Mars 2020

Radar Imager for Mars' subsurFAce eXperiment (RIMFAX)

PDS Archive

Calibrated Data Record (CDR) Software Interface Specification

Rev. 0.7

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Addressing Review Liens

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Calibrated Data Record (CDR)

Software Interface Specification

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Co	ntont	
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Introduction	1
Document Change Log	1
TBD Items	1
Abbreviations	1
Glossary	3
Overview	4
Purpose and Scope	5
Contents	5
Applicable Documents	5
Audience	6
Mars 2020 Mission	6
RIMFAX Instrument Description	7
Instrument Operation	7
Surface Operation	11
RIMFAX Data Products	12
Data Products Overview	12
Data Processing	13
Data Processing Levels	13
Nominal Data Processing	14
Processing Differences by Measurement Type	16
Position Determination	16
Data Flow	17
Standards Used in Generating Data Products	17
Time Standards	17
Coordinate Systems	18
Data Storage Conventions	21
Applicable Software	21
Backups and Duplicates	21
RIMFAX Archive Organization, Identifiers and Naming Conventions	21
Archive Structure	21
Logical Identifiers	21

LID Formation	22
VID Formation	22
RIMFAX Bundle	23
RIMFAX Collections	23
RIMFAX Calibrated Data Products	23
RIMFAX Calibrated Data Product File Naming Conventions	24
RIMFAX Product Formats	24
Data Product Formats	24
Raw Data File Structure	24
Calibrated Data File Structure	24
Browse Product Formats	26
Document Product Formats	26
PDS Labels	27
Calibrated Data Product Parameters	28
CDR Catalog Columns	35
Support Staff and Cognizant Persons	36

List of Tables

List of Tables	
Table 1: Document change log.	1
Table 2: List of TBD items.	1
Table 3: Abbreviations and their meanings.	1
Table 4: RIMFAX instrumented range (in free space) as a function of bandwidth and swe Data volume per sounding given for each sweep time.	ep time. 12
Table 5: Data processing level definitions.	13
Table 6: Coordinate frames relevant to RIMFAX location, data, and operations.	18
Table 7: Translational offsets defining the RIMFAX Antenna Frame (RAF) with respective Rover Mechanical frame (RMECH) and the Rover Navigational frame (RNAV). In frame-to-frame as well as net RAF-RNAV offsets are given. There are no rotational among these coordinate frames. * Antenna feed point (AFP) - RNAV offset is ~744 mm.	ct to the dividual l offsets 20
Table 8: The RIMFAX Bundle.	23
Table 9: Collections in the RIMFAX Bundle.	23
Table 10: Example of data product LID in the RIMFAX calibrated data collection.	23
Table 11: Fundamentally different types of records in the RIMFAX CDR data product da as identified by the data-table parameter "record_type" (in the first column of each da record).	ta table, ata-table 24
Table A1: Complete list of parameters recorded in the ASCII-text data table that make CSV-format RIMFAX CDR data product.	s up the 28
Table A2: Comments for respective rows in Table A1, as cross-referenced by the valu "Comment Reference Label" field in each table.	ie of the 33
Table B1. Partial list of column-headings in the CDR Catalog file.	35
Table C1: Archive support staff.	36

1 Introduction

This software interface specification (SIS) describes the content, generation, and format of the Planetary Data System (PDS) archive containing the Calibrated data from the RIMFAX instrument on the M2020 *Perseverance* rover mission.

1.1 Document Change Log

Table 1: Document	t change	log.
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Version	Change	Date	Affected portion
0.1	Initial draft	November 14, 2020	All
0.2	Edited draft	January 21, 2021	All
0.3	Submitted for Review	February 17, 2021	All
0.4	Re-Submitted for Review	March 23, 2021	All
0.6	Addressing Review Liens	June 24, 2021	Responses to Reviewers, Appendices, scattered elsewhere
0.7	Addressing Review Liens	July 22, 2021	Responses to Reviewers, Appendices, scattered elsewhere

1.2 TBD Items

Table 2 lists items that are not yet finalized.

Table	2:	List	of	TBD	items.
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Item	Section(s)	Page(s)

1.3 Abbreviations

Abbreviation	Meaning
ASCII	American Standard Code for Information Interchange
CDR	Calibrated Data Record
CSV	Comma Separated Value
EDR	Experiment Data Record
FFI	Forsvarets Forskningsinstitutt (Norwegian Defense Research Establishment)
FM	Frame Manager
FMCW	Frequency Modulated Continuous Wave
FTP	File Transfer Protocol
FTP	File Transfer Protocol

Table 3: Abbreviations and their meanings.

-

GDS	Ground Data Systems
GEO	PDS Geosciences Node (Washington University, St. Louis, Missouri)
GPR	Ground Penetrating Radar
НК	Housekeeping
HTML	Hypertext Markup Language
ICD	Interface Control Document
IDS	Instrument Data System
IFFT	Inverse Fast Fourier Transform
ISO	International Standards Organization
JPL	Jet Propulsion Laboratory (Pasadena, CA)
LID	Logical Identifier
LIDVID	Versioned Logical Identifier
LIS	Long Integration Sounding
M2020	Mars 2020
MMRTG	Multi-Mission Radioisotope Thermoelectric Generator
NAIF	Navigation and Ancillary Information Facility (JPL)
NASA	National Aeronautics and Space Administration
NSSDCA	National Space Science Data Coordinated Archive (Goddard Space Flight Center)
PDS	Planetary Data System
PDS4	Planetary Data System Version 4
RAF	RIMFAX Antenna Frame
RCE	Rover Compute Element
RIM	RIMFAX Instrument Manager
RIMFAX	Radar Imager for Mars' subsurFAce eXperiment
RMECH	Rover Mechanical Frame
RNAV	Rover Navigation Frame
SAPP	Surface Attitude, Position and Pointing
SIS	Software Interface Specification
SPICE	Spacecraft, Planet, Instrument, C-matrix, and Events (NAIF data format)
SPK	Spacecraft and Planetary ephemeris Kernel (NAIF)
TBD	To Be Determined
UCLA	University of California, Los Angeles
URN	Uniform Resource Name
UTC	Universal Time Coordinated
VID	Version Identifier
XML	eXtensible Markup Language

1.4 Glossary

Many of these definitions are taken from Appendix A of the PDS4 Concepts Document, <u>https://pds.nasa.gov/datastandards/about/</u>. 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 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 database 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

This SIS covers the RIMFAX Calibrated Data Product. The purpose of this SIS document is to provide users of the Calibrated data with: some instrument functionality and surface operations background; the processing by which Calibrated data is generated from Raw data; a description of Calibrated products; and the internal format and naming of Calibrated data product files. 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.

2.2 Contents

This SIS includes descriptions of how the RIMFAX instrument acquires measurements and operates, how the data are processed and calibrated from Raw to calibrated forms, and how the files are formatted, labeled, and uniquely identified. The document also discusses standards used in generating the data products. It is the document's goal that the data files, structure, and organization be described in sufficient detail to enable a user to find, read, and understand the data.

Appendices include: (A) a list of the parameters, and their definitions, included in the CDR data table; (B) ; (C) a list of support staff and cognizant persons involved in generating the archive.

2.3 Applicable Documents

- [1] Planetary Data System Standards Reference, version 1.16.0.0, April 21, 2021, https://pds.nasa.gov/datastandards/documents/sr/.
- [2] PDS4 Common Data Dictionary, Abridged, version 1.16.0.0, April 21, 2021, https://pds.nasa.gov/datastandards/documents/dd/.
- [3] PDS4 Information Model Specification, version 1.16.0.0, April 21, 2021, https://pds.nasa.gov/datastandards/documents/im/.
- [4] PDS4 Concepts Document, version 1.16.0.0, April 21, 2021, https://pds.nasa.gov/datastandards/documents/concepts/.
- [5] PDS4 Data Provider's Handbook, version 1.16.0.0, April 21, 2021, https://pds.nasa.gov/datastandards/documents/dph/.
- [6] Mars 2020 Archive Generation, Validation, and Transfer Plan, JPL D-95520.
- [7] RIMFAX PDS Node Interface Control Document (ICD).
- [8] Mars 2020 Software Interface Specification (SIS): RIMFAX Experiment Data Record (EDR) Data Products, JPL D-99964.
- [9] Mars 2020 Software Interface Specification (SIS): RIMFAX PDS Archive Bundle.
- [10] Radar Imager for Mars' Subsurface Experiment RIMFAX, Svein-Erik Hamran, David A. Paige, Hans E. F. Amundsen, Tor Berger, Sverre Brovoll, Lynn Carter, Leif Damsgård,

Henning Dypvik, Jo Eide, Sigurd Eide, Rebecca Ghent, Øystein Helleren, Jack Kohler, Mike Mellon, Daniel C. Nunes, Dirk Plettemeier, Kathryn Rowe, Patrick Russell & Mats Jørgen Øyan, Space Science Reviews 216, Article Number 128 (2020) https://doi.org/10.1007/s11214-020-00740-4

[11] Mars 2020 Rover Attitude, Positioning and Pointing (RAPP) Functional Design Description (FDD) document, JPL D-95865, ID 64632, Owner: Farah Alibay, Last Modified: 2020-05-27, Date: April 20, 2021.

