information.

3.5.3 Context Products

Context files are PDS4 label files used to define a unique identifier (LID) for physical objects (*e.g.*, spacecraft, instruments, targets), and conceptual objects (*e.g.*, institutions). The LIDs defined in context files allow other PDS4 product labels to reference associated objects unambiguously. The MESSENGER RS RDA has a context collection with LID

urn:nasa:pds:mess-rs-raw:context

MESSENGER RS RDA labels reference several context products which have already been archived in an EN context collection at https://starbase.jpl.nasa.gov/pds4/context-pds4/. Examples are listed in Table 5.

Table 5 — LIDs for Context Products in the MESSENGER RS RDA

product_data_object	**LID**
Investigation	*urn:nasa:pds:context:investigation:mission.messenger*
Instrument_Host	*urn:nasa:pds:context:instrument_host:spacecraft.mess*
Instrument	*urn:nasa:pds:context:instrument:rss.mess*
Target	*urn:nasa:pds:context:target:planet.earth*
Target	*urn:nasa:pds:context:target:planet.mercury*
Target	*urn:nasa:pds:context:target:planet.venus*

3.5.4 Document Products

Documents relevant to the MESSENGER RS RDA are members of a collection in the MESSENGER Mission bundle, which has LID

urn:nasa:pds:messenger:document-rs

Table 6 lists SIS documents for observational products, Table 7 lists SIS documents for supplementary products that are included in the MESSENGER RS RDA, and Table 8 lists other documents (including this one).

The rightmost column in each table gives the document product identifier, which is appended to the collection LID (above) to create the full product LID. In some cases, more than one version of the document is provided, reflecting that fact that the document (and, possibly, the data file) evolved during the course of the MESSENGER mission. Changes are small and are not likely to affect use of the product. Labels are based on the most recent version of the document. Documents are provided in either 7_Bit ASCII Text or PDF/A format.

See Appendix A in this document for notes on specific product types which may have been modified during the migration to PDS4. For example, the ANT file was reformatted.

Table 6 — SIS Documents for Observational Data Products

Type	SIS Title	SIS Product ID
DDOR	See data type 10 in the TNF SIS document	sis-tnf-i1 or sis-tnf-p
ODF	820-013 Deep Space Mission System, External Interface Specification; JPL D-16765, TRK-2-18 Orbit Data File Interface	sis-odf
RSR	Radio Science Receiver Standard Formatted Data Unit (SFDU)	sis-rsr
TNF	820-013 Deep Space Mission System, External Interface Specification, JPL D-16765, TRK-2-34 Tracking System Data Archival Format	sis-tnf-i1 or sis-tnf-p

Table 7 — SIS Documents for Supplementary Data Products

Type	SIS Title	SIS Product ID
ANT	Antenna Configuration data	sis-ant
ION	820-013 Deep Space Mission System, External Interface Specification, JPL D-16765, TRK-2-23 Media Calibration Interface	sis-media
LTF	JPL Light Time File	sis-ltf
MDM	The Momentum Dump File	sis-mdm
MPD	The Maneuver Performance Data file description; no SIS required, MPDINFO.TXT file included.	sis-mpd
SFF	SFF SIS Small Forces File	sis-sff
TRO	820-013 Deep Space Mission System, External Interface Specification, JPL D-16765, TRK-2-23 Media Calibration Interface	sis-media
WEA	820-013 Deep Space Mission System, External Interface Specification, JPL D-16765, TRK-2-24 Weather Data Interface	sis-wea

Table 8 — Other Relevant Documents in the MESSENGER Mission Bundle	
Document	**Product ID (file name)**
MESSENGER RS RDA PDS4 SIS	sis-rs-edr (mess_rs_edr_sis.pdf)
Instrument Description	Instrument-rs (instrument_rs.pdf)

3.6 Product Formats

3.6.1 Label Files

All label files are XML documents.

3.6.2 Data Files

The product LID uniquely identifies a product within the PDS4 domain, but it does not reveal the storage format; that information can be found in the label content. In the MESSENGER RS RDA, format may also be inferred from the file name extension.

Tabular files ("*.tab*" extension) exist in the calibration collection. All tabular files are filled with ASCII characters. Some are formatted for direct reading into data base management systems. They consist of data fields which are defined by position alone; each record has the same fields in exactly the same locations as its predecessor within a single table. Character fields may optionally be enclosed in double quotation marks ("); if so, they are padded with spaces to keep quotation marks in the same position in successive records. Values are left justified in character fields and right justified in numeric fields. The records in tabular files have fixed length, and the last two bytes of each record contain the ASCII Carriage-Return and Line-Feed characters. A single tabular file may contain more than one table, in which case the specifications for the tables may differ.

