Correlations of electromagnetic noise

Julien de Rosny – Matthieu Davy – Luis Ruigger – Mathias Fink

A short introduction

Electromagnetism

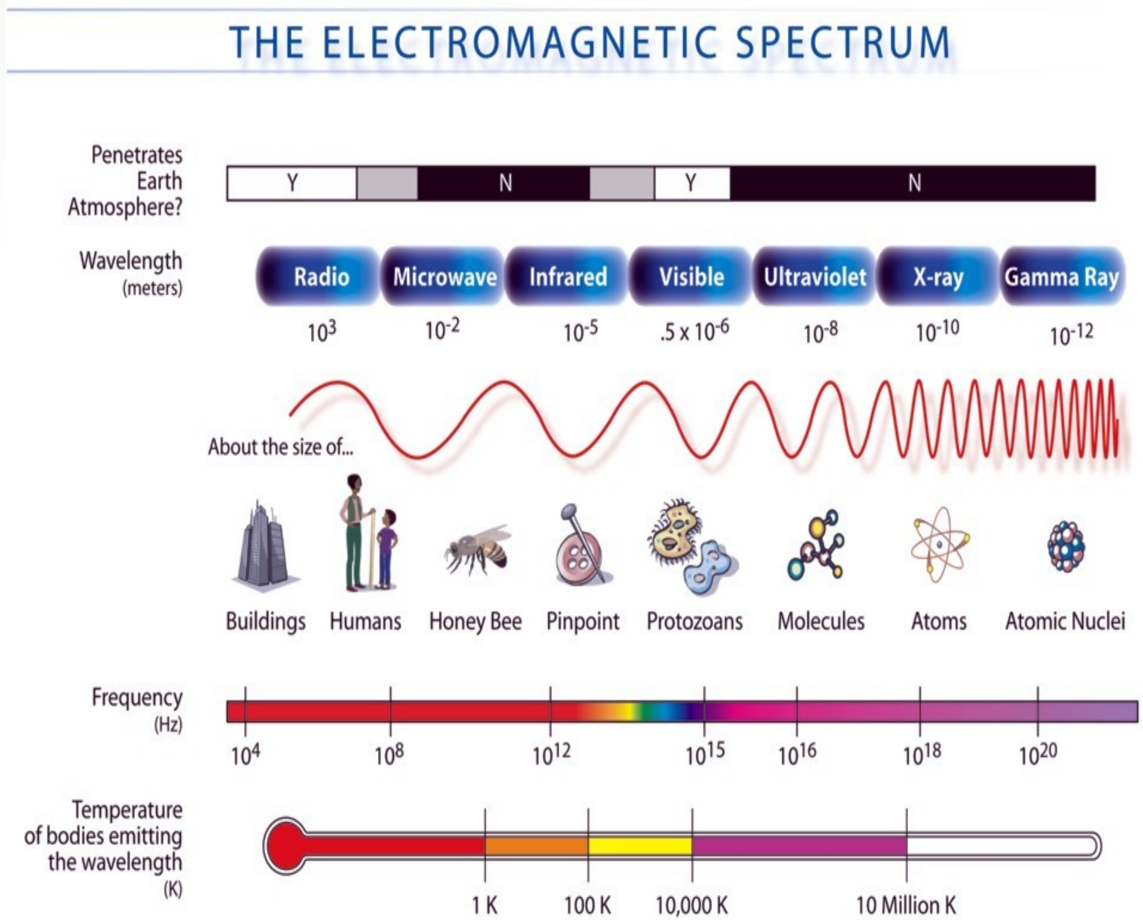
Electromagnetic force?
 * Interactions between moving charged particles (electrons, protons, …)
 * When charges are oscillating : interaction is a wave because of the coupling between magnetic and electric fields

Maxwell equations
E : Electric field
H : magnetic field

$$\nabla E = \frac{\rho}{\epsilon}$$
$$\nabla H = 0$$
$$\nabla \times E = -\mu \partial_t H$$
$$\nabla \times H = J + \epsilon \partial_t E$$

ε :Permittivity
M : Permeability

Coupling → wave
$c = 1/\sqrt{(\mu \epsilon)}$



Source : NASA

Polarizations : Vertical – Horizontal – circular Left and Right
No longitudinal wave

Main sources of noise

- Artificial ones :
  - Long range TV and Radio broadcast
  - Short range Cell Phone (GSM-2G-3G-4G) – WIFI
- Natural ones :
  - Cosmic noise (30MHz-> 300GHz)
  - Atmospheric noise (30kHz->30MHz) Ionosphere
  - Thermal radiation of solids

Overview of the talk

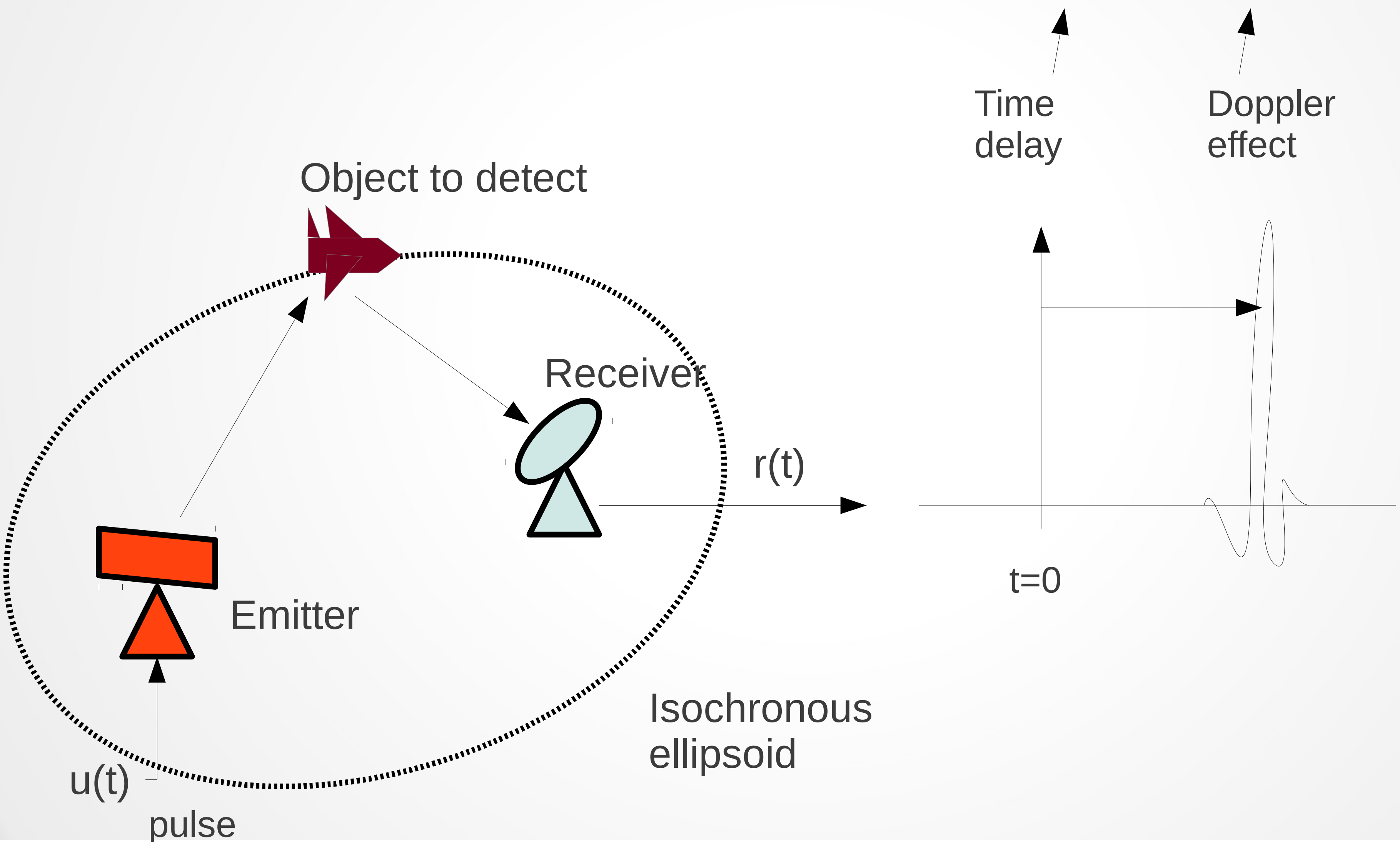
1) Bistatic RADAR using illuminators of opportunity
2) WiFi Imaging
3) Cross-correlations in reverberating media
4) Cross-correlations of thermal noise in cavities

