CLOUDS DETECTED BY THE MARS ORBITER LASER ALTIMETER.

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Introduction

The Mars Orbiter Laser Altimeter (MOLA) [1,2] instrument operated as an atmospheric lidar system as well as an altimeter, detecting absorptive clouds in northern latitudes shortly after orbit insertion in October, 1997, and reflective clouds over the north polar cap at the start of the Science Phasing Orbits in March, 1998. Global cloud measurements commenced with the primary mapping mission in March, 1999, with nearly continuous coverage for 1.25 Mars years. MOLA tracked several dust storms, culminating with a major dust storm in June, 2001. Reflective clouds, exhibiting distinctive patterns governed by insolation and the dynamics of the atmosphere, were detected at elevations up to 20 km above the surface, chiefly in the polar winter night. MOLA distinguishes cloud returns by pulse width and energy measurements. Unusually strong and brief reflections with minimal extinction suggest precipitation of CO_2 snow under supercooled conditions. Weaker cloud reflections occurred at all latitudes. Some reflective daylight clouds at low latitudes, 7-10 km high, suggested convective vortices or "dust devils". Ground fogs composed of dust and H_2O ice formed at night along the seasonal frost line. Absorptive clouds, while not resolved altimetrically, tracked the advancing and receding edges of the seasonal polar caps. The absorptive and reflective clouds provide a seasonal profile of atmospheric activity spanning two Martian years. Winter reflective cloud activity declined to background levels earlier in the second year at both poles, and was followed by the global dust storm of 2001, suggesting interannual warming.

Figure 1 shows the laser energy and ranging performance versus seasonal longitude of Sun (L_s) for 1.25 Mars years of nadir mapping. Transmitted energy (A) varied with environmental temperature, declining overall with age.The majority of laser shots returned ground triggers. The fraction of shots (B) that did not trigger at all varied from practically zero to nearly 6%, but performance was not affected by the two-fold variation in laser output. Nearly all of the missing triggers resulted from seasonal atmospheric effects.

Non-ground returns (C) were chiefly noise, but increased during polar winters. A level of returns that exceeded a statistical noise background resulted from cloud reflections. The diffuse nature of Martian aerosols limited the rate of cloud triggers (excursions above the baseline in Figure 1C) to a fraction of a percent, but overall >500,000 clouds were recorded.

The MOLA instrument generated atmospheric lidar observations for a duration spanning two martian years (Figure 3). As an active instrument, it was uniquely suited to both daytime and nighttime observations of clouds. Some types of clouds were visible in daylight, particularly dust devils (Figure 2). Reflective CO_2 clouds were seen chiefly in the polar night [3]. These clouds were controlled primarily by transient eddies and stationary waves [4,5]. To a lesser extent they were initiated by topographic discontinuities. As many as 10% of shots were reflected by clouds, but seldom were clouds so dense that they obscured the ground on adjacent shots. A work in press describing the history of cloud observations by MOLA is available via anonymous ftp to **ftp://ltpftp.gsfc.nasa.gov/projects/tharsis/cloudpaper**

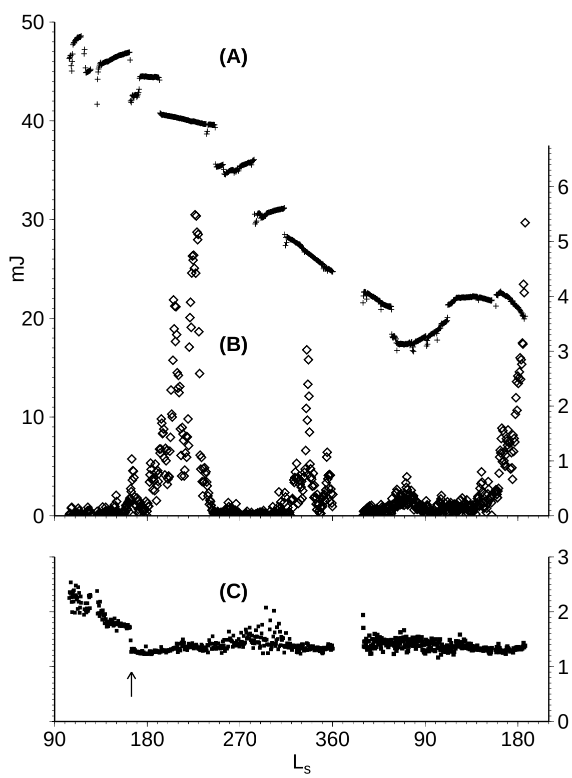

Figure 1: Ranging performance versus season (L_s). Daily averages of (a) laser energy (crosses, with scale on left); (b) missed triggers (diamonds) and (c) non-ground triggers (squares). Missed triggers are due to absorptive clouds, while non-ground returns are due to reflective clouds and background noise. The threshold of channel 1 was raised in July 1999 (arrow), reducing noise.

as "clouds.pdf", together with ancillary data.

