Transmission des mesures d'un réseau de capteurs environnementaux en bande ISM. Une approche semilogicielle

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Context and Objectives

✓ Context

– Need from the French public institution involved in the Earth Science field

- Automatic Water quality monitoring

✓ Current application limitations

– data loggers requiring manual downloading

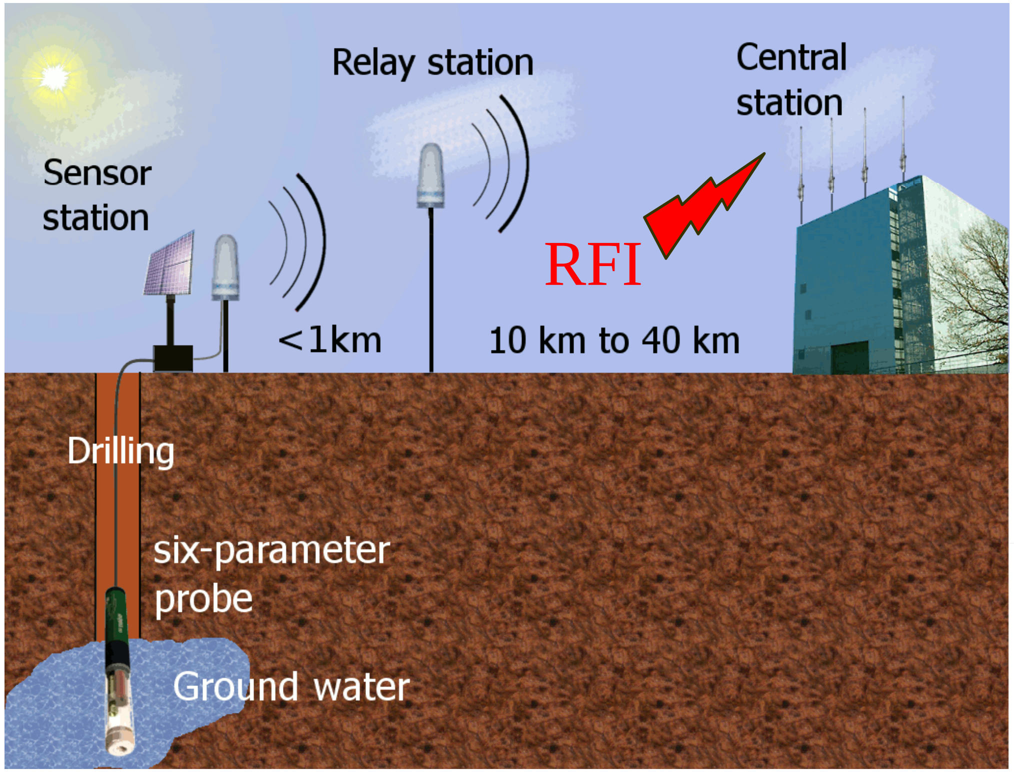
– No « real time » sampling (e.g. monthly)

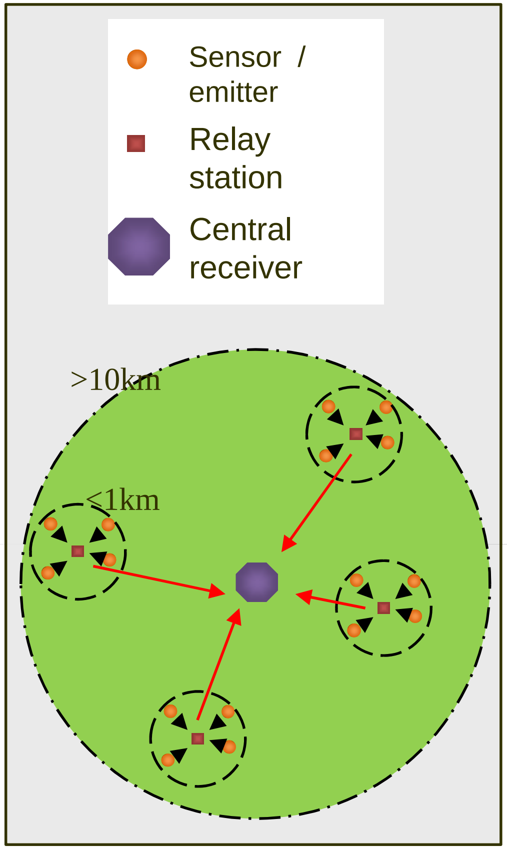
✓ Objectives

– Design of a remote sensor network :