Comma separated value (CSV) files ("*.csv*" extension) exist in the calibration collection. All CSV files are filled with ASCII characters. Some are formatted for direct reading into database management systems. They consist of data fields which are separated by commas. Character fields may also be enclosed by pairs of double quotation marks ("); a comma within a pair of double quotes is taken to be part of the field value rather than a field delimiter. The records in CSV files generally have variable length. The last two bytes of each record contain the ASCII Carriage-Return and Line-Feed characters. A single CSV file may contain more than one delimited table, in which case the specifications for the tables may differ.

Text files ("*.txt*" extension) exist in the calibration and document collections. All text files are filled with 7-bit ASCII characters, but there is no specific structure. The last two bytes of each record contain the ASCII Carriage-Return and Line-Feed characters. A single text file may contain more than one text digital object, in which case the specifications for the text objects may differ.

Portable document format (PDF) files ("*.pdf*" extension) exist in the document collection. PDF files are encoded byte streams in a format developed by Adobe Systems. The Adobe proprietary format was released as an open standard in 2008 (ISO 32000-1:2008). The PDF/A-1a (preferred) and PDF/A-1b versions are especially suitable for archiving since they embed all fonts and disallow encryption (ISO 19005-1); no other PDF versions are allowed in PDS4.

Binary files ("*.dat*" extension) exist in the observational data collections. File formats are described at the bit level in accompanying SIS documents. In the MESSENGER RS RDA, all binary files contain binary tables meaning that data fields are defined by position alone; each record has the same fields in exactly the same locations as its predecessor within a single table. Individual fields may contain numerical values in integer, floating point, character or other formats. A single binary file may contain more than one digital data object, in which case the specifications for the digital objects may differ. No two digital data objects may be interleaved in a single file, and no digital object may extend beyond a single file.

4 Documentation

4.1 Controlling Documents

The following govern the structure and content of the MESSENGER RS RDA:

Planetary Data System Standards Reference, JPL D-7669, Part 2, version 1.13.0, Pasadena, CA: Jet Propulsion Laboratory, October 1, 2019.

Planetary Data System Standards Reference, JPL D-7669, Part 2, version 1.14.0, Pasadena, CA: Jet Propulsion Laboratory, May 22, 2020.

Planetary Data System Information Model, version 1.13.0.0, including schemas
https://pds.nasa.gov/pds4/pds/v1/PDS4_PDS_1D00.xsd
https://pds.nasa.gov/pds4/pds/v1/PDS4_PDS_1D00.sch

Planetary Data System Information Model, version 1.14.0.0, including schemas
https://pds.nasa.gov/pds4/pds/v1/PDS4_PDS_1E00.xsd
https://pds.nasa.gov/pds4/pds/v1/PDS4_PDS_1E00.sch

See also the documents listed in Tables 6-8 of this document.

4.2 Other Documents

4.2.1 Reference documents

The following provide important background and contextual information for understanding PDS4 archives, individual product types, and MESSENGER RS instrumentation:

Data Design Working Group, *PDS4 Concepts*, version 1.14.0, Planetary Data System, May 19, 2019 (available at https://pds.nasa.gov/datastandards/documents/concepts/Concepts_1.14.0.pdf).

Asmar, S. W., and N. A. Renzetti, The Deep Space Network as an Instrument for Radio Science Research, Jet Propulsion Laboratory Publication, 80-93, Rev. 1, 15 April 1993.

Asmar, S. W., R. G. Herrera, and T. Priest, Radio Science Handbook, JPL D-7938, Volume 6, Jet Propulsion Laboratory, Pasadena, CA, 1995.

DSN Geometry and Spacecraft Visibility, Document 810-5, Rev. D, Vol. 1, DSN/Flight Project Interface Design, Jet Propulsion Laboratory, Pasadena, CA, 1987.

Malouf, P. M., and R. E. Wallis, The medium-gain antenna of the MESSENGER spacecraft, *Microwave Journal*, **48** (10), 110-114, October 2005.

Moyer, T., Formulation for Observed and Computed Values of Deep Space Network Data Types for Navigation, JPL Publication 00-7, Jet Propulsion Laboratory, Pasadena, 2000.

Pavlis, D. E., S. Poulose, C. Deng, and J. J. McCarthy, GEODYN II System Documentation, SGT-Inc., Greenbelt, Maryland, Contractor report, 2007.

Pavlis D. E., J. McCarthy, and J. Wimert, GEODYN II system description, vol. 1-5, contractor report, SGT Inc., Greenbelt, MD., 2012.