MOLA recorded cloud returns on one of four parallel filter channels, integrating pulses over durations of 20, 60, 180, and 540 ns, revealing a broad spectrum of cloud types. Channel 1 normally triggered first on level ground, where sufficient photons returned within the equivalent of 3 m range, but could also trigger on clouds. Channel 4, with the longest time-constant, was designed to trigger on ground slopes of up to 40°. When channel 4 triggered on clouds, the returning photons were scattered from a layer >81 m thick. MOLA could only return one trigger per laser shot, and lacked the bandwidth to return cloud waveforms, but the pulse width and energy were measured. From these, and the corresponding energy of adjacent ground returns, backscatter and extinction coefficients may in principle be estimated. Work is underway to quantify these coefficients at 1064 nm.

Non-reflective or absorptive clouds (Figure 4) occured both day and night with nearly equal frequency. These clouds or hazes were distributed widely (typically extending over hundreds of kilometers), were often visible in images, but seldom returned sufficient photons within a given interval of time to trigger. MOLA was designed for an average daytime opacity of 0.5. Absorptive clouds often attenuated ground returns to extinction, implying opacity >2. Opacity events resulted in loss of signal for many seconds during passes 21, 24, 30, and 35 during the Aerobraking Hiatus in the absence of reflective clouds, and continued to be observed during all seasons.

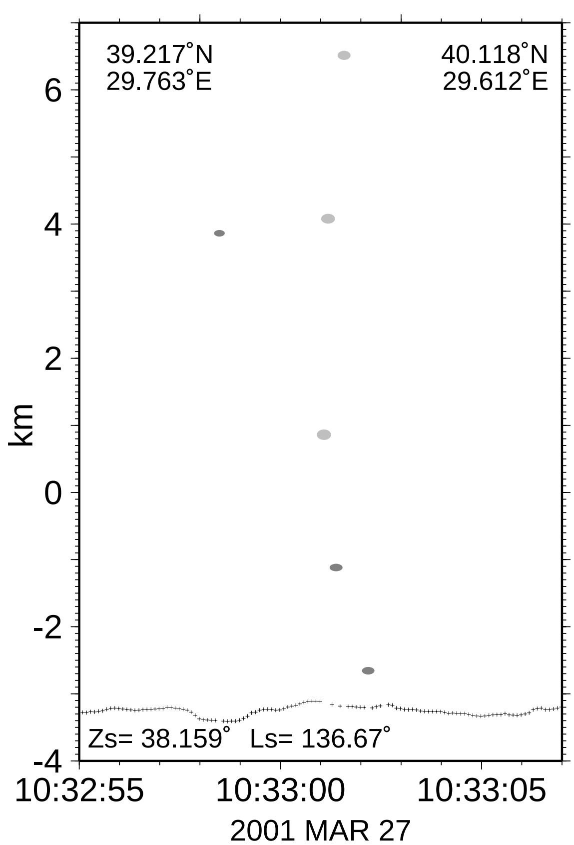

Figure 2: Daytime cloud, probably dust entrained in a convective vortex, or ”dust devil”, on MOLA profile 19166 (crosses). Clouds (ovals) triggered on channels 2 and 3. The vertical exaggeration is 5:1.

The chief source of absorptive clouds appears to have been the recession of the south polar cap, commencing in early southern winter and accelerating during southern Spring near perihelion. A similar line of clouds tracks the recession of the northern seasonal cap near the end of winter. Absorptive clouds often obscured the bottom of Hellas, the deepest feature on Mars.