- Autonomous low cost sensors
- Central receiver in a urban area (radio frequency interference)
- Emitter/Receiver range >10 km
- Daily sampling
- free Band (no fees)

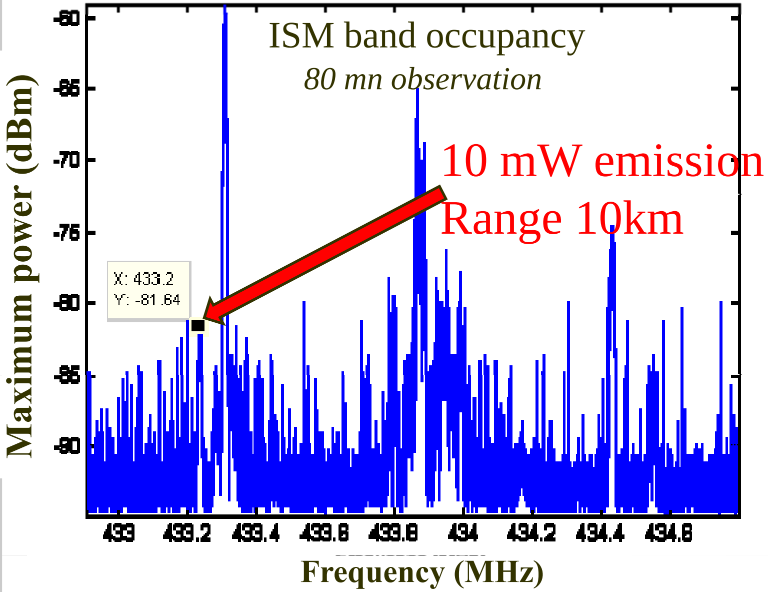
Sensor network characteristics

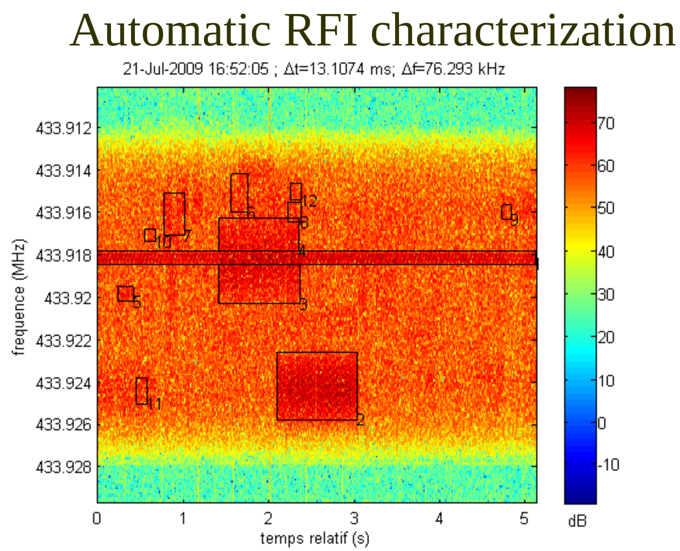




- ✓ **RF transmission**
  - BPSK (ISM band at 433MHz, baud rate=1200 bit/s)
  - TDMA

RFI monitoring in the 433MHz band





n°, when	f_0 (MHz)	RFI per hour	ΔT (s)	ΔF (kHz)
1, day	433.92	5277	0.3	1.6
2, night	433.92	4549	0.36	1.58
3, day	434.2	2864	0.28	1.31
4, night	434.2	567	0.32	1.33

