Introduction to thermal infrared remote sensing
-
Surface Energy Balance Basics

Z. (Bob) Su
International Institute for Geo-Information Science
and Earth Observation (ITC),
Enschede, The Netherlands
B_SU@ITC.NL, www.itc.nl/wrs

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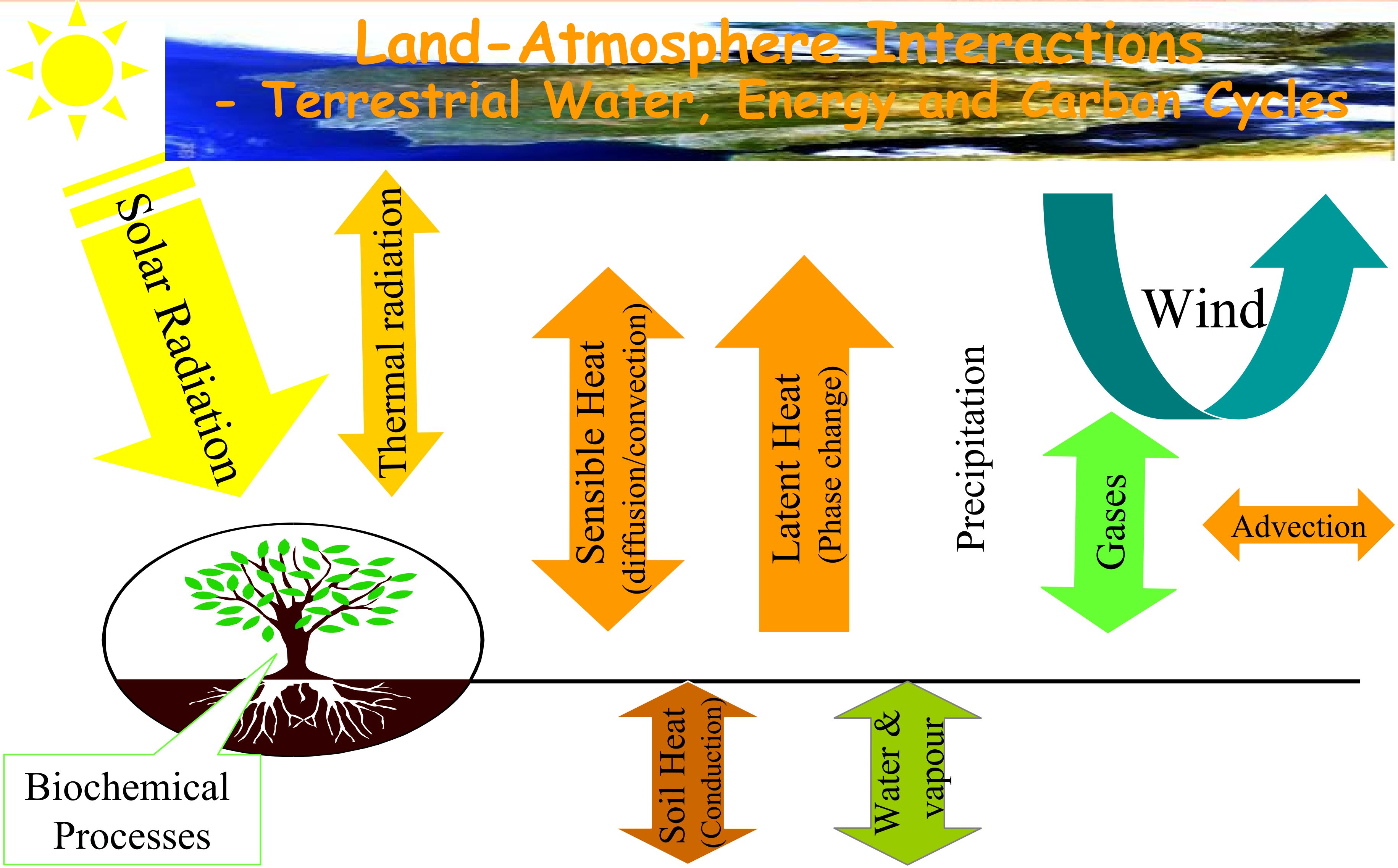
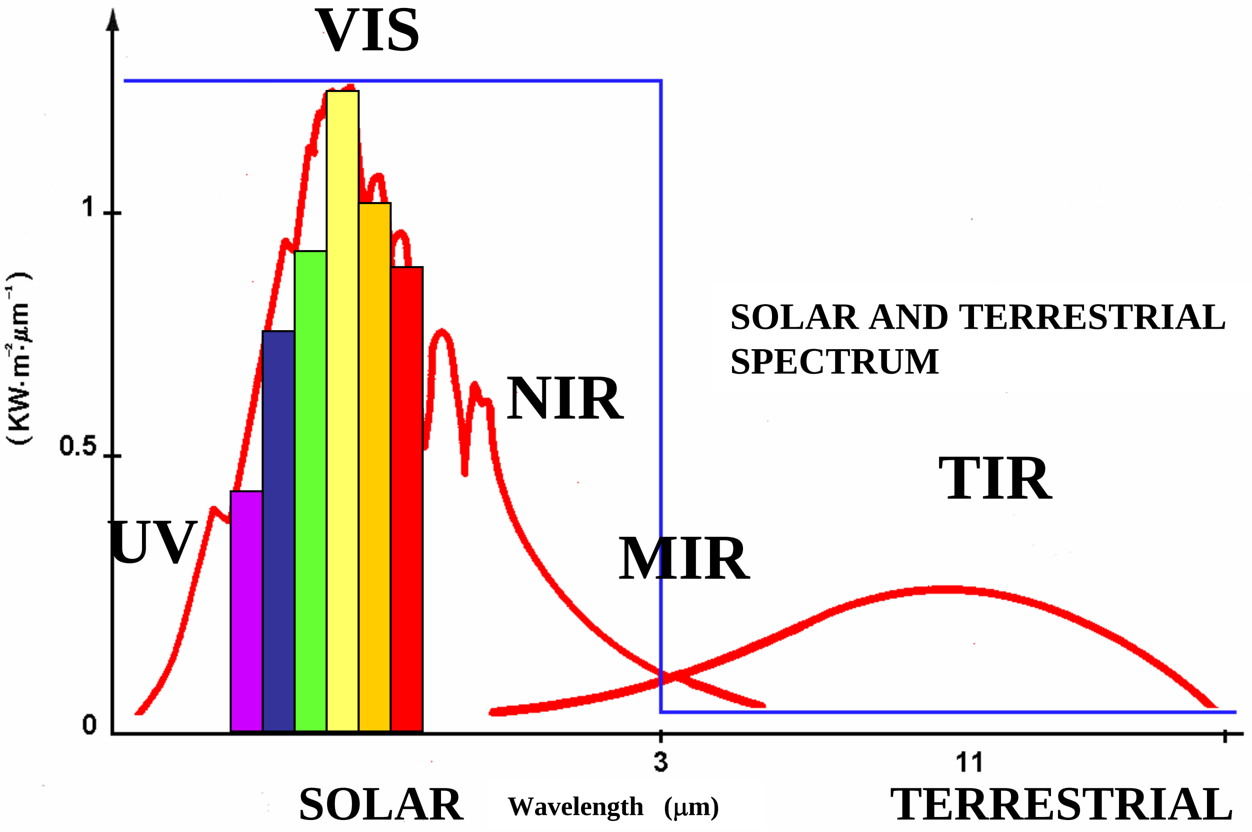
Learning Objectives

1. To understand basic concepts of surface radiation budget
2. To understand basic measurements to derive surface radiation components
3. To be able to derive surface radiation components using different information
4. To familiarize with retrieval of surface parameters

Land-Atmosphere Interactions
- Terrestrial Water, Energy and Carbon Cycles



THERMAL INFRARED RADIATION is a form of electromagnetic radiation with a wavelength between 3 to 14 micrometers (µm). Its flux is much lower than visible flux.



Source: J.-L. Casanova

SOME DEFINITIONS

RADIANT POWER: The rate of flow of electromagnetic energy, *i.e.*, radiant energy, Φ (watts, *i.e.*, joules per second.)

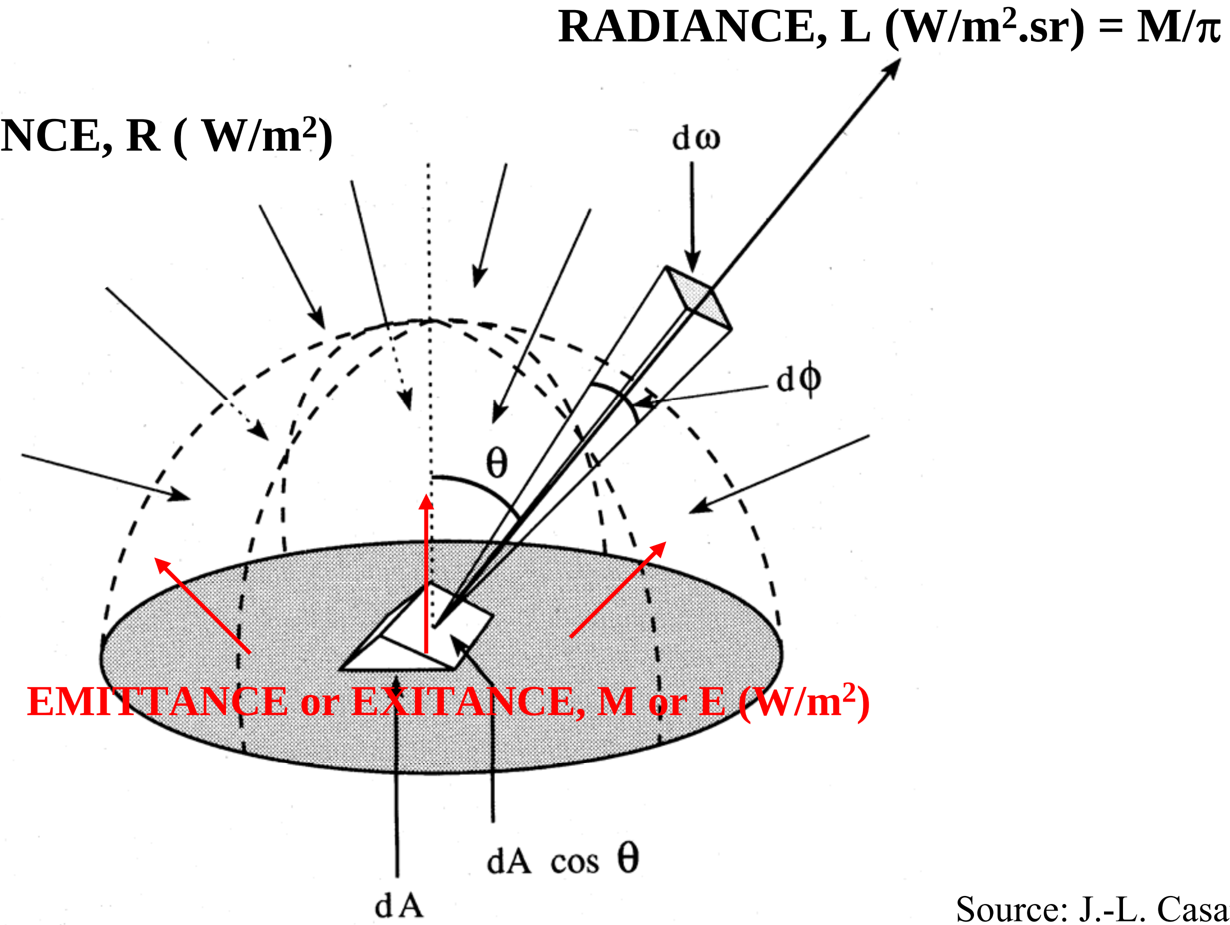
RADIANT EMITTANCE: Radiant power emitted into a full sphere, *i.e.*, 4 sr (steradians), by a unit area of a source, expressed in watts per square meter. *Synonym* radiant exitance, **flux,** radiant flux. M or E (watts/m^2)

RADIANCE: Radiant power, in a given direction, per unit solid angle per unit of projected area of the source, as viewed from the given direction. *Note:* Radiance is usually expressed in watts per steradian per square meter. L (watts/m^2.sr) = M/π

IRRADIANCE: Radiant power incident per unit area upon a surface. *Note:* Irradiance is usually expressed in watts per square meter, but may also be expressed in joules per square meter. *Synonym:* power density, **flux,** radiant flux. R (watts/m^2).

Source: J.-L. Casanova

GRAPHICAL REPRESENTATION OF R, L AND M (or E)



RADIANCE, L ($W/m^2.sr$) = M/π

IRRADIANCE, R (W/m^2)

EMITTANCE or EXITANCE, M or E (W/m^2)

Source: J.-L. Casanova

SPECTRAL MAGNITUDES

ALL THESE MAGNITUDES ARE USUALLY EXPRESSED AS SPECTRAL MAGNITUDES, THAT IS TO SAY, REFERRED TO A WAVELENGHT

RADIANT POWER: Φ_λ (watts/µm) OR (watts.cm^{-1})

RADIANT EMITTANCE: R_λ (watts/m^2.µm) OR (watts.cm^{-1}/m^2)

RADIANCE: L_λ (watts/m^2.sr.µm) OR (watts.cm^{-1}/m^2.sr) = R_λ/π

IRRADIANCE: R_λ (watts/m$^{2\cdot}$µm) OR (watts.cm^{-1}/m^2).

cm^{-1} = number of wavelenghts per cm = 10,000 . (1/ λ µm)
e.g. 1 µm ~ 10,000 cm^{-1}; 10 µm ~ 1,000 cm^{-1}; 11 µm ~ 909.09 cm^{-1}…

Source: J.-L. Casanova

Thermal emission- the Planck’s Law:

The theory to express the thermal emission is based on the black body concept: a **black body** is an object that absorbs all electromagnetic radiation at each wavelength that falls onto it. A black body however emits radiation as well, its magnitude depends on its temperature, and is expressed by the Planck’s Law:

$$B(\lambda, T_S) = \frac{c_1 \lambda^{-5}}{\exp\left(\frac{c_2}{\lambda T_S}\right) - 1}$$

$c_1 = 1.19104 \cdot 10^8$ W μm^4 m^{-2} sr^{-1}
$c_2 = 1.43877 \cdot 10^4$ μm K,
are the first radiation constant (for spectral radiance) and second radiation constant, respectively, B (λ, Ts) is given in W m^{-2} sr^{-1} μm^{-1} if λthe wavelength is given in µm.

