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# THE EFFECTS OF THE DIURNAL ATMOSPHERIC VARIABILITY ON ENTRY, DESCENT AND LANDING ON MARS

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**SUMMARY: Landing on Mars is extremely challenging task due to the fact that the Martian atmosphere is the most hostile environment in the Solar system to perform the entry, descent and landing (EDL) process, because it is thick enough to create substantial heating of the entry vehicle but not thick enough to reduce its velocity to the one necessary for safe landing. Beside this, the atmosphere is very dynamic mainly due to high eccentricity of the Martian orbit, obliquity of the orbital to the equatorial plane and close alignment of the winter solstice and the orbital perihelion. Although seasonal variations of atmospheric parameters are significantly larger than the diurnal, it is very important to analyze diurnal cycles as they can significantly change vertical and horizontal atmospheric profiles in very short time intervals. This can present a serious threat to missions which have very precise timings and specific requirements such as the requirement for the daytime landing to enable ground images acquisition during the descent and landing phase. A 3-degrees-of-freedom trajectory integration routine was combined with the Mars Global Reference Atmospheric Model (Mars-GRAM) to identify the dependence of the EDL profiles on the diurnal cycles of atmospheric parameters throughout the Martian year. The obtained results show that the influence of the diurnal cycles is the largest at the equator and decreases relatively symmetrically towards the poles with a slightly stronger influence in the northern hemisphere. Also, there is a significant influence of the orbital position of Mars on the effect of diurnal atmospheric variations which causes that, around the orbital perihelion and winter solstice, there is some kind of inversion of the dependance of optimal entry timing on latitude of the landing site comparing to the rest of the Martian year.**

**Key words. planets and satelites: atmospheres – space vehicles**

## 1. INTRODUCTION

Out of 15 missions which were designed to land on the surface of Mars up to date, only 7 of them have been fully successful. The other half failed due to variety of reasons and many of them have remained unresolved. The most recent case is the failure of Beagle 2 due to unknown reasons. While the landing on any Solar system body presents a gigantic challenge, there is no doubt that Mars distinguishes itself due to its extremely hostile atmospheric environment from the atmospheric flight mechanics point of view (Poncy et al. 2010). The difficulty of placing the spacecraft on the surface of Mars primarily arises from the fact that the Martian atmosphere is thick enough to create substantial heating of the entry vehicle but not thick enough to reduce the terminal velocity to the level necessary for safe landing. Relative to the Earth, Martian atmosphere is very thin. Its density near the surface is approximately 100 times less than at the Earth. As a result, entry vehicles tend to decelerate mainly at very low altitudes and, depending upon their mass, may never reach the subsonic terminal descent velocity. Having this in mind, a height of atmospheric portion encountered by the entry vehicle is of crucial importance for the safe landing. This is one of the reasons why all fully successful landings up to date were achieved in relatively low regions in the northern hemisphere and equatorial region whose locations are shown in Fig. 1 on the topographic map from the Mars Orbiter Laser Altimeter (MOLA) experiment (Smith et al. 1999).

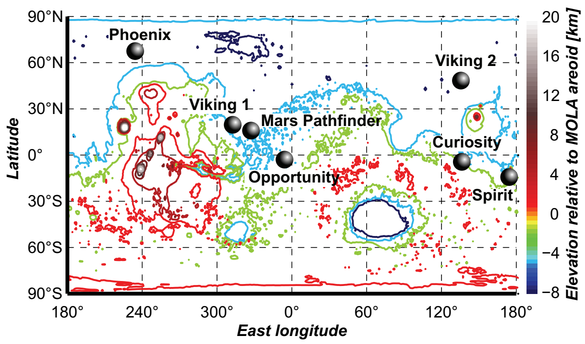


**Fig. 1.** *Locations of the previous fully successful landings.*

Mars distinguishes itself from other terrestrial planets by a very interesting feature called global dichotomy, which is reflected in the difference of the average surface elevation, impact crater density (age) and crustal thickness between the southern and northern hemisphere. The origin of the dichotomy remains puzzling with several very different suggestions to explain it, e.g. an extremely large impact in the early history of the planet (Wilhelms and Squyres 1984). Considering that the dichotomy is a very important feature of Mars, and unique among the terrestrial planets, there is no doubt that there exists a scientific interest for exploration of the whole Martian surface. Lower areas are interesting because of a greater possibility of having liquid water in the past when the atmosphere was thick enough. Even at the present state of the atmosphere, five locations have been identified to have pressure and temperature that allow liquid water to exist for some periods of Martian year (Haberle et al. 2001). On the other hand, higher areas in the southern hemisphere are interesting for exploration because of their age which dates mostly from the Noachian eon (4.6 - 3.5 Ga) of planetary evolution and are estimated to be few billion years older than the lower areas in the northern hemisphere which were under the strong influence of volcanic activity in the relatively recent history. In Fig. 1, it can be seen that due to the dichotomy, a vast portion of Mars is left outside of the reach of the landers and in situ exploration.

