PROBING ATMOSPHERIC GRAVITY WAVES ON MARS' ATMOSPHERE USING MARS EXPRESS OMEGA DATA.

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Abstract

We report the detection and characterisation of atmospheric gravity waves on the atmosphere of Mars using images from the OMEGA spectrometer onboard Mars Express space mission. These waves have already been detected by MEx (Määttänen et al., 2010; Spiga et al., 2012), although there is still an important dataset of unexploited atmospheric observations (Gondet and Bibring, 2018) to be analysed. In this study we started to build the first catalogue of atmospheric gravity waves and morphological parameters using OMEGA/MEx data by adapting the technique that was already used successfully for Venus (Silva et al., 2021). Each image was navigated and processed for optimal detection of wave features and accurate characterisation of wave properties and parameters such as time, spatial coordinates, horizontal wavelength, packet length, packet width and orientation of the wave packet, to be analysed in correlation with mars topography, illumination conditions, local time and Mars seasonal climate variability.

Introduction

Atmospheric gravity waves are mesoscale atmospheric oscillations in which buoyance acts as the restoring force, being a crucial factor in the circulation of planetary atmospheres since they transport momentum and energy, which can dissipate at different altitudes and force the dynamics of several layers of the atmosphere (Fritts and Alexander, 2003).

The source of these waves can be associated with the topographic features (orographic gravity waves) of the surface, or with jet streams and atmospheric convections (non-orographic gravity waves). Recent modelling studies showed the strong role of gravity waves on diurnal tides on Mars atmosphere (Gilli et al., 2020), however their characteristics are still not well constrained by observations.

We present here follow-up results (Brasil et al., 2021) on the detection and characterisation of atmospheric gravity waves on Mars using data from the OMEGA (Bibring et al., 2004) imaging spectrometer onboard the European Mars Express (MEx) space mission (Chicarro et al., 2004).

The OMEGA (Observatoire pour la Minéralogie, l'Eau, les Glaces et l'Activité) instrument is a mapping spectrometer onboard of Mars Express, consisting on two co-aligned grating spectrometers, the Visible and Near-Infrared (VNIR) and the Short Wavelength Infrared (SWIR) that produced hyperspectral data QUBEs covering the wavelengths from 0.38 to 5.1 μm.

The data set covers the Mars Express nominal mission of the OMEGA instrument from January 2004 (Martian year 26) to January 2006 (Martian year 27) and from June to July 2007 (Martian Year 28), constituted by 27 orbits and 4072 hyperspectral data QUBES. We used image navigation and processing techniques based on contrast enhancement and geometrical projections to characterise the morphological properties of the detected waves.

Method

We set out for a systematic analysis of the OMEGA data QUBEs in which each image is processed and inspected individually in order to identify gravity waves, where they are seen as quasi-periodical sequences of bright crests and darker throughs (Figure 1).

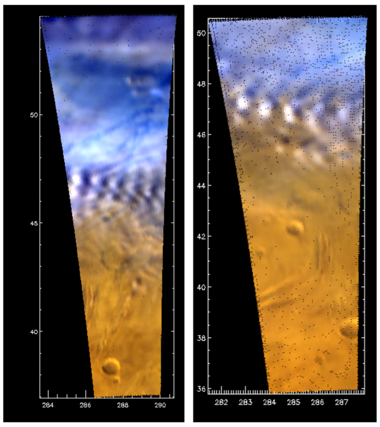

Figure 1: Atmospheric gravity waves detected on the atmosphere of Mars with the OMEGA camera on June 2007. Credit: Gondet

For the detection, we used the 0.5 and 1.7 μm since at these wavelengths, we are probing the surface and the lower atmospheric layer of Mars (Figure 1).

OMEGA data QUBEs and its IDL routines were retrieved through the PSA archive from ESA, to produce OMEGA images which were later navigated and processed individually using python scripts and ENVI software for optimal detection of wave features and accurate characterisation of wave properties, such as the horizontal wavelengths, packet width, packet length, location and orientation as shown in Figure 2.

In a given image, the oscillations produced by the presence of a wave produces a small brightness variation when compared to the background, therefore the first step to identify these features is to increase the contrast of the image. The resulting image highlights the morphological characteristics of a wave, which can then be analysed.

