The CRISM Investigation and Data Set from the Mars Reconnaissance Orbiter's Primary Science Phase

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Abstract

The CRISM investigation during the Mars Reconnaissance Orbiter's Primary Science Phase was a comprehensive investigation of past aqueous environments, structure of the planet's crust, past climate, and current meteorology. The measurements taken to implement this investigation included over 9,500 targeted observations of surface targets taken at spatial resolutions of better than 40 m/pixel, monitoring of seasonal variations in atmospheric aerosols and trace gases, and acquisition of a 200 m/pixel map covering over 55% of Mars in 72 selected wavelengths under conditions of relatively low atmospheric opacity. Here we describe CRISM's science investigations during the Primary Science Phase, the data sets that were collected, and how they have been processed and made available to the scientific community.
1. Introduction

The Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) is one of six major science instruments on the Mars Reconnaissance Orbiter (MRO), along with the High-Resolution Imaging Science Experiment (HiRISE) [McEwen et al., 2007], the Mars Color Imager and Context Imager (MARCI and CTX) [Malin et al., 2007], the Mars Climate Sounder (MCS) [McCleese et al., 2007], and the Shallow Radar (SHARAD) [Seu et al., 2007]. The three primary science objectives of the MRO mission are: (a) to search for evidence of aqueous and/or hydrothermal activity, (b) to map and characterize the composition, geology, and stratigraphy of surface deposits, and (c) to characterize seasonal variations in dust and ice aerosols and water content of surface materials, recovering science lost with the failure of the Mars Climate Orbiter. Its two secondary objectives are (d) to provide information on the atmosphere complementary to the reflown MCO investigations, and (e) to identify new sites with high science potential for future investigation. MRO has completed its Primary Science Phase (PSP), which lasted from November 2006 to November 2008. During that time the spacecraft operated in a sun-synchronous, near-circular (255x320 km altitude), near-polar orbit with a mean local solar time of 3:10 PM. The observations acquired include a variety of regional to global mapping and atmospheric monitoring campaigns, plus a series of targeted observations in which the spacecraft actively pointed the co-boresighted HiRISE, CRISM, and CTX instruments to measure a series of geologic targets at high spatial resolutions. The mission's objectives, design, and implementation were summarized by Zurek and Smrekar [2007].

In this paper we briefly review the specific objectives of the CRISM investigation during the PSP, the measurement strategies used to address them, and the key results. We summarize the data sets acquired during the PSP, and how they have been processed and made available to the scientific community. We also summarize observational and data product generation plans for MRO's second Mars year of operations, the Extended Science Phase (ESP).
2. Instrument Operation Overview

The CRISM instrument and its operating modes used during data acquisition were described in detail by Murchie et al. [2007a, 2007b]. The following summary provides background for how the instrument hardware capabilities were used in PSP measurement campaigns to address MRO's primary and secondary science objectives, and for the creation of data products from those measurements.

CRISM consists of three assemblies. The largest, the Optical Sensor Unit (OSU), contains optics, detectors, radiators, and a cryogenic system, all of which can be gimbaled, or pivoted, to track Mars' surface. A Data Processing Unit (DPU) provides power, command and control, and data editing and compression, and the Gimbal Motor Electronics (GME) runs the gimbal.

The OSU contains telescope optics that focus light on a slit to form an image one line high and approximately 600 columns wide. After the light passes through the slit, a beamsplitter directs it to two independent grating spectrometers with separate detectors. In each spectrometer, the one-line spatial image is dispersed into its component wavelengths that are re-imaged onto different rows of that spectrometer's detector. One spectrometer, denoted as visible-near infrared (VNIR), uses an array of silicon photodiodes to capture spatial/spectral images covering the wavelengths 362-1053 nm. The other spectrometer, denoted as infrared (IR), uses an array of HgCdTe diodes to take spatial/spectral images at 1002-3920 nm. Both spectrometers sample the spectrum at 6.55 nm per detector row. Both detectors have fixed-mounted filters with two or three wavelength zones, to block higher orders from the grating and, in the case of the IR detector, to attenuate thermal emissions from the spectrometer cavity. Each detector is also wider than the image of the scene; spare columns at the sides of the detectors do not contain scene information, but do detect wavelength-dependent, diffuse scattering of light from the grating that has to be removed during calibration. A cryogenic cooling system maintains the IR detector at -148°C to -163°C to limit noise, and the spectrometer housing is cooled by a passive radiator to -70°C to -78°C to limit thermal background. The temperature of the VNIR detector drifts with that of the spectrometer housing, and typically is -55°C to -65°C.
The DPU provides power and command-and-control, and also data editing capabilities to manage downlink and to establish operating modes for the instrument. To remove smear, an along-track gimbaling capability can be used to track a point on the surface and scan across it slowly. Frame rates of 1, 3.75, 15 and 30 Hz can also be used to manage pixel smear. Data editing capabilities include selection of which wavelength channels are downlinked, and binning of pixels in the spatial direction. The two major choices for the number of wavelengths is the 544 detector rows with useful amounts of scene radiance, or 72 rows selected for their coverage of key wavelengths that separate major mineral phases [Pelkey et al., 2007]. (In each case, one extra detector row is included for calibration purposes.) Spatial binning of pixels can be done using groups of 1, 2, 5, or 10 pixels in the cross-track spectral direction. Pixels are "squared" in the along-track direction by adjusting frame rate and/or the rate of gimbal motion.

