Thermal (TIR) Remote Sensing

29th Oct 2012

Emitted Energy

- **Optical remote sensing** (visible and near-IR)
  - – Examine abilities of objects to reflect solar radiation
- **Emissive remote sensing** (mid-IR and microwave)
  - – Examine abilities of objects to absorb shortwave visible and near-IR radiation and then to emit this energy at longer wavelengths

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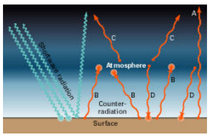
Surface Properties



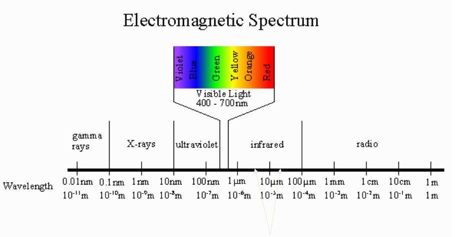
- Albedo -- shortwave reflectance
- Emissivity -- capability to emit longwave radiation

(Wikipedia – Infrared)

Infrared remote sensing, to measure …

- Surface temperature, through the atmosphere
- Atmospheric sounding
  - – Temperature and humidity
  - – Trace gas concentrations
- Radiation balance
- Emissivity

Thermal Infrared Spectrum



Thermal IR

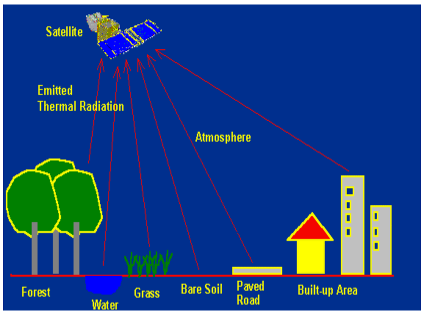
Infrared (IR) waves:

- Near IR:0.7 to 1.3 µm
- Mid IR: 1.3 to 3 µm
- Thermal IR: 3 to 14 µm

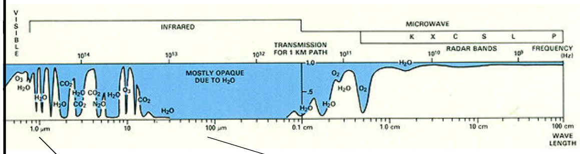
Thermal IR Remote Sensing

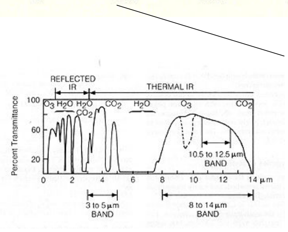
- Thermal infrared radiation refers to electromagnetic waves with a wavelength of between 3 and 20 micrometers.
- Most remote sensing applications make use of the 3 to 5 and 8 to 14 micrometer range (due to absorption bands).
- The main difference between thermal infrared and near infrared is that thermal infrared is emitted energy, whereas the near infrared is reflected energy, similar to visible light.

Thermal Remote Sensing



Atmospheric Transmission





The windows normally used for aircraft platforms are in the 3-5 micron and 8-14 micron wavelength regions
Spaceborne sensors commonly use windows between 3 and 4 micron and between 10.5-12.5 micron
None of the windows transmits 100 % because water vapor and carbon dioxide absorb some of the energy across the spectrum and ozone absorbs energy in the 10.5-12.5 micron

Principles of Emitted Radiation

- The amount of radiation emitted by an object is determined primarily by its:
  - internal temperature; and
  - emissivity

Planck Radiation (Blackbody) Law

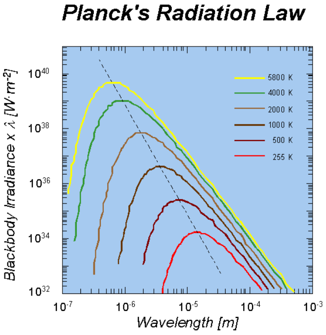
$$E(\lambda, T) = \frac{2\pi hc^2}{\lambda^5 (e^{hc/\lambda kT} - 1)}$$

E= Energy or total radiant exitance, W m^{-2}
h = Placnk's constant
k = Boltzmann constant
c = speed of light (constant)
T = temperature (in K)
λ = Wavelength

