وكالة الإمارات للفضاء
UAE SPACE AGENCY

مركز محمد بن راشد للفضاء
MOHAMMED BIN RASHID SPACE CENTRE

Emirates Mars Mission

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ASU
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EMIRS Data Product Guide

Document No. 401023

Approvers List

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-	Initial Release	Nathan Smith
A	Added Level 3 Products (CR#451024)	Kezman Saboi
B	Modifications to Level 3 Products (CR#451025)	Kezman Saboi

0.1 Table of Contents

1.0 ABBREVIATIONS

ASU	Arizona State University
AWS	Amazon Web Services
CCSDS	Consultative Committee for Space Data Systems
DFT	Discrete Fourier transform
DLaTGS	Deuterated L-alanine doped Triglycine Sulfate
EMIRS	Emirates Mars InfraRed Spectrometer
EMM	Emirates Mars Mission “Hope”
FITS	Flexible Image Transport System
FOV	Field of View
FPGA	Field Programmable Gate Array
FTIR	Fourier Transform Infrared
IFOV	Instantaneous field of view
IRF	Instrument response function
ITF	Instrument Team Facility (ASU/NAU)
JST	Japan Standard Time
L0	Level 0 Data – raw instrument packets
L1	Level 1 Data – uncalibrated data
L2	Level 2 Data – calibrated data
L3	Level 3 Data – derived physical parameters
Ls	Solar Longitude (Mars Season)
MOC	Mission Operations Center
NAU	Northern Arizona University
NE∆T	Noise Equivalent Delta Temperature
NESR	Noise Equivalent Spectral Radiance
S/C	Spacecraft
SDC	Science Data Center
ZPD	Zero path difference

2.0 Introduction

2.1 Scope

This document describes the EMIRS data products and their generation. It is intended to serve as a reference to the public data user.

2.2 Mission Overview

The Emirates Mars Infrared Spectrometer (EMIRS) instrument onboard the Emirates Mars Mission (EMM) dubbed “Hope” was launched to Mars on 19 July 2020 at 21:58:14 UTC (20 July 2020 06:58:14 JST) from the Tanegashima launch site in Japan. EMM started its primary science phase on May 23, 2021. EMIRS will aid the mission goals of EMM by characterizing the state of the lower atmosphere of Mars through systematic observations that enable near-complete geographic coverage over the full martian day on sub-seasonal timescales from its 20,000-43,000 km elliptical orbit. More specifically, the science objectives of the EMIRS investigation are to: 1) Determine the three-dimensional thermal state of the lower atmosphere and its diurnal variability on sub-seasonal timescales, 2) Determine the geographic and diurnal distribution of key constituents in the lower atmosphere on sub-seasonal timescales.

2.3 EMIRS Instrument Description

The Emirates Mars Mission Emirates Mars Infrared Spectrometer will provide remote measurements of the martian surface and lower atmosphere in order to better characterize the geographic and diurnal variability of key constituents (water ice, water vapor, and dust) along with temperature profiles on sub-seasonal timescales. EMIRS is a FTIR spectrometer covering the range from 6.0-100+ μm (1666-100 cm^{-1}) with a spectral sampling as high as 5 cm^{-1} and a 5.4-mrad IFOV and a 32.5x32.5 mrad FOV.

The EMIRS optical path includes a flat 45˚ pointing mirror to enable one degree of freedom and has a +/-60˚ clear aperture around the nadir position which is fed to a 17.78-cm diameter Cassegrain telescope. The collected light is then fed to a flat-plate based Michelson moving mirror mounted on a dual linear voice-coil motor assembly. An array of deuterated L-alanine doped triglycine sulfate (DLaTGS) pyroelectric detectors are used to sample the interferogram every 2 or 4 seconds (depending on the spectral sampling selected). A single 0.846 μm laser diode is used in a metrology interferometer to provide interferometer positional control, sampled at 40 kHz (controlled at 5 kHz) and infrared signal sampled at 625 Hz. The EMIRS beamsplitter is a 60-mm diameter, 1-mm thick 1-arcsecond wedged chemical vapor deposited diamond with an antireflection microstructure to minimize first surface reflection.

EMIRS relies on an instrumented internal v-groove blackbody target for a full-aperture radiometric calibration. The radiometric precision of a single spectrum (in 5 cm^{-1} mode) is $<3.0 \times 10^{-8}$ W cm^{-2} sr^{-1}/cm^{-1} between 300 and 1350 cm^{-1} over instrument operational temperatures (< ~0.5 K NEΔT @ 250 K). The absolute integrated radiance error is < 2% for scene temperatures ranging from 200-340 K.

The overall EMIRS envelope size is 52.9 x 37.5 x 34.6 cm and the mass is 14.72 kg including the interface adapter plate. The average operational power consumption is 22.2 W, and the standby power consumption is 18.6 W with a 5.7 W thermostatically limited, always-on operational heater.

EMIRS was developed by Arizona State University and Northern Arizona University in collaboration with the Mohammed bin Rashid Space Centre with Arizona Space Technologies developing the electronics. EMIRS was integrated, tested and radiometrically calibrated at Arizona State University, Tempe, AZ.