Bistatic noise detection

Active Bistatic Radar

Controlled source (pulses – sweep - ...)

$$\varphi(\tau,\delta f)=\int u(t)\,r(t-\tau)\exp(-i\,2\pi\,\delta f\,t)\,dt$$



Active Bistatic Radar

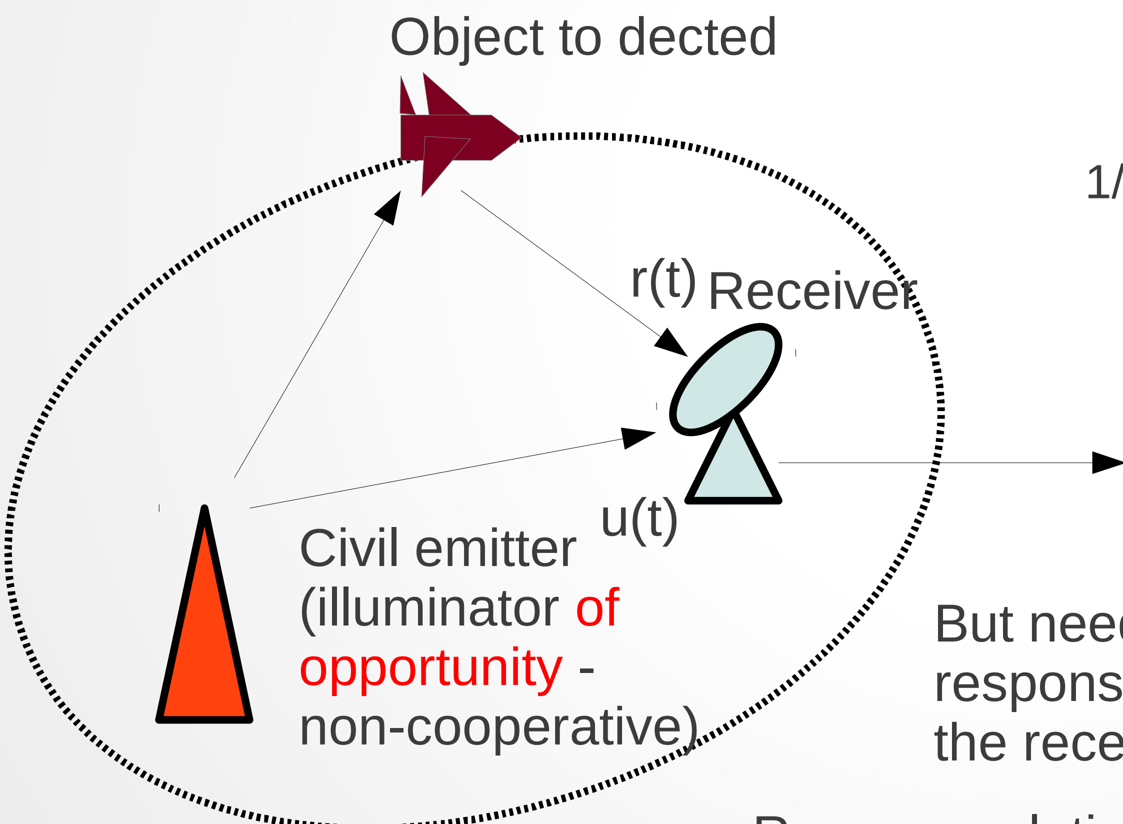
Noise sources (TNT, FM, GSM, ...)