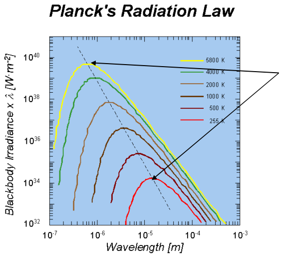
Plank's Radiation Law for blackbodies gives the position of the peak and total spectral radiance (area under the curve) of an object as a function of its temperature

Blackbody Curves

Planck's law solved for λ at constant T



Developments from Planck’s Law
Wien’s Displacement Law



Notice that the peak of the Blackbody curve shirts to shorter wavelengths as temperature increases

This peak represents the wavelength of maximum emittance (λ_{max})

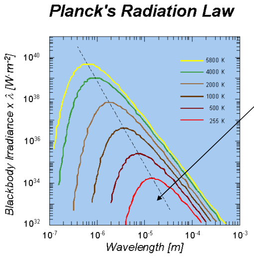
Wien’s Displacement Law

- As the temperature of an object increases, the total amount of radiant energy (area under the curve, in W/m^2) increases and the wavelengths at which the objects emits the most energy decreases.
- To determine this peak wavelength (λmax) for a blackbody:

  $$\lambda max = A/T$$

  where A is a constant (2898 µm K) and T is the temperature in Kelvins.
- The 300 K Earth’s peak emmitance wavelength is: 2898 / 300 = 9.7 µm, in the thermal IR
- What wavelength is the Sun’s radiant energy peak (6000 K)?

Developments from Planck’s Law
Stefan-Boltzmann Law



The area under the Planck curve represents the total energy emitted by an object
at a given temperature

The Stefan-Boltzmann law
gives this energy for a blackbody

Developments from Planck’s Law
Stefan-Boltzmann Law

The Stefan-Boltzmann law is derived by integrating the Planck function with respect to wavelength:

$$E = \sigma T^4$$

σ is called the Stefan-Boltzmann constant.
σ = 5.667 x 10^{-8}

Energy or the radiant flux (rate of flow of EM energy)

Stefan-Boltzmann Law: the amount of energy emitted from an object is primarily a function of its temperature.

Interaction of Thermal Radiation with Terrain Elements

The energy radiated from an object usually is the result of energy incident on the feature

$$E_I = E_A + E_R + E_T$$

The energy incident on the surface of the terrain element

$$\frac{E_I}{E_I} = \frac{E_A}{E_I} + \frac{E_R}{E_I} + \frac{E_T}{E_I} = 1$$

$$\alpha(\lambda) = \frac{E_A}{E_I}, \rho(\lambda) = \frac{E_R}{E_I}, \tau(\lambda) = \frac{E_T}{E_I}$$

Transmittance of the terrain element

Absorptance of the terrain element

Reflectance of the terrain element

Interaction of Thermal Radiation with Terrain Elements

$$\varepsilon(\lambda) = \alpha(\lambda)$$

Kirchhoff radiation law states that the spectral emissivity of an object equals to its spectral absorbance
(Good absorbers are good emitters):

So: $$\varepsilon(\lambda) + \rho(\lambda) + \tau(\lambda) = 1$$

Assuming opaque objects: $$\varepsilon(\lambda) + \rho(\lambda) = 1$$

Basic Thermal Radiation Principles

- Kinetic temperature: Internal temperature of an object determined by random molecular motion
- Thermal scanning detects energy which is function of temperature (radiant temperature); Radiant flux emitted by a body at a given temperature.

Interaction of Thermal Radiation with Terrain Elements

The kinetic temperature of an object is related to its radiant temperature by:

$$T_{rad} = \varepsilon^{1/4} T_{kin}$$

Thermal sensors detect radiation from the surface of ground objects (approximately the first 50 μm)

Emissivity

- ERM is emitted by all objects above absolute zero (0k, or -273 c), and the magnitude and spectral range of the emitted ERM is governed by the temperature and emissivity of the material
- Kelvin = Celsius + 273
- There are no blackbodies is nature.
- Blackbody is a hypothetical, ideal radiator that perfectly absorbs and reemits all energy that is incident upon it.
- All natural objects are graybodies, they emit a fraction of their maximum possible blackbody radiation at a given temperature.