Further details of the EMIRS instrument can be found in the EMIRS instrument overview paper:

Edwards, C. S., Christensen, P. R., Mehall, G. L., Anwar, S., Tunaiji, E. A., Badri, K., Bowles, H., Chase, S., Farkas, Z., Fisher, T., Janiczek, J., Kubik, I., Harris-Laurila, K., Holmes, A., Lazbin, I., Madril, E., McAdam, M., Miner, M., O'Donnell, W., Ortiz, C., Pelham, D., Patel, M., Powell, K., Shamordola, K., Tourville, T., Smith, M. D., Smith, N., Woodward, R., Weintraub, A., Reed, H., & Pilinski, E. B. (2021). The Emirates Mars Mission (EMM) Emirates Mars InfraRed Spectrometer (EMIRS) Instrument. *Space Science Reviews, 217*(7), 77. http://dx.doi.org/10.1007/s11214-021-00848-1

3.0 Data Overview

3.1 Data Processing Levels

Table 1: EMIRS Data Processing Levels

EMIRS Level	PDS4 Processing Level	Description
0	Telemetry	Spacecraft CCSDS packets delivered to the SDC by the MOC, including Science and Housekeeping. EMIRS telemetry is defined in Appendix A.
1a	Raw	Raw interferograms including ancillary and housekeeping data. Not Calibrated.
1b	Raw	Uncalibrated spectra including ancillary and housekeeping data.
2	Calibrated radiance	Calibrated radiance spectra in physical units ($W/cm^2/sr/cm^{-1}$) with geometry information. Using reconstructed ephemeris. Also includes associated quantities, e.g., brightness temperature.
3	Derived	Retrieved physical atmospheric parameters: Surface temperature, emissivity, water ice, water vapor, dust opacity, vertical atmospheric temperature profiles

3.2 Products

Table 2: Released EMIRS Data Products

EMIRS Level	Released Product	Description
0	None	
1a	FITS Archive	Raw interferograms including ancillary and housekeeping data. Not Calibrated. One FITS file per observation.
1b	FITS Archive	Uncalibrated spectra including ancillary and housekeeping data. One FITS file per observation.
2	FITS Archive	Calibrated radiance spectra in physical units (W/cm^2/sr/cm^-1) with geometry information. Using reconstructed ephemeris. Also includes associated quantities, e.g., brightness temperature. One FITS file per observation.
	Quicklook images, png	For each observation, Quicklook images are produced, displaying atmospheric brightness temperature and surface temperature in the observed area, each as both individual IFOV footprint spots and using a simple interpolation across the observed region.
3	L3emiss FITS files	Derived physical surface parameters: Surface temperature, emissivity, etc. One FITS file per observation.

EMIRS Level	Released Product	Description
	L3atm FITS files	Retrieved physical atmospheric parameters: water ice, water vapor, dust opacity. One FITS file per observation.
	L3 Gridded FITS files	Global maps combining multiple observations from a particular range of L_s, displaying retrieved atmospheric properties. These maps are recorded as machine readable numeric data.
	L3 Gridded Quicklook pngs	Global maps combining multiple observations from a particular range of L_s, displaying retrieved atmospheric properties. These map images are recorded as human-readable pre-rendered quicklook figures.

3.3 Data Flow

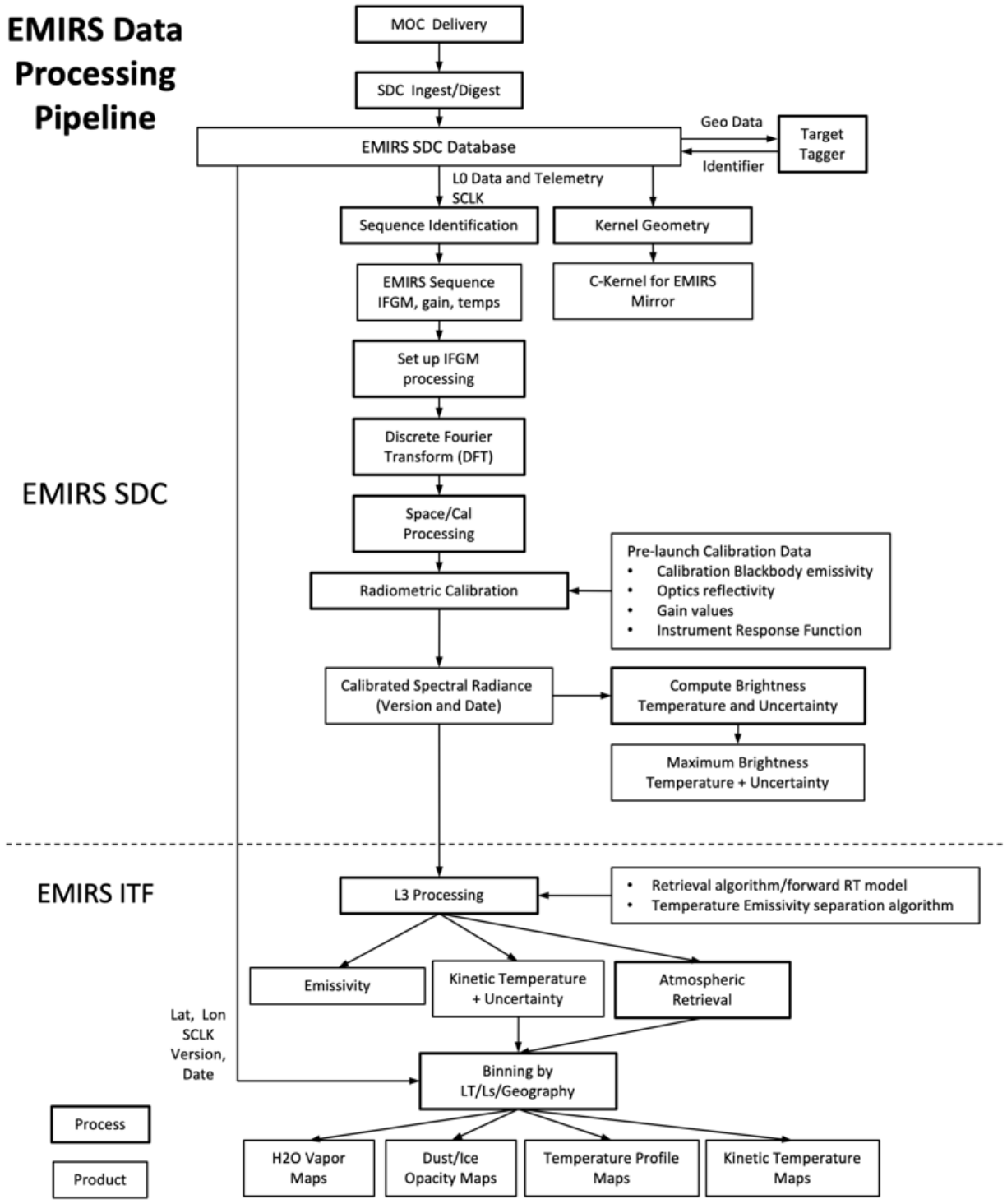

Figure 1: EMIRS Data Processing Pipeline

3.4 Standards Used in Generating Data Products

3.4.1 Time Standards

The spacecraft clock time value (sclk) stored with each standard data product is the value of the spacecraft clock at the time of the end of the scan period.

