

1 ☐ Matter-energy interactions in the optical region

2 ☐ 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

3 ☐ Overview

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

4 ☐ 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)

5 ☐ 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

6 ☐ 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
 - BOREAS (central Canada)
 - http://www-eosdis.ornl.gov/BOREAS/boreas_home_page.html
 - LBA (Amazon area in Brazil)
 - http://daac.ornl.gov/lba_cpctec/lba/indexi.html

7 ☐ 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

8 ☐ 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

9 ☐ 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

10 ☐ 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

11 ☐ 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

12 ☐ Reflective spectral radiance

View scene element from direction μ_r, ϕ_r (μ_r is the cosine of the zenith view angle and ϕ_r the azimuth when the corresponding sun angles are μ_0, ϕ_0)

$$\begin{aligned} L(\mu_0, \phi_0; \mu_r, \phi_r) &= 1/\pi \int \int f_r(\mu, \phi; \mu_r, \phi_r; \rho) E_{\text{TOTAL}}(\mu, \phi) d\mu d\phi \\ &= 1/\pi \delta(\mu - \mu_0) \delta(\phi - \phi_0) f_r(\mu_0, \phi_0; \mu_r, \phi_r; \rho) E_{\text{SUN}} \\ &\quad + 1/\pi \int \int f_r(\mu, \phi; \mu_r, \phi_r; \rho) E_{\text{DIFFUSE}} d\mu d\phi \end{aligned}$$

where: f_r = bidirectional reflectance distribution function

ρ = a set of parameter biophysical descriptors for the target (parameter variable, L = (spectral) radiance

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

13 ☐ BRDF

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

14 ☐ 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

15 ☐ 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

16 ☐ 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: σ = the Stefan-Boltzmann constant

17 ☐ Energy-budget conservation eq

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

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

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, κ , subject to boundary conditions)

18 ☐ Energy-budget conservation eq

- These boundary conditions are:

$$d^2T / dz^2 = 1/\kappa dT / dt$$

19 ☐ 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

20 ☐ 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

21 ☐ 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

22 ☐ 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

23 ☐ 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

24 ☐ 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

25 ☐ 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

26 ☐ 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

27 ☐ 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

28 ☐ 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

29 ☐ 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

30 ☐ 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

31 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

32 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

33 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

34 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

35 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

36 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

37 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

38 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