✓ **Results**

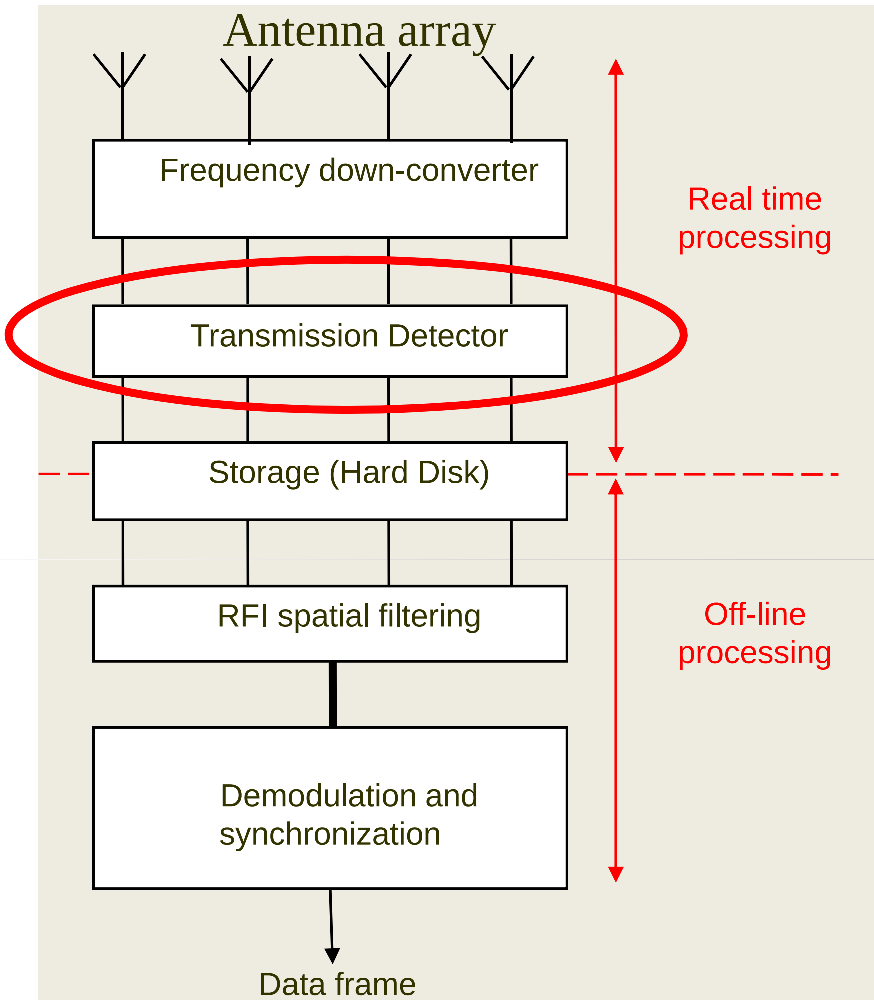
- High RFI occupancy
- 95% RFI < 1s
- Average duration *ΔT*: 30 ms
- Average bandwidth *ΔF*: ~1,3 kHz
- Low activity during the night