The spacecraft clock value is equal to the number of seconds since the J2000 epoch (2000-01-01 00:00 UTC). This number can vary from the number of seconds recorded on earth due to variations in the spacecraft's oscillator or relativistic effects. The portion of the number that occurs after the decimal point is a count of "clock ticks" which are $1/65536^{th}$ of a second long; the decimal portion will always be between 0 and 65,535. All data products also contain time values in UTC (Universal Coordinated Time) formats, translated from the spacecraft event times.

3.4.2 Coordinate Systems

Geometry is stored in J2000 planetocentric latitude and longitudes, with footprint boundaries defined by a 21-point polygon. This polygon is recorded as either a "flat" 2D polygon in latitude-longitude space on Mars' surface, or as a 3D polygon with explicit latitude, longitude, and radius from Mars' barycenter defined for each boundary point. All distances are recorded in kilometers. Latitudes and longitudes are recorded in degrees, with longitude increasing to the East. When Mars body-fixed cartesian coordinates are used, +X is taken to be the vector towards 0° latitude, 0° longitude, and +Z is the vector extending from the North pole, with +Y following the right-handed convention.

3.4.3 Orbit Numbering Conventions

An orbit is defined as beginning and ending when the spacecraft crosses midnight, i.e., when the Spacecraft is directly opposite the Sun from Mars. Cruise phase activities are listed as Orbit 0, and Orbit 1 began when the EMM spacecraft achieved Mars Orbit Insertion on 2021-02-09, 15:41:39 UTC. The reported orbit number is the orbit during which an activity began.

4.0 Archive generation

The Emirates Space Data Center (ESDC) will serve as the UAE's primary data archive for all space missions. It is being built by the Emirates Mars Mission to act as the mission archive, but will persist beyond the end of the mission and serve as the UAE's long-term archive and public data repository. The ESDC Archive will store all publicly released mission data, metadata, documentation, and software after the end of the operational mission. The contents of the EMM archive will be maintained for a minimum of five years after the end of the mission and the decommissioning of the mission's Science Data Center (SDC).

4.1 Data Processing and Production Pipeline

Following delivery of Level 0 data from the MOC and reconstructed ephemeris from the navigation team to the SDC, automated processing will be triggered in the SDC to produce an EMIRS Camera-Kernel (C-Kernel) and Level 1a products. These raw interferograms undergo Discrete Fourier Transform (DFT) processing to produce the uncalibrated spectra of Level 1b, which are then calibrated against a combination of pre-launch laboratory measurements and contemporaneous observations of EMIRS' internal calibration target and the cold dark of space. This processing, also performed in the SDC, produces Level 2 calibrated spectra and associated observed quantities such as brightness temperature. Further analysis carried out at the EMIRS Instrument Team Facility (ITF) calculates the underlying

physical quantities associated with each observation using an atmospheric retrieval algorithm. These quantities are then aggregated to produce global maps, binned by time, season (Ls) and location, to be archived as Level 3 data products in the SDC.

4.2 Data Validation

Each delivered dataset undergoes manual inspection to ensure the desired data is being correctly written into each data product. FITS files are directly derived from the internally Hierarchical Data Format (HDF) file utilized by the processing pipeline. FITS files are examined for any anomalous shapes, unusual number of samples, etc. that may indicate a decompression error, poor calibration, or undesirable instrument artifacts to be corrected in future revisions. Quicklook images are reviewed to check that data displays correctly and appears as expected based on conditions (such as local time) and that interpolated products are accurately representing the EMIRS point data.

4.3 Data Delivery Schedule

Public data releases of Level 2 data products will occur every 3 months starting in October 2021, and Level 3 data products covering the same period will follow on a three-month delay. A nominal schedule of these data releases is captured in the table below.

Table 3: Nominal Schedule of EMM Level 2 (and included lower-level data products) and 3 Data Releases. (From EMM Product Data Management Plan, Doc No. 140892)

Release Date	Contents
Oct 2021	Quicklook images. After initial release, they will be released on a regular basis with a 2-week delay.
Oct 2021	Level 2 data products, February - May 2021 (MOI + 3 months)
Jan 2021	Level 2 data products, May - Aug 2021 Level 3 data products, February - May 2021
April 2022	Level 2 data products, September - November 2021 Level 3 data products, May - August 2021
Jun 2022	Level 2 data products, December 2021 - February 2022 Level 3 data products, September - November 2021
	and so on through end of nominal mission, until all data is released

4.4 Backups and Duplicates

In order to ensure scalable, stable, and redundant data storage, the EMM Science Data Center uses the Amazon Web Services (AWS) cloud for “dynamic” storage, i.e. that needed to support the access component, and MBRSC storage hardware for the archive component, thereby maintaining a copy of all science data within the UAE. It is anticipated that the EMIRS portion of the archive will reach 200 Gb including all derived products by the end of the primary mission.

