Instruments pour la mesure in situ des flux de gaz
H_2O – CO_2 - …

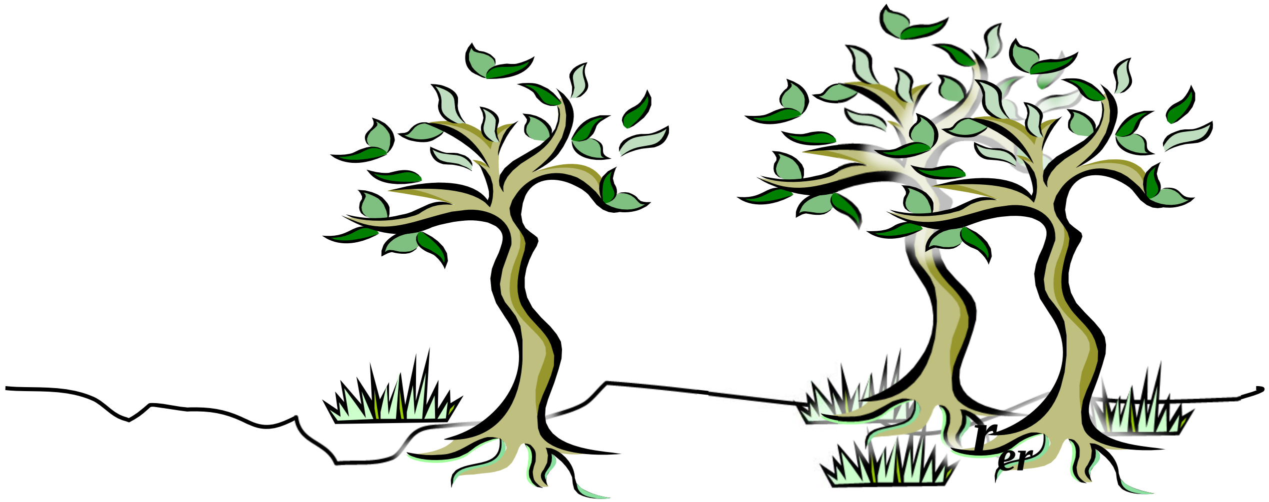
Jean-Martial Cohard

IGE

What is Evapotranspiration

q_a : specific atm. moisture

A water flux between ground to the atmosphere …

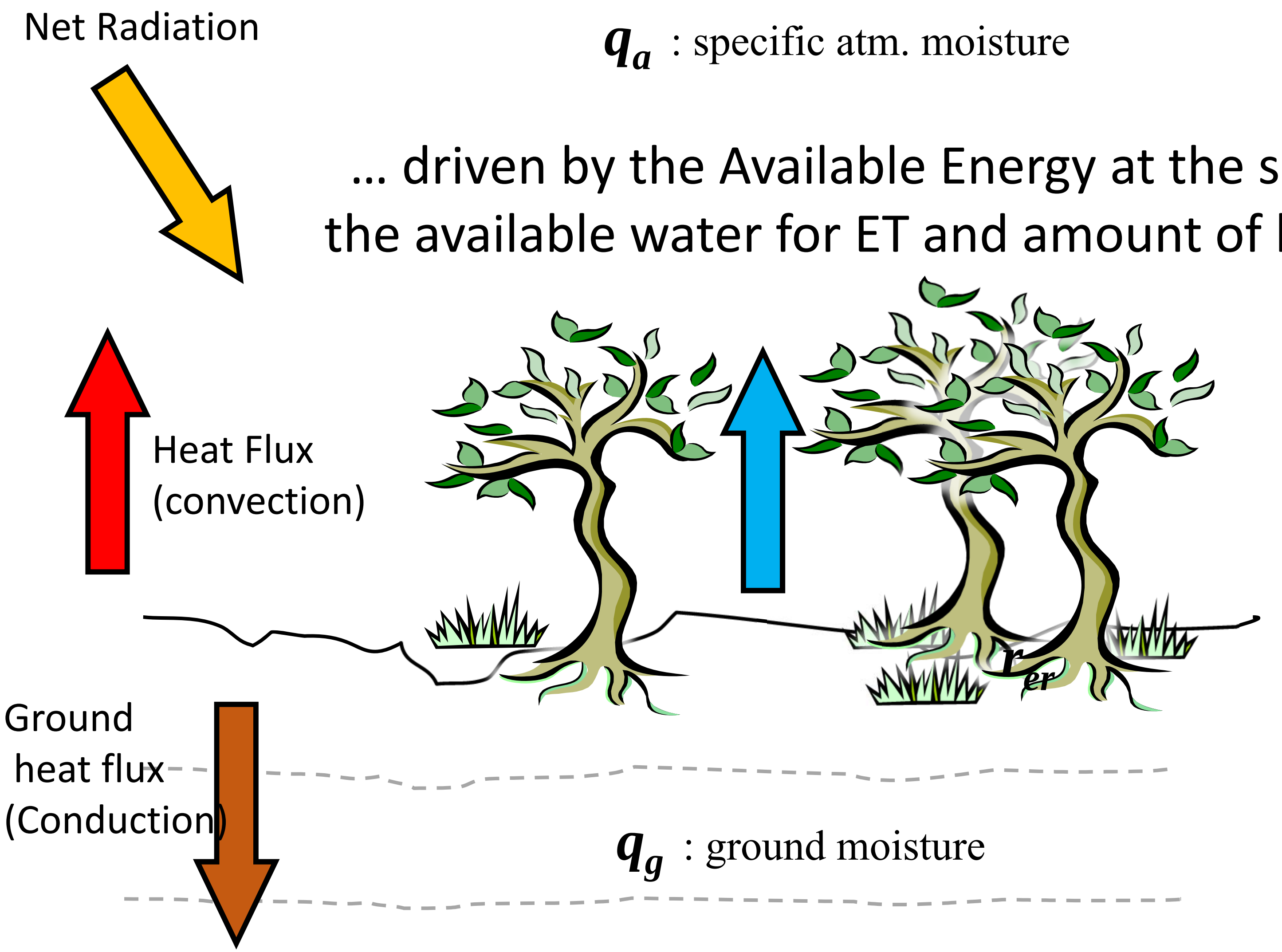


q_g : ground moisture

What is Evapotranspiration

q_a : specific atm. moisture

… driven by the Available Energy at the surface, the available water for ET and amount of biomass



q_g : ground moisture

What is Evapotranspiration

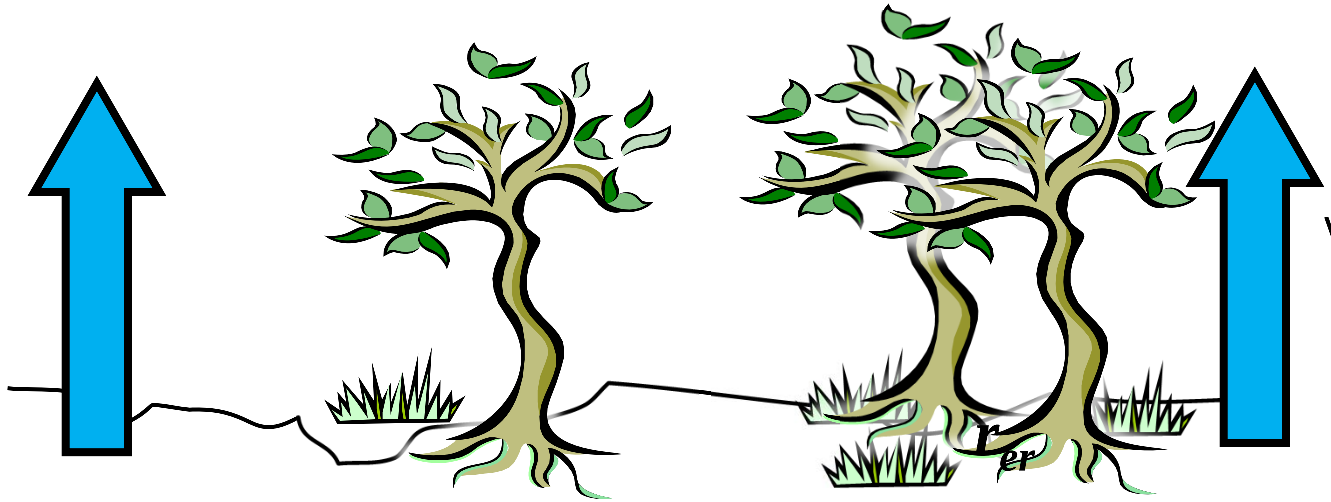
q_a : specific atm. moisture

Evaporation

Atmospheric capacity to
« absorb » water molecule:
Stability of the atmosphere

Transpiration

Atmospheric capacity to
« absorb » water molecule:
Stability of the atmosphere



Vegetation properties,
root, trunc, leaves
caracteristics

Ground properties,
succion, relative
permeability, …

q_g : ground moisture

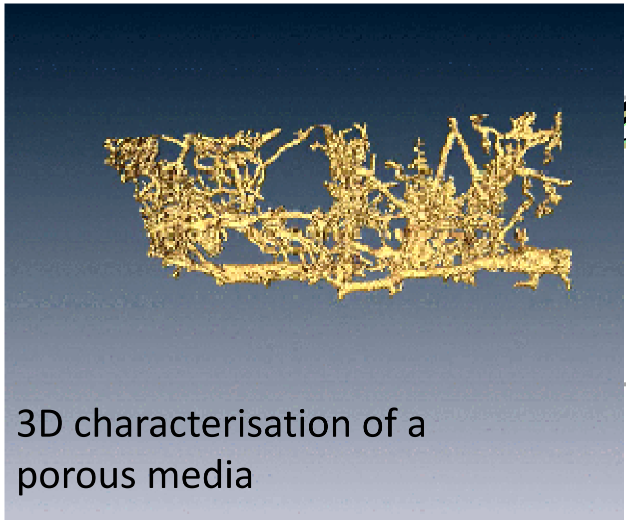
Ground properties,
succion, relative
permeability, …