Basic Thermal Radiation Principles

- Emissivity (ε) describes the absorption and emission properties of real objects. It is the ratio of the emittance (radiant flux) from an object at a given temperature to that of a blackbody

ε(λ)= radiant flux of an object at given temperature/
radiant flux of a blackbody at same temperature

ε varies with wavelength and somewhat with temperature

If the emissivity of an object varies with wavelength, the object is said to be a selective radiant

Basic Thermal Radiation Principles

- A graybody has ε<1 but is constant at all wavelengths.
- At any given wavelength, the radiant flux from a graybody is a constant fraction of that of a blackbody.

Basic Thermal Radiation Principles

- Many materials radiate like blackbodies over certain wavelength intervals.
- Most thermal sensing is performed in the 8-14 μm region of the spectrum not only because it includes an atmospheric window, but because it contains the peak energy emissions for most surface features.

Basic Thermal
Radiation Principles

- For any given material type, emissivity is often considered constant in the 8-14 µm range (graybodies)

<u>BUT</u>

- Values vary considerably with wavelength
- Value vary considerably with material condition

Blackbody/Graybody/Selective Radiator

A black body has

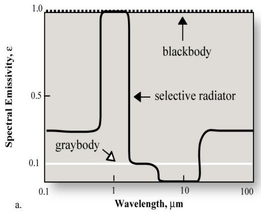
$\varepsilon_\lambda = 1$

a gray body has

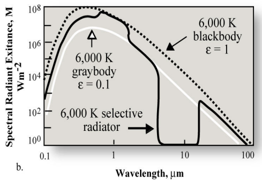
$\varepsilon_\lambda = \text{constant}$

and a selective radiator has

$\varepsilon_\lambda = \text{fn}(\lambda)$



Spectral emissivity of a blackbody, a graybody, and a hypothetical selective radiator



Spectral radiant exitance distribution of the blackbody, graybody, and hypothetical selective radiator

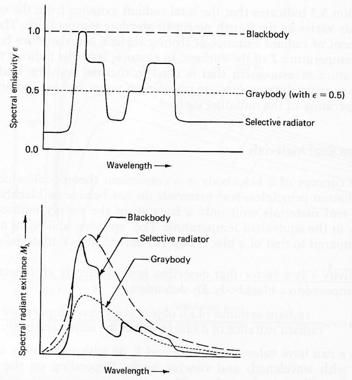
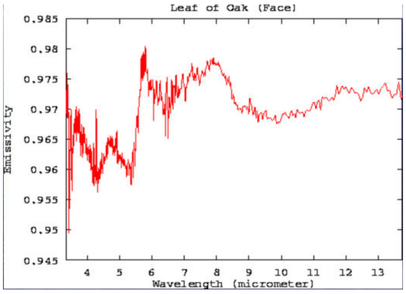
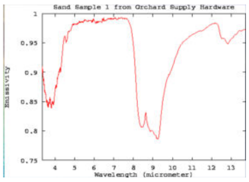


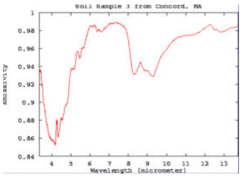
Figure 5.12 Spectral emissivities and radiant exitances for a blackbody, a graybody, and a selective radiator. (Adapted from Hudson, 1969.)

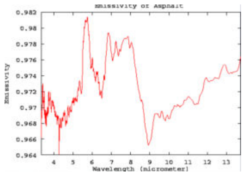
Emissivity vs. Wavelength

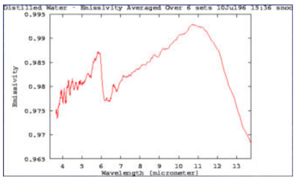


Sand, Soil, Asphalt, Water









Thermal Spectra of Minerals

- In an ideal situation, the emissivity of an object - especially if recorded over several wavelength regions - may be used to uniquely identify that feature

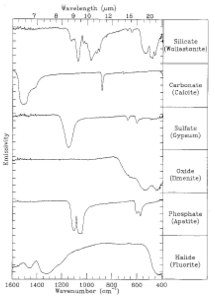


Figure 1. Example of library emission spectra (normalized) of several mineral classes demonstrating the wide variety in absorption band position and shape between each mineral class. Library sample numbers are (from top to bottom) ASU-60, 91, 82, 35, 96, 59.

