Contribution of new technologies for the monitoring of hydraulic plants: the EDF experience

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- **EDF context**
  - EDF has to monitor several hundreds kilometers dykes in France to prevent them from breakthroughs
  - Currently, visual inspections are done to detect leaks which can constitute a risk in a long time

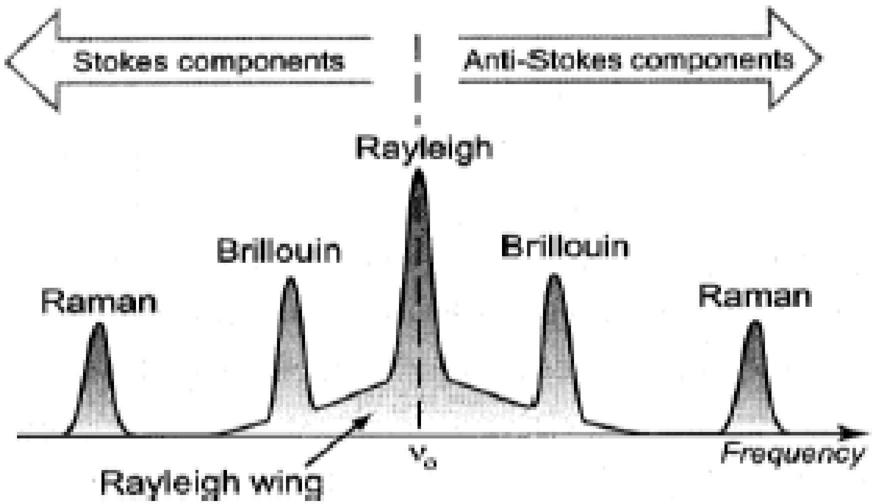
- **EDF objective**
  - EDF searches for a continuous measurement capable of “seeing” leaks
  - Thermometry has then been chosen by making the following hypothesis:
    - if there is no leak, the soil temperature should be quite near from the air one
    - if there is a leak, the soil temperature should be quite near from the water one
  - The only way to make this distance-along temperature measurement is using the fiber optic

FIBER OPTIC THERMOMETRY FOR DETECTION AND QUANTIFICATION OF LEAKS IN DYKES

- **Measuring temperature with fiber optic : how does it work ?**
  - Raman effect: a fiber optic excited with a laser backscatters two waves with a different frequency than that emitted, these two waves are called Stokes and Anti-Stokes
  - Temperature is linked with the ratio between Stokes and Anti-Stokes intensities thanks to the Boltzmann factor:

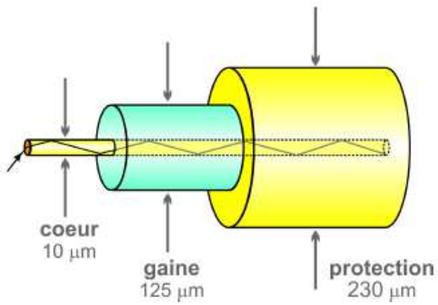
$$R(T) = \left(\frac{\lambda_s}{\lambda_a}\right)^4 \exp\left(-\frac{h\nu_0}{kT}\right)$$

  - The first devices using this effect appear in 1985, but the technology is really useful with a sufficient precision since about 2000



FIBER OPTIC THERMOMETRY FOR DETECTION AND QUANTIFICATION OF LEAKS IN DYKES

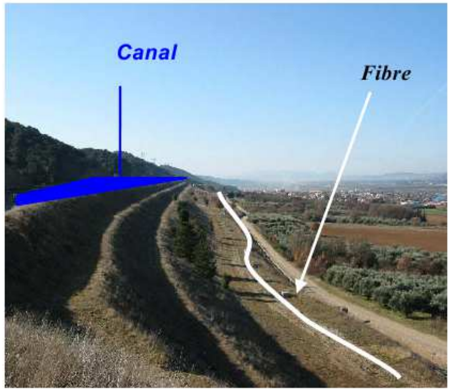
- **Technology principles**
  - The measurement system consists in an interrogator which emits the laser impulsions and receives the backscattered light and in a fiber optic which can be several kilometers long
  - The measurement relies on the optical time-domain reflectometry (OTDR): it exploits the equivalence between time and distance to extract the information at a given position



FIBER OPTIC THERMOMETRY FOR DETECTION AND QUANTIFICATION OF LEAKS IN DYKES

- **EDF implementation**
  - The fiber optic has been installed at the bottom of the downstream facing of dykes to monitor potential leaks at a depth of minimum 80 cm.
  - The temperature profiles are acquired every two hours during several months
  - The resulting data are so time-distance 2D arrays which are to process to extract the desired information

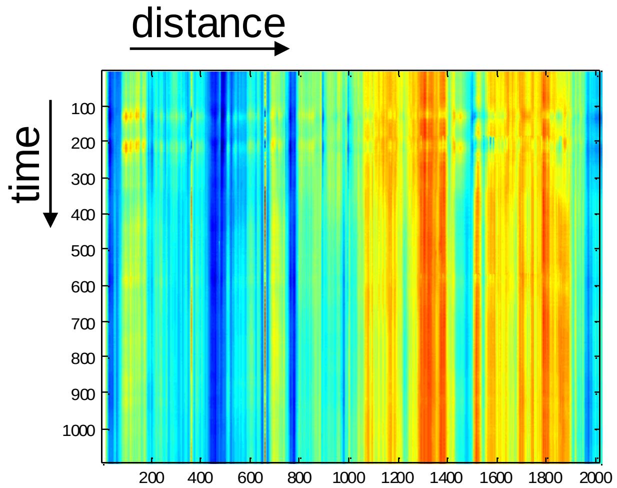
- **Studies made using these data**
  - Detection and localization of leaks using blind source separation techniques: thesis of A.A. Khan (2006-2009) with the Gipsa-lab laboratory in Grenoble (France)
  - Quantification of the Darcy leak speed: thesis of S. Kerzalé (2010-2013) with the LEMTA, University of Lorraine (France)
  - Detection/localization algorithms provided to the measurement and auscultation EDF department
  - Quantification algorithms transferred in the next years



FIBER OPTIC THERMOMETRY FOR DETECTION AND QUANTIFICATION OF LEAKS IN DYKES

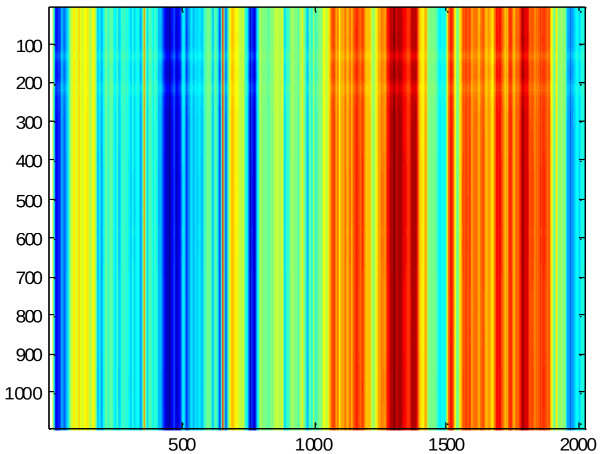
- **Detection/localizations algorithms**
  - First step: PCA
  - The first component is much more energetic than the following ones: it represents the "ground response" and is subtracted before continuing the processing