Srinivasan, D. K., R. E. Wallis, D. W. Royster, J. R. Bruzzi, P. M. Malouf, and K. B. Fielhauer, Spacecraft-level testing and verification of an X-band phased array, Institute of Electrical and Electronics Engineers (IEEE) Aerospace Conference, IEEEAC paper 1059, 9 pp., Big Sky, MT, March 5- 12, 2005.

Srinivasan, D. K., R. M. Vaughan, R. E. Wallis, M. A. Mirantes, T. A. Hill, S. Cheng, J. R. Bruzzi, and K. B. Fielhauer, Implementation of an X-band phased-array subsystem in a deep space mission, Institute of Electrical and Electronics Engineers (IEEE) Aerospace Conference, IEEEAC paper 1067, 11 pp., Big Sky, MT, March 5-12, 2005.

Srinivasan, D. K., M. E. Perry, K. B. Fielhauer, D. E. Smith, and M. T. Zuber, Application of the MESSENGER radio frequency subsystem to meet the mission radio science objectives, *Space Science Reviews*, **131**, 557-571, 2007.

4.2.1 Publications and Presentations

The following are selected publications and presentations relating to the MESSENGER radio science observations, related observations, and results:

Blair, D. M., A. M. Freed, P. K. Byrne, C. Klimczak, L. M. Prockter, C. M. Ernst, S. C. Solomon, H. J. Melosh, and M. T. Zuber, The origin of graben and ridges in Rachmaninoff, Raditladi, and Mozart basins, Mercury, *Journal of Geophysical Research: Planets*, **118**, 47-58, doi:10.1029/2012JE004198, 2013.

Elgner, S., A. Stark, J. Oberst, M. E. Perry, M. T. Zuber, M. S. Robinson, and S. C. Solomon, Mercury's global shape and topography from MESSENGER limb images, *Planetary and Space Science*, **103**, 299-308, 2014.

Fassett, C. I., J. W. Head, D. M. H. Baker, M. T. Zuber, D. E. Smith, G. A. Neumann, S. C. Solomon, C. Klimczak, R. G. Strom, C. R. Chapman, L. M. Prockter, R. J. Phillips, J. Oberst, and F. Preusker, Large impact basins on Mercury: Global distribution, characteristics, and modification history from MESSENGER orbital data, *Journal of Geophysical Research*, **117**, E00L08, doi:10.1029/2012JE004154, 2012.

Freed, A. M., S. C. Solomon, T. R. Watters, R. J. Phillips, and M. T. Zuber, Could Pantheon Fossae be the result of the Apollodorus crater-forming impact within the Caloris basin, Mercury?, *Earth and Planetary Science Letters*, **285**, 320-327, 2009.

Freed, A. M., D. M. Blair, T. R. Watters, C. Klimczak, P. K. Byrne, S. C. Solomon, M. T. Zuber, and H. J. Melosh, On the origin of graben and ridges within and near volcanically buried craters and basins in Mercury's northern plains, *Journal of Geophysical Research*, **117**, E00L06, doi:10.1029/2012JE004119, 2012.

Gold, R. E., S. C. Solomon, R. L. McNutt, Jr., A. G. Santo, J. B. Abshire, M. H. Acuna, R. S. Afzal, B. J. Anderson, G. B. Andrews, P. D. Bedini, J. Cain, A. F. Cheng, L. G. Evans, W. C. Feldman, R. B. Follas, G. Gloeckler, J. O. Goldsten, S. E. Hawkins, III, N. R. Izenberg, S. E. Jaskulek, E. A. Ketchum, M. R. Lankton, D. A. Lohr, B. H. Mauk, W. E. McClintock, S. L. Murchie, C. E. Schlemm, II, D. E. Smith, R. D. Starr, and T. H. Zurbuchen, The MESSENGER mission to Mercury: Scientific payload, *Planetary and Space Science*, **49**, 1467-1479, 2001.

Goudge, T. A., J. W. Head, L. Kerber, D. T. Blewett, B. W. Denevi, D. L. Domingue, J. J. Gillis-Davis, K. Gwinner, J. Helbert, G. M. Holsclaw, N. R. Izenberg, R. L. Klima, W. E. McClintock, S .L. Murchie, G. A. Neumann, D. E. Smith, R. G. Strom, Z. Xiao, M. T. Zuber, and S. C. Solomon, Global inventory and characterization of pyroclastic deposits on Mercury: New insights into pyroclastic activity from MESSENGER orbital data, *Journal of Geophysical Research: Planets*, **119**, 635-658, doi:10.1002/2013JE004480, 2014.

Hauck, S. A., II, S. C. Solomon, and D. A. Smith, Predicted recovery of Mercury's internal structure by MESSENGER, *Geophysical Research Letters*, **34**, L18201, doi:10.1029/2007GL030793, 2007.