5.0 Detailed Data Product Specifications

5.1 Archive Contents

The EMIRS data archive contains the products detailed in Table 1 produced on the timeframe described in Table 3. Higher order products (e.g. L1a, L2, L3) may not be produced for all products, as not all products may be designed to produce these data product levels (e.g. special observations for alignment, etc.). Additional revisions of files (due to reprocessing associated with geometry updates etc.) and associated pipeline revisions will become available in the archive in subsequent releases after they follow the validation process outlined in §3.2.

5.2 Directory Structure

All EMM instruments follow the same directory structure. Files will be organized and stored within the SDC using a hierarchical directory structure, as follows. Products are broken down into different directories by product level in lower case files (e.g. l1a, l1b, l2, l2ql) and then by year and month. Within each product data level directory, if a mode is provided in the filename (such as available for each quicklook product or l3 product), a sub-directory is created.

Web interfaces available also permit browsing of data products according to this structure.

- instrument
- level
- (mode) – optional
- year
- month

Example without a subdirectory: /emm/data/emirs/l1a/2022/12/

Example with a subdirectory: /emm/data/emirs/l3/atm/2022/12/

5.3 Data Product Filenames

emm_<instrument>_<dataLevel>_<startTime>_<orbnum>_<mode>_<dataProductDescriptor>_<predict/reconstruct>_<versionInfo>.<filetype>

Field	Description
instrument	Three-letter instrument or source identifier. EMIRS=emr
dataLevel	An indicator of the data level of the data product: l1a l1b l2 l2ql l3atm l3emiss

Field	Description
	l3grid l3gridql
startTime	The spacecraft UTC time at which data within the file begin. The format used should follow the following standard: yyyymmdd or yyyymmddthhmmss.
orbnum	Orbit number in which observation began. Orbit numbering begins and ends at midnight. Cruise is designated orbit number 0.
mode	An optional field used to indicate the data product mode
dataProductDescriptor	This is an optional field that may be used to further describe the data contained within the file, as there may be multiple products associated with a given dataLevel. If a descriptor contains multiple components, hyphens are used to separate those components.
predict/reconstruct	“p” or “r” depending on whether file is generated with predict or reconstructed ephemeris
versionInfo	Format: vNN-##. The NN indicates the pipeline version while the ## indicates the number of revisions the data product has undergone and is sequentially incrementing. Revision changes are due to changes in underlying SPICE kernels that trigger reprocessing. As the major version number is indicative of the overall pipeline version the best practice for EMIRS data is to pick the highest revision number as it will include the latest integration of SPICE kernels and pipeline processing revision.
filetype	An extension indicating the type/format of the data product, e.g. “fits”, “png”, “tiff”

5.3.1 Other Conventions

Case: Filenames will consist of all ***lowercase*** characters.

Restricted characters: underscores ("_") are only used to separate formal filename attributes.

5.4 FITS File Formats

For Level 1a, Level 1b, Level 2, L3emiss, and L3atm data products, **Appendix A** details the contents of each FITS file type including data types for each field, descriptions, and units.

For Level 3 Gridded products, **Appendix B** details the contents and structure of each FITS file.

5.5 Documentation

This document serves as the primary documentation for the EMIRS data product archive. All telemetry information is contained within the FITS file.

Appendix A - Detailed FITS File Contents

The following table describes the contents of the Level 1a, Level 1b, Level 2, L3atm, and L3emiss FITS data product files.

Table 4: FITS data product contents. The first column gives the FITS header label associated with an item, Column 2 gives the number of values and data type of this item, Columns 3-5 indicate with a checkmark which data product levels include this item, and Column 6 provides a brief description.

FITS header label	Data Qty, Type	L1a	L1b	L2	L3atm	L3emiss	Description
acq_cmd_dwell_stat	1, 32-bit integer	✓					Indicates the current dwell number during an acquisition command sequence
acq_cmd_pause_stat	1, 32-bit integer	✓					Indicates the current pause number during an acquisition command sequence.
acq_cmd_row_stat	1, 32-bit integer	✓					Indicates the current column status in an acquisition. Units in unsigned integers.
acq_cmd_sample_counter	1, 32-bit integer	✓					Indicates the number of samples taken during the current observation period. Default is 0x0 on power up.
acq_cmd_stat_ccw_dir	1, 32-bit integer	✓					Start Angle Direction. 0 = Clockwise, 1 = Counter Clockwise.
acq_cmd_stat_executing	1, 32-bit integer	✓					0 = not executing, 1 = executing. Default is not executing.
acq_cmd_stat_go_home_enabled	1, 32-bit integer	✓					Go Home. 0 = Disabled, 1 = Enabled. When enabled, the Data Acq command will return home prior performing any calibration dwells.
acq_cmd_step_stat	1, 32-bit integer	✓					Indicates the current step count during an acquisition command sequence. MS Byte sent first.
acq_id	1, 32-bit integer	✓					Acquisition ID echo from acquisition command. Default is 0x0 on power up.
ang_fov_size	1, 32-bit float	✓					Angular size of IFOV (in radians) Fixed value.
ang_targ_and_fov	1, 32-bit float	✓					Angle between target center and center of detector IFOV (radians)

