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Fundamentals of remote sensing and direct modelling

Michel M. Verstraete
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Institute for Environment and Sustainability

General outline

- Lecture 1: Fundamentals of remote sensing and direct modelling
  - Basic principles
  - Anisotropy and terminology
  - Elements of radiation transfer (RT) theory
  - BRDF models (1D, 3D, homogeneous, heterogeneous)
  - AnisView as a BRDF visualisation tool using RPV
- Lecture 2: Information retrieval by explicit inversion
  - Model benchmarking (RAMI)
  - Principles of model inversion
  - Look-up tables and examples
  - Exploiting RPV to characterize vegetation canopy structure
- Lecture 3: Information retrieval by implicit inversion
  - Application-driven approaches, optimal estimators
  - Performance evaluation
  - High-level applications

Outline

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Elements of signal and information theory

- Emitter generates signals
- Signals may interact with other objects or media
- Receiver intercepts signals
  - Ø Measured signals thus contain information on all these processes and interactions, including the source and the sensor
- Data processing aims at interpreting signals, i.e., attributing signal variance to the causal factors
- In the case of remote sensing, signals are electromagnetic waves
- The information associated with an event *e* in a signal is inversely related to its likelihood:

$$I(e) = -\log(P(e))$$

- In remote sensing, spatial, temporal, spectral, directional and polarimetric signal variations have been exploited to characterize the environment

Engineering issues: orbits

- Types of orbits
  - Low Earth Orbit (LEO, e.g., Shuttle, Space Station): h ~ 300 to 500 km
  - Polar (often Sun synchronous) orbit: h ~ 700 to 900 km, 98° inclination
  - GPS systems: h ~ 20,200 km, 55° inclination
  - Geostationary orbit: h ~ 36,000 km above Equator, 0° inclination

- Orbit maintenance, satellite ephemerids

- Altitude affects spatial resolution (for a given instrument)

- Altitude and inclination affect repeat time (identical observation)

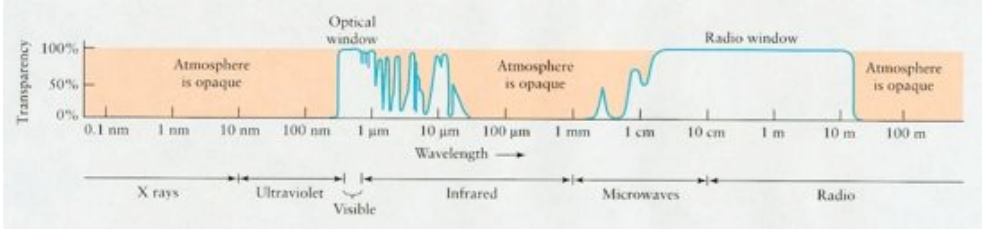
- Altitude affects costs

- Swath width affects revisit time (observation of same site)

Engineering issues: sensors

- Geometry
  - Spatial resolution and geolocation
  - Point spread function
  - Instantaneous field of view and swath
  - Directionality, pointing accuracy
- Radiometry
  - Intensity (traceable to SI standards)
  - Response linearity and attenuation
- Spectrum
  - Wavelength (or frequency) range
  - Instrument response
- Time
  - Stability, repeatability
  - Repeat and revisit frequency
- Polarization
  - Sensitivity
  - Phase

Useful spectral ranges for Earth Observation



- Atmospheric transparency
  - § Low: study TOA
  - § High: study surface
- Solar spectral range
  - § Passive (source: Sun) or Active (source: laser on satellite)
  - § λ: 0.01 – 0.4 µm (UV), 0.4 – 0.7 µm (VIS), 0.7 – 1.1 µm (NIR), 1.1 – 3.0 µm (SWIR)
- Thermal range
  - § Passive (source: Earth)
  - § λ: 3.0 – 4.0 µm and 10.0 – 15.0 µm
- Microwave range
  - § Passive (source: Earth) or Active (source: MW emitter on satellite)
  - § λ: 1 cm – 10 m or bands (in MHz): P (225 – 390), L (390 - 1,550), S (1,550 - 3,900), C (3,900 - 6,200), X (6,200 - 10,900), K (10,900 - 36,000), etc.

Ref. figure: http://www.astro.uiuc.edu/classes/astr210/Images/atmtrans.jpg
Ref. bands: http://www.jneuhaus.com/fccindex/letter.html

Sensors, electronics and product levels

- Sensors are electronic devices sensitive to electromagnetic radiation
- Device output is typically an electrical current or voltage
- Signal perturbations: stray light, sensor degradation, etc
- Electronic measurements are
  - amplified
  - converted to digital numbers
  - combined with ancillary data (e.g., timing)
  - possibly multiplexed with other data
  - transmitted through a communication link (e.g., X-band microwave) to a receiving station on the ground
- Raw data is de-multiplexed, merged with calibration information and reformatted into Level-0 data
- These data look like this: 10010110001111010011101…
- Calibration (on-board, vicarious) into radiometric products at Level-1
- Extraction of core geophysical products at Level-2
- Generation of integrated products (Level 3 and 4)

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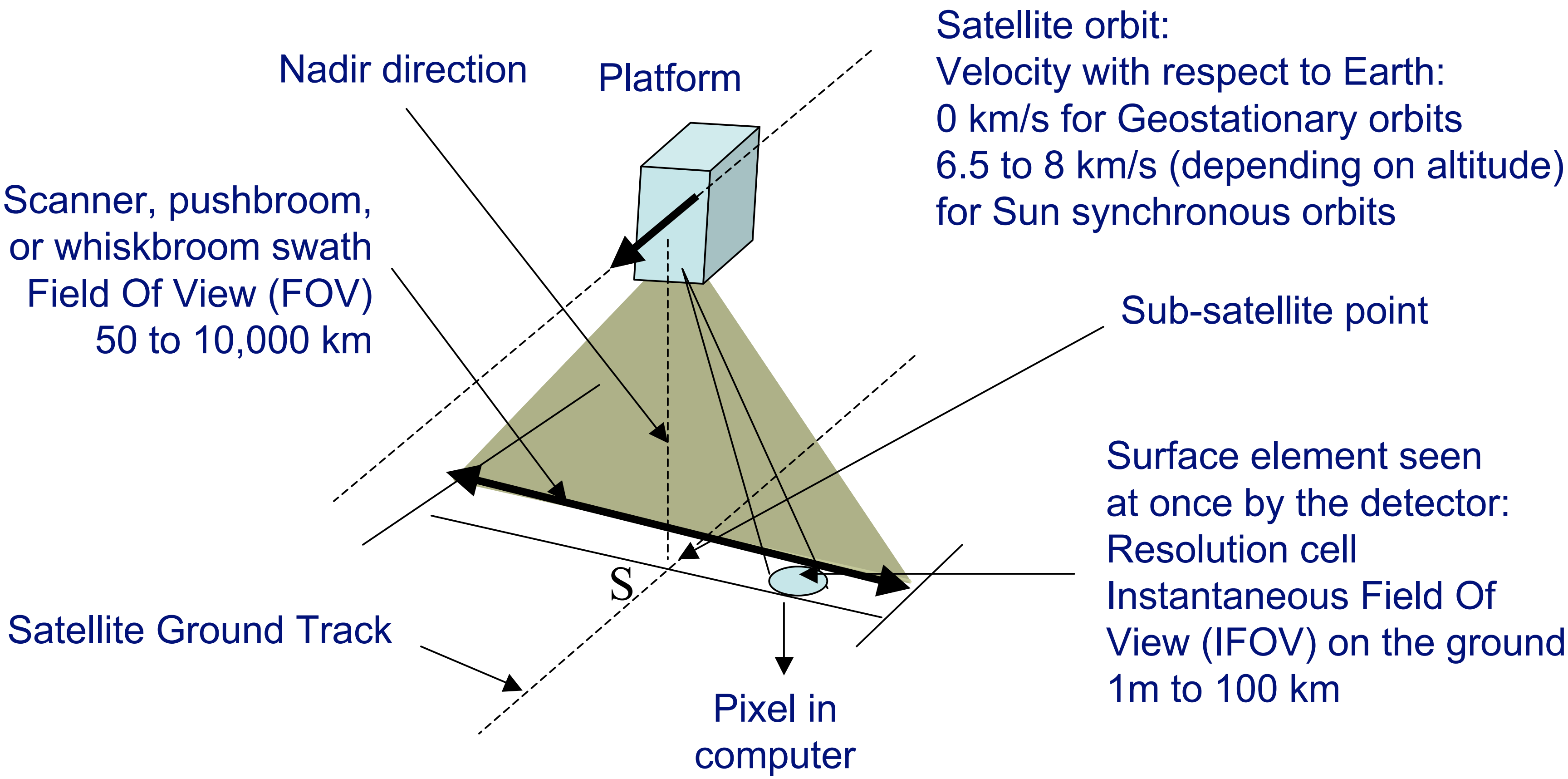
Acquiring data with optical sensors



Spatial resolution: the smallest distance between two objects that can be distinguished