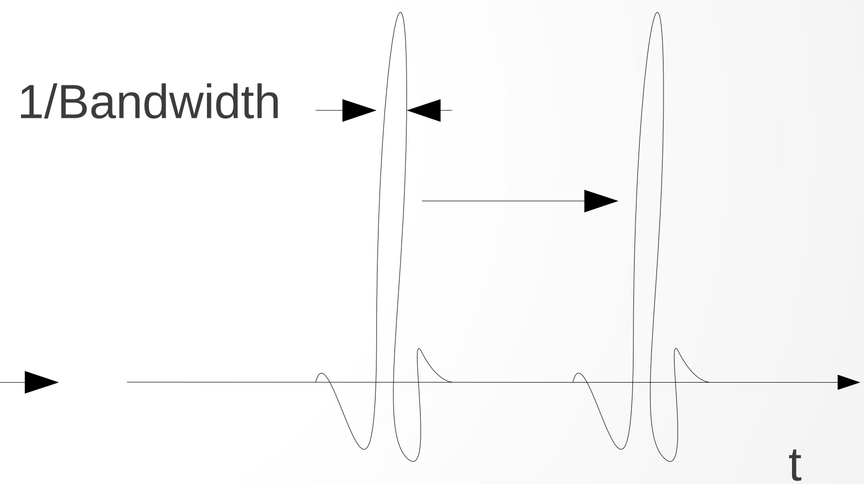
Correlation with doppler effect

$$\varphi(\tau,\delta f)=\int u(t)\,r(t-\tau)\exp(-i\,2\pi\,\delta f\,t)\,dt$$

Time delay

Doppler effect

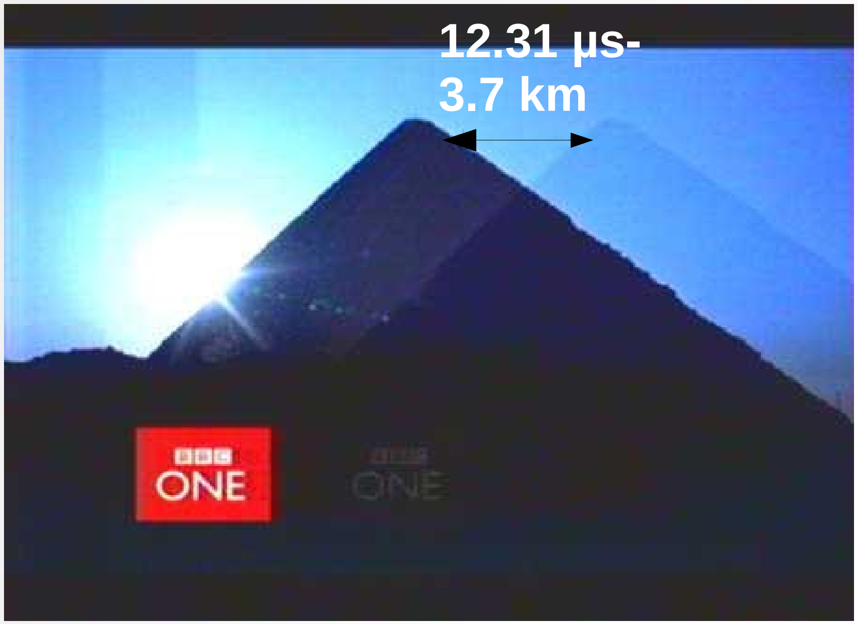


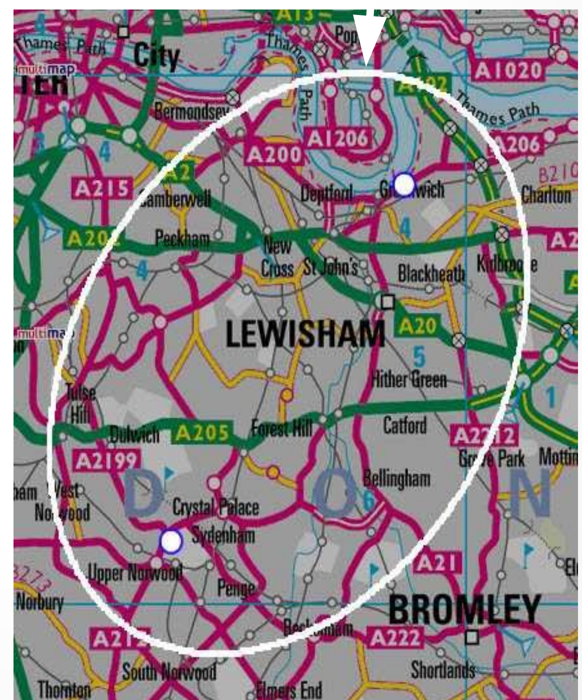


But need to estimate the direct response between the emitter and the receiver

Range resolution ~ c_0/B

Ghost effect





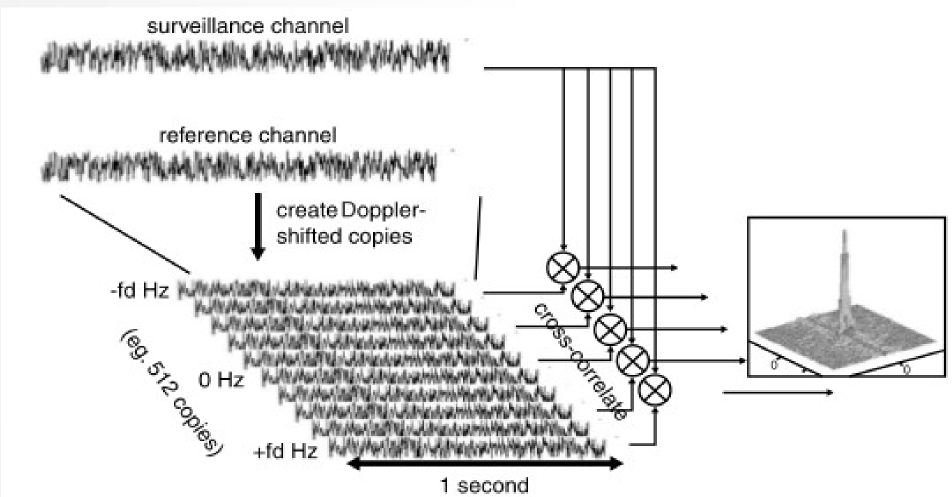
Analog TV
470-790 MHz
Reflections on buildings

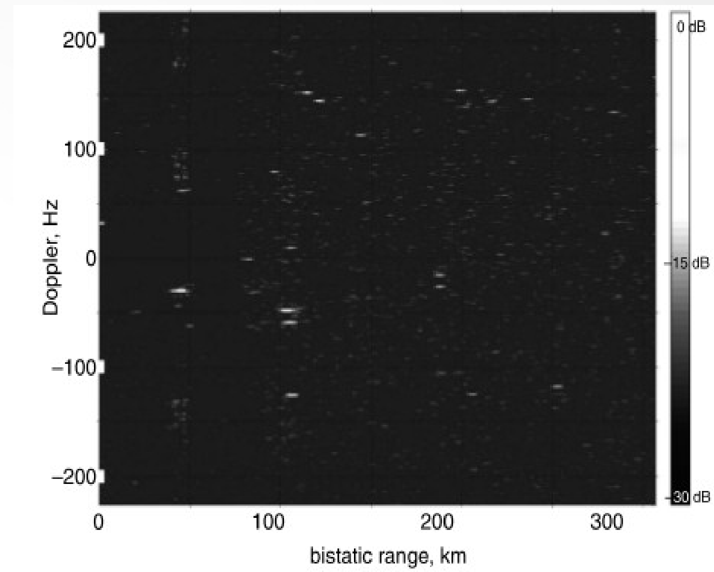
Source:http://www.frisnit.com/radar/

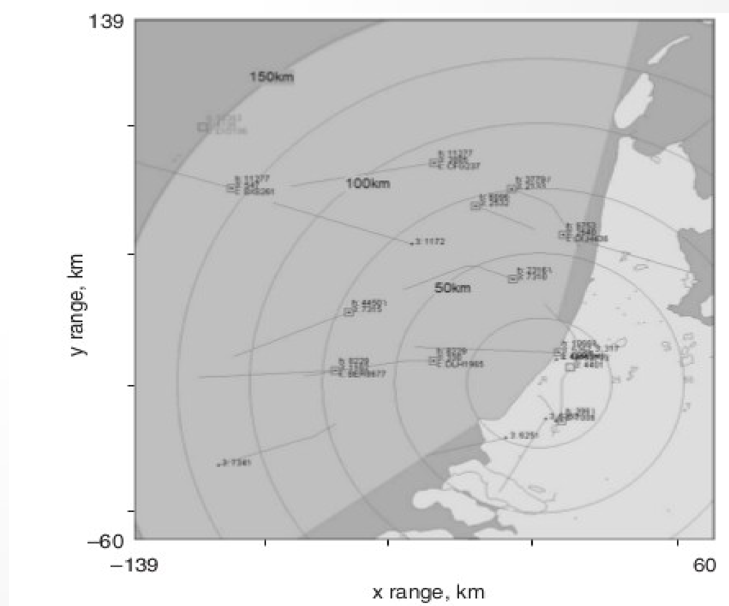
Application to aircraft detection

PE Howland, D Maksimiuk, G Reitsma - … -Radar, Sonar and Navigation, 2005 - IET

Illuminator of opportunity
FM emitter





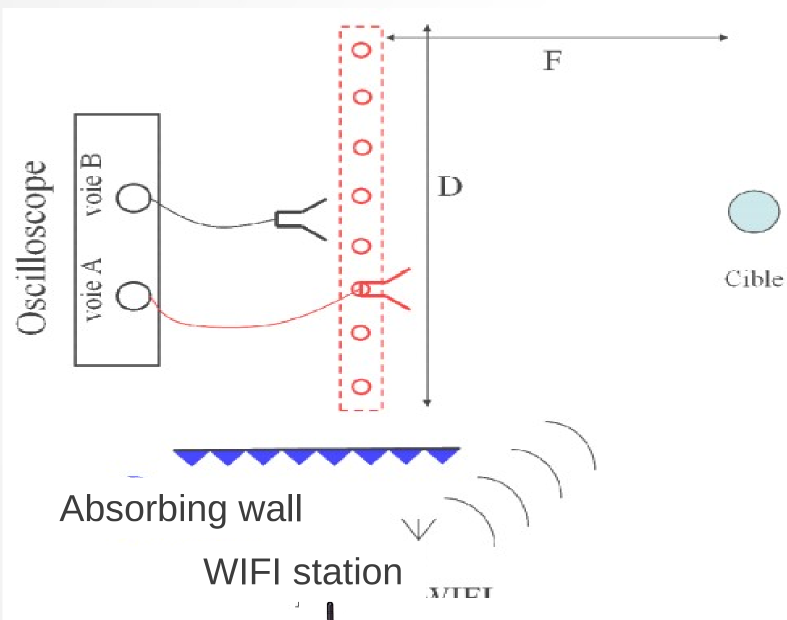


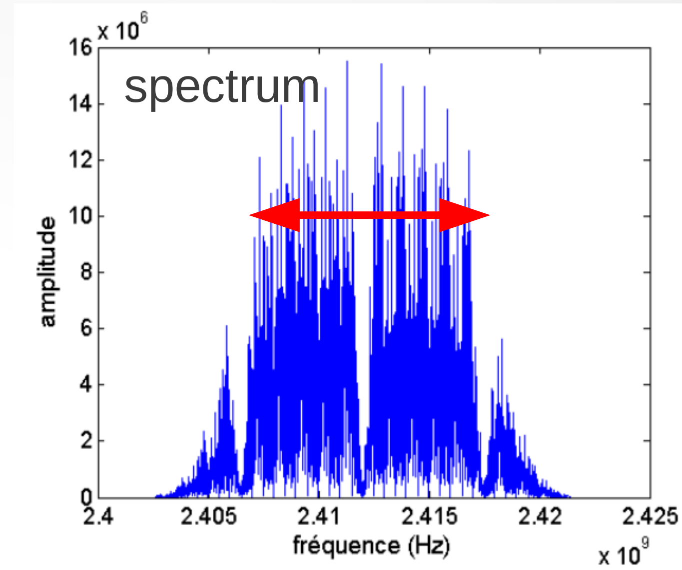
Resolution : 100kHz bandwidth → 1.5km

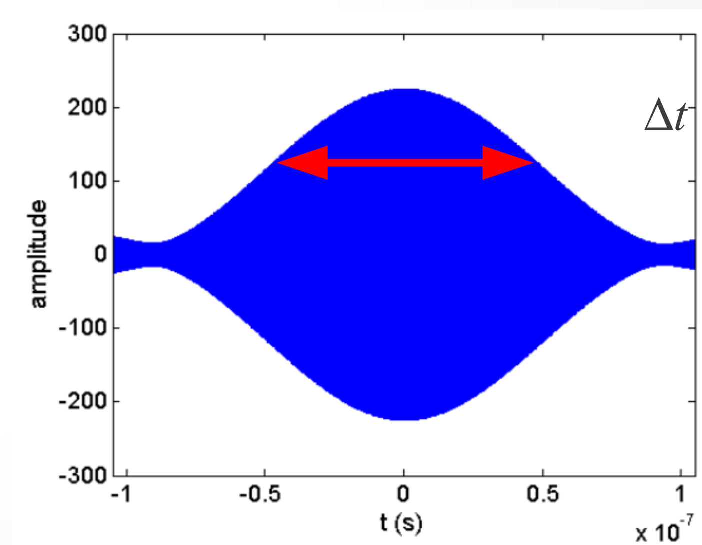
Multistatic passive RADAR with source of opportunity

