Mars Soil Temperature and Thermal Properties from InSight HP^3 Data

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Key Points:

- We measured the temperature and its diurnal and annual variations in the top 40cm of the Martian soil at the InSight landing site
- The soil temperature allows the formation of thin films of brine; its deliquesence may explain the formation of the observed duricrust
- The soil thermal diffusivity was calculated from the diurnal and annual surface and soil temperature variations and increases with depth

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Abstract

Temperature is of primary importance for many physical properties in the Martian soil. We measured diurnal and annual soil (and surface) temperature variations using the NASA InSight Mars mission's HP^3 radiometer and thermal probe. At the depth of the probe of 0.5 - 36c̃m, an average temperature of 217.5 K was found varying by 5.3 - 6.7 K during a sol and by 13.2 K during the seasons. The damping of the surface temperature variations in the soil were used to derive a thermal diffusivity of $2.30 \pm 0.03 \times 10^{-8}$ m^2/s for the depth range of the diurnal wave - thermal skin depth 2.5 ± 0.04 cm - and 3.74 $\pm$ 0.61×10^{-8} m^2/s for that of the annual wave, with a thermal skin depth of 84 ± 10 cm. The temperatures measured are conducive to the deliquesence of thin films of brines in the soil. These are of astrobiological interest and may explain the formation of the observed cemented duricrust.

Plain Language Summary

Temperature is of primary importance for many physical properties of the Martian soil as it determines how rapidly physical processes and chemical reactions will proceed, including the transport of heat and materials. Temperature is of particular interest to astrobiology, informing the habitability of the soil and whether water or brine may exist on which microorganisms could live. We measured the temperature in the soil during several Martian days and over a Martian year using the NASA InSight Mars mission's Heat Flow and Physical Properties Package. Over the depth extent of its thermal probe of about 40cm, an average temperature of -56°C was measured, varying by 5 to 7 degrees during the day - only a tenth of the daily surface temperature variation - and by 13 degrees during the seasons. The temperature is subfreezing for water but allows the formation of thin films of salty brine for 10h or more during a Martian day. The solidification of the brine could have caused cementation of the soil and explain the observed few tens of cm thick duricrust, a layer of consolidated, cohesive sand, which is thought to have hampered the penetration to greater depth of the mission's thermal probe.

1 Introduction

The temperature in the Martian soil has been estimated but is mostly unknown. Orbiter and surface lander and rover missions have measured the surface temperature and thermal inertia but the temperature in the soil at more than millimeters depth has never before been measured. (Compare the near-surface soil temperatures measured by the Phoenix TECP instrument using a 15 mm long spike sensor, e.g., Zent et al. (2010).) Soil temperature is of primary importance for the values of physical properties such as elasticity, seismic velocity, thermal conductivity and heat capacity, which are temperature dependent (e.g., Morgan et al., 2018). Its value and the manner in which it varies in time and space determines the rates and directions of soil physical processes and of energy and mass exchange with deeper layers and the atmosphere (e.g., Hillel, 2001). Moreover, temperature governs the rates of chemical reactions that take place in the soil, including biological processes and is of particular interest to astrobiology (e.g., Jones et al., 2011) and future human exploration (e.g., Rapp, 2023). For life to flourish in the subsurface, temperature needs to be above the freezing point of water or the eutectic temperature of brine that may be contained in the soil and used as essential solvents by organisms (e.g., Cockell, 2014).

Soil temperature varies in time and space driven mostly by changes at the surface and the transport of heat in the soil by solid state heat conduction, heat advection through gas transport and latent heat exchange upon e.g., freezing and thawing. Heat transport in the Martian soil has been modelled by e.g., Grott et al. (2007) but because of the complex transport processes in the soil and the temperature dependence of material parameters, modeling of the thermal regime is a formidable task. Here, we report the first measurement of soil temperature at a depth of up to 36cm using the Nasa InSight Mars mission's Heat Flow and Physical Properties Package HP^3. Even though we measured soil temperature only at one location on Mars close to the equator, the data can serve as a valuable reference for future modeling and to inform astrobiological considerations and simulation experiments (e.g., Boston et al., 2009). By comparing the amplitude and phase of the sub-surface with the surface temperature we calculated the thermal diffusivity of the soil.