Terminology in Thermal Remote Sensing

- Thermodynamic (kinetic) temperature
- Brightness temperature
- Directional radiometric surface temperature & Directional emissivity
- Hemispheric broadband radiometric surface temperature & Hemispherical broadband emissivity

Source: J. Norman, and F. Becker, 1995

Thermodynamic (kinetic) temperature

- Thermodynamic (kinetic) temperature (T) is a macroscopic measure to quantify the thermal dynamic state of a system in thermodynamic equilibrium with its environment (no heat transfer) and can be measured with a infinitesimal thermometer in good contact with it.
- By maximizing the total entropy (S) with respect to the energy (E) of the system, T is defined as

$$\frac{dS}{dE} = \frac{1}{T}$$

- which is consistent with the definition of the absolute temperature by the ideal gas law

$$PV = RT$$

- where is P is pressure, V volume, R the gas constant ($R = kN_0$, k is Boltzmann constant, N_0 number of molecules in a mole).

Brightness temperature

- Brightness temperature ($T_{b,i}$) is a directional temperature obtained by equating the measured radiance ($R_{b,i}$) with the integral over wavelength of the Planck's black body function multiplied by the sensor response f_i.

$$R_{b,i}(\theta,\phi) = R\left(T_{b,i}(\theta,\phi)\right) = \int_{\lambda_1}^{\lambda_2} \frac{f_i(\lambda)C_1}{\lambda^5\left(\exp\left(\frac{C_2}{\lambda T_{b,i}(\theta,\phi)}\right)-1\right)}d\lambda$$

$\int_{\lambda_1}^{\lambda_2} f_i(\lambda)d\lambda = 1$ is the detector relative response.

Directional radiometric surface temperature & Directional emissivity

By appying the Kirchhoff law (energy conservation) to a black body and a real (grey) body, the emissivity is defined - The emittance of a real body is always lower than that of the black body at the same temperature. In order to measure its temperature using a radiometer, we need to introduce a factor called **"emissivity", $\varepsilon < 1$**, to equate its emittence to that of the block body.

$\alpha_\lambda = A_\lambda / I_\lambda = 1$

$\rho_\lambda = R_\lambda / I_\lambda = 0$

$\alpha_\lambda + \rho_\lambda = 1$

BLACK BODY

$A_\lambda = I_\lambda = M_\lambda$ (black body definition)

$\alpha'_\lambda = A'_\lambda / I_\lambda < 1$

$\rho'_\lambda = R'_\lambda / I_\lambda > 0$

$\alpha'_\lambda + \rho'_\lambda = 1$

As the body is in thermal equilibrium: $A'_\lambda = M'_\lambda = \alpha'_\lambda I_\lambda$

$M'_\lambda / \alpha'_\lambda = I_\lambda = M_\lambda$

GREY BODY

$M'_\lambda = \varepsilon_\lambda . M_\lambda = \varepsilon_\lambda . M'_\lambda / \alpha'_\lambda$ $\boldsymbol{\varepsilon_\lambda = \alpha'_\lambda}$ $\varepsilon_\lambda = 1 - \rho'_\lambda$

α_λ: absorptance
A_λ:absorbed flux
I_λ: incident flux
ρ_λ: reflectance
R_λ: reflected flux
ε: emissivity

Directional radiometric surface temperature & Directional emissivity

- The spectral radiance (R_R) measured by a directional radiometer is the sum of the emitted black body radiance modified by the emissivity and the reflected radiation within an infinitesimal wavelength band.

$$R_{R,\lambda}(\theta,\phi) = \varepsilon_\lambda(\theta,\phi) R_{B,\lambda}(\theta,\phi)$$

$$+ \int_0^{2\pi} \int_0^{\pi/2} \rho_{b,\lambda}(\alpha,\beta,\theta,\phi) \cos(\alpha) L_\lambda(\alpha,\beta) \sin(\alpha) d\alpha d\beta$$

Bidirectional reflectance distribution function

Sky radiance

If the incident sky radiance is isotropic, we have

$$\int_0^{2\pi} \int_0^{\pi/2} \rho_{b,\lambda}(\alpha,\beta,\theta,\phi) \cos(\alpha) L_\lambda(\alpha,\beta) \sin(\alpha) d\alpha d\beta = \rho_\lambda(\theta,\phi) L_\lambda$$

Therefore for opaque bodies at thermal equilibrium,

$$\varepsilon_\lambda(\theta,\phi) = 1 - \rho_\lambda(\theta,\phi)$$

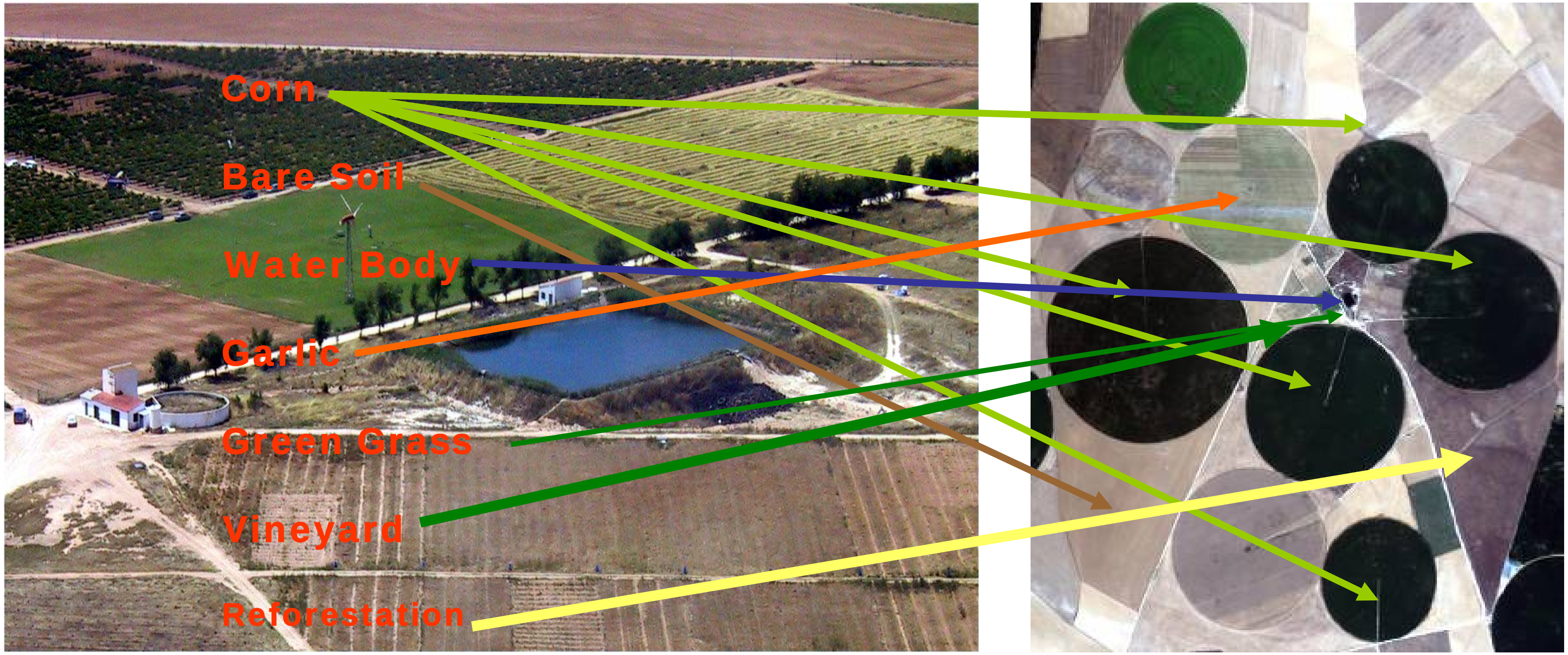
Hemispheric broadband radiometric surface temperature & Hemispherical broadband emissivity

- A hemispheric radiometric surface temperature is used to provide an estimate of the emitted radiance (R_l) over a broad wavelength and the full hemisphere of view

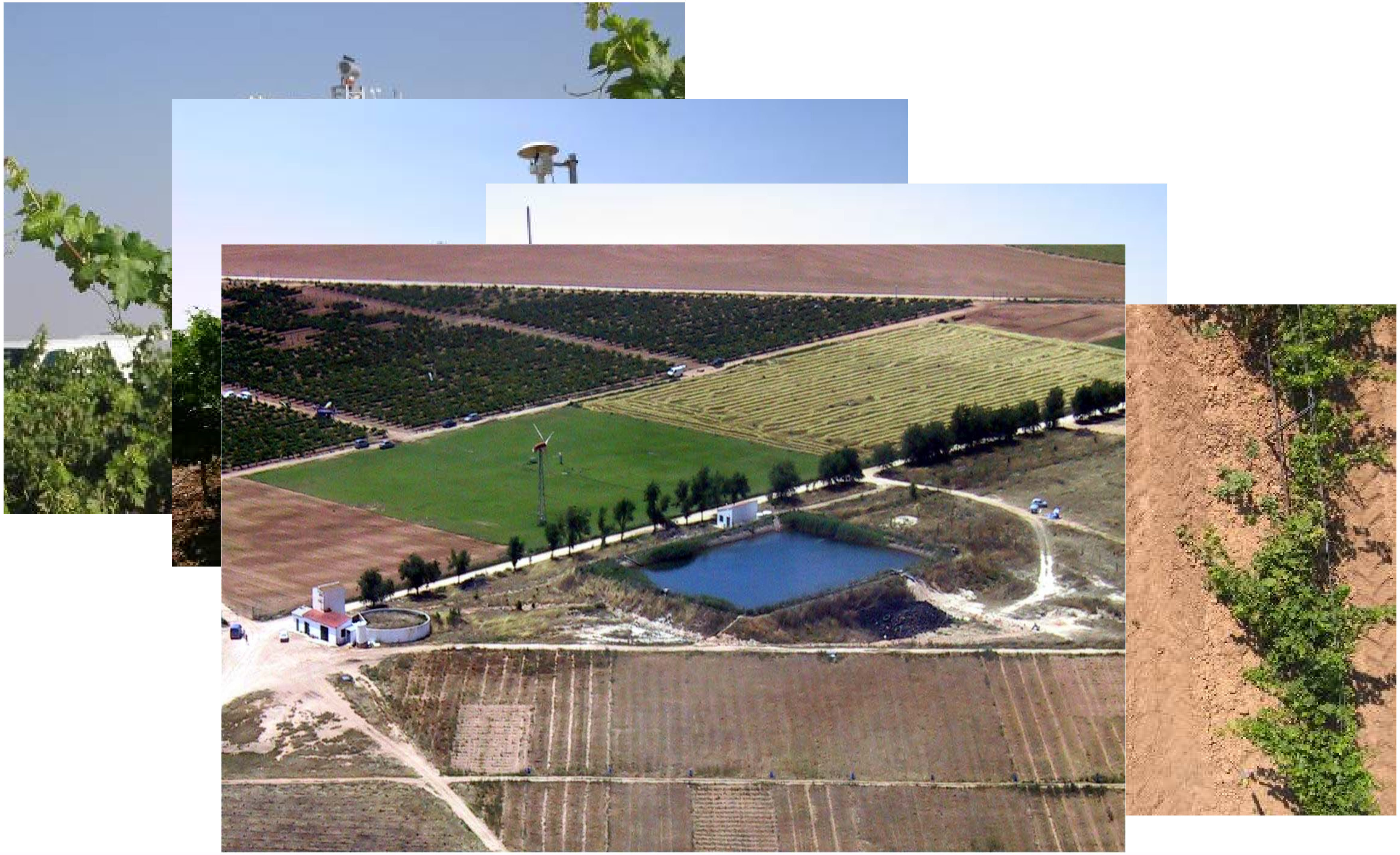
$$R_l = \int_0^{2\pi} \int_0^{\pi/2} \int_{\lambda_1}^{\lambda_2} \varepsilon_\lambda(\theta,\phi) R_{B,\lambda}(\theta,\phi) \sin(\theta) \cos(\theta)\, d\lambda\, d\theta\, d\phi = \varepsilon_\lambda \sigma T_R^4$$

In-Situ measurements of Surface Energy Balance- EAGLE/SPARC Campaign 2004, Barrax, Spain

- Situated in the area of La Mancha, in the west of the province of Albacete, 28 km from Albacete
- Geographic coordinates: 39º 3’ N; 2º 6’ W
- Altitude (above sea level): 700 m

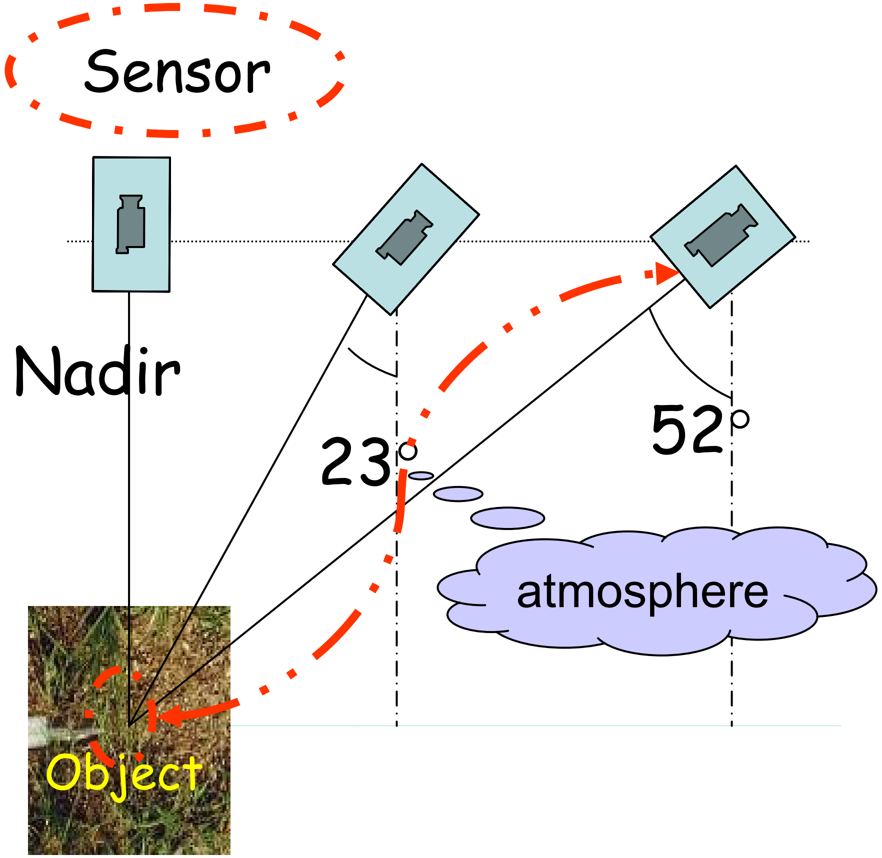


The Canopy from Different Perspectives



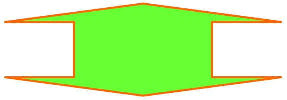
The Fundamental of Earth Observation

(Sensor - Object Radiative Relationship)