CRISM's two basic operating modes are targeted, in which the gimbal is used for image motion compensation, and fixed pointing at spacecraft nadir. In targeted observations the gimbal is scanned to track a point on the surface and prevent smear from motion of the spacecraft. A superimposed scan slowly sweeps the field-of-view across a region approximately 10 km x 10 km over 2-3 minutes to acquire an unsmearred image of a target area. For geologic targets, surrounding the time of closest approach, 350 to 540 image lines are acquired at a frame rate of 3.75 Hz. Spatial sampling is 18 m/pixel using no spatial pixel binning, or 36 m/pixel for 2x binning. Ten to twelve additional abbreviated, 10x spatially binned images are taken before and after the main image, providing measurements of the same scene with different path lengths through the atmosphere. This sequence of multiple measurements at different geometries is called an emission phase function, or EPF. When analyzed using a radiative transfer model that incorporates a model of surface scattering and wavelength-dependent attenuation by atmospheric gases and aerosols, an EPF allows separation of atmospheric and surface radiances. For investigation of the atmosphere, the central image can also be 10x binned to minimize data volume. All targeted measurements are taken in 544 wavelength channels covering 0.36-3.92 microns with 6.55 nm spectral sampling. The eleven to thirteen spatial images taken during the gimbal's tracking of a target constitute a single, multi-image observation.
CRISM can also build up images using passive, fixed pointing, and this is done in either of two ways. First, images are acquired at 15 Hz with 10x spatial pixel binning, or 30 Hz with 5x spatial pixel binning, yielding pixel footprints of 200 or 100 meters respectively. When it operates in this mode, CRISM returns data from only 72 wavelengths. The 200 m/pixel mode is used almost exclusively to map Mars globally, or to "ride-along" with MRO's other cameras when the available downlink or a crowded observing schedule limits the number of targeted observations. Second, data can be taken at a lower frame rate of 3.75 Hz using 10x spatial pixel binning and all 544 wavelengths. The mode of operation measures a 10x10 km spot hyperspectrally with minimal data volume and is used to monitor atmospheric gases.

Internal instrument calibrations are taken interleaved with and as part of all observations. An internal shutter is closed to take dark measurements (of IR background due to emission inside the instrument) every 3 minutes. One or more times daily a sequence of dark images is taken at different exposure times to estimate the "bias," or response of the IR detector to zero input photons. Also multiple times daily, an onboard, closed-loop controlled integrating sphere is measured to provide a snapshot of the detectors' time-variable responsivity to input radiance. During the PSP, in addition to the background measurements acquired as part of 35,735 observations of Mars' surface and atmosphere, and additional 6,523 free-standing calibration observations were obtained.
3. Science Objectives and Measurement Strategy

As described by Murchie et al. [2007a], CRISM addresses all five of MRO's primary and secondary objectives using its ability to measure absorption features diagnostic of the primary igneous minerals olivine and pyroxene, their alteration products including phyllosilicates, zeolite, sulfate, carbonate, and silica, and the atmospheric trace gases CO, H₂O, and O₃. For surface measurements, the instrument's capability for high spatial resolution enables resolving mineralogic differences over ~40-meter scales. The mapping of MRO's primary and secondary objectives to CRISM's objectives, the series of measurement campaigns used to address those objectives, and key results from the PSP are summarized in Table 1.

During the PSP, CRISM used three distinct measurement campaigns to address its science objectives. These are described in Table 2. The first campaign was acquisition of a global, 200 m/pixel, 72-wavelength map. This data set, known as the "multispectral survey," shows the distribution of major crustal components at about fives times the average spatial resolution of the OMEGA data set [Bibring et al., 2005], and allows identification of previously undiscovered exposures of aqueous minerals and their follow-up investigation at high spatial resolution. The gimbal is pointed at nadir, data are collected at a frame rate of 15 Hz, and spatial pixels are binned cross-track by 10x yielding a data set with ~200 m/pixel spatial sampling. During the PSP approximately 63% of the planet was covered using 15,855 multispectral survey observations, each consisting of one or more image strips acquired over a 3-minute or shorter duration (to allow interspersing of background measurements). File names of data products generated from these observations all begin with the character string "MSP." Part of these data were acquired during the 2007 global dust event. Excluding those data most affected (from the period 25 June 2007 through 29 September 2007), a total spatial coverage of just over 55% was obtained and is illustrated in Figure 1.

The second measurement campaign was the atmospheric survey, whose objective was to characterize seasonal variations in the total columns abundances of atmospheric dust and ice aerosols and trace gases including CO, H₂O, and O₃, and seasonal variations in the water content
of surface materials. This campaign was intended to complement daily maps of the spatial
distributions of aerosols and trace gases by MCS. At the beginning of the PSP, the atmospheric
survey consisted of repetitive global grids of EPFs. A dense grid was taken over about a two-
week period in six parts, every ten weeks. In each of the six parts the along-track spacing
between EPFs was about 22°, and the groundtracks were 54° of longitude apart (six or seven
terminator-to-terminator sequences of EPFs were taken every other orbit for one Mars sol). The
six parts, or sols, were staggered both in longitude and time to yield 11° latitude sampling and 9°
longitude sampling. The exact repeat times of this pattern every ten weeks were selected to
provide repetitive coverage of surface coordinates to within ±50 km, and SHARAD
measurements were taken simultaneously to track changes in surface dielectric properties as
surface water content changed. Between the ten-week repeats, two other groups of two Martian
sols were similarly devoted to EPFs on every other orbit, with each group of two sols providing
about 27° longitude sampling of the atmosphere. Thus, on average, a grid of EPFs sampled the
atmosphere about every 5° of solar longitude (Ls), and the dense grids on ten-week repeats
provides sampling every ~36° of Ls. Over the course of the PSP 3,828 gimbaled observations
consisting solely of 10x-binned EPFs were taken as part of these grids. File names of data
products generated from these observations all begin with the character string "EPF." At times of
high MRO data downlink rates, selected observations within the grids were upgraded to higher
spatial resolution targeted observations.

