

## Matter-energy interactions in the optical region

## Overview

- Terrain elements
  - Individual subelements – leaves; or aggregates of subelements – vegetation canopies
  - Need sufficient numbers of scatterers or emitting elements that comprise the media under study

## Overview

- Optical properties of terrain elements considered – ignore phase coherence
- Apply macroscopic approaches
  - Radiative transfer theory
  - Energy budget relationships

## Mathematical development

- Extensive mathematical analysis
  - Developed equations describing energy interactions with bulk matter
  - Analytical solutions not possible
  - Numerical approaches are used
- Difficulty with interaction mechanisms
  - Problem of linking biological & physical properties of the target elements to bulk average quantities (volume attenuation coefficient)

## Models

- Reflective region – several process-oriented models available to describe the bidirectional reflectance distribution function for different resource classes
- Thermal region – more complex models that are beginning to include vegetation layers superimposed upon a soil substrate

## Experimental datasets

- LACIE – Large Area Crop Inventory Experiment
- Agristars – Agriculture and Resources Inventory Surveys Through Aerospace Remote Sensing
- ISLSCP – International Satellite Land Surface Climatology Project) Field Experiment
  - FIFE (Konza Prairie, Kansas)
    - [http://www-eosdis.ornl.gov/FIFE/FIFE\\_Home.html](http://www-eosdis.ornl.gov/FIFE/FIFE_Home.html)
  - BOREAS (central Canada)
    - [http://www-eosdis.ornl.gov/BOREAS/boreas\\_home\\_page.html](http://www-eosdis.ornl.gov/BOREAS/boreas_home_page.html)
  - LBA (Amazon area in Brazil)
    - [http://daac.ornl.gov/lba\\_cptec/lba/indexi.html](http://daac.ornl.gov/lba_cptec/lba/indexi.html)

## Experimental datasets

- High-quality experimental data with sufficient supporting target parameter determinations for modeling purposes
- Intercomparisons of various modeling approximations
- Develop theoretical basis for heterogeneous target categories & terrain elements with irregular geometries

## Objective

- Various descriptions to predict the optical reflective or thermal radiance properties of terrain materials – function of target or scene characteristics
  - Use predictive relationships for sensor and algorithm design studies; a guide for field studies
- Inverse problem of inferring target characteristics from measured responses

## Energy flow process

- Radiative interactions of scene elements
  - Simple, homogeneous targets: few m – 10s of m or several different element types
  - Consider scene element in its environment, surrounded by other interacting elements, subjected to both time and space-varying energy sources & sinks

## Energy flow process – optical reflective region

- Trace flow of incident flux from sun (& diffuse sky sources) through the atmosphere to the scene element (target/background composite), then from scene element back through the atmosphere & into a sensor
- Target temporal variations – generally slowly varying with respect to measurement integration intervals

## Energy flow process – optical reflective region

- Measured radiance variations – attributed to fluctuating irradiance conditions, atmospheric state, or true *intrinsic* variations in scene-element composition or condition
- Radiance variations include: changes in intensity, spectral composition, angular pattern
- Focus on radiative interactions occurring on the surface
  - Consider atmospheric & sensor considerations later

## Reflective spectral radiance

View scene element from direction  $\mu, \phi$ , ( $\mu$ , is the cosine of the zenith view angle and  $\phi$ , the azimuth when the corresponding sun angles are  $\mu_0, \phi_0$ )

$$L(\mu_0, \phi_0; \mu, \phi) = 1/\pi \iint f_r(\mu, \phi; \mu_r, \phi_r; \rho) E_{\text{TOTAL}}(\mu, \phi) d\mu d\phi$$

$$= 1/\pi \delta(\mu - \mu_0) \delta(\phi - \phi_0) f_r(\mu_0, \phi_0; \mu_r, \phi_r; \rho) E_{\text{SUN}}$$

$$+ 1/\pi \iint f_r(\mu, \phi; \mu_r, \phi_r; \rho) E_{\text{DIFFUSE}} d\mu d\phi$$

where:  $f_r$  = bidirectional reflectance distribution function  
 $\rho$  = a set of parameter biophysical descriptors for the target (parameter variable,  $L$  = (spectral) radiance

