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THE EXOMARS CLIMATE SOUNDER (EMCS) INVESTIGATION.

J. T. Schofield, D. M. Kass, A. Kleinböhl, D. J. McCleese, M. A. Allen, M. C. Foote, M. Jeganathan, *Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA, (John.T.Schofield@jpl.nasa.gov), F. Forget, A. Spiga, O. Talagrand,* *Laboratoire de Météorologie Dynamique, ISPL, CNRS, Paris, France, F. Lefèvre, A. Määttänen,* *Laboratoire Atmosphères, Milieux, Observations Spatiale, Paris, France, T. Fouchet,* *Laboratoire d'Études Spatiales et d'Instrumentation en Astrophysique, Observatoire de Paris, Paris, France, N. Bowles, S. B. Calcutt, P. G. J. Irwin, P. L. Read,* *Atmospheric, Oceanic and Planetary Physics, Department of Physics, University of Oxford, UK, S. R. Lewis,* *Department of Physics and Astronomy, The Open University, Milton Keynes, UK, J. R. Barnes,* *Oregon State University, Corvallis, Oregon, USA, S. W. Bougher,* *AOSS Department, University of Michigan, Ann Arbor, Michigan, USA, R. M. Haberle,* *NASA/Ames Research center, Moffett Field, California, USA.*

Introduction:

The ExoMars Climate Sounder (EMCS) investigation plans to map daily, global, pole-to-pole profiles of temperature, dust, water and CO₂ ices, and water vapor from the proposed 2016 ExoMars Trace Gas Orbiter (EMTGO). The measurements cover all local times, adding a new dimension to data previously obtained from sun-synchronous spacecraft. These profiles are to be assimilated into Mars General Circulation Models (MGCMS) to generate global, interpolated fields of measured and derived parameters such as wind.

Measured and assimilated fields from EMCS clearly delineate the diurnal, day-to-day, and seasonal variation of atmospheric state. Temperature and aerosol fields are essential for characterizing photochemical processes and heterogeneous chemistry, water vapor acts as a key source gas for odd hydrogen (HO_x) photochemistry in the Martian atmosphere, and the wind field is critical for localizing the sources that govern the distribution of trace gases measured by other proposed EMTGO instruments.

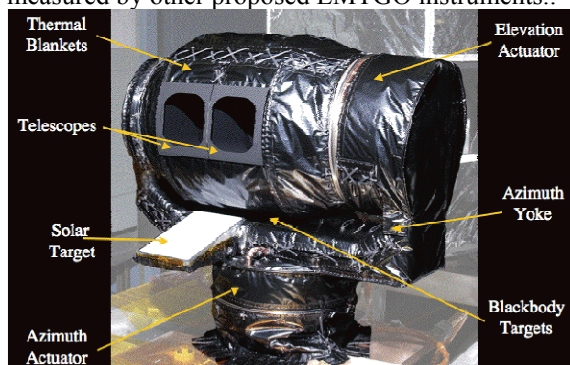


Figure 1 – The MRO/MCS instrument during thermal vacuum testing at JPL

EMCS is a copy of the Mars Climate Sounder (MCS) instrument on the Mars Reconnaissance Orbiter (MRO) spacecraft [McCleese et al., 2007], with low impact modifications to 2 of 9 spectral filters and for interfaces with the proposed EMTGO spacecraft. MCS is now in its 5th year of returning atmospheric profiles from Mars [McCleese et al., 2008]. The MCS flight instrument is shown in Figure 1.

EMCS is an infrared, limb sounding, filter radiometer which uses 9 spectral channels from 12 - 45

µm to address its measurement objectives. EMCS instrument parameters are summarized in Table 1. The 270° elevation/azimuth articulation of the instrument provides full coverage of the downward hemisphere allowing limb observations in all directions and giving daily, global, pole-to-pole coverage of Mars from the $74 \pm 10^\circ$ inclination EMTGO orbit. Uncooled, 21-element, linear thermopile arrays in each spectral channel are the enabling technology of EMCS, permitting atmospheric profiles to be derived from limb staring observations with better sensitivity and geometrical stability than limb scanning.