This SIS is consistent with PDS4 Documents [1 - 6]. These documents are subject to periodic revision. The most recent versions may be found at https://pds.nasa.gov/pds4. The PDS4 products specified in this SIS have been designed based on the versions current at the time, which are those listed above.

2.4 Audience

This SIS is intended to be used by data users wishing to understand the format and content of the RIMFAX Calibrated Data. Typically these individuals would include scientists, data analysts, and software engineers, whether part of the project or part of the broader planetary science community.

2.5 Mars 2020 Mission

The primary goals of the Mars 2020 Perseverance rover mission are to search for biosignatures, or evidence of past life, and to return samples of martian geologic materials to Earth for analysis. The suite of scientific instruments included on the rover is intended to interpret landing-site geologic history, find and characterize habitable environments, and document textural, mineralogical and organic biosignatures. The rover will also collect, store, and cache ~ 30 geologic samples and characterize their geologic and paleoenvironmental context.

The Mars 2020 mission was launched from Cape Canaveral, Florida, on July 30, 2020 and landed on Mars on February 18, 2021. The landing site, in Jezero Crater, was chosen to optimize chances of achieving the mission's goals, and should elucidate Mars' past in addition to local history. Evidence collected from previous missions suggests the crater once contained a lake, several billion years ago. Today, the most striking feature at the site is a well-preserved, layered sequence of sediments exhibiting channel-like structures, interpreted as a delta. Surroundings also show possible carbonate rocks, lacustrine sediments, silica-rich deposits, and volcanic materials. All together, this represents an environment with high potential for former habitability, biosignature preservation, and provision of a diverse suite of informative samples.

Perseverance will carry the first GPR on the surface of Mars, RIMFAX. Data from RIMFAX will provide information on the structure and geophysical properties of the subsurface. Findings will yield insight into stratigraphic relationships, links between separated outcrops, regolith and bedrock densities, geologic context for samples, processes affecting biosignature preservation over time, and rover strategic and tactical planning.

2.6 **RIMFAX** Instrument Description

The RIMFAX instrument and science investigation are more fully described in the publication "Radar Imager for Mars' Subsurface Experiment – RIMFAX", Svein-Erik Hamran, David A. Paige, Hans E. F. Amundsen, Tor Berger, Sverre Brovoll, Lynn Carter, Leif Damsgård, Henning Dypvik, Jo Eide, Sigurd Eide, Rebecca Ghent, Øystein Helleren, Jack Kohler, Mike Mellon, Daniel C. Nunes, Dirk Plettemeier, Kathryn Rowe, Patrick Russell & Mats Jørgen Øyan, Space Science Reviews 216, Article Number 128 (2020) <u>https://doi.org/10.1007/s11214-020-00740-4</u>

In this section, a brief overview of the RIMFAX instrument is provided to familiarize the reader with the instrument's primary functionality and operational implementation.

The principal goals of the RIMFAX investigation are to image the shallow subsurface structure beneath the rover and provide information regarding subsurface composition. The data provided by RIMFAX will aid the Mars2020 rover in its mission to explore the ancient habitability of its field area and to select a set of promising samples for caching and eventual sample return.

2.6.1 Instrument Operation

RIMFAX is a ground penetrating radar (GPR) that uses a single antenna to transmit (Tx) and receive (Rx) electromagnetic waves over a range of frequencies (150 to 1200 MHz) into/from the subsurface. A principle block diagram of the instrument is given in Figure 1. The instrument can be operated in either active (Tx and Rx) or passive (Rx-only) modes. Transmitted waves propagate downward until they are reflected back by shallow (\leq 10s of m) subsurface interfaces in geologic materials or structures, across which exist discontinuities in permittivity (the storage of electrical energy in an electric field).



Figure 1: Principle block diagram of the RIMFAX instrument.

Each sweep across the radar's frequency range, or bandwidth, produces a radar measurement known as a "sounding". A raw FMCW RIMFAX sounding is a record of the reflected power returned at each frequency over the bandwidth. A processed RIMFAX sounding, more analogous

to most terrestrial-use GPRs, is a time series of the reflected power. The receival time of each sample is related to the position in the subsurface from which the received power was reflected. The RIMFAX instrument paper [10] describes this relationship, which is largely modulated by the velocity of the signal in the medium, in turn influenced by the material's dielectric and physical properties. As the rover (and RIMFAX) moves along its traverse path, successive soundings are taken at fixed increments of distance along the surface. The 2-D display of these soundings according to their acquisition location is an image known as a "radargram", with distance along the traverse increasing towards the right, and time (related to depth, as above), increasing downwards. Measurements can also be made while the rover (and RIMFAX) is stationary with respect to the surface, and successive co-located stationary soundings can build a time series. Such a dataset may capture how the dielectric properties of the surface/subsurface at that individual location may change over a given period (e.g., in response to thermal influences).

To properly convert the vertical dimension from the time delay, t, to depth, d, it is necessary to apply values of permittivity, e, to the subsurface to correct for the speed of light in the medium as follows:

$$d = v * t$$
,

where:

$$v = c / sqrt(e)$$
.

Further, ancillary navigation data from the rover are necessary to determine the location of each sounding.

Waveform

RIMFAX uses a Frequency Modulated Continuous Wave (FMCW) waveform. In FMCW radar the baseband signal is low-pass filtered before being sampled. This filter effectively removes deeper reflectors and yields an ambiguity-free range interval. The RIMFAX FMCW waveform uses a gating technique that allows a single antenna to be used both as a transmitter and receiver.

The working principle of an FMCW radar is illustrated in Figure 2. A signal, Tx, is swept through the full bandwidth, B, of frequencies (from f_1 to f_2) over the time span, T_s (from t_1 to t_2), and is transmitted through the antenna (as represented by the solid line Tx). A signal reflected from a distance, d, is received by the antenna delayed by the two-way travel time, t, equal to 2d/v, where v is the wave velocity in the material. This delayed received signal, Rx, has a different frequency than the signal currently being transmitted (represented by the dashed line Rx). Multiplying the received signal with the signal currently being transmitted gives a baseband signal, $S_b = Rx \times Tx$. At any point in time, this baseband signal has a frequency equal to the frequency difference between the transmitted and received signals. For a stationary reflector this frequency difference is constant over the sweep. The frequency of this constant baseband signal, called the beat frequency, f_b , is proportional to the delay time, t, and thereby to the distance range, expressed as 2d/v, to the reflector. The proportionality constant is given by the ratio between the sweep bandwidth and the duration of the sweep, or B/T_s . The frequency of the beat signal is thus:

$$f_{b} = \frac{2Bd}{vT_{s}}.$$

Measuring the beat frequency thus yields the range to the reflector. The amplitude of the received sine-wave signal gives the reflection strength. If several reflectors are present the baseband signal will be a summation of all the different reflected signals. Spectral estimation techniques like Fourier transforms can calculate the reflected signal.



Figure 2: Illustration of RIMFAX signal generation, including beat frequency, f_b , and baseband signal amplitude, S_b .

Gating

The FMCW signal is gated in a switch before being amplified and fed to the antenna through the antenna switch (Figure 1). The gating switches the FMCW signal on and off with a duty cycle up to 50%. The gating frequency is much lower than the transmitted-signal frequency and higher

than the baseband signal spectrum. The reflected signal response will be a convolution between the gated, square-wave transmitted signal and the square wave of the receiver gating. This response function will be a triangular waveform producing an effective linear gain on the received signal as a function of depth. Typically the maximum of the gating function will correspond to the maximum instrumented range. After the gating peak a linear reduction in amplitude will be combined with the spherical loss and attenuation in the media reducing the reflected signal rapidly.

If the receiver gating waveform is turned on with a slight delay after the transmitter gating signal turns off, there will be a time window where no signal is entering the receiver. This is illustrated in Figure 3, in which the receiver gate signal delay time is represented by T_R . Any reflected signal from the exterior or subsurface that arrives during the time-delay window from 0 to T_R does not enter the receiver. The radar response as a function of time will then be a symmetric triangular shape with a flat-peaked top of time-length T_R , giving a linear gain with travel time and depth. If the frequency of the square wave gating signal is F_G , then the total gating window length in time is:

$$T_{g} = 1 / F_{g}$$
.