Sensor Response

A. How much radiation is detected?
B. When does it arrive?



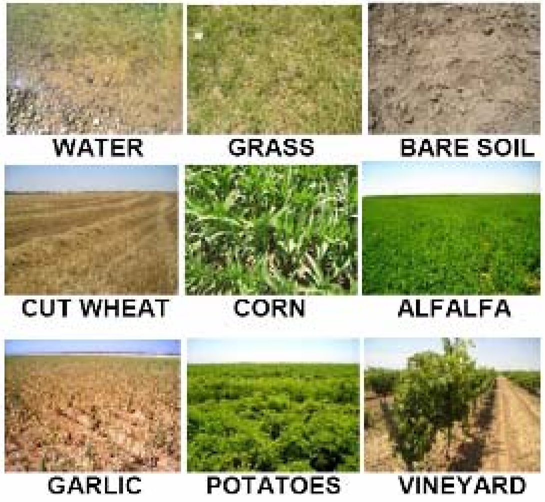
Object Properties:

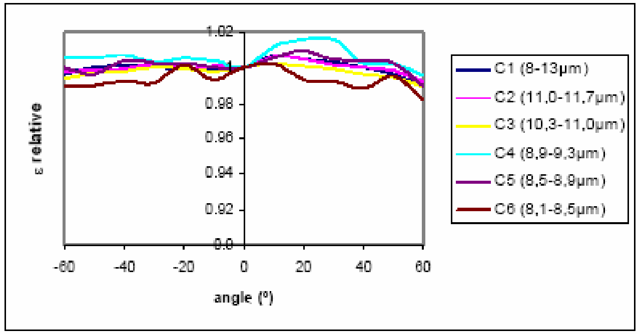
Its range, its combined temperature & Emissivity (or reflectivity) at different times, at different spatial resolution, at different wavelengths, at different direction, at different polarization

A: A Passive Sensor System
A+B: An Active Sensor System

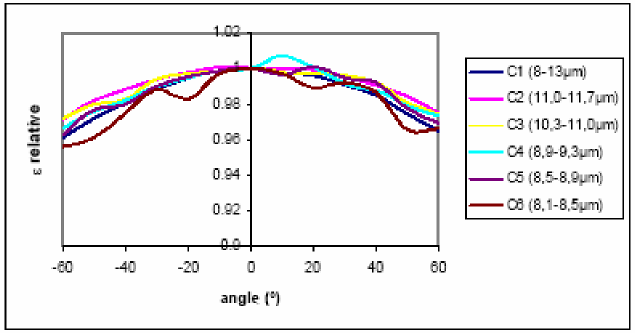
Factors Influencing the Emissivity ε

- The material (minerals, water etc.)
- The surface geometry (roughness of the surface)
- The wavelength of the radiation
- The view angle

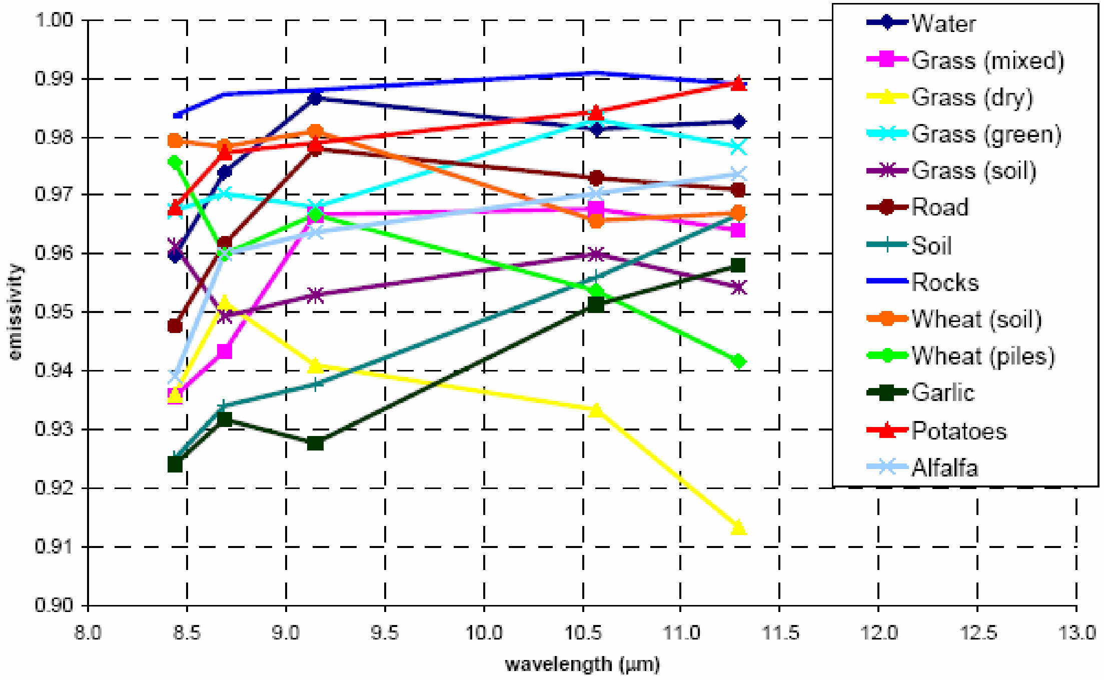




a)Bare soil during the night campaign

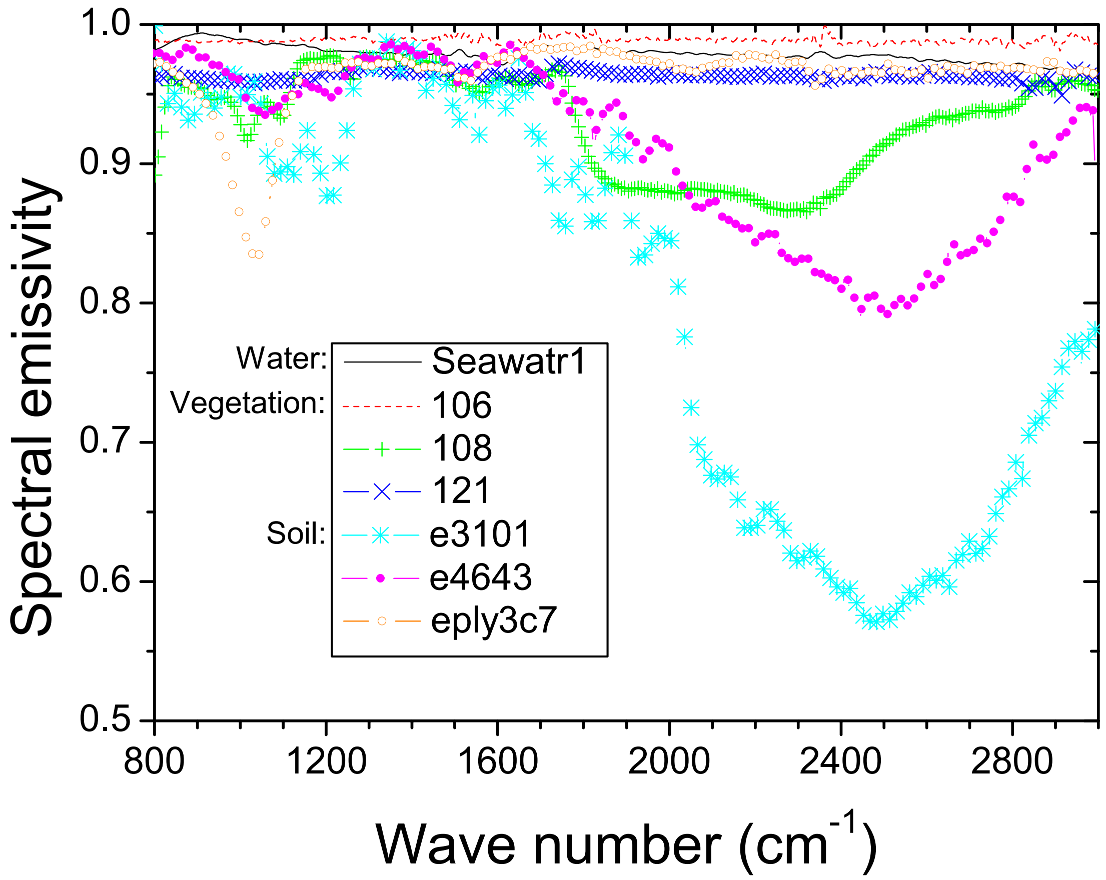


b)Green grass during the night campaign

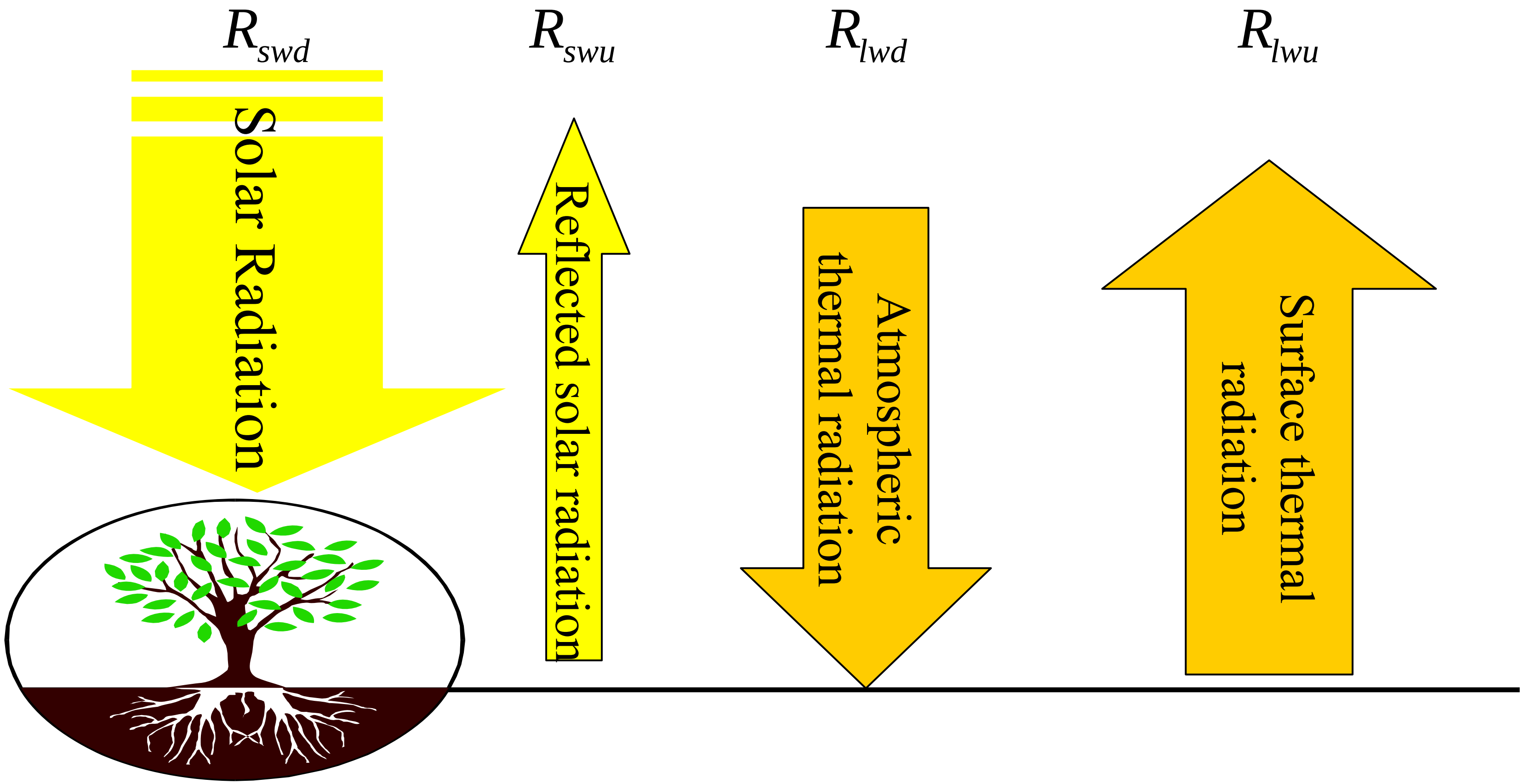


(Source: Sobrino et al., 2005)

Spectral emissivity extracted from MODIS UCSB Emissivity Library



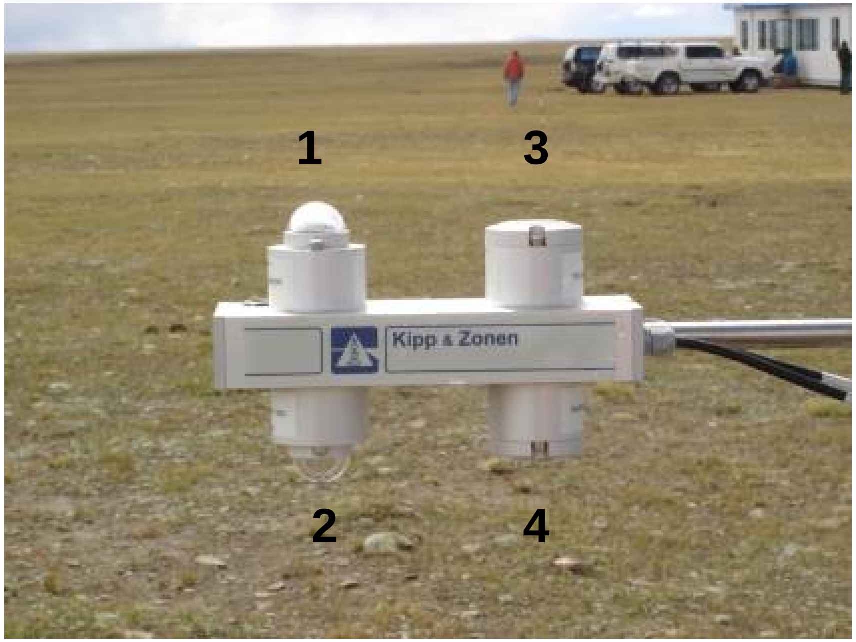
Surface Radiation Budget - Measurements



Net radiation

$$R_n = R_{swd} - R_{swu} + R_{lwd} - R_{lwu}$$

Surface Radiation Budget - Measurements



CNR1 net radiometer:

Spectral response
- Pyranometer: 305 to 2800 nm
- Pyrgeometer: 5000 to 50000 nm

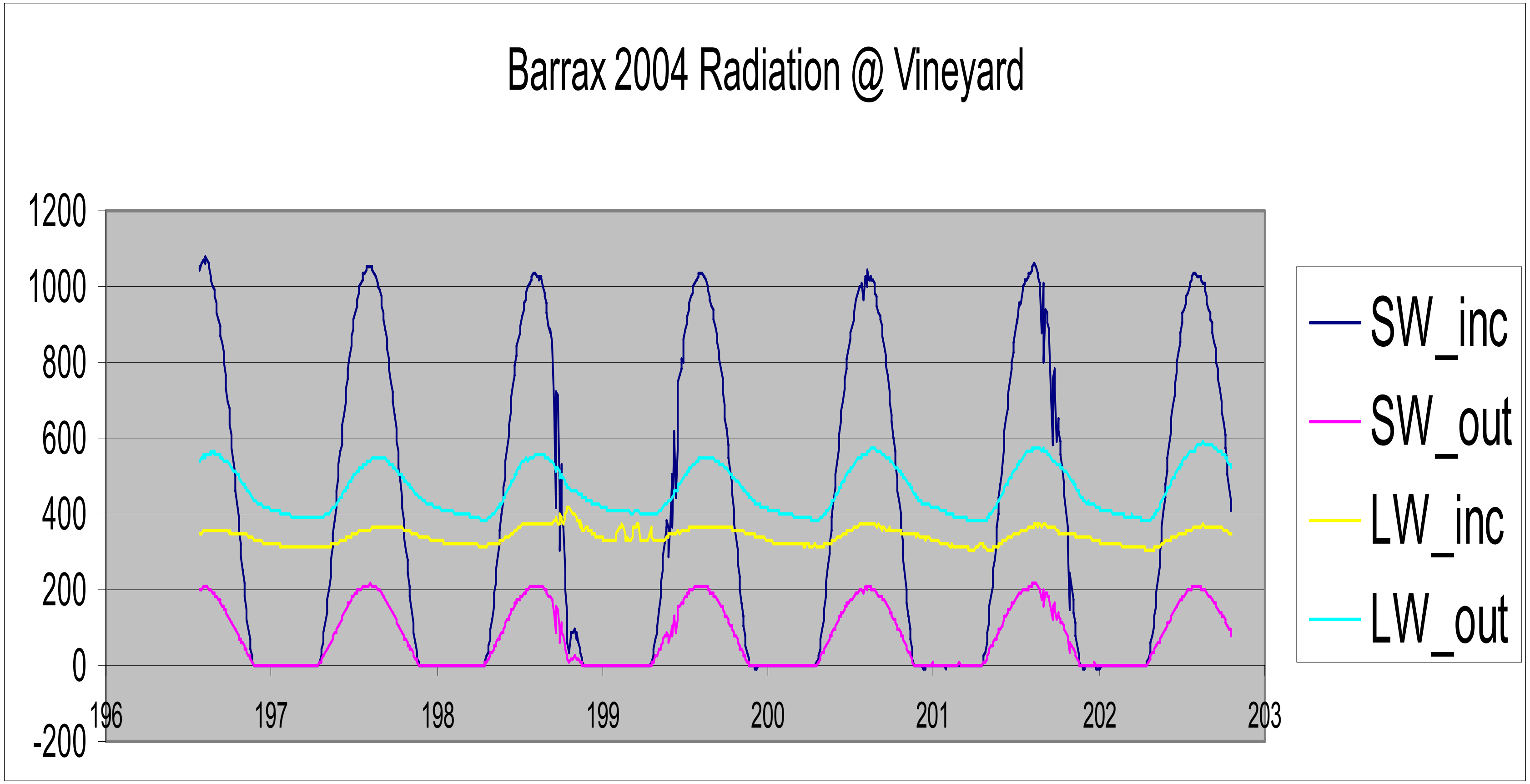
$$5\,\mu m - 50\,\mu m$$

$$(1\,\mu m = 1000\ nm)$$

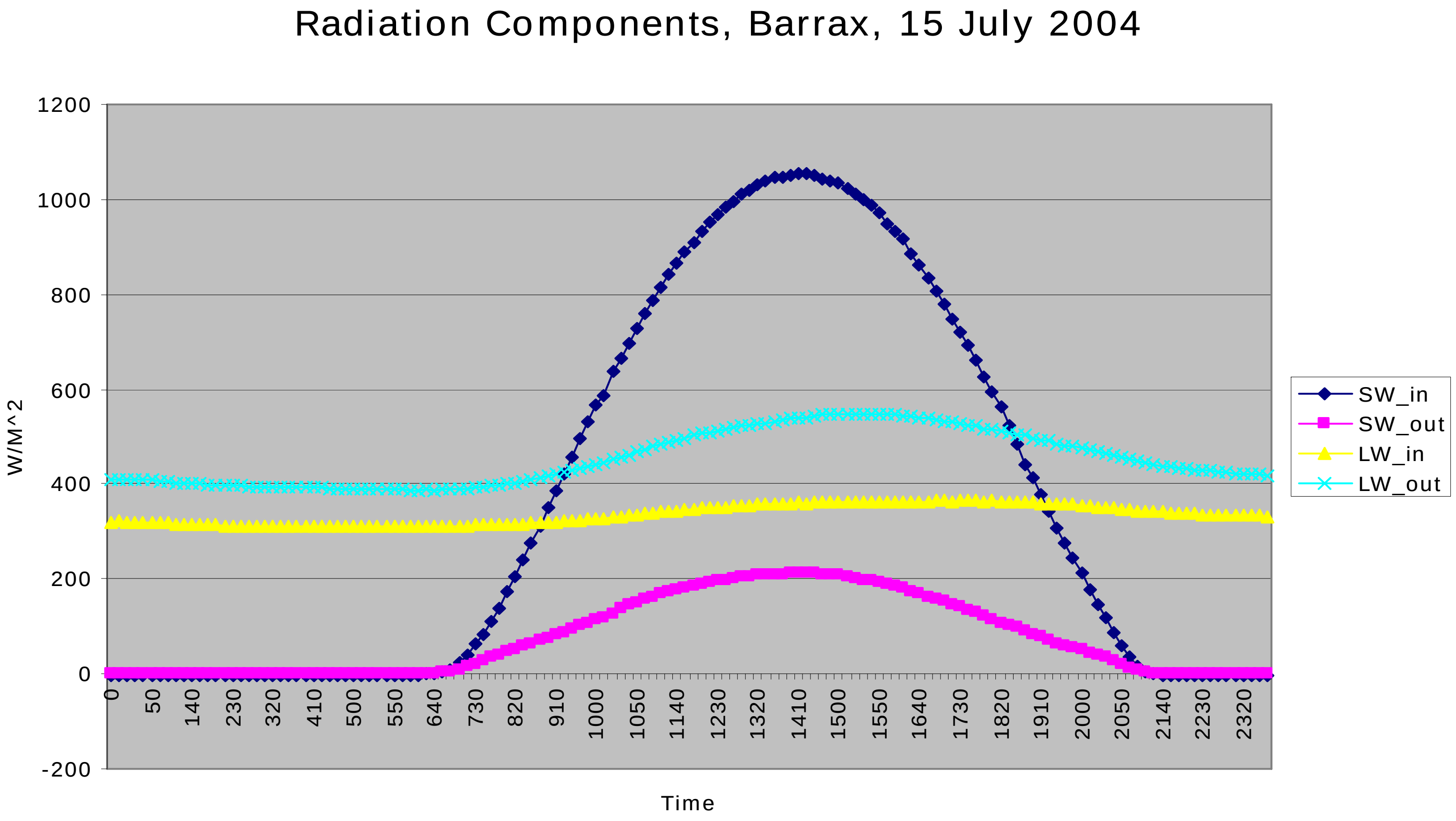
Radiation components:
1. incoming short-wave radiation
2. surface-reflected short-wave radiation
3. incoming long-wave thermal infrared radiation
4. outgoing long-wave TIR radiation

Albedo: ratio of scattered to incident electromagnetic radiation

EAGLE/SPARC Campaign 2004, Barrax, Spain



EAGLE/SPARC Campaign 2004, Barrax, Spain

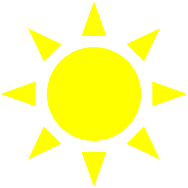


EAGLE/SPARC Campaign 2004, Barrax, Spain

Exercise:

1. Calculate the net radiation
2. Explain the pattern of the radiation components
3. Calculate the statistics of the radiation components
4. Calculate the albedo from the radiation components

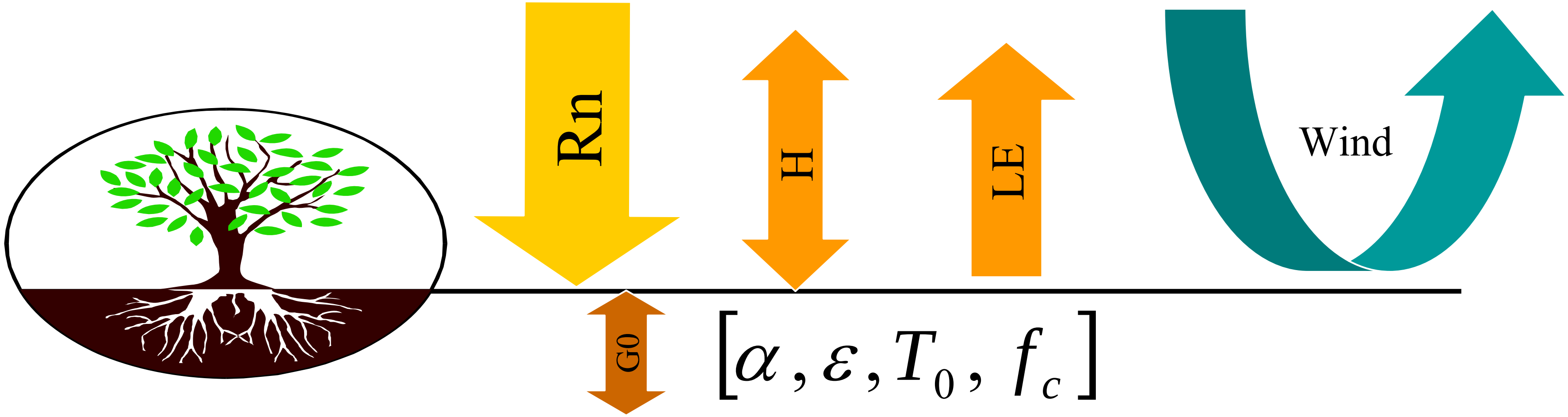
How is the net radiation consumed?



$$R_n = G_0 + H + LE + \Delta S$$

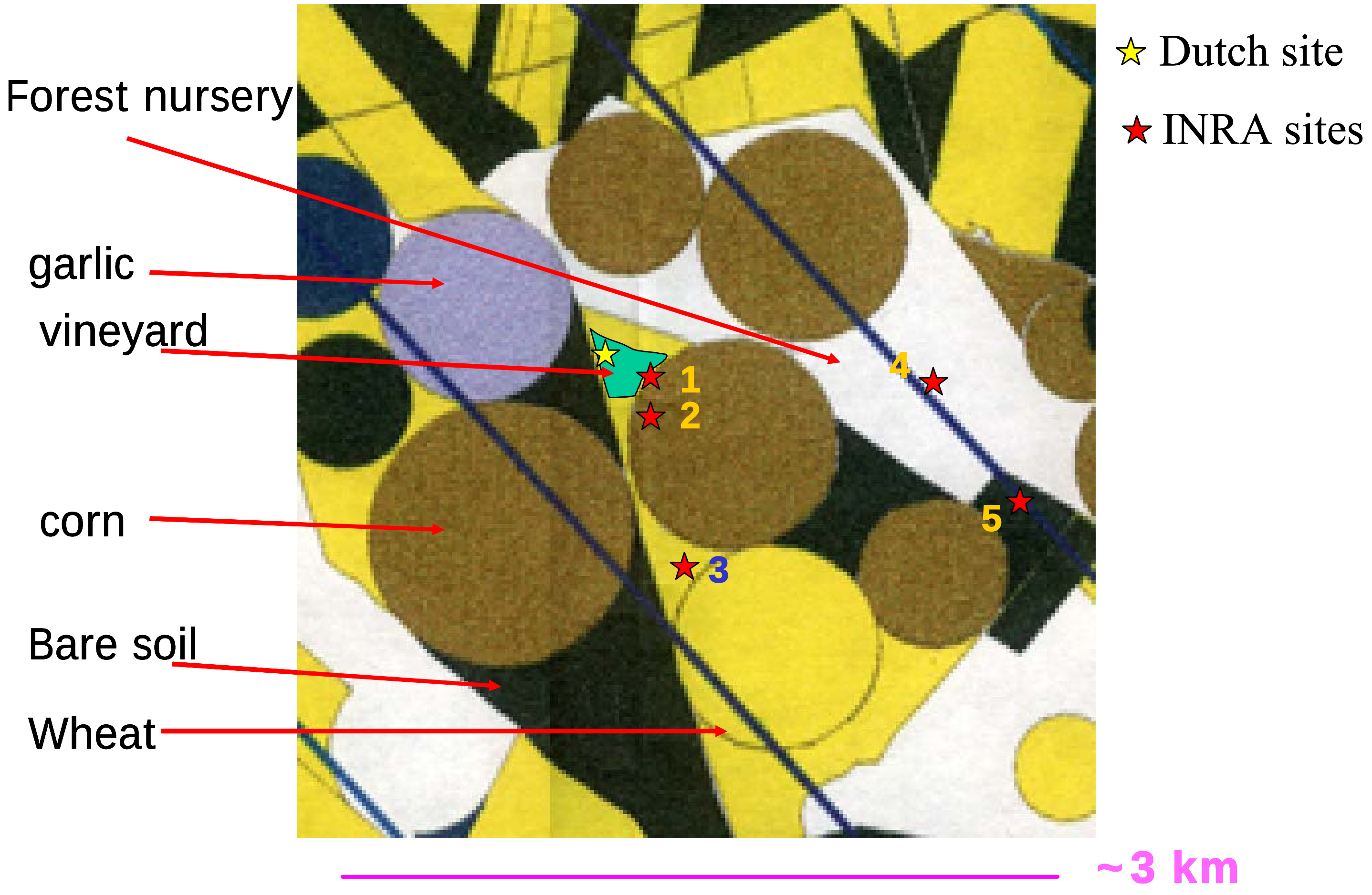
$$\Delta S \approx 0$$

Right hand side:
1. Soil heat flux (warming up of the soil layer)
2. Sensible heat flux (warming up of the air layer)
3. Latent heat flux (phase change, evaporation and transpiration)
4. Heat storage and biological activities