Ref.: Re-drafted from QUARS-2005 Lecture by François Becker

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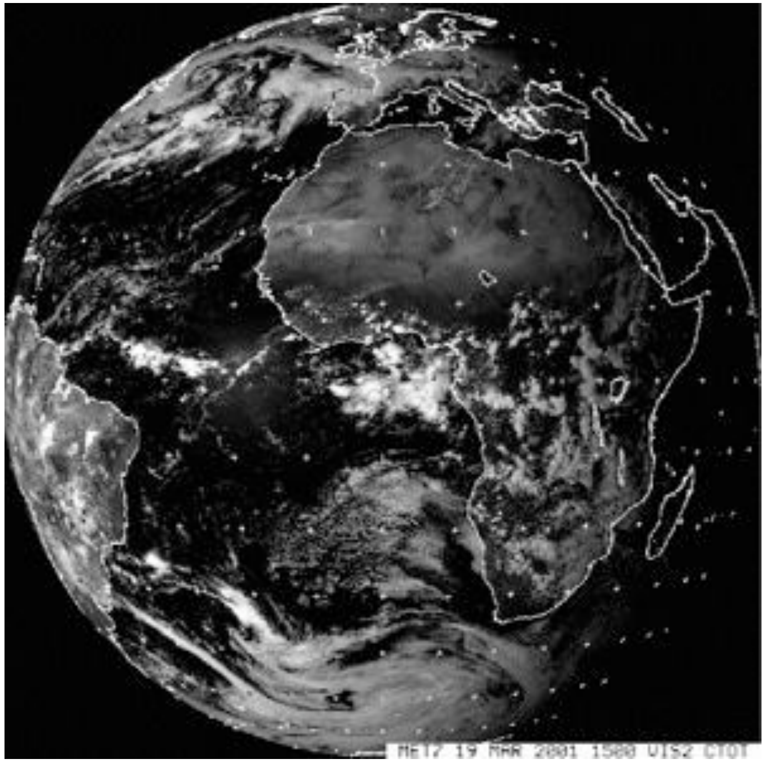
Spatial variability



Meteosat 7
19 April 2001
λ: 0.4–1.0 µm
Resolution: 5 km

EUMETSAT

Ikonos
28 August 2004
λ: RGB composite
Resolution: 4 m

SPACE IMAGING

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Temporal variability

EUMETSAT

Spectral variability

MERIS
14 July 2003
λ: RGB composite
Resolution: 300 m

Ref. figure: http://earth.esa.int/showcase/env/UK/TheChannel_MER_FR_Orbit07162_20030714.htm

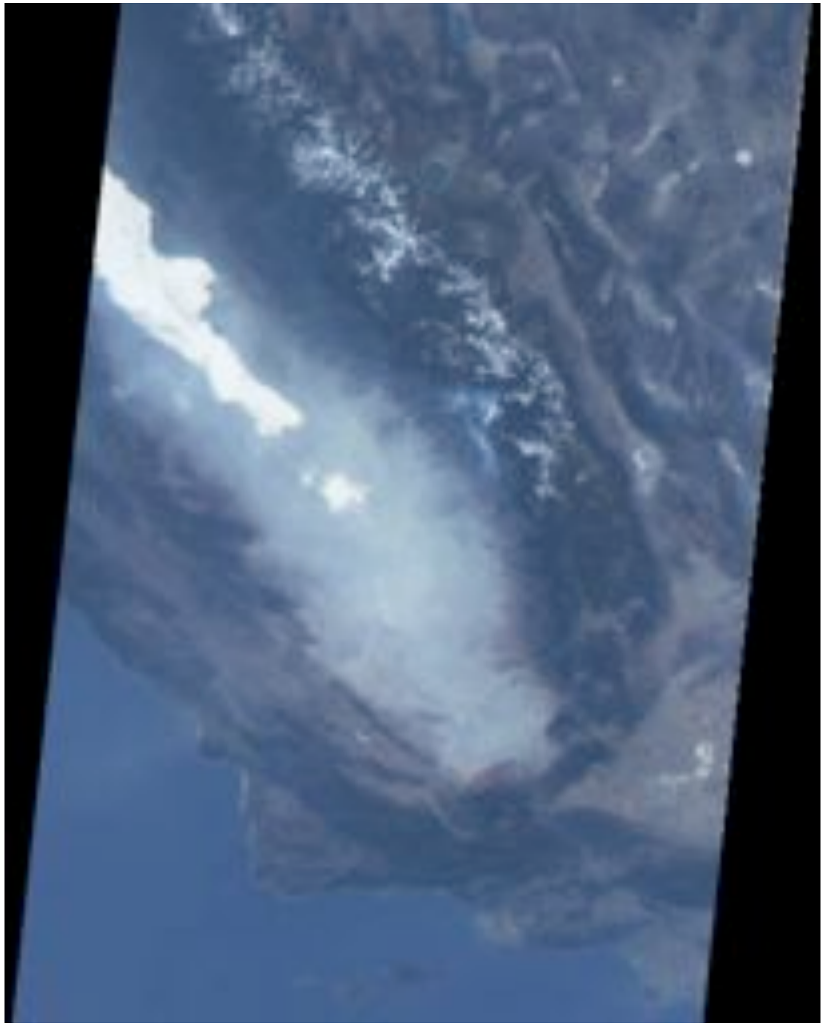
Example 5a: Directional variability

MISR
3 January 2001
λ: RGB composite
Resolution: 250 m
Nadir view

San Joaquin Valley, CA

Ref. figure: http://www.spaceimaging.com/gallery/top10_2003/top10_7.htm

Example 5b: Directional variability



MISR

3 January 2001

λ: RGB composite

Resolution: 250 m

70º forward view

San Joaquin Valley, CA

Ref. figure: http://www.spaceimaging.com/gallery/top10_2003/top10_7.htm

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Anisotropy primer (1)

- Solar illumination is highly directional, especially under clear skies
- All surfaces and media, natural or artificial, and in particular water, soils, vegetation, snow and ice, are anisotropic (i.e., reflect light differently in different directions)
- Anisotropy is controlled by the structure and optical properties of the geophysical media
- Hence, the reflectance of geophysical media is bidirectional (Ω_0, Ω)
- Atmospheric constituents also interact anisotropically with the radiation fields (Rayleigh, Mie scattering)
- Anisotropy is itself a spectrally-dependent property
- Examples: specular reflectance, hot spot, Lambertian panel

Anisotropy primer (Examples)

Photo from STS-36 mission

MODIS picture over Suriname

Ref: http://www.astronautix.com/graphics/0/10063854.jpg and
http://veimages.gsfc.nasa.gov/4779/Suriname.A2002262.1405.1km.jpg

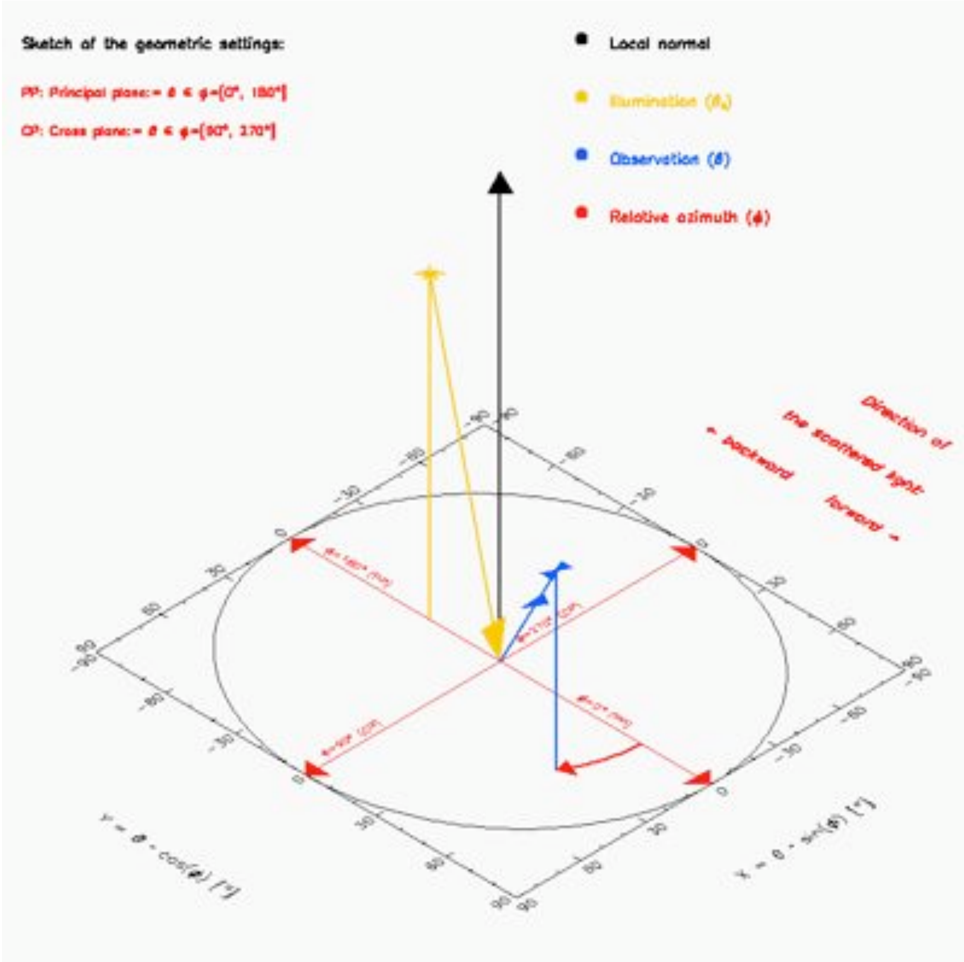
Anisotropy primer (2)

