Thermal infrared of EM spectrum

- All objects have a temperature above absolute zero (0 K) emit EM energy (in 3.0-14 µm).
  - Human being has normal 98.6 °F (37 °C)
- Our eyes are only sensitive to visible energy (0.4-0.7 µm). Human sense thermal energy through touch. While detectors (sensors) are sensitive to all EM spectrum.
- All objects (vegetation, soil, rock, water, concrete, etc) selectively absorb solar short-wavelength energy and radiate thermal infrared energy.
Thermal infrared remote sensing measures:

- Land and ocean surface temperature,
- Atmosphere sounding
  - Temperature and humidity
  - Trace gas concentrations
- Radiation balance
- Emissivity
- **Applications** such as:
  - Determine the type of materials based on materials’ emission characteristics
  - Evaluate if significant changes of emission characteristics have taken place through time. In this manner, it is possible to identify certain diseases in humans, stress in plants, thermal pollution in water bodies, the loss of heat from buildings due to insulation.
Kinetic heat, radiant flux and temperature,

- The energy of particles of matter in random motion is called kinetic heat (also referred to as internal, real, or true heat).
- We can measure the true kinetic temperature ($T_{\text{kin}}$) or concentration of this heat using a thermometer.
  - We perform this *in situ* (in place) temperature measurement when we are ill.
  - We can also measure the true kinetic internal temperature of soil or water by physically touching them with a thermometer.
- When these particles (have kinetic heat) collide they change their energy state and emit electromagnetic radiation called **radiant flux** (watts). The concentration of the amount of radiant flux exiting (emitted from) an object is its radiant temperature ($T_{\text{rad}}$).
- There is usually a high positive correlation between the true kinetic temperature of an object ($T_{\text{kin}}$) and the amount of radiant flux radiated from the object ($T_{\text{rad}}$). Therefore, we can utilize radiometers placed some distance from the object to measure its radiant temperature which hopefully correlates well with the object’s true kinetic temperature. *This is the basis of thermal infrared remote sensing.*
- Unfortunately, the relationship is not perfect, with the remote measurement of the radiant temperature always being slightly less than the true kinetic temperature of the object. This is due to a thermal property called **emissivity**.
Thermal Radiation

- Blackbody (perfect absorber and emitter)
- Stenfan-Boltzmann Law \( (M_B = \sigma T^4 \text{ in Wm}^{-2} ) \)
- Wien’s Displacement Law \( (\lambda_{\text{max}} = 2898/T) \)
- Emissivity \( (\varepsilon = M_R / M_B) \) at the same temperature
  - \( M_B = \sigma T_{\text{kin}}^4 \)
  - \( M_R = \sigma T_{\text{rad}}^4 \)
  - \( \varepsilon = M_R / M_B = T_{\text{rad}}^4 / T_{\text{kin}}^4 \)

The dominant wavelength \( (\lambda_{\text{max}}) \) provides valuable information about which part of the thermal spectrum we might want to sense in. For example, if we are looking for **800 °K forest fires** that have a dominant wavelength of approximately **3.62 µm** then the most appropriate remote sensing system might be a **3-5 µm** thermal infrared detector.
  - MODIS band 20-25 are in **3-5 µm**.

If we are interested in **soil, water, and rock with ambient temperatures on the earth’s surface of 300 °K** and a dominant wavelength of **9.66 µm**, then a thermal infrared detector operating in the **8 - 14 µm** region might be most appropriate.
  - Landsat image thermal band (6) is in **10.4-12.5 µm**
  - ASTER band 12 and 13 are in **8 - 14 µm**
  - MODIS band 29-30 and 31-32 are in **8 - 14 µm**
• The *diurnal cycle* encompasses 24 hours. Beginning at sunrise, the earth begins intercepting mainly short wavelength energy (0.4 - 0.7 µm) from the Sun. From about 6:00 am to 8:00 pm, the terrain intercepts the *incoming short wavelength energy* and reflects much of it back into the atmosphere where we can use optical remote sensors to measure the reflected energy.

• However, some of the incident short wavelength energy is absorbed by the terrain and then re-radiated back into the atmosphere as thermal infrared long wavelength radiation (3 - 100 µm). The *outgoing longwave radiation* reaches its highest value during the day when the surface temperature is highest. This peak usually lags two to four hours after the midday peak of incoming shortwave radiation, owing to the time taken to heat the soil.

• The contribution of reflected short wavelength energy and emitted long wavelength energy causes an energy surplus to take place during the day. Both incoming and outgoing shortwave radiation become zero after sunset (except for light from the moon and stars), but outgoing longwave radiation continues all night.
Peak Period of Daily Outgoing Longwave Radiation and the Diurnal Radiant Temperature of Soils and Rocks, Vegetation, Water, Moist Soil and Metal Objects

At the thermal crossover times, most of the materials have the almost same radiant temperature, it is not wise to do thermal remote sensing.