Table 1 – EMCS instrument parameters.

Parameter	Property/Performance
Instrument Type	Filter Radiometer
Spectral Range & Channels	12 to 45 µm in nine spectral channels
Telescopes	Two identical, 4cm aperture, f/1.7 telescopes
Detectors	Nine, 21-element, linear thermopile arrays at 290 K
Fields-of-View (Limb)	Detector IFOV: 3.3 x 6.2 mrad 5.0x9.4 km Instrument IFOV: 70 x 70 mrad 110 x110 km
Instrument Articulation	Two-axis Az/EI - Range/Resolution: 270°/0.1°
Operation Modes	Single Operating Mode, 2.048 s signal integration period
Observation Strategy	Limb, nadir and off-nadir staring In-track, Cross-track, and Off-track viewing
Mass	11.2 kg (Radiometer + IEM + Mounting Bracket)
Power	18.4 W Mean, (Radiometer + IEM + 10% Actuator)
Data Rate	2150 bps, 186 Mbits/Day, 134 Gbits/Mars Year

Science and Measurement Objectives:

The baseline science and measurement objectives of the EMCS investigation are to:

Enhance understanding of Mars photochemistry by providing daily, global, high vertical resolution fields of atmospheric state, aerosol distribution, and water vapor concentration.

EMCS atmospheric state measurements, combined with data assimilation, characterize the transport, sources and sinks of trace gases measured by the proposed EMTGO. The aerosol measurements reveal the heterogeneous photochemical pathways of trace gases. EMCS plans to map water vapor, the key source gas for odd hydrogen, known to be important in martian photochemistry.

Extend the MRO/MCS climatology of high vertical resolution measurements of the lower and middle atmosphere of Mars, with the improved

coverage of local time provided by the proposed EMTGO.

EMCS would determine the diurnal, seasonal & long-term variability of temperature and aerosol, and its impact on photochemistry. EMCS climatology, combined with earlier data, would relate EMTGO observations to earlier trace gas measurements.

Support future Mars missions with measured climatology and near real-time density profile retrievals for landing and aerocapture, in the same way that MRO/MCS supported the Phoenix landing and is supporting the Mars Science Laboratory (MSL) landing.

EMCS could be the only instrument in orbit able to support Entry, Descent and Landing (EDL) for the proposed ExoMars 2018 Rover Mission.

French and UK Co-Investigators make a key contribution to the EMCS investigation. The European component of the science team assimilates measured atmospheric fields into Mars General Circulation Models. The assimilation scheme is being developed using MRO/MCS data and will provide the derived fields, such as wind, needed to understand the transport, sources, and sinks of trace gases.

Based on the performance of MRO/MCS, and water vapor retrieval simulations, EMCS obtains atmospheric profiles with an accuracy of 1 - 2 K in temperature, $< 0.0001 \text{ km}^{-1}$ in aerosol opacity, and $< 10 \text{ ppm}$ (0.7 pr. μm) in water vapor mixing ratio, with 5 km vertical resolution and 0 - 90 km vertical coverage. This vertical resolution is necessary to resolve important atmospheric structure and to match the high vertical resolution trace gas measurements of the microwave and solar occultation instruments.

The 270° elevation and azimuth articulation of EMCS gives the instrument 360° coverage of the limb. This allows EMCS to compensate for spacecraft yaw and obtain pole-to-pole coverage every orbit, with daily resolution of 3.5° latitude and 30° longitude. By combining in-track limb and nadir observations, retrieved profiles could be extended to the surface over much of the planet.

EMCS measurements are uniquely synergistic with the rest of the proposed EMTGO payload. They would provide daily global fields to supplement the more sparsely sampled solar occultations, and supply the dust and ice opacities not available to microwave measurements. Furthermore, the articulation provided by the actuators allows coincident measurements with occultation, limb, and nadir sounding instruments regardless of their orientation on the spacecraft.