MOLA observations showed active, highly variable processes producing intermittent clouds at elevations from 0 to 20 km. Cloud density in the south polar winter was strongly influenced by stationary atmospheric waves. Observations suggest that cloud cover has decreased during the two years of mapping at both poles. Analyses using thermal emission spectroscopy and radio occultations confirm that at least two aerosol species, dust and dry ice, are involved. It is very probable that water ice is also detected both as concentrated ground fog and as a dispersed attenuation over major volcanoes. Cloud measurements provide a window into the changing climate of the red planet, and have generated some puzzling findings as well. Most peculiar are the south polar winter clouds that triggered on channel 1, for which the most likely explanation is CO_2 snowfall.

References

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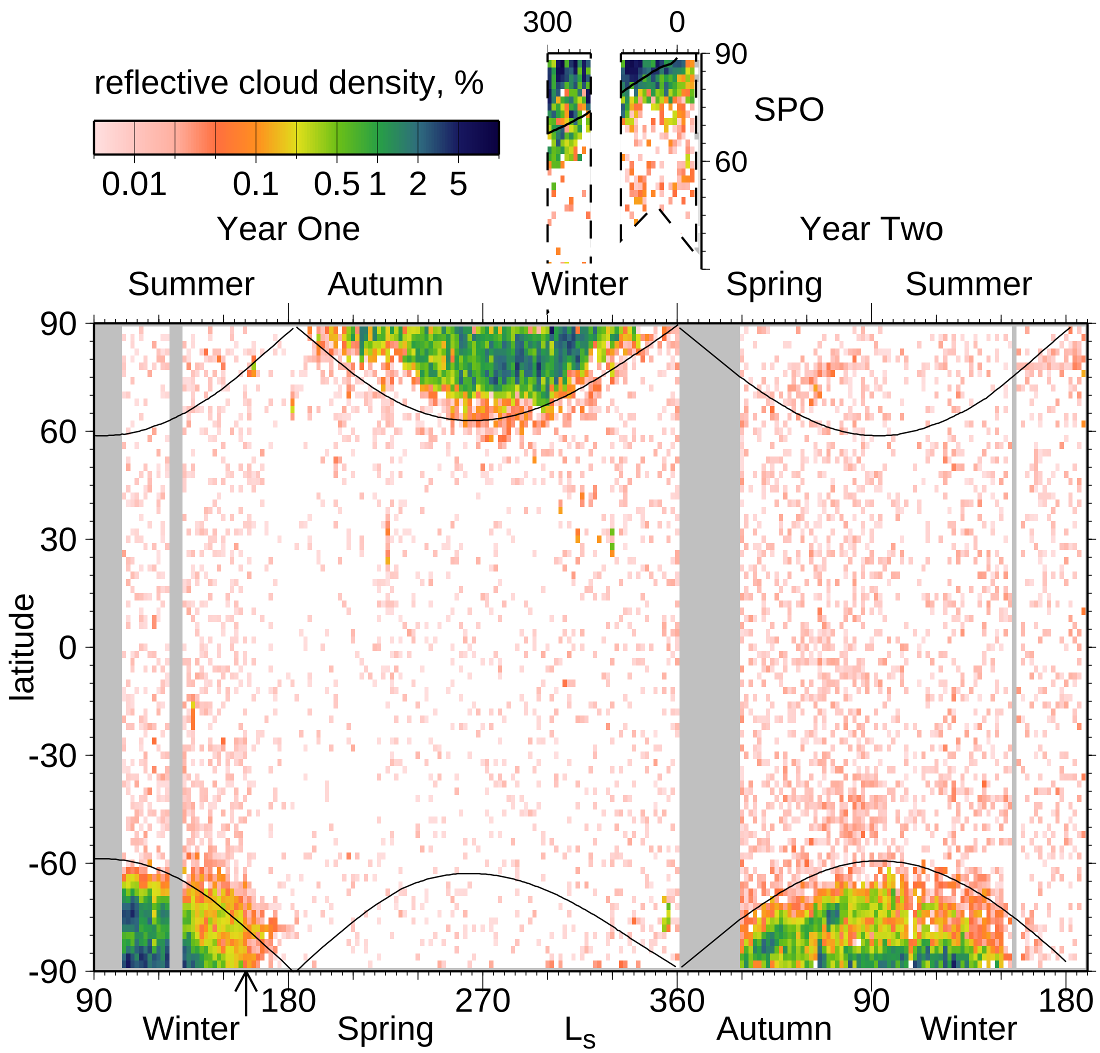

Figure 3: Percentage of reflective cloud counts in 2°x2° bins, as a function of the solar longitude L_s and latitude. Cloud frequency as a fraction of nadir-looking shots is normalized by laser energy, nominally 25 mJ, to account for differences in link margin. Inset shows extent of coverage during Science Phasing Orbits (SPO). Curves show limit of polar winter total darkness, and summer total day. Arrow shows time at which threshold of channel 1 was raised to mitigate saturation of ground returns.