FITS header label	Data Qty, Type	L1a	L1b	L2	L3atm	L3emiss	Description
ang_targ_size	1, 32-bit float	✓					Angular size of target (major axis of limb ellipse) (in radians)
bb_temp1	1, 32-bit float	✓					Black Body Temperature 1
bb_temp2	1, 32-bit float	✓					Black Body Temperature 2
bb_temp3	1, 32-bit float	✓					Black Body Temperature 3
bb_temp4	1, 32-bit float	✓					Black Body Temperature 4
beamsplitter_temp	1, 32-bit float	✓					Beamsplitter Temperature
bore_flag	1, unsigned byte	✓	✓	✓	✓	✓	0 = boresight does not intersect with target 1 = boresight intersects with target
bore_intcpt	3, 32-bit float	✓					Point on the surface where detector boresight intersects with the target body. Expressed as 3 value array of (Longitude, Latitude, Radius) in units of (degrees, degrees, km)
brightness_temp	700, 32-bit float			✓			Computed brightness temperature (K) at each instrument channel
cal_flag_status	1, unsigned byte	✓					Indicates when the pointing mirror is pointed at the calibration target. (Derived from pointing mirror position) 0 = pointed at calibration target (mirror at home) 1 = not pointed at calibration target (default)
calibrated_radiance	700, 32-bit float			✓	✓		Computed calibrated radiance at each instrument channel
cant_find_home	1, 32-bit integer	✓					Mechanism Position Anomaly
chi2a	1, 64-bit float				✓		Quality of aerosol fit (chi-squared difference).
chi2temp	1, 64-bit float				✓		Quality of atmospheric temperature fit. This is a chi-squared difference between best fit and obs.
ccsds_id	1, 32-bit integer	✓			✓		Packet ID of Science Packet. (internal identifier)

FITS header label	Data Qty, Type	L1a	L1b	L2	L3atm	L3emiss	Description
cmd_acc_cnt	1, 32-bit integer	✓					Number of accepted instrument commands. Rolls over after 255.
cmd_fc_echo	1, 32-bit integer	✓					Echo of last valid instrument command received (command packet function code). Note this does not include spacecraft commands (Time Update and Spacecraft Status).
cmd_rej_cnt	1, 32-bit integer	✓					Number of accepted time update commands. Rolls over after 255.
cmd_seq_id_echo	1, 32-bit integer	✓					Echo of the Sequence ID of the last valid command received. Note this does not include spacecraft commands (Time Update and Spacecraft Status)
coarse_led1	1, 32-bit integer	✓					Stepper Motor Coarse LED 1 Power b01 = ON b10 = OFF b00 = UNCHANGED b11 = UNCHANGED
coarse_led2	1, 32-bit integer	✓					Stepper Motor Coarse LED 2 Power b01 = ON b10 = OFF b00 = UNCHANGED b11 = UNCHANGED
compression_status	1, unsigned byte	✓					"0001" for compression, "0000" for no compression
converter_temp_k	1, 32-bit float	✓					Converter Case Temp (Temp 14).
dec	1, 32-bit float		✓	✓	✓	✓	Declination of the IFOV boresight (degrees) (J2000)
declination	1, 32-bit float	✓					Declination of the IFOV boresight (degrees) (J2000)
det_num	1, unsigned byte	✓	✓	✓	✓	✓	Detector number corresponding to an observation.
detector_temp1	1, 32-bit float	✓					IR Detector Temp 1 (Temp 1).
detector_temp2	1, 32-bit float	✓					IR Detector Temp 2 (Temp 2).

FITS header label	Data Qty, Type	L1a	L1b	L2	L3atm	L3emiss	Description
dustuncert	1, 64-bit float				✓		Estimated uncertainty in dust optical depth.
edac_diag_stat	1, 32-bit integer	✓					Single Bit Error Counter. Counts the number of single bit errors detected in memory. Single bit errors are corrected.
emission	1, 32-bit float	✓	✓	✓	✓	✓	Emission angle at the center of the IFOV footprint.
emissivity	1, 64-bit float					✓	Surface emissivity
fine_led1	1, 32-bit integer	✓					Stepper Motor Fine LED 1 Power b01 = ON b10 = OFF b00 = UNCHANGED b11 = UNCHANGED
fine_led2	1, 32-bit integer	✓					Stepper Motor Fine LED 2 Power b01 = ON b10 = OFF b00 = UNCHANGED b11 = UNCHANGED
fpga_code_ver	1, 32-bit integer	✓					Hex version of FPGA code rev number (i.e. 3.27 = 0x00147)
fpga_temp_k	1, 32-bit float	✓					FPGA Temp (Temp 13).
fringe_count	1, 32-bit integer	✓					Fringe Count.
fringe_offset	1, 32-bit float	✓					Fringe Analog Offset
gain	1, 32-bit integer	✓					0 = x1 Gain, 1 = x2 Gain.
gain_cal_res	1, 32-bit float	✓					Calibration Resistor Gain (Temp 15). Average of 8 samples. MS Byte sent first. Conversion Formula: volts conversion, V = [(5 x Counts / 65536) – 2.5] which should always measure 2.320 Volts
gain_convert	1, 32-bit float	✓					Derived value (from gain) 0.5 = 1x gain 1 = 2x gain

FITS header label	Data Qty, Type	L1a	L1b	L2	L3atm	L3emiss	Description
gravity_comp_status	1, 32-bit integer	✓					Gravity Compensation Status, 0 = Off, 1 = On.
iceuncert	1, 64-bit float				✓		Estimated uncertainty in water ice optical depth.
image_expected_checksum	1, 32-bit integer	✓					Indicates the expected Fletcher checksum from the IMAGE_STORE command
image_store_checksum	1, 64-bit float	✓					Indicates Fletcher checksum calculated by FSW of image data written to SRAM which is to be copied via the Image Store command. A value of 0xFAFAFA indicates byte-by-byte comparison by FSW of flash written and the SRAM source has failed.
img_boot_select	1, 32-bit integer	✓					Which boot image is running. Reflects the lower 3 bits of the Image Select register at 0xA100 0018.
img_check_checksum	1, 64-bit float	✓					Indicates Fletcher checksum of the Image data (data written to SRAM), in response to the IMAGE_CHECK command. Only valid for SRAM, not flash.
incidence	1, 32-bit float	✓	✓	✓	✓	✓	Solar Incidence Angle at the center of the IFOV footprint
instr_safed	1, 32-bit integer	✓					EMIRS Go Safe, 0 = SC Nominal operation, 1 = Go Safe. EMIRS will transition to a safe configuration and stay in this configuration as long as the Go Safe bit is set. Power to EMIRS may be turned off 30 seconds after this bit is set.
kinetic_temp	1, 64-bit integer					✓	Surface kinetic temperature
kinetic_temp_uncertainty	1, 64-bit integer					✓	Uncertainty in surface kinetic temperature
kinetic_temp_wave	1, 64-bit integer					✓	Wavenumber at which surface temperature was determined.
l_sub_s	1, 32-bit float	✓			✓		Solar Longitude of Mars at the time of observation
laser	1, unsigned byte	✓					Set to 1.