- Imaging instruments with a small IFOV sample the reflectance of the surface-atmosphere system in the direction of the sensor, measure the hemispherical-conical reflectance of the geophysical system

- These measurements thus depend on the particular geometry of illumination and observation at the time of acquisition

  - all sensors, including ‘nadir-looking’, are affected
  - applications that do not exploit anisotropy must nevertheless account for these effects
  - unique information on the observed media (e.g., structural characteristics) can be derived from observations of these angular variations

Illumination and observation geometry



Illumination direction:
$\Omega_0 = [\theta_0, \varphi_0]$

Observation direction:
$\Omega = [\theta, \varphi]$

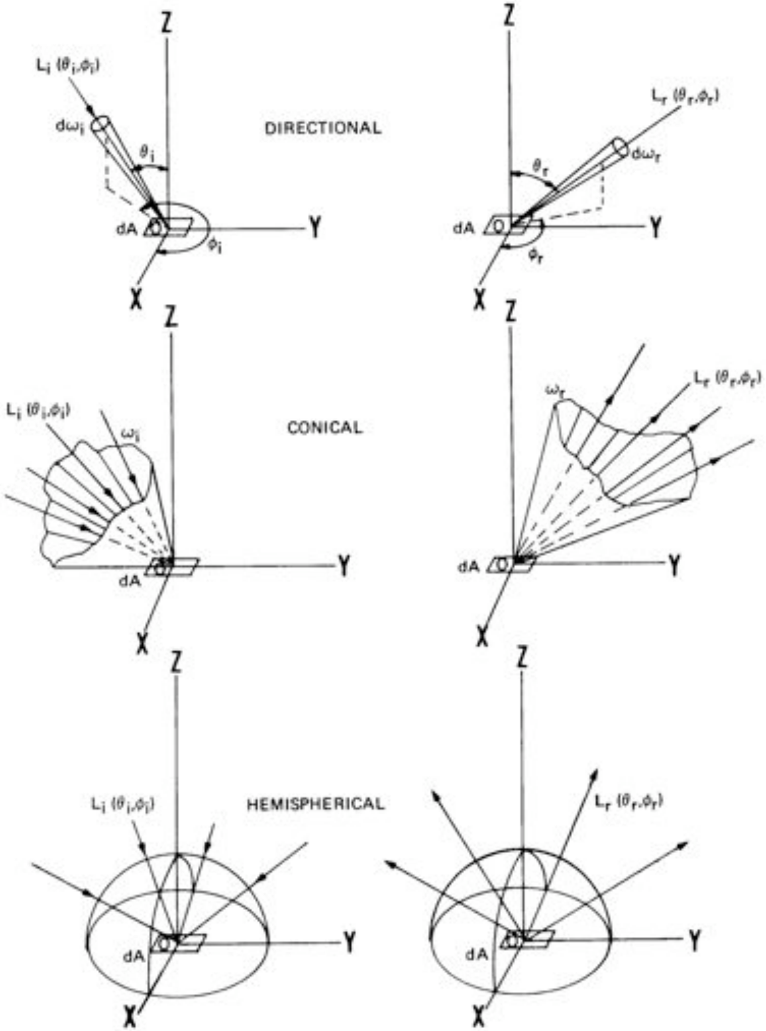
$\mu_0 = \cos\ \theta_0$

$\mu = \cos\ \theta$

Ref: Vogt and Verstraete (2002) RPV IDL tool

Nomenclature (1)

Incoming

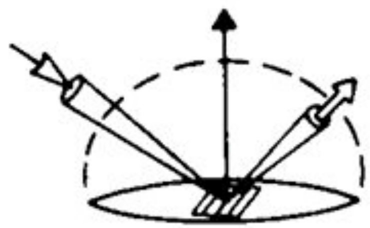


Outgoing

Ref: Nicodemus et al. (1977) NBS Monograph

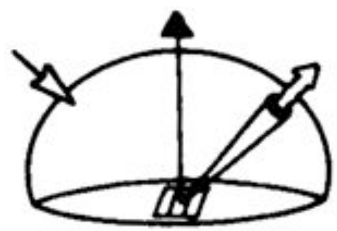
Nomenclature (2)

BRDF: Bidirectional Reflectance Distribution Function.
Units: [sr^{-1}], non-measurable.



BRF: Bidirectional Reflectance Factor, is BRDF normalized by the reflectance of a reference Lambertian surface, identically illuminated and observed. Units: [N/D], approximately measurable in the laboratory as a biconical reflectance factor.

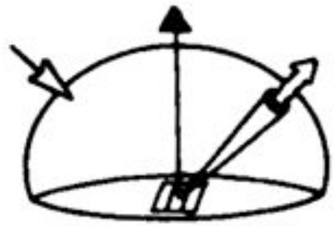
HCRF: Hemispherical Conical Reflectance Factor.
Units: [N/D], common measurement.



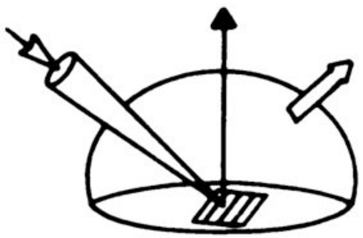
Ref: Nicodemus et al. (1977) NBS Monograph

Nomenclature (3)

HDRF: Hemispherical Directional Reflectance Factor, single integral of BRDF on the incoming directions (i.e., direct + diffuse illumination).



DHR: Directional Hemispherical Reflectance, single integral of BRDF on the outgoing directions (“black sky albedo”).



BHR: Bi-Hemispherical Reflectance (also known as albedo or “white sky albedo”), double integral of BRDF.

Ref: Nicodemus et al. (1977) NBS Monograph.

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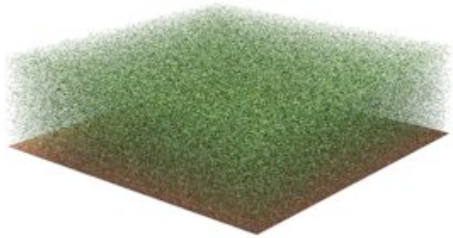
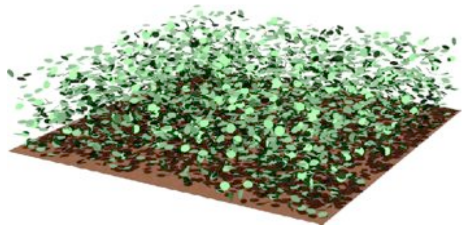
Families of BRDF models

- 1-D turbid medium models simulate the reflectance of homogeneous scenes (computationally inexpensive)



- These models have been expanded to account for the finite nature of leaves and for the hotspot (possibly specular reflection)



- 3-D ray-tracing (or radiosity) models simulate the reflectance of arbitrarily complex heterogeneous scenes (realistic but computationally expensive)

- Parametric models simulate the shape of the BRDF function without providing a physical explanation (computationally extremely fast)

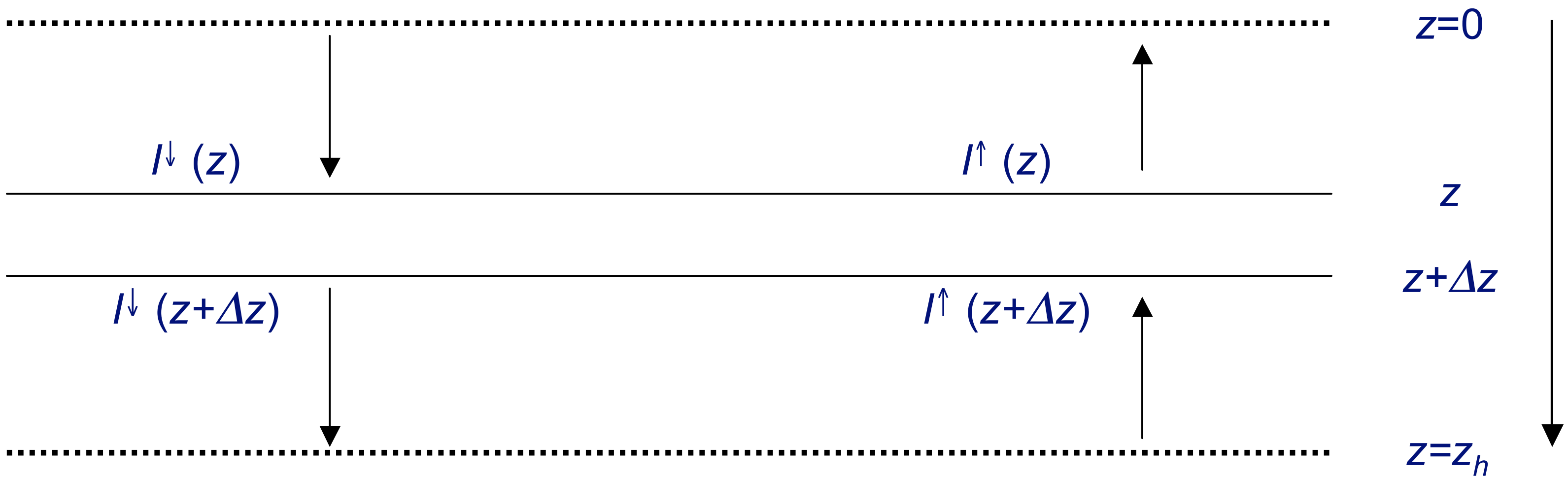
1-D radiation transfer (1)

- Consider a simplified 1-D ‘turbid medium’ system
  - composed of an infinitely large horizontal layer bounded by two parallel planes (plane-parallel medium)
  - containing a very large number of infinitely small particles
- Mean monochromatic radiant energy fluxes are denoted *I* [W m^{-2} sr^{-1}])
  - radiation originates outside the layer
  - can be scattered in only two directions: upward and downward
- Physical interaction processes include
  - extinction *E* (change in the intensity of radiation propagating in a given direction)
  - scattering *S* (change in the direction of propagation)
  - absorption *K* (conversion of electromagnetic energy into another form, typically heat)

  where $E = S + K$

Ref: Pinty, B. and M. M. Verstraete (1998) ERCA, Volume 3.