What is Evapotranspiration

q_a : specific atm. moisture

Evaporation

Particle flow driven by turbulence



3D characterisation of a porous media

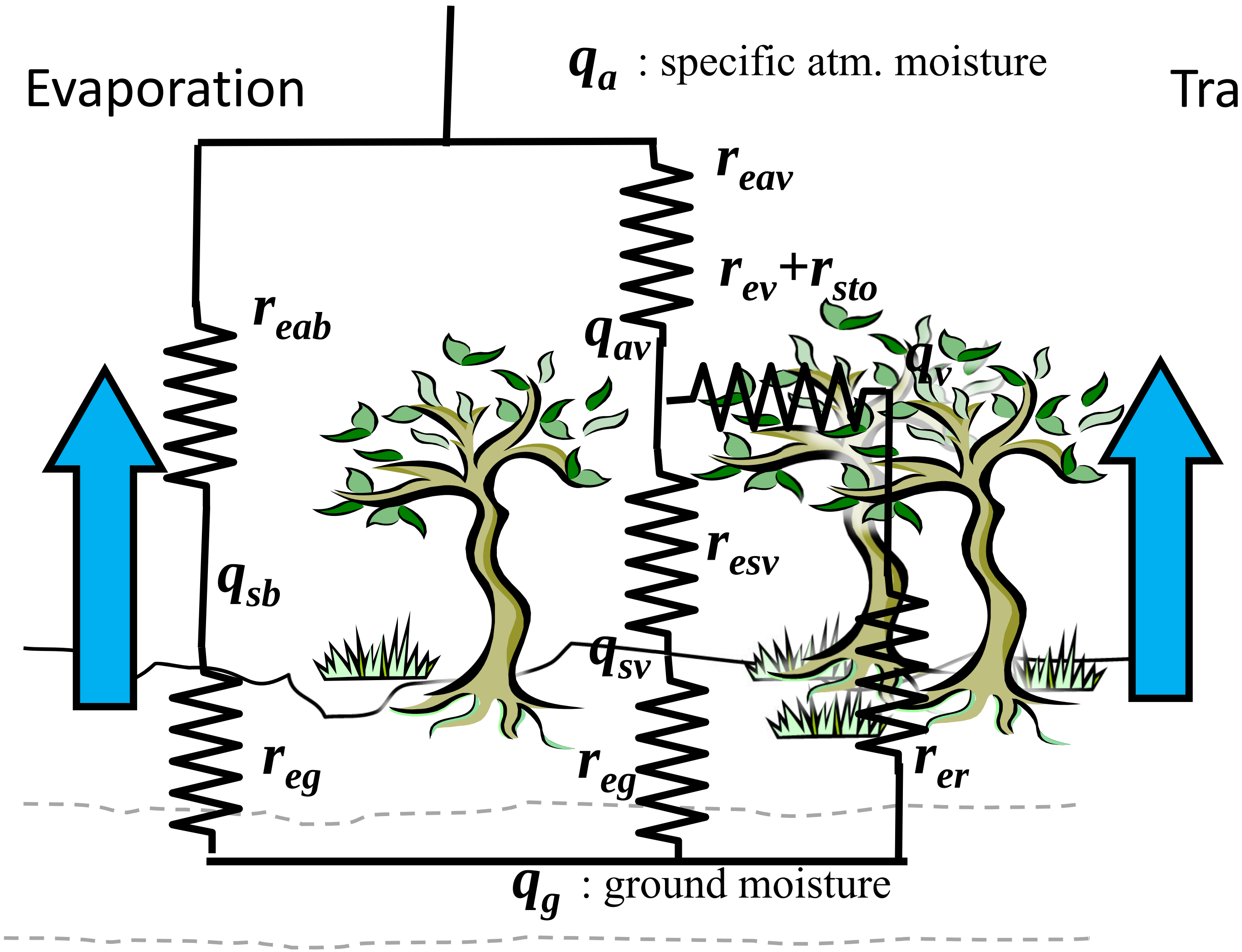
q_g : ground moisture

Transpiration

Stomata under a leaf

Tree roots

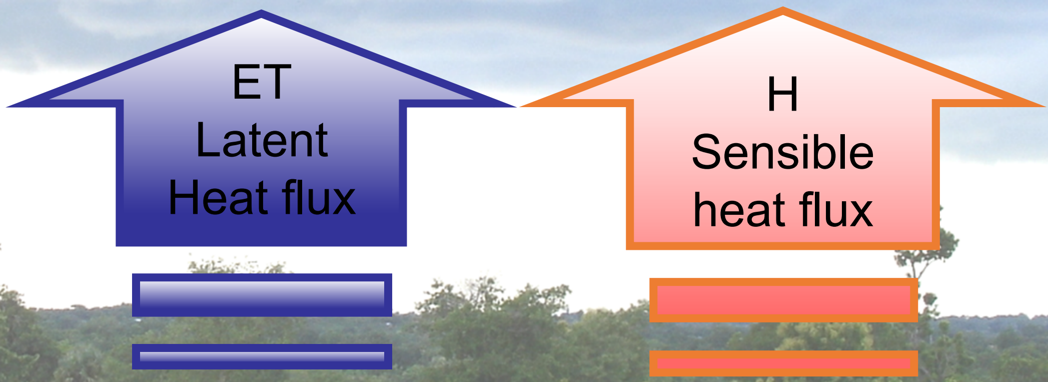
What is Evapotranspiration



Turbulent fluxes definition

$$LE = \mathcal{L}\overline{w'q'} = \mathcal{L}u^*q^*$$

$$H = \rho c_p \overline{w'T'} = \rho c_p u^* T^*$$



$$q = \overline{q} + q', \quad T = \overline{T} + T', \quad w = \overline{w} + w'$$

humidité spécifique; température; vitesse vent vertical

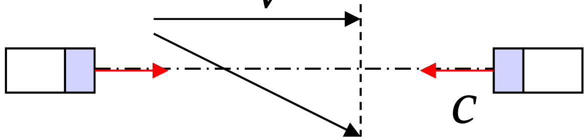
u, T*, q** are turbulent scales for wind velocity, temperature and moisture

The Eddy Covariance Method

$$M = \rho \overline{u'w'}, \quad H = \rho C_p \overline{\theta' w'}, \quad LE = \mathcal{L}.\overline{q'w'}$$

Need to sample all turbulent scales …

… 20Hz is our best sampling rate !



$$t_1 = \frac{L}{c+v} \qquad t_2 = \frac{L}{c-v}$$

$$\frac{1}{t_1} - \frac{1}{t_2} = \frac{2.v}{L} \qquad \frac{1}{t_1} + \frac{1}{t_2} = \frac{2.c}{L}$$

sonic Anemometer and gas analyser

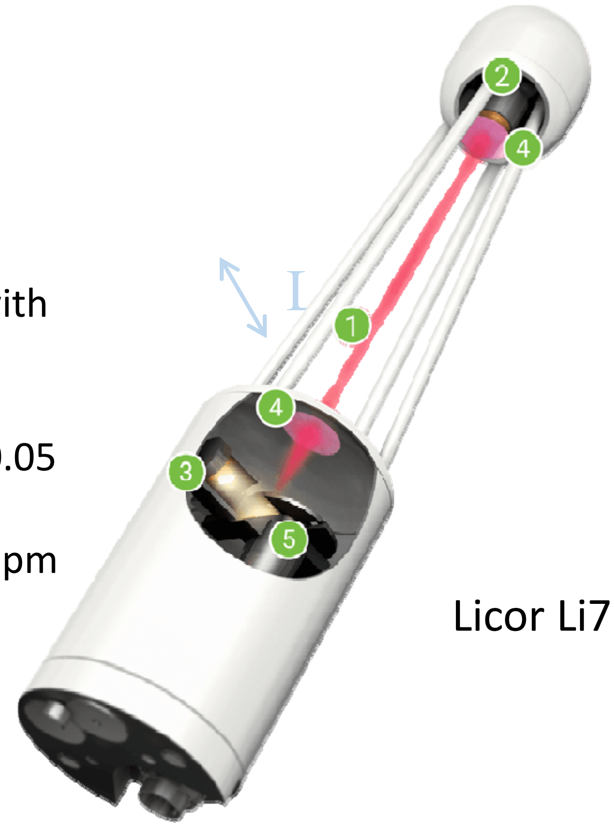
$$c = \left(\frac{P\gamma}{\rho} \right)^{1/2} \rightarrow T_v$$

