

MAPPING SURFACE PRESSURE ON MARS WITH THE MARS EXPRESS OMEGA SPECTROMETER

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Introduction: Surface pressure measurements help to achieve a better understanding of the main dynamical phenomena occurring in the atmosphere of a planet. Recent meteorological studies however pointed out the scarce spatial and temporal coverage of the actual meteorological measurements. An alternative solution can be the remote measurement of surface pressure from orbit. In the present study, reflectances from the Mars Express OMEGA spectrometer in the CO₂ absorption band at 2 μm are used to retrieve surface pressure with a precision sufficient to draw maps of this field, analyze meteorological events in the Martian atmosphere, and provide new inputs to the Martian meteorological models.

Measurement Principle: The absorption by CO₂ of the solar light reflected by the Martian surface can easily be measured, providing a good indicator of the amount of CO₂ in the atmosphere, and thus of the hydrostatic surface pressure (equivalent to the pressure measured by *in situ* barometers if non-hydrostatic vertical motions can be neglected). The CO₂ absorption band at 2 μm never saturates at OMEGA resolution under Martian conditions, but is strong enough to provide a clear signal almost proportional to surface pressure.

To perform the pressure measurement with a maximum accuracy, 25 OMEGA “spectels” affected by CO₂ between 1.8 and 2.2 μm are used. For these 25 spectels, we have developed a complete and accurate forward model (based on a line-by-line radiative transfer model) to simulate an ‘OMEGA-like’ spectrum for any given observing geometry, surface spectrum, atmospheric temperature, aerosol content, and, of course, surface pressure. The surface pressure retrieval is carried out by determining the value of the surface pressure which provides the best fit between the synthetic spectrum and the observed spectrum, with the other parameters being estimated from an external source (temperature, aerosol content) or directly from the OMEGA observations (observing geometry, surface spectrum and albedo). Computational performance of the pressure retrievals is enhanced by the use of multi-dimensional look-up tables. An example of pressure measurement is given in figure A.

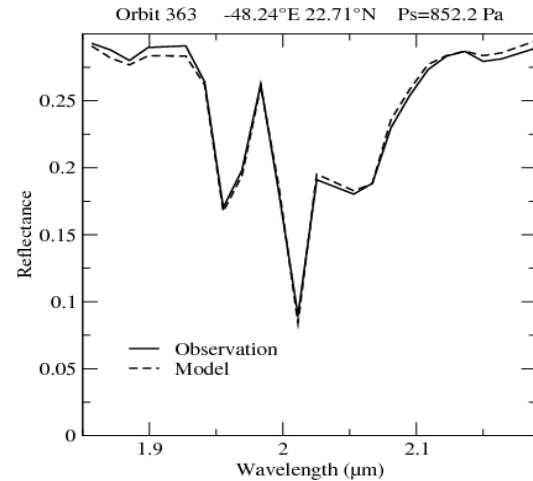


Figure A: Example of pressure measurement at the VL1 location. OMEGA observed spectra vs. synthetic spectra generated with the forward model

Error estimations:

(1) *Atmospheric temperatures.* The temperature profiles are provided for the Martian Year 24 (thought to be typical with regards to the dust cycle) by the LMD Mars General Circulation Model which are available from the Mars Climate Database (version 4.1). Albeit PFS data and MGS radio-occultation measurements show good agreement with the predicted temperature from the “typical” MY24 scenario, different atmospheric conditions may exist during a given OMEGA measurement. In addition, specific radiative forcings may be unresolved at the GCM resolution (*e.g.* insolation effects on the topographical slopes), as can be highlighted in OMEGA surface temperature measurements. To estimate the error on the surface pressure measurement due to the atmospheric temperature uncertainties, we performed pressure retrievals on a reference spectrum generated with the full line-by-line radiative transfer model. We show that an underestimation of 15K leads to an overestimation of the measured surface pressure of 15 Pa, and vice-versa.