Early in the PSP, MCS suspended regular nadir measurements and focused on another of its
measurement objectives, limb profiles, eliminating the high spatial- and temporal-frequency
measurements of trace gas abundances that were initially assumed to complement EPF
measurements. To replace this vital complementary measurement set, a new CRISM operating
mode was defined using existing instrument capabilities. Beginning at Ls 290°, short bursts of
nadir-pointed measurements using all 544 wavelengths and 10x spatial binning were acquired
during times when no other observation type was being taken, to sample a 10x10 km region
every 2° of latitude along track. These samples provide a capability to estimate column
abundances of trace gases, but without an emission phase function the accuracy is less, and dust
opacity cannot be uniquely retrieved. Through the end of the PSP, 3,784 observations consisting
of sequences of the bursts were taken. File names of data products generated from these
observations all begin with the character string "TOD." Figure 2 shows the latitude and Ls
distribution of atmospheric survey measurements during the PSP; the addition of TODs
dramatically improved spatial and temporal sampling of trace gas variations.

CRISM's third (and its primary) measurement campaign was to identify and map the distribution
of key minerals at high spatial resolution, at thousands of high priority targets including
candidate sedimentary deposits, volcanic regions, crustal sections exposed in steep escarpments,
and sites which exhibit evidence for concentrations of aqueously formed minerals. This was
accomplished using targeted observations with unbinned or 2x-binned central images. Binning
was used in some cases to conserve downlink, and in other cases to allow acquisition of a longer
central image (10x20 km) in the same amount of time, when areal coverage was deemed more
important than spatial resolution. The regions of interest selected for targeting were initially
compiled from mineralogical exposures identified by OMEGA, TES, and THEMIS, formations
with light-toned layering identified in MOC and THEMIS images, and sites for polar monitoring
identified from OMEGA, THEMIS and MOC data. Later, regions of interest identified in CTX
images and in CRISM's multispectral survey were also targeted. File names of data products
generated from targeted observations being with the character string "FRT" if the central image
is unbinned, "HRS" if it is 2x-binned but comparable in size, or "HRL" if 2x-binned and
extended in length along-track. During the PSP 9,514 targeted observations were acquired of
which 6,674 were FRTs, 1,905 were HRLs, and 935 were HRSs. Their locations are shown on a
MOLA elevation map in Figure 3. Targeted observations are globally distributed, but
concentrated in areas with previously known exposures of aqueous mineralogy including Valles
Marineris, Terra Meridiani, and the regions around Mawrth Vallis and Nili Fossae.
4. Data Product Generation

The processing of CRISM data into data products delivered to the Planetary Data System (PDS) is shown schematically in Figure 4. Data products in PDS-compliant formats are generated in near-real time and delivered every three months. Two types of products are delivered, "standard products" produced for all observations, and "special products" generated on a best-effort basis.

4.1. Radiometric and Geometric Calibration

Mars scene images are calibrated to I/F in eight major steps, using the accompanying and interleaved instrument calibrations as well as ground-based calibrations. More detail is provided by Murchie et al. [2007a, 2007b]. In each case, scene data are processed using a time-weighted average of the internal calibrations having the same frame rate, that are taken close in time and bracketing the time of a scene measurement.

1) The component of the raw data numbers (DNs) due to counted phones photons values is isolated and is corrected for the slightly non-linear response of the detectors. To do this, for the IR detector, the DN levels are extracted from measurements taken during daily bias calibrations at multiple exposure times. For each detector element the measurements are fit linearly and the zero exposure-time intercept is taken as the bias, or response of the detector to zero photon inputs. The bias estimate is subtracted from shutter-closed background measurements, sphere measurements, and scene measurements. In each case the result is divided by the non-linear response of the detector as a function of DN that was measured on ground. The result is a value in units of corrected DN that is proportional to counted photons. For the VNIR detector, the operating temperature is sufficiently low that shutter-closed background measurements sample only bias without measurable dark current, so the background measurements are used instead to estimate bias.

2) For the IR detector only, bias-corrected and linearized DNs from interleaved background measurements are subtracted from similarly corrected scene and integrating sphere
measurements. This step removes internal emissions of the spectrometer cavity that illuminate the IR detector.

3) For both detectors, bias-, linearity-, and background-corrected scene and sphere data are divided by exposure time, yielding a result that is proportional to measured radiance.

4) For both detectors, at each row, the scattered light from the grating that is measured in dedicated columns at the edge of the scene and sphere images is subtracted from the data.

5) For both detectors, sphere measurements are divided by a ground-based model of the sphere's spectral radiance, yielding a measure of responsivity of each detector element. That responsivity is time-variable, and affected by detector temperature and temperature-dependent transmissivities of the beam splitter and of the detector-mounted filters. However at VNIR wavelengths <560 nm the transmissive optics are spectrally featureless and the integrating sphere has low spectral radiance, so a ground-based measurement of responsivity is used instead.

6) The processed scene data are divided by the responsivity model, yielding estimated scene spectral radiance.