Water and vegetation have higher thermal capacity. In different time of thermal images, there are different performances even the materials.
Emissivity

Two rocks lying next to one another on the ground could have the same true kinetic temperature but have different radiant temperatures when sensed by a thermal radiometer simply because their emissivities are different. The emissivity of an object may be influenced by a number of factors, including:

- **color** -- darker colored objects are usually better absorbers and emitters (i.e. they have a higher emissivity) than lighter colored objects which tend to reflect more of the incident energy.

- **surface roughness** -- the greater the surface roughness of an object relative to the size of the incident wavelength, the greater the surface area of the object and potential for absorption and re-emission of energy.
Emissivity (2)

- **moisture content** -- the more moisture an object contains, the greater its ability to absorb energy and become a good emitter. Wet soil particles have a high emissivity similar to water.
- **compaction** -- the degree of soil compaction can affect emissivity.
- **field-of-view** -- the emissivity of a single leaf measured with a very high resolution thermal radiometer will have a different emissivity than an entire tree crown viewed using a coarse spatial resolution radiometer.
- **wavelength** -- the emissivity of an object is generally considered to be wavelength dependent. For example, while the emissivity of an object is often considered to be constant throughout the 8 - 14 mm region, its emissivity in the 3 - 5 mm region may be different.
- **viewing angle** - the emissivity of an object can vary with sensor viewing angle.
- We must take into account an object’s emissivity when we use our remote radiant temperature measurement to measure the object’s true kinetic temperature. This is done by applying Kirchoff’s radiation law
Spectral emissivity library

Source: Jeff Dozier
Kirchoff’s radiation law

\[ \Phi_i(\lambda) = \Phi_r(\lambda) + \Phi\tau(\lambda) + \Phi\alpha(\lambda) \]

\[ 1 = r(\lambda) + \tau(\lambda) + \alpha(\lambda) \]

Kirchoff found in the infrared portion of the spectrum \( \alpha(\lambda) = \varepsilon(\lambda) \)

Most materials do not lose any incident energy to transmittance, i.e. \( \tau(\lambda) = 0 \), so we can get

\[ 1 = r(\lambda) + \alpha(\lambda) = r(\lambda) + \varepsilon(\lambda) \]

This means reflectivity and emissivity has an inverse relationship; “good absorbers are good emitters” and “good reflectors are poor emitters”
Planck equation, brightness temperature, and physical (surface) temperature

- Black body radiation (W m\(^{-2}\)µm\(^{-1}\)sr\(^{-1}\)) using Planck equation:
  \[ B(\lambda, T) = \frac{2hc^2}{\lambda^5 \left( e^{hc/\lambda kT} - 1 \right)} \]

  - We call T is the physical (kinetic) temperature

- Through radiance recorded by a remote sensor, if we use the Planck equation, we can get a temperature, which we call brightness temperature \( T_b \), which is less than the real physical (or surface) temperature T.

\[
R(\lambda, T_b) = \frac{2hc^2}{\lambda^5 \left( e^{hc/\lambda kT_b} - 1 \right)} = \varepsilon_\lambda \cdot B(\lambda, T) = \varepsilon_\lambda \cdot \frac{2hc^2}{\lambda^5 \left( e^{hc/\lambda kT} - 1 \right)}
\]

\[
T = \frac{hc}{k\lambda \cdot \ln(1 - \varepsilon_\lambda + \varepsilon_\lambda e^{hc/k\lambda T_b})}
\]
NASA’s Earth Observing System missions with Thermal IR capability

- Landsat systems (MSS, TM, ETM+)
  - ETM+ has a 60 m band at 10.5-12.5 µm
- TRMM
  - CERES
- EOS Terra (Dec. 1999)
  - CERES, MODIS, ASTER, MOPITT
- EOS Aqua (May 2002)
  - AIRS, CERES, MODIS
- EOS Aura (July 2004)
  - HIRDLS, TES
CERES—Cloud-Earth Radiant Energy System

Source: Jeff Dozier
ASTER spectral bands on model atmosphere

Source: Jeff Dozier
ASTER—Advanced Spaceborne Thermal Emission and Reflection Radiometer

- 14 bands (15-90 m) in VIS, NIR, SWIR, and TIR

Mauna Loa images

Source: Jeff Dozier
AIRS—Advanced Infrared Sounder

- 2400 bands in IR (3.7-15 μm) and 4 bands in visible (0.4-1.0 μm)
  - Absorption “signature” around 4.2 μm and 15 μm (CO₂) and 6.3 μm (H₂O) enables temperature and humidity sounding to 1 km vertical resolution
  - Spatial resolution is 13.5 km
- Complemented by microwave sounders to deal with clouds

Source: Jeff Dozier
HIRDLS—High-Resolution Dynamic Limb Sounder

- Sound upper troposphere, stratosphere, and mesosphere for temperature and a variety of gases
  - $O_3$, $H_2O$, $CH_4$, $N_2O$, $NO_2$, $HNO_3$, $N_2O_5$, CFC-11, CFC-12, ClONO$_2$
- 21 bands from 6.12 $\mu$m to 17.76 $\mu$m