FITS header label	Data Qty, Type	L1a	L1b	L2	L3atm	L3emiss	Description
latitude	1, 32-bit float	✓	✓	✓	✓	✓	Latitude at the center of the IFOV footprint
led1	1, 32-bit integer	✓					Linear Motor LED 1 Power b01 = ON b10 = OFF b00 = UNCHANGED b11 = UNCHANGED
led2	1, 32-bit integer	✓					Linear Motor LED 2 Power b01 = ON b10 = OFF b00 = UNCHANGED b11 = UNCHANGED
local_true_solar_time	1, 32-bit float	✓			✓		Local True Solar Time at the center of the IFOV footprint
longitude	1, 32-bit float	✓	✓	✓	✓	✓	Longitude at the center of the IFOV footprint
ltime	1, 32-bit float		✓	✓	✓	✓	Local True Solar Time at the center of the IFOV footprint
m12v	1, 32-bit float	✓					-12 V Supply Voltage.
m5v	1, 32-bit float	✓					-5 V Supply Voltage
max_brightness_temp	1, 32-bit float			✓			Derived from Brightness Temp spectrum. Echoes the maximum temperature in the spectrum (K).
motor_driver_board_temp	1, 32-bit float	✓					Motor Driver Board Temp (Temp 5).
motor_temp	1, 32-bit float	✓					Linear Motor Temp (Temp 3).
nchan	1, 32-bit integer			✓	✓	✓	Number of channels in the voltage spectrum. Differs between 2- and 4-sec scans.
nfov	1, 32-bit float		✓	✓	✓	✓	Derived field based on ang_fov, ang_target, and ang_target_and_fov. How many FOVs away from a limb any particular FOV is. Positive values are off body. 0 or negative values are on-body.

FITS header label	Data Qty, Type	L1a	L1b	L2	L3atm	L3emiss	Description
npts2d	1, unsigned byte	✓	✓	✓	✓	✓	Number of points in 2D FOV boundary polygon.
npts3d	1, unsigned byte	✓					Number of points in 3D FOV boundary polygon.
nsamples	1, 32-bit integer	✓	✓				Number of samples in interferogram. Varies between 2- and 4- second scans and how the linear motor is moving.
offset_cal_res	1, 32-bit float	✓					Calibration Resistor Offset (Temp 16)
on_off	1, unsigned byte	✓					Is IFOV boresight center on-body or off body? 0 = off-body 1 = on-body
one_pps_counter	1, 32-bit integer	✓					Counts the number of 1PPS pulses received. Rolls over after 255.
optical_det_num	1, unsigned byte	✓					Optical detector number (as opposed to electronics order) See EMIRS instrument kernel for how these numbering arrangements compare.
os_pos	1, 32-bit integer	✓					Linear Motor Optical Switch Position
p12v	1, 32-bit float	✓					+12 V Supply Voltage
p1v	1, 32-bit float	✓					+1 V Supply Voltage
p2_5v	1, 32-bit float	✓					+2.5 V Supply Voltage
p3_3v	1, 32-bit float	✓					+3.3 V Supply Voltage
p5v	1, 32-bit float	✓					+5 V Supply Voltage
p5vd	1, 32-bit float	✓					+5 V Digital Supply Voltage
parm_sub_addr	1, 32-bit integer	✓					Sub Commutated Parameter Sub-Address. Identifies the sub commutated parameter block. Estimated cycle time through all parameters is 1 minute.
peak_fringe	1, 32-bit float	✓					Peak to Peak Fringe Analog Signal.

FITS header label	Data Qty, Type	L1a	L1b	L2	L3atm	L3emiss	Description
phase	1, 32-bit float	✓	✓	✓	✓	✓	Phase angle of surface at IFOV center
pnt_mirror_at_home	1, 32-bit integer	✓					Scan Mirror Home, 0 = Not at Home, 1 = At Home.
pointing_mirror_pos	1, 32-bit integer	✓					Current position of pointing mirror relative to 0 (home position). Unit is SIGNED integer.
pps_timer_mode	1, 32-bit integer	✓					Indicates PPS timer mode (oscillator, nominal, pps, command) "0001" oscillator mode "0010" nominal mode "0100" pps mode "1000" command mode
press0	1, 64-bit float				✓		Estimated surface pressure (mbar)(from model, NOT retrieved).
primary_temp1	1, 32-bit float	✓					Primary Mirror Temp (Temp 10).
proc_wd_enabled	1, 32-bit integer	✓					Processor Watchdog Ena/Dis Status, 0 = Disabled, 1 = Enabled, Default is enabled.
prum	1, 64-bit float				✓		Water vapor column abundance (precipitable microns).
prum_quality_flag	1, 32-bit integer				✓		0=Retrieval is bad, 1=Retrieval is good
pwr_cycle_requested	1, 32-bit integer	✓					Byte 31, Bit 4 (unused)
pwr_off_request	1, 32-bit integer	✓					Byte 31, Bit 5 (unused)
quality	1, 32-bit integer			✓			Reserved for spectrum quality flags (currently unused)
quaternion	4, 32-bit float	✓					Hope EMIRS fixed reference frame orientation expressed as a quaternion, relative to mars body fixed frame (does not include mirror or detector orientation)
ra	1, 32-bit float		✓	✓	✓	✓	Right Ascension of the IFOV boresight (J2000)
range_to_ctr	1, 32-bit float	✓			✓		Range (km) from SC to the center of Mars.