Multistatic passive detection

Wide-band – directive and vertically polarized antenna







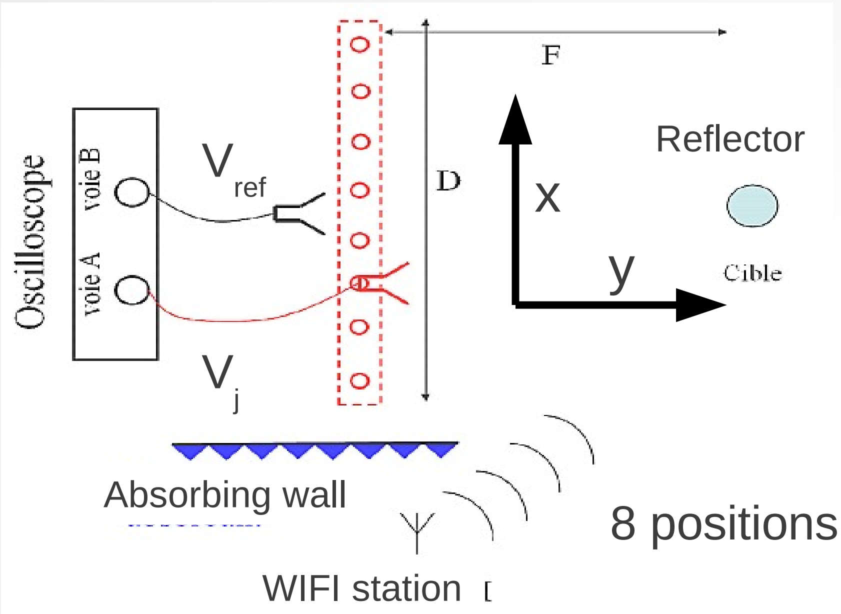
Δt =0.1µs

Range resolution : $\Delta t/2c$ = 15 m

M. Davy PhD

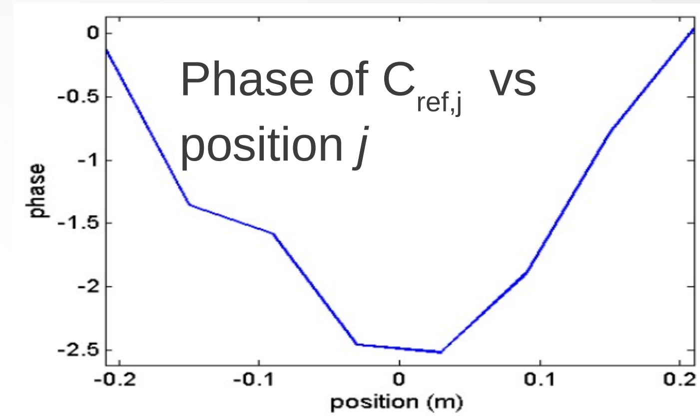
→ Monochromatic detection at indoor scale

Multistatic passive detection



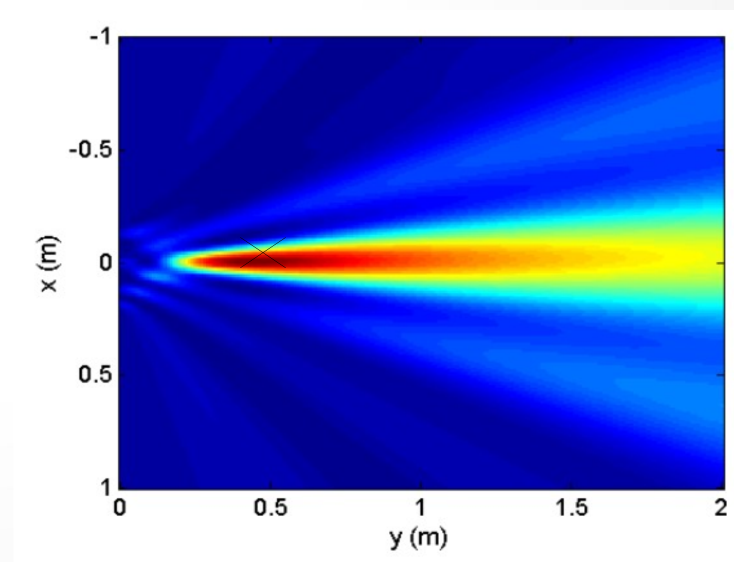
$C_{ref,j}$=<V_{ref} V_j*>

Cross-correlations averaged over 10000 acquisitions



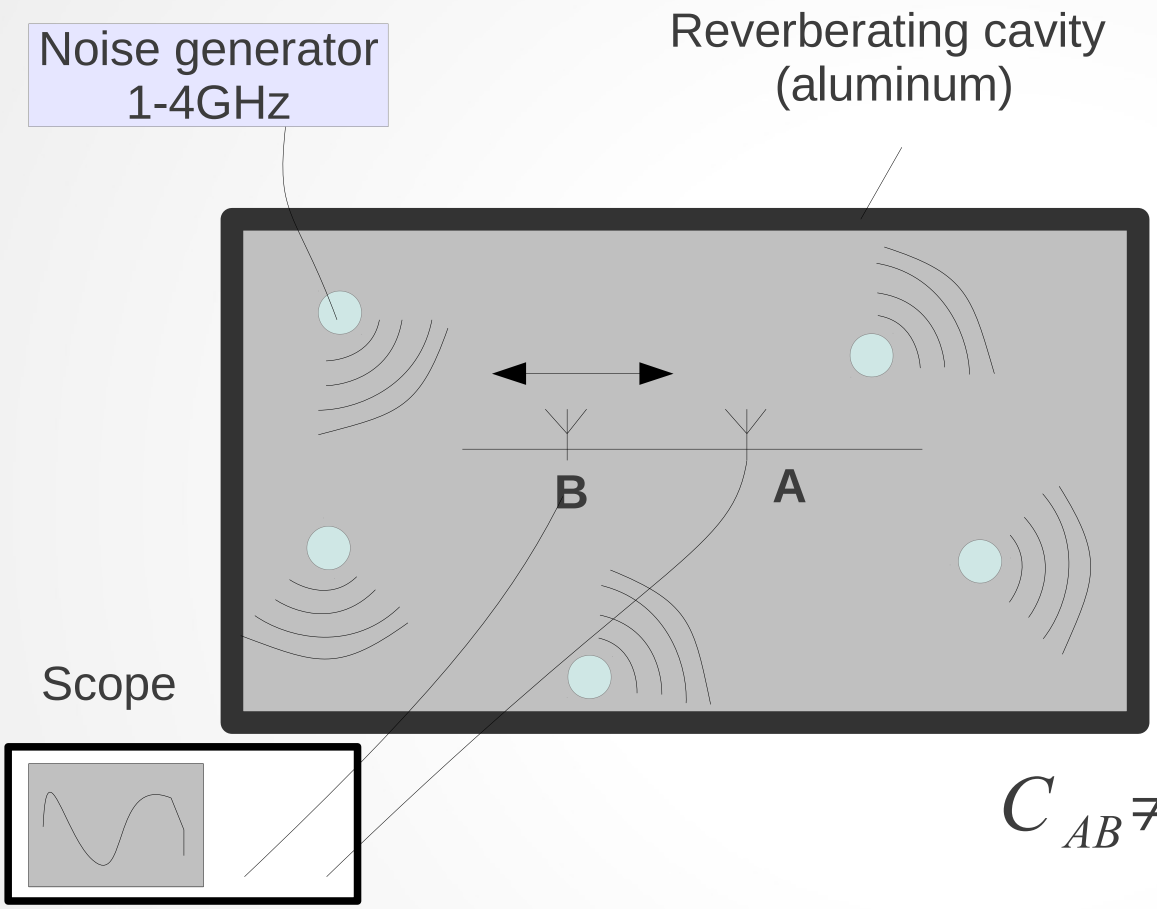
Classical beam-forming

$$I(x,y)=\left|\sum_{positions} C_{ref,j}\exp\left(-j k_0\sqrt{(x-j\delta x)^2+y^2}\right)\right|$$