The HP^3 package was originally planned to measure the planetary surface heat flow and the thermal and mechanical properties of the Martian soil up to 5 m depth (Spohn et al., 2018). The mission has been described in e.g., Banerdt et al. (2020); the landing site and its Geology have been described in Golombek et al. (2020). The lander is located at 4.502°N, 135.623°E at an elevation of -2,613.43 m with respect to the geoid in what has been informally named *Homestead Hollow* in Elysium Planitia in the Early Hesperian Transition unit (Golombek et al., 2020).

Temperature sensors printed on a 5m long Kapton™ tether would have been brought to the target depth of 3–5m by a small penetrator, nicknamed the mole. The 40cm long mole which requires friction on its hull to balance remaining recoil from its internal hammer mechanism did not penetrate to the targeted depth. The root cause of the failure - as was determined through an extensive, almost one Martian year long campaign described in detail in Spohn, Hudson, Witte, et al. (2022) and Spohn, Hudson, Marteau, et al. (2022) - was a lack of friction in an unexpectedly thick cohesive - possibly cemented - duricrust. During the recovery campaign, the mole penetrated to a final tip-depth of about 36 cm with an inclination to vertical of 30°, bringing the mole's back-end about 1 cm below the surface. Penetration was aided by friction applied to the mole with the scoop at the end of the robotic Instrument Deployment Arm (Trebi-Ollennu et al., 2018) and by direct support to its back-cap.

The penetration record was used to infer a layering of the soil and its thermo-mechanical properties (Spohn, Hudson, Marteau, et al., 2022). Accordingly (compare Fig. 1), a 7–20 cm thick duricrust underlies a 1–2 cm dust layer. Underneath the duricrust is a 10–23 cm thick sand layer followed by a gravel/sand mixture. The duricrust has a penetration resistance of 0.3–0.7 MPa, while the gravel layer ($>$ 30 cm depth) a resistance of 4.9 $\pm$ 0.4 MPa. Using the mole's thermal sensors and internal heaters, the average soil temperature, thermal conductivity and the soil density were measured. The average value of the thermal conductivity was found to be 0.039 W/m K (Grott et al., 2021) varying by $\pm$ 5 % over the seasons (solar longitude between 8° and 210°) and with atmosphere pressure (Grott et al., 2023). The conductivity likely increases from 0.014 W/m K to 0.034 W/m K through the topmost sand/dust layer, keeping the latter value in the duricrust and the sand layer underneath and then increasing to 0.064 W/m K in the sand/gravel layer (Spohn, Hudson, Marteau, et al., 2022). The density decreases from 1200 kg/m^3 in the sand/dust layer to 950–1100 kg/m^3 in the duricrust, then increases to 1300–1500 kg/m^3 in the sand layer underneath and further to 1600 kg/m^3 in the sand/gravel layer.

Prior to each thermal conductivity measurement, the soil temperature was recorded for 48h. The diurnal and seasonal variations of the soil temperature are reported in this paper. The data are complemented by housekeeping (H/K) temperature data taken inside the mole at the motor block at times when the HP^3 instrument was powered on. A comparison with the surface temperature allows the calculation of the thermal diffusivity and a more precise estimate of the depth to the mole in the soil. The sensors have been described in Spohn et al. (2018) and more specifically in the Supporting Information Text S1.