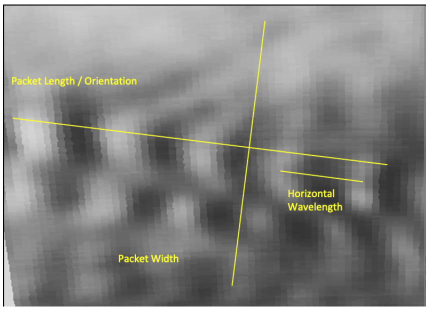

Figure 2: Wave-packet in detail with the morphological properties gathered: Horizontal wavelength, packet length, packet width and orientation.

Morphological characterisation usually entails measuring the distance between two points of interest in a wave-packet. For example, to measure the Horizontal Wavelength (Figure 2), we take into account the distance between two consecutive crests. The calculation of this distance (Dist in 1 represents the distance measurement) is performed using equation 1 with the radius of the planet (a) plus the altitude of the cloud deck we are observing (h). However, to guarantee an accurate measure of horizontal wavelength, packet length and packet width, we measure several times from one crest to the other, maintaining the perpendicularity between oscillations.

$$Dist. = \frac{\pi\sqrt{(\lambda_2-\lambda_1)^2\cos^2(\bar{\phi}\frac{\pi}{180})+(\phi_2-\phi_1)^2}}{180}(a+h) \quad (1)$$

Packet length and packet width are retrieved in the same form as horizontal wavelength. This process is repeated for each crest on several locations (depending on the size and morphology of the wave) within the wave packet to examine the consistency of measurements. In Figure 3 is shown three different wave-packets detected in a OMEGA image.

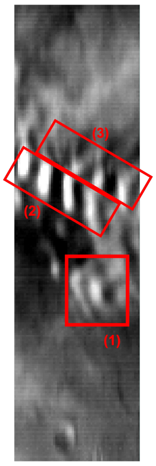

Figure 3: Typical wave-packets detected and characterised in a given OMEGA image, where it can be seen three different wave packets (1), (2) and (3).

The example in Figure 3 show some of the difficulties that arise when charaterising the wave train, such as the irregularity in its form, i.e., the distance between different crest may not be the same for every crest on the wave-packet or the shape of the waves makes it harder to measure the exact location of consecutive crests and precise perpendicularity.

Other difficulties associated with the caracterisation can be related to poor contrast of the image, which makes it impossible to resolve each crest individually and also depending on the distance between the planet and the satellite, the OMEGA track can be very narrow to detect and characterise the wave-packets that could be present in these images.

The orientation of the wave-packet is measured alongside the packet length, taking advantage of the known latitude and longitude values between the origin and the endpoint of measurement. The following equation 2 gives us the orientation of the wave-packet:

$$Orientation\ \theta = arctan\left(\frac{\Delta\phi}{\Delta\lambda}\right) \quad (2)$$

Where $\Delta\phi$ is the difference between the maximum and minimum latitude values for the wave-packet and $\Delta\lambda$ is the difference between the maximum and minimum values of the wave-packet. This equation gives the angle that the wave fronts make with a parallel with latitude equal to ϕ_1.

Some difficulties occur when measuring the orientation of the wave-packet that are related to its morphology, since in most of the cases the waves can be broken or the orientation can change from crest to crest. For that we take into account the direction of the propagating wave when measuring the orientation.

Preliminary results

During the observing periods (4072 data QUBES analysed from January 2004 to January 2006 and from June to July 2007), we detected and characterised fifty four wave-packets at 0.5 and 1.72 μm. The distribution of the gravity waves detected are present in the topographic map of Mars in figure 4.

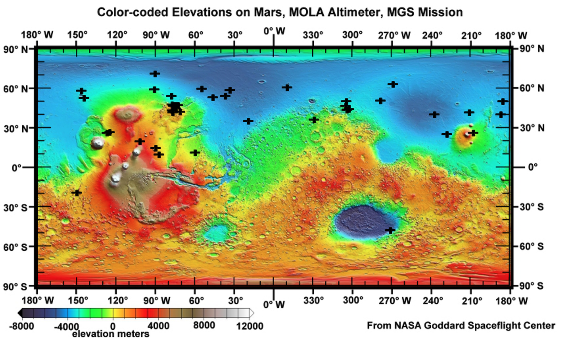

Figure 4: Distribution of characterised wave packets represented by black crosses on Mars during the period of observation. The topography map was made from data from the Mars Orbiter Laser Altimeter onboard Mars Express (Smith et al., 2001).