Wideband diffuse artificial noise

Correlations in cavity

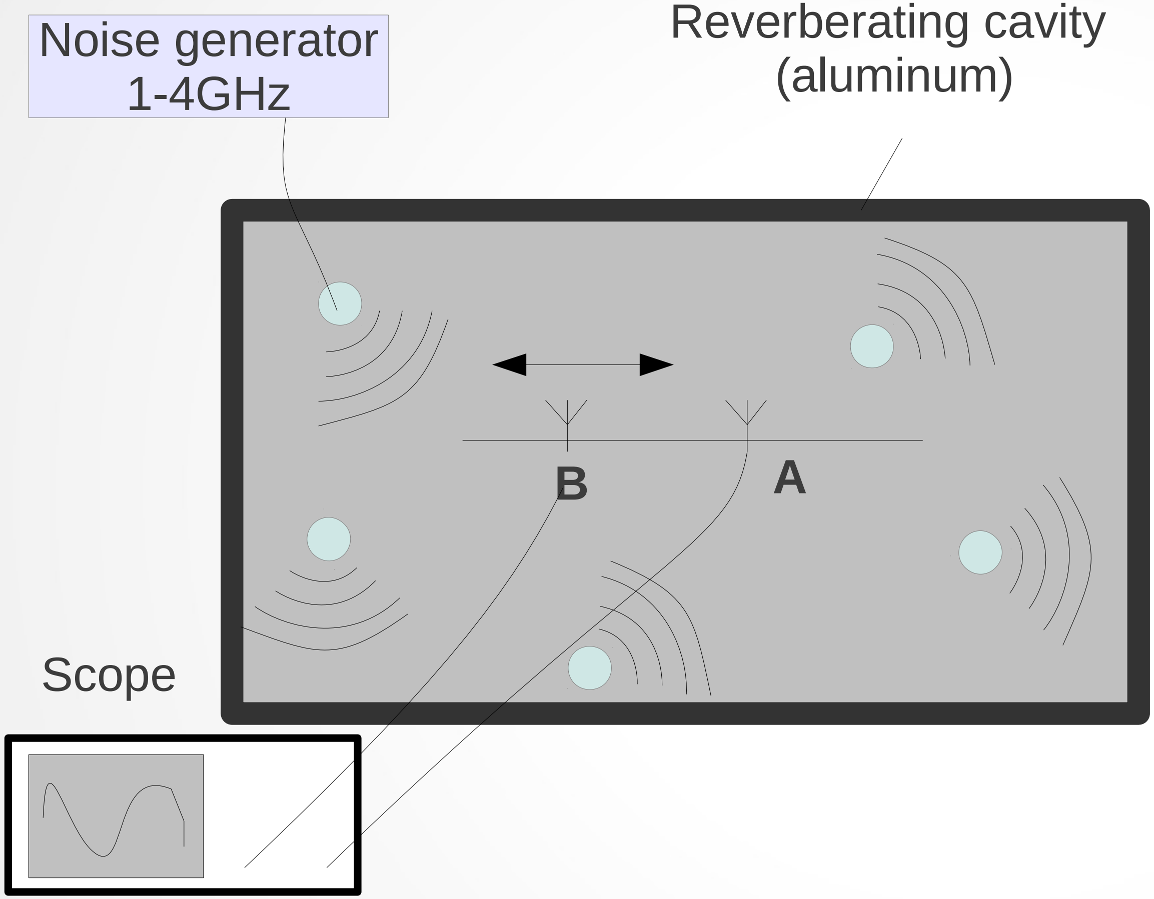


But : coupling between antennas when they are close

$$C_{AB} \neq G(A,B,t) - G(A,B,-t)$$

Solution?

Correlations in cavity



Correlations of correlation

Antenna A is a fixed reference antenna and we compute

$$C_{BB'} \approx \frac{C_{AB} C_{AB'}}{C_{AA}}$$

Fourier domain

Inverse Fourier transform

Setup

Reverberation cavity used in experimental set-up containing an **elliptic mirror** as a reflector, **emitting** dipole and horn **antennas** (1-6), a **stationary receiver antenna** (A) and a **moving receiver** (B); MIMO switch allows for successive emission from sources

Empty chamber

- With **6 noise sources**
- **“correlation of correlation”** technique
  - Zero “antenna distance” possible
  - Less noise
- clearly **symmetric** around t=0 until d=30 cm

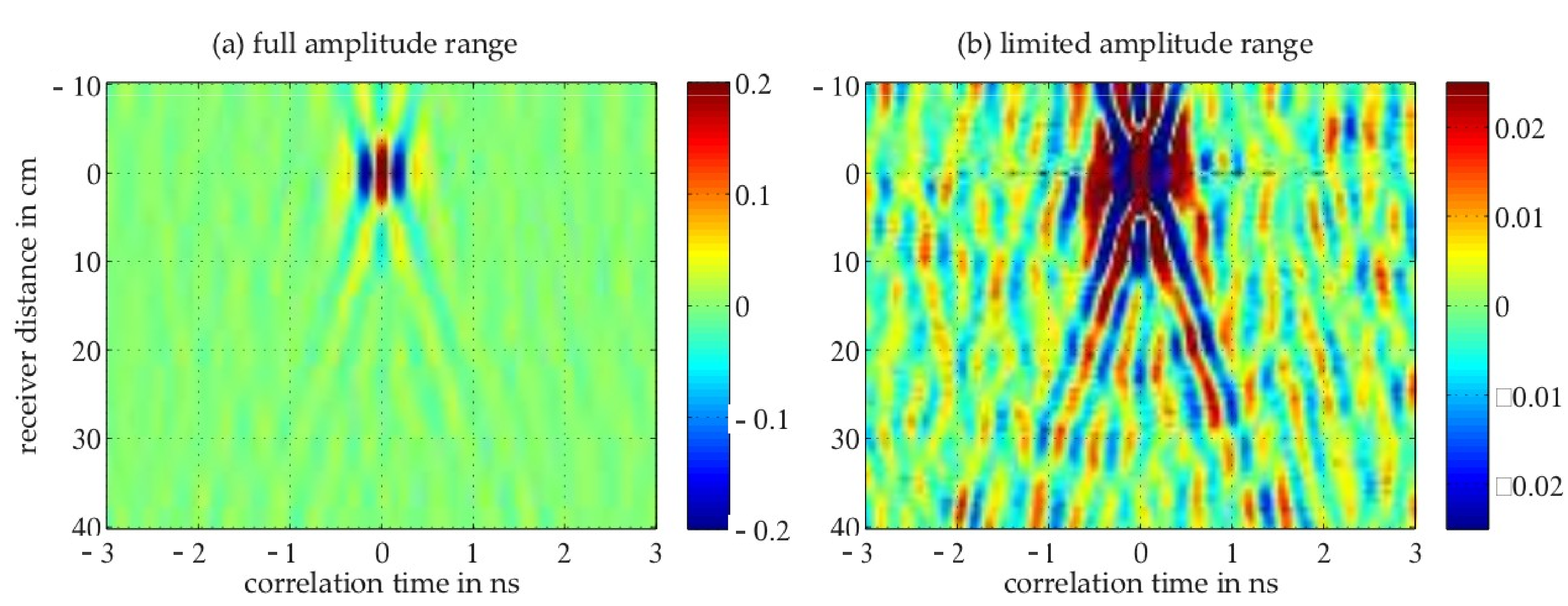
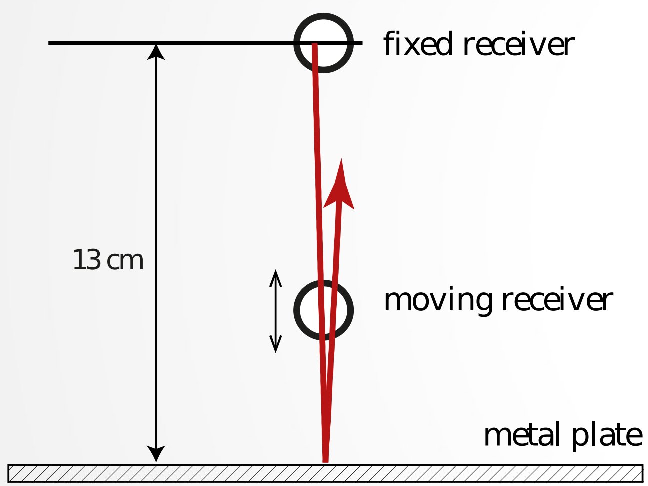
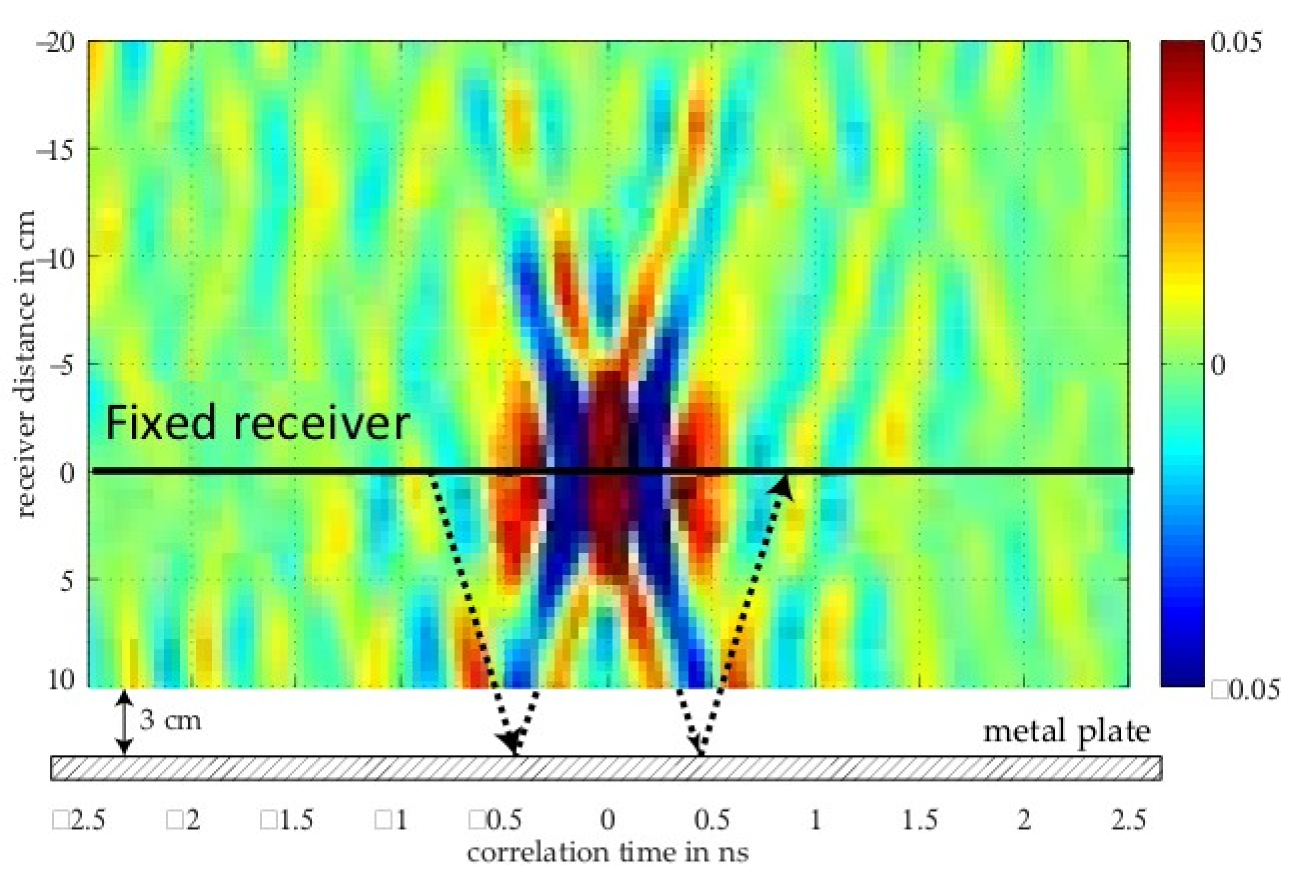