Our approach : selective acquisition and off-line processing

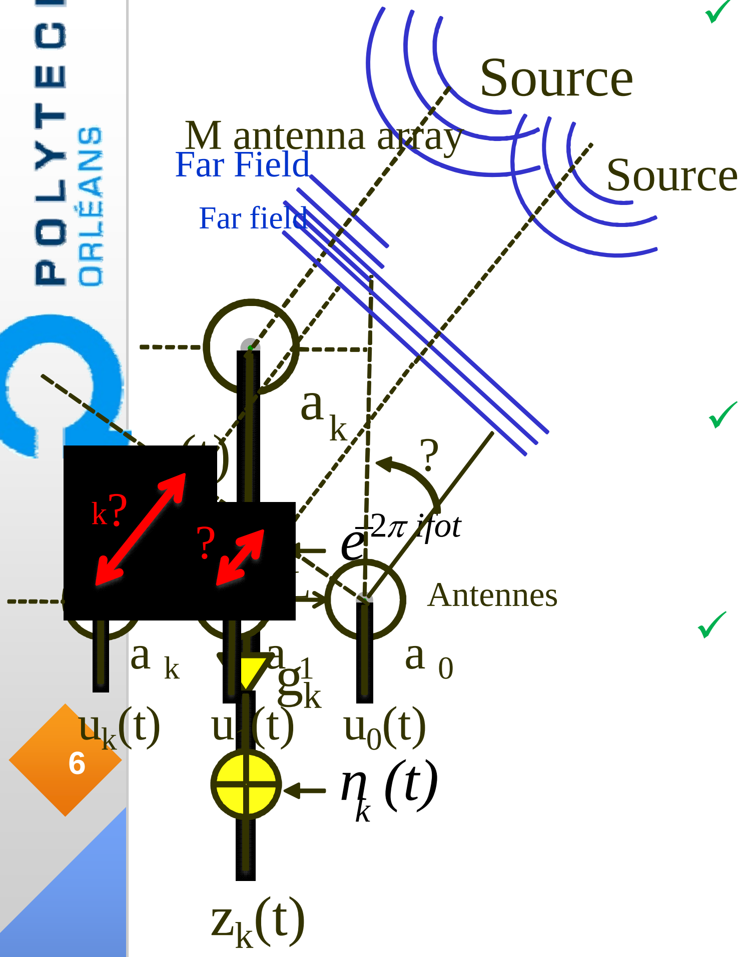
- ✓ **Specifications**
  - – Short data frame (<100ms)
  - – Daily transmission

→ Don't need a continuous reception

- ✓ **Concept**
  - – Selective acquisition by detecting sensor transmission
  - – Data waveform storage
  - – Antenna array for spatial processing



Antenna array model



✓ **Signal**

$$s(t)e^{i(2\pi fot+\varphi o)}$$

$$u_k(t) = s(t-k\tau)e^{i(2\pi fo(t-k\tau)+\varphi o)}$$

$$u_k(t) = s(t)e^{-i2\pi fok\tau+i\varphi o}e^{i2\pi fot}$$

✓ **antenna output**

$$z_k(t) = \underbrace{g_k e^{-i2\pi fok\tau+i\varphi_o}}_{a_{sk}} s(t) + n_k(t)$$

✓ **Antenna array model**

$$\mathbf{z}(t) = \underbrace{\begin{bmatrix} a_{s0} \\ \vdots \\ a_{sM-1} \end{bmatrix}}_{\text{source}} s(t) + \underbrace{\mathbf{a_r} r(t)}_{\text{RFI}} + \underbrace{\mathbf{n}(t)}_{\text{Noise}}$$

Hypothesis

Far field
range > 1km

Narrow band

$$\frac{\Delta fo}{fo} << 1$$

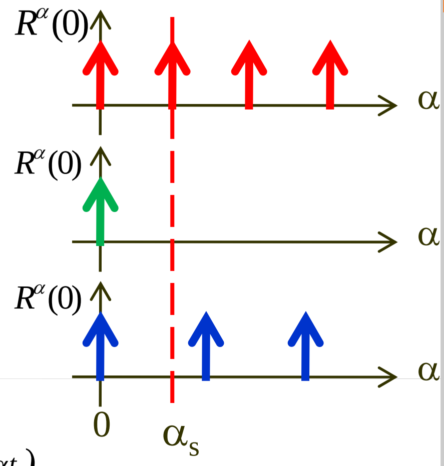
1 source s(t)
1 RFI r(t)

Cyclostationary detector (1)

Cyclic autocorrelation: $R^{\alpha}_{x,x*}(\tau) = E\left\{x(t+\frac{\tau}{2})x^*(t-\frac{\tau}{2})e^{-i2\pi\alpha t}\right\}$