To be prepared for different situations that can be encountered, EDL missions assume wide uncertainty range of the atmospheric profiles that exceed the diurnal variations for the specific landing site. Some uncertainty ranges are also assumed for other variables such as aerodynamic coefficients, initial conditions etc. Typical example of the uncertainty range for the atmospheric density is shown in Fig. 2 (Desai and Knocke 2004). In this figure the uncertainty range is, given with respect to Kass-Schofield model (Colombek et al. 2003), developed specially for the Mars Exploration Rover (MER) mission landing sites.

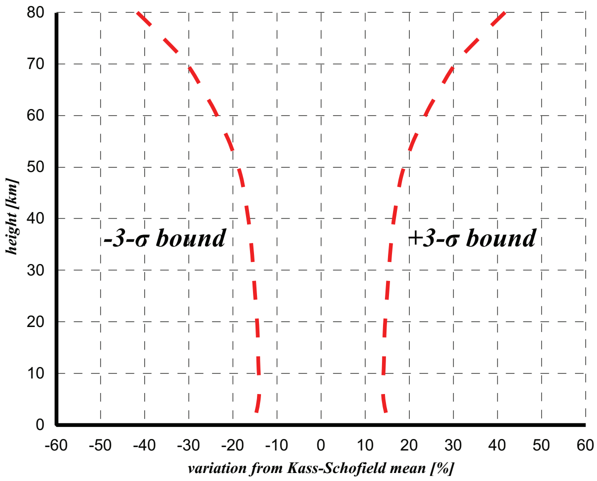


**Fig. 2.** *Density variation from the Kass-Schofield model (Desai and Knocke 2004).*

The aim of this analysis is to qualitatively and quantitatively define the influence of the nominal diurnal variations of the atmospheric parameters as given by Mars-GRAM atmospheric model (Justus et al. 1996, Justus et al. 2002) on the EDL sequence, and to determine if they can be strong enough to significantly alter the achievable landing site elevation. The intention is also to identify possible optimal conditions for the EDL in regard to the local true solar time (LTST). This is often limited by positions of the Sun, Earth and Mars for power and communication purposes, but some level of adjustment could be possible, especially for the entry from the orbit as in the case of Viking missions.

## 2. RECAPITULATION OF THE PREVIOUS LANDINGS

The first soft landing on Mars was accomplished on December 2, 1971 by Mars 3 spacecraft. Unfortunately, just after 20 seconds the instruments stopped working. The reason has never been determined and the most probable cause was the strong dust storm at the time and location of landing which was 45° S, 202° E. Beginning with the landing of Viking 1 on July 20, 1976, there were seven fully successful landings on Mars until now. As mentioned above, unlike Mars 3 which landed in the southern hemisphere at the elevation of +1666 m relative to MOLA areoid (Smith et al. 1999), all of them were accomplished in the lower areas of Mars in the northern hemisphere or in the equatorial region. In Fig. 3 are shown seasons (areocentric longitudes of the Sun, Ls) and LTST of 11 of 15 previous missions which did not failed prior to the EDL and for which the data could be found, both successful and unsuccessful (Braun and Manning 2007, Vasavada et al. 2012).

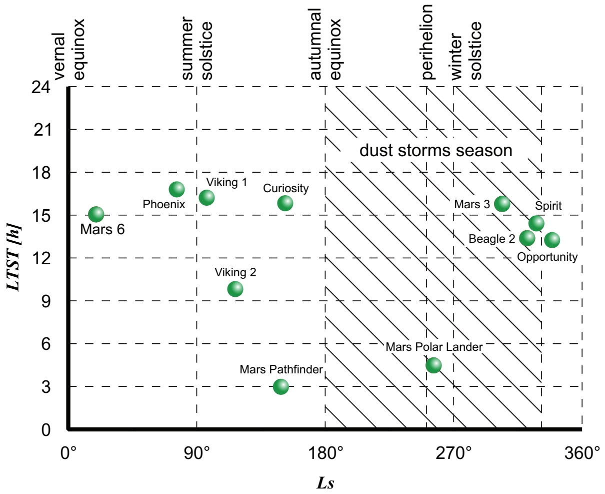


**Fig. 3.** *Seasons and LTSTs of 11 previous landings.*

From Fig. 3 one can see that previous landings happened under various conditions ranging from the early summer to late winter and from predawn, through the early morning to middle afternoon, but that 8 of 11 missions shown in Fig. 3 tried to land during day light hours, between 13h and 17h. In this figure can also be seen that 3 of 4 unsuccessful missions tried to land during the dust storm season when Mars is close to its orbital perihelion. However, it cannot be claimed that the dust storms are responsible for the failure of all of these missions.