Plate reflector

Reflective metal plate

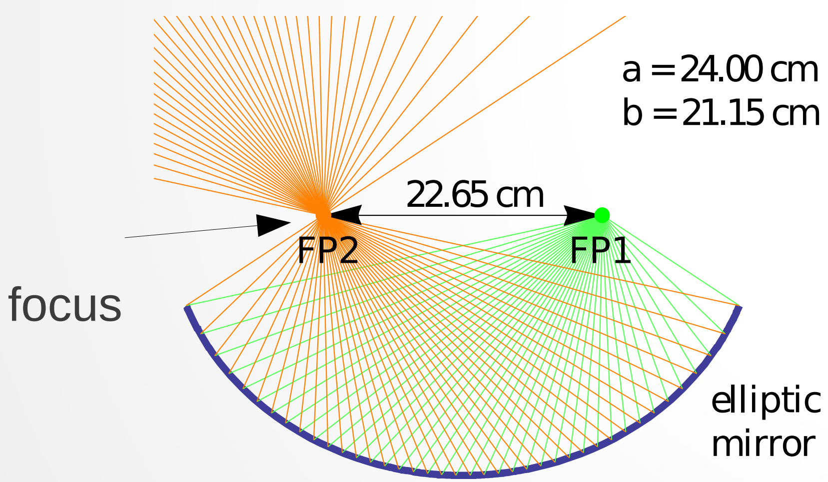




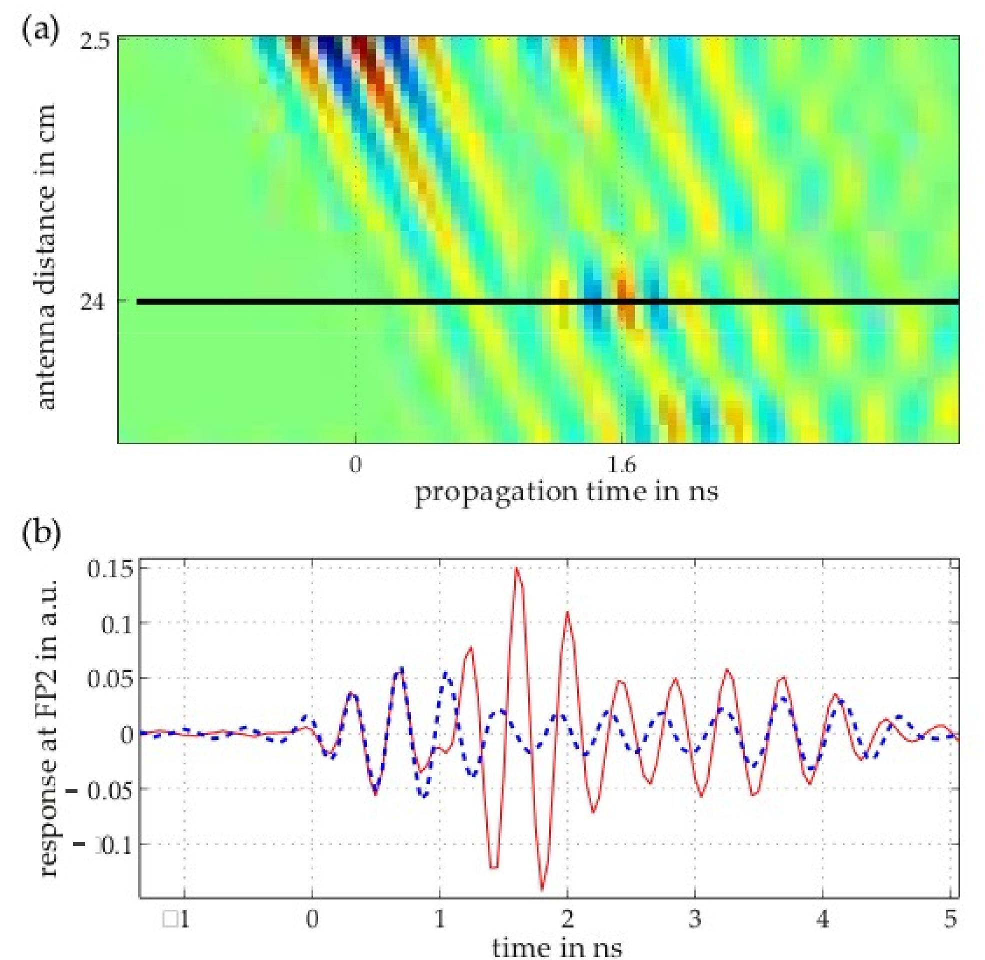
Elliptic reflector

Elliptic mirror

- Energy from focal point FP1 is refocused on FP2
- Strong “signature” in Green’s function