$$\left[\alpha, \varepsilon, T_0, f_c\right]$$

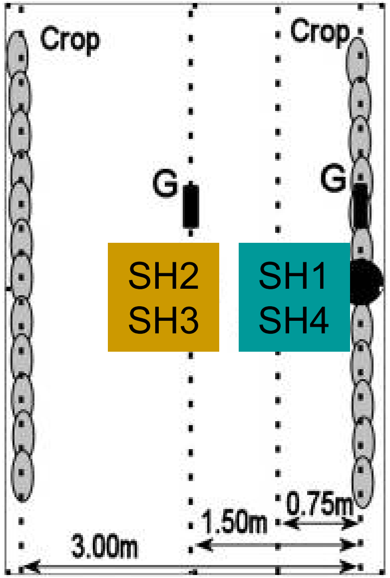
Locations of measurements



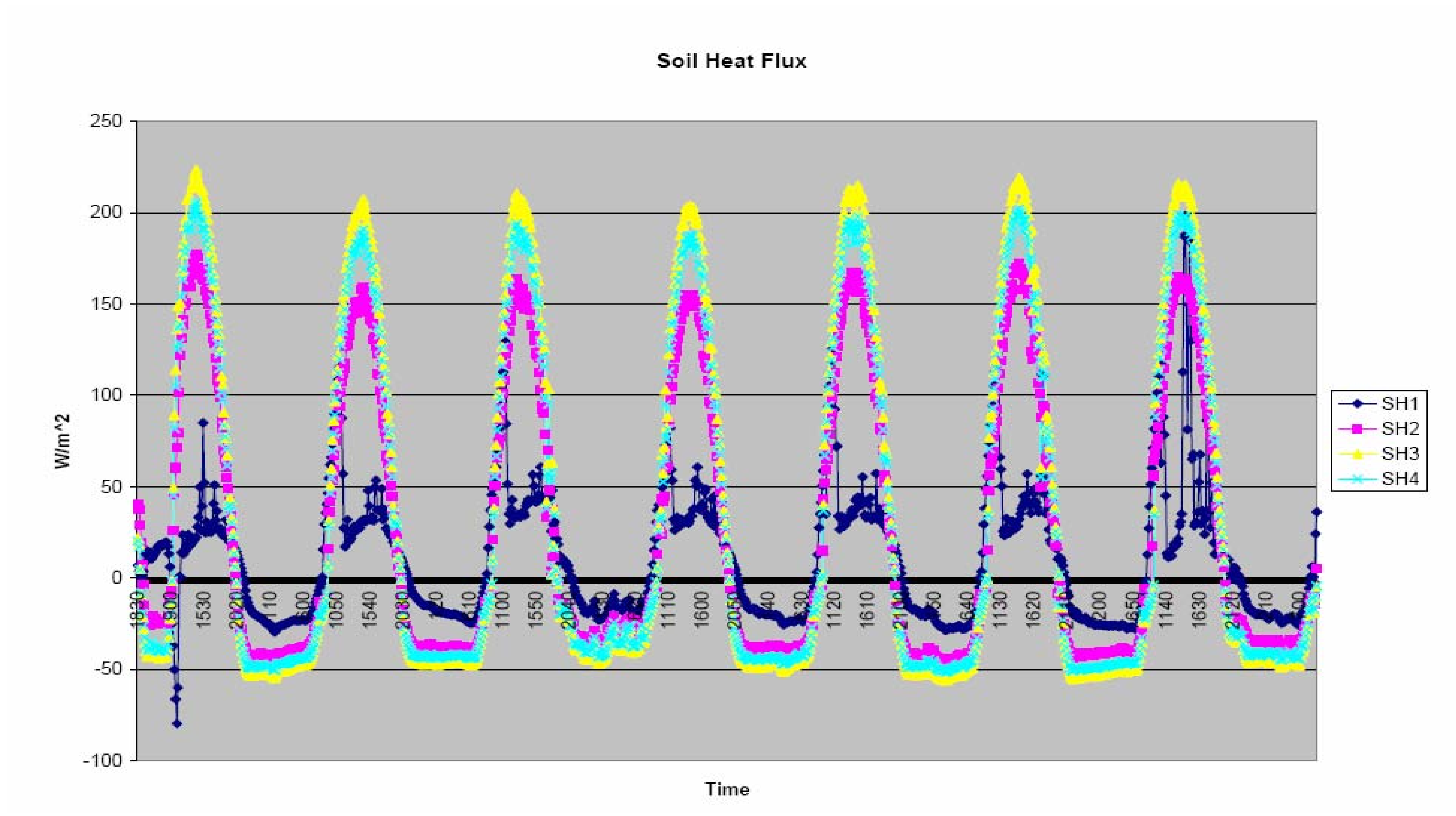
Soil heat flux: measurements with soil heat flux plates

- The soil heat fluxes were measured with 4 soil heat fluxes buried at a depth of 1cm below surface, with two placed in the middle of the row and two under the vine and shaded.

- Soil heat flux plates:
- SH1 and SH4 were in the shade
- SH2 and SH3 were in the sunlit areas

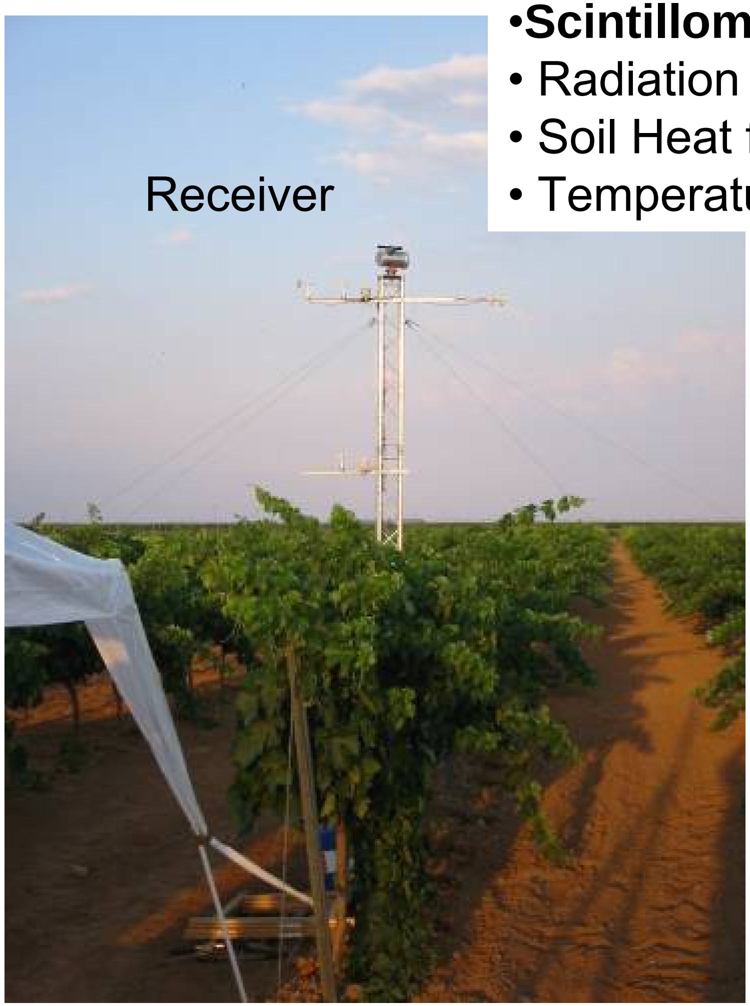


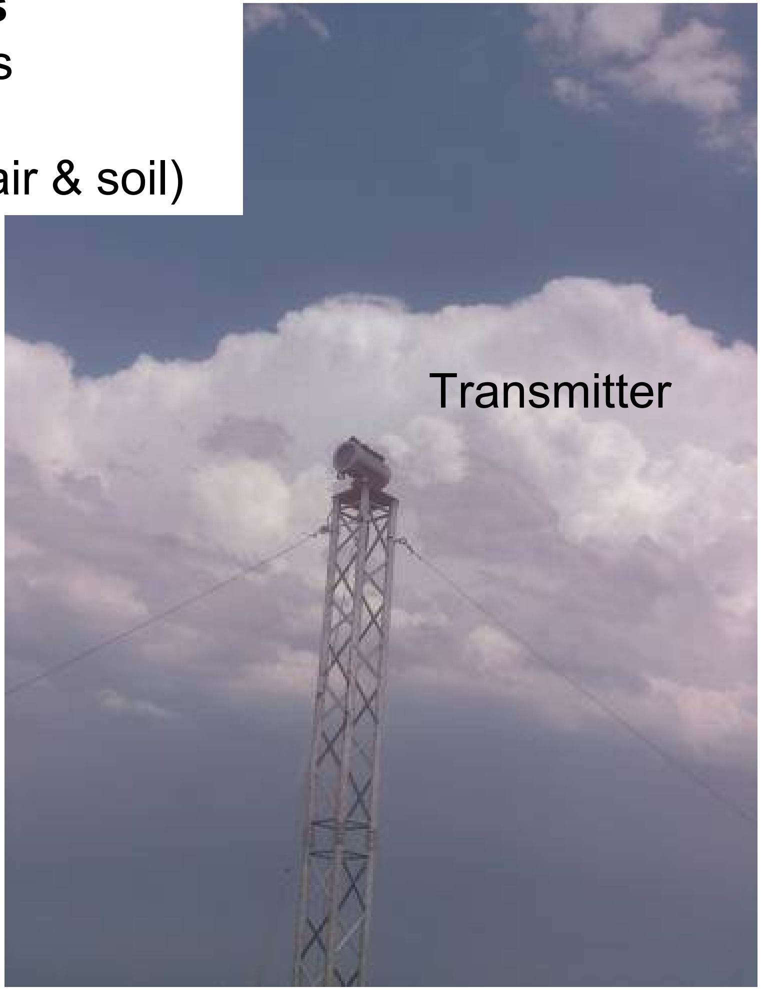
Soil heat flux: measurements with soil heat flux plates



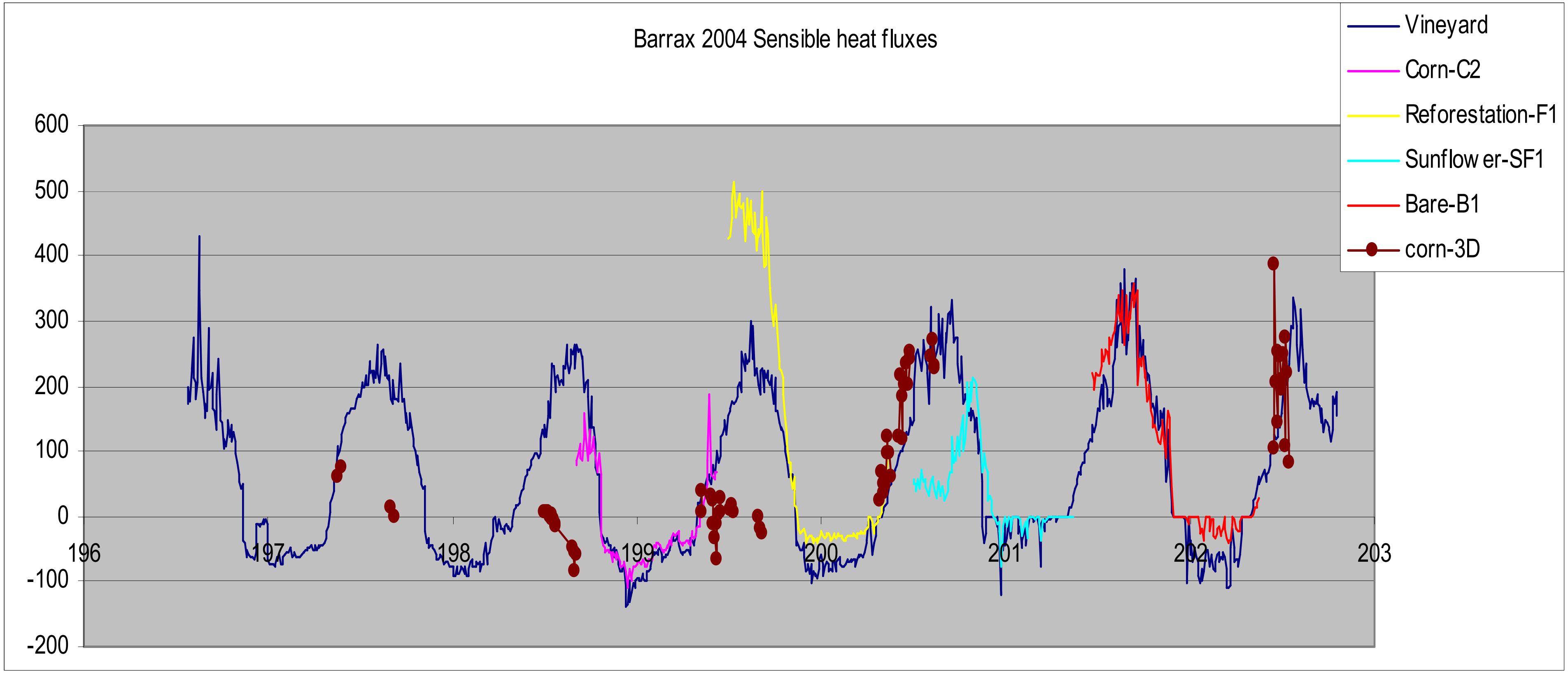
Sensible heat flux: scintillometer measurements

- **Scintillometer, 2 Sets**
- Radiation components
- Soil Heat flux plates
- Temperature profile (air & soil)