The Eddy Covariance Method

$$M = \rho\overline{u'w'}, \quad H = \rho C_p\overline{\theta' w'}, \quad LE = \mathcal{L}.\overline{q'w'}$$

gas analyser

- ➔ Measure **H2O** & **CO2** concentrations
- ➔ **IR** absorption (2590 nm et 4260 nm):
- ➔ **20Hz** measurements
- ➔ **open path,** open to let the turbulent flow or **close path** with an inlet within the sonic anemometer sample volume.
- ➔ H2O : Gamme 0 – 60 mmol/mol, précision 1%, T° drift +-0.05 mmol/mol
- ➔ CO2 : Gamme 0 – 3000 ppm, précision 1%, T° drift +-0.3 ppm
- ➔ Path : 12.5 cm
- ➔ Spining miror, T° Correction en T°, …



Licor Li7500

The Eddy Covariance Method

$$M = \rho\overline{u'w'}, \quad H = \rho C_p\overline{\theta' w'}, \quad LE = \mathcal{L}.\overline{q'w'}$$

gas analyser

Open Path (Bellefoungou, Bénin)

Pb de séparation des capteurs

Close Path (Lautaret)

Pb de délai et diffusion dans le tube
Pompage énergivore, condensation, …

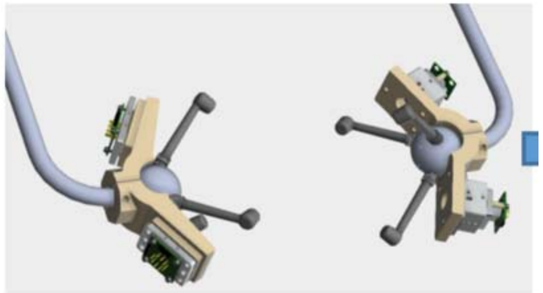
The Eddy Covariance Method

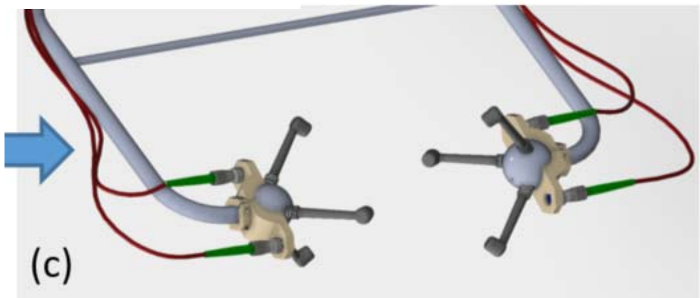
$$M = \rho\overline{u'w'},\quad H = \rho C_p\overline{\theta' w'},\quad LE = \mathcal{L}.\overline{q'w'}$$

gas analyser

Open Path (Bellefoungou, Bénin)

Pb de séparation des capteurs
Irgason (Campbell Sci)





Développement en cours (Université de Reims Champagne Ardenne & INRAE)

The Eddy Covariance Method

$$M = \rho \overline{u' w'}, \quad H = \rho C_p \overline{\theta' w'}, \quad LE = \mathfrak{L}.\overline{q' w'}$$

gas analyser

Mesure de la concentration de CH4 :Open Path (Lac Luitel)

Mesure de la concentration de CH4 (Chatuzange)

Li7700 (Licor)
Wavelength Modulation Spectroscopy (8000nm)

Path : 63 m !
Freq. : 20Hz

The Eddy Covariance Method

$$M = \rho\overline{u'w'}, \quad H = \rho C_p \overline{\theta' w'}, \quad LE = \mathfrak{L}.\overline{q'w'}$$

gas analyser

Mesure de concentration de H2O – CO2 - CH4

LGR (Licor)
Off-Axis Integrated Cavity Output Spectroscopy
Plusieurs autre gaz disponible (N2O, CO, NH3)
Freq. : 10Hz

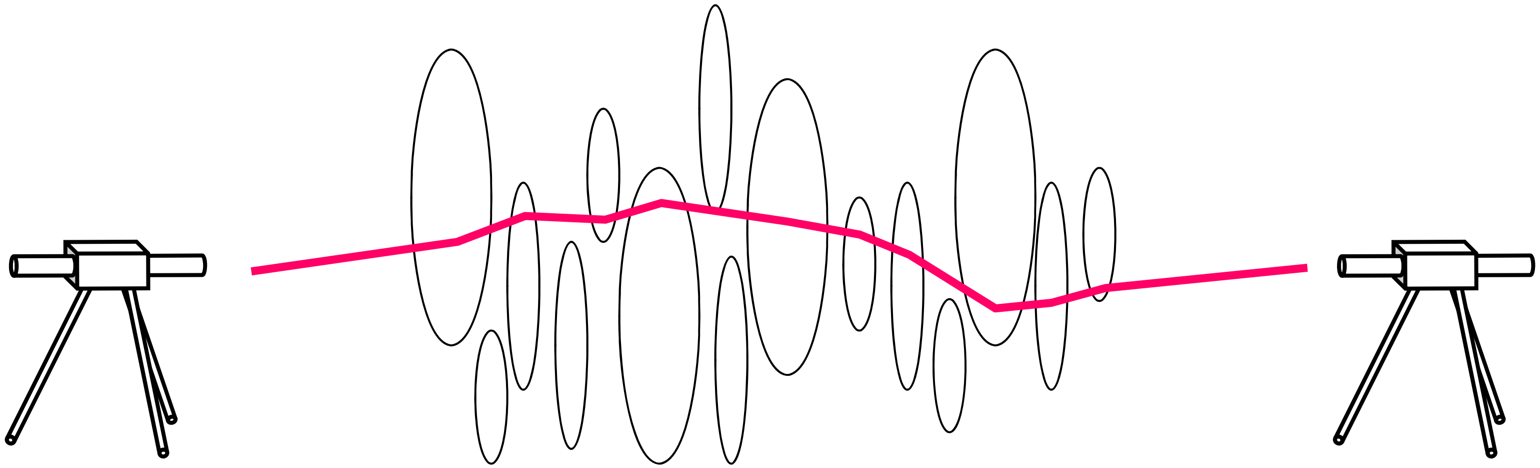
Scintillation: a turbulent indicator

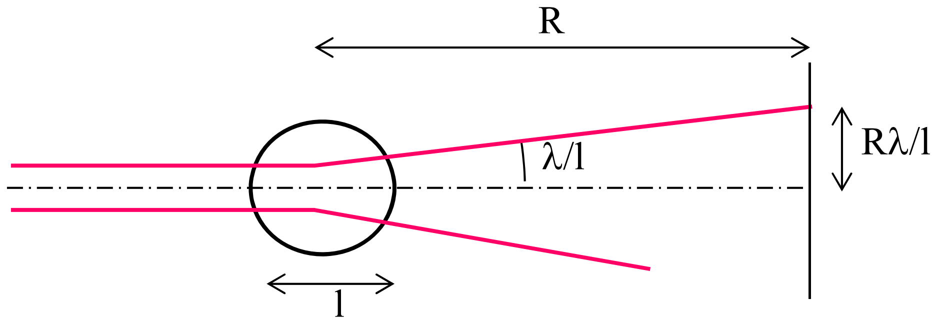
Fluctuations of a propagating signal in a turbulent media are function Cn²:
The structure parameter for the refractive index of the air

$$D_c(\vec{\rho}) = \left\langle \left(c'(\vec{r}+\vec{\rho},t) - c'(\vec{r},t) \right)^2 \right\rangle \approx \frac{1}{T}\int_0^T \left(c'(\vec{r}+\vec{\rho},t) - c'(\vec{r},t) \right)^2 dt = C_c^2 \rho^{2/3}$$

Scintillometry method – Tatarski 1961

Geométrical optic approach (without refraction)





Diffraction négligeable

$$R\lambda/l \ll 1$$

Smallest eddies are the most diffractant because they have the strongest curvature

$$\sqrt{R\lambda} \ll l_0$$

Scintillometry method – Tatarski 1961

From propagation equation of an electromagnetic signal

$$\Delta(\psi_1) + 2\nabla\psi_1\nabla\psi_0 + 2n_1k^2 = 0$$

general solution :

$$\psi_1(r) = \frac{k^2}{2\pi u_0(r)} \int_V n_1(r')\, u_0(r') \frac{e^{ik|r-r'|}}{r-r'}\, dv'$$