The gating makes it possible to remove strong reflectors from the receiver signal before the signal is digitized, effectively increasing the dynamic range coverage of the radar system.



Figure 3: RIMFAX gating illustration. X-axis represents increasing time.

Calibration cable

The RIMFAX electronics unit has two different outputs for transmitting the FMCW signal: an antenna port, where the antenna is connected via the antenna cable running through the rover bulkhead, and the calibration port, where a 2.8-m calibration cable is connected. The calibration cable is placed close to the RIMFAX electronics, inside the rover, and is shorted at the end to produce a reflection from the end of the cable. An electronic switch controls whether the calibration cable or the antenna is used.

The main purpose of the calibration cable is to provide measurements of gain variations in the transmitter and receiver. During operations on Mars the calibration cable measurements will be performed at specific distances during a traverse, for example every 10 meters, or at specific time intervals during stationary activities, for example every hour. The reflected signal from the calibration cable termination will be used to calibrate for temperature-dependent variations in radar amplitude and timing.

2.6.2 Surface Operation

RIMFAX is designed to operate in different modes in which radar parameters are set to optimize data collection for different subsurface conditions and depths. The RIMFAX gating makes it possible to omit the recording of close-range reflections, typically from the antenna and surface, which would otherwise limit the dynamic range. The removal of these reflections makes it possible, when desired, to increase the radar's gain to capture weak subsurface reflections. Shifting the receiver dynamic range window particularly to each mode effectively increases the radar's total dynamic range when soundings from different modes are considered together.

1. Surface Mode

The antenna reflection is captured in the receiver window.

Measures the surface reflection and the very upper subsurface only.

2. Shallow Mode

The antenna reflection is removed from the receiver window.

Measures the surface reflection and the shallow subsurface.

3. Deep Mode

The antenna and surface reflections are removed from the receiver window.

Measures reflections from the upper subsurface ($\sim 1 \text{ m depth}$) through the instrumented range.

Together, these modes extend the dynamic range of RIMFAX up to 62 dB above the dynamic range of a single mode, giving an approximate total dynamic range of 160 dB. For stationary measurements, the dynamic range can be further increased by doing a Long Integration Sounding (LIS), in which a few to several hundred soundings are summed together (on the rover RCE) to increase the processing gain.

Instrumented range and resolution can also be selected within each mode to optimize measurements based on subsurface composition and penetration depth. This is accomplished by choosing combinations of frequency range (i.e.,bandwidth) and sweep time of the waveform over the frequency range, which also results in different data volumes (Table 5).

		Swep time [ms]							
		100	50	25	12.5	6.25	3.125	1.5625	0.78125
Bandwidth [MHz]	450	974 m	486 m	242 m	120 m	59 m	28 m	13 m	5.4 m
	750	583 m	291 m	144 m	71 m	34 m	16 m	6.9 m	2.3 m
	1050	416 m	207 m	102 m	50 m	24 m	11 m	4.3 m	1.0 m
Data volume [bytes]]	19530	9764	4882	2440	1220	610	304	152

Table 4: RIMFAX instrumented range (in free space) as a function of bandwidth and sweep time. Data volume per sounding given for each sweep time.

Typically, a high resolution using the full bandwidth is selected in the shallow mode, when most frequencies will be able to penetrate to the full, shallow instrumented range. In the deep mode, a narrower bandwidth limited to the lower part of the frequency range is used, and there is a tradeoff between data volume (based on number of samples per sounding) and penetration depth. Choices of sweep time are limited to the 8 values in Table 5. Bandwidth can be set between 0 and 1050 MHz (i.e., not limited to values in Table 5) within the frequency range 150-1200 MHz.

For sweep times less than 100 ms, sweeps are repeated and signal is averaged until the total collection time period reaches 100 ms. This practice ensures that the processing gain is equal for each sounding, independent of radar configuration.

The nominal plan for operation on Mars is to collect soundings from each of three modes every 5-10 cm along the rover traverse, During a drive, the distance the antenna has moved is determined and tracked solely by the FM, with no memory, modifications, or correction by RIMFAX (Section 3.2.4). When the tactically planned interval distance (since the previous measurement) has been attained as the rover moves along its path, the RIMFAX Instrument Manager (RIM) on the Rover Computer Element (RCE) commands RIMFAX to make the subsequent measurement.

In addition to nominal, active operation, RIMFAX can be operated in passive modes with the transmitter off but the receiver on, connected to either the antenna or the calibration cable. An ambient spectrum can be measured through the antenna, or an estimation of self-induced noise can be made with the calibration cable and used as an input to signal processing to increase system performance.

3 **RIMFAX Data Products**

3.1 Data Products Overview

The primary RIMFAX CDR data product is a table containing RIMFAX measurement data. This Calibrated data product contains a single, CSV-format file composed of a data table of ASCII text fields. This table includes all processed radar data, housekeeping data, calibration arrays, associated parameters, and a header row. One Calibrated data product is generated for each M2020 Sol in which RIMFAX obtained measurements, and contains measurements from only one Sol. There are no Calibrated data products from before landing. The radar data present in this table has been processed as described in Section 3.2 into time-domain samples (equal time increments), each containing the value of the ratio of the measured received signal to the radiated signal. Each CSV file is accompanied by an eXtensible Markup Language (XML) format PDS4 label file (.xml). Details of the Calibrated product file structure are provided in Section 5.1.2, while this Section 3 focuses on processing of the Raw data into the Calibrated data product.

3.2 Data Processing

This section describes the processing of RIMFAX Raw data to Calibrated data. The data is calibrated to physical units, and these calibration steps and algorithms are described. The level of processing incorporated in these Calibrated products was chosen with the aim of bringing the RIMFAX radar data to a state at which it would likely most resemble a familiar starting point to typical terrestrial GPR users. The individual algorithms and the processing as a whole is designed such that these steps may be reversed to the state of the original data, with no information lost.

3.2.1 Data Processing Levels

Data processing levels mentioned in this SIS refer to the PDS4 processing level described in Table 4. The RIMFAX data products described in this SIS are PDS4 processing-level "Calibrated". The data has been calibrated to physical units and the products include positional and geometric information on the RIMFAX antenna, the *Perseverance* rover, and the sun.

PDS4 processing level	PDS4 processing level description	CODMAC level (used in PDS3)	NASA level (used in PDS3)
n/a	Telemetry data with instrument data embedded. PDS does not archive telemetry data.	1	0
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.	2	1A
Partially Processed	Data that have been processed beyond the raw stage but which have not yet reached calibrated status.	3	1 A

Table 5: Data processing level definitions.

Calibrated	Data converted to physical units, which makes values independent of the instrument.	4	1B
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+	2+

3.2.2 Nominal Data Processing

This section describes the processing applied to Raw data to result in Calibrated-level data products, ie CDRs. The nominal case is considered to be active antenna soundings, made either while the rover is stationary or moving along a traverse. The flow of data from JPL's Instrument Data System (IDS), through processing steps, and to PDS is shown in Figure 4.



Figure 4. RIMFAX data and processing flow from IDS to PDS.

Raw sounding data contain RIMFAX science data in the frequency domain. Part of the processing is done in the frequency domain. Eventually, RIMFAX science data is transformed to time domain, undergoes further processing, and the resulting Calibrated data are in the time domain. The following processing steps described here are nominally for active sounding data - differences between Stationary and Traverse soundings and for passive radiometry data are given in the next section.

Apply amplitude and phase correction

To apply amplitude and phase correction of the RIMFAX instrument, one could use separate corrections for the antenna and the electronics. Gain measurements of the antenna have been performed, but the interaction with the rover has not been investigated in detail. During the early part of the mission, a sufficient amount of soundings should be collected in order to estimate how the stationary parts, i.e. the rover, interacts with RIMFAX, and corrections can be estimated.

The amplitude and phase corrections each consist of a 1D, floating-point array with the same number of elements as the frequency-domain radar data. The Calibrated data product data table contains parameters (amplitude_correction_ref and phase_correction_ref) that each contain an integer-valued reference to the data-table record in which the respective correction array (applied during calibration of the current data record) is held. Please see Section 5.1.2 for further details on locating these correction arrays within a Calibrated data product.

Apply radiometric correction

The radiometric correction gives the return level with reference to the transmitted level, meaning that the power level of the sounding data can be expressed in dBm.

The radiometric correction is a single float value used to correct all the frequency domain sounding data values equally. The frequency domain data is multiplied by the radiometric correction scalar.