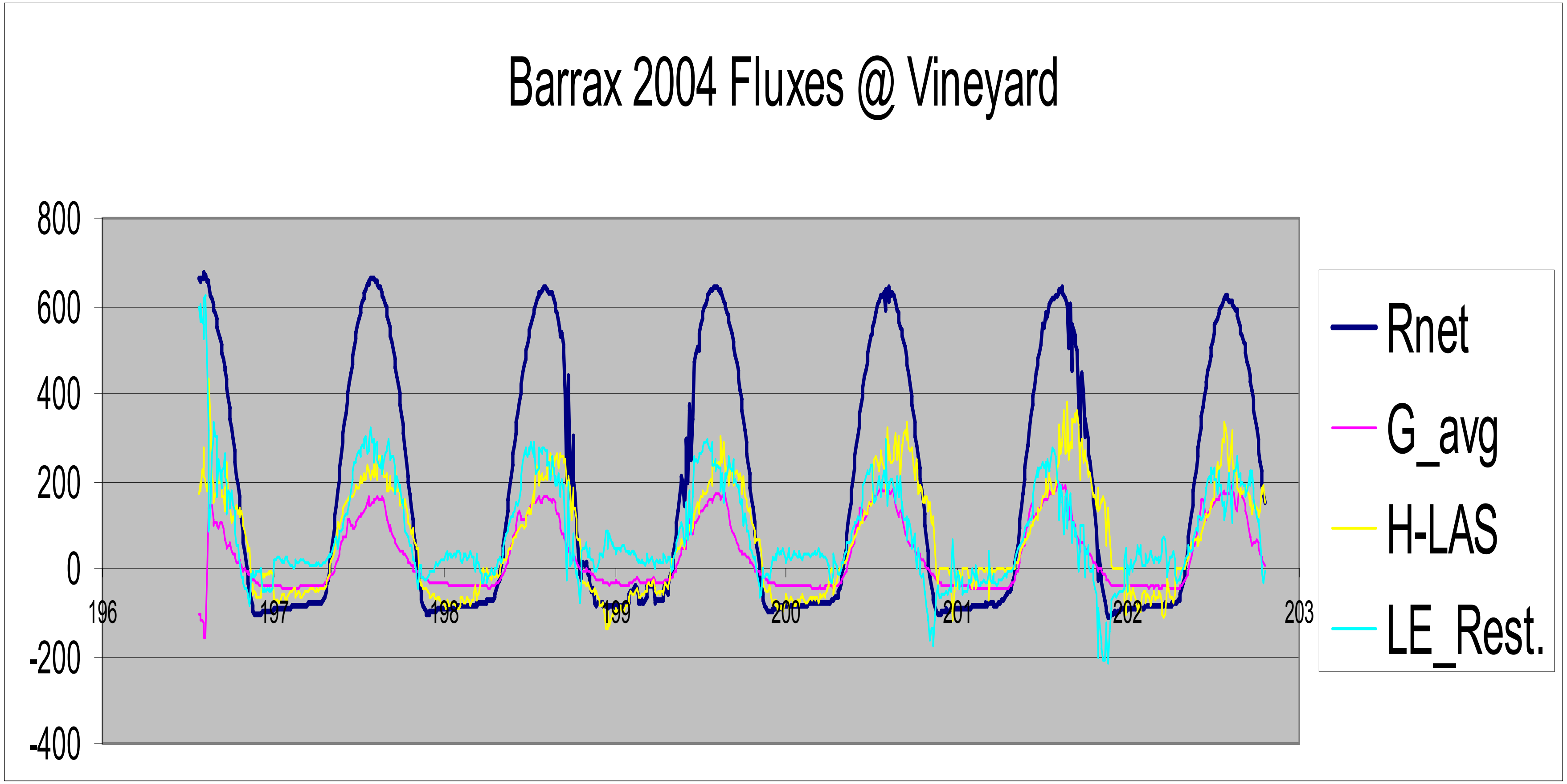

Receiver


Transmitter

Scintillometer Data, EAGLE/SPARC Campaign 2004, Barrax, Spain



Scintillometer Data, EAGLE/SPARC Campaign 2004, Barrax, Spain



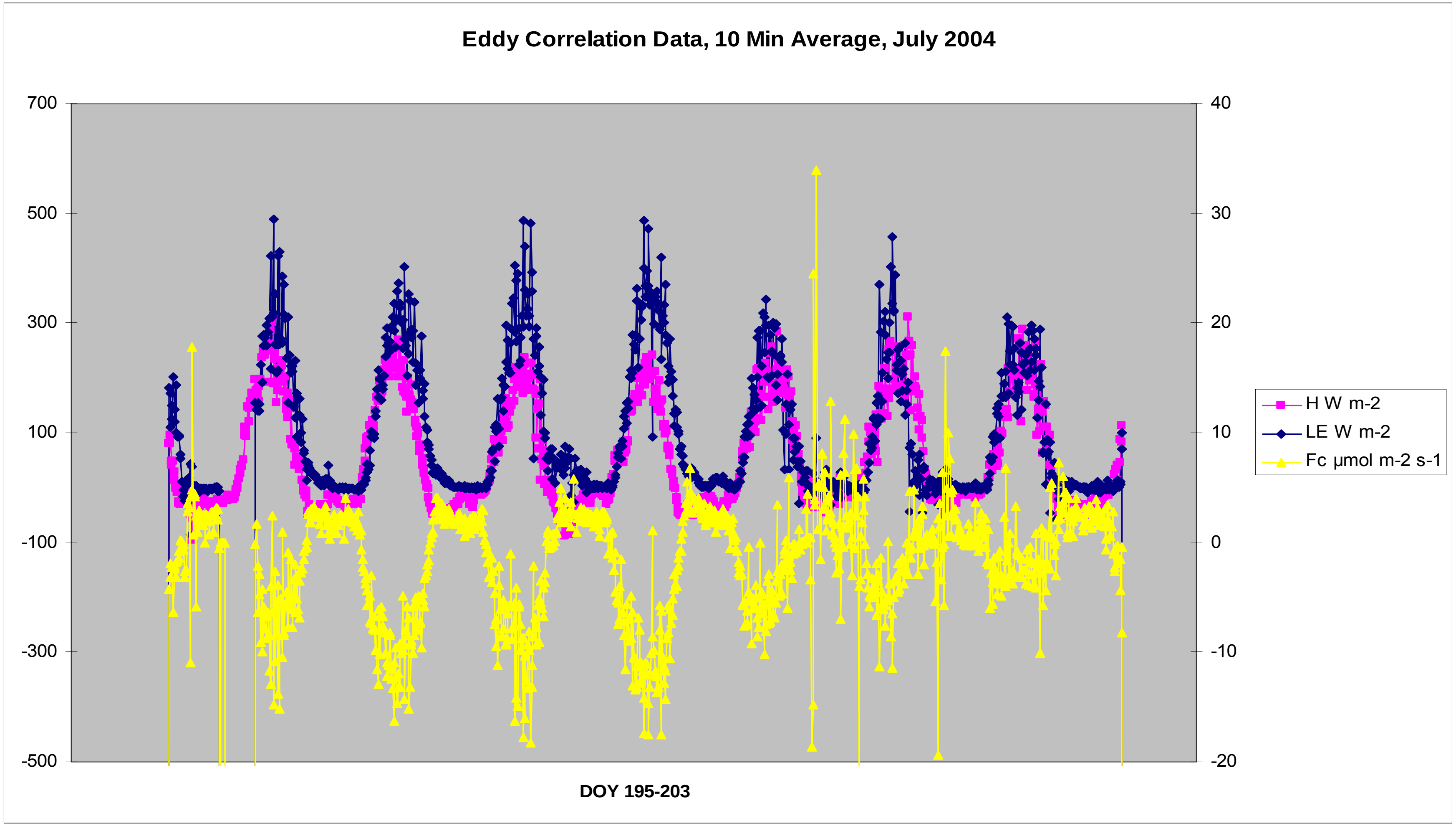
Sensible & latent heat fluxes: Eddy Covariance Measurements

Canopy level measurements:

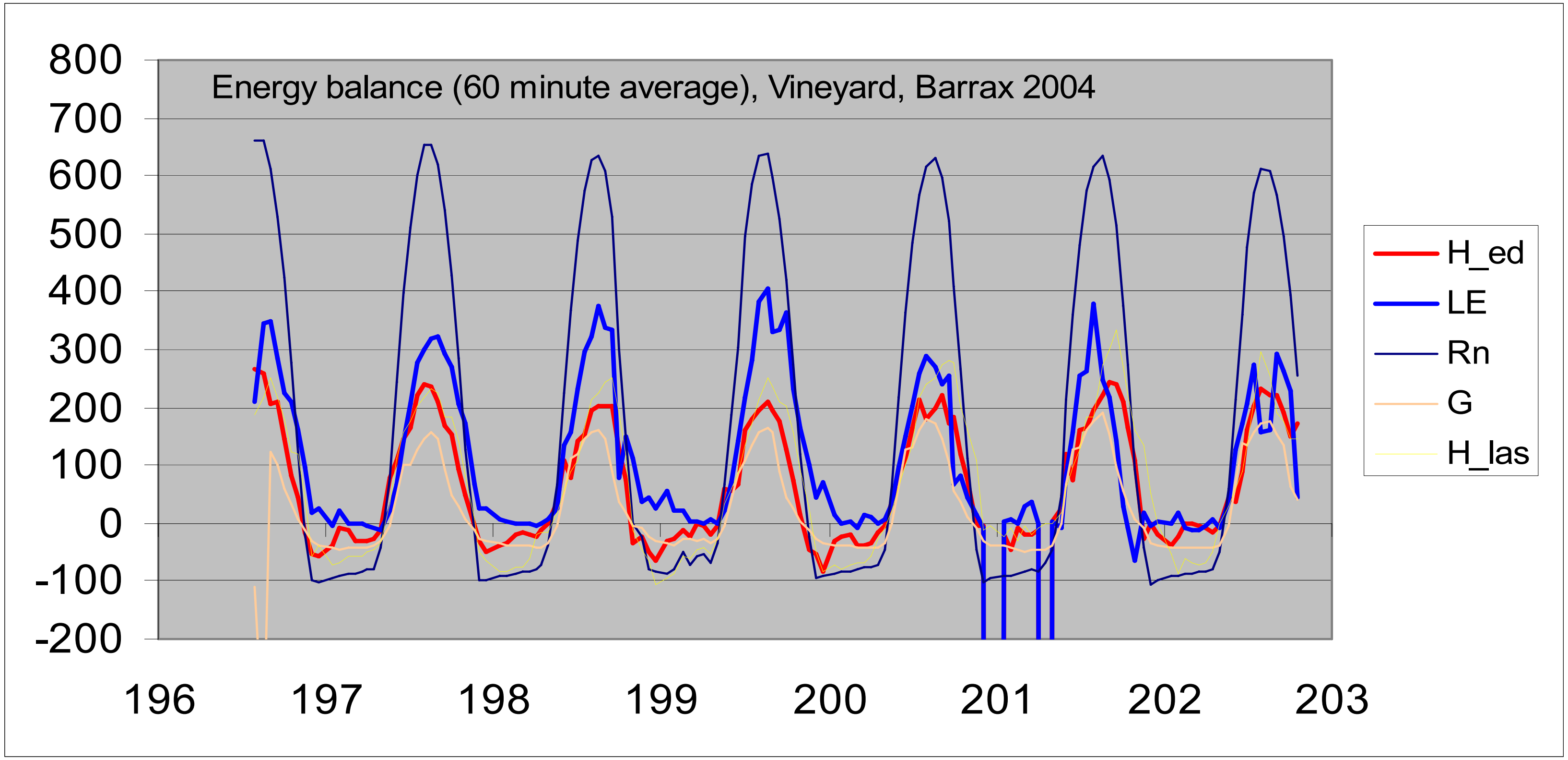
Eddy covariance system
(Gill 3D sonic + closed path Licor gasanalyser: CO_2 and H_2O + nitrogen reference gas + pneumatic mast + data loggers)