✓ **Different cyclic signatures**

- Source (BPSK) $\alpha_s = \frac{k}{T_{sym}}$ ⟹ $R^{\alpha}_{s,s*} \neq 0$
  - Baud rate $1/T_{sym}$
- Noise = stationary ⟹ $R^{\alpha_s}_{n,n*} = 0$
- RFI $\alpha_r \neq \alpha_s$ ⟹ $R^{\alpha_s}_{r,r*} = 0$



✓ **Multidimensional case** $\mathbf{R}^{\alpha}_{z,z*} = E\left\{\mathbf{z}(t)\mathbf{z}^H(t)e^{-i2\pi\alpha t}\right\}$

$$\mathbf{R}^{\alpha}_{z,z*} = \mathbf{a_s}\underbrace{E\left\{ss^He^{-i2\pi\alpha t}\right\}}_{R^{\alpha}_{s,s*}}\mathbf{a_s}^H + \mathbf{a_r}\underbrace{E\left\{rr^He^{-i2\pi\alpha t}\right\}}_{R^{\alpha}_{r,r*}\to 0}\mathbf{a_r}^H + \underbrace{E\left\{\mathbf{nn}^He^{-i2\pi\alpha t}\right\}}_{R^{\alpha}_{n,n*}\to 0}$$

$\alpha = \alpha_s$

$$\mathbf{R}^{\alpha_s}_{z,z*} = \mathbf{a_s}\mathbf{a_s}^H R^{\alpha_s}_{s,s*}$$

Cyclostationary detector (2)

✓ **Detector criteria**

– Singular value decomposition $\mathbf{R}^{\alpha}_{z,z^*} = \left[r_{ij} \right] = \mathbf{U}_c \mathbf{\Lambda}_c \mathbf{V}_c^{\,H}$

- With $\alpha = \alpha_s$,asymptotically :

$$\Lambda_c = \begin{bmatrix} \lambda_s & & 0 \\ & 0 & \\ 0 & & 0 \end{bmatrix}_{\infty} \Longrightarrow \lambda_{max} \lessgtr \text{threshold}$$

Issue =>Real time implementation

– Frobenius norm

$$\left\| \mathbf{R}^{\alpha}_{z,z^*} \right\|_F^2 = \sum_{i=1}^{M} \sum_{j=1}^{M} \left| r_{ij} \right|^2 = \sum_{k=1}^{M} \left| \lambda_k \right|^2$$

- With $\alpha = \alpha_s$,asymptotically :

$$\left\| \mathbf{R}^{\alpha}_{z,z^*} \right\|_F^2 = \left| \lambda_s \right|^2 \Longrightarrow \left\| \mathbf{R}^{\alpha_s}_{z,z^*} \right\|_F^2 \lessgtr \text{threshold}$$

Simulations (1)

✓ Detector performance evaluation

– Hypothesis

- No transmission: H0 → $\mathbf{z}(t) = \sqrt{\rho}\mathbf{a}_{\mathbf{r}} r(t) + \sqrt{1-\rho}\mathbf{n}(t)$
- Transmission: H1→ $\mathbf{z}(t) = \sigma_s \mathbf{a}_{\mathbf{s}} s(t) + \sqrt{\rho}\mathbf{a}_{\mathbf{r}} r(t) + \sqrt{1-\rho}\mathbf{n}(t)$
- 4 detector criteria : ⇒
- SNR = σ^2_s