1-D radiation transfer (2)



- Upward and downward intensities vary along *z* and depend on the volumetric (particle cross-section × number particles per unit volume) coefficients of absorption *K* (in m^{-1}) and of scattering *S* (in m^{-1}).
- 1/*S* (1/*K*) have dimensions of length and may be interpreted as the absorption (scattering) mean free paths, i.e., the average distance before an absorption (scattering) event occurs.

Ref: Pinty, B. and M. M. Verstraete (1998) ERCA, Volume 3.

1-D radiation transfer (3)

- In the slab (z to z+Δz), let $P^{\uparrow\downarrow}$ ($P^{\downarrow\uparrow}$) be the probability that a photon directed upward (downward) is scattered downward (upward). Then

$$I^{\downarrow}(z) + S\Delta z P^{\uparrow\downarrow} I^{\uparrow}(z+\Delta z) = K\Delta z I^{\downarrow}(z) + S\Delta z P^{\downarrow\uparrow} I^{\downarrow}(z) + I^{\downarrow}(z+\Delta z)$$

$$I^{\uparrow}(z+\Delta z) + S\Delta z P^{\downarrow\uparrow} I^{\downarrow}(z) = K\Delta z I^{\uparrow}(z+\Delta z) + S\Delta z P^{\uparrow\downarrow} I^{\uparrow}(z+\Delta z) + I^{\uparrow}(z)$$

- rearranging the terms and dividing by Δz,

$$\frac{I^{\downarrow}(z+\Delta z) - I^{\downarrow}(z)}{\Delta z} = -KI^{\downarrow}(z) - SP^{\downarrow\uparrow} I^{\downarrow}(z) + SP^{\uparrow\downarrow} I^{\uparrow}(z)$$

$$\frac{I^{\uparrow}(z+\Delta z) - I^{\uparrow}(z)}{\Delta z} = KI^{\uparrow}(z+\Delta z) + SP^{\uparrow\downarrow} I^{\uparrow}(z+\Delta z) - SP^{\downarrow\uparrow} I^{\downarrow}(z)$$

- and taking the limit $\Delta z \to 0$,

$$\frac{\partial I^{\downarrow}(z)}{\partial z} = -KI^{\downarrow}(z) - SP^{\downarrow\uparrow} I^{\downarrow}(z) + SP^{\uparrow\downarrow} I^{\uparrow}(z)$$

$$\frac{\partial I^{\uparrow}(z)}{\partial z} = KI^{\uparrow}(z) + SP^{\uparrow\downarrow} I^{\downarrow}(z) - SP^{\downarrow\uparrow} I^{\downarrow}(z)$$

Ref: Pinty, B. and M. M. Verstraete (1998) ERCA, Volume 3.

1-D radiation transfer (4)

- When the geophysical medium is isotropic,
  - $P^{\uparrow\downarrow} = P^{\downarrow\uparrow}$
  - $P^{\uparrow\uparrow} = P^{\downarrow\downarrow}$ and
  - $P^{\uparrow\downarrow} + P^{\uparrow\uparrow} = P^{\downarrow\uparrow} + P^{\downarrow\downarrow} = 1$
- The asymmetry factor *g* is a real number, defined as the mean cosine of the scattering angle (–1 or +1 in our case):

$$g = (+1)P^{\downarrow\downarrow} + (-1)P^{\downarrow\uparrow} \quad \text{or} \quad g = (+1)P^{\uparrow\uparrow} + (-1)P^{\uparrow\downarrow}$$

- Typically:
  - g = +1 for strict downward scattering,
  - g = –1 for strict upward scattering and,
  - g = 0 for isotropic scattering
- Hence, when the medium is isotropic,

$$P^{\uparrow\downarrow} = P^{\downarrow\uparrow} = (1-g)/2$$
$$P^{\uparrow\uparrow} = P^{\downarrow\downarrow} = (1+g)/2$$

Ref: Pinty, B. and M. M. Verstraete (1998) ERCA, Volume 3.

1-D radiation transfer (5)

- Normalizing the RT equations by $E = S + K$,

$$\frac{1}{E}\frac{\partial I^{\downarrow}(z)}{\partial z} = -\frac{K}{E}I^{\downarrow}(z) - \frac{S}{E}P^{\downarrow\uparrow}I^{\downarrow}(z) + \frac{S}{E}P^{\uparrow\downarrow}I^{\uparrow}(z)$$

$$\frac{1}{E}\frac{\partial I^{\uparrow}(z)}{\partial z} = \frac{K}{E}I^{\uparrow}(z) + \frac{S}{E}P^{\uparrow\downarrow}I^{\downarrow}(z) - \frac{S}{E}P^{\downarrow\uparrow}I^{\downarrow}(z)$$

- which can be rewritten, for an isotropic medium, as:

$$\frac{1}{E}\frac{\partial I^{\downarrow}(z)}{\partial z} = -I^{\downarrow}(z) + \omega\frac{(1+g)}{2}I^{\downarrow}(z) + \omega\frac{(1-g)}{2}I^{\uparrow}(z)$$

$$\frac{1}{E}\frac{\partial I^{\uparrow}(z)}{\partial z} = +I^{\uparrow}(z) - \omega\frac{(1+g)}{2}I^{\uparrow}(z) - \omega\frac{(1-g)}{2}I^{\downarrow}(z)$$

- where ω = *S/E* is the single scattering albedo (0 for total absorption and 1 for conservative scattering)

Ref: Pinty, B. and M. M. Verstraete (1998) ERCA, Volume 3.

1-D radiation transfer (6)

- Introduce the optical thickness

$$\tau = \int_0^z E dz = \int_0^z (S + K) dz$$

- then rewrite the RT equations in terms of this new coordinate:

$$\frac{\partial I^{\downarrow}(z)}{\partial \tau} = -I^{\downarrow}(z) + \omega \frac{(1+g)}{2} I^{\downarrow}(z) + \omega \frac{(1-g)}{2} I^{\uparrow}(z)$$

$$\frac{\partial I^{\uparrow}(z)}{\partial \tau} = +I^{\uparrow}(z) - \omega \frac{(1+g)}{2} I^{\uparrow}(z) - \omega \frac{(1-g)}{2} I^{\downarrow}(z)$$

- or, in a more compact form (2-stream model or equations):

$$\frac{\partial (I^{\downarrow} - I^{\uparrow})}{\partial \tau} = -(1-\omega)(I^{\downarrow} + I^{\uparrow})$$

$$\frac{\partial (I^{\downarrow} + I^{\uparrow})}{\partial \tau} = -(1-\omega g)(I^{\downarrow} - I^{\uparrow})$$

Ref: Pinty, B. and M. M. Verstraete (1998) ERCA, Volume 3.

1-D radiation transfer (7)

- This simple model can be extended to take into account the transfer of radiation in more directions (4-stream model, etc). When the number of allowed directions becomes infinite, the RT equation is

$$-\mu \frac{\partial I(z,\Omega)}{\partial z} + \tilde{\sigma}(z) I(z,\Omega) = \int_{4\pi} \tilde{\sigma}_s(z,\Omega' \to \Omega) I(z,\Omega') d\Omega'$$

- where the single scattering albedo ω is

$$\int_{4\pi} \tilde{\sigma}_s(z,\Omega' \to \Omega) d\Omega = \omega(z) \tilde{\sigma}(z)$$

- where $\tilde{\sigma}_s(z,\Omega' \to \Omega)$ is the differential scattering coefficient and $\tilde{\sigma}(z)$ is the extinction coefficient.
- The main advantage of 2-stream models is that they can readily be incorporated into atmospheric models, but pay attention to their proper implementation (see paper by Pinty et al., 2006)

Ref: Pinty, B. and M. M. Verstraete (1998) ERCA, Volume 3.

1-D radiation transfer (8)

Satellite

"ToA"

Atmosphere

- Non-oriented small scatterers
- Infinite number of scatterers
- Low density turbid medium

"ToC"

Vegetation

- Oriented finite-size scatterers
- Finite number of scatterers
- Dense discrete medium

Soil

- Oriented small-size scatterers
- Finite number of clustered scatterers
- Compact semi-infinite medium

Ref: Pinty, B. and M. M. Verstraete (1998) ERCA, Volume 3.