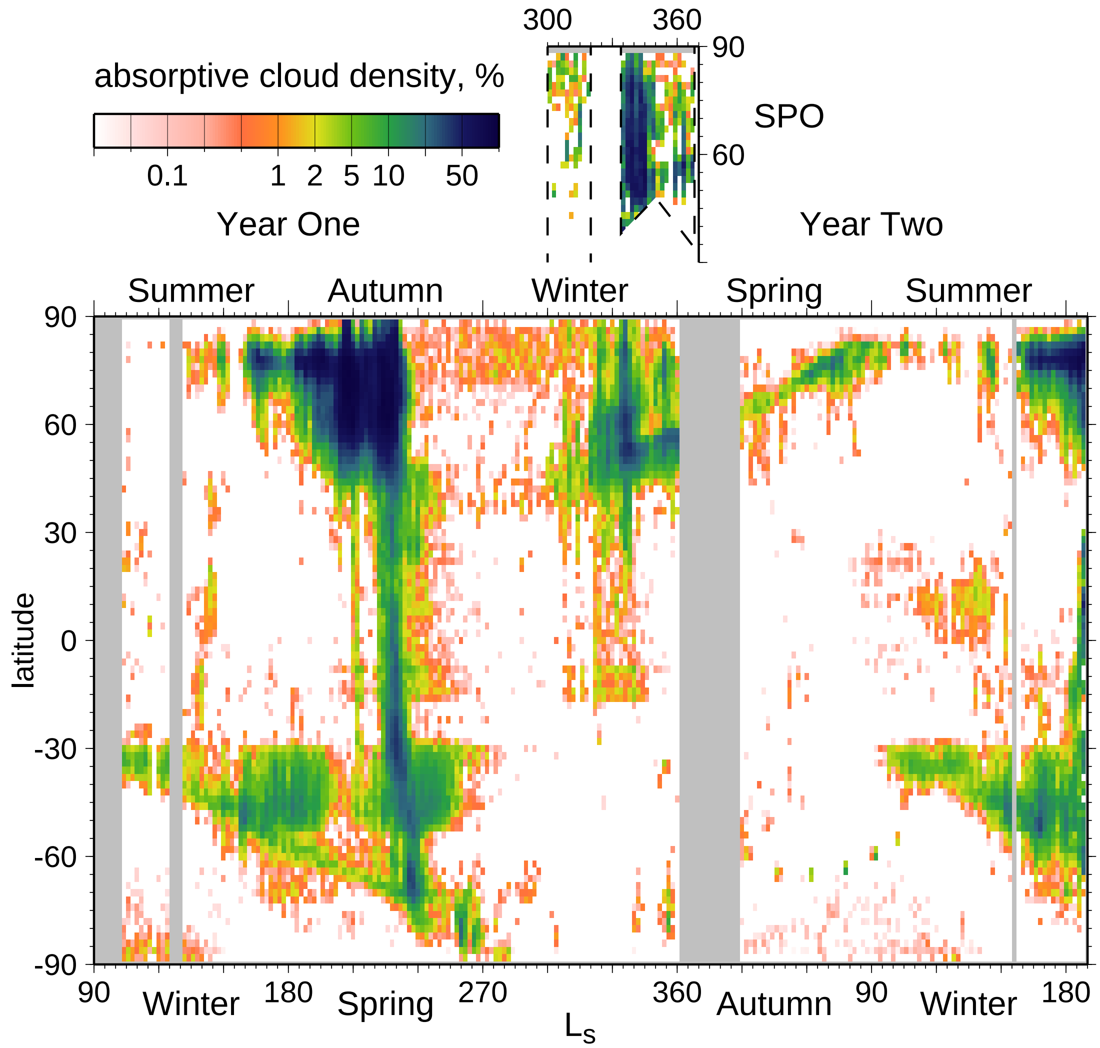

Figure 4: Frequency of absorptive clouds with latitude and season. Nadir frames with average reflectivity-transmission product < 0.02, or more than 2 shots that return no ranges, indicate significant opacity. The percentage of frames in bins of 2° by 2° in L_s and latitude is colored in a quasi-logarithmic scale.