We found that around 10% of the images had gravity waves present and that most of the waves characterised were located on the northern hemisphere of Mars. It should be noted that the most part of the inspected images were sensing the northern hemisphere, which means that we could have a bias due to the location of the detected waves. The detected wave packets on Figure 4 represent the total number of characterisations, including the same wave packet detected at different times.

Also, it should be noted that some of the gravity waves detected are visible within a range of observing wavelengths (from 0.5 to 1.72 μm, which will depend if the waves can be seen in the visible or in the near-infrared, and the choice of a different wavelength on several cases is due to better visibility of the feature on that particular filter (better contrast or less instrumental artifacts). Most of the waves detected and characterised are in the wavelength range of 1.7-2.3 μm.

The histograms on Figure 5, show the variation of the morphological properties taken from the wave-packets. We see a large variability of values in each histogram, and it is possibly due to the small amount of characterised waves which makes the statistical distribution of the detected morphological properties to be very large.

This Figure shows that the horizontal wavelength, i.e. the distance between crests retrieved from the wave-packets, can go from around 10 to 70 km, with a large concentration of waves detected for smaller horizontal wavelengths. This can be an indication that smaller wave-packets are more common in the Mars atmosphere, and larger wave-packets can be associated with the topography of Mars and non-orographic effects that generate gravity waves.

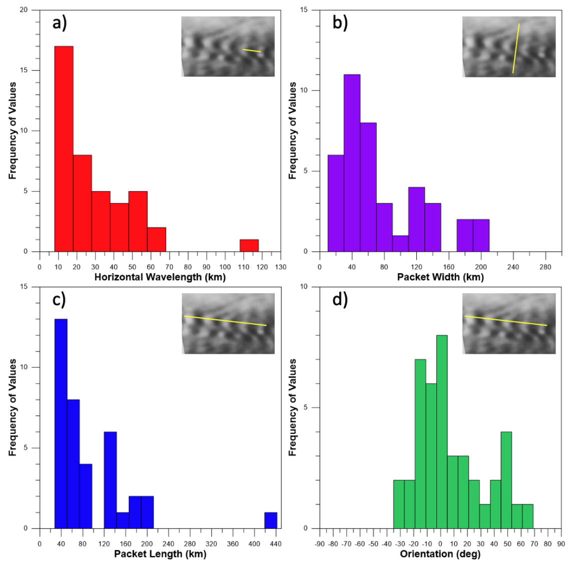

Figure 5: Histograms showing the values of several morphological properties of the wave-packets and how they are distributed. a) Horizontal wavelength; b) Packet length; c) Packet width; d) Orientation from the parallel.

Regarding the distribution of the morphological properties in respect of their latitude, Figure 6 show also the same variability of values for each propertie and also the concentration of values on the northern hemisphere.

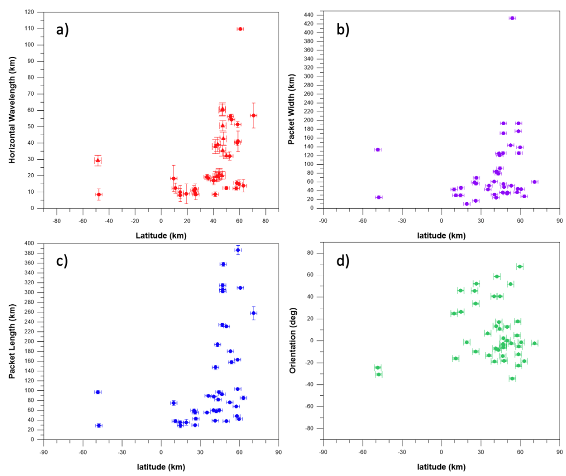

Figure 6: Distribution of the morphological properties of the wave-packets related to the latitude. a) Horizontal wavelength; b) Packet length; c) Packet width; d) Orientation from the parallel.