(2) *Dust opacity.* The optical depth of a given OMEGA observed scene is assumed to be close to the value retrieved at the same solar longitude and the same location in a previous year by the Thermal Emission Spectrometer dust observations. In addition to this approximation, dust may not be perfectly well-

mixed, and local dust lifting may occur. Although the actual presence of atmospheric dust is checked qualitatively with color images built with the OMEGA visible channel, we estimated a (pessimistic) 0.2 uncertainty on the prescribed dust opacity. An error estimation shows that underestimating the dust opacity by 0.2 leads to underestimate the pressure by about 7 to 35 Pa, depending on the assumed surface albedo. Towards darker regions, the influence of dust increases because the contrast with the bright airborne dust is then stronger. We thus avoid this kind of region for the pressure measurement.

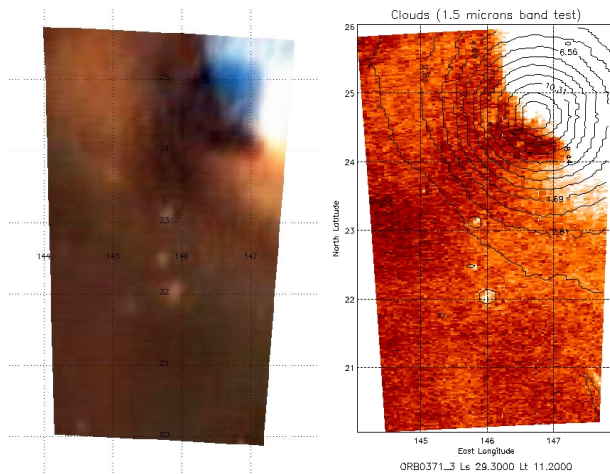


Figure B: Cloud monitoring with OMEGA in the Elyseum Mons region : visible image (Thanks to G. Bellucci) and IR test

(3) *Pyroxenes and hydrated minerals.* The IR signatures of Martian mineralogy can affect the spectra observed by OMEGA, and thus falsify the pressure measurements. Hydrated minerals are only observed in few specific locations, which are easy to avoid. High-calcium and low-calcium pyroxenes, on the other hand, have been mapped by OMEGA and shown to cover significant part of Mars in low-albedo regions and old terrains. Their spectral influence over the 25 spectels used for the pressure measurements can be estimated using the Modified Gaussian Model (MGM) approach. Completely neglecting the effect of LCP or HCP in a location where their signature is maximum (which is very rare) would lead to errors reaching 20 Pa. However, the accuracy of the MGM spectral fit of the OMEGA data is usually better than a few percent, and the resulting uncertainty on pressure is only a few pascals.

(4) *Water ice influence.* Water ice clouds and frosts can distort the CO₂ absorption band at 2 μ m, and may thus falsify the pressure retrieval. IR and visible OMEGA spectra are used to assess carefully the presence of ices in the atmosphere or on the ground.

The spectral signature of water ice is not included in our model, thus we simply avoid the regions with clouds or frosts (figure B).

(5) *Instrumental noise.* The standard deviation on surface pressure due to the OMEGA instrumental statistical noise (which do not depend on the incoming flux, except for very bright regions with high reflectances) is very low: 1.3 Pa. In the 2 μ m band, the signal-to-noise ratio (SNR) is in most cases excellent; we just have to avoid the very dark terrains in the IR.

Total relative errors. Previous sources of errors may act quite differently from one OMEGA session to another. To evaluate the total relative error, we performed a Monte-Carlo error analysis, randomly combining all the previous uncertainties. The standard deviations (*i.e.* the 1- σ relative error) of retrieved surface pressure with albedos of respectively 0.3-0.2-0.15 is 7-10-15 Pa.

Total systematic errors. A systematic bias, nearly constant throughout the mission or at least during a season, may also affect the pressure measurement. It is mostly due to uncertainties in (1) the instrument response functions absolute spectral position (1.2%) and exact shape in each spectel (1%), (2) in the spectroscopic line parameters (<1%), (3) in the CO₂ mixing ratio (<0.5%). The total systematic bias should thus be significantly lower than 4%.