For a spherical wave : $u = u_0 \exp(ik\, r_0)$

$$\overline{\left(\mathrm{Re}(\Psi_1)\right)^2} = \sigma_\chi^2 = 4\pi k^2 \int_0^L \int_0^\infty \kappa\, \Phi_n(\kappa) \sin^2\left(\frac{\kappa^2 x(L-x)}{2kL}\right) d\kappa\, dx$$

with : $\Phi_n(\kappa) = 0{,}033 \times C_n{}^2 \kappa^{-11/3}$

$$\sigma_\chi^2 = 0{,}124\, \overline{C_n^2}\, k^{7/6} L^{11/6}$$

pour : $L_0 >> \sqrt{\lambda L} >> l_0$

Scintillometry method – Hill 1980

$$C_{n^2} = \frac{A_T^2}{T^2} C_{T^2} + \frac{A_q^2}{q^2} C_{q^2} + 2\frac{A_q A_T}{qT} C_{Tq}$$

A_T, A_q, are coefficients function of the signal wave length

For the optical and near IR domains, C_n^2 is mainly proportional to C_T^2

$$C_{n^2/IR} \approx \frac{A_T^2}{T^2} C_{T^2} \left(1 + 0.03/\beta_o\right)^2$$

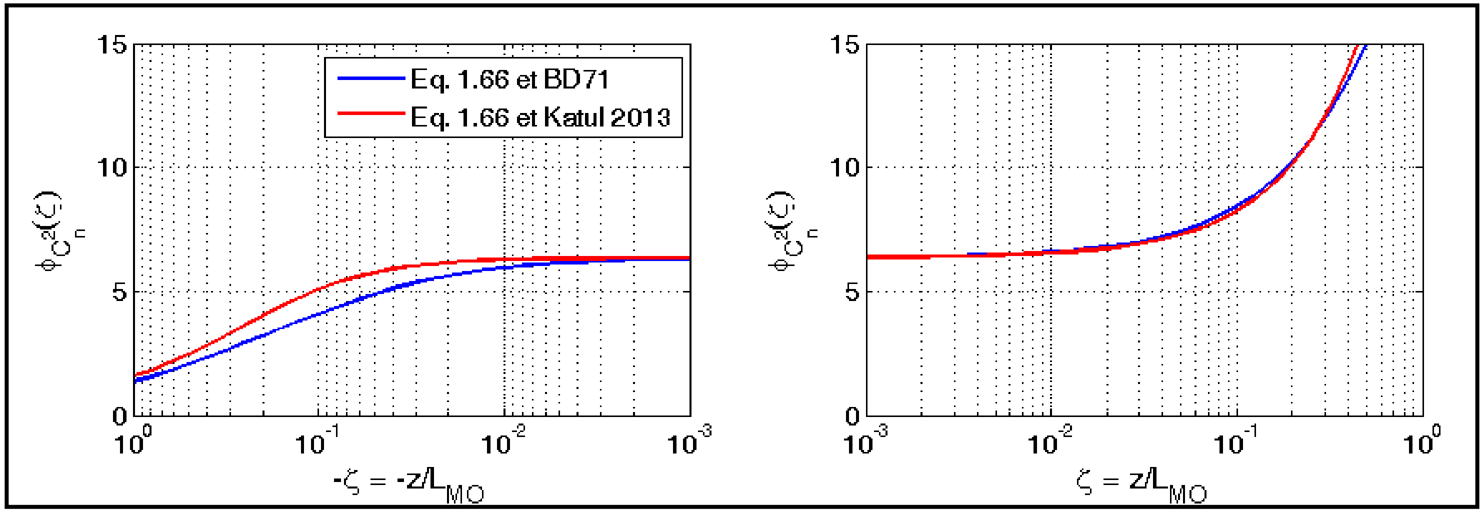
$\beta_o = H / LE$ Is the Bowen ratio

17

MOST applies for $C_T^2 \rightarrow T^*$

$$H = \rho C_p \overline{\theta' w'} = \rho C_p u^* T^*, \quad LE = \mathfrak{L}.\overline{q' w'} = \mathfrak{L}.u^* q^*$$

(Kaimal, 1994; Katul et al 2013)

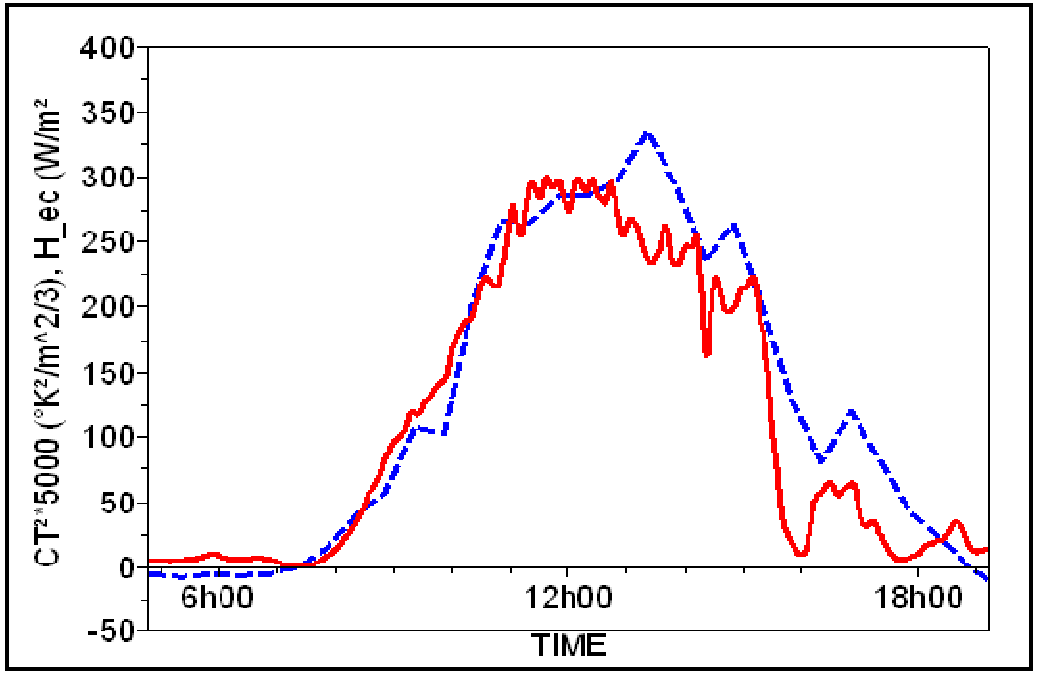


$$C_{T^2}{}^2 \Rightarrow T^* \; ; C_{q^2}{}^2 \Rightarrow q^*$$

18

MOST applies for C_T^2 → T*

$$H = \rho C_p \overline{\theta' w'} = \rho C_p u^* T^*, \quad LE = \mathfrak{L}.\overline{q' w'} = \mathfrak{L}.u^* q^*$$



$$C_{T^2}^{\;2} \Rightarrow T^* \;; C_{q^2}^{\;2} \Rightarrow q^*$$

19

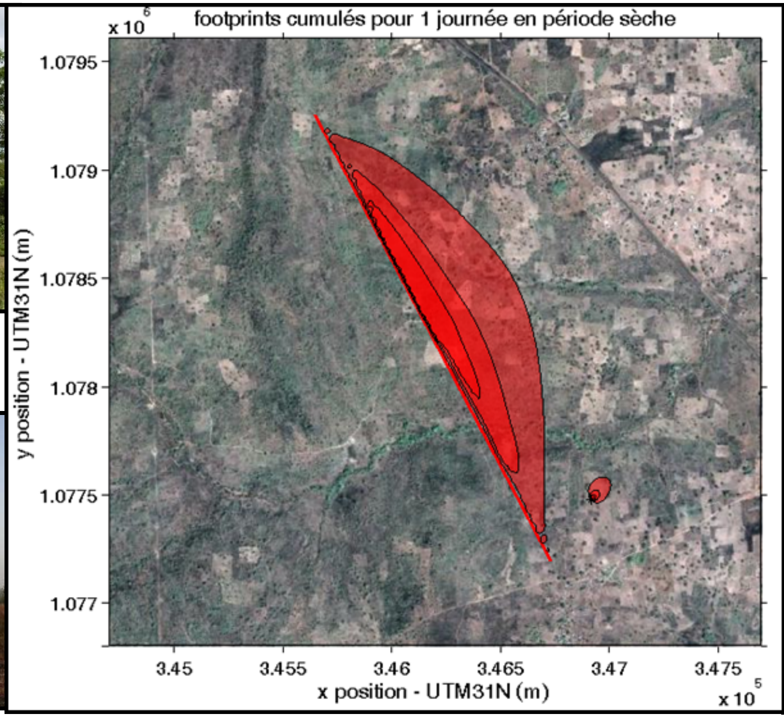
IR scintillometry ($\lambda < 1\mu m$) ➔ T* ➔ H