Hauck, S. A., II, J.-L. Margot, S. C. Solomon, R. J. Phillips, C. L. Johnson, F. G. Lemoine, E. Mazarico, T. J. McCoy, S. Padovan, S. J. Peale, M. E. Perry, D. E. Smith, and M. T. Zuber, The curious case of Mercury's internal structure, *Journal of Geophysical Research: Planets*, **118**, 1204-1220, doi:10.1002/jgre.20091, 2013.

Hurwitz, D. M., J. W. Head, P. K. Byrne, Z. Xiao, S. C. Solomon, M. T. Zuber, D. E. Smith, and G. A. Neumann, Investigating the origin of candidate lava channels on Mercury with MESSENGER data: Theory and observations, *Journal of Geophysical Research: Planets*, **118**, 471-485, doi:10.1029/2012JE004103, 2013.

James, P. B., M. T. Zuber, R. J. Phillips, and S. C. Solomon, Support of long-wavelength topography on Mercury inferred from MESSENGER measurements of gravity and topography, *Journal of Geophysical Research: Planets*, **120**, 287-310, 2015.

Leary, J. C., R. F. Conde, G. Dakermanji, C. S. Engelbrecht, C. J. Ercol, K. Fielhauer, D. G. Grant, T. J. Hartka, T. A. Hill, S. E. Jaskulek, M. A. Mirantes, L. E. Mosher, M. V. Paul, C. E. Person, D. F. Persons, E. H. Rodberg, D. K. Srinivasan, R. M. Vaughan, and S. R. Wiley, The MESSENGER spacecraft, *Space Science Reviews*, **131**, 187-217, 2007.

Margot, J.-L., A Mercury orientation model including non-zero obliquity and librations, *Celestial Mechanics and Dynamical Astronomy*, **105**, 329-336, 2009.

Margot, J.-L., S. J. Peale, S. C. Solomon, S. A. Hauck, II, F. D. Ghigo, R. F. Jurgens, S. Padovan, and D. B. Campbell, Mercury's moment of inertia from spin and gravity data, *Journal of Geophysical Research*, **117**, E00L09, doi:10.1029/2012JE004161, 2012.

Mazarico, E., A. Genova, S. Goossens, F. G. Lemoine, G. A. Neumann, M. T. Zuber, D. E. Smith, and S. C. Solomon, The gravity field, orientation, and ephemeris of Mercury from MESSENGER observations after three years in orbit, *Journal of Geophysical Research: Planets*, **119**, doi:10.1002/2014JE004675, 2014.

Mohit, P. S., C. L. Johnson, O. Barnouin-Jha, M. T. Zuber, and S. C. Solomon, Shallow basins on Mercury: Evidence of relaxation? *Earth and Planetary Science Letters*, **285**, 355-363, 2009.

Padovan, S., J.-L. Margot, S. A. Hauck, II, W. B. Moore, and S. C. Solomon, The tides of Mercury and possible implications for its interior structure, *Journal of Geophysical Research: Planets*, **119**, 850-866, doi:10.1002/2013JE004459, 2014.

Padovan, S., M. A. Wieczorek, J.-L. Margot, N. Tosi, and S. C. Solomon, Thickness of the crust of Mercury from geoid-to-topography ratios, *Geophysical Research Letters*, **42**, 1029-1038, doi:10.1002/2014GL052487, 2015.

Peale, S. J., The Free Precession and Libration of Mercury, *Icarus*, **178**, 4-18, 2005.

Peale, S. J., The proximity of Mercury's spin to Cassini state 1 from adiabatic invariance, *Icarus*, **181**, 338-347, 2006.

Peale, S. J., R. J. Phillips, S. C. Solomon, D. E. Smith, and M. T. Zuber, A procedure for determining the nature of Mercury's core, *Meteoritics and Planetary Science*, **37**, 1269-1283, 2002.

Peale, S. J., M. Yseboodt, and J.-L. Margot, Long-period forcing of Mercury's libration in longitude, *Icarus*, **187**, 365-373, 2007.

Peale, S. J., J.-L. Margot, and M. Yseboodt, Resonant forcing of Mercury's libration in longitude, *Icarus*, **199**, 1-8, January 2009.

Peale, S. J., J.-L. Margot, S. A. Hauck, II, and S. C. Solomon, Effect of core-mantle and tidal torques on Mercury's spin axis orientation, *Icarus*, **231**, 206-220, 2014.

Peale, S. J., J.-L. Margot, S. A. Hauck, II, and S. C. Solomon, Consequences of an inner core on Mercury's spin configuration, *Icarus*, **264**, 443-455, 2016.