Y =



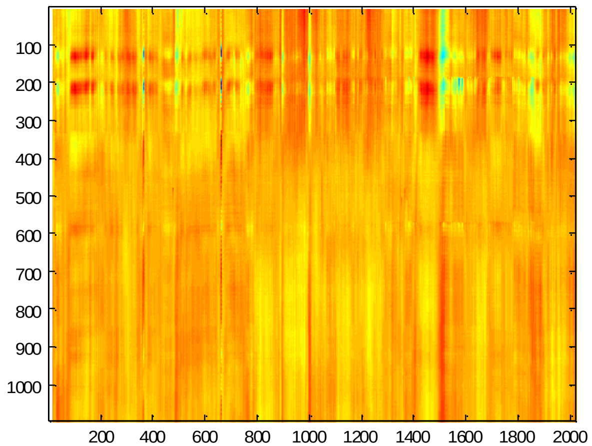
$$Y_{residue} = Y - Y_{signal}$$

$$Y_{signal} = \sigma_1 \mathbf{u}_1 \mathbf{v}_1^T + \ldots + \sigma_m \mathbf{u}_m \mathbf{v}_m^T$$



(signal subspace for m=1)

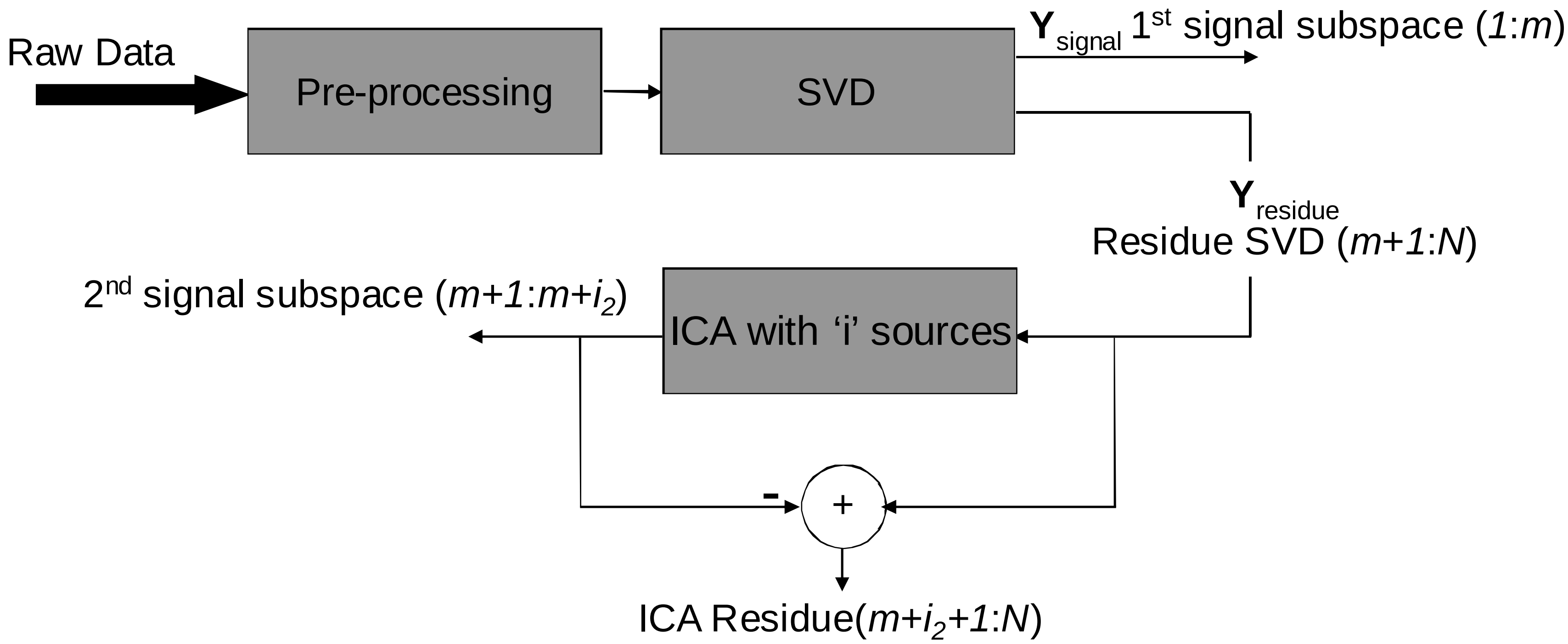
$$Y_{residue} = \sigma_{m+1} \mathbf{u}_{m+1} \mathbf{v}_{m+1}^T + \ldots + \sigma_N \mathbf{u}_N \mathbf{v}_N^T$$



(noise subspace for m=1)

FIBER OPTIC THERMOMETRY FOR DETECTION AND QUANTIFICATION OF LEAKS IN DYKES

- **Detection/localizations algorithms**
  - The first proposed approach combined ICA and PCA



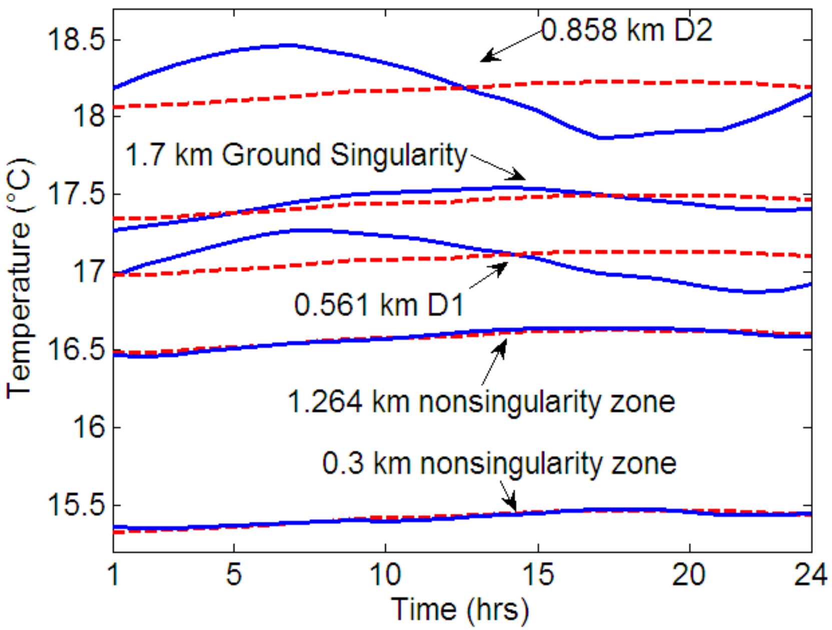
m = number of singular values to construct 1^{st} signal subspace

i = number of sources to be estimated by ICA

i_2 = number of ICA sources to construct 2^{nd} signal subspace

FIBER OPTIC THERMOMETRY FOR DETECTION AND QUANTIFICATION OF LEAKS IN DYKES

- **Detection/localizations algorithms**
  - Evolutions of the algorithm
    - Precipitations modify the behavior of the temperature: a test based on higher-order statistics (kurtosis) has been developed to automatically select the homogenous time intervals
    - Reduction of the time period to perform the PCA: under the hypothesis that leaks zones are sparse, a PCA on 24h data permits to identify regular zones from singular ones by comparing the profile at each distance with the one obtained as the first singular vector
      - When the two profiles are too much different, a singularity can be supposed
      - The remaining question is to get sufficient comparison elements to be sure that the singularities seen by the algorithm are effectively leaks