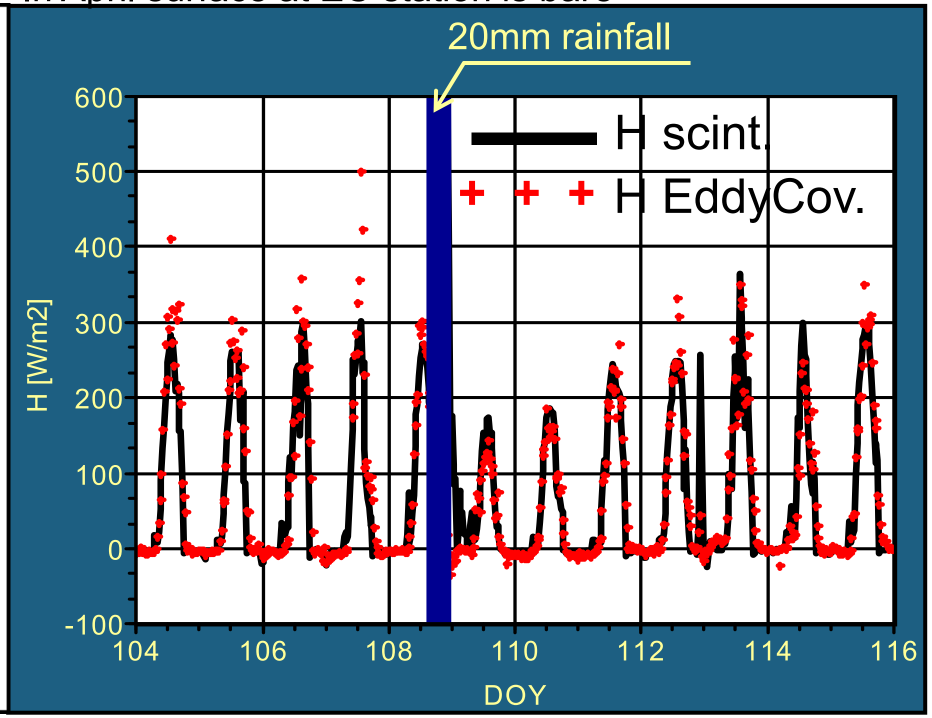
$$H = \rho c_p u^* T^*$$

u* is estimated from a wind velocity measurement, the surface roughness, …

<u>Sensible heat fluxes estimated from scintillometry at Nalohou (9,4° N) during the dry season</u>

In April surface at EC station is bare





Guyot *et al* 2009

Consistent results but no validation ! Estimated uncertaintes : ~13%

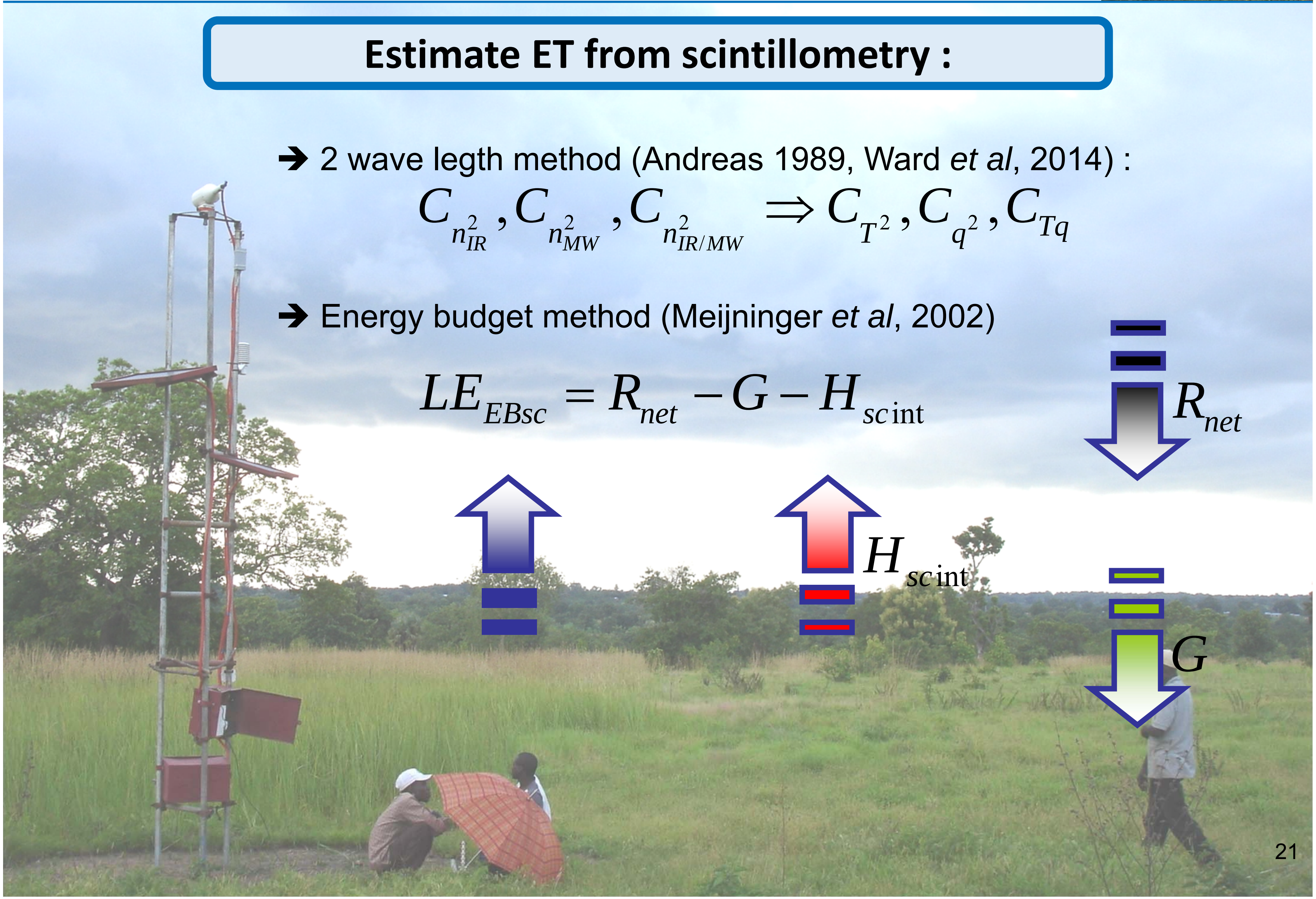
Estimate ET from scintillometry :

➔ 2 wave legth method (Andreas 1989, Ward *et al*, 2014) :

$$C_{n^2_{IR}}, C_{n^2_{MW}}, C_{n^2_{IR/MW}} \Rightarrow C_{T^2}, C_{q^2}, C_{Tq}$$

➔ Energy budget method (Meijninger *et al*, 2002)

$$LE_{EBsc} = R_{net} - G - H_{scint}$$



Estimate ET from scintillometry :

➔ méthode à 2 longueurs d'onde (Andreas 1989, Ward *et al*, 2014) :

$$C_{n^2_{IR}}, C_{n^2_{MW}}, C_{n^2_{IR/MW}} \Rightarrow C_{T^2}, C_{q^2}, C_{Tq}$$

2 wave length method : IR + μ-wave

$$C_{n^2} = \frac{A_T^2}{\overline{T}^2} C_{T^2} + \frac{A_q^2}{\overline{q}^2} C_{q^2} + 2\frac{A_q A_T}{\overline{qT}} C_{Tq}$$

A_T, A_q are wave length dependant

Optic and Near IR (<1 μm) :

$$C_{n_{IR}^2} \approx \frac{A_{T\_IR}^2}{\overline{T}^2} C_{T^2}$$

$$C_{n_{IR}^2} \Rightarrow C_{T^2} \underset{\text{Similarity theory}}{\Rightarrow} T^* \underset{(u^*)\ +/-}{\Rightarrow} H \underset{\text{Energy Budget}}{\Rightarrow} LE$$

Micro-Onde (1mm ➔ 3cm) : $C_{n_{MW}^2} = \frac{A_{T\_MW}^2}{\overline{T}^2} C_{T^2} + \frac{A_{q\_MW}^2}{\overline{q}^2} C_{q^2} + 2\frac{A_{q\_MW} A_{T\_MW}}{\overline{qT}} C_{Tq}$

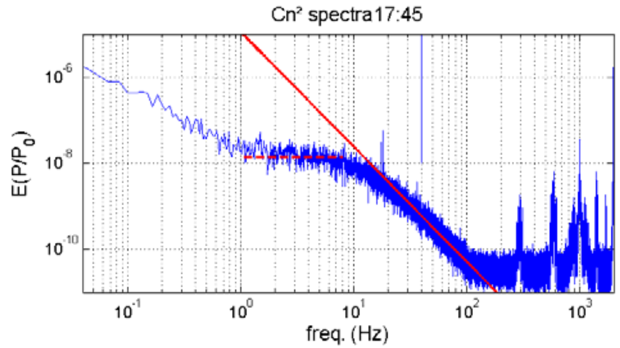
$$C_{n_{IR}^2}, C_{n_{MW}^2}, C_{n_{IR}n_{MW}} \Rightarrow C_{T^2}, C_{q^2}, C_{Tq} \underset{\text{Similarity theory}}{\Rightarrow} T^*, q^* \underset{(u^*)}{\Rightarrow} H, LE$$