Shift to time-zero (t=0) at antenna delay

Shifting the data such that "time-zero" (t=0 ns) corresponds to the antenna delay, physically corresponding to the antenna feed point (Section 3.3.2), is most easily and precisely done in the Fourier domain. The antenna delay is in ns, and the shift is performed by multiplying the frequency domain sounding data with the frequency vector in radians.

The position of the Mars ground surface in the Calibrated sounding data will be directly related to the distance of the antenna above the surface that it is "seeing". While rover attitude and surface topography will cause some variability from sounding to sounding, this distance should remain relatively constant at ~74.4 cm over the mission, which would nominally translate to a ~5.0 ns two-way travel time delay from the start of a calibrated sounding (the first data-sample of which starts at time = 0 ns in all CDR table records). This value should assist users constrain the location of the surface return in the CDR sounding data.

Multiply with window function

To reduce sidelobe levels, a window function is multiplied with the data in the last step before transforming to the time domain. It is important to use a window function that has no zeros at each end, in order to be able to revert the operation if later desired. A Blackman-Harris (TBC) window function is used.

Perform IFFT with 16x interpolation

The data is transformed to the time domain by an inverse Fast Fourier transform (IFFT). The number of samples in the output is increased by a factor of 16 by interpolation.

Correct amplitude for gating function

The gating function is not a perfect triangle, due to switch rise time for instance. Measured window functions are used to correct the amplitude as a function of time delay.

The gating amplitude correction consists of a 1D, floating-point array with the same number of elements as the time-domain radar data. The Calibrated data product data table contains a parameter (gating_amplitude_correction_ref) that contains an integer-valued reference to the data-table record in which the correction array (applied during calibration of the current data record) is held. Please see Section 5.1.2 for further details on locating this correction array within a Calibrated data product.

3.2.3 **Processing Differences by Measurement Type**

Calibration cable measurements (as opposed to nominal measurements through the antenna) differ from soundings through the antenna by not including the antenna amplitude correction or shifting of t=0 to the antenna center point. The calibration cable measurements also do not include corrections for electronics.

Due to continued development of the RDR processing pipeline, the current version of the CDR data product includes: 1) Stationary sounding data has no background subtraction correction applied, because the current method requires incorporation of many adjacent soundings and is thus only feasible along a traverse; 2) Passive radiometric data is maintained in its raw, unprocessed, uncalibrated state, in terms of received amplitude. Future iterations of the CDR may apply a processing algorithm to convert these passive measurements to physical units, such as radiance.

3.2.4 Position Determination

As with any GPR data set, RIMFAX data is highly dependent on spatial information to be able to construct 2D radargrams and allow investigators to place these radargrams (as well as individual soundings) in context with local geology. Because there is no mechanism internal to the RIMFAX instrument that maintains spatial knowledge or performs spatial calculations, the investigation depends entirely on rover subsystems and ground processes to determine the location of each sounding's intersection with the Mars surface and in relation to features and objects in the instrument's vicinity.

The rover's attitude and position is determined by the rover's Surface Attitude, Position and Pointing (SAPP) software at a frequency of 8 Hz, based on Rover Inertial Measurement Unit (RIMU) accelerometers and gyroscopes, wheel rotation information, and, when available, visual odometry. Attitude and position are recorded for a number of rover-, surface- and celestial-related coordinate frames that are maintained and updated by the rover's Frame Manager (RFM) software. More detailed descriptions and additional relevant documents are given in the Rover Attitude, Positioning, and Pointing (RAPP) FDD [11].

The position and orientation of the RIMFAX antenna is encapsulated by the The RIMFAX Antenna Frame (RAF). The definition of the RAF is given in terms of rover coordinate frames and is stored within the RFM (The RAF and pertinent coordinate systems are described in Section 3.3.2). The offsets of the RAF in position and in orientation from surface-related

coordinate frames is determined via transformation through these rover coordinate systems by the RFM. These offsets are recorded in RIMFAX sounding and housekeeping metadata files (EDM, EHM, respectively [8]).

For various reasons, the rover's knowledge and calculations of its position will contain small errors. Days after downlink of data and telemetry to Earth, the rover's position is re-determined with additional and reconstructed information. During CDR generation, RAF offsets are applied to these optimized, finalized rover localizations. This results in the RIMFAX antenna's 3D location and orientation on the Mars surface, as presented in the CDRs for each data record. Note that this allows for deviations from the planned and commanded interval between soundings.

3.2.5 Data Flow

This section describes only those portions of the M2020 data flow that are directly connected to RIMFAX archiving. A full description of M2020 data flow is provided in the M2020 Archive Generation, Validation, and Transfer Plan [6]. RIMFAX instrument data products are downlinked to JPL along with other *Perseverance* instrument and spacecraft data. At JPL, the Instrument Data System (IDS) is responsible for generating RIMFAX Raw-level data products, which are also archived at PDS [8]. The Raw radar data in binary format ("EDR") is read in, processed, calibrated (as described in Section 3), and converted to tabular text format, at FFI. These processed-data files, their corresponding Raw metadata "EDM" products, Raw housekeeping "EHK" products, and their Raw metadata "EHM" products, are all ingested to the RIMFAX Ground Data System (GDS) at UCLA. All of these data are combined into a chronologically ordered data table and output as a single Calibrated-level data product (or Calibrated Data Record, CDR) in CSV-text format, on a per-Sol basis (data-table structure details in Section 5.1.2). These Calibrated data products are transferred to the PDS Geosciences Node for archiving as the Calibrated data collection within the RIMFAX bundle [9] (archive details in Section 4).

3.3 Standards Used in Generating Data Products

RIMFAX products and labels comply with Planetary Data System standards, including the PDS4 data model, as specified in applicable documents [1 - 6].

3.3.1 Time Standards

Dates and times for the Calibrated data product are derived from the system spacecraft clock. The Raw value of "sclk" (spacecraft clock in whole seconds measured from 1980-01-01T00.00.00 UTC) is replicated in the Calibrated data. The Raw value of "sclk_subsecond" is replaced by the Calibrated value "sclk_sub_ns", which is the fraction of a second expressed in an integer number of nanoseconds. The translation between Raw sclk_subsecond and Calibrated sclk_sub_ns is:

$$sclk_sub_ns = int((sclk_subsecond / 2^12)) * 954e-9) * 1e9)$$

The derived date and time values are "utc" (which gives date and time in UTC format), "jdate" (Julian Date), "year" (Earth year), "doy" (Earth day of year), "mars_year" (where a value of 0 represents May 24, 1953), "ls" (Solar Longitude in degrees, measured from North Spring Equinox), "soltime_mean" (Mars local mean solar time), and "soltime_true" (Mars local true solar time). The NAIF Spice Toolkit will be used to derive these values.

3.3.2 Coordinate Systems

M2020 Coordinate Frames

The RFM defines dozens of coordinate frames, each with particular applications [11]. Four of these coordinate frames are important to the products and processes described in this SIS: the Rover Navigation frame (RNAV), the Rover Mechanical frame (RMECH), the Local Level frame (LL), and the Site frame (Table 6).

Frame Name	Short Name	Defining	Coordinate Frame	
(Raw Label)	(RAPP FDD)	Frame	Origin	Orientation
ROVER_NAV_FRAM E	RNAV	Enclosing SITE_FRAME	Attached to rover	Aligned with rover (parallel to RMECH orient.)
ROVER_MECH_FRA ME	RMECH	Enclosing SITE_FRAME	Attached to rover	Aligned with rover (parallel to RNAV orient.)
LOCAL_LEVEL_FR AME	LL	Enclosing SITE_FRAME	Attached to rover (coincident with RNAV origin)	North/East/Nadir
SITE_FRAME	SITE(n)	Previous SITE_FRAME	Attached to surface	North/East/Nadir

Table 6: Coordinate frames relevant to RIMFAX location, data, and operations.

RNAV is the frame used for surface navigation and mobility, and is the most commonly referred to when discussing general rover location. It is attached/fixed to the rover and moves with it when the rover moves on the surface. The +X axis points to the front of the rover, +Y points to the right side of the rover, and +Z points down, perpendicular to the chassis deck. The origin is centered along Y between the left and right sets of wheels, centered along X in between the front and back of the rover's middle wheels, and centered along Z at the Mars surface (more accurately, the origin in Z is defined as the fixed position (with respect to the rover body) that would be at the surface were the rover standing on a flat, horizontal, planar surface).

RMECH is oriented identically to RNAV, but its origin is defined slightly forward of RNAV's and upward of RNAV's. RMECH's origin in Z is at the top of the rover deck. There is no offset in Y of these two frames.