The hardware and EDL scenarios of the previous missions are described in detail in the literature (Braun et al. 1995, Steltzner et al. 2003, Desai et al. 2006, Desai et al. 2011), and they are summarized in Fig. 4 (Desai and Knocke 2004) for the case of the MER mission which was analyzed in this paper.

One of the most important EDL variables, considering the possibility for landing on higher elevations, is the parachute deployment height above the local ground level. The parachute must be deployed at a sufficiently high altitude in order to have enough time to perform all other necessary EDL operations to ensure the safe landing. This time is shown to be linearly related to the parachute deployment height (Marčeta et al. 2014). Because of this, parachute systems have evolved from the time of Viking landers in order to sustain larger mechanical and aerodynamic loads induced by deployments on higher Mach numbers (M) and dynamic pressures (q) (Braun and Manning 2007, Desai et al. 2006, Prince et al. 2011). This evolution is shown in Fig. 5.

The chronology of previous successful landings shows the intention to deliver higher masses on higher landing sites. This requires improvement of existing and development of new technologies, but also emphasizes the importance of better understanding the behavior of the Martian atmosphere for future landings.

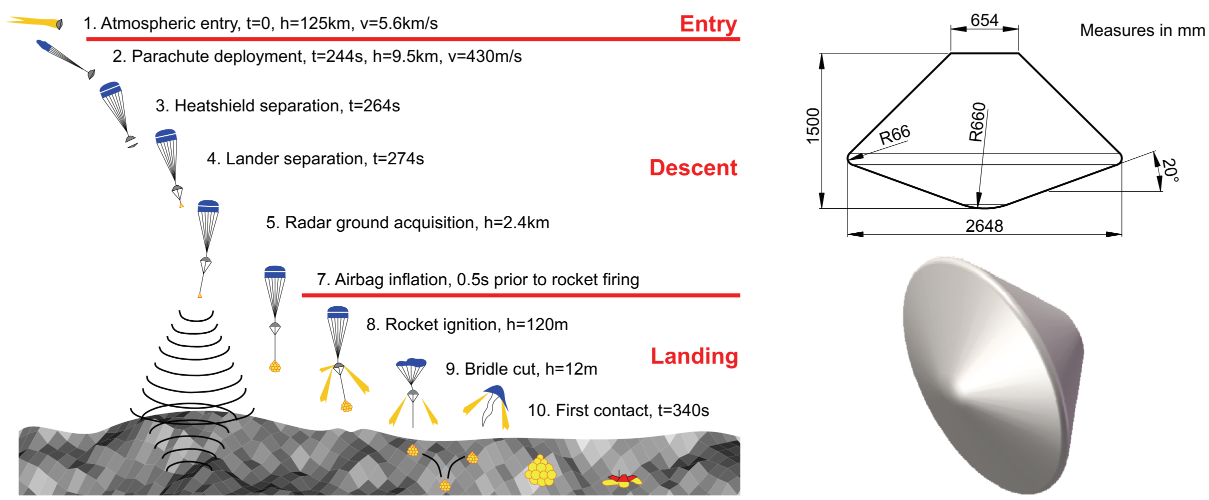


**Fig. 4.** *EDL sequence and the capsule geometry for the MER mission (Desai and Knocke 2004).*

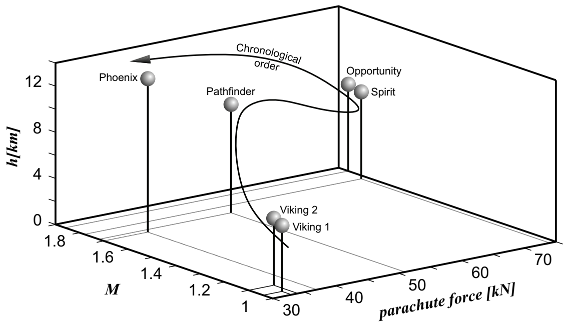


**Fig. 5.** *Parachute deployment conditions for previous landings.*

## 3. VARIABILITY OF THE ATMOSPHERE

Using the physical laws and in situ and remote measurements of atmospheric parameters, a number of global, regional and local models of the Martian atmosphere have been developed. The most frequently used global atmospheric model is the NASA/Ames Mars Global Circulation Model (GCM) (Leovy and Mintz 1969). Based on this GCM, a very useful environmental statistics have been obtained and summarized in the Mars Global Reference Atmospheric Model (Mars-GRAM) (Justus et al. 1996, Justus et al. 2002), which is used for the analysis presented in this paper.

The complexity of the Martian atmosphere arises from many sources, but the most important is a very strong sensitivity to the amount of energy received from the Sun due to its extremely law heat capacity. Comparing to the Earth, about 100 times less energy is needed to change the temperature for one Kelvin of the same volume of gas near the surface Mars than on the Earth. This characteristic is extremely emphasized by the obliquity of Martian orbital plane of 25.19°, large eccentricity of Martian orbit of 0.0935, and a very close alignment of the winter solstice (Ls=270°) and the orbital perihelion (Ls=251°). These features are responsible for very large variations of the insolation of the Martian surface throughout the Martian year which is shown in Fig. 6.