7) Residual calibration non-uniformity is removed using a "flat-field" correction. Scene measurements are in principle flat-fielded using the radiometric model of the onboard integrating sphere, but there are artifacts in that model at the scale of one to several detector elements. To remove these, a flat-field image was constructed from multiple measurements of bland, dusty regions of Mars, whose radiances were normalized to unity at each wavelength. The radiances of other scenes are divided by the flat-field to correct the propagated artifacts.

8) Flat field-corrected scene radiances are divided by a solar spectrum convolved through CRISM's bandpasses measured onground, scaled to Mars' solar distance, yielding I/F.

Pointing calculations and geolocation are done on a pixel-by-pixel basis. Latitude and longitude are calculated for each pixel using the line-of-sight intercept of the field-of-view with the MOLA shape model of Mars. Photometric angles are evaluated relative both to the shape model and relative to the MOLA areoid. Ancillary data useful for further processing steps, including MOLA slope and slope azimuth, and TES bolometric albedo and thermal inertia, are resampled from
publicly released data sets into the non-map projected sensor space of each detector element in
the radiance and I/F data.

The results of these steps are four complementary data sets containing raw data and the
calibration files needed to process them, as well as data calibrated using the best algorithms
available at the time of processing:

- Experiment Data Records, or EDRs, contain raw images taken either as scene measurements
  or during internal calibrations.
- Targeted Reduced Data Records, or TRDRs, contain hyperspectral image data for all types
  of scene observations, calibrated to units of radiance and I/F.
- Derived Data Records, or DDRs, contain image planes with the latitude, longitude,
  photometric angles, and other information for each image pixel in the TRDRs. The latitude
  and longitude support map projection of the TRDRs, whereas the photometric angles and
  ancillary information support correction of the TRDRs for illumination and atmospheric
  effects.
- Calibration Data Records, or CDRs, contain the vectors and matrices used to process data
  from raw form, including those derived from in-flight calibrations as well as ground-derived
  values. The calibration process is obviously complicated and users are not recommended to
  attempt to redo processing to the TRDR level themselves; rather, this is for archival
  purposes to assist in diagnosing artifacts in the calibrated data.

4.2. Additional Radiometric Corrections

The most basic step in further processing of data calibrated to I/F is a correction for illumination
effects and for attenuation by atmospheric gases. Three methods have been developed for this
purpose. The first method, the "volcano scan correction," is the correction typically applied to
single targeted observations. The data are divided by the cosine of the solar incidence angle and
by a scaled atmospheric transmission spectrum obtained during an observation crossing Olympus
Mons [Bibring et al., 2005; Mustard et al., 2008]. This corrects for atmospheric gases but not
aerosols. All of the information required for this operation is included with the data set delivered
to the PDS. I/F comes directly from TRDRs, and solar incidence angles from the DDRs. The
scaled atmospheric transmission spectrum and an explanation of its application are included as files formatted as CDRs, whose nomenclature begins with the string "CDR4_AT." There are separate versions for each instrument configuration, as explained in documentation accompanying the delivered data. (A similar set of files containing the wavelengths for each detector element, used in spectral data analysis, has a nomenclature that begins with the string "CDR4_WA." )

The second atmospheric/photometric correction method, the "Lambert albedo correction," is applied during standard processing to mosaics of multispectral data acquired over a range of atmospheric and illumination conditions. That method is discussed in more detail in section 4.4. The third method is applied to selected targeted observations. Using the climatological values of atmospheric gas and aerosol abundances discussed in section 4.4 as a starting guess, DISORT is run iteratively to model both surface and atmospheric radiances to minimize atmospheric gas bands, and Lambert albedo is retrieved.

4.3. Data Accuracy and Precision

4.3.1. Radiometric Calibration

The goals for radiometric calibration accuracy developed for CRISM prior to MRO launch were:

a) 10% absolute accuracy at 630 nm (to support mixture modeling using laboratory spectra);
b) 1% relative accuracy, comparing 0.45 and 0.75 μm (to measure the decrease in reflectance below 0.8 μm due to ferric iron);
c) 0.5% relative accuracy, for adjacent channels near 1 μm (to measure the 1-μm absorption due to ferrous and ferric minerals);
d) 0.25% relative accuracy, for adjacent channels near 2.3 μm (to measure absorptions due to phyllosilicates, hydrated silica and sulfates, and carbonates); and
e) 1% relative accuracy, comparing 1.6 μm vs. 2.5 μm and 2.5 vs. 3.1 μm (to measure spectral continuum, pyroxene absorption bands, and depth of the 3-μm H2O absorption).

Attainment of these goals was evaluated over the VNIR wavelength range by comparing CRISM data with simultaneously acquired PANCAM measurements of large, uniform areas at the MER
landing sites (e.g., "Cliff Hanger" in Fig. 19 of Arvidson et al. [2008]). Over the IR wavelength range it was evaluated by comparison of CRISM data with OMEGA measurements of the same sites. In both cases, corrections for photometric and atmospheric effects were made to simulate OMEGA or PANCAM data at CRISM geometry. In the comparison of CRISM's VNIR wavelength range with PANCAM data, goal "a" (absolute calibration) is met, and goal "b" (spectral slope at 0.45-0.75 μm) is close to being met. The relative accuracy of wavelengths near 1 μm does not meet goal "c" and is closer to 1%. Systematic channel-to-channel variations appear in multiple scenes and may be attributable to errors in the radiometric model of the integrating sphere; reduction of these artifacts is currently being pursued. The relative accuracy channel-to-channel near 2.3 μm either meets or is close to goal "d," 0.25%.