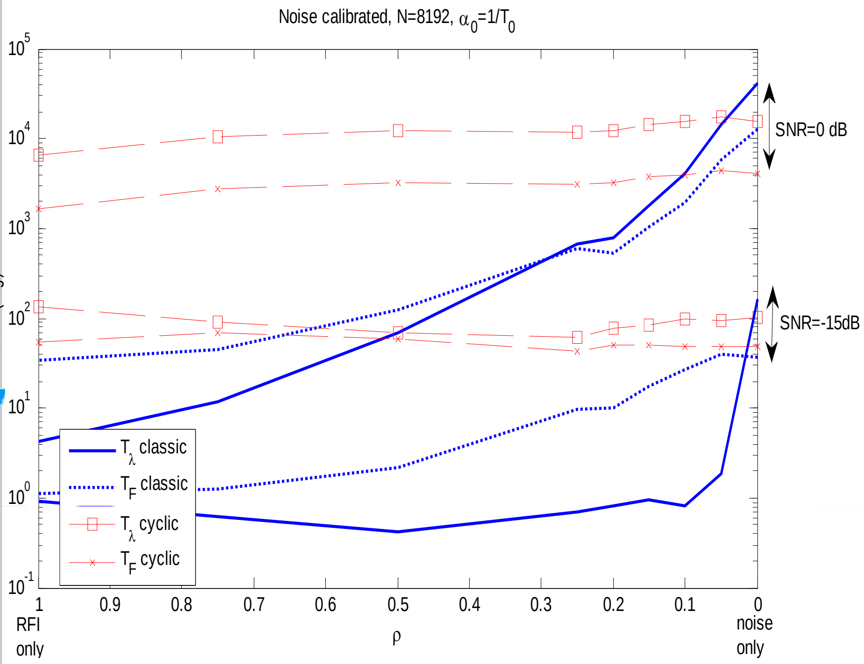
$T(\mathbf{z})$	$\mathbf{R}^{0}_{z,z^*}$	$\mathbf{R}^{\alpha_s}_{z,z^*}$
Dominant singular value	T_λ classic	T_λ cyclic
Frobenius Norm	T_F classic	T_F cyclic

– Performance criterion : Fisher criteria

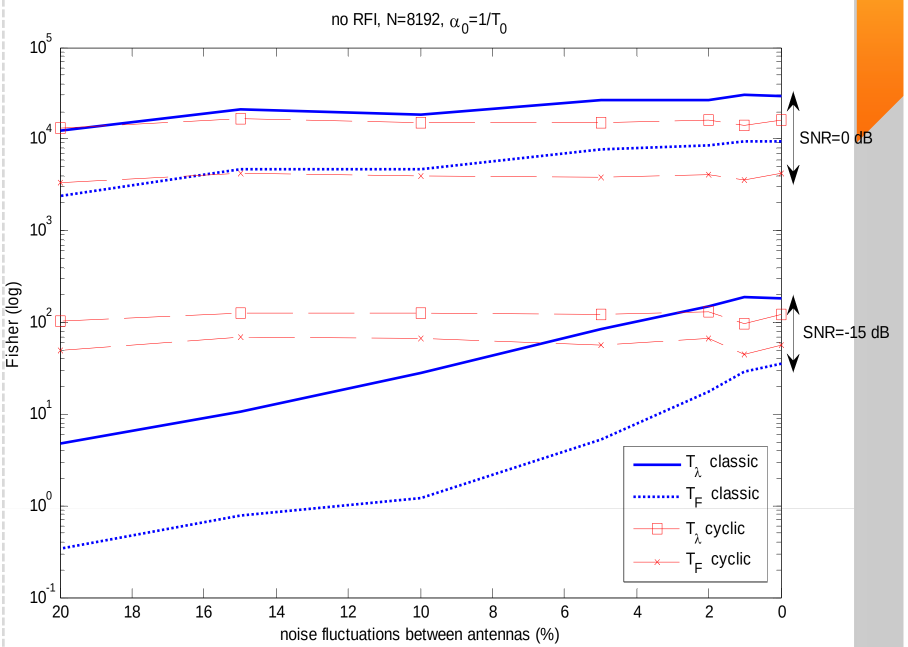
$$F = \frac{\left(E_{H1}\left[T(\mathbf{z})\right] - E_{H0}\left[T(\mathbf{z})\right]\right)^2}{Var_{H1}\left[T(\mathbf{z})\right] + Var_{H0}\left[T(\mathbf{z})\right]}$$