1-D radiation transfer (9)

Satellite

$$\frac{I_{sat}^{\uparrow}(z_{sat},\Omega,\Omega_0)}{I^{\downarrow}(z_{ToA},\Omega') = I_0 ä(\Omega' \rightarrow \Omega_0)}$$

"ToA"

Atmosphere

$$\frac{I^{\uparrow}(z_0,\Omega,\Omega_0) = (1/\pi)\int_{2\partial} \rho_{sfc}(z_0,\Omega' \rightarrow \Omega) \times I^{\downarrow}(z_0,\Omega',\Omega_0)\left|\mu'\right| d\Omega'}{I^{\downarrow}(z_0,\Omega',\Omega_0) = I^{\downarrow}(z_{ToA},\Omega')\exp[-\tau_a/\mu_0] + I_d^{\downarrow}(z_0,\Omega')}$$

"ToC"

Surface

- A critical issue is thus the determination of the scattering and extinction coefficients for the plant canopy and soil system.

Ref: Pinty, B. and M. M. Verstraete (1998) ERCA, Volume 3.

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Radiation transfer in plant canopies (1)

- If plants are characterized by these radiative properties:
  - the Leaf Area Index (LAI, non-dimensional or $m^2\ m^{-2}$) is the total one-sided area of all leaves in the canopy per m^2 of ground

$$LAI = \sum_{i=1}^{N} \lambda_i = \sum_{i=1}^{N} n_i a_i$$

  where λ_i=LAI, n_i=number of leaves and a_i=size of leaves in layer $i=1, N$
  - the leaves are deemed to be flat oriented plates with an orientation distribution function $g_l(z, \Omega_l)$ such that

$$\frac{1}{2\pi}\int_{2\pi} d\phi_l \int_0^1 d\mu_l\, g_l(z,\Omega_l) = 1$$

- Then the extinction coefficient, which is the probability, per unit path length, that the photon hits a leaf, amounts to

$$\sigma_e(z,\Omega) = G(z,\Omega)\lambda_l(z)$$

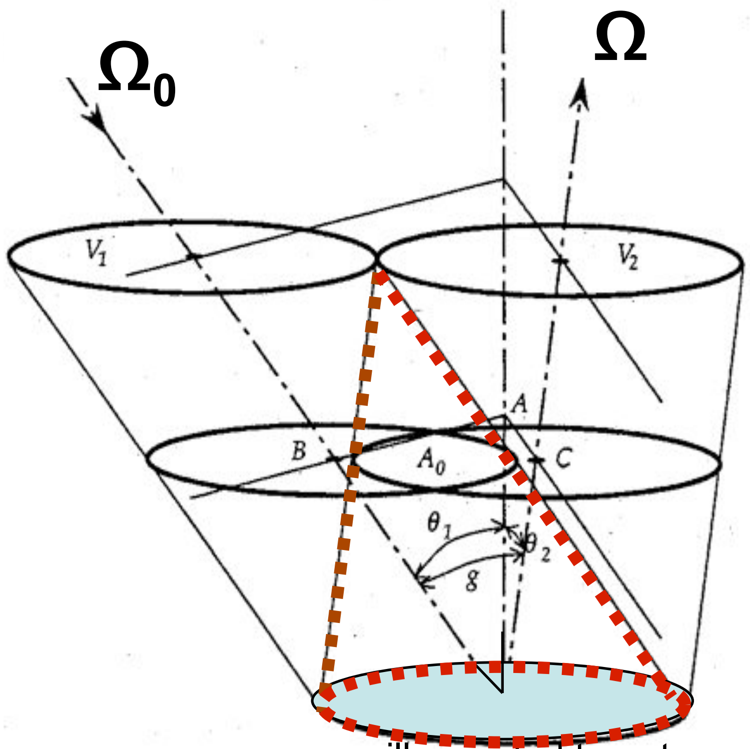
where

$$G(z,\Omega) = \frac{1}{2\pi}\int_{2\pi} g(\Omega_l)\,|\,\Omega_l \bullet \Omega\,|\,d\Omega_l$$

Ref: Ross, J. (1981) or Gobron, N. et al. (1997) 'A semi-discrete model for the scattering of light by vegetation', *Journal of Geophysical Research*, **102**, 9431-9446.

Radiation transfer in plant canopies (2)

- The transfer of radiation in plant canopies composed of finite leaves must be modified because the far field approximation of turbid media is not valid (shading). This generates the 'hot spot' phenomenon:



Ref: Verstraete, M. M. et al. (1990) 'A physical model of the bidirectional reflectance of vegetation canopies; Part 1: Theory and Part 2: Inversion and validation', *Journal of Geophysical Research*, **95**, 11,755-11,775.

Radiation transfer in plant canopies (3)

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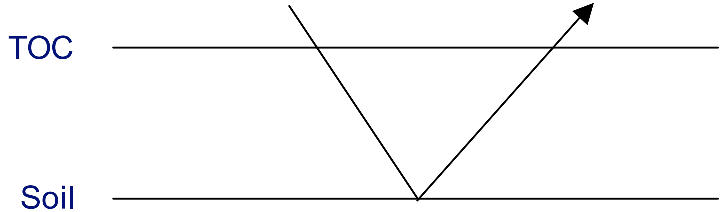
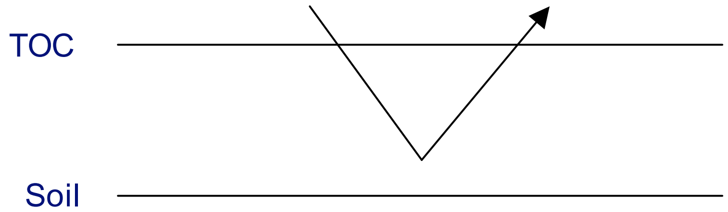
- The reflectance of the canopy $\rho(z_0,\Omega,\Omega_0)$ is calculated as the sum of contributions:
  - uncollided