The Local Level frame's origin is coincident with that of RNAV, and is fixed to and moves with the rover. LL's orientation, however, always remains aligned with the planetary cardinal directions: the +X axis points North, +Y points East, and +Z points down to nadir along the local gravity vector.

The Site frame's origin is fixed to a position on Mars' surface and does not move with the rover, but it is oriented identically to the Local Level frame (wrt to N/E/gravity). New Site frames covering new exploration areas are generated episodically throughout the rover's journey on Mars. A particular Site frame remains the basis for the more frequently recorded offsets of other

coordinate frames (e.g., RNAV, RAF) until a new one is defined. This method reduces accumulating error in offset as the rover and mission progress. The specific Site frame (and corresponding longitude, latitude, and elevation of the Mars surface) pertinent to any RIMFAX measurement and RAF offset is referenced and accessed by means of the Rover Motion Counter (RMC) index "system_rmc_site", which is included in EDM/EHK metadata and in the measurement's CDR data record (along with several other RMCs).

The RIMFAX Antenna Coordinate Frame

It is the position of RIMFAX's antenna, rather than the rover, that is most relevant to RIMFAX measurements and their location with respect to contextual features on or below the surface of Mars. Specifically, the physical location on the antenna from which the radar signal emanates is conceptualized by a point referred to as the antenna feed point (AFP). The RIMFAX AFP is located on the underside of the antenna near the apex of the antenna peak, laterally centered. It is this physical point that is attributed a two-way travel time delay value of 0 ns in the "time zero" correction step of RIMFAX CDR processing (Section 3.2.2). The origin of RAF (introduced above) is defined by the downwards projection of the AFP (perpendicularly) onto the horizontal basal plane of the antenna, which represents the RAF X-Y plane (Figure 5).

The RIMFAX antenna is rigidly affixed to the rover, can not move independently, and has no moving parts or mechanisms. It is precisely aligned to point nadir, is centered on the rover's longitudinal axis, and all 3 dimensions/axes of the RAF are parallel with their respective rover (RMECH and RNAV) counterparts: the RAF +X axis points to the front of the rover, +Y points to the right side of the antenna, and +Z points down (perpendicular to the chassis deck, which is perpendicular to the Mars surface below if the antenna and rover are on a flat, horizontal surface). The RAF is defined with respect to RMECH, which in turn is defined in terms of RNAV. These defining, constant offsets (individual and net) are clearly all translational, with no rotational components (Table 7). Thus, determination of the rover's position and orientation effectively prescribes those of the RIMFAX antenna.

It is important to note that the AFP, equivalent to "time-zero" in radar soundings, is above (-Z direction) the RAF origin on the antenna basal (X-Y) plane by \sim 5.8 cm. Thus, the AFP-RNAV net vertical distance is \sim 74.4 cm. This quantity is significant as the nominal AFP-Mars surface distance (on flat, horizontal ground), and is useful for constraining the location of the surface reflection return in radar sounding data by the return's time delay.

Table 7: Translational offsets defining the RIMFAX Antenna Frame (RAF) with respect to the Rover Mechanical frame (RMECH) and the Rover Navigational frame (RNAV). Individual frame-to-frame as well as net RAF-RNAV offsets are given. There are no rotational offsets among these coordinate frames. * Antenna feed point (AFP) - RNAV offset is ~744 mm.

Frama	Reference	Translational Offset (mm)					
гташе	Frame	X	Y	Z			
RAF	RMECH	-1104.8	0	+447.6			
RMECH	RNAV	+90.02	0	-1133.38			
RAF	RNAV	-1014.8	0	-685.8*			



Figure 5: The RIMFAX antenna, highlighted yellow, is mounted to the aft of the rover, beneath the MMRTG (large, tilted, square object). The RIMFAX Antenna coordinate Frame (RAF) is identified here by its X and Z axes (red, Y pointing out of page); its origin is on the antenna basal (X-Y) plane, directly beneath the antenna feed point (AFP, green dot).

3.3.3 Data Storage Conventions

RIMFAX Calibrated data products are stored as ASCII text Comma Separated Value (CSV) tables. Each CSV table has a detached PDS4 label in XML format.

3.4 Applicable Software

None.

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 National 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 **RIMFAX** Archive Organization, Identifiers and Naming Conventions

This section describes the basic organization of the RIMFAX archive under the PDS4 Information Model [1, 3], including the naming conventions used for the bundle, collections, data product unique identifiers, and data product files.

4.1 Archive Structure

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 collection types. A collection is a set of one or more related basic products that are typically all of the same product type. Bundles and collections are logical structures, not necessarily tied to any physical directory structure or organization. A product consists of a file containing one or more digital objects (e.g., a table of data, an image, or a document) and described by an accompanying label file.

4.2 Logical Identifiers

Every product in PDS is assigned a Logical Identifier (LID)that allows it to be uniquely identified across the system. Each product also has a Version Identifier (VID) that 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. For convenience they may be combined in a single string called a LIDVID, with two colons between the LID and the VID. LIDs and VIDs are assigned by PDS and are formed according to the conventions described in Sections 4.1.1 and 4.1.2 below. The uniqueness of a product's LID and VID may be verified using the PDS Registry and Harvest tools.

4.2.1 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. Within one of these prescribed components dash, underscore, or period are used as separators. LIDs are limited in length to 255 characters.

M2020 RIMFAX 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>

Example: urn:nasa:pds:mars2020_rimfax

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>

Example: urn:nasa:pds:mars2020_rimfax:data_calibrated

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.

• *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>

Example:

```
urn:nasa:pds:mars2020 rimfax:data calibrated:rimfax calibrated 0001
```

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 4.5 below for examples of RIMFAX data product LIDs.

4.2.2 VID Formation

Product VIDs consist of major and minor components separated by a "." (M.n). 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.

4.3 **RIMFAX Bundle**

The complete M2020 RIMFAX archive is organized into a single bundle as described in Table 8 [9].

Table 8: The RIMFAX Bundle.

Bundle Logical Identifier	Description
urn:nasa:pds:mars2020_rimfax	The RIMFAX Bundle.

4.4 **RIMFAX** Collections

The RIMFAX Bundle contains the three collections listed in Table 9 [9].

Table 9: Collections in the RIMFAX Bundle.

Collection Logical Identifier	Collection Type	Content Description
urn:nasa:pds:mars2020_rimfax:data_raw	Data	Contains RIMFAX raw data products, in varied formats.
urn:nasa:pds:mars2020_rimfax:data_hk	Data	Contains RIMFAX housekeeping data products, in varied formats.
urn:nasa:pds:mars2020_rimfax:data_calibrated	Data	Contains RIMFAX calibrated data products, in CSV format.
urn:nasa:pds:mars2020_rimfax:browse_radargram	Browse	Contains browse radargram products compiled from traverse sounding data for select calibrated data products, in PNG format.
urn:nasa:pds:mars2020_rimfax:document	Document	Contains documentation, including this Calibrated Data SIS, the Raw Data SIS, the Archive Bundle SIS, and the RIMFAX Calibrated Catalog.

4.5 **RIMFAX Calibrated Data Products**

Each Calibrated data product (or Calibrated Data Record, CDR) within the RIMFAX data collection contains a text file (CSV format), along with its respective label file. An example of such a data product and corresponding LID is given in Table 10. These CDR file pairs are organized into subdirectories by Earth year, named, e.g., 2021, 2022, etc.

Table 10: Example of data product LID in the RIMFAX calibrated data collection.

Example Calibrated Data Product LID	Description
urn:nasa:pds:mars2020_rimfax:data_calibrated:rimfax_calibrated	Contains a CSV-format text file,
_0001	composed of a single data table.

4.6 **RIMFAX** Calibrated Data Product File Naming Conventions

RIMFAX Calibrated data product files (CSV format) contain one Sol's worth of data and are named according to the format:

rimfax_calibrated_<SOLNUMBER>.<SUFFIX>

For example:

rimfax_calibrated_0001.csv

rimfax_calibrated_0001.xml

5 **RIMFAX Product Formats**

Data that comprise the RIMFAX data archive are formatted in accordance with PDS specifications [1 - 6]. This section provides details on the formats used in the types of products in the RIMFAX archive.

5.1 Data Product Formats

This section describes the format and data-table record structure of the CSV-format text file within the Calibrated data product.

5.1.1 Raw Data File Structure

RIMFAX Raw data products are not described in this SIS, but are described in [8].

5.1.2 Calibrated Data File Structure

The CDR data product is a CSV-format text file composed of a data table of ASCII text fields. This data table includes all processed radar measurements, housekeeping data, calibration arrays, and associated parameters.