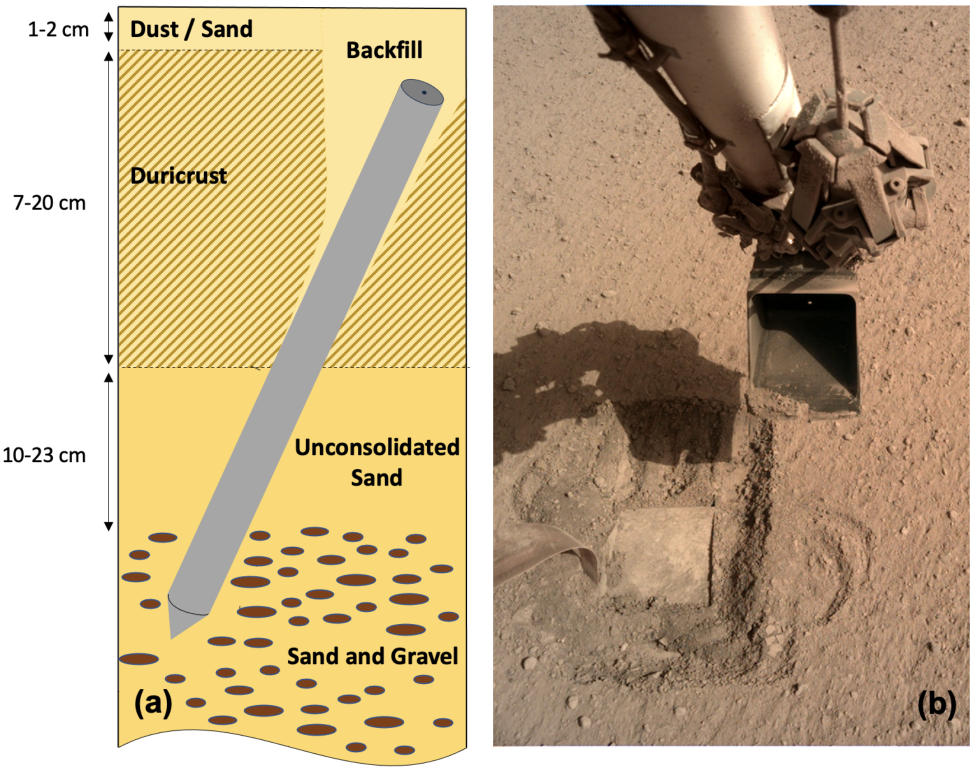

Figure 1. a) Sketch of the mole in the soil and of the soil layering. b) The mole pit filled with soil and compressed with the scoop of the robotic Instrument Deployment Arm (IDA) after sol 754, the sol of the final penetration test. A solar day (sol) on Mars is 24 Mars hours of 61.65 min. The sols are counted starting with the landing of InSight on sol 0.

2 Results

The first 48h diurnal soil temperature measurement using the TEM-A thermal sensors on the fully buried mole was taken on sol 680, shortly after buriage (Spohn, Hudson, Marteau, et al., 2022) on sol 673 but before the soil was tamped on sols 686 and 734 with the robotic arm as in Fig. 1b. On Sol 754, the mole motor was operated to see whether the mole would penetrate further on its own after being buried and the soil consolidated. When it failed to clearly penetrate further during a 506 hammer strokes long campaign - the final "Free Mole Test" - the attempts to bring the mole to greater depth were abandoned because the diminishing resources were needed for other instruments on the mission. The TEM-A measurement on sol 795 was the first measurement after the Free Mole Test hammering. This hammering may have contributed to a further settling and compaction of the pit fill. The six 48h TEM-A measurements thereafter were all done in the same configuration.

Fig. 2 top panel shows the soil temperature as a function of local true solar time LTST and for sols 681–1202. The temperature curves are largely parallel except for sol 681. The situation in the soil before the Free Mole Test and the final tamping of the sand scraped into the pit may have contributed to the anomaly. The small rate of increase of temperature after noon of sol 681 was likely caused by the shadow of the scoop which was just above the mole at the time. Moreover, InSight ICC images and camera data (https://mars.nasa.gov/insight/multimedia/raw-images, see also Lemmon et al. (2015)) suggest that it was a particularly dusty sol at Homestead Hollow.

Fig. 2 bottom panel shows the diurnally averaged TEM-A and mole motor housekeeping (H/K) temperature values as a function of time in sols starting with sol 681 and extending to sol 1245, the last sol on which HP^3 data were taken. The H/K temperatures are consistent with the TEM-A values. In addition, we plot the average of the diurnal peak values of the surface temperature measured by the RAD sensor (Spohn et al., 2018; Mueller et al., 2020) at surface spot2 (compare Supporting Information Text S1). Spot2 is located opposite to the location of the mole with respect to the lander and is centred at a distance of about 4 m from the center of the lander. The surface temperature was recorded during the second InSight Mars year at 6:00 and 13:00 LTST, covering the daily maximum and minimum values. The values plotted in Fig. 2 are the average values between the two. We further plot the 24h-averaged surface temperature for 8 sols for which data were taken together with an estimate of the average surface temperature calculated from the 6:00 and 13:00 LTST values and using a relation between the 24h-averaged temperature and the average between the peak-to-peak values derived from the data of InSight year 1. Both curves differ notably by 8 K in the winter and by 13 K during the summer. The difference is due to the non-symmetry of the variation of the surface temperature during a sol (compare Fig. S3 in the Supporting Information).