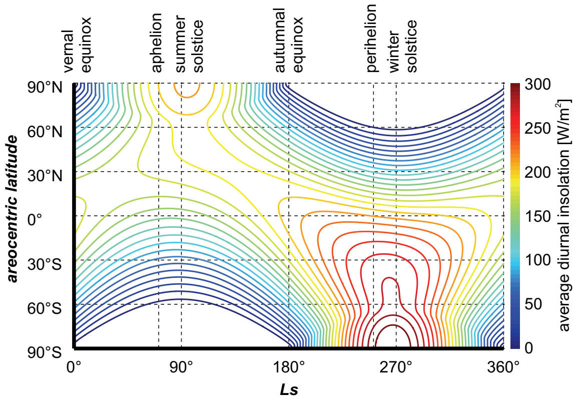


**Fig. 6.** *Averaged daily insolation at the top of the atmosphere.*

In this figure one can notice a large asymmetry with respect to the equator, which is a consequence of the mentioned close alignment of the winter solstice and the orbital perihelion, and of the large orbital eccentricity. The consequence of this asymmetry is also asymmetric behavior of the atmospheric parameters, an example of which is shown in Fig. 7.

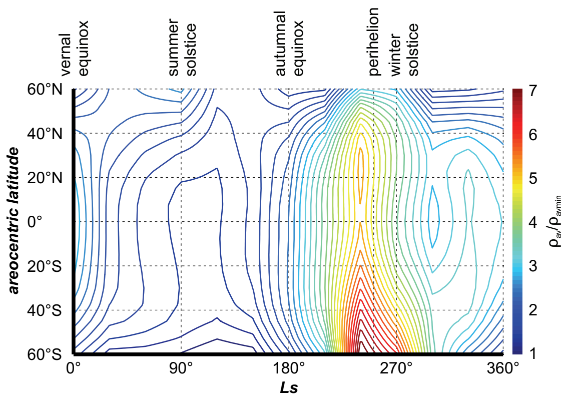


**Fig. 7.** *Seasonal and latitudinal variations of daily averaged atmospheric density at 50km height.*

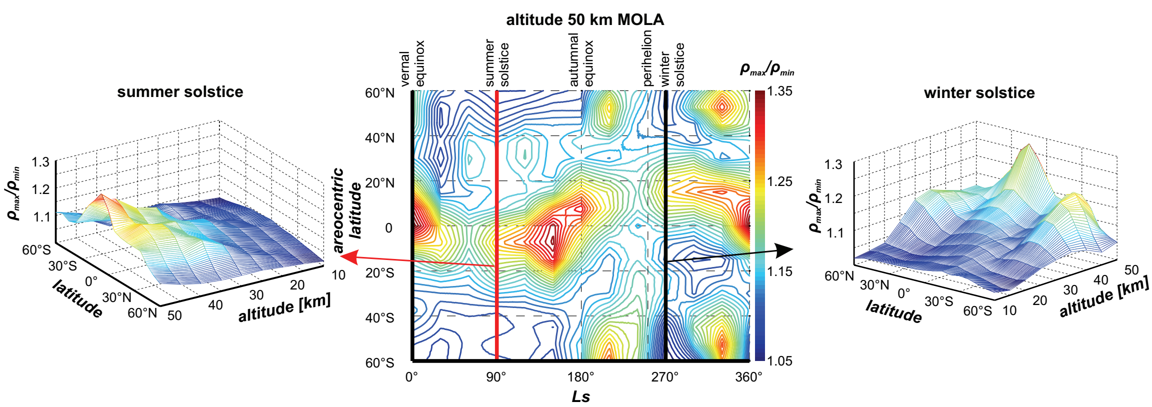


**Fig. 8.** *Diurnal variations of atmospheric density.*

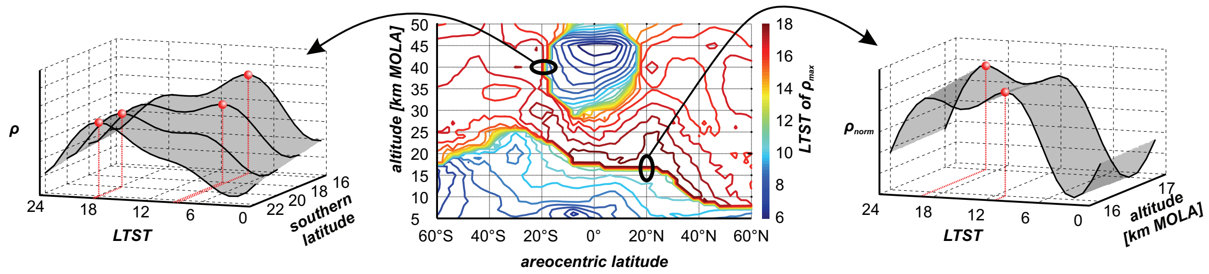


**Fig. 9.** *LTST of daily maximum atmospheric density.*

As mentioned above, due to the large sensitivity to the amount of energy received from the Sun, there are also very strong diurnal cycles of the atmospheric parameters. In Fig. 8 are shown diurnal variations ($\rho_{\max}/\rho_{\min}$) of the atmospheric density throughout the Martian year and across the 0° longitude meridian.