Emissivity of Common Materials

Clear water	0.98-0.99	Dry mineral soil	0.92-0.94
Wet snow	0.98-0.99	paint	0.90-0.96
Human skin	0.97-0.99	Dry vegetation	0.88-0.94
Rough ice	0.97-0.98	Dry snow	0.85-0.90
Vegetation	0.96-0.99	Granite rock	0.83-0.87
Wet soil	0.95-0.98	Glass	0.77-0.81
Asphalt concrete	0.94-0.97	Sheet iron (rusted)	0.63-0.70
Brick	0.93-0.94	Polished metals	0.16-0.21
Wood	0.93-0.94	Aluminum foil	0.03-0.07
Basalt rock	0.92-0.96	Highly polished gold	0.02-0.03

Emissivity

The emissivity of an object may be influenced by a number 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.
- **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 effect 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.

Emissivity—objects are not blackbodies

- Kirchhof's Law: emissivity = absorptance
  - Probability of emission of a photon at a given frequency and angle is same as probability of absorption at same frequency and angle
- Emissivity + Reflectance + Transmittance = 1
  - (all functions of wavelength and angle)

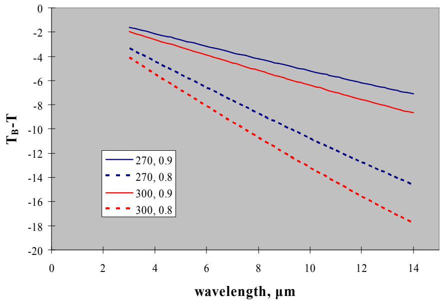
Definition of *brightness temperature* T_B

$$\frac{2hc^2}{\lambda^5\left(e^{hc/k\lambda T_B}-1\right)}=\varepsilon_\lambda(\theta)\frac{2hc^2}{\lambda^5\left(e^{hc/k\lambda T}-1\right)}$$

$$\text{So } T_B=\frac{hc}{k\lambda\ln\left(\dfrac{\varepsilon+e^{hc/k\lambda T}-1}{\varepsilon}\right)}$$

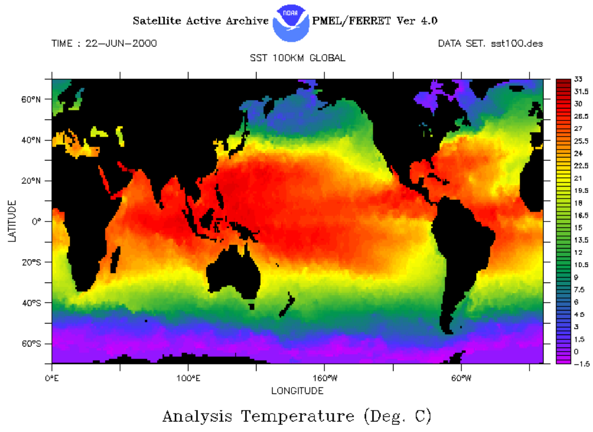
$$\text{Or } T=\frac{hc}{k\lambda\ln\left(1-\varepsilon+\varepsilon e^{hc/k\lambda T_B}\right)}$$

Relationship between *T* and T_B



“Split-window” methods—atmospheric correction for surface temperature measurement

- Water-vapor absorption in 10-12 μm window is greater than in 3-5 μm window
  - Greater difference between T_B (3.8 μm) and T_B (11 μm) implies more water vapor
  - Enables estimate of atmospheric contribution (and thereby correction)
- Best developed for sea-surface temperatures
  - Known emissivity
  - Close coupling between atmospheric and surface temperatures
- Liquid water is opaque in thermal IR, hence instruments cannot see through clouds



Thermal Properties of Materials

Thermal conductivity K (cal.cm^{-1} ⊙sec^{-1}⊙°C^{-1})
is a measure of the rate at which heat passes through a material

- heat passes through metals much faster than through rocks
- Water has a higher K value than many other materials
- It takes a longer time for water to transfer heat over a given distance than many other materials

Thermal Properties of Materials

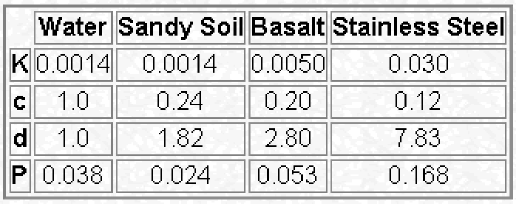
Thermal capacity C (cal/g^{-1}°C^{-1}) determines how well a material stores heat.