The first record (row) of the table contains column headings. The next several records (minimum of 3 in all Sols with radar measurements) contain one of the three types of calibration arrays discussed in Section 3.2.2. Each subsequent record contains data from a single measurement, either radar data or housekeeping data, in chronological order down the table (Figure 6).

The first column of each record contains the parameter record_type, which indicates which type of information the record contains, according to Table 11.

Table 11: Fundamentally different types of records in the RIMFAX CDR data product data table, as identified by the data-table parameter "record_type" (in the first column of each data-table record).

Value of record_type Parameter	Record Type	Data-Sample Columns Content
record_type = 0	Active sounding data	time-domain data samples
record_type = 1	Passive radiometry data	frequency-domain data samples
record_type = 5	Housekeeping data	empty
record_type = 8	Calibration array	time-domain or frequency-domain elements

The next dozens of columns (N=85) of each record contain fields of parameters associated with that record's data (listed and described in Appendix A). Depending on which type of record it is (according to Table 11), some or many of these fields may be empty (in the CSV data format, an empty field would have no ASCII character between the two commas bounding the field).

The latter range of columns (typically N=100s - 1000s) contain radar-data samples (either active sounding data in the time domain or passive radiometry data in the frequency domain) or

calibration array elements (only in the first few data-table records). These columns are all empty for housekeeping data records.

Active-sounding measurement data (Parameter record_type=0) have been processed as described in Section 3.3 from the frequency domain into the time domain. These time-domain data are presented as samples of equal-time increment, and are listed one sample per column, starting from time zero and increasing in time with column number. The total number of columns is determined by the longest sounding of the Sol; records containing shorter soundings have empty fields at their ends. Active-sounding data-sample values are calibrated to be the ratio of the measured received power to the radiated power, over the increment of time represented by the sample.

Passive radiometry measurement data (Parameter record_type=1) are maintained in the frequency domain, and are presented as samples of equal-frequency increment, also listed one sample per column, starting with the lowest frequency and increasing in frequency with column number. In the current version of the CDR data product, passive radiometric data is maintained in its raw, unprocessed, uncalibrated state, in terms of received amplitude. Future iterations of the CDR may apply a processing algorithm to convert these passive measurements to physical units, such as radiance.

Housekeeping measurement data (Parameter record_type=5) comprise two different temperature parameters, and have no entries in the data-column fields in the latter part of their data-table records.

Parameter record_type=8 are calibration arrays. These records always and only occupy the first several records of the data table, immediately following the header row. Which arrays are used in the processing of a record, and the calibration step (Section 3.2.2) in which they are applied, is indicated by 3 respective parameter fields for that record: amplitude_correction_ref, phase_correction_ref, and gating_amplitude_correction_ref. Each of these parameter fields contains an integer-valued reference to the matching calibration_array_object field in the same record as the data samples representing the applicable calibration array. The lengths of amplitude correction arrays and phase correction arrays are the same as the number of frequency-domain samples of the radar measurements to which they are applied; the length of gating amplitude correction arrays are the same as the number of time-domain samples in the final, processed active-sounding records.



Figure 6: Generalized and simplified schematic representation of data-table regions and cell-content, within RIMFAX CDR data product. Unless labeled as "Housekeeping" or "Passive", measurement records represent Active soundings.

5.2 Browse Product Formats

Browse images of radargrams are compiled from traverse sounding data from select calibrated data products. Browse products are included only from traverses of non-trivial length (typically > \sim 1-2m), and only for the Shallow mode. These images are in PNG format. On the radargrams, the horizontal axis is distance (meters) along the traverse (which is not necessarily along a straight line in a single heading because of rover turns during its drive), and the primary vertical axis is the two-way travel-time delay of the returned signal (nanoseconds). The secondary vertical axis has been converted to *estimated* depth (meters) using the given assumed wave velocity in the ground (set constant for whole radargram). Two versions are provided: "browse" products, which contain the image of the radargram only (suffix " browse.png"), and "annotated browse" products, which include all axes and labels (" browsea.png" suffix). The processing steps applied to each raw sounding during creation of the browse product are identical to those applied to each raw sounding in deriving the numerical radar-data values in the CDR data table, as described in Section 3.2.2. The browse-product radargram is thus the direct, greyscale image representation of numerical radar-data values present in the CDR data table. In other words, browse-product images are radargrams compiled from sounding data in the CDR data table, with no additional or different processing steps applied.

5.3 Document Product Formats

Document products in this archive are generally in PDF/A format (<u>www.pdfa.org/download/pdfa-in-a-nutshell</u>) or plain ASCII text if no special formatting is required.

The RIMFAX CDR Catalog is a CSV-format text file that contains select information from and about the Calibrated data product CSV-format files. The purpose of this catalog is to collect in one location characteristics and ranges of data type, content, amount, collection mode, timing, and other attributes, so that the user may obtain an overview of the entire RIMFAX dataset or a

particular sol-range or parameter(s) of interest by scanning a single file, digitally or manually. This will hopefully assist the user in narrowing the files they wish to open or query for their own specific purposes.

The first row is a header row. Each subsequent row contains the summary values of one Calibrated data product CSV file (and therefore of a single Sol).

For the most part, columns contain the minimum and maximum values of corresponding parameters in the CDR data table (with column-headings of *Parameter_min* and *Parameter_max*, respectively). Some, not all, of the CDR parameters are included. The parameter columns are generally in the same order in each document, with the exception that *sol* (which doesn't have separate min and max columns) is listed in the first column of the Catalog.

Five of the CDR data-file parameters selected for inclusion and summary in the Catalog can have a small, limited number of possible values. For these parameters, the Catalog presents the frequency with which each of these possible values occurs in the given sol's CDR (instead of min and max values of the parameter). This is implemented in the Catalog file using column-headings of the form *Parameter_i*, where *i* is the value of *Parameter* in the CDR data file, and the value of *Parameter_i* is the number of times *i* occurs in that Sol's CDR. These Catalog column-headings and their definitions are listed individually in Table B1.

5.4 PDS Labels

Each RIMFAX Calibrated product (data, document, and browse types) 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 file (or files) they describe (with the exception of the Product_Bundle label). There is one label for every product, in RIMFAX's case there is one label for each Sol's .CSV data file. The RIMFAX PDS4 label file has the same name as the data product it describes, but with the extension ".xml".

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.

Documents are also considered products, and have PDS4 labels just as data products do.

For the M2020 mission, the structure and content of PDS labels will conform to the PDS master schema and schematron based upon the PDS Information Model [3]. By use of an XML editor the schema and schematron 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 is a set of validation rules that are applied to PDS4 labels.

The PDS master schema and schematron documents are produced, managed, and supplied to M2020 by the PDS. In addition to these documents, the M2020 mission has produced additional XML schema and schematron documents which govern the products in this archive. These documents contain attribute and parameter definitions specific to the M2020 mission.

Appendix A Calibrated Data Product Parameters

Table A1: Complete list of parameters recorded in the ASCII-text data table that makes up the CSV-format RIMFAX CDR data product. Each successive row of Table A1 corresponds to a successive column in the CDR data table, starting with "record_type" in Table A1, Row 1 and in CDR data-table Column 1. (The parameter rows of this table map to the "Parameter Columns" area in the schematic illustration of the CDR data table in Figure 6 of this SIS.) Internal grey-shaded headings in this SIS version are intended as groupings of parameters to facilitate organization for the reader, and are not present in the CDR data table. * Possible record types are: Housekeeping Measurement, Active Sounding, Passive Radiometry, Calibration Array. ** Precision in number of characters, number of places after; preceded by "-" if negative values possible. *** Label values in this column reference the respective row-label values in Table A2, which contains the corresponding comments to rows in this table.