$$\rho_0(z_0,\Omega,\Omega_0)$$



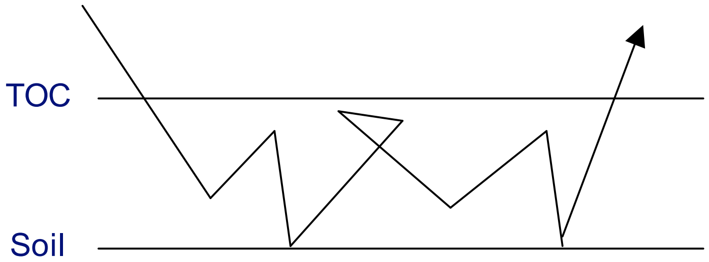
  - single collided

$$+\ \rho_1(z_0,\Omega,\Omega_0)$$



  - multiply collided

$$+\ \rho_M(z_0,\Omega,\Omega_0)$$

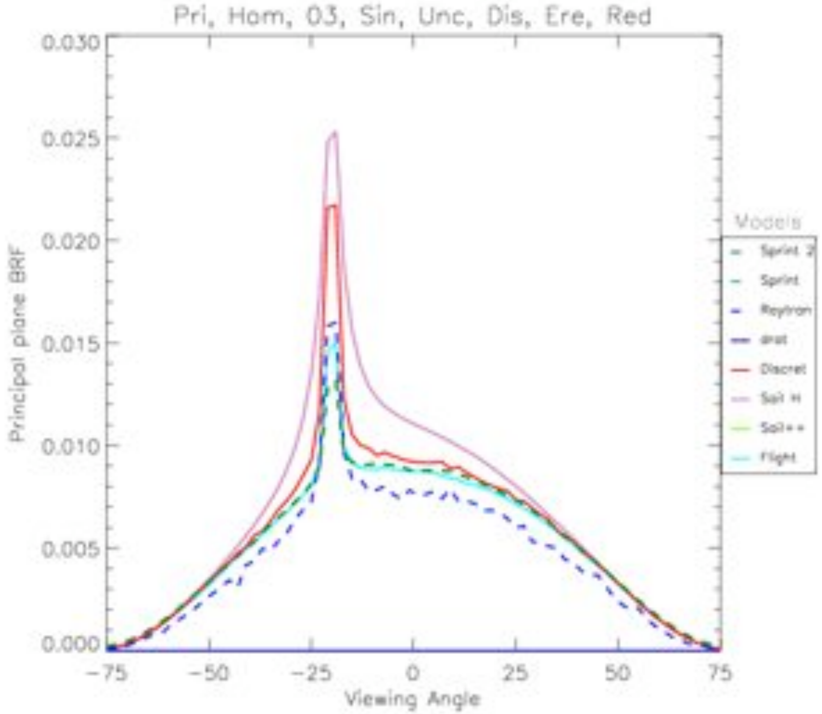


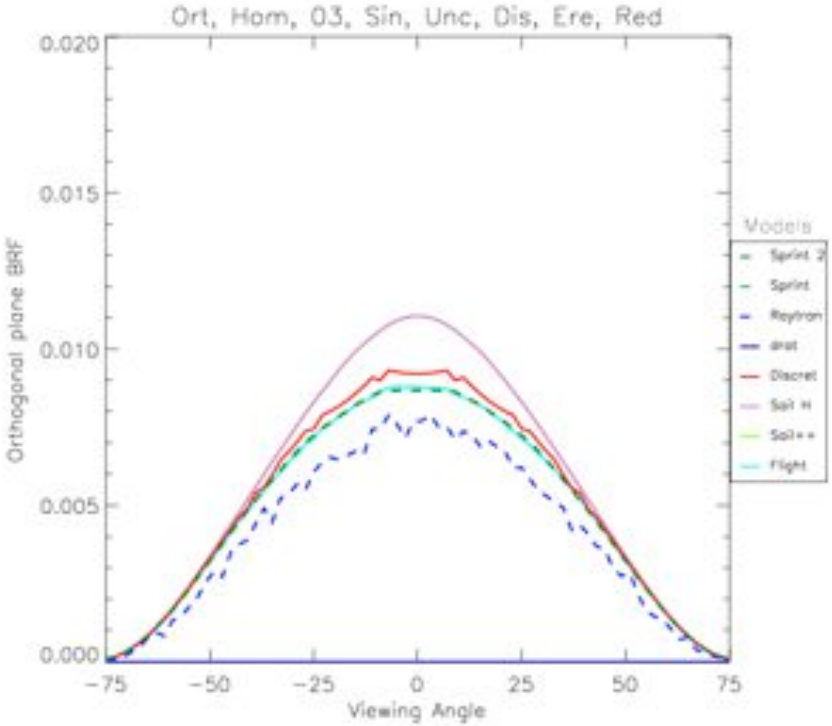
$$\rho(z_0,\Omega,\Omega_0) = \rho_0(z_0,\Omega,\Omega_0) + \rho_1(z_0,\Omega,\Omega_0) + \rho_M(z_0,\Omega,\Omega_0)$$

Ref: Gobron, N. et al. (1997) 'A semi-discrete model for the scattering of light by vegetation', *Journal of Geophysical Research*, **102**, 9431-9446.

Radiation transfer in plant canopies (4)

- Examples of uncollided radiation in the principal and cross planes:





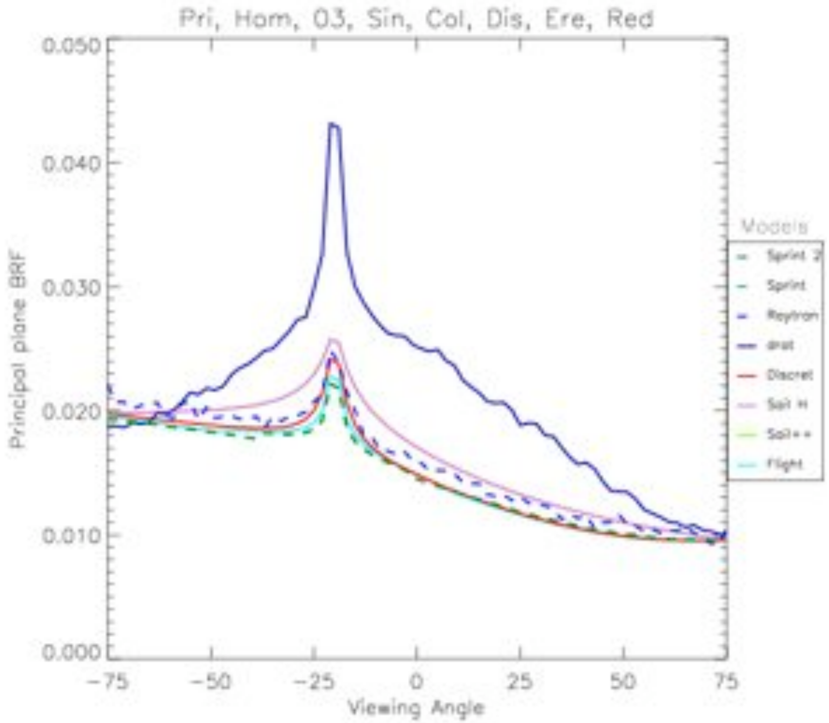
Solar Zenith Angle:	20 [deg]
Solar Azimuth Angle:	0 [deg]
Radius:	0.05 [m]
Leaf Area Index:	3.0 [m^2 m^{-2}]
Canopy height:	2.0 [m]

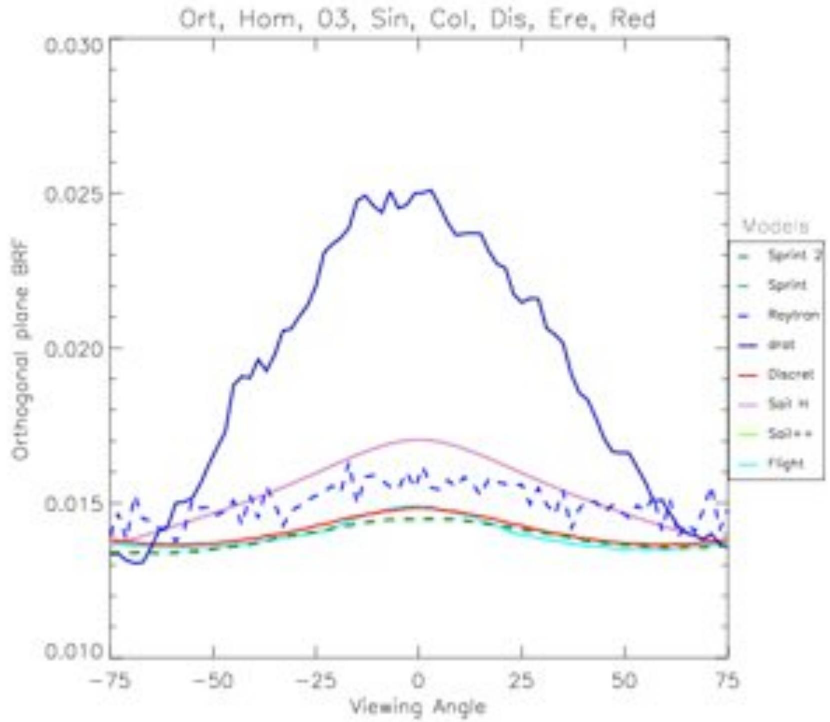
Normal Distribution:	Erectophile
Leaf scattering law:	Bi-Lambertian
Leaf reflectance:	0.0546
Leaf transmittance:	0.0149
Soil scattering law:	Lambertian
Soil reflectance:	0.127

Ref: http://rami-benchmark.jrc.it/.

Radiation transfer in plant canopies (5)

- Examples of single collided radiation in the principal and cross planes:





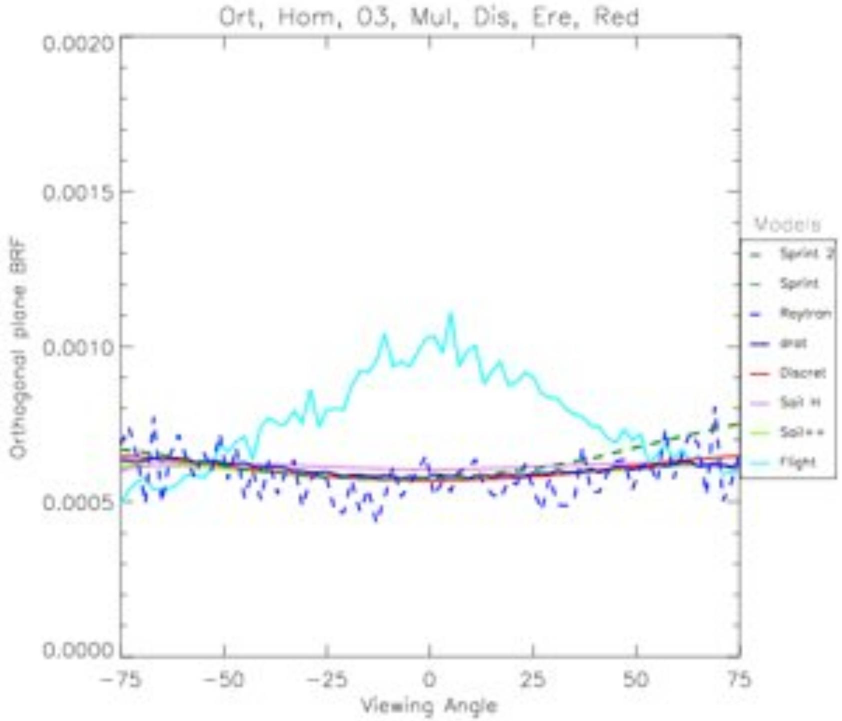
Solar Zenith Angle:	20 [deg]
Solar Azimuth Angle:	0 [deg]
Radius:	0.05 [m]
Leaf Area Index:	3.0 [m^2 m^{-2}]
Canopy height:	2.0 [m]