- Water has a high thermal capacity compared to other material types
- It takes more energy for water to warm up to the same temperature than many other materials do
- Rank of heat capacity
  Water > forest > grass > land
- In other words, for a given amount of energy, water warms up slower than many other materials

Thermal Properties of Materials

- Thermal Inertia (P) -- Resistance of a material to temperature change.
- It increases with an increase in material conductivity, capacity, and density
- In general, materials with high thermal inertia have more uniform surface temperatures throughout the day and night than materials of low thermal inertia

Thermal Properties



	Water	Sandy Soil	Basalt	Stainless Steel
K	0.0014	0.0014	0.0050	0.030
c	1.0	0.24	0.20	0.12
d	1.0	1.82	2.80	7.83
P	0.038	0.024	0.053	0.168

Stainless steel shows the smallest temperature fluctuations during a 24-hr heating/cooling cycle
Sandy soil shows the largest temperature fluctuations

Important Thermal IR Sensors

- TIROS (Television IR Operational Satellite), launched in 1960
- GOES (Geostationary Operational Environmental Satellite), TIR at 8 km spatial resolution, full-disk of Earth day and night
- HCMM (Heat Capacity Mapping Mission), launched in 1978- 600 m spatial resolution, 10.5 – 12.6 micron range
- CZCS (Coastal Zone Color Scanner) on Nimbus 7, launched in 1978, for SST
- AVHRR (Advanced Very High Resolution Radiometer), 1.1 and 4 km
- TIR bands TIMS (Thermal Infrared Multispectral Scanner), Airborne, 6 bands
- ATLAS (Airborne Terrestrial Applications Sensor)
- Landsat ETM+ Band 6- 10.4 – 12.5 micron range
- ASTER (Advanced Spaceborne Thermal Emmission and Reflection Radiometer) on Terra, 5 bands :8.125-11.65 micron range

Infrared spectral regions

	attributes	**disadvantages**
3.5–4.5 μm (Mid IR)	Clearest atmospheric window and finest spatial resolution for measuring temperature.	Cloud cover. Less energy than 8–12 μm. Mixed with solar radiation in daytime.
8–12 μm (Thermal IR)	Atmospheric window. Peak of energy emitted from Earth. Most accurate temperatures.	Cloud cover. Coarser spatial resolution than MWIR.

Geometry of Thermal Images

- Tangential scale distortion
  - caused by varied viewing distance
- Aircraft instability
  - roll: side by side motion
  - crab (yaw): by compensating drift
  - pitch: head/tail motion

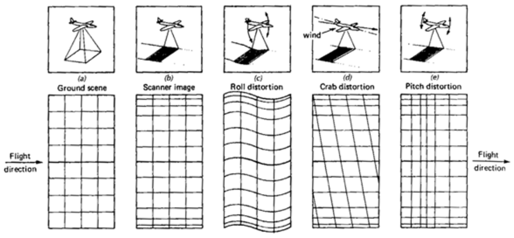


Figure 5.31 Across-track scanner imagery distortions induced by aircraft attitude deviations: (*a*) ground scene; (*b*) scanner image; (*c*) roll distortion; (*d*) crab distortion; (*e*) pitch distortion.

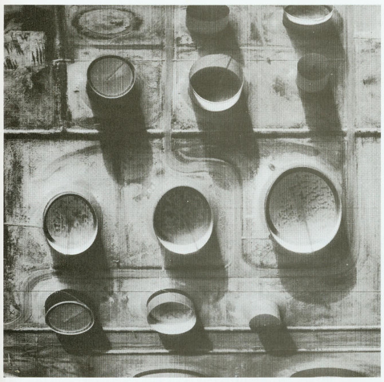


Figure 5.26 Across-track thermal scanner image illustrating tangential distortion, 100 m flying height. (Courtesy Texas Instruments, Inc.)

Geometry of Thermal Images

- Relief displacement
  - differs from that of aerial photography
  - vertical features on thermal images displaced from the nadir for each scan
  - vertical features on air photo displaced radially from the principal point

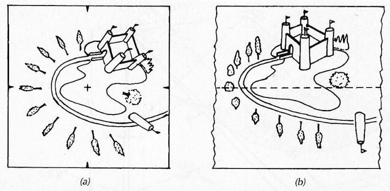


Figure 5.29 Relief displacement on a photograph versus an across-track scanner image. (*a*) In a vertical aerial photograph vertical features are displaced radially from the principal point. (*b*) In an across-track scanner image vertical features are displaced at right angles from the nadir line.