Spectral Channel Selection:

Table 2 summarizes the coverage of the nine EMCS spectral channels, their distribution between the two instrument telescopes, and the primary measurement function of each channel. With the excep-

tion of A6, their functions are identical to those of MRO/MCS. A6 was a broad-band visible channel, designed for polar radiative balance measurements, which cannot be addressed from the 74° inclination proposed EMTGO orbit. It has been replaced by a spectral interval designed to improve low altitude temperature and CO₂ ice extinction profiling.

Table 1 – The response and measurement function of the nine EMCS spectral channels.

Telescope/ Channel #	Bandpass cm ⁻¹	Band Center - μm	Measurement Function
A1	595 - 615	16.5	Temperature 0-30 km
A2	615 - 645	15.9	Temperature 30-50 km, Pressure
A3	635 - 665	15.4	Temperature 50-90 km, Pressure
A4	820 - 870	11.8	Water ice extinction 0-90 km
A5	400 - 500	22.2	Dust extinction 0-90 km
A6	575 - 595	17.1	Temperature 0-15 km, CO ₂ ice extinction 0-90 km
B1	290 - 340	31.7	Dust and ice extinction 0-90 km
B2	220 - 260	41.7	Water Vapor 0-40 km, Dust ice extinction 0-90 km
B3	231 - 243	42.2	Water ice extinction 0-30 km

Original MCS Channels
Substituted for visible channel to enhance temperature and CO₂ ice profile retrievals

Figure 2 compares the four EMCS temperature sounding channels with atmospheric limb emission spectra calculated for five tangent altitudes. The calculations were performed at high spectral resolution by the MCS line-by-line transmission code and were smoothed to 5 cm⁻¹ for clarity. The spectra are dominated by emission from the 15-micron band of CO₂. As noted in Table 2, the channels are optimized for different altitude ranges by placing them at differing opacities in the long-wavelength wing of the band. As the spectroscopy and mixing ratio of CO₂ are well known, these channels allow accurate measurements of temperature. Pressure is also derived from the ratio of A3 and A2 measurements.

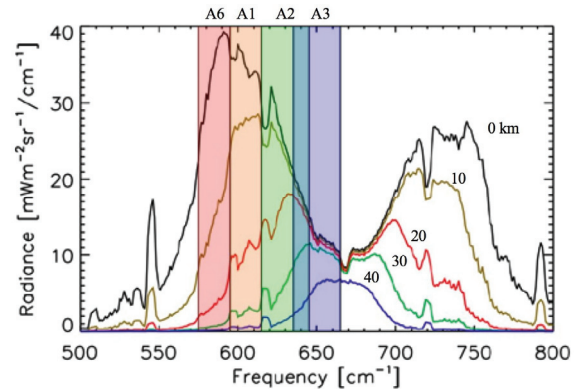


Figure 2 - EMCS temperature sounding channels.

Figure 3 compares the EMCS aerosol sounding channels with extinction efficiency spectra calculated for dust, water ice, and CO₂ ice models. These calculations assume Mie scattering, with particle sizes described by modified gamma distribution functions. The model effective radii are 1.06 μm for dust, 1.41 μm for water ice, and 2.0 μm for CO₂ ice. The strong absorption feature of CO₂ ice is masked by the gaseous CO₂ band but, when the atmosphere is cold, A6 is sensitive primarily to CO₂ ice. The B

telescope channels provide sensitivity to aerosols at higher opacities in the limb path, when A4 and A5 are opaque, and also to water ice at low temperatures when the concentration of water vapor is negligible.