Comparisons of OMEGA data with an earlier version of calibrated of CRISM data indicated systematic differences between the two data sets in continuum slope at >1.5 μm (goal "e") as well as recurring, systematic features near 1.85 μm and 2.55 μm. To address these, CRISM observations of Deimos were acquired and compared with ground-based measurements across CRISM's wavelength range [Lynch et al., 2007]. Deimos is an ideal calibration target because its spectrum is smooth, and the Deimos measurements showed the same features as suggested by the OMEGA data. They were tracked down to two systematic issues during ground calibration, incomplete removal of atmospheric water vapor from the spectra of the ground calibration standard used for the integrating sphere, and to a small pointing error at the standard which slightly vignetted it in the ground measurements (affecting how the multi-zoned gratings were sampled in the ground measurements). Corrections for both effects were derived from first principles of instrument performance, and applied to a newer version of the calibration.

The current version of TRDRs being released to the PDS is "version 2." Four known issues in version 2 are being investigated, and will be addressed in "version 3" or later versions. The first issue is systematic channel-to-channel variations, discussed above. The second issue is temporal drift in wavelength calibration, that is, the mapping of detector rows to wavelengths. Seasonal variations in optics temperatures introduced a time-dependent variation in CRISM's wavelength calibration about 1 nm in magnitude (0.15 detector rows) [Smith et al., 2009]. The inaccuracy in wavelength calibration results in errors in removal of CO₂ gas absorptions, and elevation-
dependent errors in the 2-μm wavelength region in atmospherically corrected data. The resulting artifact introduces error into 1.9- to 2.1-μm absorptions due to ices and bound water. The time-dependent wavelength calibration has subsequently been characterized with an accuracy of about 0.13 nm, largely removing this effect. The third issue is high time-frequency variations in detector bias, or "noisy pixels," which affect up to a couple percent of the IR detector elements. In spatial images at some wavelength, this appears as streaks, and the effect is worse and affects more detector elements at higher detector temperatures. The effects of these bias variations is being addressed using data filtering techniques currently in development. The fourth issue is a spurious peak or trough near 3.18 μm that appears in parts of the field-of-view, intermittently. It is believed to be another manifestation of incorrectly removed detector bias and is also being investigated.

Three other radiometric calibration issues are so integral to the data that further corrections are not likely. The first of these latter issues is incomplete removal of grating scatter at <0.44 μm. At these wavelengths, for most Mars scenes, radiance is low and strongly affected by residuals from the correction for grating scatter. The next issue is high spectral-frequency oscillations at >3300. These are due to a Fabry-Perot effect in the zone of the detector-mounted filter that blocks out-of-order light at >2.7 μm. Small variations in that filter's temperature (thickness) between observations of Mars and of the internal integrating sphere cause ~5% oscillations in system response as a function of wavelength not to cancel out. The final issue is leakage of light though boundaries of different zones of the detector-mounted filters. This leakage is scene-dependent and cannot be accurately estimated and removed.

Given the various issues outlined above, some guidelines can be prescribed for reliability of the radiometric calibration at different wavelengths. The following channels can be routinely excluded:

• VNIR: wavelengths less than 410 nm, between 644 and 684 nm, and greater than 1023 nm.
• IR: wavelengths less than 1021 nm, 2694 and 2701 nm, and greater than 3924 nm.
• IR wavelengths surrounding 3180 nm where a large spectral peak or trough is observed.
The following channels may be degraded in their accuracy in some observations, but intra-scene variations appear to be valid. In other words, information from the following channels can be recovered by ratioing to some spectrally bland part of the same scene, preferably in the same column(s) of an image.

- VNIR wavelengths less than 442 nm (due to artifacts from the correction for grating scatter, in very contrasty scenes).
- VNIR wavelengths greater than or equal to 970 nm and IR wavelengths less than 1047 nm (the radiances misalign between detectors; the reason is speculated to be uncorrected effects of beamsplitter temperature).
- IR wavelengths 2660-2800 nm (the reason is uncertain but may be due to problems with correction of water vapor in measurements of the ground calibration standard).
- IR wavelengths greater than 3700 nm (there is a scene-dependent turndown in radiances beyond 3700 nm due to unknown causes)

4.4.2. Geometric Calibration

The goal for accuracy in projection of CRISM data onto the MOLA shape model was 600 m. That goal was derived from an error estimate including expected knowledge of gimbal pointing, spacecraft position and attitude, and Mars cartographic control. In practice overlapping images have typically mosaicked with errors of 200 m or less indicating superior performance of all aspects of MRO and CRISM pointing.

4.4. Assembly of Map-projected Multispectral Data

Data taken as part of the multispectral survey are processed further, applying an estimated correction for atmospheric and photometric effects, mosaicking the image strips, and calculating spectral parameters that give an overview of the data content. The assembled map is divided into 1,964 separate tiles, each covering 5° in latitude with an approximately square outline.
4.4.1. Correction for Atmospheric and Photometric Effects

The procedure for correcting multispectral survey measurements for atmospheric and photometric effects is described in detail by McGuire et al. [2008]. The correction is done using three external, pre-generated, hyperdimensional look-up tables. Using the latitude, longitude, elevation, Ls, and local solar time for a pixel extracted from the appropriate DDR, the column abundances of atmospheric gases and aerosols are retrieved from a "climatology" look-up table ("ADR_CL") that represents average conditions from previous Mars years measured by TES. Next for the latitude, Ls, surface slope azimuth and magnitude, and TES bolometric albedo and thermal inertia retrieved from the DDR and the dust and ice aerosol opacities retrieved from the ADR_CL, surface-temperature for the pixel is retrieved from another look-up table ("ADR_TE"). Finally, for an I/F at some wavelength from the scene data, and values retrieved from the corresponding pixel location in the DDR and from the ADRs, a multiplicative correction that was pre-computed using DISORT [Stamnes et al., 1988] is retrieved from a third look-up table ("ADR_AC") and applied. The output, "Lambert albedo," is an estimate of the surface I/F for hypothetical normal illumination and viewing geometry in the absence of an atmosphere.