Interpreting Thermal Scanner Imagery

- Application in:
  - Determining rock types, structure
    soil types, soil moisture
  - Locating water springs
    forest fires, subsurface fires
- Qualitative information collection:
  relative differences in radiant temperatures

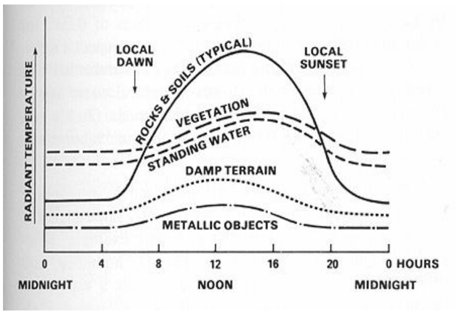
Interpreting Thermal Scanner Imagery

- Landscape factors
  - surface material: land vs. water
  - topography: sunlit vs. shadowed
  - vegetation cover: land, grass, forest, water
  - moisture
- Quantitative data analysis
  e.g. water temperatures
- Times of day (diurnal temperature variations)
  - Thermal images will vary in appearance depending on whether they are acquired during the warm part of the day or after a night of absence of the sun and resultant cooling of the atmosphere as well as heat loss from the surface and shallow depths beneath
- Temperature extremes, heating & cooling rates

Interpreting Thermal Scanner Imagery

- Direct sunlight heats objects according to their thermal characteristics and sunlight absorption
- Predawn imagery: stable temperatures
- Darker tones: cooler temperatures
- BUT, Limitations
  - thermal images contain noise and errors
  - differences in emitted energy is not directly related to differences in temperature, must know emissivity of each material
  - sensors only record the radiance at the surface

Changes in radiant temperatures of five surface-cover types during a 24-hour thermal cycle

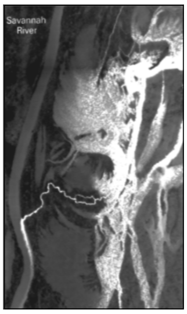


Day versus Night Image

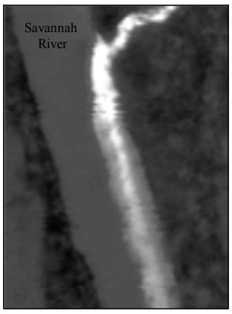
Day Night

Day image: Contrasts between heated buildings and streets and areas in shadow create a scene that resembles an aerial photo
Night image: Many streets are evident because, being asphalt paved, they absorp more heat and remain warmer through the night

Pre-dawn Thermal Infrared Image of Effluent Entering the Savannah River Swamp System



2x reduction



March 31, 1981
4:28 am; 3 x 3 m

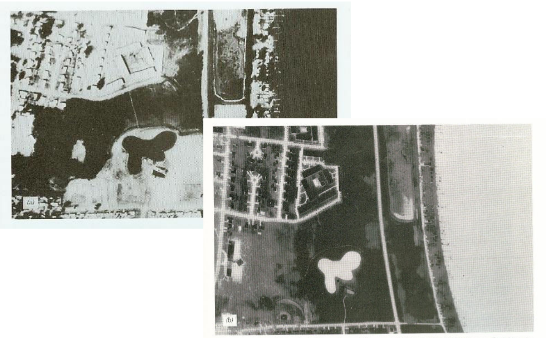


Figure 5.16 Daytime and nighttime thermal images, Middleton, WI: (*a*) 2:40 P.M., (*b*) 9:50 P.M.; 600 m flying height, 5 mrad IFOV. (Courtesy National Center for Atmospheric Research.)

