Satellite Remote Sensing: Review and Applications in Africa

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Outline

Basics of Satellite Meteorology
- Meteorological satellite orbits and scanning geometry
- Basic radiation laws
- Radiative Transfer

Retrieval of meteorological parameters
- Surface temperature & reflectance
- Clouds and Precipitation
- Vertical profiles of temperature and humidity
- Winds
- Aerosols and Air Chemistry (dust, smoke)
- Land surface properties
- Lightning
Why Satellite Remote Sensing?

Annual Global Monitoring 1-15/10/2008
SYNOP reports made at 00, 06, 12 and 18 UTC at RBSN stations

Percentage of reports received:
- 90 to 100% (2912 stations)
- 45 to 90% (697 stations)
- Less than 45% (325 stations)
- Silent stations (350 stations)

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Sample Daily Satellite Coverage

Data Coverage, 10 April 2009

a) AMV: 00 UTC
Total number of obs = 287995

b) ATOVS: 00 UTC
Total number of obs = 383039

c) AIRS: 00 UTC
Total number of obs = 63417

d) SCAT: 00 UTC
Total number of obs = 283851

e) TRMM Ascending Orbit

f) TRMM Descending Orbit
Basics of satellite remote sensing
Global Operational Satellite Observation System

Began with TIROS1 in April 1960
Satellite geometry and orbits

- Geostationary
- Polar orbiting
- Low earth orbit (LEO)
Satellite Scanning Geometry

Cross-track

Conical cross track
Satellite Scanning Geometry

TRMM Satellite Microwave Sensors

- TRMM Radar (TR)
- TRMM Microwave Imager (TMI)

Radar swath width = 220 km
Microwave radiometer swath width = 850 km
Flight direction

5 km
5 - 40 km

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Tropical Rainfall Measurement Mission (TRMM)

TRMM - first spaceborne rain radar, plus microwave radiometric data, measures precipitation distribution over tropics

Orbits between 40S-40N
Electromagnetic Spectrum

**Electromagnetic Spectrum**

- **Frequency (Hertz):**
  - GHz: $10^{9}$
  - MHz: $10^{6}$
  - kHz: $10^{3}$

- **Wavelength (m):**
  - $10^{-14}$
  - $10^{-12}$
  - $10^{-10}$
  - $10^{-8}$
  - $10^{-6}$
  - $10^{-4}$
  - $10^{-2}$
  - 1
  - $10^{2}$
  - $10^{4}$
  - $10^{6}$

- **Wavelength Units:**
  - 1 nm
  - 1 μm
  - 1 cm
  - 1 km

**Atmosphere mostly opaque due to absorption by H₂O**

- Oxygen ($O_2$), Ozone ($O_3$), Water Vapor ($H_2O$), Carbon Dioxide ($CO_2$), Methane ($CH_4$), Nitrous Oxide ($N_2O$)

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Radiance

• A useful concept in radiation is a blackbody: Object that absorbs all incident radiation and emits maximum amount of energy at all wavelengths.

• Energy per photon emitted, \( e = h\nu \), where \( h \) is Planck’s constant, \( \nu \) is frequency of photons

• Radiance: amount of energy per unit time/area/wavelength/solid angle
Radiance & Brightness Temperature

• Radiance emitted by blackbody can be expressed as a Planck function:

\[ B_\lambda (T) = \frac{c_1 \lambda^{-5}}{\exp \left( \frac{c_2}{\lambda T} \right) - 1} \]

where \( \lambda \) = wavelength, \( T \) = absolute temperature (K), \( c_1 = 1.1910439 \times 10^{-16} \text{ Wm}^{-2} \text{ sr}^{-1} \), and \( c_2 = 1.438769 \times 10^{-2} \text{ m K} \)

• **Brightness temperature**, \( T \), determined by inverting Planck function. At microwave wavelengths (mm, cm) & for earth and atmospheric temperature range, radiance to temperature is a simple proportion.
Fundamentals Laws of Radiation

• By integrating Planck function over all wavelengths, we get **Stefan-Boltzmann Law**

\[ E = \sigma T^4 \]

where \( T \) is \( T(K) \) and \( \sigma = 5.68 \times 10^{-8} \text{ Wm}^{-2}\text{K}^{-2} \)

• **Wien’s Displacement:**

\[ \lambda_{\text{max}} = \frac{2898}{T} \]