- Turbulence, sensible heat flux, H_2O, CO_2 fluxes
- CO_2 concentrations

Flux data SPARC 2004

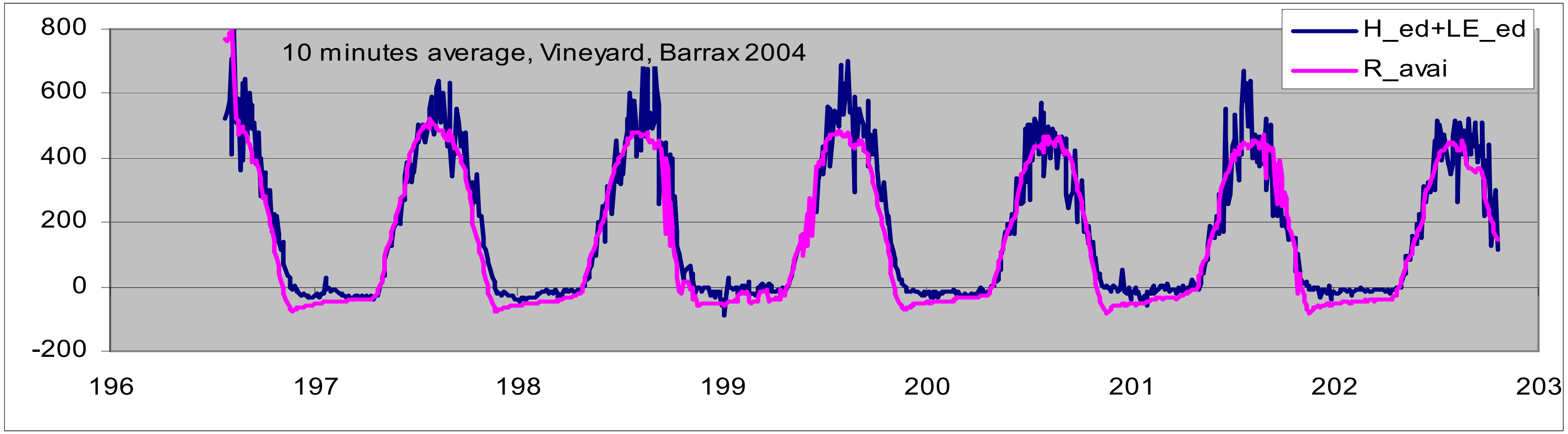


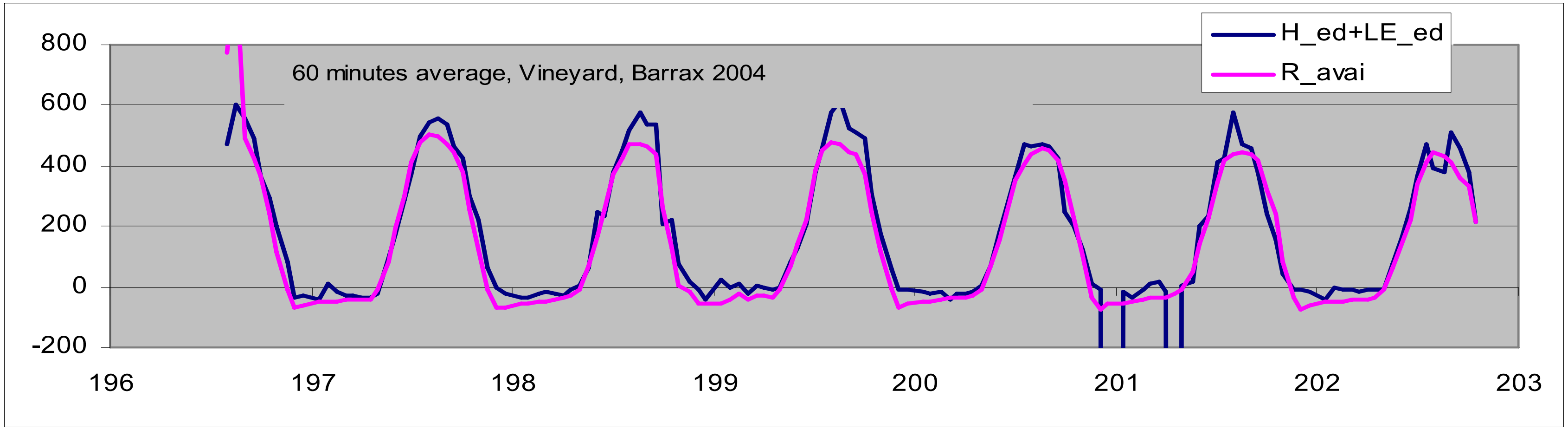
Energy balance components



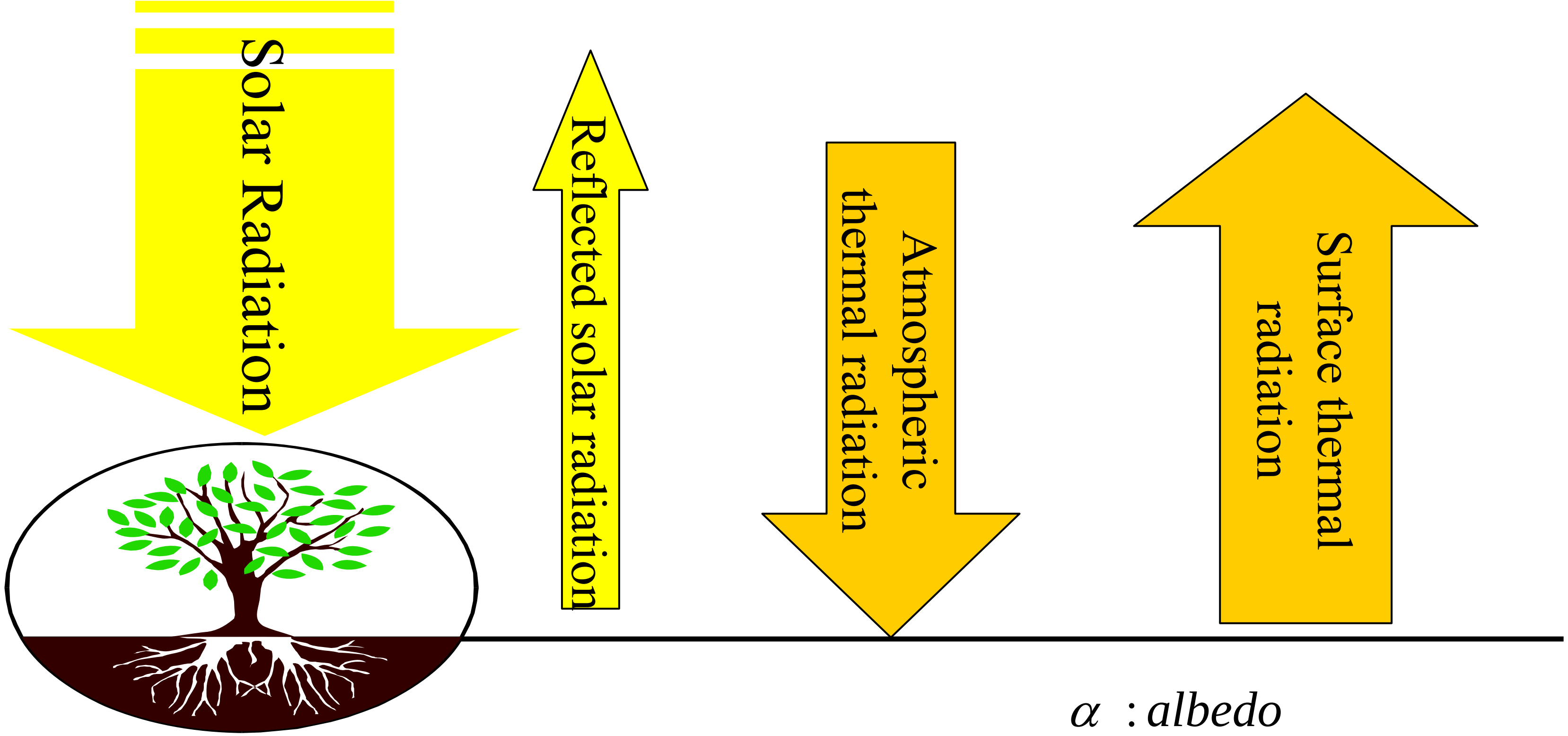
Energy balance closure ??

(Sum of H and LE exceeds the available energy)





Surface Radiation Budget - Parameterisation

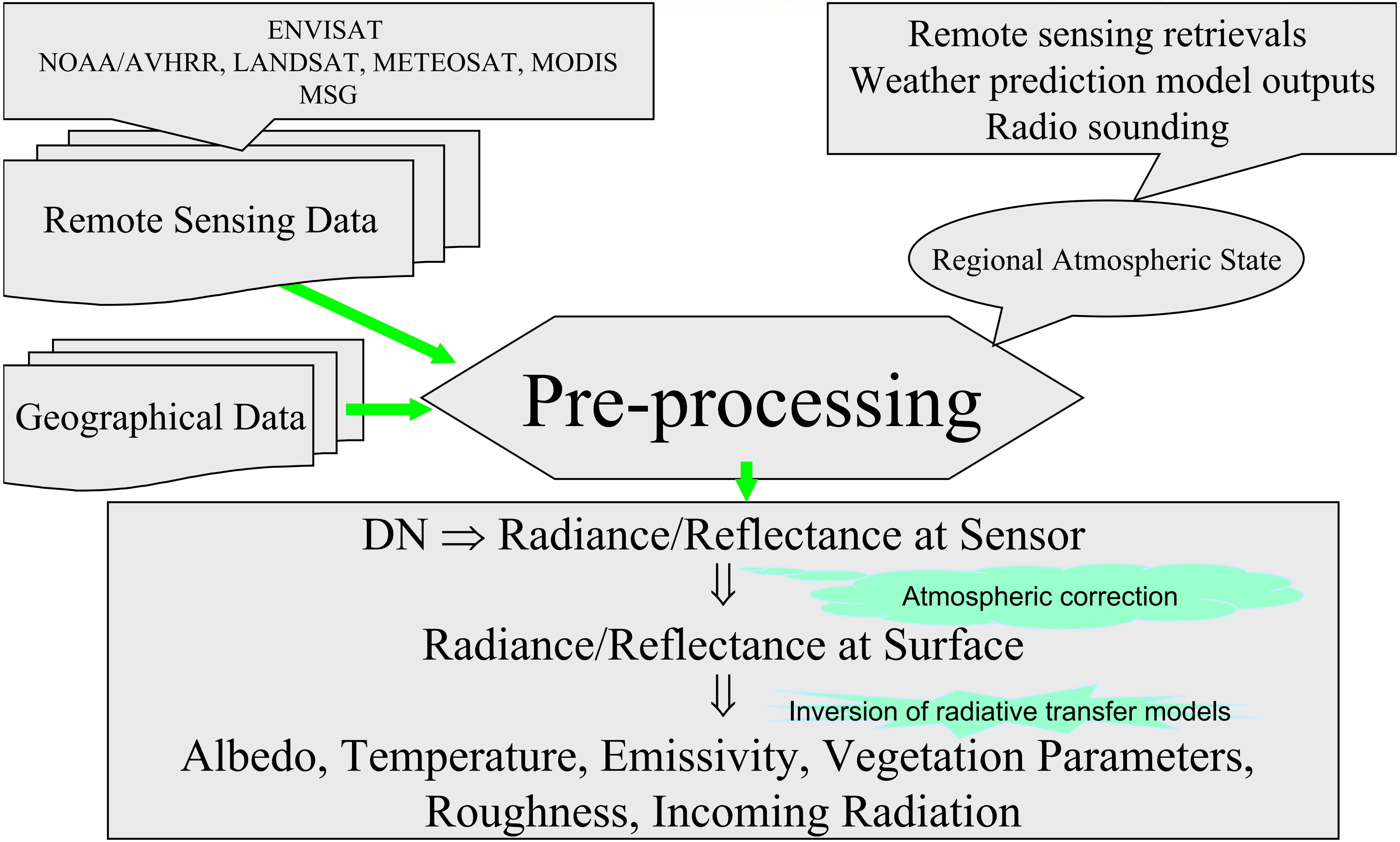


α : albedo

ε : emissivity

T_0 : Surface Temperature

$$R_n = (1-\alpha)\cdot R_{swd} + \varepsilon \cdot R_{lwd} - \varepsilon \cdot \sigma \cdot T_0^4$$



ENVISAT
NOAA/AVHRR, LANDSAT, METEOSAT, MODIS
MSG

Remote sensing retrievals
Weather prediction model outputs
Radio sounding

Remote Sensing Data

Regional Atmospheric State

Geographical Data

Pre-processing

DN ⇒ Radiance/Reflectance at Sensor

⇓ Atmospheric correction

Radiance/Reflectance at Surface

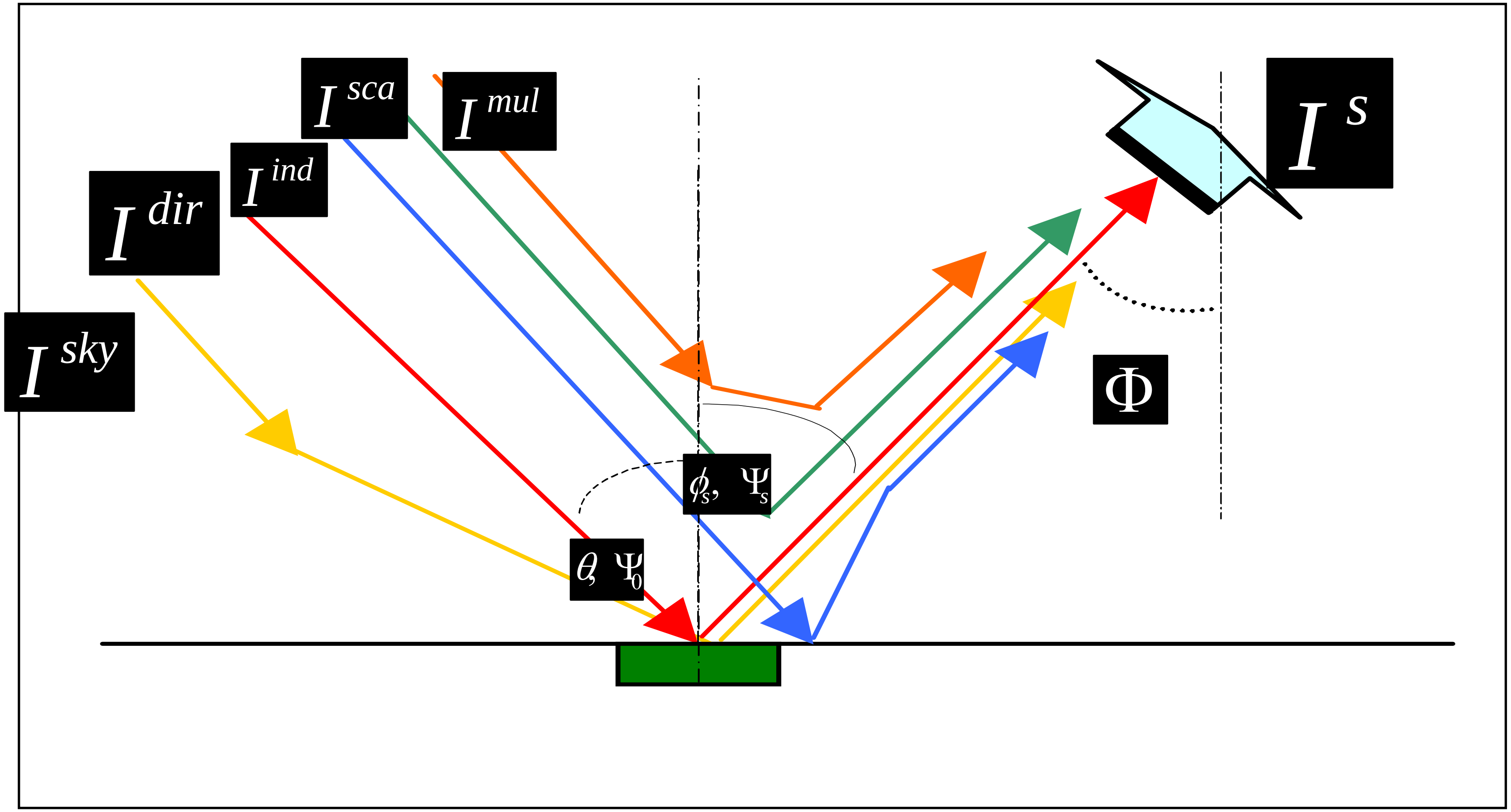
⇓ Inversion of radiative transfer models

Albedo, Temperature, Emissivity, Vegetation Parameters, Roughness, Incoming Radiation

Derived Surface Parameters/variables

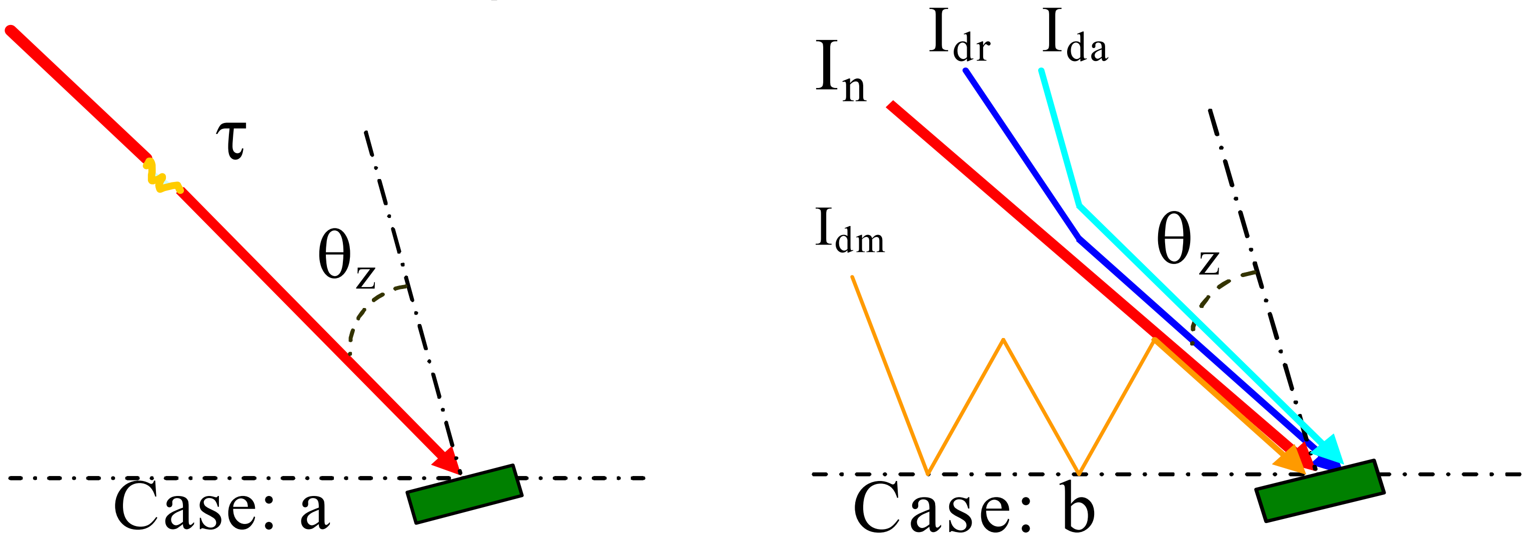
- Incoming global radiation
- Albedo
- Vegetation cover, Leaf Area Index
- Surface temperature
- Emissivity
- Roughness

Components of reflected and scattered solar beams received at the satellite



Incoming global radiation

- **Input parameters:**
  - **Group 1: date, time, location (latitude) and DEM (elevation, slope, aspect) to compute solar declination, eccentricity, solar zenith angle for a horizontal surface, solar azimuth angle, solar zenith angle on slopes**
  - **Group2: weather condition - Optical properties of the atmosphere (at the time of calculation)**



Incoming global radiation

- Case a: use total optical depth
- $$I = I_{sc} \cdot e_0 \cdot \cos\theta_z \cdot \exp(-m \cdot \tau)$$
- **where I_{sc} is the solar constant, e_0 the eccentricity factor, θ_z solar zenith angle, m air mass, τ the optical depth**

Incoming global radiation (cont.)