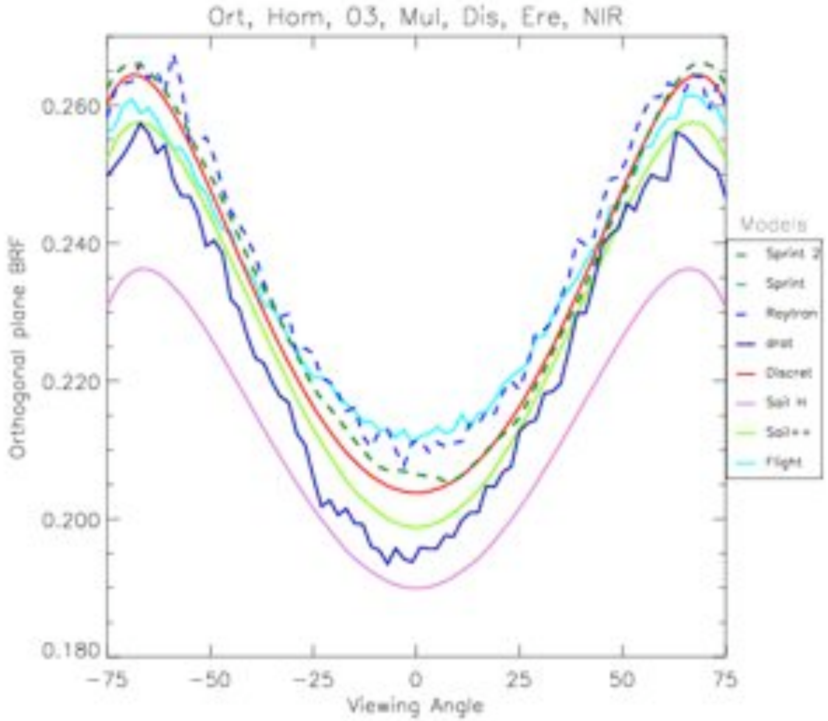
Normal Distribution:	Erectophile
Leaf scattering law:	Bi-Lambertian
Leaf reflectance:	0.0546
Leaf transmittance:	0.0149
Soil scattering law:	Lambertian
Soil reflectance:	0.127

Ref: http://rami-benchmark.jrc.it/.

Radiation transfer in plant canopies (6)

- Examples of multiply collided radiation in the cross plane (RED and NIR):





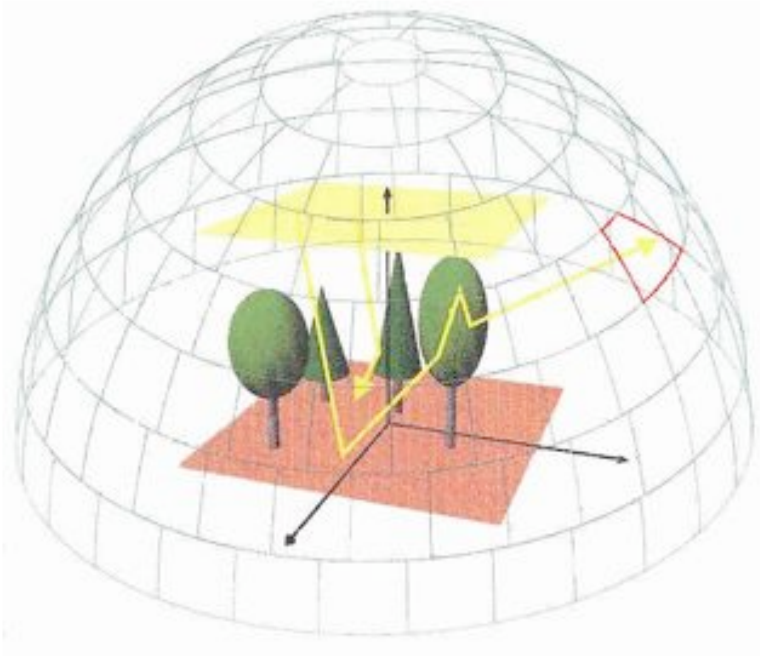
Solar Zenith Angle:	20 [deg]
Solar Azimuth Angle:	0 [deg]
Radius:	0.05 [m]
Leaf Area Index:	3.0 [m^2 m^{-2}]
Canopy height:	2.0 [m]

Normal Distribution:	Erectophile
Leaf scattering law:	Bi-Lambertian
Leaf reflectance:	0.0546
Leaf transmittance:	0.0149
Soil scattering law:	Lambertian
Soil reflectance:	0.127

Ref: http://rami-benchmark.jrc.it/.

3-D radiation transfer: Ray tracing (1)

- Hypotheses:
  - Light propagation is described exclusively in terms of geometric optics
  - Incident radiation can be simulated with a finite number of rays that do not interact with each other
  - Scattering events are elastic, neglecting the effects of quantum transitions and diffraction
  - The structural properties of the medium can be described with geometrical primitives
  - The optical properties of the elements can be defined with probability distribution functions
- Rays are propagated within the scene (stochastic processes)
- Displace complexity from PDE to scene description



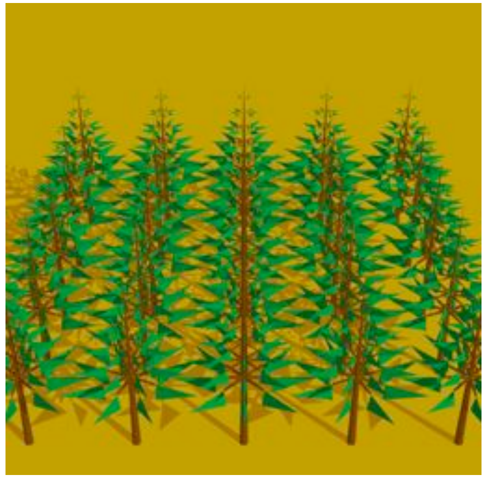
Ref: Govaerts and Verstraete (1996) 'Raytran: A Monte Carlo Ray-Tracing Model to Compute Light Scattering in Three-Dimensional Heterogeneous Media', *IEEE TGRS*, **36**, 493-505.

3-D radiation transfer: Ray tracing (2)

- Scene is assembled as a set of objects with geometric and spectral properties
  - Constructive solid geometry
  - L-systems

- Take advantage of latest computer graphics methods

- Collect statistics about fate of all rays to estimate scattering and absorption



Ref: Govaerts and Verstraete (1996) 'Raytran: A Monte Carlo Ray-Tracing Model to Compute Light Scattering in Three-Dimensional Heterogeneous Media', *IEEE TGRS*, **36**, 493-505.

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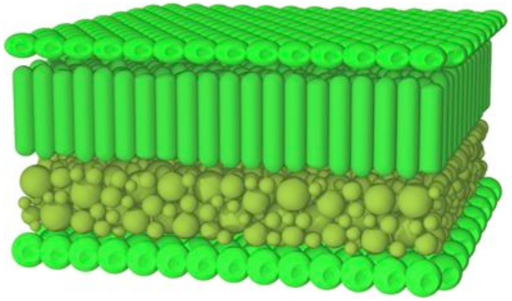
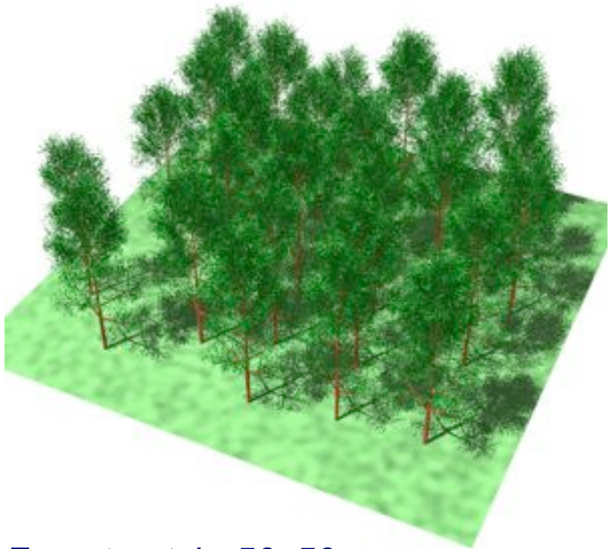
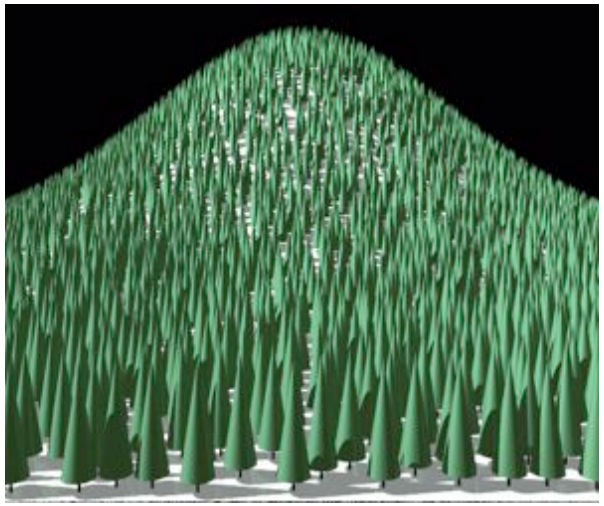
3-D radiation transfer: Examples



Dicotyledon leaf: 5x5 mm



Forest patch: 50x50 m



Forested hill: 300x300 m

Outline

1. Basic principles
2. Anisotropy and terminology
3. Elements of radiation transfer (RT) theory
4. BRDF models (1D, 3D, homogeneous, heterogeneous)
5. AnisView as a BRDF visualisation tool using RPV