In this figure, a different behavior of the atmosphere around the orbital perihelion is evident also on the diurnal level. Although the diurnal density variations are significantly smaller than the seasonal ones, which can be seen comparing Figs. 7 and 8, they are very important because they can change the atmospheric parameters by significant amount in very short time intervals. Another characteristic of the atmosphere is that it is very unstable with respect to the LTST which is shown in Fig. 9.

From this figure one can see that there are regions of extremely large gradients which can cause that LTST of maximum daily atmospheric density changes for 12 hours in just 2 degrees of latitude which is shown in the left diagram. Similar situation is with altitude where LTST of $\rho_{\max}$ can change for 6 hours in just 1 km of altitude which is shown in the right diagram of Fig. 9. All these variations which are shown to be significant in the size and in gradients of variations clearly illustrate the importance of the analysis of their influence on the EDL scenarios.

## 4. ANALYSIS

Since the aim of this analysis is to determine the qualitative and quantitative influence of diurnal atmospheric variations on the EDL profiles, 3744 trajectories have been analyzed for 13 landing sites along the 0° meridian, from 60°S to 60°N with a 10° step, for every one hour of the LTST and for 12 sols of the Martian year for every 30° of Ls starting from 2013 August, 1 which corresponds to the vernal equinox. As in the analysis of the influence of the seasonal cycles on the EDL profiles (Marčeta et al. 2014), the EDL sequence has been simulated by using the aerodynamic model of the MER entry vehicle whose geometry is shown in Fig. 4. The initial conditions and the trigger for the parachute deployment were taken to be the same as they were for the entry of the MER-B (Opportunity), with initial velocity of 5.5 km/s at 120 km altitude, initial flight path angle ($\gamma$) of -11.47° and dynamic pressure for the parachute deployment of 725 Pa.

To calculate the trajectories of the entry vehicle, a trajectory routine has been developed in MATLAB to integrate 3-degrees-of-freedom trajectories using governing Eqs. (1) for translation within the atmosphere, relative to the rotating planet (Tewari 2007).

$$
\begin{aligned}
&\dot{r} = v \sin\gamma, \\
&\dot{\varphi} = \frac{v}{r}\cos\gamma\cos A, \\
&\dot{\lambda} = \frac{v\cos\gamma\sin A}{r\cos\varphi}, \\
&m\dot{v} = -D - mg_c\sin\gamma + mg_\varphi\cos\gamma\cos A \\
&-m\omega^2 r\cos\varphi\left(\cos\gamma\cos A\sin\varphi - \sin\gamma\cos\varphi\right), \\
&mv\cos\gamma\dot{A} = m\frac{v^2}{r}\cos^2\gamma\sin A\tan\varphi \\
&-mg_\varphi\sin A + m\omega^2 r\sin A\sin\varphi\cos\varphi \\
&-2m\omega v\left(\sin\gamma\cos A\cos\varphi - \cos\gamma\sin\varphi\right), \\
&mv\dot{\gamma} = m\frac{v^2}{r}\cos\gamma - mg_c\cos\gamma - mg_\varphi\sin\gamma\cos A \\
&+m\omega^2 r\cos\varphi\left(\sin\gamma\cos A\sin\varphi + \cos\gamma\cos\varphi\right) \\
&+2m\omega v\sin A\cos\varphi,
\end{aligned}
\tag{1}
$$

where $m$ is the mass of the entry vehicle, $r$ is the areocentric radius, $v$ is the velocity relative to the atmosphere, $\varphi$ is the areocentric latitude, $\lambda$ is the areocentric longitude, $\gamma$ is the flight path angle, $A$ is the velocity azimuth, $D$ is the drag force, $g_c$ and $g_\varphi$ are the radial and transverse components of the acceleration due to gravity toward center and north, respectively, and $\omega$ is the angular velocity of Mars. The entry interface corresponding to the Eqs. (1) is shown in Fig. 10.

To account for the gravity effects the gravity model that includes the first zonal harmonic coefficient $J2 = 1960.454E - 06$ (Spohn et al. 1998) has been used. Higher order harmonics are much smaller and can be neglected over the short time interval of EDL.