4.4.2. Calculation of Summary Products

Summary products are described by Pelkey et al. [2007] and represent spectral indices indicative of the occurrence of different mineral phases and atmospheric constituents. Summary products may also be affected by dependencies on solar incidence angle, surface slopes, atmospheric conditions, detector artifacts, and response to phases other than what the products were intended to show. Still, the the summary products are useful as a guide indicating regions of possible mineralogic interest where further spectral analysis may be conducted to positively identify mineral phases.

45 summary products are currently routinely calculated from CRISM data, and are described by Murchie et al. [2007b]. 2 are Lambert albedos at reference wavelengths. Thirty-two, which are calculated from Lambert albedo, represent spectral ratios or band depths possibly indicative of
absorptions due to H2O and CO2 ices, Fe minerals, sulfates, phyllosilicates, or additional phases such as carbonates. Eleven more, calculated from I/F without additional corrections, represent spectral ratios or band depths indicative of atmospheric aerosols or trace gases. Most of the summary products are based on variations that occupy a few percent or less of the dynamic range at their respectively wavelengths, so noise-reduction filtering is applied to lessen the effects of systematic instrument artifacts that escape correction during calibration.

4.4.3. Construction of Map Tiles

To create a more user-friendly, systematic product, the data are organized into 1,964 separate tiles (Multispectral Reduced Data Records, or MRDRs) that sample the planet's surface at 256 pixels per degree. The resulting map pixel size of 231 m is well-matched to the native resolution and the multispectral survey, and the tiles provide a convenient approach to managing the extremely large data volume (2.6 TB) of the whole map. The full map consists of five parallel data product sets: I/F, Lambert albedo, summary products, and ancillary data for both the I/F and Lambert albedo tiles. The ancillary information provides traceability to source observations (observation number, line and sample in the source product) and their conditions (e.g., photometric geometries and solar longitude). Images are map-projected using nearest-neighbor resampling to preserve values in the original data. The order of stacking is with minimum incidence angle on top, to maximize the area covered at favorable illumination and with a minimum of frost or ice cover. To exclude images obscured by the global dust event of 2007, only observations acquired prior to 25 June 2007 and after 29 September 2007 are used to build MRDRs.

Figure 5 provides an example of the contents of the map tiles, using two tiles (750 and 751) that cover part of Tyrrhena Terra. The I/F version of the tiles (Fig. 5a) retains all of the spectral and spatial variations due to illumination and atmospheric conditions as well as geologic materials on the surface. It provides a useful starting point for alternative corrections to those applied in the data processing pipeline, and its accompanying ancillary data support those corrections. Mapped Lambert albedo (Fig. 5b) exhibits improved continuity between nearby strips of multispectral survey data. However some individual strips mismatch their neighbors where atmospheric
conditions significantly departed from past climatology, and where high solar incidence angles yielded poor corrections. In addition Lambert albedos at <800 nm are spuriously low. This is attributable to the palagonite-based scattering model for atmospheric dust used in the pre-computed corrections. It was found to differ significantly from scattering properties actually measured by CRISM during the 2007 global dust event [Wolff et al., 2007]. The mapped summary products (Fig. 5c) exhibit good cross-track continuity except in strips where the actual atmospheric conditions departed from climatologic averages. Summary products showing mineralogic absorptions at <0.8 \( \mu \)m are inaccurate due to poor corrections for atmospheric dust, and those showing mineralogic absorptions near 2.0 \( \mu \)m exhibit weak artifacts of elevation due to errors in modeling and removing atmospheric CO\(_2\). In the part of Mars shown in Figure 5, most spectral variations are related to differences in the relative strengths of absorptions due to olivine and high-calcium pyroxene. Fe/Mg-phyllosilicates are exposed in crater walls, rims, and ejecta.
5. Plans for the Extended Science Phase

CRISM's investigation during the ESP will build on results from the PSP. Five major goals for targeted observations are to:

- Sample thousands more outcrops identified in the multispectral survey that probe the structure of the Noachian crust and the distribution of aqueous minerals;
- Map the lateral variations in crustal layering exposed in the walls of Valles Marineris;
- Densely sample geologically complicated aqueous deposits (e.g., in Valles Marineris, Mawrth Valles and Nili Fossae);
- Monitor interannual variations in condensation and sublimation of seasonal polar ices; and
- Image targets to support selection and characterization of future landing sites.

Typically, observations will be coordinated with HiRISE and CTX. CRISM will also continue building up multispectral and atmospheric survey observations with the objectives of:

- Filling gaps in the multispectral survey; and
- Continued monitoring of the atmosphere using EPF grids and TODs.

