Thermal Infrared Remote Sensing

Lecture 7
October 16, 2007
All objects have a temperature above absolute zero (0 K) emit EM energy (in 3.0-100 µm).

- Human being has normal 98.6 ºF (37 ºC)

- 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,
- Atmospheric
  - Temperature and humidity
  - Trace gas concentrations
- Radiation balance
- Emissivity
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.*
Planck equation

Black body radiation (W m\(^{-2}\)\(\mu\)m\(^{-1}\)) using Planck equation:
We call T the physical (kinetic) temperature

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

The distribution of energy from a blackbody at 70°F.

http://tes.asu.edu/MARS_SURVEYOR/MGSTES/TES_emissivity.html
Not a perfect emitter

The distribution of energy from quartz at two different temperatures: purple = 50°F, blue = 100°F.

http://tes.asu.edu/MARS_SURVEYOR/MGSTES/TES_emissivity.html
Emissivity

- Emissivity spectrum is the ratio of radiance spectrum of a non-perfect emitter over that of a perfect emitter (blackbody) at the same temperature.

Quartz emissivity spectrum: the result of dividing quartz radiance by blackbody radiance at the same temperature.
Emmisivity used to identify mineral composition
Brightness temperature, and physical (surface) 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 $T$.

$$L(\lambda, T_b) = \frac{2\pi hc^2}{\lambda^5 (e^{hc/\lambda kT_b}) - 1} = \varepsilon_\lambda \cdot B (\lambda, T) = \varepsilon_\lambda \cdot \frac{2\pi hc^2}{\lambda^5 (e^{hc/\lambda kT}) - 1}$$

$$T = \frac{hc}{k\lambda \cdot \ln(1 - \varepsilon_\lambda + \varepsilon_\lambda e^{hc/k\lambda T_b})}$$

$h$, Planck’s constant $= 6.626 \times 10^{-34}$ Ws$^2$

$T$, Kelvin (K)

c, $3 \times 10^8$ m/s

$k$, Boltzmann’s constant$= 1.38 \times 10^{-23}$ Ws/K

$L$ or $B$, radiance (Wm$^{-2}$$\mu$m$^{-1}$)

$c1=2\pi hc^2=3.74 \times 10^{-16}$ Wm$^2$

$c2=ch/k=0.0144$ mK
Thermal Radiation Raw

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

The dominant wavelength \( \left( \lambda_{\text{max}} \right) \) 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 \( \mu m \) then the most appropriate remote sensing system might be a 3-5 \( \mu m \) thermal infrared detector.
  - MODIS band 20-25 are in 3-5 \( \mu m \).

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 \( \mu m \), then a thermal infrared detector operating in the 8 - 14 \( \mu m \) region might be most appropriate.
  - Landsat image thermal band (6) is in 10.4-12.5 \( \mu m \)
  - ASTER band 12 and 13 are in 8 - 14 \( \mu m \)
  - MODIS band 29-30 and 31-32 are in 8 - 14 \( \mu m \)
• 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.
Kirchhoff’s radiation law

- \( \Phi_i = \Phi_r + \Phi_t + \Phi_\alpha \)
- \( 1 = r_\lambda + \tau_\lambda + \alpha_\lambda \)
- Kirchhoff found in the infrared portion of the spectrum \( \alpha_\lambda = \epsilon_\lambda \): “good absorbers are good emitters”
- Most materials does not lose any incident energy to transmittance, i.e. \( \tau_\lambda = 0 \), so we can get \( 1 = r_\lambda + \alpha_\lambda = r_\lambda + \epsilon_\lambda \) (or \( A + \epsilon \))
- This means reflectivity and emissivity has a inverse relationship: “good reflectors are poor emitters”
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
  - O₃, H₂O, CH₄, N₂O, NO₂, HNO₃, N₂O₅, CFC-11, CFC-12, CIONO₂
- 21 bands from 6.12 µm to 17.76 µm

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.icess.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)
Calibration and validation of MODIS T and E in Sevilleta, NM
Examples of the Global MODIS LST Product

(courtesy of the MODI.AND browse page)

(daytime 3 Aug 2001)

(nighttime 3 Aug 2001)
Urban Heat Island (UHI) effect and mitigation

- 2 to 10°F (1 to 6°C) hotter than nearby rural areas
- Elevated temperature can impact us by increasing peak energy demand, air conditioning costs, air pollution levels (ozone), rainfall, and heat-related illness and mortality
- Hard surfaces and vegetation loss contribute to flooding and water quality deterioration
- Cool technologies - reflective and green roofing, paving with light colored or porous materials, and a greatly expanded forest canopy
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
Heat Transfer

Convection

Conduction

Radiation
Ocean surface temperature from MODIS

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

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

- \( f \) 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 (6-50 µm)

- Mars Odyssey
  - THEMIS (5 visible at 18m, 10 thermal (6.78-10.88 µm) at 100m)

- Mars Spirit Rover
  - Mini-TES

- Mars opportunity Rover
  - Launched 7/7/2003, landed 1/24/2004
  - Mini-TES
What is TES?  

Thermal Emission Spectroscopy

- **Michelson Interferometer**, is the thermal IR portion of TES, covers the $6-50 \ \mu \text{m}$ (1655-200 cm$^{-1}$) wavelength range, with spectral sampling 5 and 10 cm$^{-1}$ (spectral resolution $\sim$10 - 20 cm$^{-1}$), 286 or 142 bands

- **Bolometric thermal radiance channel** ($5.5 \text{ to } \sim100 \ \mu \text{m}$)

- **Solar reflectance channel** ($0.3 \text{ to } 2.7 \ \mu \text{m}$), to measure the brightness of reflected solar energy
MGS - TES

Entered Mars orbit on board the MGS on Sep.11, 1997
How does TES determine surface composition?

**Mixed Spectra**

- Rocks are a *mixture* of minerals
- Emissivity spectrum from individual components of a mixture add together in a simple linear fashion.
- The linearity of the mixed spectrum allows it to be deconvolved.
Two distinct surface types found on Mars

Type 1 - Similar to Basalt
( < 52 wt% SiO₂)
Mostly in southern highlands

Type 2 – Andesite?
( 52-63 wt% SiO₂)
Mostly in northern lowlands

(note the larger percentage of high silica glass is the main diff.)

Bandfield et al. (2000), Hamilton et al. (2001)
Basalt (Type 1 spectra) concentrated in Southern Highlands
Bandfield et al. (2000), Hamilton et al. (2001)
Andesite (type 2 spectra) appears concentrated in Northern Lowlands, but also intermixed with basalt in Southern Highlands. Bandfield et al. (2000), Hamilton et al. (2001)
Mars Hematite detected by 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.

Rocks at the Mars Opportunity Rover landing site (on 1/24/2004, launched 7/7/2003)
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
One application: detection of loss of heat from buildings due to faulty insulation
Typical IR imagery of Heat Loss in Residential Structures
Energy Gain (Floor Leak)

Missing Insulation in Vaulted Ceiling Area

Heat Loss

Moisture

Receptacle

Area
Min  Max
16.5  25.1

Heat Loss

Heat Loss
Typical Institutional Building Heat Loss

Typical Air Leak Patterns
Typical air in-leakage at doors
Apartment balcony door during the summer the A/C system reads a slight positive pressure but this building is under a negative pressure, bringing in warm, moist air into the building through walls, doors, ceilings and under the floor system.
Air Leakage from non-insulated areas and window frames.