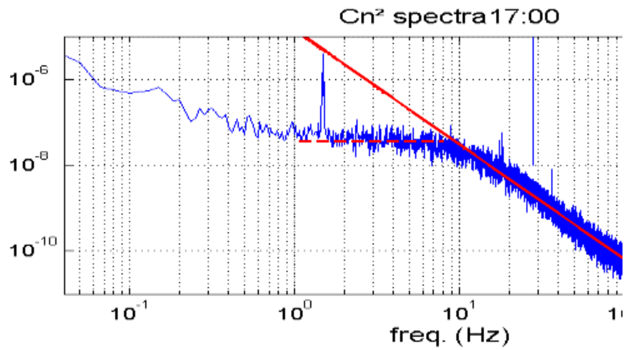
Andreas 1989, Ward 2015

Development μ-onde scintillometer prototype

- Development of a **94GHz** scintillometer (Rutherford Appleton Laboratory (UK), LTHE)
- Lab view data logger (frequence aq.: **~1kHz**)
- **Synchronisation** of IR & μ-wave scintillomètres

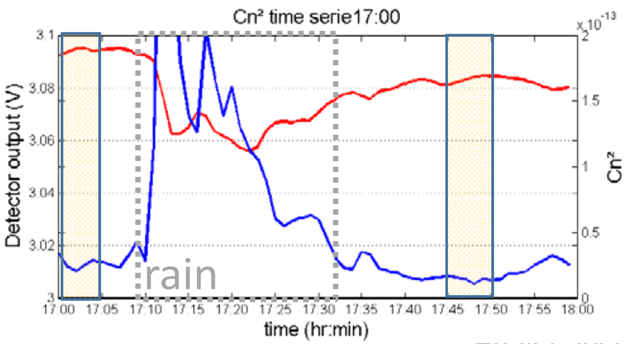
Scintillation frequency distribution





Puissance signal reçu

Cn²

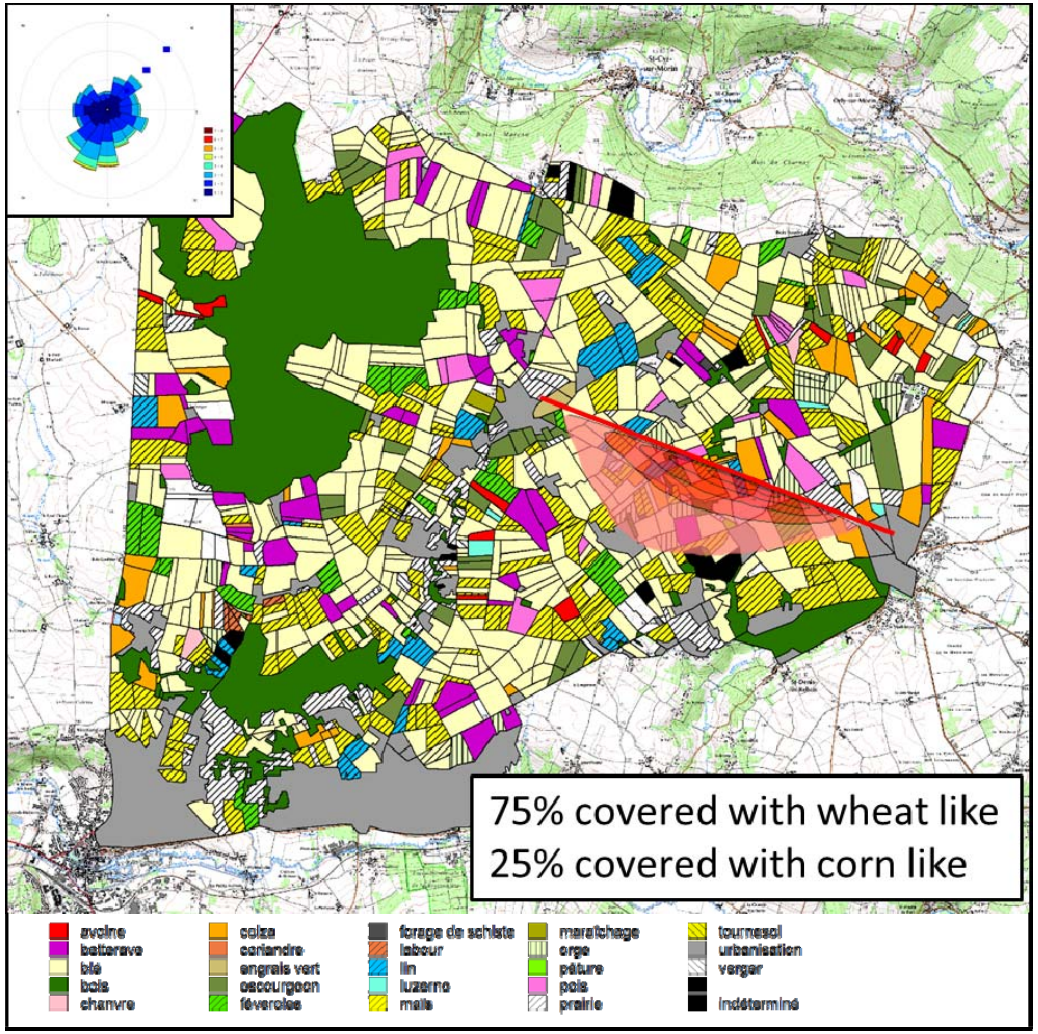


Scintillation Spectra

Kolmogorov ($k^{-8/3}$)