Deliveries of standard data products to the PDS will continue as during the PSP. Two major classes of special products are being developed for release. The first new class of products is a second generation of MRDRs to reduce known data artifacts. The time-dependent wavelength calibration will be incorporated into the correction of multispectral data to Lambert albedo. This update will minimize or remove the 2-μm artifact from inaccurate removal of the atmospheric CO₂ absorption. CRISM and MARCI data are being used together to develop an updated version of the climatology look-up table ("ADR_CL") that represents actual atmospheric conditions during the PSP, rather than a prediction based on climatology. This update will minimize the mismatch of overlapping MSP strips acquired at different times. Finally, scattering properties of atmospheric dust are being updated using results from CRISM EPF measurements, and a second version of the look-up table to correct from I/F to Lambert albedo ("ADR_AC") will yield improved accuracy at <0.8 μm.
Second, an atmospherically corrected and map projected version of targeted observations is being developed for release. These new products will be generated using approaches similar to those used to create MRDRs, with three exceptions:

1) Each map product will show only a single image.

2) The map scale will be 3072 pixels per degree, yielding a map pixel 19.3 meters in scale, which is well-matched to the native resolution of targeted observation.

3) A simplified atmospheric and photometric correction will be employed. Values of I/F are divided by cosine of the solar incidence angle, and by a scaled atmospheric transmission spectrum obtained during observations crossing Olympus Mons [Bibring et al. 2005, Mustard et al. 2008]. This approach corrects for atmospheric gases but not aerosols.
6. References

Arvidson, R.E., S. Ruff, R.V. Morris, D.W. Ming, L. Crumpler, A. Yen, S.W. Squyres, R.J.
Grant, E.A. Guinness, K.E. Herkenhoff, J. Hurowitz, J.R. Johnson, G. Klingelhöfer, K. Lewis,
R. Li, T. McCoy, J. Moersch, H.Y. McSween, S. Murchie, M. Schmidt, C. Schröder, A. Wang,
Columbia Hills, Gusev Crater: Mission overview and selected results from the Cumberland

Bibring, Jean-Pierre, Yves Langevin, Aline Gendrin, Brigitte Gondet, François Poulet, Michel
Berthé, Alain Soufflot, Ray Arvidson, Nicolas Mangold, John Mustard, P. Drossart, and the
OMEGA team (2005) Mars surface diversity as revealed by the OMEGA/Mars Express
observations, Science, 307, 1576-1581.

Mustard, J.-P. Bibring, and the MRO CRISM Team (2007) Sulfates and mafic minerals in
Juventae Chasma as seen by CRISM in coordination with OMEGA, HIRISE and context images,
7th Internat. Conf. on Mars, Abstract #3350.

Bishop J. L., E. Z. Noe Dobrea, N. K. McKeown, M. Parente, B. L. Ehlmann, J. R. Michalski, R.
Phyllosilicate diversity and past aqueous activity revealed at Mawrth Vallis, Mars, Science, 321,
830-833.

Ehlmann, B.L., J.F. Mustard, C.I. Fassett, S.C. Schon, J.W. Head III, D.J. DesMarais, J.A. Grant,
and S.L. Murchie (2008a) Clay-bearing minerals and organic preservation potential in sediments
from a Martian delta environment, Jezero crater, Nili Fossae, Mars, Nature Geosciences, 1, 355-
358.
Ehlmann, B., J. Mustard, S. Murchie, F. Poulet, J. Bishop, A. Brown, W. Calvin, R. Clark, D.


Malin, M. C., J.F. Bell III, B.A. Cantor, M.A. Caplinger, W.M. Calvin, R.T. Clancy, K.S. Edgett,
L. Edwards, R.M. Haberle, P.B. James, S.W. Lee, M.A. Ravine, P.C. Thomas, and M.J. Wolff

investigation of thermal and water vapor structure, dust and condensate distributions in the
atmosphere, and energy balance of the polar regions, *J. Geophys. Res.*, 112, E05S06,

Grant, V.C. Gulick, K.E. Herkenhoff, L. Keszthelyi, R.L. Kirk, M.T. Mellon, S.W. Squyres, N.

Roush, S. C. Cull, K. A. Lichtenberg, S. M. Wiseman, R. O. Green, T. Z. Martin, R. E. Milliken,
P. J. Cavender, D. C. Humm, F. P. Seelos, K. D. Seelos, H. D. Taylor, B. L. Ehlmann, J. F.
surface Lambert albedos for multispectral mapping of Mars with DISORT-based radiative
McKeown, N.K. J.L. Bishop, E.Z. Noe Dobrea, M. Parente, B.L. Ehlmann, J.F. Mustard, S.L.