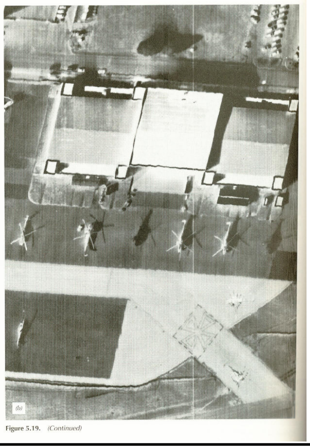


Figure 5.19. *(Continued)*

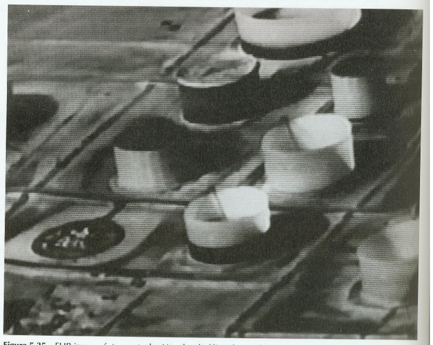


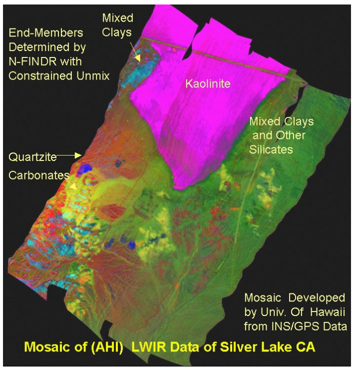
Figure 5.35 FLIR image of storage tanks. Note level of liquid in each tank. (Courtesy Texas Instruments, Inc.)

Great Lakes -- Night

TM band 6 on Landsat

The land appears cool (darker tones) with little detail

Multispectral Thermal Spectroscopy



Mosaic of (AHI) LWIR Data of Silver Lake CA

RGB TIMS Composite Image: Death Valley

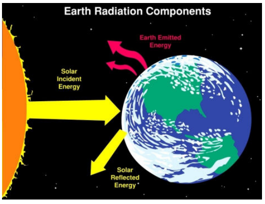
1,3,5 RGB

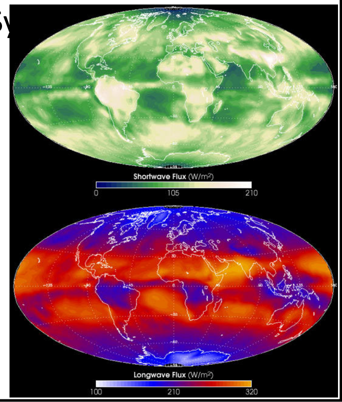
Alluvial fans appear in reds, lavender, and blue greens; saline soils in yellow; and other saline deposits in blues and greens.

NASA’s Earth Observing System—missions with IR capability

- TRMM
  - CERES
- Landsat-7 (launched April 1999)
  - ETM+ has 60 m band at 10.5-12.5 μm
- EOS Terra (launched December 1999)
  - CERES, MODIS, ASTER, MOPITT
- EOS Aqua (launched May 2002)
  - AIRS, CERES, MODIS
- EOS Aura (launched July 2004)
  - HIRDLS, TES

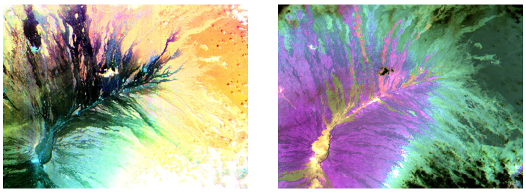
CERES—Cloud-Earth Radiant Energy Sy





ASTER—Advanced Spaceborne Thermal Emission and Reflection Radiometer

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

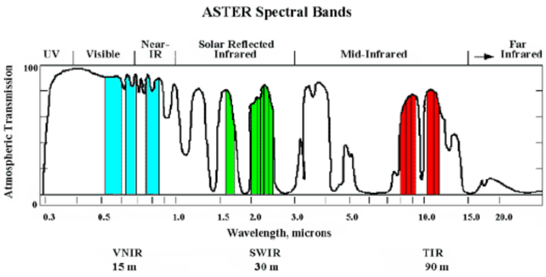


Shortwave infrared

Thermal infrared

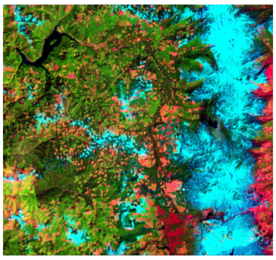
Mauna Loa images

ASTER spectral bands on model atmosphere



ASTER Bands 432 RGB

- This ASTER sub-scene was acquired on May 20, 2000 and shows an area in west central Oregon.
- In this composite, snow appears blue, forests are green, and clear-cut areas are orange-pink.