Perry, M. E., D. S. Kahan, O. S. Barnouin, C. M. Ernst,, S. C. Solomon, M. T. Zuber, D. E. Smith, R. J. Phillips, D. K. Srinivasan, J. Oberst, and S. W. Asmar, Measurement of the radius of Mercury by radio occultation during the MESSENGER flybys, *Planetary and Space Science*, **59**, 1925-1931, 2011.

Perry, M. E., G. A. Neumann, R. J. Phillips, O. S. Barnouin, C. M. Ernst, D. S. Kahan, S. C. Solomon, M. T. Zuber, D. E. Smith, S. A. Hauck II, S. J. Peale, J.-L. Margot, E. Mazarico, C. L. Johnson, R. W. Gaskell, J. H. Roberts, R. L. McNutt, Jr., J. Oberst, The low-degree shape of Mercury, *Geophysical Research Letters*, **42**, doi:10.1002/2015GL065101.

Scott, C. J., J. V. McAdams, D. P. Moessner, and C. J. Ercol, Modeling the effects of albedo and radiation pressures on the MESSENGER spacecraft, Astrodynamics Specialist Conference, American Astronautical Society/ American Institute of Aeronautics and Astronautics, paper AAS 11-552, 18 pp., Girdwood, AK, July 31 - August 4, 2011.

Smith, D. E., M. T. Zuber, X. Sun, G. A. Neumann, J. F. Cavanaugh, J. F. McGarry, and T. W. Zagwodzki, Two-way laser link over interplanetary distance, *Science*, **311**, 53, 2006.

Smith, D. E., M. T. Zuber, R. J. Phillips, S. C. Solomon, G. A. Neumann, F. G. Lemoine, S. J. Peale, J.-L. Margot, M. J. Talpe, J. W. Head III, S. A. Hauck II, M. H. Torrence, C. L. Johnson, M. E. Perry, O. S. Barnouin, R. L. McNutt, Jr., and J. Oberst, The equatorial shape and gravity field of Mercury from MESSENGER flybys 1 and 2, *Icarus*, **209**, 88-100, 2010.

Smith, D. E., M. T. Zuber, R. J. Phillips, S. C. Solomon, S. A. Hauck, II, F. G. Lemoine, E. Mazarico, G. A. Neumann, S. J. Peale, J.-L. Margot, C. L. Johnson, M. H. Torrence, M. E. Perry, D. D. Rowlands, S. Goossens, J. W. Head, and A. H. Taylor, Gravity field and internal structure of Mercury from MESSENGER, *Science*, **336**, 214-217, 2012.

Solomon, S. C., R. L. McNutt, Jr., R. E. Gold, M. H. Acuna, D. N. Baker, W. V. Boynton, C. R. Chapman, A. F. Cheng , G. Gloeckler, J. W. Head, III, S. M. Krimigis, W. E. McClintock, S. L. Murchie, S. J. Peale, R. J. Phillips, M. S. Robinson, J. A. Slavin, D. E. Smith, R. G. Strom, J. I. Trombka, and M. T. Zuber, The MESSENGER mission to Mercury: Scientific objectives and implementation, *Planetary and Space Science*, **49**, 1445-1465, 2001.

Stark, A., J. Oberst, F. Preusker, S. J. Peale, J.-L. Margot, R. J. Phillips, G. A. Neumann, D. E. Smith, M. T. Zuber, and S. C. Solomon, First MESSENGER orbital observations of Mercury's librations, *Geophysical Research Letters*, **42**, 7881-7889, doi:10.1002/2015GL065152, 2015.

Verma, A. K., A. Fienga, J. Laskar, H. Manche, and M. Gastineau (2014), Use of MESSENGER radio science data to improve planetary ephemeris and to test general relativity, A&A, 561, A115, doi:10.1051/0004-6361/201322124.

Verma, A. K., and J.-L. Margot, 2016. Mercury’s gravity, tides, and spin from MESSENGER radio science data. J. Geophys. Res. (Planets) 121, 1627–1640. doi: 10.1002/2016JE005037.

Wallis, R. E., and S. Cheng, Solid-state phased-array antenna system for the MESSENGER deep space mission, Institute of Electrical and Electronic Engineers (IEEE) Aerospace Conference, Paper 2.0104, 9 pp., CD Track 2: Space Missions, Systems, and Architecture, Big Sky, MT, March 10-17, 2001.

Wallis, R. E., J. R. Bruzzi, and P. M. Malouf, Testing of the MESSENGER spacecraft phased-array antenna, Antenna Measurements Techniques Association 26th Annual Meeting and Symposium, pp 331-336, October 2004. (article reprinted in *IEEE Transactions on Antennas and Propagation*, **47** (1), February 2005.)

Yseboodt, M., J.-L. Margot, and S. J. Peale, Analytical model of the long-period forced longitude librations of Mercury, *Icarus*, **207**, 536-544, 2010.