<table>
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<tr>
<th>MRO science objective</th>
<th>CRISM science objective</th>
<th>Relevant CRISM Measurements</th>
<th>Key Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Search for evidence of aqueous and/or hydrothermal activity</td>
<td>Identify and map mineral deposits indicating the characteristics and distributions of past water environments</td>
<td>Multispectral survey mapping to inventory the distribution and geologic settings of aqueous deposits</td>
<td>At least 10 distinctly classes of deposits with different morphologies, geologic settings, and ages contain concentrations of aqueous minerals.</td>
</tr>
<tr>
<td>Map and characterize the composition, geology, and stratigraphy of surface deposits</td>
<td>Map the distribution of mineral phases indicative igneous and sedimentary rock units</td>
<td>Multispectral survey mapping to provide context</td>
<td>Noachian crust contains a complex stratigraphy of volcanic materials of different composition with phyllosilicate and carbonate-bearing materials. This is superposed by Hesperian-aged hydrated silica- and sulfate-containing deposits.</td>
</tr>
<tr>
<td>Characterize seasonal variations in dust and ice aerosols and water content of surface materials</td>
<td>Monitor spatial and seasonal variation in trace gases and aerosols Monitor formation and ablation of H2O and CO2 ices in the seasonal cap</td>
<td>Regular emission phase functions, in repeating lat./lon. grid Nadir hyperspectral measurements fill time between targeted observations and multispectral survey Regular monitoring of volatile condensation and sublimation at selected circumpolar sites, coordinated with HiRISE and CTX imaging</td>
<td>Spatial and seasonal variations in CO, H2O vapor, O3, and dust and ice aerosols. 2007 global dust event was monitored, and more accurate radiative properties of dust determined. Monitoring of selected polar sites revealed processes of H2O and CO2 condensation and sublimation.</td>
</tr>
<tr>
<td>Provide information on the atmosphere complementary to refloated MCO investigations</td>
<td>Measure record of Mars’ early climate recorded as mineral deposits</td>
<td>High spectral resolution targeted measurements to identify minerals diagnostic of past environments and search for carbonates</td>
<td>A regional occurrence of carbonate rocks traps CO2, but not enough for an early, thick atmosphere. A diversity of hydrated silicate and sulfates phases marks temporal and spatial variations in the near-surface environment.</td>
</tr>
<tr>
<td>Identify new sites with high science potential for future investigation</td>
<td>Identify previously undiscovered sites with a mineral record of past water environments</td>
<td>Multispectral survey mapping at key wavelengths to identify new mineral exposures Follow-up high-resolution coordinated observations by CRISM, HiRISE, and CTX</td>
<td>New classes of deposits discovered include carbonates, hydrated silica, mixed kaolinite/acid sulfates, phyllosilicate-rich deltaic deposits. ~10,000 exposures &gt;1 km² predominantly in Noachian units.</td>
</tr>
</tbody>
</table>

1 Murchie et al., 2009a  
2 Mustard et al. 2008  
3 Bishop et al. 2008  
4 Ehlmann et al. 2008b  
5 Milliken et al. 2008  
6 Murchie et al. 2009b  
7 Bishop et al. 2007  
8 Roach et al. 2009  
9 McKeown et al. 2009  
10 Smith et al. 2009  
11 Wolff et al. 2007  
12 Titus et al. 2008  
13 Grant et al. 2008  
14 Ehlmann et al. 2008a  
15 Wray et al. 2009
Table 2. Descriptions of CRISM’s observation campaigns and the data products generated by them.

<table>
<thead>
<tr>
<th>Observing Campaign</th>
<th>Gimbal Pointing and Number of Images</th>
<th>Observations Type and Description</th>
<th>Data Product Nomenclature</th>
</tr>
</thead>
</table>
| Targeted Observations | Gimbal tracks surface with superimposed scan for each image 1 high-resolution image, 10 reduced-resolution EPF images | Full resolution targeted  
Spatial pixels unbinned for target (18 m/pixel @300 km)  
Spatial pixels 10x binned for EPFs | FRT* |
| | Half resolution short targeted  
Spatial pixels 2x binned for target (36 m/pixel @300 km)  
Spatial pixels 10x binned for EPFs | HRS* |
| | Half resolution long targeted  
Spatial pixels 2x binned for target (36 m/pixel @300 km; 2x swath length as above)  
Spatial pixels 10x binned for EPFs | HRL* |
| Atmospheric Survey | Gimbal track surface with superimposed scan for each image 11 or 13 reduced-resolution images | EPF; spatial pixels 10x binned (~200 m/pixel @300 km)  
9° lon. x 11° lat. grid every ~36° of Ls  
27° lon. x 11° lat. grid every ~5° of Ls | EPF* |
| | Nadir-pointed; multiple images | Tracking Optical Depth  
Spatial pixels 10x binned (200x900 m/pixel @300 km) | TOD* |
| Multispectral Survey | Nadir-pointed; multiple images | Multispectral survey  
73 channels, spatial pixels 10x binned (~200 m/pixel @300 km) | MSP* |
| | | Multispectral windows  
73 channels, spatial pixels 5x binned (~100 m/pixel @300 km) | MSW* |
Figure 1. Coverage by multispectral survey data acquired during the PSP. The data are shown here in Mollweide projection centered at 0° latitude, 0° longitude, with the 0.60-, 0.53-, and 0.44-μm wavelengths displayed in the red, green, and blue image planes.
Figure 2. Coverage of Mars in latitude and Ls by CRISM’s atmospheric survey acquired during the PSP. The values shown are estimated precipitable microns of atmospheric H2O vapor, calculated from several narrow absorptions near 2.6 μm. Coarser sampling prior to Ls 290° is where only EPFs were used, and denser sampling later is when both EPFs and TODs were used. Adapted from Smith et al. [2009].
Figure 3. Coverage of Mars by CRISM targeted observations taken during the PSP, indicated by black symbols overlain on a color-coded MOLA elevation map in which redder colors indicate higher elevations. The map is in equirectangular projection centered at 0° latitude, 0° longitude.
Figure 4. Schematic representation of pipeline processing of CRISM data products delivered to the Planetary Data System.
Figure 5. Examples of the three versions of map-projected multispectral survey data that are delivered to the Planetary Data System, shown overlain on a THEMIS day-IR mosaic. The two tiles shown, 750 and 751, cover part of Tyrrhena Terra. (a) I/F, with 2.53-, 1.50-, and 1.08-µm wavelengths shown in the red, green, and blue image planes. (b) Same as in "a," except that the data have been corrected to Lambert albedo. (c) Summary products with OLINDEX (a measure of the strength of the 1-µm absorption due to olivine) shown in the red image plane, D2300 (a measure of the 2.3-µm absorption due to Fe/Mg-phyllosilicates) in the green image plane, and HCPINDEX (a measure of the strengths of 1- and 2-µm absorptions due to pyroxene) in the blue image plane.