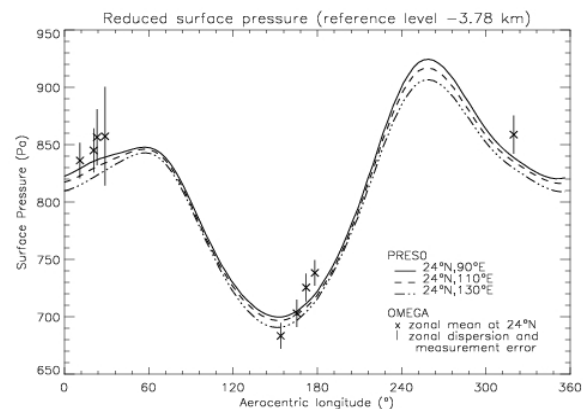


Figure C: Seasonal variations of surface pressure in Isidis Planitia. Crosses are OMEGA measurements, and lines are outputs of the surface pressure predictor included in the MCD

Measurement examples:

Comparison with in-situ measurements. Assuming that pressure is primarily controlled by season and local time, and that the mass of the Mars atmosphere has not varied for thirty years, we can compare OMEGA pressure measurements with previous lander missions estimates. The retrieved value of 852 Pa in the ORB0363_3 session can be compared to the VLI

measurement of 831 Pa for the same season and local time.

Monitoring seasonal variations. Surface pressure at any locations on Mars can be predicted by interpolating the VL1 record vertically thanks to the accurate MOLA topography, and refined by taking into account GCM predictions. A more general validation of the pressure measurements is then possible. For example, even if seasonal variations in a given location are not easy to monitor with the OMEGA instrument, selected pressure measurements obtained in a flat area of Isidis Planitia at 24N show a good agreement with the surface pressure predictor, and enable to monitor the strong pressure variations resulting from the condensation and sublimation of the CO₂ atmosphere in the polar caps (figure C).

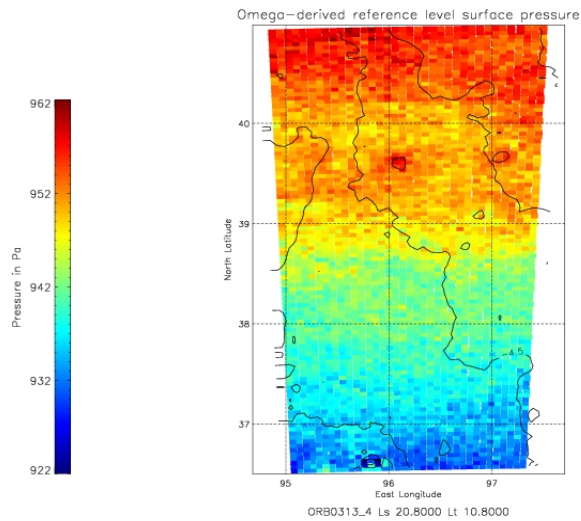


Figure D: OMEGA surface pressure field with “sea-level” pressure reduction. Topography is contoured, slope is ~600m.

Map Processing: The topographical first-order influence is removed from the surface pressure field as on Earth, using a “sea-level” pressure reduction. This process is nothing more than a normalization, using the barometric equation, of all the pressure measurements P made at various locations (x,y) (and consequently at various altitudes z):

$$P_{lev}(x, y) = e^{-\frac{z(x,y) - z_{ref}}{H(x,y)}} P(x, y).$$

We use a constant scale height H defined with the 1 km temperature, high enough above the slope wind layer, but low enough to keep the consistency of the barometric integration.

Mountain and crater positions were found to be slightly shifted in the OMEGA pressure field, compared to the reference field derived from MOLA. Thus, registration shift correction is performed prior to any topography removal process.