Zuber, M. T., O. Aharonson, J. M. Aurnou, A. F. Cheng, S. A. Hauck, II, M. H. Heimpel, G. A. Neumann, S. J. Peale, R. J. Phillips, D. E. Smith, S. C. Solomon, and S. Stanley, The geophysics of Mercury: Current status and anticipated insights form the MESSENGER mission, *Space Science Reviews*, **131**, 105-132, 2007.

Zuber, M. T., L. G. Montesi, G. T. Farmer, S. A. Hauck II, J. A. Ritzer, R. J. Phillips, S. C. Solomon, D. E. Smith, M. J. Talpe, J. W. Head III, G. A. Neumann, T. R. Watters, and C. L. Johnson, Accommodation of lithospheric shortening on Mercury from altimetric profiles of ridges and lobate scarps measured during MESSENGER flybys 1 and 2, *Icarus*, **209**, 247-255, 2010.

Zuber, M. T., D. E. Smith, R. J. Phillips, S. C. Solomon, G. A. Neumann, S. A. Hauck, II, S. J. Peale, O. S. Barnouin, J. W. Head, C. L. Johnson, F. G. Lemoine, E. Mazarico, X. Sun, M. H. Torrence, A. M. Freed, C. Klimczak, J.-L. Margot, J. Oberst, M. E. Perry, C. M. Ernst, R. J. McNutt, Jr., J. A. Balcerski, N. Michel, M. J. Talpe, and D. Yang, Topography of the northern hemisphere of Mercury from MESSENGER laser altimetry, *Science*, **336**, 217-220, 2012.

Appendix A – Notes from the PDS3 to PDS4 Migration

A.1 DDOR Files

DDOR files are actually TNF (TRK-2-34) files that contain only TNF data type 10 records. The TNFs in the MESSENGER archive do not contain data type 10 records.

Release of new TRK-2-34 software interface specification (SIS) documentation is not coordinated with release of new TNF generation software. Both evolve slowly and in parallel; but they are not synchronized. Check the date when a DDOR was generated and find a TRK-2-34 with a similar date; two versions of the SIS are included with the MESSENGER archive, roughly bracketing the lifetime of the mission. Other versions can be found in the Radio Science Documentation bundle at

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

Original (PDS3) files were archived with K-headers; K-headers are explained in Appendix B of the TNF (TRK-2-34) SIS. K-headers were an attempt by the DSN to attach a PDS3-like minimal label to the data file. The files archived under PDS3 were accompanied by detached PDS3 minimal labels, sometimes with different keyword=value pairs. For the PDS4 archive, the K-headers were removed and discarded; completely new, full PDS4 labels were created for each DDOR.

Three original (PDS3) DDOR files had corrupted records in which hexadecimal values 0x0a (one byte) had been replaced by 0x0d0a (two bytes). This may have occurred when a binary DDOR was transferred between two locations as though it were text. The files are:

```
080671245sc236dss25ddor_234.dat
080751200sc236dss25ddor_234.dat
080761205sc236dss25ddor_234.dat
```

In the migration from PDS3 to PDS4, the 0x0d0a values have been converted back to 0x0a.

quasar_id in bytes 27-38 of each VLBI CHDO is an ASCII string. The string typically includes one or more ASCII 00 (null) characters.

A.2 ODF Files

The following files were improperly transferred at some point during the PDS3 archiving process as 'text' rather than binary. Every occurrence of what appeared to be an ASCII Line-Feed (0x0a) was converted to an ASCII Carriage-Return Line-Feed pair (0x0d 0x0a), adding 786 bytes to the file size and throwing off alignment of all records after the first occurrence. Those errors have been corrected in the PDS4 archive. In a small number of cases, there was a legitimate 0x0d 0x0a pair in the original binary data; those have been identified and restored.

```
mess_rs_07155_156_10s_odf.dat
mess_rs_07155_156_60s_odf.dat
```

```
mess_rs_07156_158_10s_odf.dat
mess_rs_07156_158_60s_odf.dat
```

A.3 RSR Files

No comments regarding the PDS3 to PDS4 migration.

A.4 TNF Files

DDOR files are actually TNF (TRK-2-34) files that contain only TNF data type 10 records. The TNFs in the MESSENGER archive do not contain data type 10 records.