Temperature in the soil varied by 5.3 K during a sol for the coldest sol sampled, sol 871, to 6.7 K for the warmest sol, sol 1202. Over the seasons, TEM-A 24h-averaged

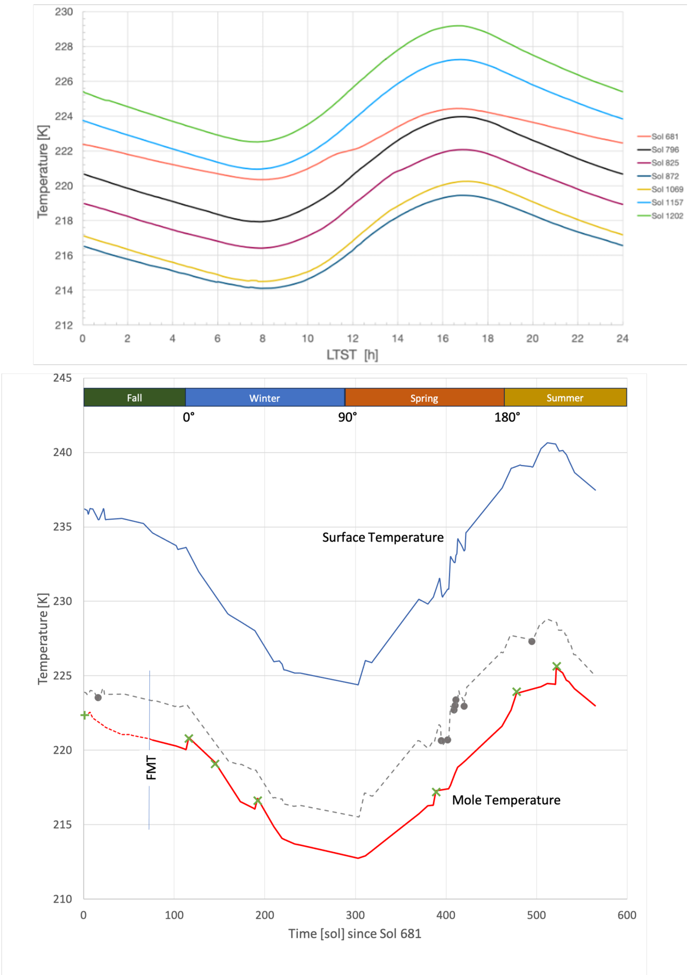

Figure 2. Top: Soil temperature as measured by the TEM-A sensor as a function of local true solar time (LTST) on the sols indicated. The uncertainty of the temperature measured with TEM-A is estimated to be 0.1 K (Grott et al., 2019). Bottom: Surface and TEM-A and motor H/K temperatures versus time in Martian solar days (sol). The blue line gives the surface temperature averaged using radiometer readings at 6:00 and 13:00 LTST. Their uncertainty is estimated to be 2 K (Mueller et al., 2020). The grey dots give the available 24h-averaged surface temperatures. Their uncertainty is about 3K, given the uncertainty of up to 6K of temperature measurements in the late afternoon. The dashed grey line gives an estimate of the 24h-averaged temperature using the diurnal minimum and maximum temperatures of year 2 (blue line) and a mapping derived from 24h averages and peak-to-peak averages from year 1. The green crosses give the soil temperature measured by TEM-A from the top panel and averaged over one sol. The red line gives the mole motor H/K temperature, averaged using readings at 6:00 and 13:00 LTST with an uncertainty of 1 K. FMT indicates the sol (754) at which the Free Mole Test occurred. Additionally marked are the Northern hemisphere seasons and the solar longitude.

temperatures varied by 9 K from 216.8 K at sol 871 to 225.8 K at sol 1202. Note that the TEM-A measurements missed the temperature low around sol 980 (211.8 K at sol 981, Fig. 2 bottom) suggesting a temperature difference through the Martian year of 13.3 K. The annual average temperature calculated from the TEM-A recordings and the H/K data is 217.5 K. These compare with an annual average surface temperature of 221.6 K.