FIBER OPTIC THERMOMETRY FOR DETECTION AND QUANTIFICATION OF LEAKS IN DYKES

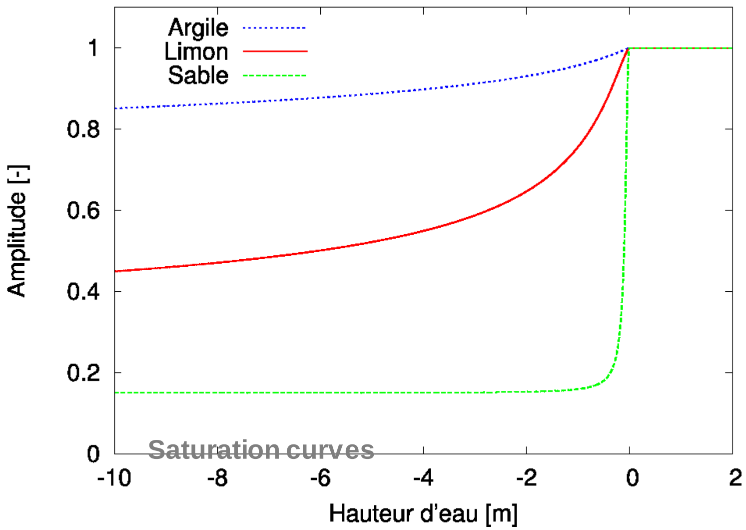
- **Leak Darcy speed quantification**
  - Once a leak has been detected, the next question is to evaluate the speed of the flow, which is the indicator for the stability of the dyke
  - In this case, there is a need for a data-model comparison
  - Two great categories of model can be used:
    - Physics-based quite simple transfer function model: thesis of P. Cunat with EDF measurement department and LTHE laboratory in Grenoble
    - 2D PDE model for hydrogeology associated with a 1D thermal model (advection-dispersion-diffusion): thesis of S. Kerzalé with EDF R&D and LEMTA laboratory in Nancy
  - The two approaches need to know air temperature and water temperature
  - The first approach is more consuming in data duration, because it needs to calibrate the model parameters while estimating the speed

FIBER OPTIC THERMOMETRY FOR DETECTION AND QUANTIFICATION OF LEAKS IN DYKES

- **2D Hydrogeological model**
  - Conservation law on the piezometric head (~water pressure) coupled with the Richards' equation

$$[S_0 S(\psi) + \varepsilon \partial_\psi S(\psi)]\partial_t \psi = f_\mu \partial_x \left[K_h K(S(\psi))\partial_x \psi\right] + f_\mu \partial_x \left[K_v K(S(\psi))\partial_y (\psi + y)\right]$$

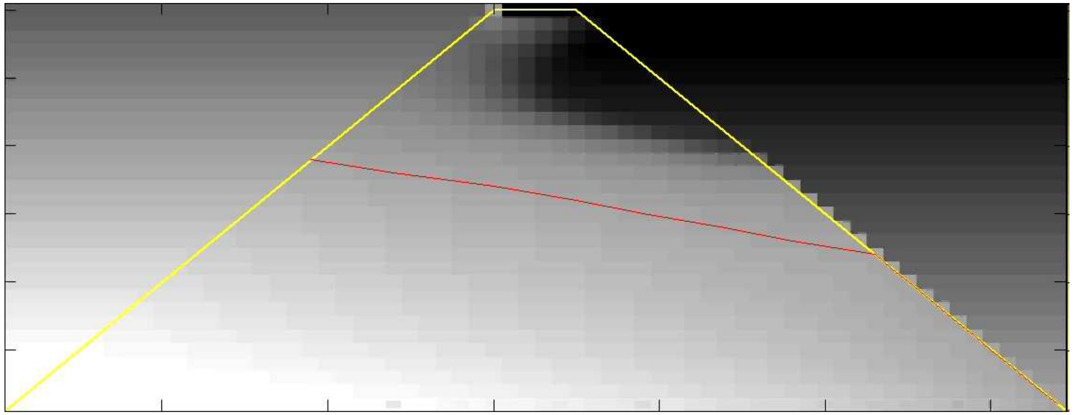
  - K_h and K_v horizontal and vertical permeabilities (different because of the soil compaction) and *K(S)* relative permeability function of the saturation (itself function of the piezometric head like Van Genuchten model)