FITS header label	Data Qty, Type	L1a	L1b	L2	L3atm	L3emiss	Description
range_to_surf	1, 32-bit float	✓			✓		Range (km) from SC to sub-SC point on surface.
raw_ifgm	2500, 32-bit float	✓					The unprocessed interferogram returned from the instrument.
right_ascension	1, 32-bit float	✓					Right Ascension of the IFOV boresight (J2000)
sample_dir	1, 32-bit integer	✓					: Sample Direction Status, 0 = Samples taken during forward motion (toward beam splitter), 1 = Samples taken during backward motion (away from beam splitter).
sample_timing_mode	1, 32-bit integer	✓					Servo Controller/Sample Timing Status 00 = Closed Loop, Fringe based samples 01 = Closed Loop (tach), Timer based samples 10 = Open Loop, Fringe based samples 11 = Open Loop, Timer based samples
sc_altitude	1, 32-bit float		✓	✓	✓	✓	Spacecraft altitude over Mars' surface (km)
sc_pos	3, 32-bit float	✓	✓				Spacecraft position in Mars-centered body-fixed cartesian coordinates. XYZ, (km)
sc_safed	1, 32-bit integer	✓					SC Safe Status, 0 = SC is nominal, 1 = SC in Safe Mode. This is a copy of the SC Safe Bit from the Spacecraft Status 2Hz command.
sc_stat_cmd_acc_cnt	1, 32-bit integer	✓					Number of accepted spacecraft status commands. Rolls over after 255.
sc_wd_enabled	1, 32-bit integer	✓					SC Status Update Watchdog Ena/Dis Status, 0 = Disabled, 1 = Enabled. Default is Enabled.
scan_period	1, 32-bit integer	✓	✓	✓	✓	✓	Scan Period, 0 = 4 seconds, 1 = 2 seconds. Default is 0 (4 seconds).
sci_data_size	1, 16-bit integer	✓					# bytes in science payload (after compression, if applicable). This number is always divisible by 4. The pad bytes need to be subtracted from this number to arrive at the size of the science data packet.

FITS header label	Data Qty, Type	L1a	L1b	L2	L3atm	L3emiss	Description
sci_packet_length	2, 16-bit integer	✓					Compressed size of the science data (not the entire packet) in bytes. Dependent on compression ratio.
sci_packet_seq_count	3, 16-bit integer	✓					Segment Flag (Bits 1:0) = 0b11 Source Sequence Count (Bits 15:2) = Incrementing count from 0x1 to 16,383 then rolls-over.
sci_pad_bytes	1, unsigned byte	✓					# of pad bytes (0 - 3)
sclk	1, 32-bit integer	✓	✓	✓	✓	✓	Spacecraft clock time corresponding to the start of a scan. Count of seconds since J2000 epoch.
sclk_sub	1, 32-bit integer	✓	✓	✓	✓	✓	Sub-second component of Spacecraft Clock time. Each bit represents 1/65,536 of a second.
searching_for_home	1, 32-bit integer	✓					Found Home Status, 0 = nominal operation, 1 = Searching for home.
servo_pwr_on	1, 32-bit integer	✓					Linear Motor Pwr Status, 0 = Off, 1 = On
spare_temp	1, 32-bit float	✓					Spare Temp (Temp 11).
stepper_motor_offset	1, 32-bit integer	✓					Offset (in steps) between digital home position count and optical switch adjusted home position count. Updated every time the motor is returned to the home position.
stepper_motor_temp	1, 32-bit float	✓					Stepper Motor Temp (Temp 12).
sub_com_param_1	1, 32-bit integer	✓					Sub-Commutated Parameter 1
sub_com_param_2	1, 64-bit float	✓					Sub-Commutated Parameter 2
sub_com_param_3	1, 32-bit integer	✓					Sub-Commutated Parameter 3
sub_com_param_4	1, 32-bit integer	✓					Sub-Commutated Parameter 4
sub_com_param_5	1, 32-bit integer	✓					Sub-Commutated Parameter 5
sub_com_param_6	1, 64-bit float	✓					Sub-Commutated Parameter 6
sub_com_param_7	1, 32-bit integer	✓					Sub-Commutated Parameter 7

FITS header label	Data Qty, Type	L1a	L1b	L2	L3atm	L3emiss	Description
sub_com_param_8	1, 32-bit integer	✓					Sub-Commutated Parameter 8
sun_event_ctr	1, 32-bit integer	✓					Sun Event Counter. Increments on each sun event. Rolls over after 15.
sun_fault_event	1, 32-bit integer	✓					Sun Fault Protection Event Status, 0 = No Sun Event, 1 = Sun Event. Default is no event.
sun_vect_prot_enabled	1, 32-bit integer	✓					Sun Vector Fault Protection Ena/Dis Status, 0 = Disabled, 1 = Enabled. Default is Enabled.
sun_vector	3, 64-bit float	✓					Vector to Sun in SC body frame. Cartesian coordinates, distances in km.
sw_cmd_acc_count	1, 32-bit integer	✓					Number of commands software has accepted. Counter rolls over. All commands accepted by SW will also show as an Instrument Accepted Command as well, since they must pass through the HW FPGA. But not all Instrument Accepted Command will increment SW Command Accept Count. See description below for SW Command Reject Count.
sw_cmd_rej_count	1, 32-bit integer	✓					Number of commands software has rejected. Example if a second Data Acq cmd is received while one is running, reject this command.
sw_cmd_rej_echo	1, 32-bit integer	✓					Function Code of last command rejected.
sw_stat_flash_pwr_on	1, 32-bit integer	✓					Software Status Flash Power, 0 = Off, 1 = On
target_range	1, 32-bit float		✓	✓	✓	✓	Distance from SC to target (km)
target_type_num	1, 32-bit integer		✓	✓	✓	✓	Indicates target type. 1 = Space 2 = Internal cal 3 = Otherwise (default)
taudust	1, 64-bit float				✓		Dust column extinction optical depth at 1075 cm-1.
taudust_quality_flag	1, 32-bit integer				✓		0=Retrieval is bad, 1=Retrieval is good