Release of new TRK-2-34 software interface specification (SIS) documentation is not coordinated with release of new TNF generation software. Both evolve slowly and in parallel; but they are not synchronized. Check the date when a TNF was generated and find a TRK-2-34 with a similar date; two versions of the SIS are included in the PDS4 MESSENGER document-rs collection, roughly bracketing the lifetime of the mission. Other versions can be found in the Radio Science Documentation bundle at

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

Original (PDS3) files were archived with K-headers; K-headers are explained in Appendix B of the TNF (TRK-2-34) SIS. K-headers were an attempt by the DSN to attach a PDS3-like minimal label to the data file. The files archived under PDS3 were accompanied by detached PDS3 minimal labels, sometimes with different keyword=value pairs. For the PDS4 archive, the K-headers were removed and discarded; completely new, full PDS4 labels were created for each TNF.

After removal of the K-headers, the remaining records were sorted by data type. The original (PDS3) records were in absolute time order; after sorting, the records within each record type remained in time order. The aggregation of sorted records was then concatenated into a new file so that all records of data type 0 preceded all records of data type 1, which preceded all records of data type 2, etc. Not all data types are represented in every file; in fact, typical TNF files have only a half dozen data types.

The reason for sorting was to keep the PDS4 label to a manageable size. In the original (PDS3) file almost every record would have required a separate Table_Binary definition in the label. Each TNF data record of type 0 (162 bytes) would have required over 50 kilobytes of label space; a typical 30 MB TNF might need a label of over 10 GB. XML parsers are limited to much smaller files. The only practical solution was to sort the TNFs so that labels would describe (at most) 18 binary tables. Data in the ODF (TRK-2-18) have always been sorted according to data type.

The data description identifier (DDI) in a TNF record has one of the following values: C123, C124, C125, C126, or C127. Some original (PDS3) files have records with DDI values C043, C044, and C045; these records were intended for internal (DSN) use and are not covered by TNF documentation. They have been removed from the sorted PDS4 data files.

A.5 ANT Files

The MET field in the PDS3 file has variable width. The double quotes around the MET value have been removed, and the field has been padded by adding spaces on the right. An extra space between the UTC and MET times has been removed so that each record has exactly 40 bytes. The header record has been edited to be more informative and to align better with the data records. The PDS4 file is described as a Header object followed by a Table_Character object.

A.6 ION Files

No comments from the PDS3 to PDS4 migration.

A.7 LTF Files

Data files are described as a 15-line Header followed by a multi-row Table_Character with 82-byte rows subdivided into 7 fields. There is only one complication in generating the PDS4 labels — eight of the files contain light times for Deep Space Communication Complexes (DSCC) rather than individual DSN antennas. Those files have light times given to precisions of milliseconds; the remaining 310 (antenna-specific) files have precisions of microseconds. Two label templates were used when generating PDS4 labels, one describing the light time fields as having format %10.3f and the other having format %10.6f. The files with DSCC data are:

```
mess_rs_2006318_2007211_ltf.tab
mess_rs_2007205_2008136_ltf.tab
mess_rs_2008016_2008302_ltf.tab
mess_rs_2008016_2008366_ltf.tab
mess_rs_2008016_2009364_ltf.tab
mess_rs_2008086_2008302_ltf.tab
mess_rs_2009211_2011077_ltf.tab
mess_rs_2012001_2014231_ltf.tab
```

A.8 MDM Files

Adapted `sis_mdm.pdf` from the PDS3 file `MDM_DESC.TXT` with light editing.

A.9 MPD Files

Adapted `sis_mpd.pdf` from the PDS3 file `MPD_DESC.TXT` with light editing.

Data files are described as one Header object (first seven lines) and 10 Table_Character objects. Five of the tables have more than one record; the last record in each of those five is shorter than the other records. An ASCII space was inserted at the end of the last record in those five cases so all records in any given PDS4 table have equal lengths.

Parameter CMUNCERT appears in the data files but was not defined in `MPD_DESC.TXT`; it is assumed to be the uncertainty in center of mass position in both coordinate systems.

It is assumed that UTC times are at spacecraft (spacecraft event time, or SCET).

The date and time format for MANEUVER_INITIAL_EPOCH (the first table) changed on 2015/111. That file and the ones following were hand-edited so that the format is always `yyyy-dddThh:mm:ss.ssss`. The DOY format was converted to YMD during labeling.

A.10 SFF Files

Each of the first 7 records in an SFF file contains a keyword=value pair; the records have different lengths. The PDS4 label recognizes the first 6 records as a Header object. In PDS4 the 7th record is defined to be a one record Table_Character (the Start Date and Time Table); PDS4 fields have been defined for start date and start time. Record 8 contains the character string "$$EOH" and is ignored in PDS4. Records from 9 to the end of each file are a Table_Character with fixed-length records having fixed-width fields; these are the small forces data (the Small Forces Table).

