Differential Thermal Inertia - a tactical measure of soil properties

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Summary Thermal inertia is a volume property of materials that describes its efficiency at changing temperature. It is a function of density, heat capacity, and thermal conductivity, but for most geological materials the dominant term is density: thus, rocks have a relatively high thermal inertia but soils have a lower thermal inertia. Thermal inertia is thus useful for detecting and mapping areas of sand.

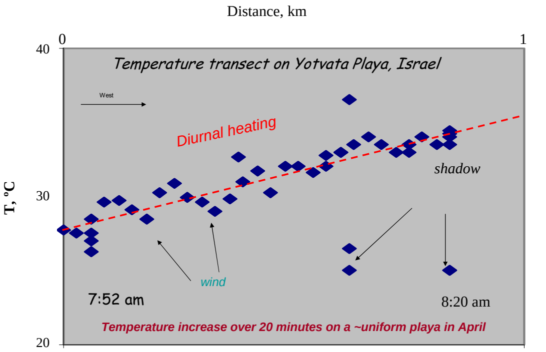
Thermal inertia is controlled not only by properties at the surface, but also by properties of the subsurface within the diurnal heating wave, about 25 cm. Therefore, thermal inertia is useful for distinguishing between deep particulate deposits and, for example, thin sand sheets that appear similar in optical images.

Thermal inertia is higher for wetter soils, because the water in soil pores absorbs heat and thus soil temperatures change more slowly than for dry soils. Thermal inertia thus can reveal areas of wet soils on fans or playas, even areas with a dry crust overlying wet soils that may be traffic hazards.

Thermal inertia is commonly calculated from day/night pairs of thermal images, taken at noon and midnight to give the full thermal contrast, plus a daytime albedo image. Image registration and the possibility of rainfall, cloudiness, formation of dew, or heat loss to wind all limit the accuracy of the day/night approach. It is also awkward to apply: the nighttime overpass of many satellites may be a week or more later than the daytime overpass, giving weather a chance to change. UAVs can, of course, overcome this problem, but even with images only 12 hours apart weather changes can affect recovery accuracy. Furthermore, in a tactical setting it may be problematical to wait 12 hours for information on terrain conditions.

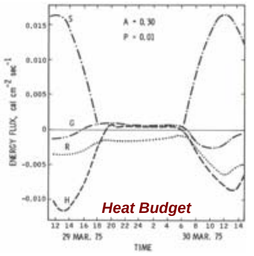
The slope of the daily heating curve, dT/dt, is also proportional to thermal inertia. dT/dt is greatest in mid-morning after sun-up and evening after sun-down (~5-15 K/hr), out of phase with the day/night times of measurement. Measuring dT/dt overcomes most of the difficulties associated with changeable weather, and is less sensitive to albedo than the day/night approach. If albedo is ignored, the his opportunity for misregistration is reduced. The limiting factor is probably measurement error, generally on the order of 0.25 K for ASTER and modern thermal cameras. Therefore, if SNR>10 is desired, image repeat times must be 15-45 min or more. More than a factor ten faster than the day/night method.

Thermal inertia (TI): $TI = \sqrt{\rho c K}$
Where π = density, c = heart capacity, K = thermal conductivity.



Previous Work: Early work on remote-sensing thermal inertia was done by Lunar astronomers. It was adapted to terrestrial work by Pohn et al. (1973). Kahle (1977) developed a 4-D inversion model that estimated thermal inertia from day/night images plus DEMs to account for diurnal heating and slope, and Gillespie & Kahle (1977) applied the model to high-resolution images, demonstrating the effectiveness of thermal inertia at finding veneers of sand over lava. Kahle and Alley (1980) pointed out the inaccuracies due to weather and recommended using an approximate apparent thermal inertia (ATI) instead of the full inversion, and this approach has been followed by most users since (ATI=(1-a)$(T_d-T_n)^{-1}$), where *a* = albedo, and *d* and *n* refer to the day and night maximum and minimum temperatures. Some current Mars geologists use ignore albedo in calculating thermal inertia from day/night THEMIS images. Sabol (accompanying poster) has calculated thermal inertia to map soil moisture on Soda lake playa, California.