FITS header label	Data Qty, Type	L1a	L1b	L2	L3atm	L3emiss	Description
tauice	1, 64-bit float				✓		Water ice column extinction optical depth at 825 cm-1.
tauice_quality_flag	1, 32-bit integer				✓		0=Retrieval is bad, 1=Retrieval is good
temp	20, 64-bit float				✓		Array of retrieved atmospheric temperatures. The 19 values are temperatures every 0.25 pressure scale heights beginning at 0.25 and ending at 4.75 scale heights above the surface. The profile is oversampled. Actual vertical resolution is roughly 1–1.5 scale heights.
temp_quality_flag	1, 32-bit integer				✓		0=Retrieval is bad, 1=Retrieval is good
time_upd_cmd_acc_cnt	1, 32-bit integer	✓					Number of accepted time update commands. Rolls over after 255.
utc	23, ASCII characters	✓	✓	✓	✓	✓	UTC string corresponding to the start of the scan. Converted from sclk time.
vspec	700, 32-bit float		✓				Voltage spectrum (frequency domain Fourier transform of the raw interferogram)
wateruncert	1, 64-bit float				✓		Estimated uncertainty in water vapor abundance.
x2d	30, 32-bit float	✓	✓	✓	✓	✓	Longitudes of the points defining the 2D IFOV boundary polygon. (degrees)
x3d	30, 32-bit float	✓					Longitudes of the points defining the 3D IFOV boundary polygon. (degrees)
xaxis	700, 32-bit float		✓	✓	✓	✓	Wavenumber of each instrument channel (cm^-1)
y2d	30, 32-bit float	✓	✓	✓	✓	✓	Latitudes of the points defining the 2D IFOV boundary polygon. (degrees)
y3d	30, 32-bit float	✓					Latitudes of the points defining the 3D IFOV boundary polygon. (degrees)
z3d	30, 32-bit float	✓					Radii (in km from Mars barycenter) of the points defining the 3D IFOV boundary polygon.
zdust	1, 64-bit float				✓		Height of the top of the dust that was used in retrieval.

FITS header label	Data Qty, Type	L1a	L1b	L2	L3atm	L3emiss	Description
zh20	1, 64-bit float				✓		Water vapor condensation level used in the retrieval.
zpd	1, 32-bit float		✓				Zero Path Difference (when the two paths through the interferometer are equal). Expressed in terms of sample number (out of all nsamples) of the interferogram.

Appendix B - FITS File Contents for L3-Gridded Products

Each L3 gridded product presents a rasterized or gridded map of some derived atmospheric quantity, combining observations between some specified local time of day, and spanning some time range. The individual measurements that match these constraints are interpolated and smoothed using convolution and kernel density estimation techniques. This is performed using Astropy's `convolve` and `Gaussian2DKernel` algorithms. The resulting interpolated map has a uniform grid of lat-lon points with a resolution of 2 pixels per degree.

The atmospheric quantity being mapped can be the optical depth of dust or ice (each unitless), or water vapor column abundance (in μm). Currently, the products are generated based on daytime only, spanning from morning to evening. In the near future, products will be created based on the local time of the day.

To build up a complete map in each local time bin, observations over several days are combined. Current products use a time range of one EMM orbit, approximately 55 hours.

The PrimaryHDU part of the FITS file contains the gridded map data, formatted as a 2D array of values, i.e., a standard FITS image. The metadata associated with each product is saved in HDU table format, and is described in the following table.

Table 5: FITS data product contents. Column 1 gives the FITS header label associated with an item, column 2 describes the data type, and column 3 gives a brief description of the label.

FITS header label	Data Type	Description
Tsurf	1, 64-bit float	Best estimate of surface temperature
Date	ASCII characters	Date on which the FITS file was created
Param	String	Parameter that is interpolated (taudust, prum, tauice)
Qualflag	1, 32-bit integer	Quality flag of the interpolated parameter. Qualflag = 0 implies bad retrieval and Qualflag=1 implies good retrieval
lon_min	1, 32-bit float	Minimum longitude [degrees]
lon_max	1, 32-bit float	Maximum longitude [degrees]
lat_min	1, 32-bit float	Minimum latitude [degrees]
lat_max	1, 32-bit float	Maximum latitude [degrees]
cent_lon	1, 32-bit float	Center longitude [degrees]
ls_min	1, 32-bit float	Minimum solar longitude [degrees]
ls_max	1, 32-bit float	Maximum solar longitude [degrees]
Orb_min	1, 32-bit int	Minimum EMM orbit number
Orb_max	1, 32-bit int	Maximum EMM orbit number
Data_min	1, 32-bit float	Minimum value of the data
Data_max	1, 32-bit float	Maximum value of the data
UTC_min	ASCII characters	Minimum UTC time
UTC_max	ASCII characters	Maximum UTC time
Loct_min	1, 32-bit float	Minimum local time [hours]
Loct_max	1, 32-bit float	Maximum local time [hours]
Em_A_Min	1, 32-bit float	Minimum emission angle [degrees]

FITS header label	Data Type	Description
Em_A_Max	1-, 32-bit float	Maximum emission angle [degrees]
In_A_Min	1, 32-bit float	Minimum incidence angle [degrees]
In_A_Max	1, 32-bit int	Maximum incidence angle [degrees]
Sigma_ga	1, 32-bit int	Gaussian smoothing value
BTMP_min	1, 32-bit Int	Minimum brightness temperature [Kelvins]
BTMP_max	1, 32-bit Int	Maximum brightness temperature [Kelvins]
Det_num	1, 32-bit Int	Detector number