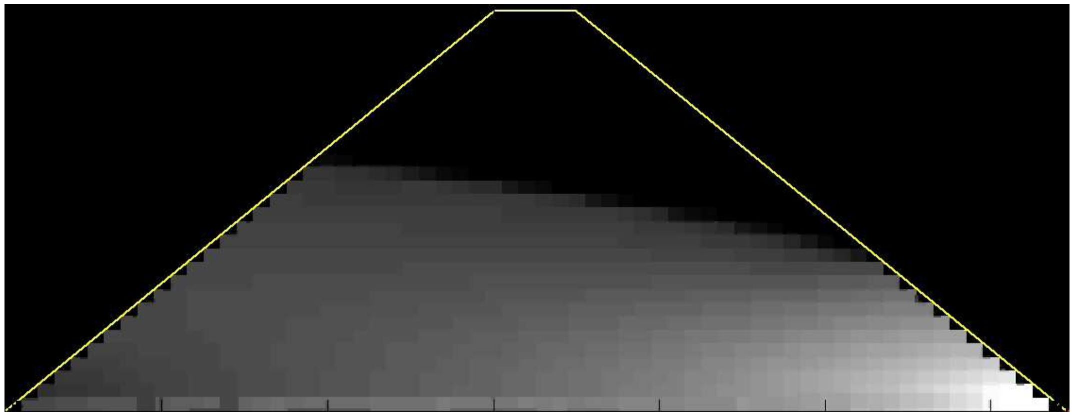
Saturation curves

FIBER OPTIC THERMOMETRY FOR DETECTION AND QUANTIFICATION OF LEAKS IN DYKES

- **2D Hydrogeological model**
  - Piezometric head at equilibrium



  - Horizontal velocity at equilibrium



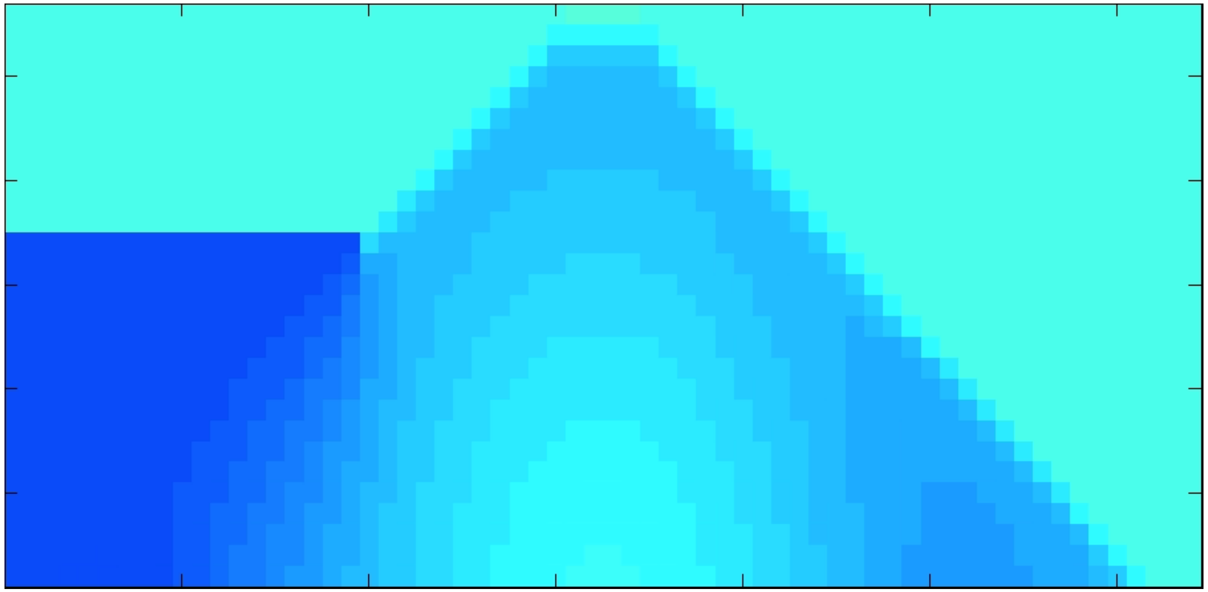
FIBER OPTIC THERMOMETRY FOR DETECTION AND QUANTIFICATION OF LEAKS IN DYKES

- **2D Thermal model**
  - Conservation law on the temperature coupled with the Fourier law

Thermal inertia — Leak velocity — Diffusion

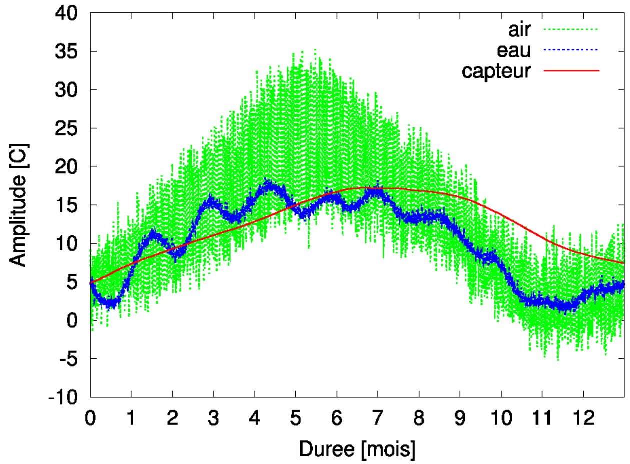
$$\left(\varepsilon S(\psi)(\rho C)^{w}+(1-\varepsilon)(\rho C)^{m}\right)\partial_t T+(\rho C)^{w}\vec{v}.\vec{\nabla}T=div\left(\Lambda\vec{\nabla}T\right)$$

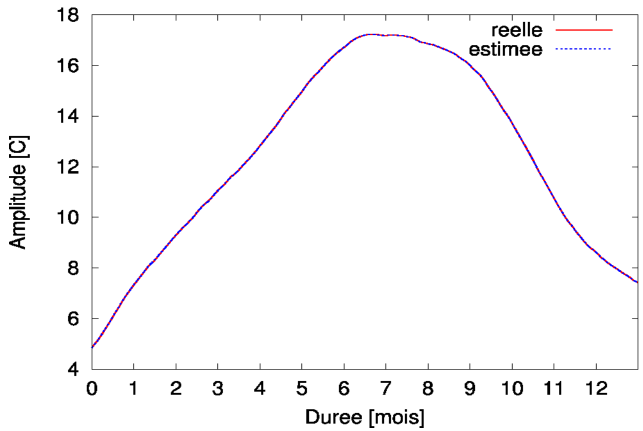
  - 2D model used for simulation and comparison with the 1D case in estimation

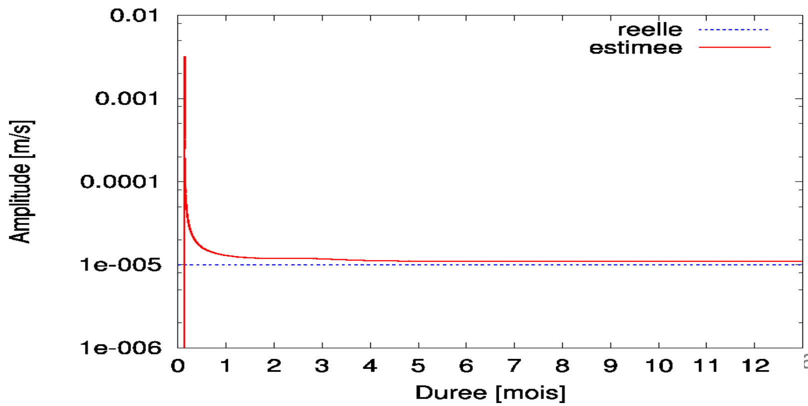


FIBER OPTIC THERMOMETRY FOR DETECTION AND QUANTIFICATION OF LEAKS IN DYKES

- **Leak velocity estimation**
  - First method: Extended Kalman Filter (EKF) on a 1D thermal model
    - Simultaneous reconstruction of the temperature on a current line of the 2D hydrogeological model and of the leak velocity: pertinent for quite important velocities