$E_{\text{TOTAL}}$  = total irradiance at surface,  $E_{\text{SUN}}$  = solar irradiance at surface,  $E_{\text{DIFFUSE}}$  = sky irradiance incident on the terrain element,  $\delta$  = represents the Dirac delta function

## BRDF

- BRDF – bidirectional reflectance distribution function – an intrinsic property
- Describe models on how  $f_r$  can be related to underlying scene biophysical attributes,  $\rho$
- Models will consider multiple scattering & absorption of shortwave radiation within the media under consideration

## Optical thermal region

- Classical description of energy-flow response becomes more complex, depending on scope of discussion & level of detail considered
  - *Simple* soil or snow surface, different than for dense vegetation
  - Consider scattering & the emission of long-wave radiative flux within the terrain element
  - Several energy source & sink terms estimated

## Long-wave flux transfers

- Consider surrounding terrain elements & sky, convective transfers, conduction, sensible heat, evapotranspiration, condensation, & other similar processes
- Processes tightly coupled to the environment through several time-dependent control variables
- $L(\mu_r, \phi_r)$  – thermal radiance – very dependent on factors other than the intrinsic properties of the terrain element under consideration

## Black-body temperature, T

- Rather than report thermal radiance from terrain elements, convert the measurement to an effective or equivalent black-body temperature, T, for the target:

$$T(\mu_r, \phi_r) = [\pi L(\mu_r, \phi_r)]^{1/4} \sigma^{-1}$$

where:  $\sigma$  = the Stefan-Boltzmann constant

## Energy-budget conservation eq


- Time-dependent nature of thermal radiance and its dependence upon both intrinsic target properties,  $\rho$ , and meteorological driving variables,  $u$ , (including antecedent conditions) is usually indicated through an energy-budget conservation equation

$$F(T, \mu; \rho) = dT / dt$$

where  $t$  = time,  $F$  is sum of energy terms (or a heat-flow equation for layered media in direction  $z$ , characterized by a thermal diffusivity,  $\kappa$ , subject to boundary conditions)


## Energy-budget conservation eq

- These boundary conditions are:  
 $d^2T / dz^2 = 1/\kappa dT / dt$



## Relating remote sensing observables to scene phenomena

- Fundamental measurable remote sensing quantity for a scene element is its spectral radiance
- Want to infer scene status, either identity or condition, from these observed radiance measurements



## Relating remote sensing observables to scene phenomena

- Most frequently used data analysis or information-extraction procedure is mapping scene elements, based on their radiance measurements into information classes using pattern recognition classes



## Direct mapping of variables

- LAI or biomass mapping – use correlation between these variables & various functions of spectral radiance
- Use statistical regression techniques – variability in radiance measurements due to differing view & illumination geometries
- Transform radiances into spectral channel ratios – get better predictive relationships



## Other models

- Use information-extraction methods based on an understanding (models) of the physical radiative interactions with terrain elements
- Use various indirect sensing techniques for the underlying scene parameters
- Can derive various function transformations of the spectral radiance that are better related to intrinsic scene information



## Temporal methods

- Satellite observations capable of obtaining multiple measurements of terrain elements – both seasonally & diurnally
- Additional temporal methods to relate observed radiances to underlying scene characteristics
  - Need considerable amount of ancillary data
  - Understanding of the physical interactions of medium with its environment



## Temporal methods

- Example – statistical characterization of seasonal crop profiles to estimate date of emergence or other phenology states:
  - Reflective: link statistical curve fit parameters of crop profile patterns to fundamental canopy characteristics using submodels
  - Thermal: multiple diurnal thermal radiance determinations of terrain elements – sampling of the response of scene elements to surrounding environment
- Example – geological applications, use thermal inertia properties