Theoretical foundation: Early work on remote-sensing thermal inertia was done by Lunar astronomers. It was adapted to terrestrial work by Pohn et al. (1976). Kahle (1977) developed a 4-D inversion model that estimated thermal inertia from day/night images plus DEMs to account for diurnal heating and slope, and Gillespie & Kahle (1977) applied the model to high-resolution images, demonstrating the effectiveness of thermal inertia at finding veneers of sand over lava. Kahle and Alley (1980) pointed out the inaccuracies due to weather and recommended using an approximate apparent thermal inertia (ATI) instead of the full inversion, and this approach has been followed by most users since (ATI=(1-a)(T_d-T_n)-1), where *a* = albedo, and *d* and *n* refer to the day and night maximum and minimum temperatures. Some current Mars geologists use ignore albedo in calculating thermal inertia from day/night THEMIS images. Sabol (accompanying poster) has calculated thermal inertia to map soil moisture on Soda lake playa, California. If the range of temperatures is small enough (<30 K) $L_d-L_n \approx x(T_d-T_n)$ (L= radiance, x= scaling factor).



Ground temperature depends on the solar flux ***S*** and topographic slope and aspect), sensible heat flux $\boldsymbol{H_s}$ (wind); heat diffusion into the ground ***G***, latent heat $\boldsymbol{L_W}$ (moisture), outgoing longwave radiation ***R***, and physical parameters ρ, ***c***, and ***K***. The change of ground temperature dT/dt is related to thermal inertia. Surface temperatures are controlled strongly by evaporation and wind: apparent TI will be nearly infinite for moist soils. Sensible heat transport also exerts strong control.

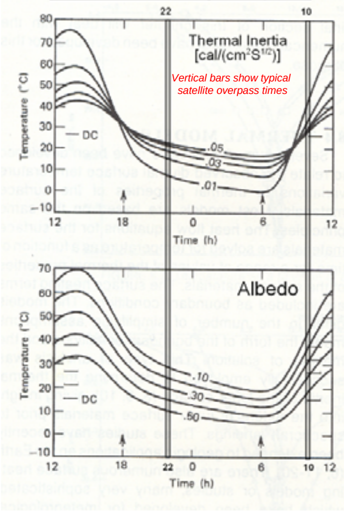
S~(1-a)*cos i; I = incidence angle
R = ε σ T⁴; σ=Stefan-Boltzmann constant

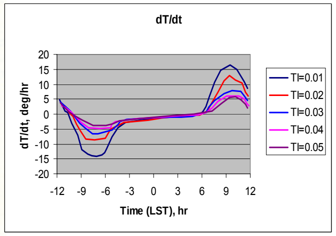
$$\frac{\partial G}{\partial z} = -\rho c \frac{\partial}{\partial z}\left(K \frac{\partial T}{\partial z}\right) = -\rho c \boxed{\frac{\partial T}{\partial t}}$$

G =heat flux;
z = depth

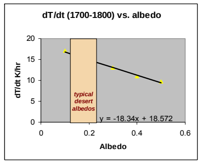
$$\boxed{S + R + H_s + L_w + G = 0}$$

Kahle thermal models from Siegal & Gillespie, 1980

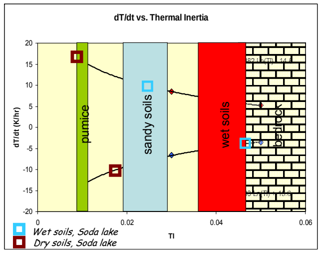




Diurnal temperature curves show that (T_d-T_n) can be 70 K or more in deserts with dry soils. The range decreases with increasing TI. Increasing albedo reduces the absorbed sunlight, primarily lowering the heating curve.