Case b: use water-vapor / horizontal visibility

$$I = I_n + I_d$$

$$= I_n + I_{dr} + I_{da} + I_{dm} = \left(I_n + I_{dr} + I_{da}\right)\cdot \frac{1}{1-\rho_g \cdot \rho_a'}$$

where the direct solar radiation is

$$I_n = 0.9751\cdot I_{sc}\cdot e_0\cdot \cos\left(\theta_z\right)\cdot \tau_r\cdot \tau_o\cdot \tau_g\cdot \tau_w\cdot \tau_a$$

etc.

References:

M. Iqbal (1983) An introduction to solar radiation, Academic Press, Toronto. p.188-191.
R. Bird and R.L. Hulstrom (1980) Direct insolation models, Trans. ASME J. Sol. Energy Eng., 103, 182-192.
R. Bird and R.L. Hulstrom (1981) A simplified clear sky model for direct and diffuse insolation on horizontal surfaces, SERI/TR-642-761, Solar Energy Research Institute, Golden, Colorado.

Surface Albedo & NDVI

- Algorithms
- - Calculate surface bidirectional reflectance of narrow band
- - Derive surface broad-band albedo from narrow surface reflectance
- Derive NDVI from band RED & NIR surface reflectance
- (Ref. Lecture Jose Moreno)

Surface temperature

- **Algorithms**

- **Land surface temperature derived by using a theoretical split-window algorithm**

- **`References: Sorino et al.(2004)`**

The radiative transfer equation for LST retrieval

- The at-sensor radiance for a given wavelength (λ) s:

$$L_{\lambda\theta}^{at-sensor} = \left[\varepsilon_{\lambda\theta} B_{\theta}(\lambda, T_S) + (1-\varepsilon_{\lambda\theta}) L_{\lambda}^{atm\downarrow}\right] \tau_{\lambda\theta} + L_{\lambda\theta}^{atm\uparrow}$$

- where
  - $\varepsilon_{\lambda\theta}$ is the surface emissivity,
  - $B_\theta(\lambda, T_s)$ is the radiance emitted by a blackbody at temperature T_s of the surface,
  - $L_{\lambda}^{atm\downarrow}$ is the downwelling radiance,
  - $\tau_{\lambda\theta}$ is the total transmission of the atmosphere (transmittance) and
  - $L_{\lambda\theta}^{atm\uparrow}$ is the upwelling atmospheric radiance. All these magnitudes also depend on the observation angle θ.

- According to Sobrino et al. (1996), the upwelling and downwelling atmospheric radiance can be substituted, respectively, by:

$$L_{\lambda}^{atm\uparrow} = (1 - \tau_{i\theta}) B_i (T_a)$$

$$L_{\lambda}^{atm\downarrow} = (1 - \tau_{i53}) B_i (T_a)$$

where T_a is the effective mean atmospheric temperature and τ_{i53} is the total atmospheric path transmittance at 53 degrees.

Split-window equations to derive land surface temperature

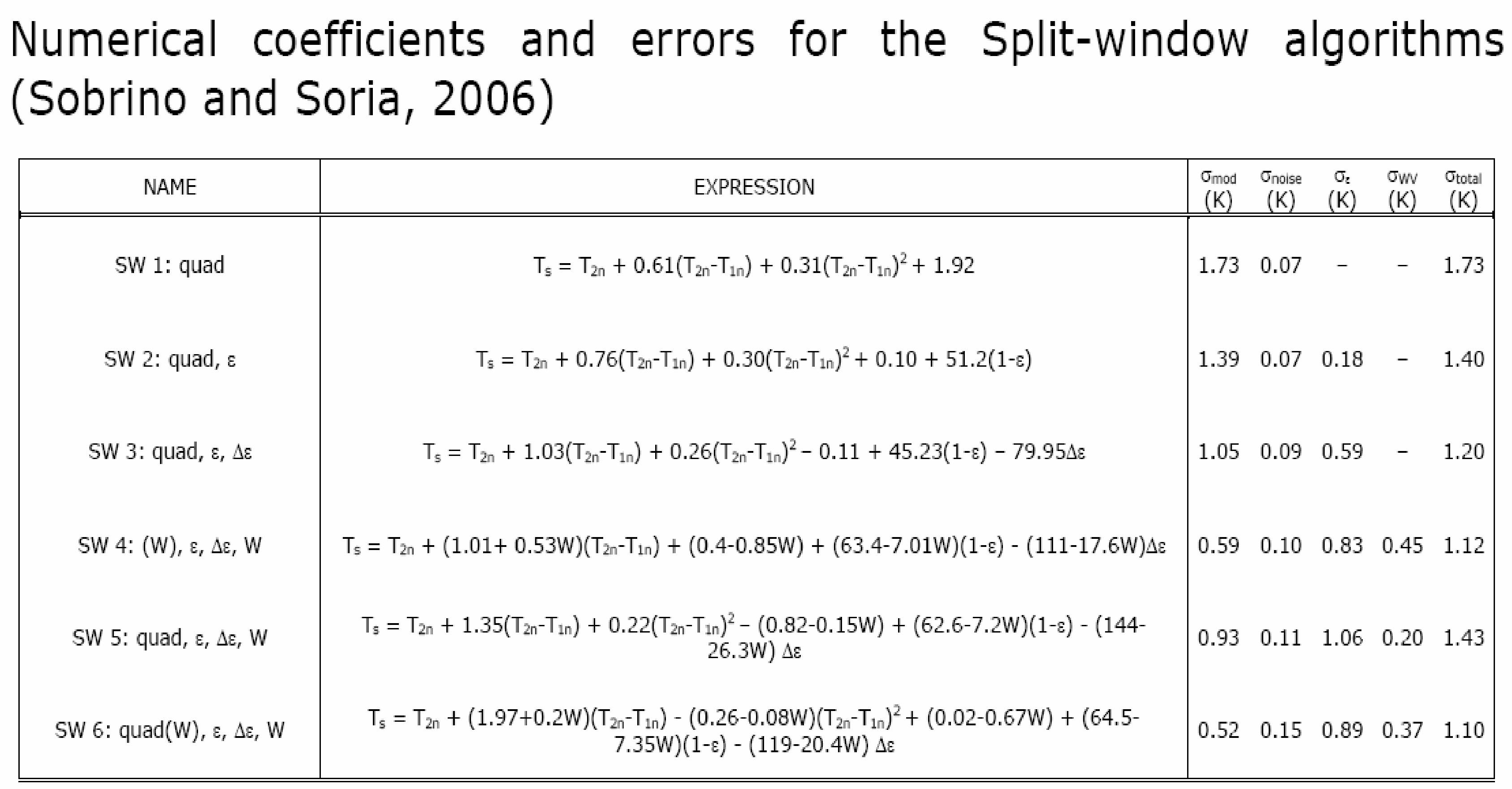
- Substituting both atmospheric radiances in the radiative transfer equation, an algorithm involving temperatures can be obtained using a first-order Taylor series expansion of the Planck's law and writing the equation for i and j (i and j being two different channels observed at the same angle, Split-Window method):

$$T_s = T_i + A(T_i - T_j) - B_0 + (1 - \varepsilon_i) B_1 - \Delta\varepsilon_\theta B_2$$

where A and B_i are coefficients that depend on atmospheric transmittances, ε_i is the mean value of the emissivities of channels i and j, $\Delta\varepsilon_\theta$ is the spectral variation, T_i and T_j are the brightness temperatures for two different channels with the same view angle.

This equation is the so-called split-window equation and gives a separation between the atmospheric and emissivity effects in the retrieval of surface temperature.

The structure of the split-window and dual-angle algorithms with the final values of the coefficients calculated by the minimization process



Numerical coefficients and errors for the Split-window algorithms (Sobrino and Soria, 2006)

NAME	EXPRESSION	σ_{mod} (K)	σ_{noise} (K)	σ_{ε} (K)	σ_{WV} (K)	σ_{total} (K)
SW 1: quad	$T_s = T_{2n} + 0.61(T_{2n}-T_{1n}) + 0.31(T_{2n}-T_{1n})^2 + 1.92$	1.73	0.07	–	–	1.73
SW 2: quad, ε	$T_s = T_{2n} + 0.76(T_{2n}-T_{1n}) + 0.30(T_{2n}-T_{1n})^2 + 0.10 + 51.2(1-\varepsilon)$	1.39	0.07	0.18	–	1.40
SW 3: quad, ε, Δε	$T_s = T_{2n} + 1.03(T_{2n}-T_{1n}) + 0.26(T_{2n}-T_{1n})^2 - 0.11 + 45.23(1-\varepsilon) - 79.95\Delta\varepsilon$	1.05	0.09	0.59	–	1.20
SW 4: (W), ε, Δε, W	$T_s = T_{2n} + (1.01+ 0.53W)(T_{2n}-T_{1n}) + (0.4-0.85W) + (63.4-7.01W)(1-\varepsilon) - (111-17.6W)\Delta\varepsilon$	0.59	0.10	0.83	0.45	1.12
SW 5: quad, ε, Δε, W	$T_s = T_{2n} + 1.35(T_{2n}-T_{1n}) + 0.22(T_{2n}-T_{1n})^2 - (0.82-0.15W) + (62.6-7.2W)(1-\varepsilon) - (144-26.3W)\ \Delta\varepsilon$	0.93	0.11	1.06	0.20	1.43
SW 6: quad(W), ε, Δε, W	$T_s = T_{2n} + (1.97+0.2W)(T_{2n}-T_{1n}) - (0.26-0.08W)(T_{2n}-T_{1n})^2 + (0.02-0.67W) + (64.5-7.35W)(1-\varepsilon) - (119-20.4W)\ \Delta\varepsilon$	0.52	0.15	0.89	0.37	1.10

- notation:
- n: Nadir view;
- f: Forward view;
- SW: Split-Window Method (two spectral channels at the same observation angle)
- quad: algorithm that includes a squadratic dependence on (Ti-Tj);
- (1): AATSR Channel 1 (12 μm);
- (2): AATSR Channel 2 (11 μm);
- W: algorithm with water vapor content dependence;
- ε: algorithm with emissivity dependence;
- $\Delta\varepsilon$: algorithm including spectral or angular emissivity difference.

Emissivity

- **Algorithms**

- **Estimation of surface emissivity using the theoretical model of Caselles and Sobrino (1989).**

- **References:**
- **V. Caselles and J.A. Sobrino (1989) Determination of frosts in orange groves from NOAA-9 AVHRR data, RSE, 29:135-146.**
- **E. Valor and V. Caselles (1995) Mapping land surface emissivity from NDVI: Application to European, African, and Sourth American Areas, RSE, 57:167-184.**
- **Sobrino and Soria (2006)**

Thresholds Method (NDVITHM)

- A simplified method based on the estimation of emissivity, ε, using atmospherically corrected data in the visible and near infrared channels (Sobrino and Raissouni, 2000), which considers three different type of pixels depending on the NDVI value: bare soil pixels ($NDVI<0.2$), mixed pixels ($0.2<NDVI<0.5$) and fully vegetation pixels ($NDVI>0.5$). The $NDVI^{THM}$ have been applied for NOAA channels 4 and 5 (Sobrino et al., 2001) and for MODIS channels (Sobrino et al., 2003).

- This method is also applied to AATSR thermal channels using the Salisbury's spectra (Salisbury and D'Aria, 1992) and the AATSR response functions to obtain the appropriate expressions to estimate absolute emissivity. The NDVI value have been calculated with the well-known equation that uses reflectivity values from the Red region (ρ_{red}) and Near Infrared (ρ_{nir}) region, according to:

$$NDVI = \frac{\rho_{red} - \rho_{nir}}{\rho_{red} + \rho_{nir}}$$

- AATSR channels centred in 0.67 μm and 0.87 μm have been used for ρ_{red} and ρ_{nir} respectively.

Thresholds Method (NDVITHM)

- The final expressions obtained for this method are for bare soil pixels (NDVI < 0.2),
- $\varepsilon = 0.9825 - 0.051\ \rho_{red}$
- $\Delta\varepsilon = -0.0001 - 0.041\ \rho_{red}$

- for mixed pixels (0.2 NDVI 0.5),
- $\varepsilon = 0.971 + 0.018\ Pv$
- $\Delta\varepsilon = 0.006\ (1 - Pv)$

- and for vegetation pixels (NDVI > 0.5),
-
- $\varepsilon = 0.990$

- with Pv being the vegetation proportion, given by

$$P_v = \frac{NDVI - NDVI_{\min}}{\left(NDVI_{\max} - NDVI_{\min}\right)^2}$$

- where $NDVI_{min}$=0.2 and $NDVI_{max}$=0.5. The main constraint of this method is that it can not be used to extract water emissivity values because it is not possible to apply the NDVI and Pv equations for water pixels.

Roughness

Total roughness

$$Z_0 = \sqrt{Z_{0\,or}^2 + Z_{0\,vg}^2}$$

Orographic roughness

$$Z_{0\,or} = \frac{1}{p_{size}} \cdot v$$

Vegetation roughness

$$Z_{0\,vg} = f(h, f_c)$$

(h - vegetation height, fc – fractional coverage)

Questions:

1. What is surface radiation budget
2. List some methods to derive surface radiation components
3. What information is needed in order to derive surface radiation components using the above mentioned methods
4. What are the essential surface parameters in determination of surface radiation balance

References/Further Readings

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