Parameter Name	Record Type for which Parameter Field will contain values *	Description	Data Type	Units	Precis -ion Requi -red **	Com- ment Refer- ence Label ***
record_numb er	HK Active Passive CalArray	Numerical ordinal label of CDR table record	int		4	
record_type	HK Active Passive CalArray	Type of CDR table record: 0 = Active Sounding Measurement, 1 = Passive Radiometry Measurement, 5 = Housekeeping Measurement, 8 = Calibration Array	int		1	
calibration_a rray_object	CalArray	Integer label of the Calibration Array object contained in this table record. This field is referenced by the integer values of the parameters: amplitude_correction_ref, phase_correction_ref, gating_amplitude_correction_ref	int		2	1
Date/Time Pa	rameters		-	•		
utc	HK Active Passive	Universal Time Coordinated	char	YYYY-M M-DDTH H:MM:S S.SSS	23	
jdate	HK Active Passive	Julian date	real	days	7.8	
doy	HK Active Passive	Day of Earth year	int	days	3	
year	HK Active Passive	Earth year	int	years	4	
local_mean_s olar_time	HK Active Passive	Local mean solar time (LMST)	char	HH:MM :SS.SSS [Mars]	12	
local_true_so lar_time	HK Active Passive	Local true solar time (LTST)	char	HH:MM :SS [Mars]	8	
sol	HK Active Passive	Sol of the Mars 2020 Perseverance mission [Landing Sol 0 was on Feb 18, 2021]	char	sols	5	

ls	HK Active Passive	Solar longitude, measured from northern spring equinox $= 0$	real	deg Ls	3.7	
mars_year	HK Active Passive	Mars year [April 11, 1955 = start of Year 1 OR May 24, 1953 = start of Year 0]	int	years [Mars]	2	
sclk	HK Active Passive	System time in SCLK seconds [Time 0 = midnight on Jan 1, 1980]	int	s	9	
sclk_sub_ns	HK Active Passive	System time SCLK subseconds, in whole-number of nanoseconds	int	ns	9	
Sun Parame	ters					
sun_lat	HK Active Passive	[Planetocentric] Sub-solar latitude	real	deg	-2.8	
sun lon	HK Active Passive	[Planetocentric East] Sub-solar longitude	real	deg	3.8	
sun dist	HK Active Passive	Distance between sun and Mars centers	real	AU	1.8	
sun_inc	HK Active Passive	Incidence angle of sun with respect to the normal to the local ellipsoid surface, measured from Zenith $= 0$	real	deg	2.4	
sun_az	HK Active Passive	Azimuth direction of sun within gravity-normal plane, measured clockwise from North = 0	real	deg	3.4	
Antenna Par	rameters	•		-	•	
ant_lat	HK Active Passive	[Planetocentric] Latitude of RIMFAX antenna frame origin	real	deg	2.8	2
ant_lon	HK Active Passive	[Planetocentric East] Longitude of RIMFAX antenna frame origin	real	deg	3.8	2
ant_elev	HK Active Passive	[Geodetic] Elevation of RIMFAX antenna frame origin	real	m	-4.3	2
ant_az	HK Active Passive	Azimuth angle of antenna: Angle between North and the projection of the antenna +X (forwards) axis onto the gravity-normal plane (ie, angle of rotation of the antenna around the gravity vector), measured clockwise from North = 0 .	real	deg	3.4	3
ant_pitch	HK Active Passive	Pitch angle of antenna: Angle between the antenna +X (forwards) axis and its projection onto the gravity-normal plane (ie, rotation around the antenna +Y (right-wards) axis as projected onto the gravity-normal plane). Measured in the right-hand sense, from Horizontal = 0. Pitch >0 when front of antenna is pointing up, above horizontal.	real	deg	-2.4	3
ant_roll	HK Active Passive	Roll angle of antenna: Angle between the antenna +Y (right-wards) axis and the gravity-normal plane, as measured within the antenna's YZ plane (ie, rotation around the antenna +X (forward) axis). Measured in the right-hand sense, from Horizontal = 0. Roll > 0 when right of antenna is pointing down, below horizontal.	real	deg	-2.4	3
ant_tilt	HK Active Passive	Tilt angle of antenna: Angle between the antenna's maximum tilt vector and its projection onto the gravity-normal plane, measured from Horizontal = 0 .	real	deg	2.4	3
ant_tiltaz	HK Active Passive	Tilt-azimuth angle of antenna: Angle between North and the projection of the antenna's maximum tilt vector onto the gravity-normal plane, measured clockwise from	real	deg	3.4	3

		North $= 0.$				
Rover Param	eters		-			
rover_lat	HK Active Passive	[Planetocentric] Latitude of rover RNAV frame origin	real	deg	2.8	2
rover_lon	HK Active Passive	[Planetocentric East] Longitude of rover RNAV frame origin	real	deg	3.8	2
rover_elev	HK Active Passive	[Planetocentric] Distance from center of Mars to RNAV frame origin	real	km	4.6	
rover_rad	HK Active Passive	[Geodetic] Latitude of rover RNAV frame origin	real	deg	2.8	2
rover_lat_ge odetic	HK Active Passive	[Geodetic] Elevation of rover RNAV frame origin	real	m	-4.3	2
rover_sapp_q uality	HK Active Passive	Surface Attitude, Position, and Pointing (SAPP) quality flag	int		1	4
rover_left_bo gie	HK Active Passive	Angle of left bogie joint	real	rad	-1.6	4, 5
rover_right_b ogie	HK Active Passive	Angle of right bogie joint	real	rad	-1.6	4, 5
rover_left_di fferential	HK Active Passive	Angle of left differential joint	real	rad	-1.6	4, 6
rover_right_d ifferential	HK Active Passive	Angle of right differential joint	real	rad	-1.6	4, 6
rover_steer_l f	HK Active Passive	Steer angle of left-front wheel	real	rad	-1.6	4, 7
rover_steer_l r	HK Active Passive	Steer angle of left-rear wheel	real	rad	-1.6	4, 7
rover_steer_r f	HK Active Passive	Steer angle of right-front wheel	real	rad	-1.6	4, 7
rover_steer_r r	HK Active Passive	Steer angle of right-rear wheel	real	rad	-1.6	4, 7
system_rmc_ site	HK Active Passive	Site rover motion counter (RMC 1)	int		5	4
system_rmc_ drive	HK Active Passive	Drive rover motion counter (RMC 2)	int		5	4
system_rmc_ pose	HK Active Passive	Pose rover motion counter (RMC 3)	int		5	4
system_rmc_ arm	HK Active Passive	Arm rover motion counter (RMC 4)	int		5	4
system_rmc_ sha	HK Active Passive	SHA rover motion counter (RMC 5)	int		5	4
system_rmc_ drill	HK Active Passive	Drill rover motion counter (RMC 6)	int		5	4
system_rmc_ rsm	HK Active Passive	RSM rover motion counter (RMC 7)	int		5	4
system_rmc_ hga	HK Active Passive	HGA rover motion counter (RMC 8)	int		5	4
Source Paran	neters					

edr_raw_pro duct_name	Active Passive	Name of Raw EDR data product containing this record's sounding measurement	char		50	8
hk_raw_prod uct_name	нк	Name of Raw EHK data product containing this record's Housekeeping measurement	char		50	
Environment	al Parameters					
config	нк	Identifier of RIMFAX configuration mode at time of Housekeeping Measurement	int		3	
electronics_t emp	НК	Temperature of RIMFAX electronics, an average of Term_RF1 (hkAdcB3 in EHK) and Term_RF2 (hkAdcB4 in EHK)	real	deg C	-2.3	
base_temp	нк	Temperature of VAMP UHFA/RMFX base, a 10-second average	real	deg C	-2.3	
Radar Measu	rement Parameters					
config_id	Active Passive	Identifier of RIMFAX configuration mode	int		3	
mode_name	Active Passive	General name of configuration mode	char	 	25	9
activity_nam e	Active Passive	Sequence ID for RIMFAX Activity during which measurement was collected. Used in uplink planning process and in the scheme (along with config_id/mode) for grouping measurements into EDRs	char		9	
calibration_c able	Active Passive	Indicates measured signal is: 0 = from the Antenna, 1 = from the Calibration Cable	int		1	
stationary_so unding	Active Passive	Indicates measurement is part of a: 0 = Traverse/Mobile set, 1 = Stationary set	int		1	
passive_soun ding	Active Passive	Indicates measured signal is: 0 = returned/received from Active transmission, 1 = ambient/received with no prior transmission, ie Passive or "listen only"	int		1	
long_integrat ion_sounding	Active Passive	Indicates measurement is: 0 = Nominal precision (16 bits), 1 = High precision (LIS, 32 bits)	int		1	
start_frequen cy	Active Passive	Starting frequency of measured bandwidth range	int	MHz	4	
stop_frequen cy	Active Passive	Ending frequency of measured bandwidth range	int	MHz	4	
measurement _sample_freq uency_incre ment	Active Passive	Frequency interval covered by each data sample measured	real	MHz	2.6	10
n_measurem ent_samples	Active Passive	Number of frequency-domain data samples measured	int		4	11
sweep_band width	Active Passive	Range of frequencies measured	int	MHz	4	
sweep_time	Active Passive	For Active measurements: Duration of one individual radar-signal generation sweep through frequency bandwidth; for Passive measurements: Duration of one individual receive-only sweep through frequency bandwidth	real	ms	3.5	12