Source: Jeff Dozier
**TES**—Tropospheric Emission Spectrometer

- High-resolution infrared-imaging Fourier transform spectrometer
  - Spectral coverage of 3.2 to 15.4 μm at a spectral resolution of 0.025 cm\(^{-1}\)
  - Line-width-limited discrimination of most radiatively active gases in the Earth's lower atmosphere

Source: Jeff Dozier
MODIS—Moderate-Resolution Imaging Spectroradiometer

- 36 bands, 1 in SWIR, 6 in mid IR, 10 in thermal IR
- Measurements of
  - Surface/cloud temperature
  - Atmospheric temperature
  - Cirrus clouds and water vapor
  - Ozone
  - Cloud top altitude

Source: Jeff Dozier
MODIS land surface temperature and emissivity product led by Dr. Wan

http://www.ices.ucsb.edu/modis/modis-lst.html

\[ T_s = C \left( A_1 + A_2 \frac{1-\varepsilon}{\varepsilon} + A_3 \frac{\Delta \varepsilon}{\varepsilon^2} \right) \frac{T_{31} + T_{32}}{2} \]
\[ + \left( B_1 + B_2 \frac{1-\varepsilon}{\varepsilon} + B_3 \frac{\Delta \varepsilon}{\varepsilon^2} \right) \frac{T_{31} - T_{32}}{2} \]

where

\( T_{31}, T_{32} \) brightness temperatures in bands 31,32

\( \varepsilon = \frac{\varepsilon_{31} + \varepsilon_{32}}{2} \) and \( \Delta \varepsilon = \varepsilon_{31} - \varepsilon_{32} \)

\( A, B, C \) coefficients given by multidimensional lookup tables

(they depend on angle)
Examples of the Global MODIS LST Product

(courtesy of the MODLAND browse page)

(daytime 3 Aug 2001)

(nighttime 3 Aug 2001)
Urban Heat Island of San Antonio downtown area detected by MODIS temperature product 2:30 pm (CDT), July 14, 2004

Xie and Ytuarte, 2005
Urban Heat Island of San Antonio downtown area detected by MODIS temperature product 2:00 am (CDT), July 15, 2004

Xie and Ytuarte, 2005
Calibration and validation of MODIS T and E in Sevilleta, NM
Ocean surface temperature from MODIS

- MODIS ocean web site
- Click on Quality Assurance to get the browse tool [intuitive?]

Source: Jeff Dozier
Active fire detection:
MODIS fire and thermal anomalies products

http://modis-fire.gsfc.nasa.gov/index.asp

Image caption: Fires in the Bahamas, Florida and Cuba (03 April 2004, 18:30 UTC) identified using MODIS Aqua and outlined in red on the MODIS 1km corrected reflectance product
Fire detection

- Planck equation is a steeper function of $T$ at shorter wavelengths
Consider a pixel with a small fire

\[ L_j = fB_j(T_f) + (1 - f)B_j(T_b) \]

- \( f \): fraction of pixel on fire
- \( T_f \): fire temperature
- \( T_b \): background temperature
- \( B_j \): Planck radiance in band \( j \)
- \( L_j \): sensor radiance in band \( j \)

Source: Jeff Dozier
NASA Mars missions with Thermal IR capability

- Mars global surveyor
  - TES (0.3-3.5 )
- Mars Odyssey
  - THEMIS (5 visible at 18m, 10 thermal (6.78-10.88) at 100m)
- Mars Sprit Rover
  - Mini-TES
- Mars opportunity Rover
  - Launched 7/7/2003, landed 1/24/2004
  - Mini-TES
Scientists matched Bounce Rock’s mineral signature with minerals studied in laboratories here on Earth.

They found out that Bounce Rock is made up of about 70% pyroxene minerals that are also rich in calcium.
The chemical composition of Bounce Rock is also quite similar to another Mars meteorite called EETA79001-B.

That means Bounce Rock probably has a similar origin to this meteorite, which is a basalt rock.
The matching spectra of the Shergottite meteorite and Bounce Rock suggest that both were flung far from home by a meteor impact on Mars.

A large crater south of Opportunity’s landing site may be the location of the impact that threw Bounce Rock into Opportunity’s landing area.
NOAA and other missions with Thermal IR capability

- **GOES (NOAA)**
  - 3.78-4.03 (4 km), 6.47-7.02 (8 km), 10.2-11.2 (4 km), and 11.5-12.5 (4 km)

- **AVHRR (NOAA)**
  - 3.55-3.93, 10.30-11.30, 11.5-12.5. all in 1.1 km

- **NPOESS (joint NOAA/NASA/DoD)**
  - Middle-wave thermal 8 bands, long-wave thermal 4 bands
  - [http://www.ipo.noaa.gov/Technology/viirs_summary.html](http://www.ipo.noaa.gov/Technology/viirs_summary.html)
  - 400-800 m