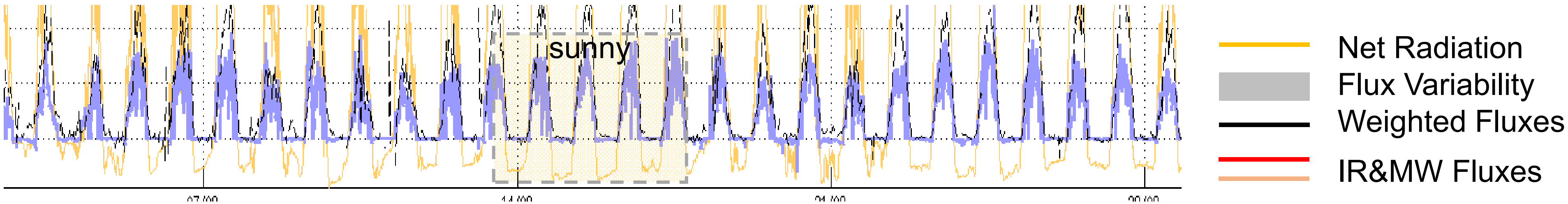
Scintillation Plateau

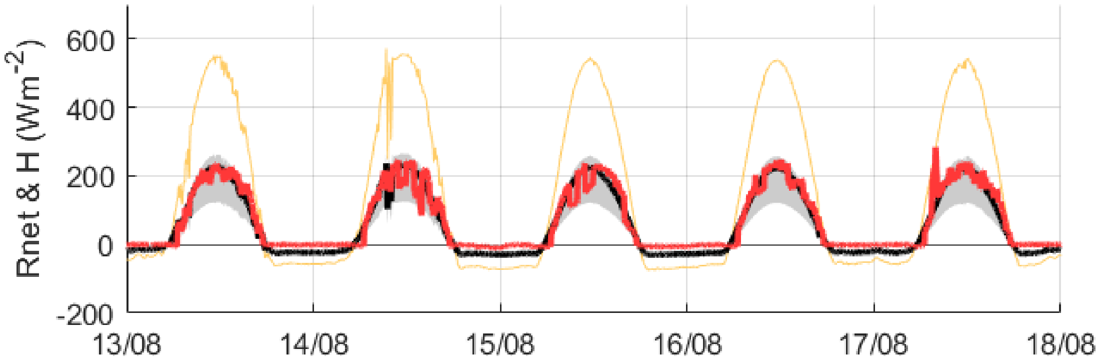
2 wave length method : IR + μ-wave

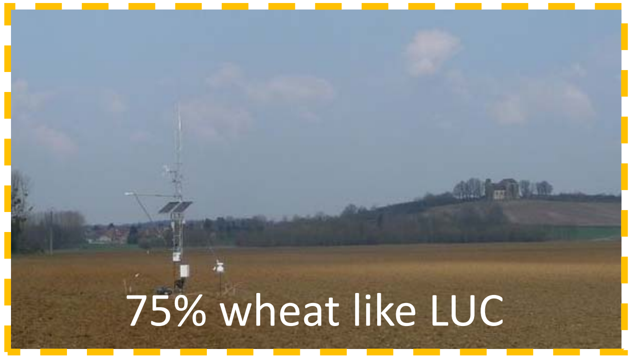


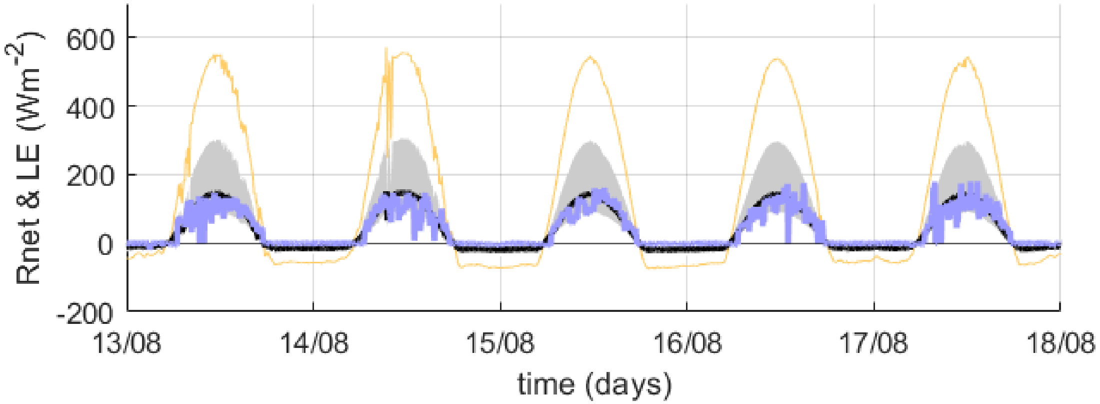
vegetation state in july-august

2 wave length method : IR + μ-wave









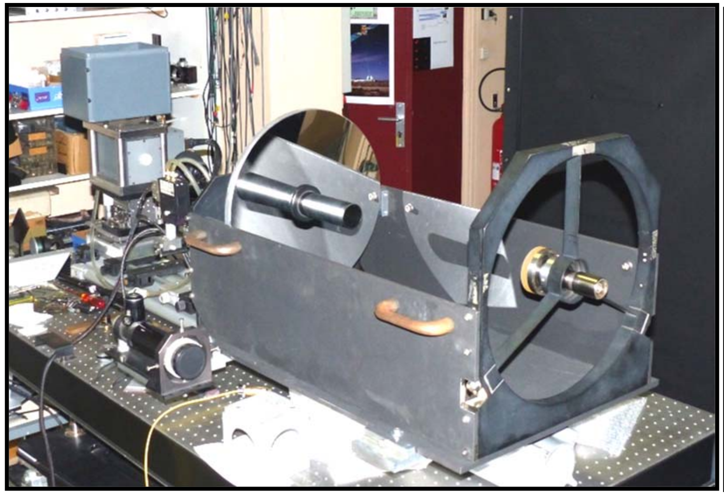
6

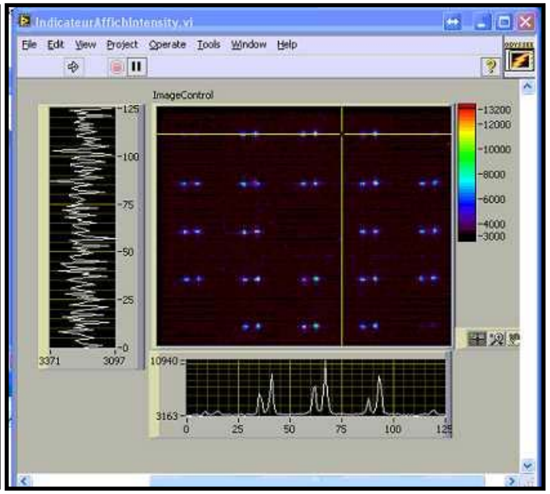
Distribution spatiale des flux de surface par scintillométrie

Le SCINDAR

Profileur de Cn²

Collaboration ONERA, INRA



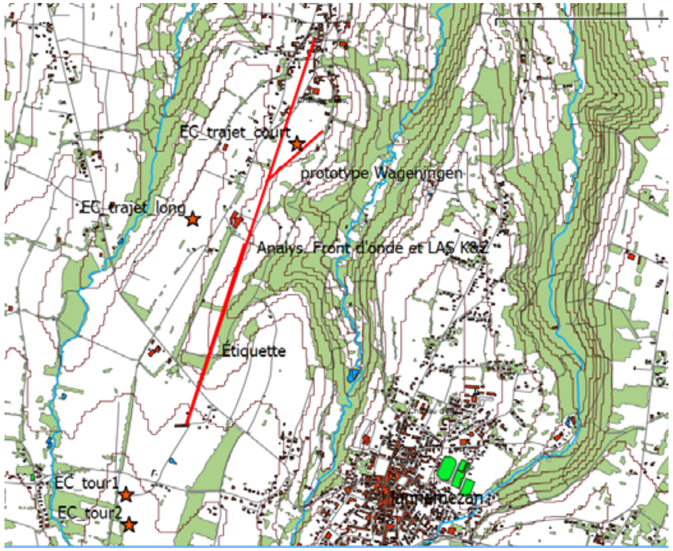


Auto-corrélation, corrélation entre source, corrélation entre image

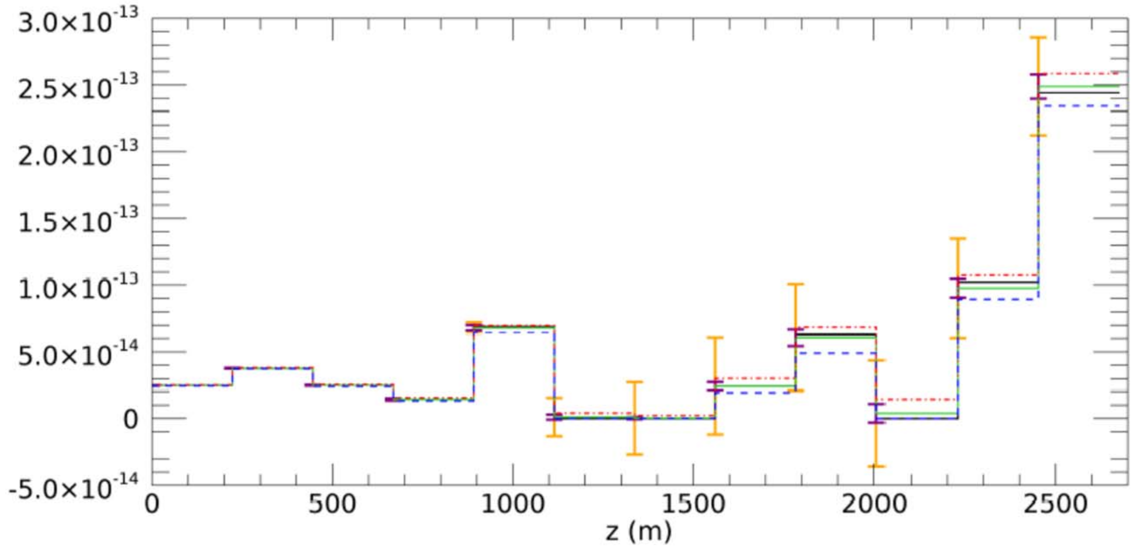
➔ Reconstruction du front d'onde

➔ Distribution de Cn² avec une résolution de l'ordre de 300m

Distribution spatiale des flux de surface par scintillométrie



Evaluation du SCINDAR lors de la campagne AMOSC à Lannemezan



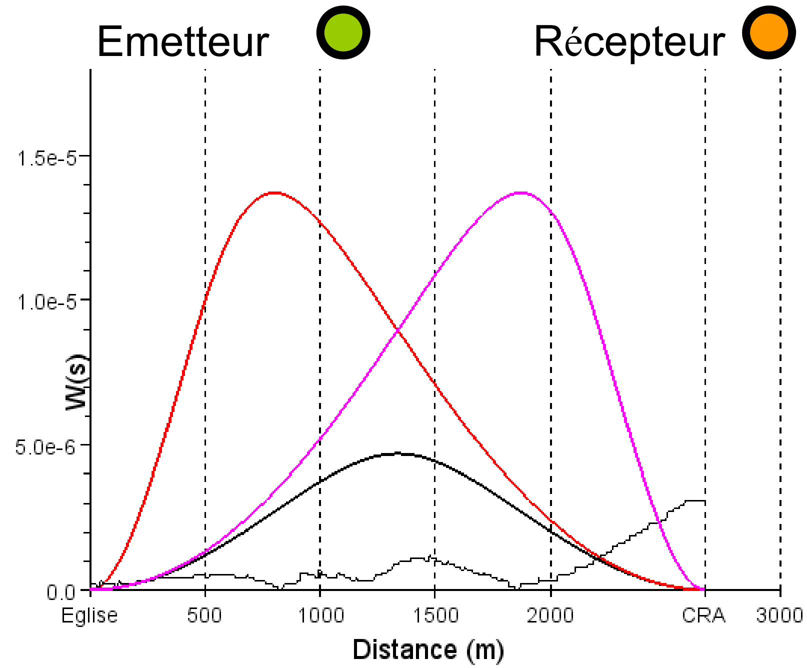
Scindar : inversion du profil de Cn² (Sauvage et al. 2021)