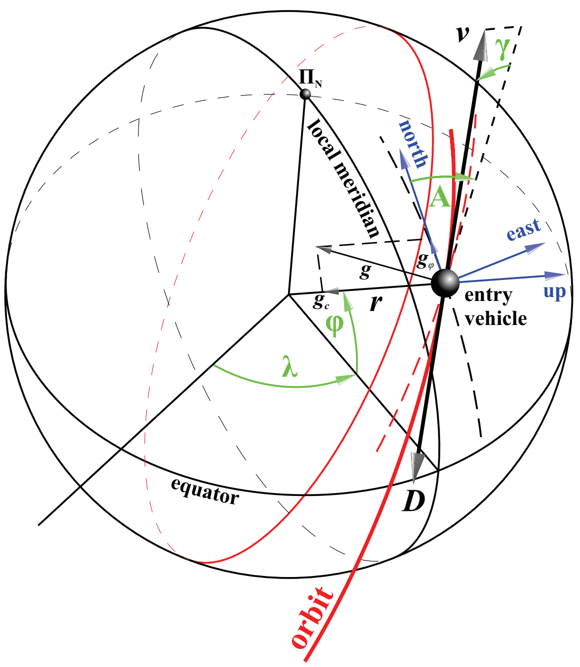


**Fig. 10.** *The entry interface.*

## 5. RESULTS

The critical variable which determines the possibility to land a certain mass on a certain altitude is the parachute deployment height. This is very important because, from the moment of the deployment to the moment of landing, there must be enough time to perform a sequence of events which are necessary for achieving a safe landing, as shown in Fig. 4. Because of this, the dependence of the parachute deployment height on latitude, Ls, and LTST has been analyzed. In Fig. 11 maximal diurnal differences of the parachute deployment height as a function of latitude of the landing site and Ls are shown.

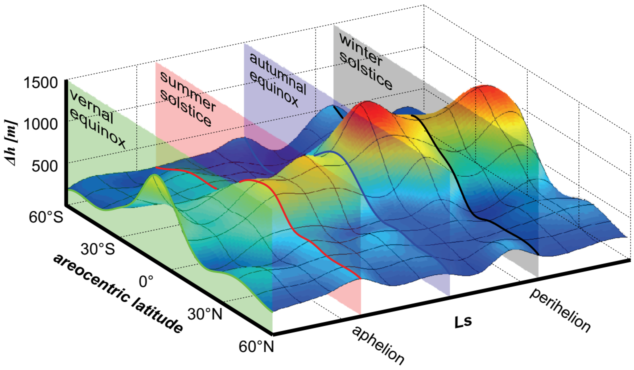


**Fig. 11.** *Maximal diurnal variations of the parachute deployment height.*

From this figure one can see that these differences at the equatorial region are very significant when the topographical characteristics of the Martian surface are taken into account (see Fig. 1). Assuming an average slope of 50 m of altitude per degree of latitude from north to south which corresponds to the data from the MOLA experiment (Smith et al. 1999), Fig. 11 shows that the diurnal variation of the achievable landing site elevation can vary by 20 degrees in latitude in the equatorial region while it is significantly smaller in the mid-latitude regions. In Fig. 12 diurnal variations of other important parameters at the moment of the parachute deployment: velocity, path angle, Mach number and the time from the beginning of the entry at 120 km altitude are presented. In this figure one can see that there are significant variations in velocity, whose typical value is about 400 m/s, and the path angle, whose typical value is about -25°. For this typical value of the deploy velocity, every m/s carries about 0.3 MJ of kinetic energy for the mass of the MER entry vehicle that has to be dissipated before the touchdown. While the relative variation of the deploy Mach number is nearly the same as that of the velocity, the variation of several percents around the typical value of about 1.8 should have only a minor influence on the flow field around the vehicle in that part of supersonic regime.

In Fig. 12 differences of the time passed until the parachute deployment are also shown. This time could be important in the case that some of the EDL events are time defined with respect to some predefined epoch. In this figure one can see that the upper part of the atmosphere is not capable of producing significant variation of this time on the diurnal level especially having in mind that it takes usually 6 minutes from the height of 120 km, where any significant influence of the atmosphere on the trajectory begins to occur, to the deployment. On the other hand, lower parts of the atmosphere can significantly alter the descent time, especially when Mars is close to its orbital perihelion when strong temperature inversions can occur in the northern mid-latitudes (Marčeta et al. 2014).