Meteorological Events: The horizontal resolution of the spectral images from OMEGA ranges from 5km to ~400 m, allowing to identify meteorological events at various scales. Three main phenomena are observed in the maps produced: horizontal pressure gradients, atmospheric oscillations, and pressure perturbations around the topographical obstacles.

(1) *Pressure Gradients.* An example of an horizontal pressure gradient is observed over a specific region in Utopia in spring (figure D). The gradient shares the same direction as the GCM-predicted gradient, but its amplitude is higher. This pressure gradient may be the signature of an atmospheric front occurring in the region. A possible influence of the pressure tide maximum is however not ruled out.

(2) *Atmospheric Oscillations.* Large-scale and mesoscale atmospheric oscillations are detected in some OMEGA surface pressure fields. These well-organized atmospheric oscillations may be the signatures of inertia-gravity waves and/or convective rolls. An example is given on the following page (figure E) in a very flat area of Amazonis Planitia during northern spring. The surface pressure map retrieved by OMEGA features an oscillation event with an horizontal wavelength of 75 km. Interestingly, similar oscillations are found in the ozone abundance field (derived from OMEGA measurements, see figure F) above 20 km altitude, but with a lower wavelength, which possibly suggests the vertical propagation of the oscillatory event. The convective rolls explanation is however not completely ruled out, as waves and rolls may be coupled. Another example (not shown here) was found to be in good accordance with rolls' structures previously predicted by mesoscale models, although the oscillation pattern may also be explained by gravity waves occurrence.

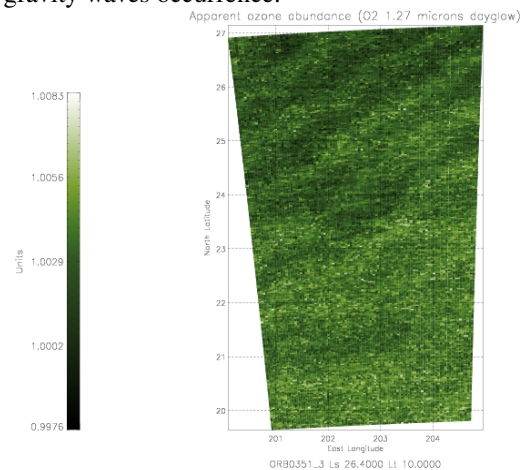


Figure F: OMEGA spectral ratio around 1.27 micron, linked to ozone apparent abundance above 20 km altitude. (Thanks to F.

Altieri for the personal communication)

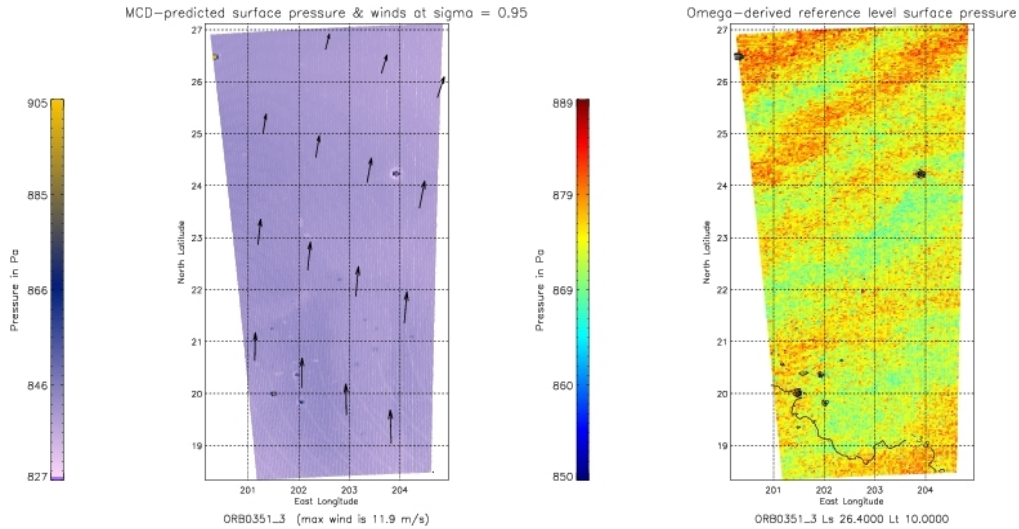


Figure E: (left) predicted MCD surface pressure field and winds at 1km altitude (right) OMEGA surface pressure field with “sea-level” pressure reduction. Topography is contoured.