We found that the detected waves were present at the solar longitudes between 240-250° and 330-340°, which corresponds almost to the beginning and the end of the dust storm seasons. This can indicate that exists a relationship between the presence of gravity waves and the dust storm events, already mentioned by Gondet and Bibring (2019).

Conclusions and Future Perspectives

We had a clear detection and characterisation of atmospheric gravity waves on Mars atmosphere at visible and near-infrared wavelengths (0.5 and 1.72 μm), using OMEGA data QUBEs from the Mars Express space mission. Using the PSA archive from ESA, we retrieved the data to detect gravity waves which were previously detected by Määttänen et al. (2010) and Spiga et al. (2012). The images were navigated and processed using IDL scripts and ENVI software for both detection and further characterisation purposes. We characterised several properties of detected wave-packets including horizontal wavelength, packet width, packet length and orientation. Preliminary results show that around 10% of the images have gravity waves present and that most of the waves present were located on the northern hemisphere of Mars. Further characterised packets could help in explaining the origin of such waves and their possible relation with dust storm events on the atmosphere of Mars and constrain current models.

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References

J.-P. Bibring, A. Soufflot, M. Berthé, Y. Langevin, B. Gondet, P. Drossart, M. Bouyé, M. Combes, P. Puget, A. Semery, et al. Omega: Observatoire pour la minéralogie, l'eau, les glaces et l'activité. In *Mars Express: the scientific payload*, volume 1240, pages 37–49, 2004.

F. Brasil, P. Machado, G. Gilli, A. Cardesín-Moinelo, J. E. Silva, D. Espadinha, and B. Gondet. Characterising atmospheric gravity waves on mars using mars express omega images–a preliminary study. In *European Planetary Science Congress*, pages EPSC2021–188, 2021.

A. Chicarro, P. Martin, and R. Trautner. The mars express mission: an overview. In *Mars Express: the scientific payload*, volume 1240, pages 3–13, 2004.

D. C. Fritts and M. J. Alexander. Gravity wave dynamics and effects in the middle atmosphere. *Reviews of geophysics*, 41(1), 2003.

G. Gilli, F. Forget, A. Spiga, T. Navarro, E. Millour, L. Montabone, A. Kleinböhl, D. Kass, D. McCleese, and J. Schofield. Impact of gravity waves on the middle atmosphere of mars: A non-orographic gravity wave parameterization based on global climate modeling and mcs observations. *Journal of Geophysical Research: Planets*, 125(3):e2018JE005873, 2020.

B. Gondet and J.-P. Bibring. More and still unexploited atmospheric omega/mex observations. In *European Planetary Science Congress*, pages EPSC2018–313, 2018.

B. Gondet and J.-P. Bibring. Mars observations by omega/mex during the dust events from 2004 to 2019. In *EPSC-DPS Joint Meeting 2019*, volume 2019, pages EPSC–DPS2019, 2019.

A. Määttänen, F. Montmessin, B. Gondet, F. Scholten, H. Hoffmann, F. González-Galindo, A. Spiga, F. Forget, E. Hauber, G. Neukum, et al. Mapping the mesospheric co2 clouds on mars: Mex/omega and mex/hrsc observations and challenges for atmospheric models. *Icarus*, 209(2):452–469, 2010.

J. E. Silva, P. Machado, J. Peralta, F. Brasil, S. Lebonnois, and M. LefŁvre. Characterising atmospheric gravity waves on the nightside lower clouds of venus: a systematic analysis. *A&A*, 649:A34, 2021. doi: 10.1051/0004-6361/202040193.

D. E. Smith, M. T. Zuber, H. V. Frey, J. B. Garvin, J. W. Head, D. O. Muhleman, G. H. Pettengill, R. J. Phillips, S. C. Solomon, H. J. Zwally, et al. Mars orbiter laser altimeter: Experiment summary after the first year of global mapping of mars. *Journal of Geophysical Research: Planets*, 106(E10):23689–23722, 2001.

A. Spiga, F. González-Galindo, M.-Á. López-Valverde, and F. Forget. Gravity waves, cold pockets and co2 clouds in the martian mesosphere. *Geophysical Research Letters*, 39(2), 2012.