sweeps_per_ sounding	Active Passive	Number of bandwidth sweeps integrated into one recorded measurement	int		3	13
gate_frequen cy	Active Passive	Frequency of the gate signal	real	MHz	2.3	
tx_delay	Active Passive	Time delay of transmitter gate	int	ns	2	
tx_attenuatio n	Active Passive	Attenuation in the transmit path, higher values represent lower output power	int	dB	2	
rx_delay	Active Passive	Time delay of receiver gate	int	ns	2	
rx_attenuatio n	Active Passive	Attenuation in the receive path, higher values represent more dampening of the received signal	int	dB	2	
sounding_gro up_spacing	Active Passive	Commanded distance between sounding groups. A group includes one soundig of each mode, each executed in immediate sequence, ie, effectively at the same location. Actual distance between measurements may deviate slightly. Value set = 0 for non-Traverse/Mobile measurements.	int	cm	3	
sounding_co unter	Active Passive	Absolute total count of soundings since start of M2020 Perseverance mission	int		7	
sounding_nu mber	Active Passive	Count of soundings since RIMFAX was last powered on (ie since last execution of "Power-On" Activity)	int		4	
sounding_nu mber_sol	Active Passive	Count of soundings since start of current Sol	int		4	
Radar Proces	ssing Parameters					
amplitude_co rrection_ref	Active	Integer-value reference to one of the integer-label fields of the calibration_array_object parameter column (in one of the first several records/rows of this data table). The record with the matching integer-label field contains an Amplitude Correction Array which was applied in the frequency domain during processing (1D array length = number of frequency samples)	int		2	
phase_correc tion_ref	Active	Integer-value reference to one of the integer-label fields of the calibration_array_object parameter column (in one of the first several records/rows of this data table). The record with the matching integer-label field contains a Phase Correction Array which was applied in the frequency domain during processing (1D array length = number_of_frequency_samples)	int		2	
gating_ampli tude_correcti on_ref	Active	Integer-value reference to one of the integer-label fields of the calibration_array_object parameter column (in one of the first several records/rows of this data table). The record with the matching integer-label field contains a Gating Amplitude Correction Array which was applied in the time domain during processing (1D array length = n_samples_time) Multiplicative factor by which values are	int		2	
correction	Active	radiometrically calibrated, applied in the time domain	real		2.5	

		during processing				
time_zero_co rrection		Change in reference time-delay (from Raw data) such				
		that the first data sample corresponds in time to a delay		ns		
	Active	of 0 ns, and corresponds physically to the antenna radar	real		2.3	
		feedpoint, applied in the frequency domain during				
		processing	<u> </u>			
window func	Active	Name of window function by which Raw data is filtered				
tion		before fourier transform is run, applied in the frequency	char		~10	
		domain during processing				
		Total number of samples on which fourier transform is				
		run. Measured Raw data samples				
zero_padding	Active	(N=n_measurement_samples) are padded with	int		5	
_samples	Active	additional samples (all containing a value of 0) above	IIIt		5	
		and below the measured frequency band, applied in the				
		frequency domain during processing				
max_time_de	Active	Maximum time-depth range of processed data (ie, the	raa1	ns	4.3	
pth		end-time of the last data sample)	leal			
Data Sample	Parameters					
sample_time	Active	Time increment of processed data samples (Active	roo1	ns	1.7	
_increment		measurement records only)	Tear			
sample_frequ	Passive	Frequency increment of unprocessed data samples				
ency_increm		(Passive measurement records only)	real	MHz	2.6	14
ent		(i ussive measurement records only)				
n_samples_ti	Active	Number of data samples in processed, time-domain data	int		5	
me		record (Active measurement records only)	m			
n_samples_fr equency	Passive	Number of data samples in unprocessed,			4	
		frequency-domain data record (Passive measurement	int			14
		records only)				
n_samples	HK Active Passive CalArray	Number of samples in table record (regardless of record	• .	~		
		type)	int	int		

Table A2: Comments for respective rows in Table A1, as cross-referenced by the value of the "Comment Reference Label" field in each table.

Comment Reference Label	Comment
1	This field only contains values in the first several table records.
2	All RIMFAX antenna-related location parameter values are constant translational offsets from those of rover frame (RNAV, RMECH). More detail in CDR SIS Section 3.3.2.
3	All RIMFAX antenna-related angle/orientation parameter values are identical to those of rover frame (RNAV, RMECH). More detail in CDR SIS Section 3.3.2.
4	See EDR SIS [8] and RAPP FDD [11] for SAPP- & RMC-related definitions.
5	The 0° point corresponds to the angle of the bogie with respect to its rocker when the vehicle sits on a flat horizontal surface. For each bogie, positive bogie angles reflect the middle wheel moving up relative to the 0° point; negative bogie angles reflect the middle

	wheel moving down with respect to the 0° point. The range of motion of each bogie is between +44° and -44°.
6	Positive [left/right] differential angle means the [left/right] front wheel will be above the [right/left] front wheel. Values are in the range of +/- pi. On flat horizontal ground, all four values would be =0.
7	Negative steering angle is measured from 0° to the left, toward the direction of the -Y axis of RMECH. Positive steering angle is measured from 0° to the right, toward the direction of the +Y axis of RMECH. (ie, positive is clockwise as looking down on the rover from above.)
8	See EDR SIS [8] for precise file-naming scheme.
9	Possible values (subject to change): "Surface", "Shallow", "Deep", "Surface_Cal", "Shallow_Cal", "Deep_Cal", "Standard_Cal", "Passive_Sweep", "Passive_Sweep_Cal", "Passive_Singlefreq"
10	Possible values (rounded): 13.82, 6.91, 3.44, 1.72, 0.86, 0.43, 0.22, 0.12, (0.00)
11	Possible values: 76, 152, 305, 610, 1220, 2441, 4882, 9765
12	Possible values: 100, 50, 25, 12.5, 6.25, 3.125, 1.5625, 0.78125, (0.00)
13	Possible values: 1, 2, 4, 8, 16, 32, 64, 128, (0)
14	Currently, Passive modes are not processed, so this is same as for measurement.

Appendix B CDR Catalog Columns

Table B1. Partial list of column-headings in the CDR Catalog file. Most Catalog column-headings are of the form column-headings are of the form convert min and convert max, derived from the corresponding convert in the CDR data table. Only those Catalog column-headings that differ from this format are included in the table below, with their descriptions.

Catalog Column-Heading	Description		
catalog_record_number	Numerical ordinal label of Catalog table record		
sol	M2020 Perseverance mission Sol covered by data in CDR		
cdr_filename	Name of CDR file, of the form: rimfax_calibrated_#####.csv, where #####=Sol num		
n_cdr_records	Number of CDR table records (excluding header row)		
n_cdr_columns	Number of CDR table columns, including both Parameters and Data Samples		
record_type_0	Number of CDR records for which record_type = 0: Active Sounding Measurement		
record_type_1	Number of CDR records for which record_type = 1: Passive Radiometry Measurement		
record_type_5	Number of CDR records for which record_type = 5: Housekeeping Measurement		
record_type_8	Number of CDR records for which record_type = 8: Calibration Array		
calibration_cable_0	Number of CDR records for which calibration_cable = 0: Received/recorded signal is from the Antenna		
calibration_cable_1	Number of CDR records for which calibration_cable = 1: Received/recorded signal is from the Calibration Cable		
calibration_cable_2	Number of CDR records for which calibration_cable = 2: Received/recorded signal alternates between Antenna and Calibration Cable, for single-frequency Passive measurements only		
stationary_sounding_0	Number of CDR records for which stationary_sounding = 0: Measurement is part of a Traverse/Mobile set		
stationary_sounding_1	Number of CDR records for which stationary_sounding = 1: Measurement is part of a Stationary set		
passive_sounding_0	Number of CDR records for which passive_sounding = 0: Received/recorded signal is returned/received from Active transmission		
passive_sounding_1	Number of CDR records for which passive_sounding = 1: Received/recorded signal is ambient/received with no prior transmission, ie Passive or "listen only"		
long_integration_soundi ng_0	Number of CDR records for which long_integration_sounding = 0: Measurement is Nominal precision (16 bits)		
long_integration_soundi ng 1	Number of CDR records for which long_integration_sounding = 1: Measurement is High precision (LIS, 32 bits)		

Appendix C Support Staff and Cognizant Persons

Table	C1: Archive	support staff.
Iuoic		support supp.

RIMFAX Team					
Name	Address	Phone	Email		
Mark Sullivan	EPSS Dept, UCLA		marks@mars.ucla.edu		
PDS Geosciences Node					
Name	Address	Phone	Email		
Susan Slavney	PDS Geosciences		susan.slavney@wustl.edu		