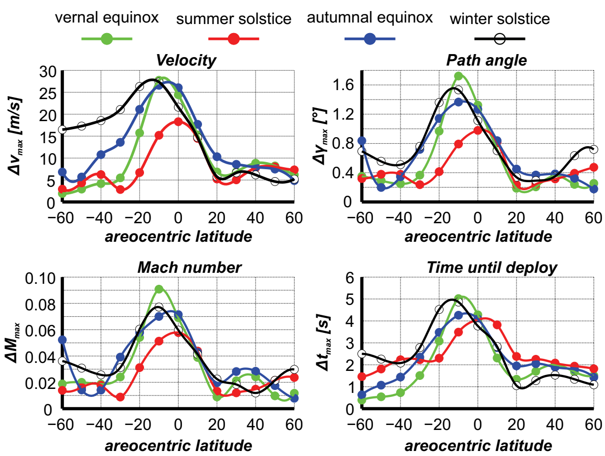


**Fig. 12.** *Maximal diurnal variations of the EDL variables.*

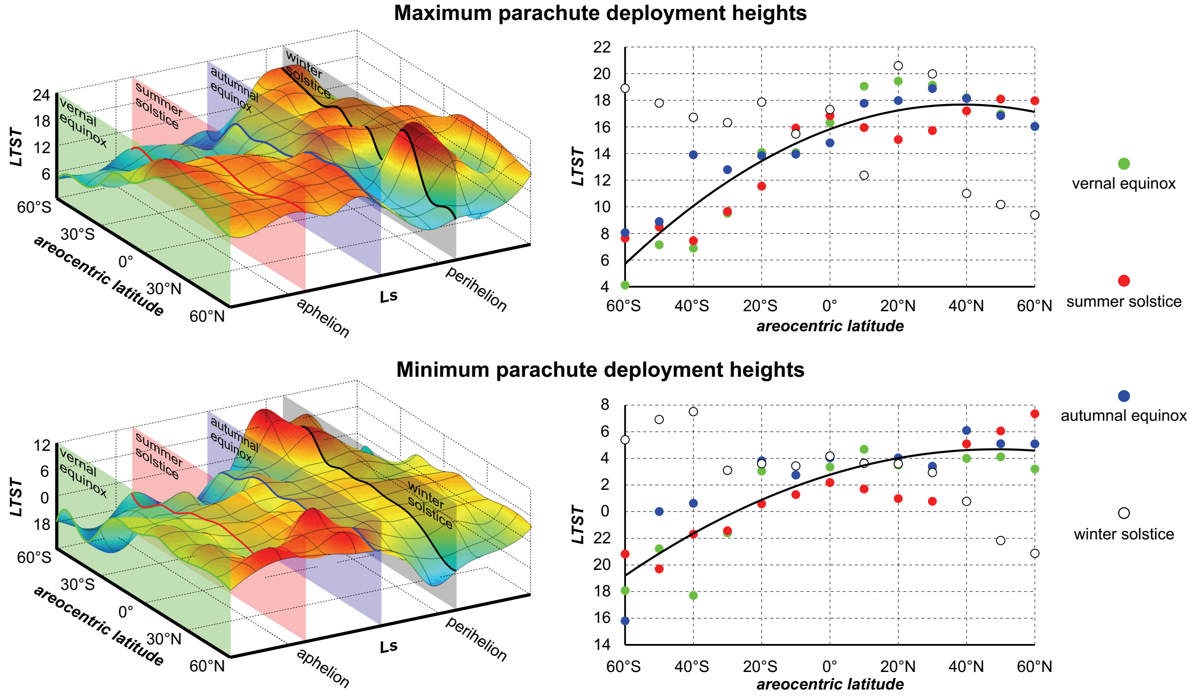


**Fig. 13.** *LSTS of minimum and maximum parachute deployment heights.*

As it is very important to identify the optimal LTST for entry, Fig. 13 shows LTSTs of minimum and maximum parachute deployment heights.

In this figure one can see that the LTST of both minimum and maximum parachute deployment heights show a similar dependence on latitude for the large part of Martian year, and a completely opposite behavior when Mars is close to its orbital perihelion and atmosphere exhibits completely different behavior due to significantly increased amount of energy received from the Sun. One can notice that the maximum parachute deployment heights occur during the daylight hours which could be a bit confusing since, at that part of sol, there is usually a higher temperature and lower density. However, this applies only to the lowest layer of the atmosphere of Mars, while in the higher altitudes there can be the opposite situation. In Fig. 14 a comparison of the two trajectories corresponding to 3h and 16h LTST for the equatorial landing site and for the sol corresponding to the vernal equinox is shown.

In this figure one can see that the differences of the density at higher altitudes cause that the trajectory corresponding to 16h LTST reaches the critical dynamic pressure of 725 Pa for the parachute deployment about 900 m higher than the trajectory corresponding to 3h LTST. This figure illustrates the importance of complex vertical profiles of the Martian atmosphere for the prediction of EDL.

## 6. SUMMARY

Considering that half of the missions designed to land on the surface of Mars have failed and some of these failures are suspected to be due to the atmospheric circumstances at the time of EDL, it is necessary to analyze the influence of the atmospheric variations on the EDL profiles. Although diurnal cycles of the atmospheric parameters are shown to be much lower than the seasonal, they can also significantly alter the EDL scenarios. From the above analysis, several conclusions can be drawn:

- The maximal diurnal variations of the parachute deployment height occur at the equator where they can reach 1 km. These variations decrease relatively symmetrically towards the poles.
- When taking into account that the average slope of surface elevation with respect to the MOLA areoid from north to south is about 50 m of elevation per degree of latitude, these variations can alter the accessible landing region around the equator by about 20° of latitude depending on the LTST of EDL.
- The velocity and the flight path angle at the moment of the parachute deployment can also be significantly influenced by the diurnal atmospheric cycles while the time till the deployment of the parachute and the deploy Mach number, although with similar relative variations, have only a minor influence on the EDL process.