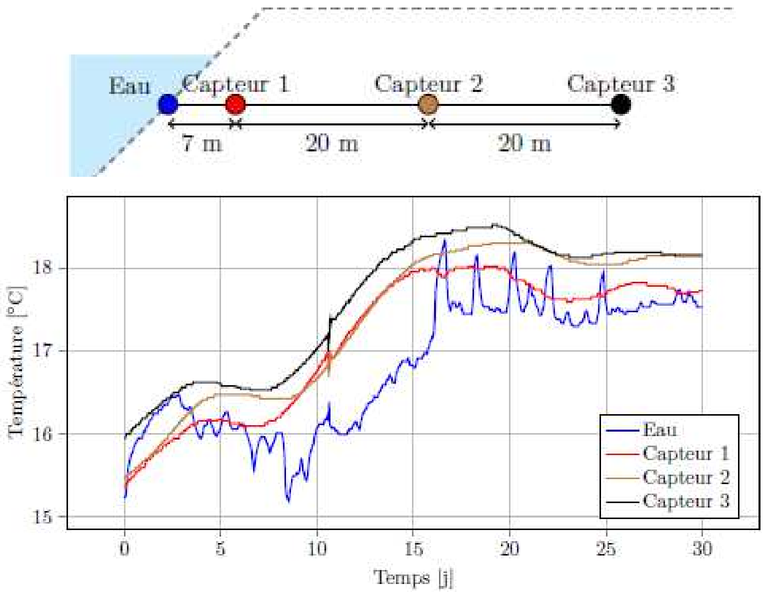




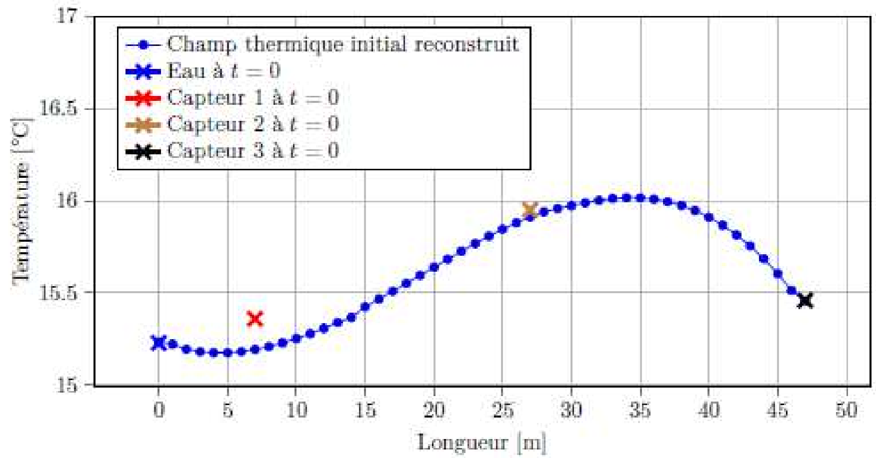
Example on synthetic data

FIBER OPTIC THERMOMETRY FOR DETECTION AND QUANTIFICATION OF LEAKS IN DYKES

- **Leak velocity estimation**
  - Second method: Extended Kalman Filter (EKF) on a 1D thermal model with initial condition estimation
    - First step: For a given initial condition simultaneous reconstruction of the temperature on a current line of the 2D hydrogeological model and of the leak velocity
    - Second step: Application of a Kalman smoother to take in account the information in the future, update of the initial condition. Goto the first step until convergence
    - This method allows to deal with weaker leak velocities
  - Third method: Optimization on a time interval, simultaneous estimation of initial condition and leak velocity, optimal control-like algorithm (adjoint problem)



Initial temperature estimation

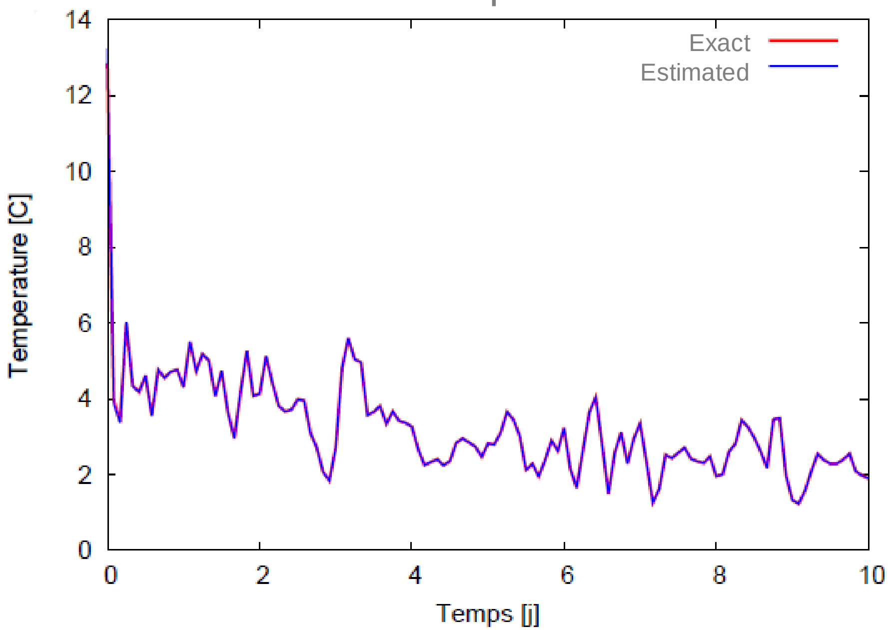


FIBER OPTIC THERMOMETRY FOR DETECTION AND QUANTIFICATION OF LEAKS IN DYKES

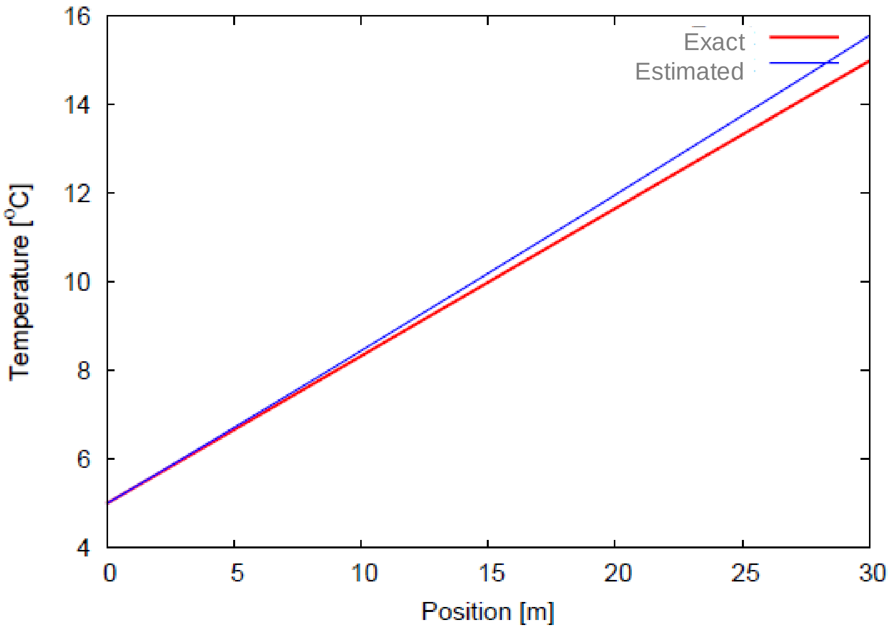
- **Leak velocity estimation**
  - Fourth method: Stochastic algorithm – Particle Swarm Optimization
    - P_i : best particle position
    - P_g : best position among the best particle positions

$$
\begin{aligned}
V_i^{k+1} &= \omega V_i^k + b_1 \left(P_i - \beta_i^k\right) + b_2 \left(P_g - \beta_i^k\right) \\
\beta_i^{k+1} &= \beta_i^k + V_i^{k+1},
\end{aligned}
$$

Sensor temperature



Initial temperature profile



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FIBER OPTIC FOR DETECTION OF DISTRIBUTED DEFORMATIONS IN DYKES

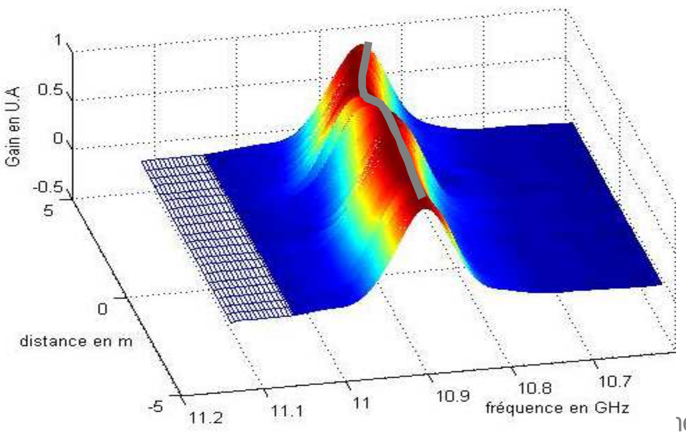
- **EDF context**
  - Always with the dykes, one other main subject of monitoring is the evolution of the ground
  - One major problem is the existence of sinkholes (kind of cavity) which can collapse, especially in clay soils