• Solar = higher temperature
  more energy at shorter wavelength
Terrestrial = lower temperature,
much less energy at longer wavelength
Radiative Transfer

Optical depth to satellite through atmosphere

Radiation changed after passing through volume element

Radiance is $L_\lambda$

Kidder and Vonder Haar
Radiative Transfer

• Rate of change of radiance, $L$, over distance, $s$, is sum of the extinction (absorption and/or scattering) and sources (emission and/or scattering into the beam), and may be written as a radiative transfer equation,

$$\frac{dL_\lambda}{ds} = -k_\lambda \rho L_\lambda + j_\lambda \rho$$

where $k_\lambda$ is the extinction cross-section (in units of area per mass) for wavelength $\lambda$, $\rho$ is density of the medium, and $j_\lambda$ is the source function coefficient.
What satellites sense

• Most fundamental unit measured by satellites is monochromatic radiance

• Signal (S) recorded by detector, usually a radiometer, after it interacts with target (T) molecules, particulates, or surfaces.

\[ S = F(T) \]

inverse, \( T = F^{-1}(S) \)

\( F \) is function that governs radiative transfer
Basic Limitations of Satellite Remote Sensing

- Radiative Transfer Function not necessarily linear and may not exist in functional form

- **Inverse Function is non-unique**
  - same radiation signal can originate from different combination of unknown targets

- Errors in mathematical solutions used
Sensor system

Sensor System
- Onboard analog-to-digital conversion and calibration

Direct telemetry to Earth or indirectly through Tracking and Data Relay Satellites (TDRS)

Ground
- Data Preprocessing
  - radiometric
  - geometric
- Visual or Digital Information Extraction
  - biophysical
  - land cover
- Distribution and use of information

Incorporation of ancillary data

Courtesy, Gizaw Mengistu
Active or Passive Remote Sensing

- **Passive**: Sense energy emitted naturally
e.g. Geostationary IR

- **Active**: Send and receive electromagnetic pulses of energy
e.g. TRMM Precipitation Radar, CloudSat
Retrieval of meteorological parameters

- Surface temperature & reflectance
- Clouds and Precipitation
- Vertical profiles of temperature and humidity
- Winds
- Aerosols and Air Chemistry
- Land surface
- Lightning
Surface Temperature & Surface Reflectance
Surface Temperature Retrieval

Radiance at sensor given by

\[ \text{LS}_j = \left[ \varepsilon_j L_j^{BB}(T) + (1-\varepsilon_j)L_j^{sky} \right] \tau \ + \ L_j^{atm} \]

where \( \text{LS}_j \) is spectral radiance observed by sensor,

- \( \varepsilon_j \) is surface emissivity,
- \( L_j^{BB} \), spectral radiance of blackbody at the surface at temperature \( T \),
- \( L_j^{sky} \), spectral radiance incident upon surface from atmosphere, calculated using radiative transfer model,
- \( L_j^{atm} \), spectral radiance emitted by atmosphere, from model,
- \( \tau \) is spectral atmospheric transmission
Surface Temperature and Emissivity Estimation

- After getting necessary data from radiative transfer model, as in previous equation,
- Radiance from surface, \( L_j \), is:

\[
L_j = (L S_j - L_j^{\text{atm}}) / \tau_j - (1 - \varepsilon_j) \ L_j^{\text{sky}} = \varepsilon_j L_j^{\text{BB}(T)}
\]

- Then obtain **temperature from Planck Function**

\[
L_j = L_\lambda(T) = \frac{c_1 \lambda^{-5}}{\exp\left(\frac{c_2}{\lambda T}\right) - 1}
\]

where \( \lambda \) = wavelength, \( T \) = absolute temperature (K), \( c_1 = 1.1910439 \times 10^{-16} \text{ Wm}^{-2} \text{sr}^{-1} \), and \( c_2 = 1.438769 \times 10^{-2} \text{ m K} \)
Emission Characteristics

- Water - good approximation of blackbody
- Quartz – poor approximation, selective absorption/emission

Courtesy Gizaw Mengistu
Surface Reflectance

- Reflected radiation, especially reflected solar and microwave radiation, are critical measurements in satellite meteorology.