The damping of the diurnal and annual surface temperature variation and the phase shift with increasing depth can be used to estimate the thermal diffusivity and the depth to the back-end of the mole. Note that the latter was not well known before but was estimated to be 1-2 cm from camera data (Spohn, Hudson, Marteau, et al., 2022). We briefly describe our calculation here. More detail can be found in the Supporting Information Text S2.

It is well known (e.g., Carslaw & Jaeger, 1959) that the peak-to-peak temperature oscillation in a half-space heated periodically at the surface decreases with $exp(z/\delta)$, where z is depth and where $\delta = \sqrt{\kappa P/\pi}$ is the thermal skin depth, with P the period of the forcing temperature variation. Averaged over the depth interval sampled by the mole, we get for the peak-to-peak variation $\overline{\Delta T}$

$$\overline{\Delta T} = \frac{1}{z_1 - z_0} \int_{z_0}^{z_1} \Delta T(z=0) e^{-z/\delta} dz \tag{1}$$

where z_0 is the depth to the mole back-end and z_1 the depth to the mole tip. The phase lag Φ of the temperature variation increases with depth according to z/δ . Because the temperature signal decreases exponentially along the mole, we calculate the average value of the phase lag by taking a weighted average over the depth extent of the mole:

$$\overline{\Phi} = \frac{\frac{1}{\delta}\int_{z_0}^{z_1} z e^{-(z-z_0)/\delta} dz}{\int_{z_0}^{z_1} e^{-(z-z_0)/\delta} dz} \tag{2}$$

The diurnal and annual thermal skin depths, respectively, are given by:

$$\delta_d = \sqrt{\frac{\kappa P_d}{\pi}} \tag{3}$$

$$\delta_a = \sqrt{\frac{\kappa P_a}{\pi}} \tag{4}$$

where P_d is a sol and P_a a Martian year in seconds.

For the diurnal wave, we use the six TEM-A 24h recordings available for sols 796 - 1202 as shown in Fig. 2. (We do not use the sol 681 TEM-A recording because it is quite anomalous, as was discussed further above.) We compare these with 24h surface temperature recordings from the HP^3 radiometer RAD. Unfortunately, these were not taken on the same sols as the TEM-A recordings. Therefore, we use the next available sol with 24h RAD data. These are sol 1075 for sol 1069 and sol 1175 for sol 1157. For sols 796, 825, 872 and 1202, we use data from a close-by sol with similar solar longitude of the previous Martian year. These are sol 120 (for 796), sol 138 (825), sol 190 (872) and sol 511 (1202). Although InSight year 2 on Mars was overall cooler by a few Kelvin than year 1, the diurnal temperature variations were very similar. Fig. 3 shows the solutions to Eqns. 1 and 2 in terms of z_0 and κ after de-trending for - albeit small - dependencies of the measured amplitude ratio and phase lag on the surface temperature and of the phase lag on the mismatch between the sols used. Accordingly, the top-most piece of the mole is at a depth of 5.07 ± 0.25 mm and the thermal diffusivity is $2.30 \pm 0.03 \times 10^{-8}$ m^2 s^{-1}. Considering the radius of the mole of 13.5 mm and its inclination towards vertical of $30 \pm 0.2°$, the center of the back-cap is at a depth of 11.8 ± 0.3 mm. The thermal skin depth is found to be 25 ± 0.4 mm and the wavelength 160 mm. The uncertainties of the measurements are detailed in the Supporting Information Text S2.