Distribution spatiale des flux de surface par scintillométrie

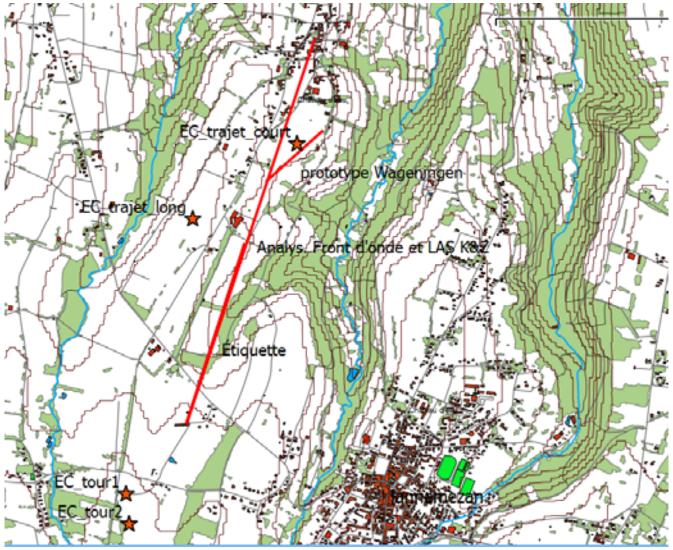
La scintillométrie asymétrique

$$\overline{C_n^2} = \int_0^L C_n^2(x)\,W(x)\,dx$$

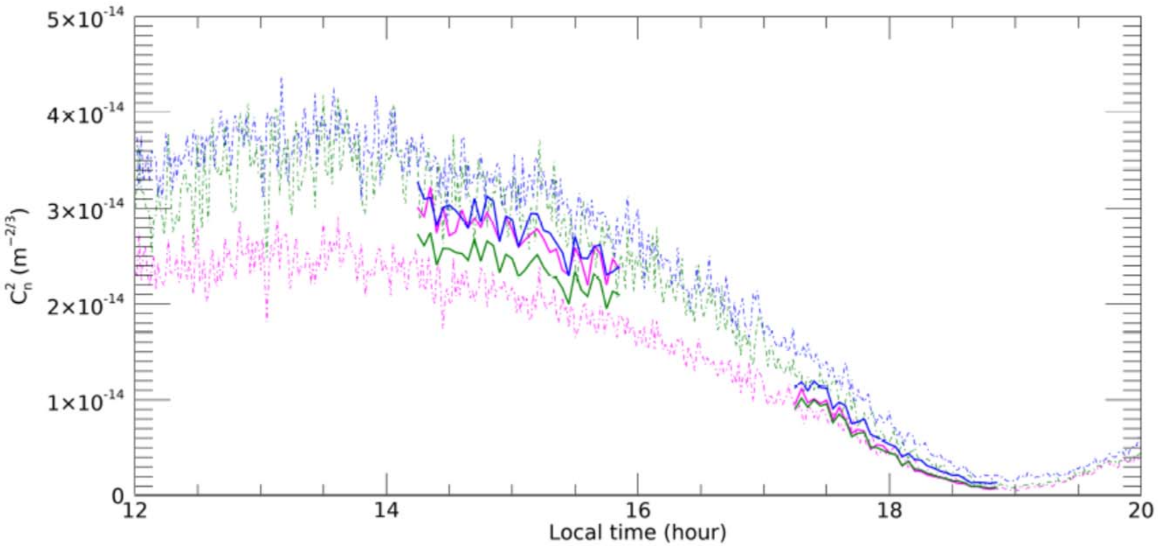
$$W(x) = \frac{4\pi^2k^2}{\overline{C_n^2}} \int_0^\infty 0.033\,\kappa_x^{-8/3} \sin^2\left(\frac{\kappa_x^2 x(L-x)}{2kL}\right) \left[\frac{2J_1\left(0,5\kappa_x D_e \frac{x}{L}\right)}{0,5\kappa_x D_e \frac{x}{L}} \cdot \frac{2J_1\left(0,5\kappa_x D_r \left(1-\frac{x}{L}\right)\right)}{0,5\kappa_x D_r \left(1-\frac{x}{L}\right)}\right]^2 d\kappa_x$$



Distribution spatiale des flux de surface par scintillométrie

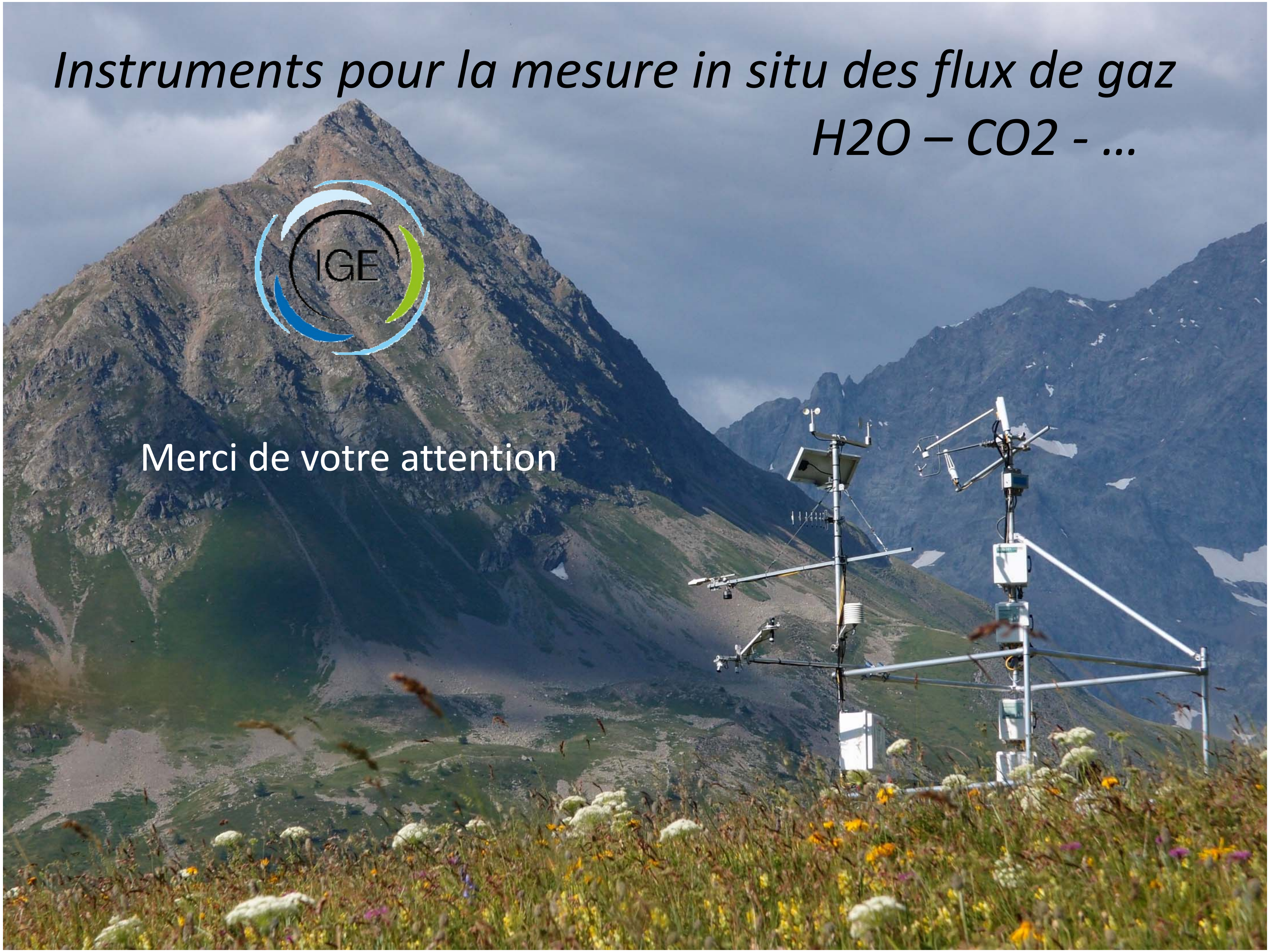


Evaluation du SCINDAR lors de la campagne AMOSC à Lannemezan



Lignes pointillées: Scintillométrie asymétrique
Lignes pleines : mesures scindar

Instruments pour la mesure in situ des flux de gaz
H_2O – CO_2 - …



Merci de votre attention