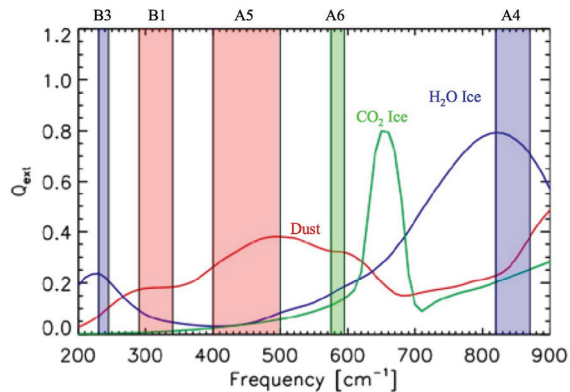


Figure 3 - EMCS dust and ice channels.

Figure 4 compares the EMCS water vapor channels with water vapor limb emission spectra. A constant water vapor volume mixing ratio of 300 ppm is assumed ($\sim 20 \text{ pr.}\mu\text{m}$). The relatively broad channel, B2, contains two strong water vapor emission features, whereas the narrow channel B3 is centered on a window in the water vapor spectrum. These co-centered channels have very similar responses to aerosol opacity, but very different responses to water vapor, allowing the two components to be separated.

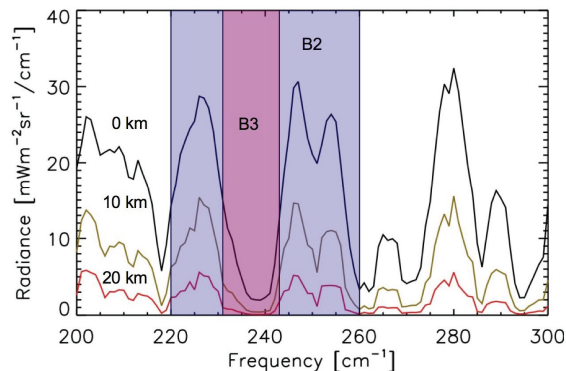


Figure 4 - EMCS water vapor channels.

Limb Staring and Vertical Resolution:

The half scale height (5 km) resolution needed to reveal key atmospheric structure is made possible by limb-viewing geometry and the 5-km field-of-view of the EMCS instrument. Micro-machined thermopile arrays are the enabling technology that allows limb staring. Compared with scanning a single detector across the limb, limb staring provides improved signal-to-noise and greatly reduces the sensitivity of measurements to spacecraft pointing drifts.

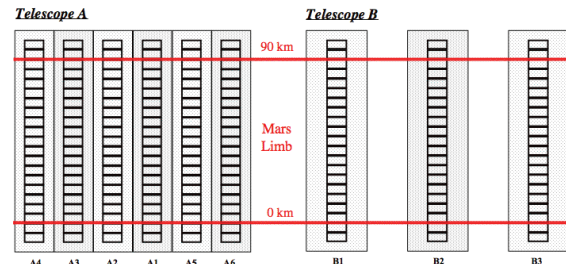


Figure 5 - Nominal EMCS detector fields-of-view.

Figure 5 shows a schematic of the nominal EMCS fields of view projected on the limb of Mars from the nominal 400-km orbit, with the surface and 90 km levels indicated. Both telescopes, including all 189 detectors, are represented. The telescope fields-of-view are coincident, with arrays A4/B1 and A6/B3 superimposed. They are separated for clarity.

The true vertical resolution of each measurement is determined by the limb path through the atmosphere as well as by its geometrical FOV. Figure 6 shows a retrieved MCS temperature profile together with a corresponding set of vertical response or weighting functions for the EMCS temperature sounding channels (Figure 2).

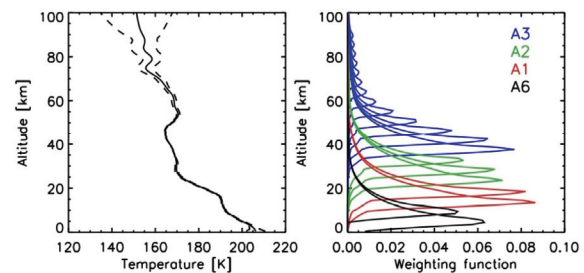


Figure 6 - EMCS weighting functions derived for a retrieved martian temperature profile.