The data for the annual wave are significantly noisier than the diurnal wave recordings, which should partly be a consequence of the weather on Mars. A total of 1.81 Martian years (1231 sols) of surface temperatures are available but only 565 sols (0.85a) of buried mole data and only 459 sols (0.69a) after the Free Mole Test with the final hammering (compare Fig. 2). For the first year, surface temperatures were recorded over 24h at a coverage varying between 2 and 5700 recordings per sol. For the second year, data were regularly taken at 6:00 and 13:00 LTST to cover the daily minimum and maximum temperatures but only a few high time-resolution recordings could be afforded. Therefore, we use the 6:00 and 13:00 LTST recordings for the analysis (see Piqueux et al. (2021) for further advantages of using the RAD peak temperature values for thermophysical considerations). As a caveat we note that because of asymmetry in the daily surface temperature variation (compare Fig. S3 in the Supporting Information), the 24h temperature average and the average between the temperature extremes differed between 8 K during the cold season and 13 K during the warmest times. At mole depth, the temperature variation is significantly more symmetric and the difference between the 24h av-

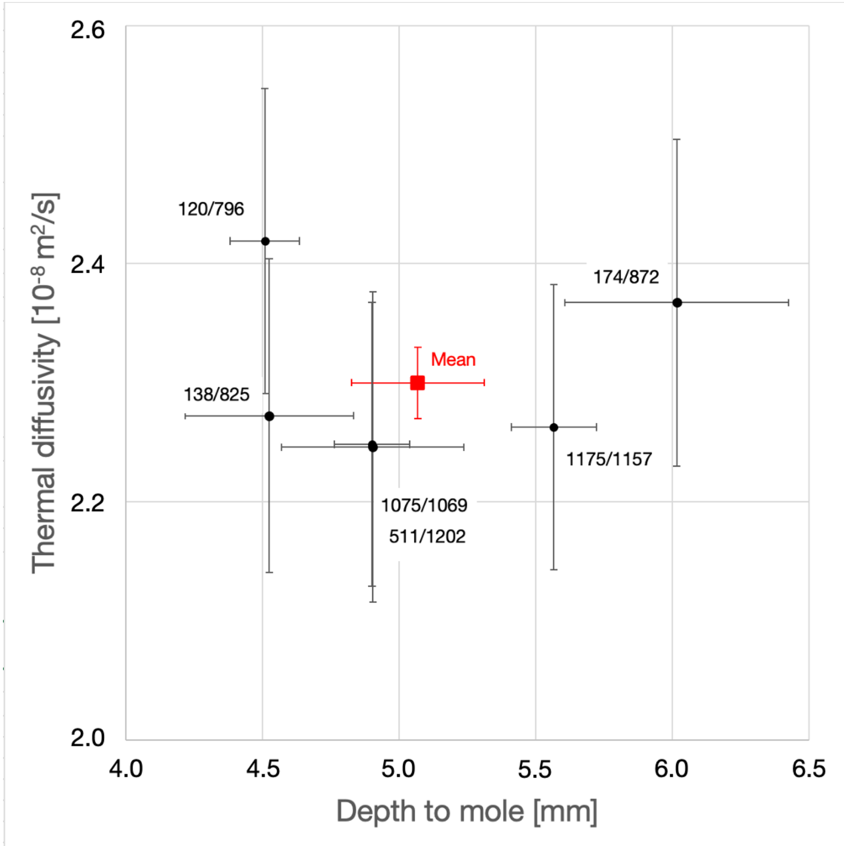

Figure 3. Thermal diffusivity versus depth to the back-end of the mole as calculated from the attenuation and the phase shift of the diurnal wave measured by the TEM-A sensor of the HP^3 mole and the HP^3 radiometer. The measurement uncertainties, the mean value and its standard error are indicated. The data points are marked by the combination of the sols used in the analysis.

erage and the average of the minimum and maximum temperatures is just a few tenth of a Kelvin.

The difference in temperature between the hottest day on the Martian surface and the coldest based on averaging the daily maximum and minimum temperatures was found to be 16.3K with an estimated uncertainty of 1K. At mole depth, 6 sols of high quality 24h TEM-A data are available, complemented by re-calibrated housekeeping data of the mole motor temperature taken at 6:00 and 13:00 LTST. The annual temperature variation at depth was found to be 13.2K, again with an estimated uncertainty of 1K. We estimate the phase shift between the surface and mole signal from a Fourier analysis of the signal. The analysis resulted in an estimate of the phase lag of 20.9 sols with an estimated uncertainty of ± 2 sols, an estimate somewhat more conservative than the discretization uncertainty of ± 1.3 sols. This should accommodate for the contribution of the uncertainty in the amplitude to the uncertainty in the phase difference.