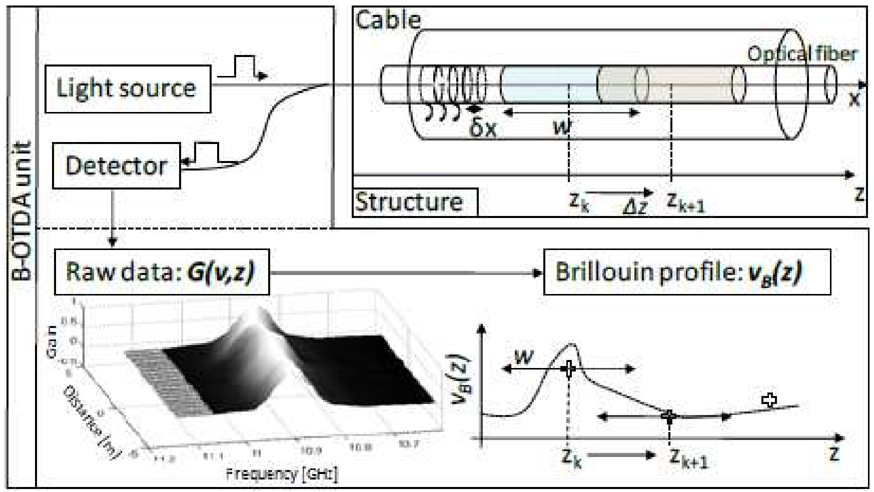
- **EDF objective**
  - EDF searches for a continuous measurement capable of “seeing” distributed deformations
  - The only way to make this distance-along deformation measurement is also using the fiber optic

FIBER OPTIC FOR DETECTION OF DISTRIBUTED DEFORMATIONS IN DYKES

- **Measuring deformation with fiber optic : how does it work ?**
  - Two effects are sensible to the deformations, Brillouin and Rayleigh:
    - Brillouin effect induces a frequency shift which is proportional to the deformation.
    - Rayleigh effect induces an amplitude modification
    - These two effects depend also on temperature. An unmixing can be necessary.

- **Technology principles**
  - The Brillouin devices are based on Stimulated Brillouin Scattering
    - An interrogator sends a laser pulse beam at one end of the fiber optic and analyses the backscattered light. This Brillouin effect measurement is called Optical Time-domain Analysis. The device estimates a frequency spectrum from which it extracts the shift of the maximum.





FIBER OPTIC FOR DETECTION OF DISTRIBUTED DEFORMATIONS IN DYKES

- **Technology principles (followed)**
  - The Rayleigh devices exploit Optical Time-domain Reflectometry or Optical Frequency-domain Reflectometry: a frequency sweep is sent in the fiber optic and the scattering is correlated with the sweep to obtain the information. EDF uses OFDR.
  - Brillouin sensor is efficient on several kilometers with an half-meter resolution whereas Rayleigh sensor is efficient only on only one hundred meters.
  - Question: how getting more resolution from Brillouin devices in areas where deformation changes ?

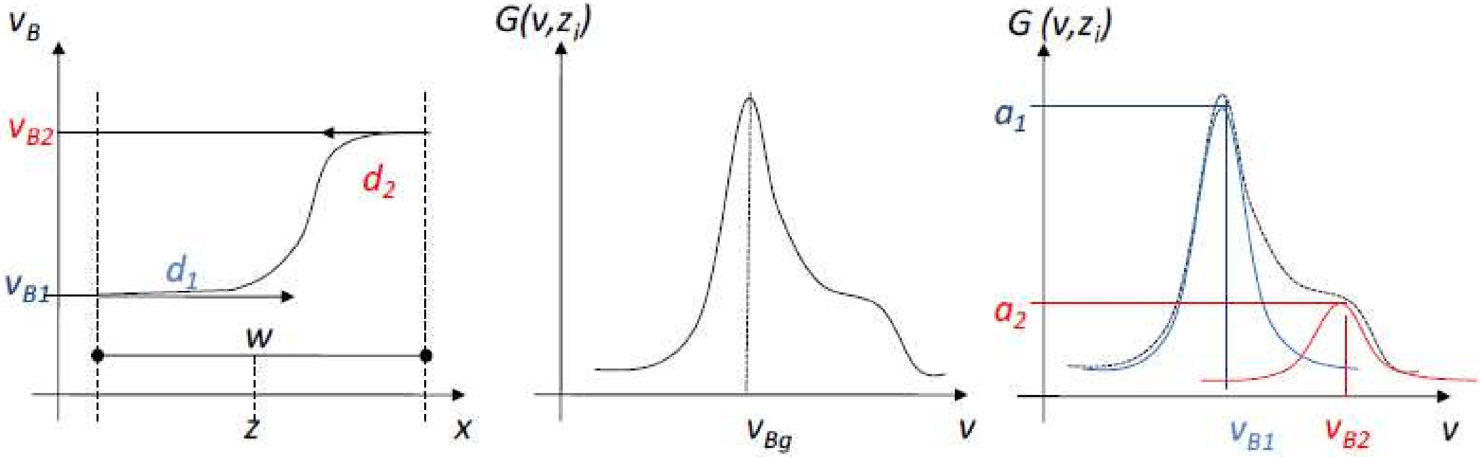
- **Improvement of the Brillouin resolution measurement**
  - Framework: thesis with the Gipsa-lab (E. Buchoud, director: J.I. Mars)
  - Guidelines:
    - Measurement:
      - On each position *x*, the Brillouin fiber optic response is an elementary spectrum (S_e) centered on a given frequency ($v_B(x)$).
      - The measured information is the integration of these elementary spectra on one meter long, with an overlapping of about one half-meter.

$$\tilde{G}(v, z_k) = \int_{z_k - w/2}^{z_k + w/2} S_e(v - v_B(x))dx$$

FIBER OPTIC FOR DETECTION OF DISTRIBUTED DEFORMATIONS IN DYKES

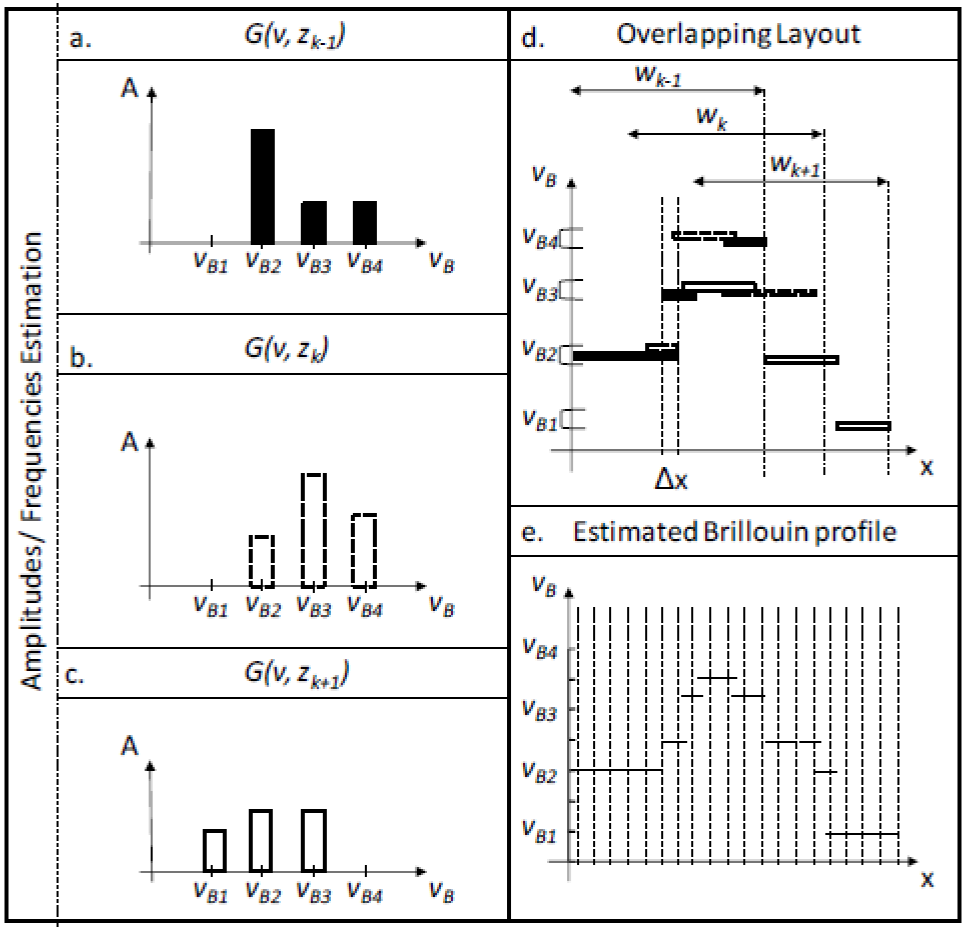
- **Improvement of the Brillouin resolution measurement**
  - Guidelines (followed):
    - Signal processing:
      - The main hypothesis is that the deformation is piecewise-constant
      - Separation of the elementary spectra (S_e) knowing the theoretical shape of this spectrum and using a nonnegative least-squares method or a nonnegative source separation algorithm
      - An heuristic has been developed to exploit the parameters of the mixing (amplitudes and central frequencies of the spectra) to extrapolate the deformation information
      - A classical inverse problem with regularization is also tested with good results