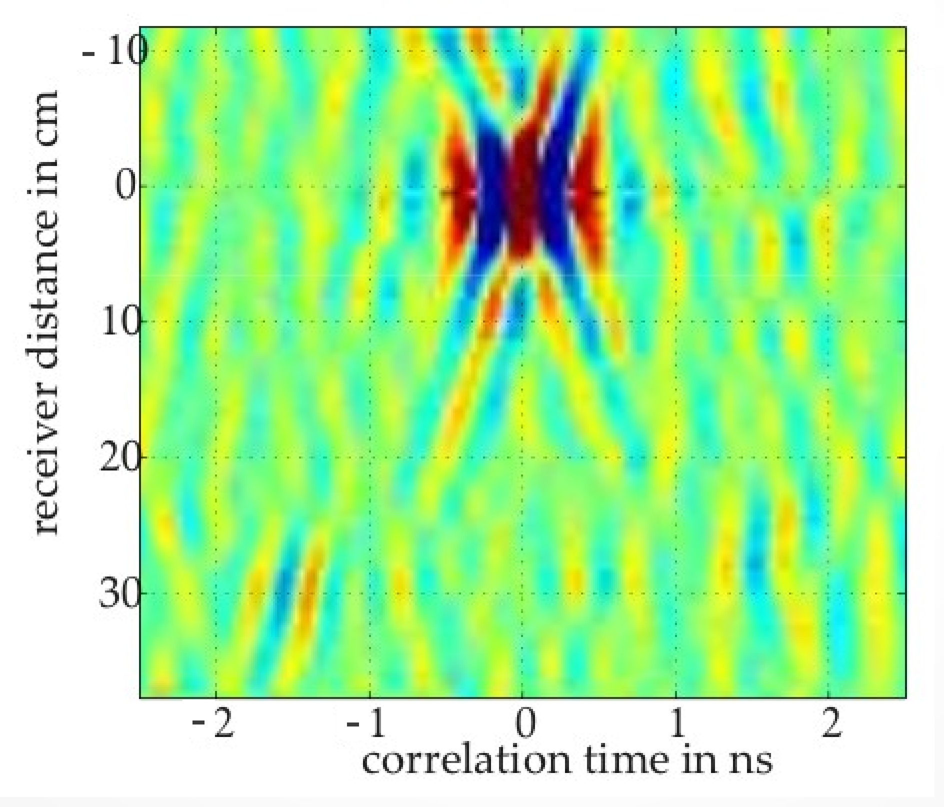


Active emission from FP1



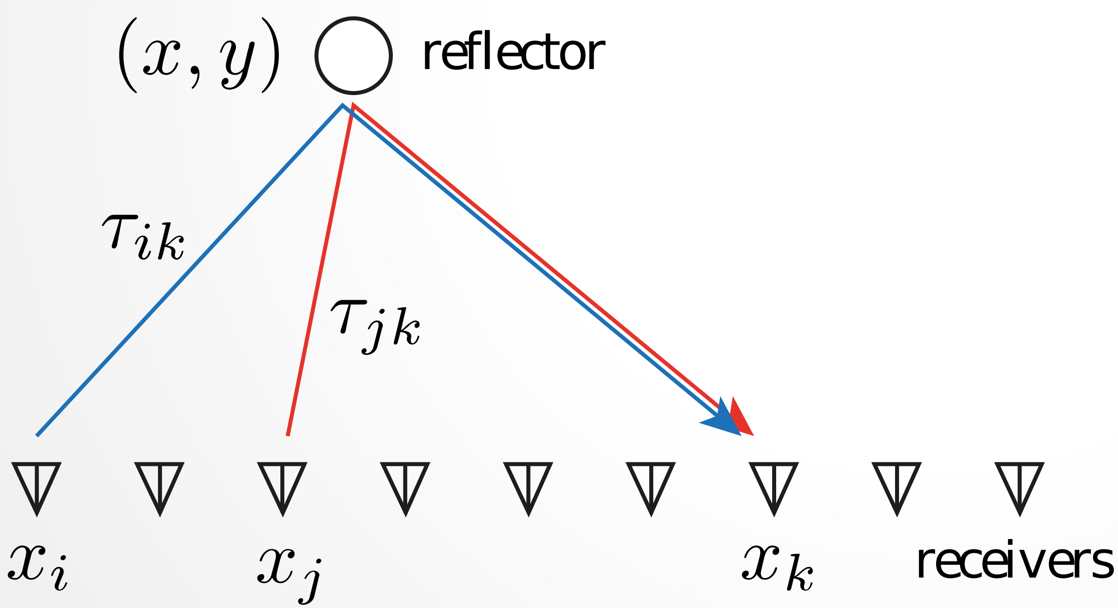
Elliptic reflector

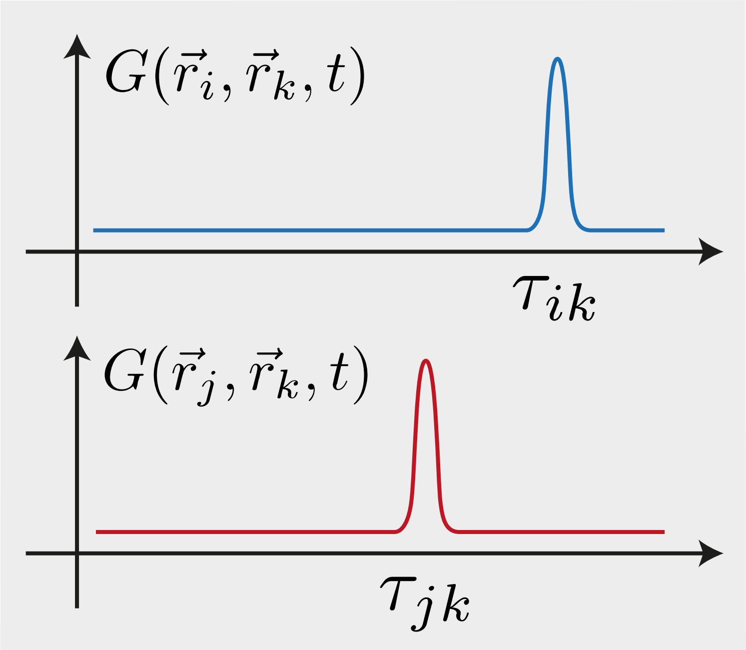
- One reference point placed on focal point
- reflection around d=25 cm (2nd focal point) visible after 1.7 ns



Beamforming

- Goal: **find reflectors** (on a map)
  - Noise cross-correlation gives access to **impulse responses between virtual transducers**
  - Suggest a reflector for every point on a plane
  - **Delay** the recovered GFs **by the theoretical travel time**
  - Integrate around t=0