## Other potential applications

- Infer spatially or temporally distributed processes of scene elements, rather than status
  - Cumulative amount of photosynthetic activity or degree of evapotranspiration occurring within a crop
  - Processes tied to crop characteristics, such as LAI, (a typical radiative transfer-model input), or represent components in a process-oriented energy-balance model for terrain elements

## Dynamic nature of RS

- State-space description
  - Separate extrinsic effects (influence scene radiance but generally not of interest) from intrinsic scene properties
  - Applicable to both optical reflective and optical thermal regions

## State-space description

- System – collection of terrain elements being measured or sensed
- System characterized by a state vector and an underlying set of governing equations that describe how the system (state vector) evolves in time, space, or other generalized coordinate
- System subject to external controlling facts that affect the state of the system
- System characterized by a set of underlying properties or parameters that influence its state

## State-space description

- In general, underlying governing equations describe the evolution of the system – function of both extrinsic control factors & intrinsic properties
- System is observed by various remote sensing devices

## State-space description

- Possible that not all or not any state vector components of the system are directly observable, but rather that only some function of the underlying state vector can be observed
- Possible that system observed or sampled only along some portions of the system trajectory in state space
- Concerned with estimating system state or system parameters in the presence of measurement errors and with uncertainty in underlying governing equations

## State-space description

- $X = F(X, u; p) + e$
  - $Z = G(X, u; p) + v$
- where X is state vector for the system, X is the variation of the state vector along some generalized coordinate (time, space, angle); p is list of underlying parameters that affect the state of the system, u is the extrinsic & variable control vector that drives the state of the system; Z is the set of observations made on the system; F and G are a set of state- & observation-equations for the system, respectively; measurement uncertainty, v; imperfect state equations, e

## State-space description

- $X = F(X, u; p) + e$
- $Z = G(X, u; p) + v$

Governing system equations,  $F$ , and observation equations,  $G$ , may be nonlinear

## Example – radiative flux

- State vector – radiative flux (radiances within different layers of a vegetation canopy, the system)
- Canopy radiative balance – subject to controlling factors: irradiance, depends on underlying canopy properties (canopy architecture, leaf & soil optical properties)
- Observations of upward radiance from only the top layer are made, over time or along a scan direction

## Example – radiative flux

- System equations:  $F$ , corresponds to various canopy reflectance models;  $G$ , corresponds to a selection function for the top nadir exiting radiance
- Simplified case: replace state vector by a constant vector of canopy parameters (biomass levels) & the observations by radiance measurements of the canopy

## Example – radiative flux

- Observation equations would then relate the measured radiance to the biomass levels & irradiance – use linear or nonlinear regression techniques
- Take the state vector as the angular variation in scene radiance & observations as some subset of these measurements

## Example – thermal

- State vector – temperature distribution within the media
- Control vector – meteorological factors (wind speed, relative humidity, irradiance)
- Parameter vector – element area & flux transfer coefficients of the media for various energy interactions

## Example – thermal

- Observational equations – correspond to radiance or effective temperature of the top layer, sampled through time
- State equations – correspond to statistical description of the temperature behavior over time



## State-space description of RS process

- Good illustration of basic difficulties encountered in the field
- Observations,  $Z$ , are hopefully a function of the desired scene properties,  $p$ , but usually indirectly
- $Z$  is more generally directly a function of the state vector,  $X$  (function of  $p$ ), and the extrinsic controlling factors,  $u$
- $F$  &  $G$  are nonlinear functions
  - Cannot assess *a priori* whether or not the system is *observable* or whether the estimation of  $p$  is feasible



## State-space description of RS process

- Preprocessing techniques in RS
  - Minimize effects of  $u$  (varying sun- & view-angle)
  - Develop new observation variables – feature vector transformations – more amenable to estimation procedures