Thermal-Infrared imaging

What is it?

- measurement of emitted radiation (temperature)
- at one or more times (thermal inertia)
- at one or more wavelengths (composition)

Why bother?

- see at night
- temperatures
- energy fluxes
- material properties (resistance to temperature change, i.e. thermal inertia)
- composition (emissivities)
Kirchhoff’s Law

\[ \varepsilon = 1 - R \]
**Restrahlen band**: $k$ maximized at fundamental vibration mode frequency

**Christiansen frequency**: $n = 1$, minimizing reflectance

Reflectance or emission spectrum results from combination of $n, k$ variations
Emissivity spectra of rocks

Emissivity Spectra

- limestone
- dolomite
- gypsum
- varnish/ss
Emissivity spectra of rocks

![Emissivity spectra of rocks](image)

- **Granite**
- **Anorthosite**
- **Basalt**
- **Dunite**
- **Obsidian**
Emissivity spectra of approximate graybodies

Emissivity of soil & graybodies

- green grass
- conifers
- ice
- snow
- dry grass
- spodosol
What compositions can be determined in the TIR?

Mostly vibrational resonance, not electronic processes therefore, relatively large molecules

Silicate minerals \((\text{SiO}_4^{-4})\); quartz \((\text{SiO}_2)\)
Sulfates \((\text{SO}_4^{-2})\); sulfur dioxide \((\text{SO}_2)\)
Carbonates \((\text{CO}_3^{-2})\); carbon dioxide \((\text{CO}_2)\)
Ozone \((\text{O}_3)\)
Water \((\text{H}_2\text{O})\)
Organic molecules
Figure 7. Thermal infrared spectra of representative silicate, carbonate, and sulfate minerals. Laboratory data are from the Arizona State University (ASU) spectral library [Christensen et al., 2000a].
Figure 7. Thermal infrared spectra of representative silicate, carbonate, and sulfate minerals. Laboratory data are from the Arizona State University (ASU) spectral library [Christensen et al., 2000a].
Thermal infrared spectral features of silicates (Clark, 1999)

CHRISTIANSEN PEAKS (TRANSMISSION MAXIMA)

INTERMEDIATE

MAFIC

ULTRAMAFIC

FELSIC

MAFIC

U MAFIC

FELSIC

WAVELENGTH, IN MICROMETERS

7 8 9 10 11 12 15 17 20 30 40

ASYMMETRIC STRETCHES

O - Si - O
Si - O - Si

SYMmetric

O - Si - O

H - O - Al

SYMmetric STRETCHES

Si - O - Si
Al - O

DIFFERENT FOR DIFFERENT FELDSPARS

Si, Al - O - Al, Si

SAME FOR ALL FELDSPARS

BENDING DEFORMATION LATTICE MODES

SYMM Si - O - Si QUARTZ

TRANSMISSION MINIMA (REFLECTION MAXIMA)
Death Valley, California
Saline Valley, California

VNIR

SWIR

TIR
Mauna Loa, Hawaii

MASTER VNIR, daytime

ASTER TIR, daytime

MTI TIR, nighttime
Effects of Particle Size, TIR

montmorillonite+hematite

slightly altered basaltic rock
Not all thermal images are dominated by *solar* heating of the surface.

Enceladus
Not all thermal images are dominated by *solar* heating of the surface

ASTER images of Yellowstone: VNIR (left) and TIR (right)
A little about solving sets of equations

If you measure R there are 2 unknowns: $\varepsilon$ and T
If you measure R at a different $\lambda$, there is another unknown $\varepsilon$

If you measure a spectrum of n bands, there are n+1 unknowns

You must have the same number of measurements as unknowns to solve a set of equations

How can you do this for TIR data?
Temperature - Emissivity Separation

• Two-time two-channel method
  • Completely determined

• Model emissivity method
  • Assume $\varepsilon_{10\mu m} = 0.96$

• Normalized Emissivity method
  • Assume $\varepsilon_{max} = 1$
But if $\varepsilon_{max} < 1 \ldots$

**Figure 11.** The emissivity error that arises from deriving sample temperature from a nonunit emissivity Christiansen feature (1359 cm$^{-1}$ is used here). Three different $\varepsilon_{CF}$ cases are plotted for four different sample temperatures.
Example of $\varepsilon_{\text{max}} < 1$: chlorides

Osterloo et al. (2008)
Thermal inertia: $\frac{dQ}{dT}$
Resistance of matter to changing temperature as heat is applied
Veg Mapping - Thermal

Red = 10:00 am
Green = 2:00 pm
Blue = 11:00 pm

Conifers cooler during day & warmer at night
Sunlight heats planetary surfaces in a sinusoidal pattern.
Surface temperature responds to heating (and lack of heating), but with a lag.
Albedo

• The *albedo* of a planetary surface ($A$) is the percent of sunlight that it reflects.

• Albedo can range from $A=1$ (pure white) to $A=0$ (pure black). For Earth, average $A$ is 0.39. For the Moon, average $A$ is 0.12.