Simulations (2)

Scenario 1 : 1 RFI + calibrated noise



Scenario 2 : no RFI + uncalibrated noise



✓ **conclusions**

- In practice, $T_F < T_\lambda$ ⟹ $\left\| \mathbf{R}^{\alpha}_{z,z^*} \right\|_F^2 = \left| \lambda_s \right|^2 + \underbrace{\sum_{k=1}^{M} \left| \lambda_{N,k} \right|^2}_{\xrightarrow[N \to \infty]{} 0}$
- Cyclostationary detectors are robust

Filtrage spatial

- ✓ **Objectifs**
  - Focaliser le réseau
  - Annuler les brouilleurs

- ✓ **Méthode de Capon**
  - Puissance reçue

$$y(t) = \mathbf{w}^H \mathbf{z(t)}$$

$$P = \left\langle \left| y(t) \right|^2 \right\rangle_\infty = \mathbf{w}^H \mathbf{R} \mathbf{w}$$

  - Critère de Capon

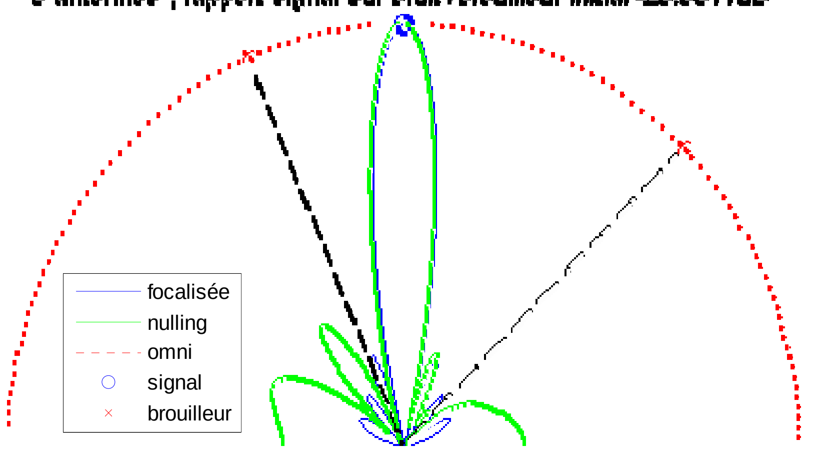
$$\min_w \mathbf{w}^H \mathbf{R} \mathbf{w}$$

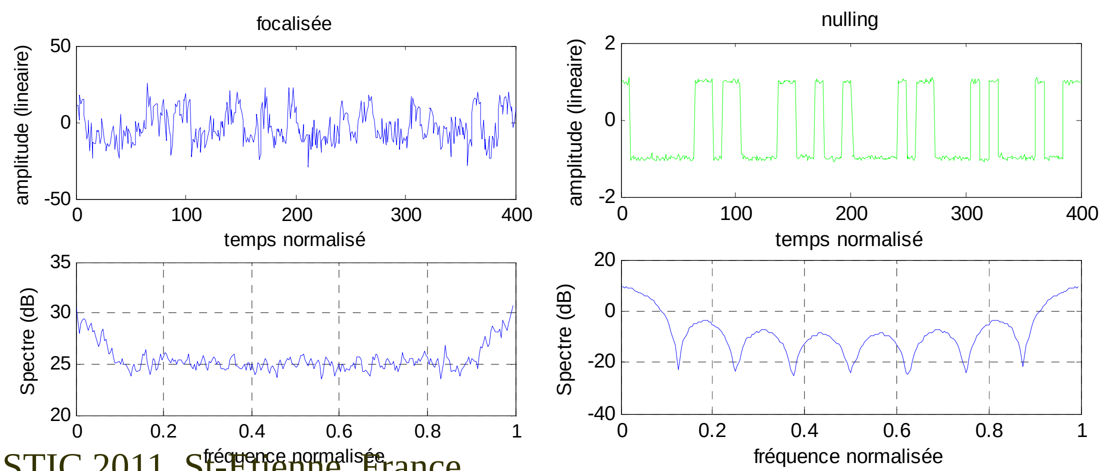
avec $\mathbf{w}^H \mathbf{a}_s = 1$

  - Solution

$$\mathbf{w}_o = \frac{\mathbf{R}^{-1} \mathbf{a}_s}{\mathbf{a}_s^H \mathbf{R}^{-1} \mathbf{a}_s}$$