$$\tilde{G}(v, z_k) = \delta x . \sum_{j=1}^{P} a_j . S_e(v - v_{Bj})$$



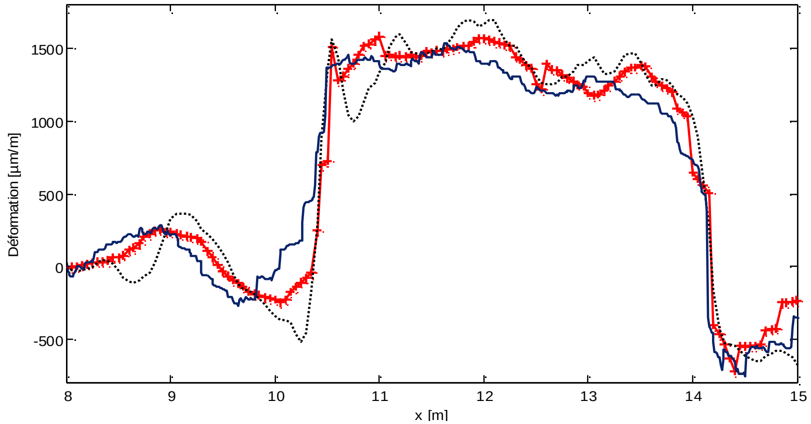
FIBER OPTIC FOR DETECTION OF DISTRIBUTED DEFORMATIONS IN DYKES

- **Description of the heuristic méthod**

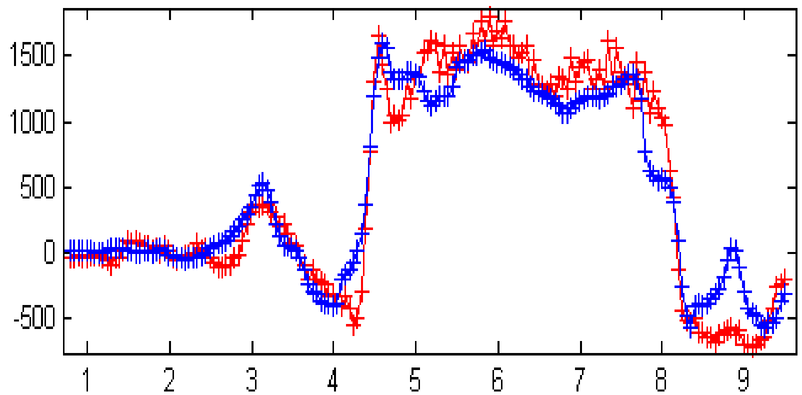


FIBER OPTIC FOR DETECTION OF DISTRIBUTED DEFORMATIONS IN DYKES

- **Results: comparison with the Rayleigh measurement**
  - Heuristic method
    - Heuristic: red and blue (depends on signal decomposition method)
    - Rayleigh: black



  - Inverse problem



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RADAR SATELLITE INTERFEROMETRY FOR DISPLACEMENTS MEASUREMENT

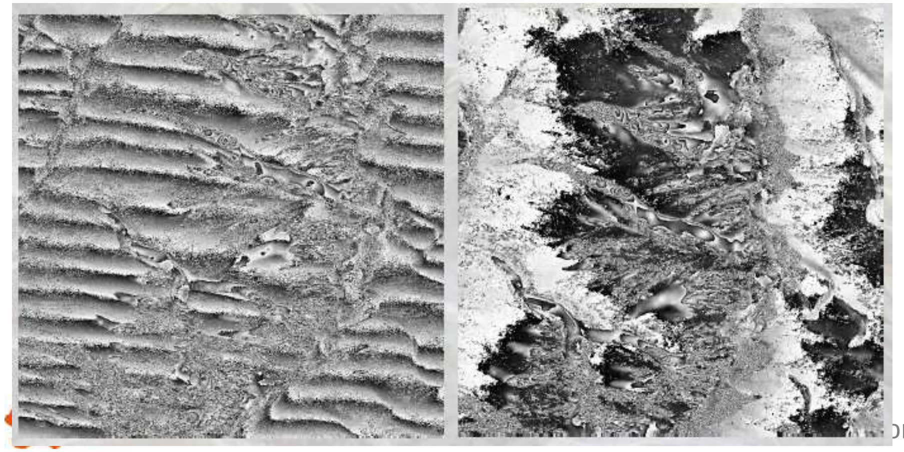
- **EDF context**
  - The dams present two sorts of displacement:
    - reversible: due to temperature, water height, seasonality
    - irreversible: due to ground movements, ageing, …
  - The dykes present also a irreversible component
  - The question is to be able to measure the global displacement. Then, by signal processing, it is possible to extract the irreversible component
  - The current measurement system consists in pendulums which are in the dams and whose data are read every year.
  - Topometric tests are also made.
  - A collaboration with the Gipsa-lab is done (G. Vasile) through a thesis in particular

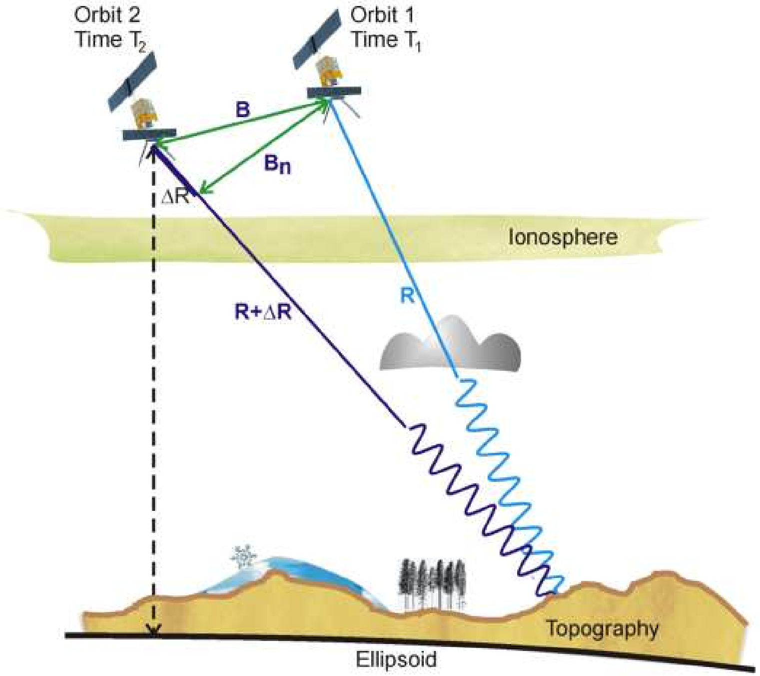
- **EDF objective**
  - The question is to be able to measure the displacement more frequently.
  - The proposal is by using radar satellite interferometry which can moreover carry out a better precision.