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

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 (CO_2) and 6.3 μm (H_2O) enables temperature and humidity sounding to 1 km vertical resolution
  - Spatial resolution is 13.5 km
- Complemented by microwave sounders to deal with clouds

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 μm to 17.76 μm

TES—Tropospheric Emission Spectrometer

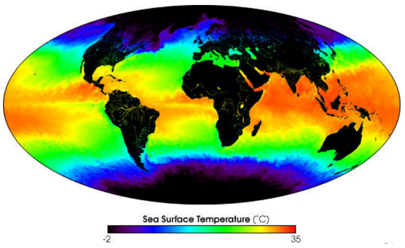
- High-resolution infrared-imaging Fourier transform spectrometer
  - Spectral coverage of 3.2 to 15.4 μm at a spectral resolution of 0.025 cm^{-1}
  - Line-width-limited discrimination of most radiatively active gases in the Earth's lower atmosphere

Operational Missions

- GOES (Geostationary Operational Environmental Satellites)
  - Imager and sounder
- POES (Polar-Orbiting Environmental Satellites, i.e. AVHRR)
  - Two satellites provide coverage with maximum delay of 6 hours
  - Latest is NOAA-15, launched May 13, 1998
- NPOESS (National Polar-Orbiting Environmental Satellite System)
  - Joint NOAA/NASA/DoD mission
  - Launch no earlier than 2011
  - Imaging, microwave, and sounding instruments

Ocean surface temperature from MODIS

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

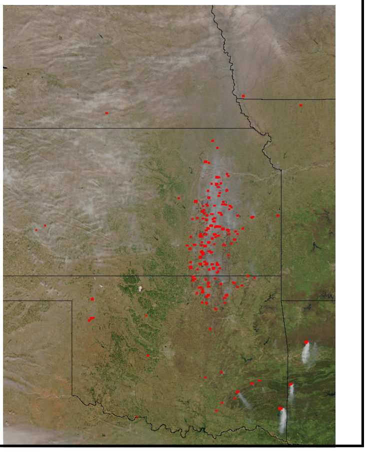


Land surface temperature from MODIS

- Go to the MODIS Land Global Browse page
- Select the MOD11/MYD11 checkbox (Surface Temperature)
- Enter date range
- Select satellite (Terra and/or Aqua)
- Select Collection (5 is most recent)

Active fire detection

- MODIS Fire and Thermal Anomaly website



How does all this work?

- As noted in previous lecture, a great feature of NASA's EOS program is that the algorithms are peer-reviewed and published in *algorithm theoretical basis documents*
- Each instrument has a page with links to these ATBDs, e.g. for MODIS, one can go to Zhengming Wan's ATBD for land surface temperature
  - The algorithm uses MODIS bands 31 (10.78-11.28µm) and 32 (11.77-12.27µm)

Dr. Wan's equation is

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

$$+ \left(B_1 + B_2 \frac{1-\varepsilon}{\varepsilon} + B_3 \frac{\Delta\varepsilon}{\varepsilon^2} \right) \frac{T_{31} - T_{32}}{2}$$

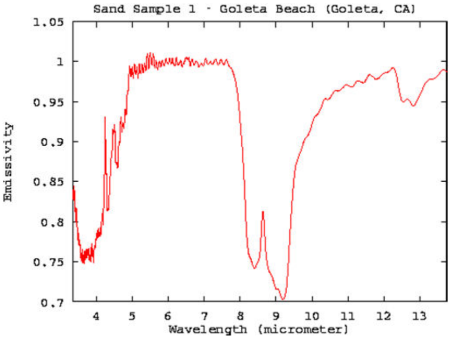
where

T_{31}, T_{32} brightness temperatures in bands 31,32

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

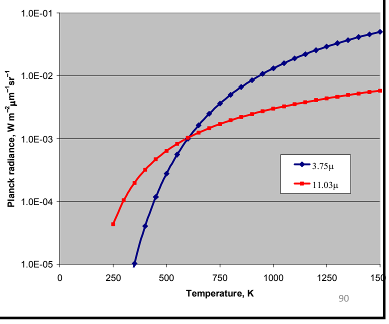
A, B, C coefficients given by multidimensional lookup tables (they depend on angle)

Spectral emissivity library



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

Can solve for *f*, T_f, if T_b is known