• The amount of sunlight absorbed by a surface is $1-A$
The effect of varying albedo on diurnal temperature curves
Other physical quantities that affect temperature

- Thermal Conductivity \((k)\) is a measure of the rate at which heat is conducted by a medium.
  \[k_{\text{rock}} < k_{\text{water}} < k_{\text{steel}}\]

- Specific heat capacity \((C)\) is a measure of the amount of heat required to raise the temperature of a given amount of material by a certain number of degrees.
  \[C_{\text{water}} > C_{\text{rocks}} > C_{\text{steel}}\]

- Density \((\rho)\) also important
Thermal Inertia

- Thermal inertia is a measure of the resistance offered by a substance undergoing temperature changes. It is given by:

\[ T.I. = (k \rho C)^{1/2} \]

Units are J m\(^{-2}\) s\(^{-1/2}\) K\(^{-1}\) (tiu)
The effect of thermal inertia on diurnal temperature curves
Thermal inertia and albedo are the two parameters that fundamentally control the shape of the diurnal temperature curve.
Thermal Inertia of Geologic Materials

\[ \text{T.I.} = (\kappa \rho C)^{1/2} \]

• For most geologic materials, \( \rho C \) only varies by a factor of two, whereas \( \kappa \) varies by many orders of magnitude.

• \( \kappa \) is mostly determined by particle size, degree of induration.

⇒ A concrete sidewalk has a much higher thermal inertia than a sandy beach!

Note that on Earth, the high \( C \) of water means moisture content also plays a big role in determining T.I.
Diurnal Temperature Curves

- Local Dawn
- Soils (Typical)
- Local Sunset
- Vegetation
- Standing Water
- Damp Terrain
- Metallic Objects

Rocks vs. Soil
- Soil
- Rock

Temperature vs. Time
Table 1. Estimated thermal properties of Mars-like geologic materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (kg m(^{-3}))</th>
<th>Specific Heat Capacity (J kg(^{-1}) K(^{-1}))</th>
<th>Thermal Conductivity (W m(^{-1}) K(^{-1}))</th>
<th>Thermal Inertia (J m(^{-2}) s(^{-1/2}) K(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basalt</td>
<td>2600</td>
<td>800</td>
<td>2.5</td>
<td>2280</td>
</tr>
<tr>
<td>Sandstone</td>
<td>2300</td>
<td>800</td>
<td>0.5</td>
<td>960</td>
</tr>
<tr>
<td>Coarse Sand</td>
<td>1750</td>
<td>800</td>
<td>0.1</td>
<td>374</td>
</tr>
<tr>
<td>Fine Sand</td>
<td>1500</td>
<td>800</td>
<td>0.02</td>
<td>155</td>
</tr>
<tr>
<td>Fine Dust</td>
<td>1000</td>
<td>800</td>
<td>0.001</td>
<td>28</td>
</tr>
</tbody>
</table>

*Assuming a basaltic mineral composition for each material.
**Assuming martian atmospheric pressures in the interstice of the porous materials.
Blues indicate low TI ⇒ Fine-grained dust

Reds indicate high TI ⇒ Lots of rocks and outcrop
Martian albedo

Martian thermal inertia
Very low T.I. on Saturn moons $\Rightarrow$ high porosity?

Howett et al. (2010)
Computation of Thermal Inertia

For terrestrial applications, commonly use “Apparent Thermal Inertia” (ATI).

\[ ATI = N \times \frac{(1-A)}{\Delta T} \]

The denominator just indicates that thermal inertia is inversely proportional to the diurnal temperature range. The numerator normalizes for amount of insolation absorbed by the surface.
Terrestrial work mostly uses Apparent Thermal Inertia (ATI)

\[ ATI = N \times (1 - A) / \Delta T \]
Peace Vallis,
Gale crater, Mars
Calculated from day-night image pairs from the THEMIS instrument around Mars

Fergason et al., 2006; Anderson & Bell, 2010
ΔT images of alluvial fans, Death Valley & Owens Valley, CA

Hardgrove et al. (2010)
Temperature and Land Cover Remote Sensing of Atlanta, Georgia in Thermal Infrared

http://www.ghcc.msfc.nasa.gov/atlanta/
Question

Below are daytime and nighttime thermal infrared images (9.60-10.2μm) of Atlanta at 10m/pixel resolution. Describe the changes in appearance of roads, buildings, forest, and water over the course of the day.

In light of this information, what should urban planners do to minimize the “urban heat island” effect?
Columbus crater (Night IR over Day IR)

Figure from Baldridge et al. (2009)
Columbus crater (Night IR over Day IR)
Columbus crater: CRISM data on HiRISE DEM

Polyhydrated sulfates

Kaolinite

Wray et al. (2011)
Near-IR spectra allowed precise mineral identification

Gypsum
(CaSO$_4$·2H$_2$O)
Thermal IR spectral data allowed estimating **abundances**

*Baldridge et al. (2013)*
Why is “How Much?” a difficult question?

**Thermal Infrared**
Dominated by single-scattering for coarse granules or rocks
~ Linear

**Visible/Near-Infrared**
Dominated by multiple-scattering, grain size and composition effect scattering
~ Non-linear
But rough surfaces can complicate thermal IR unmixing... (because single scattering no longer dominates)

Fig. 19. A schematic diagram illustrating how the light-toned rock could have a rough surface texture that promotes multiple scattering. While this property is advantageous to near-infrared spectral detection, it is disadvantageous in the thermal infrared because as the porosity increases the emission of the surface approaches that of a blackbody.
Cavity Effect

Norite rock with two drilled holes:

PHOTO

Thermal IR

Thermal IR spectra:

3D view (DTM resolution 0.002 m):

Elevation, m

Modeled apparent emissivity:

Emissivity