Records in PDS3 SFF files have variable formats and lengths both between files and (in one case) within a single file; some of these inconsistencies have been resolved by hand editing in PDS4 to simplify labeling and use. The Header object varies from 164 to 2076 bytes, mostly because of variable padding of records with ASCII blanks. The Start Date and Time Table is a single record varying from 38 to 346 bytes (also because of variable padding). Small Forces Table records vary from 349 to 353 bytes because of changes in precision of the time tag (PDS4 field 6), differences in how the mission elapsed time (MET) is presented (PDS4 field 7), and differences in use of double quotes and ASCII spaces. In all PDS3 files except one, the record formats and lengths are consistent throughout individual files. In file `mess_rs_2015098_2015098_sff.tab` two double quotation marks are missing in the PDS3 file starting at record 228; the double quotes have been added to the PDS4 file so that all records have the same structure and length.

In PDS3 `file  mess_rs_2011076_2011076_sff.tab` double quotes surround the record type value (PDS4 field 2). No other file has double quotes at this location, so the double quotes have been removed in the PDS4 file.

In PDS3 file `mess_rs_2014255_2014255_sff.tab` a double quotation mark is missing at the end of the TIME field (PDS field 6); that has been restored in the PDS4 file.

PDS3 file `mess_rs_2010004_2010004_sff.tab` has a spurious double quotation mark in its Start_Date and Time Table; that has been removed in the PDS4 file.

Through 2011, the MET is given as a nine digit integer in a 13 character field — e.g., 'xxxx123456789', where 'x' denotes an ASCII space. Four files covering 2012-04-16 through 2014-09-12 present the MET as a nine-digit integer preceded by a one-digit 'partition' in an 11 character field — *e.g.*, '1/123456789'. Files for the remainder of the mission return to the nine-digit integer format with four leading spaces. The PDS3 archive includes two format files (`mess_rs_sff.fmt` and `mess_rs_sff2.fmt`) to cover the 'integer' and 'partition' situations, respectively. Comments at the beginning of the format files indicate that they should be used before and after the date 2012-04-24. The date is incorrect, and `mess_rs_sff2.fmt` was used for all files after 2012-04-16 rather than just the four files which include the MET partition. Four templates were used to create the PDS4 labels, providing better descriptions of the actual data fields including data_type, field_location, field_length, field_format, and description.

Precision of START_TIME and STOP_TIME in PDS3 labels is milliseconds for 2007-2012 and 0.1 milliseconds (4 decimal places) for the remainder of the mission. Those precisions have been preserved in the PDS4 labels.

A.11 TRO Files

No comments from the PDS3 to PDS4 migration.

A.12 WEA Files

The WEA files have been padded to constant record length (60 bytes) for PDS4. The new files have the same file names as the originals except that the extension has been changed to *.tab.

Each day's meteorological data is described as a 'block' in the PDS4 label. A block consists of an identifier record (a one row Table_Character), a blank line, a three-line ASCII Header object, a Table_Character with measurements, and a trailing blank line.

The identifier record includes the date in yymmdd format, the day of year (a three-digit integer), and the Deep Space Communication Complex (DSCC) identifier (10, 40, or 60 for Goldstone, Canberra, or Madrid, respectively) where the data were collected. There should be only one DSCC per file.

The Header object provides ASCII column headings for the meteorological measurements which follow; it is not described in any detail in the label.

The Measurements Table comprises one or more rows with time, dew point, temperature, pressure, H_2O partial pressure, and relative humidity measured at the DSCC. Typically, the measurements are spaced by about 30 minutes and there are 49 rows in the table; but sometimes measurements are missing. On rare occasions there will be no data for a full day and the entire block will be missing.

The PDS3 archive included WEA files for partial years — for example, there are files covering the first 280, 306, and 334 days of 2009 at each DSCC as well as files covering all 365 days. The partial year files have been omitted from the PDS4 archive since all weather data for the year is captured in the final (365 day) files.

A.13 Documents

The MESSENGER RS RDA SIS was completely rewritten to reflect differences in archive organization, file naming, and formats in PDS4.

The ANT SIS (`sis_ant.pdf`) was adapted from `antinfo.txt` in the PDS3 archive.

The instrument description document (`instrument_rs.txt`) was adapted from `inst.cat` in the PDS3 archive.

The Momentum Dump Maneuver SIS (`sis_mdm.txt`) was adapted from `mdm_desc.txt` in the PDS3 archive. Three questions need clarification by the MESSENGER team:

1) Are there multiple thrusters? Is more than one used in any single maneuver? It probably doesn't matter for purposes of this file; details should be in Small Forces Files.

2) UTC times are given for thruster start and stop; are those at the spacecraft (SCET) or as seen on Earth (ERT), one light time later? SCET is assumed but needs to be confirmed.

3) Is the UTC time for "last thruster" the end of all thruster firing or the beginning of the last firing of a single thruster? The end of all thruster firing is assumed.