(3) *Pressure perturbations around the topographical obstacles.* An example of OMEGA pressure measurement in the vicinity of ~2000m deep craters is displayed on figure G. As the alignment of the perturbation cells is very similar to the predicted GCM wind direction, an attractive assumption is that these cells are signatures of the interactions between the incoming flow and the craters. Highly idealized 3D mesoscale simulations with a Martian version of the WRF model tend to show the OMEGA surface pressure signatures in the vicinity of the craters are explained qualitatively but not quantitatively. Discrepancies may be a result of the drastic mesoscale circulation occurring in areas where the topography is

particularly complex. Non-hydrostatic dynamics may play a dominant role : gravity waves, thermal forcings, slope winds, turbulent motions. In particular, the resulting mass divergence from inside the crater due to slope winds might also explain some of the observed features.

Further work: The OMEGA surface pressure maps reveal interesting meteorological events. As future work, additional OMEGA sessions will be analyzed, and more exhaustive mesoscale modeling will be achieved. We will also attempt to improve the accuracy of the measurements.

References: Bosch et al. (2006) *JGR-D* 111, Bellucci et al. (2006) *PSS* 54, Bibring et al. (2004) *ESA-SP-1240*, Fedorova et al. (2006) *JGR-E* 111, Hourdin et al. (1993) *JAS* 50, Kanner et al. (2006) *Icarus* 187, Rafkin et al. (2003) *JGR-E* 108, Renno et al. (2004) *JGR-D* 109, Skamarock et al. (2005) *WRF users guide*, Wang and Ingersoll (2002) *JGRE* 107

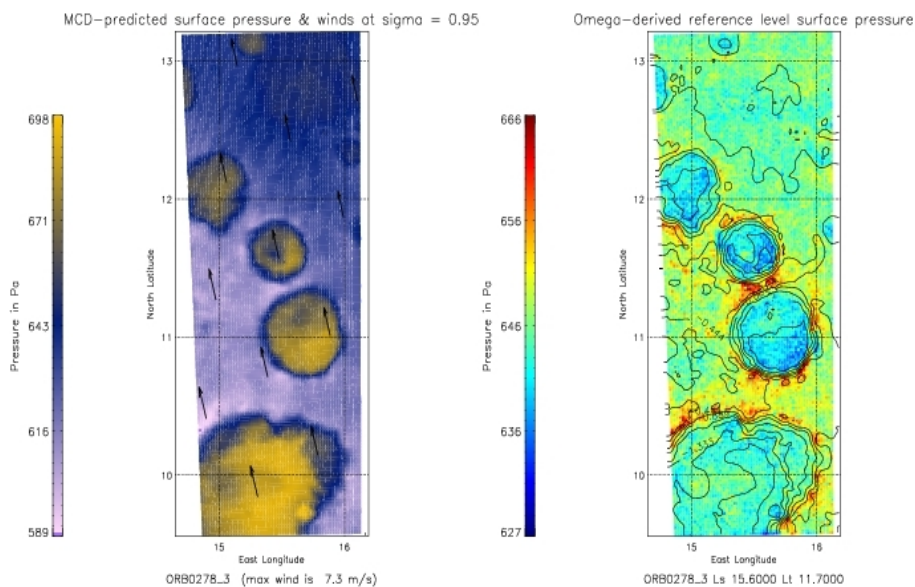


Figure G: (left) predicted MCD surface pressure field and winds at 1km altitude (right) OMEGA surface pressure field with “sea-level” pressure reduction. Topography is contoured.