- Radiance reflected from a small unit of surface is

\[ L_r(\theta_r, \phi_r) = \int_0^{2\pi} \int_0^{\pi/2} L_i(\theta_i, \phi_i) \gamma_r(\theta_r, \phi_r; \theta_i, \phi_i) \cos \theta_i \sin \theta_i \, d\theta_i \, d\phi_i. \]

where incident direction is \((\theta_i, \phi_i)\) (zenith/azimuth), \(\gamma_r\) is bi-directional reflectance, and \(\gamma_r(\theta_r, \phi_r; \theta_i, \phi_i)\) is fraction reflected in direction \((\theta_i, \phi_i)\).
Compare reflectance

Vis & Near IR Spectral Signatures

- Cloud
- Fire
- Hot area
- Smoke (sm. part.)
- Smoke (lg. part)
- Shadow

Grass
Lake
Bare soil

Apparent Reflectance

Wavelength (nm)

NOAA/UW/CIMSS
Window Regions
(Solar and Earth emitted radiation passes through window regions)

Absorption Bands
(Earth emitted radiation is absorbed & re-emitted by absorption bands)
METEOSAT SEVIRI CHANNELS

- VIS 0.6 μm
- VIS 0.8 μm
- NIR 1.6 μm
- NIR 3.9 μm
- WV 6.2 μm
- WV 7.3 μm
- IR 8.7 μm
- IR 9.7 μm
- IR 10.8 μm
- IR 12.0 μm
- IR 13.4 μm
- HRV
Clouds and Precipitation
Clouds and Precipitation

Detected from satellite

- emission (IR and microwave)
- reflection/scattering (visible and microwave)

- At IR: Clouds nearly blackbody (water, water vapor good absorbers/emitters)
- Visible: Good scatterer, by large particles (Mie Scattering) all visible wavelengths equally, appear white.
Clouds - Scatter Visible Light, Absorb/Emit IR

(shortwave) (long wave)
Pro: High temporal frequency of images, up to 15 minutes for geostationary satellites. Good for studying propagation.

Con: Cannot detect convective-scale structure and rain from warm clouds. Thick cirrus and convective precipitation appear similar.
Enhanced IR Tracking regenerating convection

Convection Episodes 7-8 Jan 2000
CloudSat – 1st millimeter-wavelength cloud radar in space. Detects smaller liquid drops and ice than weather radar, more information about cloud mass. Can infer cloud properties such as particle concentrations, cloud liquid water, and precipitation intensity, which can be used to understand climate variability.
Microwave spectrum

Electromagnetic Spectrum and Absorption by Atmospheric Gases

- Transmittance vs. Wavelength
- Wavelength (cm) vs. Frequency (GHz)
- Vertical Transmittance to Space
- Atmosphere mostly opaque due to absorption by H₂O

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Clouds and Precipitation: Microwave emissions and scattering

Visible

Microwave Ice scattering
- Detects hydrometeors expected to fall as precipitation

IR

Microwave emission
Profiles of temperature and humidity

Satellite Sounders and weighting functions
Sounding from GPS Radio Occultation
Satellite Sounding Retrieval

- Emission and absorption occur at discrete wavelengths related to molecular structure of gases or aerosols.
- By selecting different sounding wavelengths, observed radiances are used to infer temperature and humidity profiles, cloud top pressures.
- Emission source - Relatively abundant gas of known and uniform distribution, e.g. CO₂
• Attenuation by gases is strongest near center of absorption region => colder satellite brightness temperatures, energy emitted from higher up in troposphere.

• Select channels between center and "wing" of absorption band => probes atmosphere at different depths => temperature and moisture variations with height
Weighting Function

- Weighting function peaks near surface, clouds and surface features are still visible.

- However, as observed brightness temperature due to CO$_2$ becomes more dominant lower in atmosphere, lower clouds and surface features appear less distinct.

- Channels usually chosen to become more opaque with height
Satellite Sounding Retrieval

Upper troposphere

Retrieved brightness temperature

Weighting Functions
Mid-low troposphere

Retrieved brightness temperature

Weighting Functions for CO$_2$, H$_2$O
Compare Soundings

Temperature and Dewpoint Profiles

RAOB

GOES 8-15 Sounders

Simulated High Spectral Resolution Sounder

CAPE = Convective Available Potential Energy
CIN = Convective Inhibition

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GOES Sounder vs Radiosonde

• GOES sounder cannot sense through clouds disadvantage compared to radiosonde

• Provides 8-10 km average horizontal measurements; radiosonde obs are single-point measurements far apart

• Hourly obs. compared to conventional 12-hour radiosonde obs. Improve nowcasting of severe weather by diagnosing pre-convective environment before significant cloud formation

• Hyperspectral sounders - better spatial resolution
Hyperspectral Sounders

NASA Atmospheric Infrared Sounder (AIRS) (polar orbiting)

- 65 spectral radiances for temperature,
- 42 for water vapor,
- 26 for ozone,
- 23 for surface temperature

- Provide profiles of about 1 K per 1-2 km depth.