RADAR SATELLITE INTERFEROMETRY FOR DISPLACEMENTS MEASUREMENT

- **Radar Satellite Interferometry: principles**
  - Two synthesis aperture radar (SAR) satellites (e.g. TerraSAR-X) emit plane waves on the same point with slightly different positions: the two beams interfere and the resulting complex signal is measured.
  - Several effects modify the phase difference which have to be eliminated to get the interesting information:
    - Orbital correction
    - Atmospheric turbulences
    - Noise
    - Topographic effect

$$\Delta\Phi = \Phi^{orb} + \Phi^{topo} + \Phi^{depl} + \Phi^{atm} + \Phi^{bruit}$$





RADAR SATELLITE INTERFEROMETRY FOR DISPLACEMENTS MEASUREMENT

- **Signal processing**
  - The objective is to detect permanent scatterers in the image: the displacement measurement is based on the computation of the displacement estimation of these points
  - The processing is based on a statistical point of view of the image: the image is a mixing of a complex texture (the clutter) is seen as a realization of a density of probability (Spherical Independent Random Vector) and of punctual variations (the permanent scatterers)
  - A hypothesis test is performed to detect if a point belongs to the clutter (hypothesis H_0) or is a sum of a target vector and the clutter (hypothesis H_1)

$$\begin{cases} H_0 : \mathbf{k} = \mathbf{c} \\ H_1 : \mathbf{k} = \alpha\mathbf{p} + \mathbf{c} \end{cases}$$

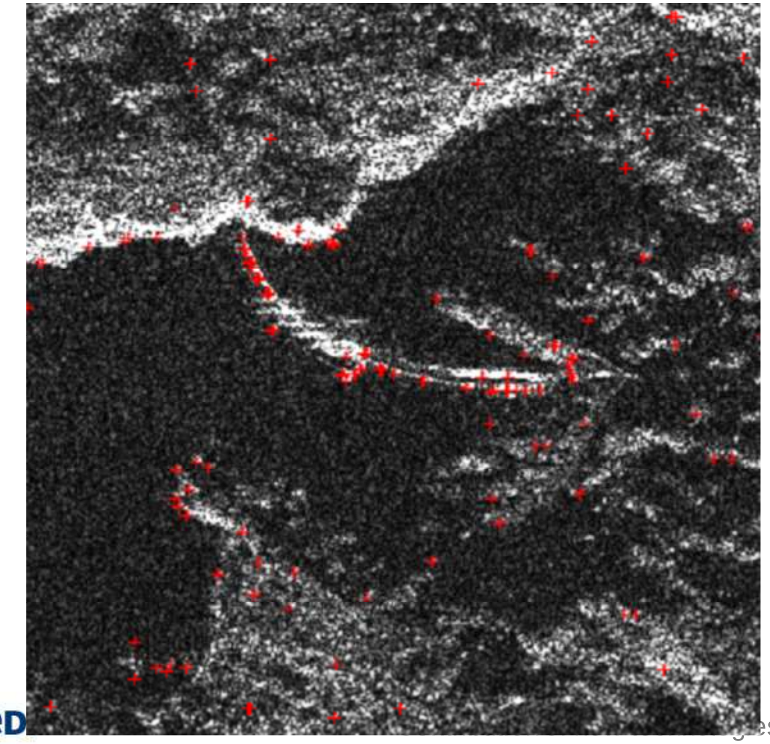
$$\Lambda([M]) = \frac{p_{\mathbf{k}}(\mathbf{k}/H_1)}{p_{\mathbf{k}}(\mathbf{k}/H_0)} = \frac{h_p\left((\mathbf{k}-\mathbf{p})^H [M]^{-1} (\mathbf{k}-\mathbf{p})\right)}{h_p\left(\mathbf{k}^H [M]^{-1} \mathbf{k}\right)} \underset{H_0}{\overset{H_1}{\gtrless}} \lambda$$

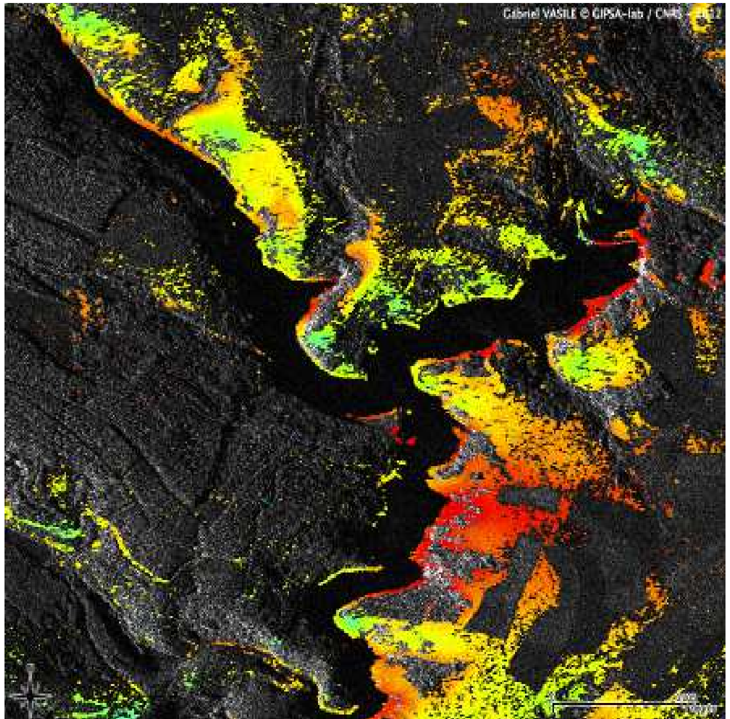
$$\Lambda([M]) = \frac{|\mathbf{p}^H [M]^{-1} \mathbf{k}|^2}{(\mathbf{p}^H [M]^{-1} \mathbf{p})(\mathbf{k}^H [M]^{-1} \mathbf{k})} \underset{H_0}{\overset{H_1}{\gtrless}} \lambda$$

RADAR SATELLITE INTERFEROMETRY FOR DISPLACEMENTS MEASUREMENT

- **Example on the Barrage of Puylaurent**
  - Detection of Permanent Scatterers
  - Displacement field computation

- **SAR in X band also useful for estimating snow water equivalent (thesis with Gipsa-lab, N. Besic, director: G. Vasile)**





THANK YOU FOR YOUR ATTENTION
ANY QUESTION ?