- The optimal entry time has a similar dependence on latitude for the large part of the Martian year but a completely opposite behavior around the winter solstice when Mars is also very close to the orbital perihelion. Maximum parachute deployment heights can be expected during the daylight hours while the minimum deployment heights can be expected around midnight.

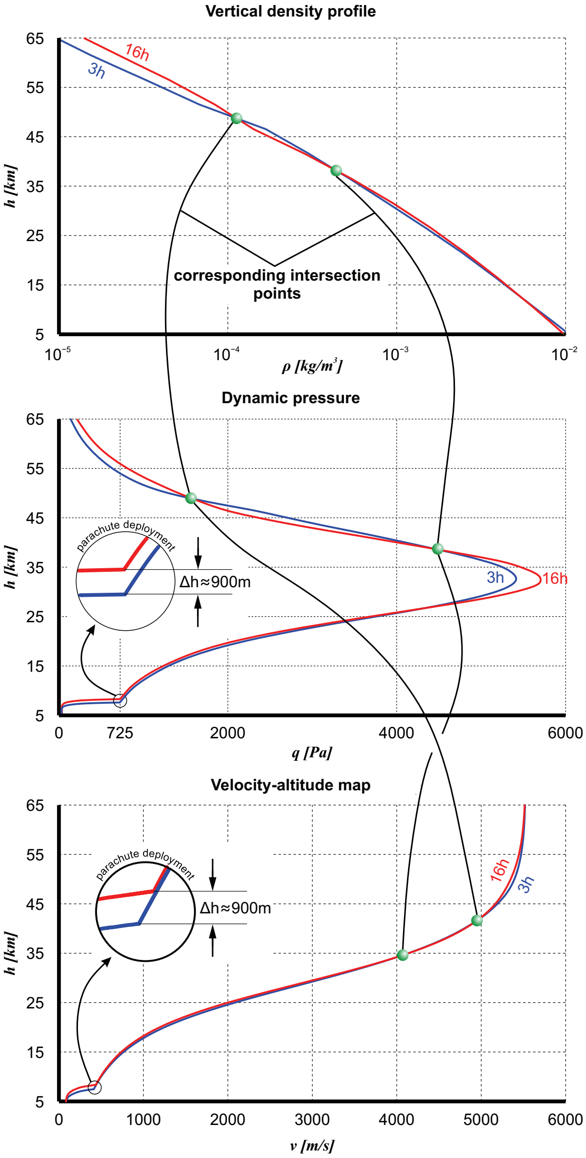


**Fig. 14.** *Comparison of the trajectories.*

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# ЕФЕКАТ ДНЕВНИХ АТМОСФЕРСКИХ ВАРИЈАЦИЈА НА СЛЕТАЊЕ КОСМИЧКИХ ЛЕТЕЛИЦА НА МАРС

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*Оригинални научни рад*

Слетање на Марс представља огроман изазов због чињенице да је Марсова атмосфера најнеприкладније окружење у Сунчевом систему за извођење овог процеса јер има довољну густину да индукује значајно загревање летелице која улази у атмосферу, али је са друге стране недовољно густа да успори летелицу довољно да би се извршило безбедно слетање. Поред овога, Марсова атмсфера је веома динамична пре свега због великог ексцентрицитета Марсове орбите, нагиба орбиталне према екваторској равни и веома блиских положаја перихела и зимског солстиција. Иако су сезонске варијације атмосферских параметара знатно веће од дневних, веома је важно истражити утицај дневних циклуса зато што они могу значајно да промене вертикалне и хоризонталне профиле атмосфере у веома кратким временским интервалима. Ово може представљати велику претњу за мисије које су временски веома прецизно дефинисане и имају специфичне захтеве, као што је на пример захтев за дневним слетањем да би се омогућило фотографисање терена за време слетања. У овој анализи је коришћен Mars-GRAM атмосферски модел који је интегрисан у рутину за израчунавање балистичких путања летелице, како би се идентификовала њихова зависност од дневних циклуса атмосферских параметара у различитим деловима Марсове године. Добијени резултати указују да је утицај дневних варијација најизраженији на екватору и да опада релативно симетрично ка половима са нешто јачим утицајем на северној хемисфери. Такође постоји и веома значајан утицај Марсовог орбиталног положаја тако да у близини перихела, између осталог, постоји нека врста инверзије зависности оптималног локалног времена слетања од латитуде у поређењу са остатком године.