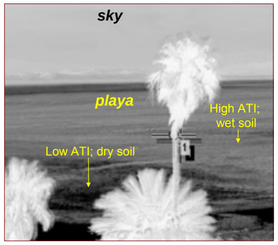


Therefore, dT/dt is not very sensitive to albedo, and for typical desert values albedo affects the dT/dt by only ~3 K/hr or less. Albedo correction is useful for quantitative work, but in the tactical environment it can be ignored.



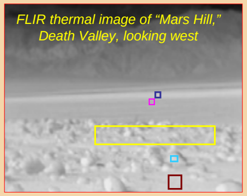
dT/dt is more sensitive to TI itself, with values ranging from ~5 to ~15 K/hr. Values for Soda Lake plotted to left correspond reasonably well to cataloged values (Kahle, 1980) but disagree from morning to evening, emphasizing the role that factors such as wind play in affecting inversions for TI. Soda Lake data were measured over 92 minutes. Although differences are ~2 x what can be attributed to albedo effects, this emphasizes that tactical measures are best used photointerpretively. Error due to measurement alone (NEΔT =0.25 K) is 0.22 K/hr and is smalle r than the data points. In order to maintain a signal/noise ratio of 10 for a surface cooling/warming at 5 K/hr, a measurement interval of 42 minutes is required. At 10 K/hr, the time is 21 minutes. Measurement with thermal cameras (many pixels) instead of radiometers (1 pixel) cuts the interval to a few minutes, practical for tactical use.

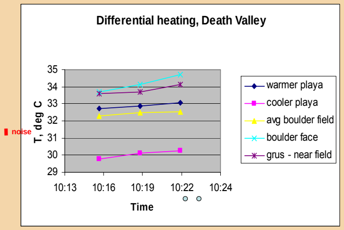
Application: Thermal images taken with FLIR cameras a few minutes or hours apart can be differenced to estimate TI. The example on the right shows Soda lake playa, with images taken near noon and midnight for maximum thermal contrast (Sabol et al., this poster series). Moist soil has very high TI due to latent heat (evaporation), but it lowers as the soil dries at the surface and lowers further as the soil dries at depth. Because the thermal connectivity operates over time via diffusion, day/night image pairs sense deeper than those made over short time intervals. Nevertheless, temperatures are affected by pre-existing temperature gradients..



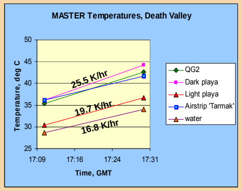
Day/night ATI image of Soda Lake, California

An ATI image made in Death Valley over only 8 minutes shows that then technique works well even under adverse conditions. The thermal image (below, left) shows a boulder-strewn slope grading to a clay/salt playa in the mid distance. Beyond are alluvial fans and the Panamint Mountains. T values taken from the boxed areas were used to estimate ATI.

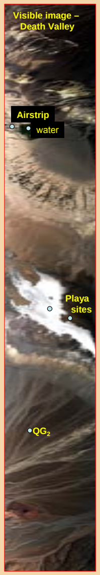




A sun-facing boulder (high TI) warmed faster than anything else in the image, because the incidence angle was small. The low-TI grus showed the next-highest rate of warming. The red bar indicates the noise level for this experiment The quantitative data become more reliable with increasing time between images.



The airborne MASTER image simulates the view of a UAV might have from 3000 m. Repeat thermal images taken 19 minutes apart at µ11 m clearly show DTI for different surface materials. Standing water has a relatively high inertia, but the DTI of all the materials correspond to low "actual" inertias found using the graph at the bottom of column 1. The reasons for this are unclear and emphasize that these relative products are best used photointerpretively.



Below, false-color DTI composite made in the afternoon from tripod-mounted thermal FLIR images taken ~1 hour apart (R is 2 hrs after B) clearly show differences in DTI for sandy soils and cobble surfaces. Sand has a low inertia, cools quickly, and therefore B>R. The cobbles have a higher inertia and are redder. The topographic low is about 45 cm across. Kit Fox Hills are in Death Valley.

Sponsors
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