Attempts to use both the phase lag and the amplitude ratio to estimate κ and z_0 as with the diurnal wave have proven to be impractical as the relative uncertainty for z_0 turned out to be several 100% in that case. Instead, we used the value of the depth to the mole determined from the diurnal wave and its uncertainty to estimate κ using the amplitude ratio and the phase lag separately. From the amplitude ratio we found κ to be $3.68{\pm}1.1{\times}10^{-8}$ W/m^2 and $3.80{\pm}0.51{\times}10^{-8}$ W/m^2 from the phase lag. Taking the average value of the two, we calculate a thermal skin depth of 84±10cm and a wavelength of 5.3m.

3 Discussion and Conclusions

We have recorded the soil temperature measured by sensors on the HP^3 mole as a function of time during 7 sols as well as during 4/5 of a Martian year. By comparing the mole temperature with the surface temperature we find a depth to the center of the mole back-end of 1.2 cm using the diurnal thermal wave. The thermal diffusivity was found to be $2.30{\pm}0.09{\times}10^{-8}$ m/s^2. Using the annual wave data we find a thermal diffusivity of 3.74 $\pm 0.61{\times}10^{-8}$ m^2/s, suggesting that the thermal diffusivity increases with depth. Independent estimates of the thickness of the layer above the back-end of the mole from camera data taken during burial and tamping suggest a 1-2 cm (Spohn, Hudson, Marteau, et al., 2022) thick layer of sand/dust above the mole. The average thermal conductivity reported by Grott et al. (2021) is $k = 0.039{\pm}0.002$ W/m K and the density 1211^{+149}_{-113} kg/m^3. Assuming a heat capacity c as given by Morgan et al. (2018) of 630J/kg K, a thermal diffusivity $\kappa = k/\rho c$ of $5.1{\pm}0.8{\times}10^{-8}$ m^2/s (not counting the error in the heat capacity) is calculated. While the diurnal wave can be considered to sample the top few cm of the regolith where the thermal conductivity is likely to be smaller than in the layer below (Spohn, Hudson, Marteau, et al., 2022; Mueller et al., 2021; Piqueux et al., 2021), the annual wave and the TEM-A thermal conductivity measurement should cover a similar depth range, albeit with the annual wave penetrating several mole lengths deeper. While the thermal diffusivity values differ, it is fair to say that their 1-σ confidence ranges overlap. We further note that the present value is close to the pre-mission estimate by Morgan et al. (2018).

A representative average value of the temperature is 217.5 K with diurnal variations of 5 to 7K and seasonal variations of 13K, respectively. The question arises for which depth or depth range the estimation should be considered representative, noting that temperature generally varies with depth in the Martian soil. The measurements of the TEM-A sensors give values averaged over at least the depth extent of the sensor foils, if not over the depth extent of the entire mole. The thermal conductivity of the mole is more than 10 times larger than that of the soil suggesting that the mole is close to isothermal. Given that a TEM-A foil is 31.5cm long and that the tilt of the mole is 30°, their depth extent will be 27.3cm. With a depth to the back-end of the mole in its final configuration of 1.2cm and a mole length of 40 cm, the mole tip is at a depth of 36 cm. Since the H/K sensor is at 17.3cm distance from the back-end, it is at a depth of 16.2cm below the datum while the mid-point of the TEM-A foil is at 17.2cm depth. The center of the mole is at a depth of 19.2cm.

Another way to approach the problem is by considering the damping of the daily and annual thermal waves and finding the depth at which the recorded temperature and its diurnal and annual variation may be expected. By considering the exponential decrease of the peak-to-peak temperature variation we find for an amplitude ratio of 0.06 for the diurnal wave a representative depth of 7cm. For the annual wave with an amplitude ratio of 0.81 a representative depth of 17 cm results. Assuming a Martian surface heat flow of 20 mW/m^2 (Plesa et al., 2018; Khan et al., 2021; Drilleau et al., 2022) and a thermal conductivity of 0.03-0.04 W/m K, consistent with the present value of κ and Grott et al. (2021), a thermal gradient of 0.5-0.7K/m results, suggesting a temperature difference between the two representative depths quoted above of less than 0.1K, smaller than the uncertainty range of even the high quality TEM-A data. We can use the gradient to estimate the temperature increase through the top 5m of the regolith to obtain 3K and a bottom temperature of 220.5K.