- Horizontal resolution, 1-10 km

Next generation geostationary satellites will have hyperspectral sounder
Soundings from GPS Radio Occultation

- Radio occultation - technique by which satellite receivers intercept signals from GPS and infer deviations in signal’s path caused by temperature and moisture gradients.

- Use information to create soundings.

John Braun Talk on Wed, 27 July
Winds: Cloud motion vectors

Automatic tracking of water vapor features in mid-upper troposphere and cloud elements in lower troposphere

- Green: > 950 hPa
- Light Blue: 800 hPa - 950 hPa
- Yellow: 650 hPa - 800 hPa
- Orange: 500 hPa - 650 hPa
- Purple: 350 hPa - 500 hPa
- Red: < 350 hPa
Scatterometer infers near-surface wind velocity by sending pulses of *microwave energy* to ocean surface and measuring backscatter from small-scale waves. Limited by directional ambiguity, rain contamination

[https://www.meted.ucar.edu/training_module.php?id=148](https://www.meted.ucar.edu/training_module.php?id=148)
Aerosols and Air Chemistry
Dust Detection: Split-Window Technique

Split Window Brightness Temperature Differences (12-11 µm) for Thin Cirrus and Dust

12 µm Diff “+” 11 µm Cooler

11 µm 12 µm Diff “-” 11 µm Warmer

Dust Layer Cirrus Cloud

T (surface) U.S. Navy/NRL

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Saharan Dust Outbreak: Winter

Meteosat Second Generation (MSG) RGB Product

Estelle de Coning Talk, Wed, 27 Jul
Dust: Summer
Dust wall with Mesoscale Convective System

http://oiswww.eumetsat.org/WEBOPS/iotm/iotm/20100705_dust/20100705_dust.html

copyright: Emmanuel Kploguede, EAMAC, Niamey
Fires, Smoke: Mozambique channel

Measurements Of Pollution in The Troposphere (MOPITT) instrument detects CO from IR emissions and methane, and CO from reflected sunlight. CO increase due to grassland burning in preparation for farming.
Volcanic Ash
Central Africa               East Africa

METEOSAT Ash and Air Mass products – track ash and chemical plume

Need to distinguish ice from ash, especially in tropics
See Estelle de Coning’s talk on Wed, 27 July
Land Surface
Vegetation and Wetness
Fraction of Photosynthetically Active Radiation (FPAR) measures how much sunlight leaves are absorbing.
Land surface wetness

Land surfaces - weak polarizers, so emissivity and brightness temperature significantly greater => strong contrast with water.

Amount of microwave radiation emitted by soil diminishes as soil moisture increases

Very dry soil - bright/warmer, saturated soil dark/colder

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Dielectric effect

Most gases and dry land-based materials have a weak dielectric effect,

Wet soil, moist vegetation, and water surfaces have a strong effect.

Aids in satellite detection of land surface wetness
Lightning Detection from Satellite

- LIS has a small, solid-state camera with special filters that admit only peak optical wavelength emitted by lightning.
- OTD detects momentary changes in optical scene that occur with lightning.
- Lightning mapper on next generation geostationary satellite
Additional Resources

• COMET Satellite Meteorology on MetEd
  https://www.meted.ucar.edu/training_detail.php?page=1&topic=12&language=1&orderBy=publishDateDesc

• Description of satellite sounding instruments and radiometers:
  http://cimss.ssec.wisc.edu/itwg/sssp/satellite_programs/instruments.html

• Introduction to Tropical Meteorology
  http://www.meted.ucar.edu/tropical/textbook/

• Meteosat and MetOp:  http://www.eumetsat.int

• Scatterometry:  https://www.meted.ucar.edu/training_module.php?id=148
F2 Tornado: Near Durban, South Africa

http://saweatherobserver.blogspot.com/search?updated-max=2008-11-16T18%3A36%3A00%2B02%3A00&max-results=30
Fog and Stratus: Southern Africa