0-D radiation transfer: Parametric models

- Represent shape of BRDF, not scattering processes
- Use simple equations for fast computations

$$\rho_\lambda = \rho_{0\lambda} F(\Omega_0, \Omega_v, k_\lambda, \Theta_\lambda^{HG}, \rho_{c\lambda})$$

$$F(\Omega_0, \Omega_v, k_\lambda, \Theta_\lambda^{HG}, \rho_{c\lambda}) = f_1(\theta_0, \theta_v, k_\lambda)\, f_2(\Omega_0, \Omega_v, \Theta_\lambda^{HG})\, f_3(\Omega_0, \Omega_v, \rho_{c\lambda})$$

$$f_1(\theta_0, \theta_v, k_\lambda) = \frac{(\cos\theta_0 \cos\theta_v)^{k_\lambda - 1}}{(\cos\theta_0 + \cos\theta_v)^{1-k_\lambda}}$$

$$f_2(\Omega_0, \Omega_v, \Theta_\lambda^{HG}) = \frac{1 - (\Theta_\lambda^{HG})^2}{[1 + 2\Theta_\lambda^{HG} \cos g + (\Theta_\lambda^{HG})^2]^{3/2}}$$

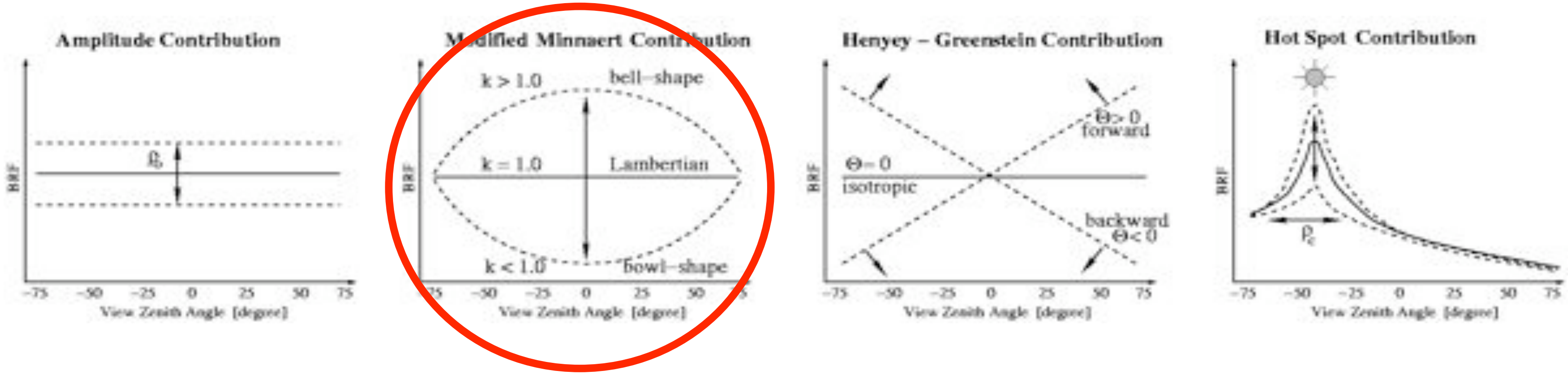
$$f_3(\Omega_0, \Omega_v, \rho_{c\lambda}) = 1 + \frac{1 - \rho_{c\lambda}}{1 + G}$$

Ref: Rahman, H., B. Pinty, and M. M. Verstraete (1993) 'Coupled surface-atmosphere reflectance (CSAR) model. 2. Semi-empirical surface model usable with NOAA Advanced Very High Resolution Radiometer data', *Journal of Geophysical Research*, **98**, 20,791-20,801.

RPV parametric model

$$BRF(z,\Omega_0 \rightarrow \Omega) = \rho_0 \times Mi\,(k) \times F_{HG}\,(\Theta) \times H\,(\rho_c)$$

ρ_0 - controls amplitude level
k - controls bowl/bell shape
Θ - controls forward/backward scattering
ρ_c - controls hot spot peak



Ref: Rahman, H., B. Pinty, and M. M. Verstraete (1993) 'Coupled surface-atmosphere reflectance (CSAR) model. 2. Semi-empirical surface model usable with NOAA Advanced Very High Resolution Radiometer data', *Journal of Geophysical Research*, **98**, 20,791-20,801.

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0-D radiation transfer: Example

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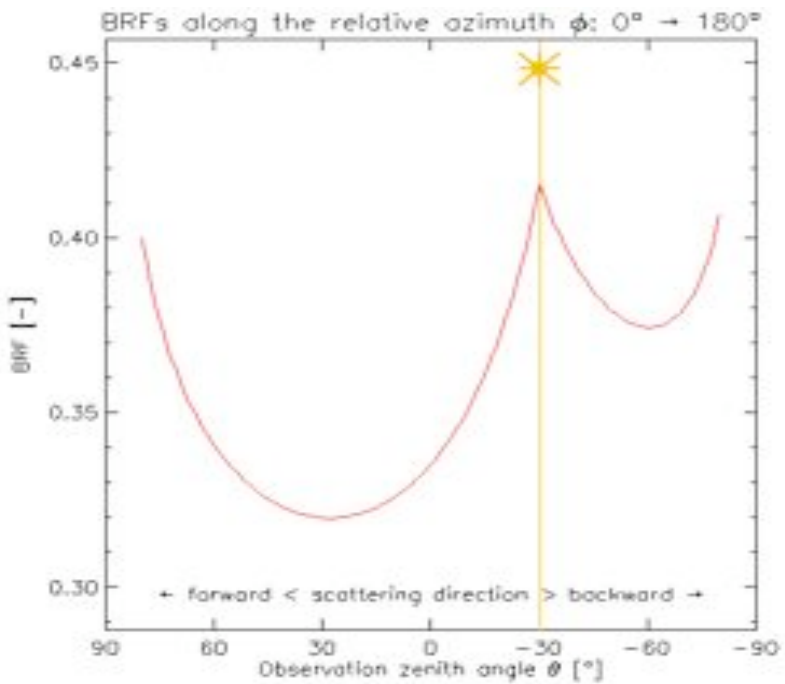

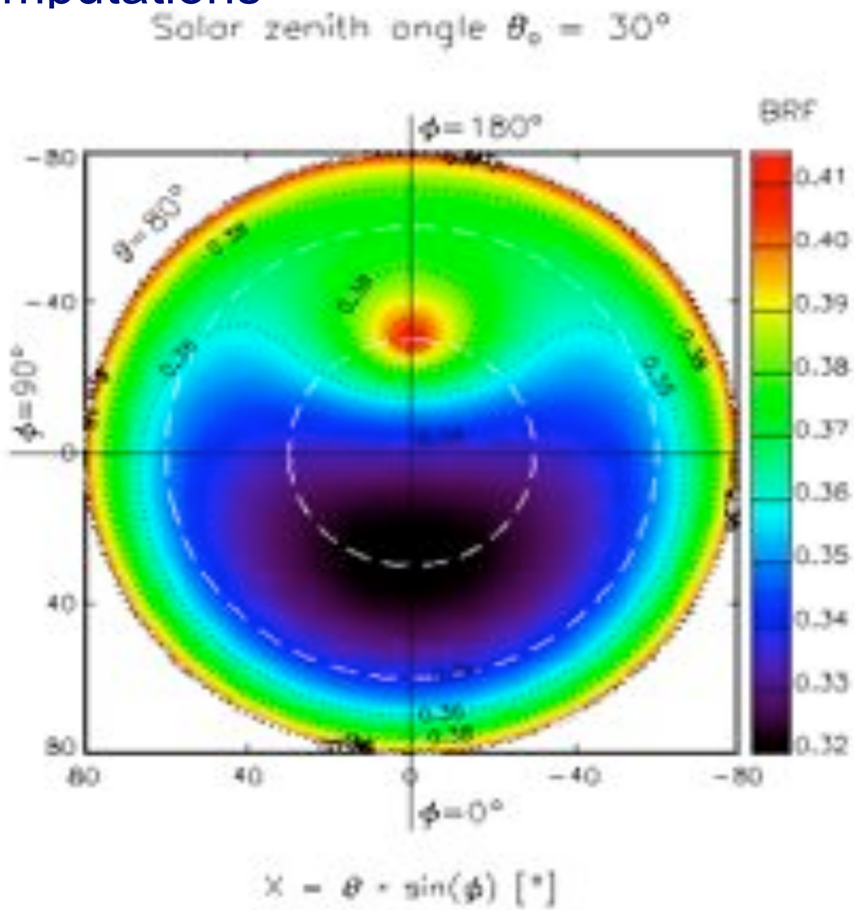

Ref: Rahman, H., B. Pinty, and M. M. Verstraete (1993) 'Coupled surface-atmosphere reflectance (CSAR) model. 2. Semi-empirical surface model usable with NOAA Advanced Very High Resolution Radiometer data', *Journal of Geophysical Research*, **98**, 20,791-20,801.

AnisView

- A stand-alone, GUI toy to play with the RPV and MRPV models (written in IDL)
- Full control of geometry and model parameters
- Immediate calculations
- Generation of statistics

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Ref: Rahman, H., B. Pinty, and M. M. Verstraete (1993) 'Coupled surface-atmosphere reflectance (CSAR) model. 2. Semi-empirical surface model usable with NOAA Advanced Very High Resolution Radiometer data', *Journal of Geophysical Research*, **98**, 20,791-20,801.