The average temperature value of 217.5K is 1 - 2K above the values given by Grott et al. (2007), lending support to the validity of this type of thermal models. These authors have assumed thermal diffusivity values between 1 and 2×10^{-8} m^2/s and 2×10^{-8} m^2/s and used the NASA/MSFC Mars GRAM model (Haberle et al., 1993) for the surface temperature. It is about 55 K below the melting temperature of pure ice I and 45 K below the triple point of the "average Mars salinity water" of Jones et al. (2011). It is about 20 K above the H_2O-$Ca(ClO_4)_2$ eutectic and above the sublimation temperature of ice at Martian atmosphere pressure. This confirms the notion that the Martian soil at Homestead Hollow should be desiccated as is to be expected for low latitude regions on Mars (e.g., Clifford et al., 2010). In general, estimates of the depth to and the thickness of the cryosphere may need revision though, given that our estimates of the thermal diffusivity are about a factor of two lower than assumed for the near surface regolith from previous studies (e.g., Clifford et al., 2010). Replacing their thermal conductivity value of 0.06 W/m K with the one calculated here results in an estimated depth to the bottom of the cryosphere smaller by 150m, or by 5%.

Jones et al. (2011) discuss a phase space for liquid water on Mars to evaluate the astrobiological potential of the planet. As an upper estimate of the surface temperature on Mars they use a value of 305K based on observations of the Opportunity rover at Meridiani Planum. We note that similar values of surface temperature have been observed by HP^3 RAD - for instance 295K on sol 1202 - but that night temperatures have then fallen to values around 200K and that the temperature in the soil stayed well below the freezing temperature of water even in the afternoon (compare Fig. 2).

Deliquesence of brines in thin films may be more realistic and has been suggested for the Phoenix landing site (e.g., Chevrier et al., 2009; Rennó et al., 2009). For deliquescence to occur, the temperature must be above the eutectic of the brine and the humidity above the deliquescence relative humidity (e.g., Nuding et al., 2014). Pál and Kereszturi (2020) have discussed the potential for deliquescence of three brines including calcium perchlorate at Elysium Planitia, the wider region of the InSight landing site. They find about 2h long intervals of favourable conditions for the formation of calcium perchlorate brines in the evening between 21:00 and 23:00 LTST in early spring. We note that the conditions in the soil at a depth of about 10cm (and beyond) would be driven by the humidity as the temperature should be continuously above the eutectic of the calcium perchlorate brine of around 200K (Nuding et al., 2014). Judging from the model of Pál and Kereszturi (2020), the brine could exist for about 10h, a conclusion similar to the finding of Nuding et al. (2014) for the Phoenix landing site albeit for a depth of 3cm, there. At 3cm depth, the time window for deliquescence at Homestead Hollow should be shorter as the temperature should fall below the eutectic at around 6:00 LTST.

Efflorescence of salt from the supersolidus brine may well have caused the formation of the about 20cm thick duricurst that hampered the mole progress as reported in

Spohn, Hudson, Witte, et al. (2022) and Spohn, Hudson, Marteau, et al. (2022). Chemical measurements of soils and alteration rinds of rocks argue for low water/rock ratio alteration due to acidic weathering via interactions of atmospheric water vapor and soils to produce chlorine and sulfur rich salts that cement near surface soils and duricrusts on Mars (Banin et al., 1992; Haskin et al., 2005; Hurowitz et al., 2006, 2007).

4 Open Research

Calibrated HP^3 radiometer and TEM-A data are archived in NASA's Planetary Data System (InSight HP^3 Science Team, 2021). The specifically selected data, the housekeeping sensor data and the Excel workbooks used to evaluate the data have been made publicly available at Spohn (2024).

Acknowledgments

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This is InSight contribution number 337.

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