Simulations

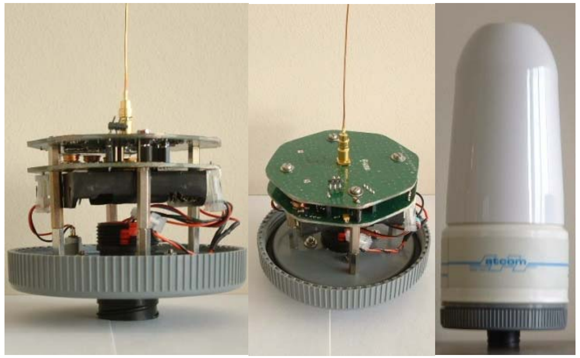


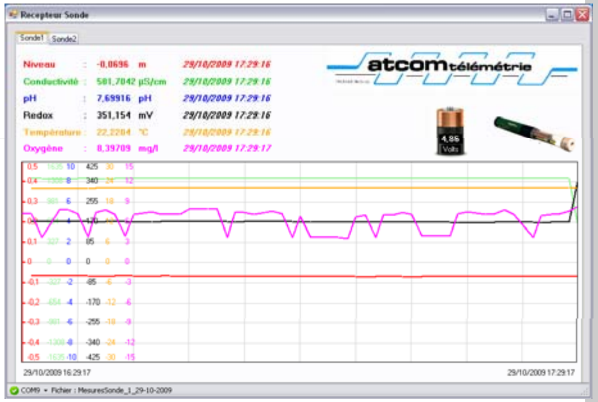


Conclusions and perspectives (1)

✓Cyclic approach is robust against RFI and uncalibrated array

✓Sensor emitter and relay station have been designed





✓Practical tests with simple receiver (no spatial processing) have shown that long range transmission are very difficult due to RFI

✓Next step : implementation of the proposed approach

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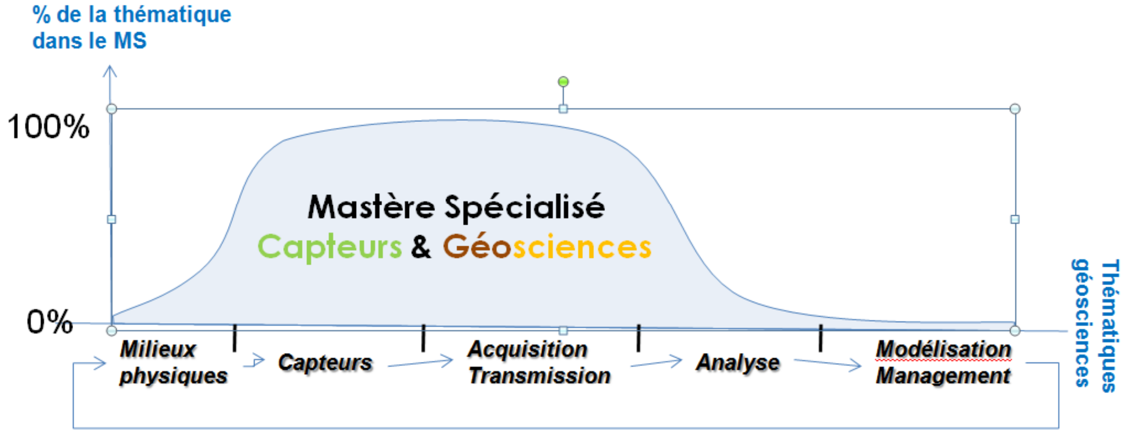

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