Atmospheric Profile Retrievals:

The retrieval of atmospheric profiles from EMCS radiances is based on a modified Chahine method [Chahine, 1970]. The team of Co-Is at JPL has extensive experience with this technique and its adaptation for limb-viewing radiometers, as the approach has been successfully implemented for MRO/MCS [Kleinböhl et al., 2009]. The retrieval code contains a fast radiative transfer scheme, which includes single scattering of radiation from aerosol. Profiles of temperature, pressure, dust and water ice opacity are retrieved simultaneously. For in-track measurements, retrievals are based on a combination of co-located limb and nadir measurements. The latter provide surface temperature, aerosol and water vapor column quantities, and improved temperature profiles near the surface. For off-track measurements, where co-located nadir measurements are not available, the temperature near the surface can be retrieved with the new A6 channel (Figure 6).

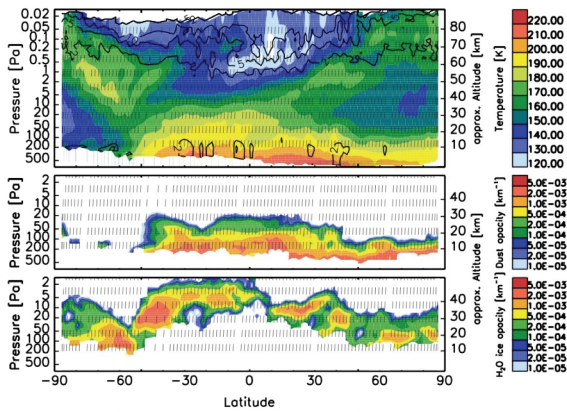


Figure 7 - Transect of MCS temperature (top), dust opacity (middle) and water ice opacity (bottom) retrievals for a single orbit at $L_s = 155^\circ$ (12/23/2006).

Figure 7 shows a nighttime pole-to-pole transect of combined limb-nadir retrievals from MRO/MCS for a single orbit. The dashed lines indicate the individual profiles, and their slope is due to the altitude dependence of tangent point location. Temperature profiles are retrieved up to ~ 90 km altitude with a typical precision between 0.5 and 2 K over most of this altitude range. Errors tend to be larger only at very high altitudes and very low temperatures. Pressure is retrieved to a precision of 1 - 2% at 20 - 30 km, and profiles of dust and water ice extinction achieve precisions of 10^{-4} - 10^{-5} km^{-1} .

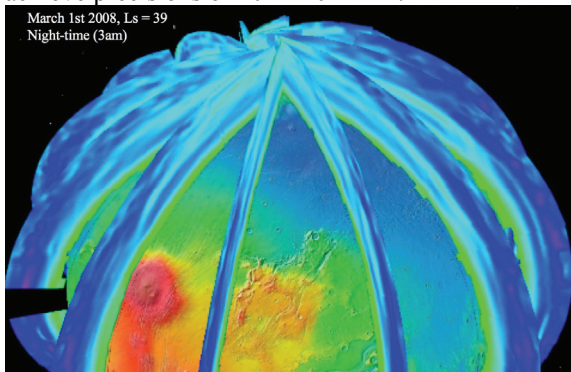


Figure 8 - One day of night-time temperature coverage of Mars from MRO/MCS.

Figure 8 shows 24 hours of MRO/MCS temperature retrievals displayed as curtains overlaid on Mars altimetry using Google Earth. The season is northern spring ($L_s = 39^\circ$) and the curtains show temperatures from 0-80 km with a vertical resolution of 5 km ranging from 120 K (purple) to 200 K (green).

Mission Operations:

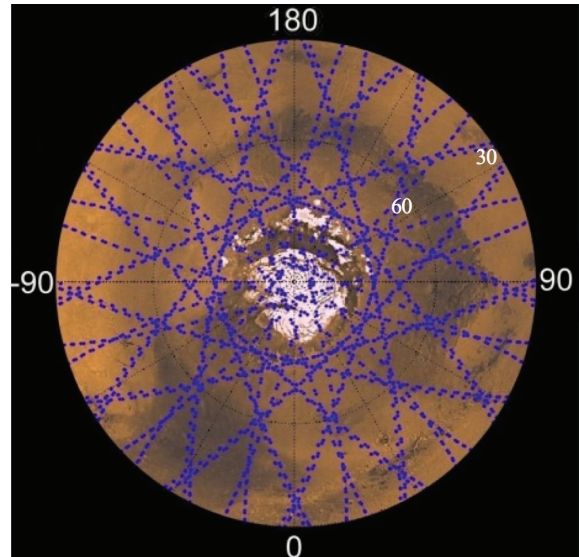


Figure 9 - EMCS 24 hr coverage of the northern hemisphere of Mars from the TGO orbit.

EMCS plans to operate continuously, day and night, from the nadir-oriented spacecraft platform provided by the proposed EMTGO spacecraft. Observational flexibility is supplied by azimuth/elevation scanning, driven by scan tables stored in the instrument and timed relative to an equator crossing time command. Modifications to the observational strategy would be implemented by uploading scan tables, but observations are able to continue indefinitely without commanding.

EMCS observations fall into the following categories. 1) Routine, repetitive, in-track and off-track limb and nadir sounding from pole-to-pole, using the azimuth actuator to compensate for spacecraft yaw. 2) Routine calibration measurements using views of space and the instrument blackbody targets. 3) Campaigns make simultaneous and coincident measurements with other instruments.

An example of the daily global coverage achieved by 1) above, from the 400 km, 74° inclination nominal orbit is shown in Figure 9. In-track observations reach 74°N and measurements made 40° off-track extend to the pole.

Data Products:

The EMCS investigation has a data analysis and archiving plan that builds strongly on MCS heritage. Table 3 summarizes the planned EMCS data products, plans for data generation, validation, reprocessing, and schedules and estimated volumes for delivery to the atmospheres node of the Planetary Data System (PDS). Team members responsible for products are indicated. This effort builds on MRO/MCS operational, software and hardware heritage.

Table 3 – Planned EMCS Data Products

EMCS Data Product Level	Data Description	Information Required	Responsibility for Processing, Archiving, and Documentation	Plans for Generation, Reprocessing, and Validation	EMCS Database and PDS Archive Delivery Schedule	Archive Size 1-Mars Year
Level 0	Unpacked, Time-Ordered, Raw Science and Housekeeping Data	Raw EMCS Science and Housekeeping Packets from SOC	Co-1 Calcutt, PI Schofield	Automated Process, No Reprocessing	Database: Upon Receipt PDS: 1-4 months later	66 Gbytes
Level 1a	Time-ordered Raw Science and Calibrated Housekeeping Data	Level 0 Data	Co-1 Calcutt, PI Schofield	Automated Process, No Reprocessing, Validated during EMCS Ground Testing	Database: After processing PDS: Not Delivered	58 Gbytes
Level 1b	Time-ordered Calibrated Radiances, Housekeeping, and supporting geometry	Level 1a Data, SPICE Kernels & NAIF tools from Project	Co-1 Calcutt, PI Schofield	Automated Process, Full reprocessing as needed, Validation based on analysis of higher order products	Database: After delivery of SPICE Kernels and processing PDS: 1-4 months later	99 Gbytes
Level 2	Time-ordered retrieved atmospheric profiles with supporting geometry	Level 1b Data	Co-Is Kleinböhl, Fouchet, Irwin	Automated Process, Full reprocessing as needed, Validation based on independent data sets	Database: After processing of Level 1b PDS: 1-4 months later	49 Gbytes
Level 3	Global atmospheric fields from the Assimilation Model	Level 2 Data, General Circulation Model for Assimilation	Co-Is Forget, Lewis, Reed	Batch Process, Reprocessing as needed, Validation based on independent models.	Database: As Assimilated fields become available. PDS: 4-7 months later	200 Gbytes

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