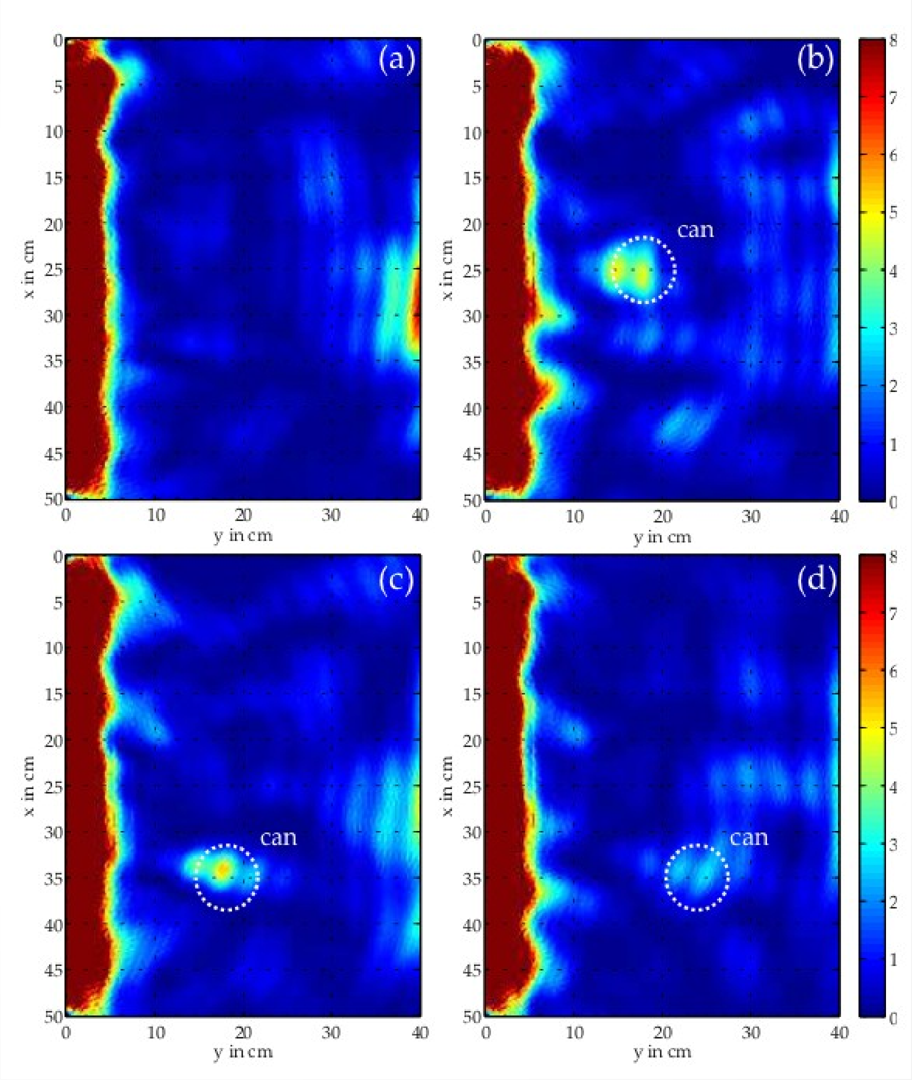




Detection of a metal can

- (a) empty cavity
- (b-d) different locations
- Better quality for small distances from transducer array
- Distorted by reflections from cavity wall at y = 40 cm

- **Compensate for lack of noise isotropy** by making use of the causal AND anti-causal part of the GF



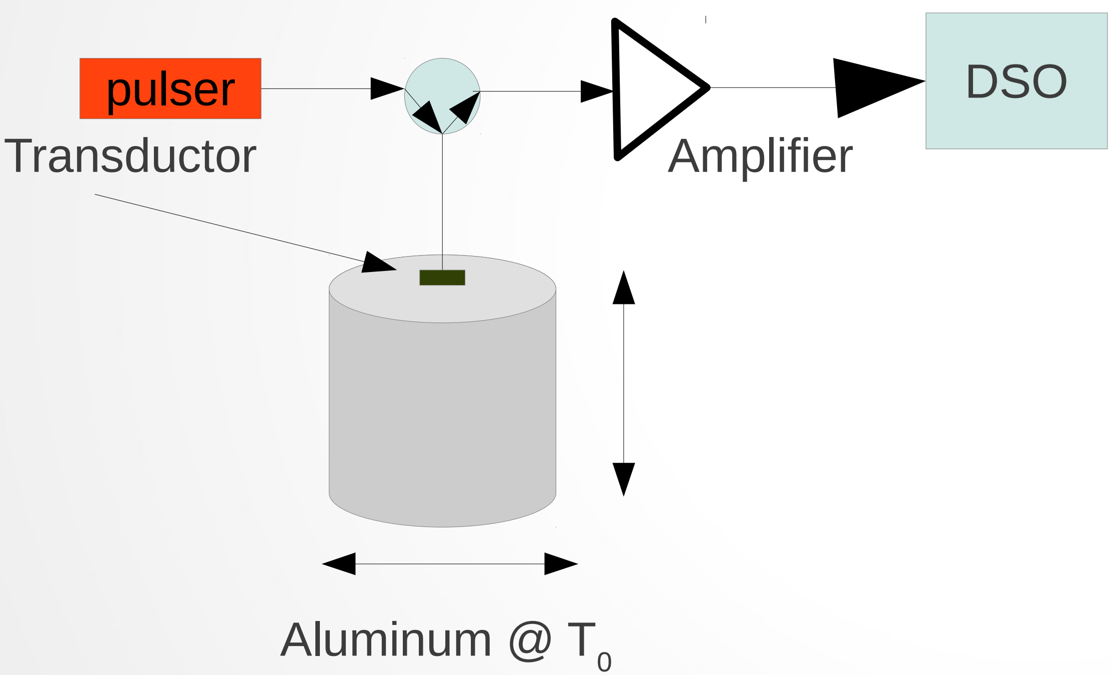
Thermal correlations

In acoustics

VOLUME 87, NUMBER 13 PHYSICAL REVIEW LETTERS 24 SEPTEMBER 2001

Ultrasonics without a Source: Thermal Fluctuation Correlations at MHz Frequencies

Richard L. Weaver and Oleg I. Lobkis
Theoretical & Applied Mechanics, University of Illinois, Urbana, Illinois 61801
(Received 5 April 2001; published 7 September 2001)



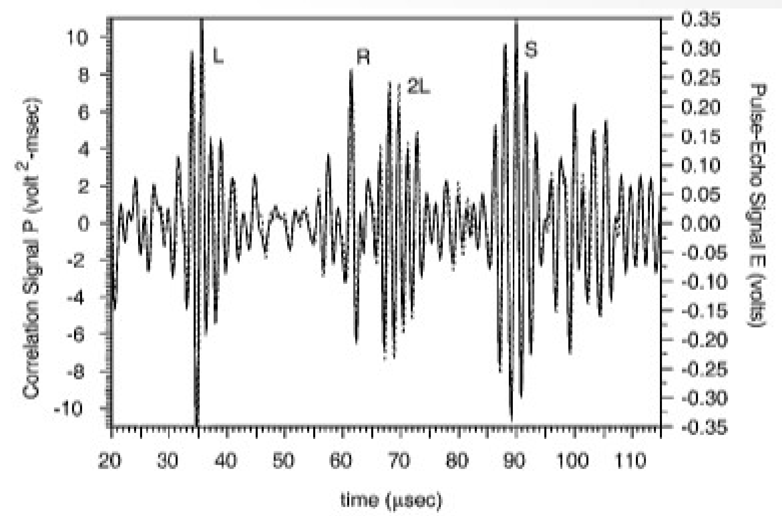


FIG. 2. Comparison of the noise autocorrelation function P (solid line) and the direct pulse/echo signal E (dotted line). They

Elastic waves

Active measurement

In acoustics

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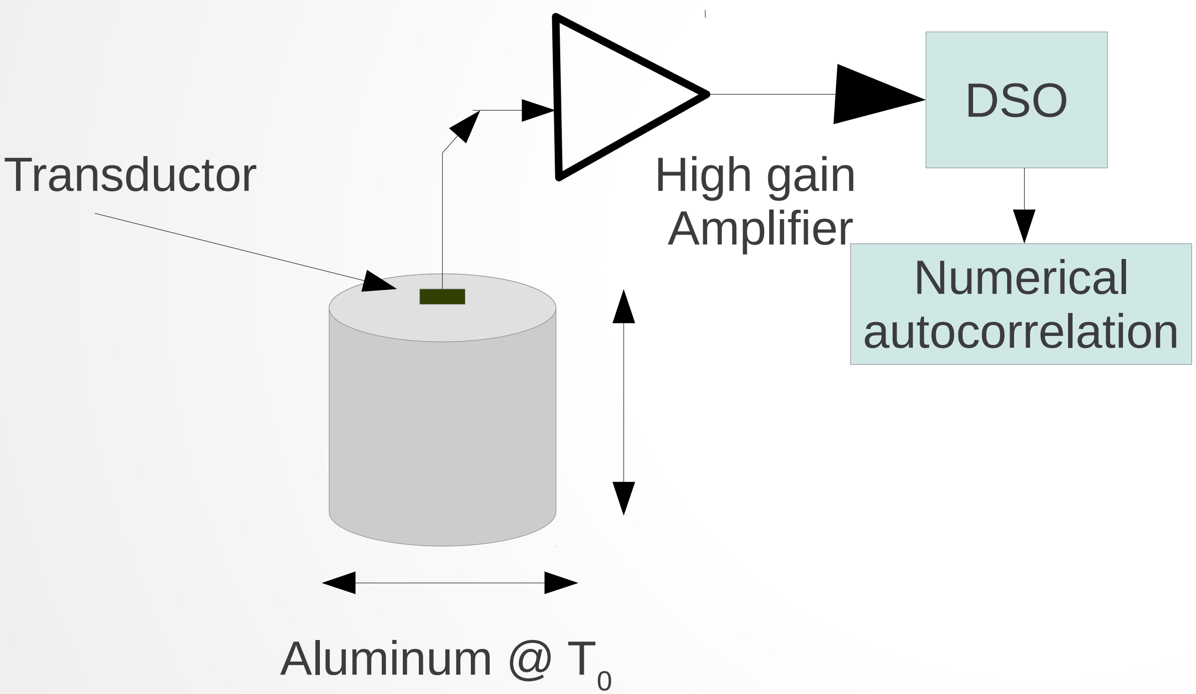


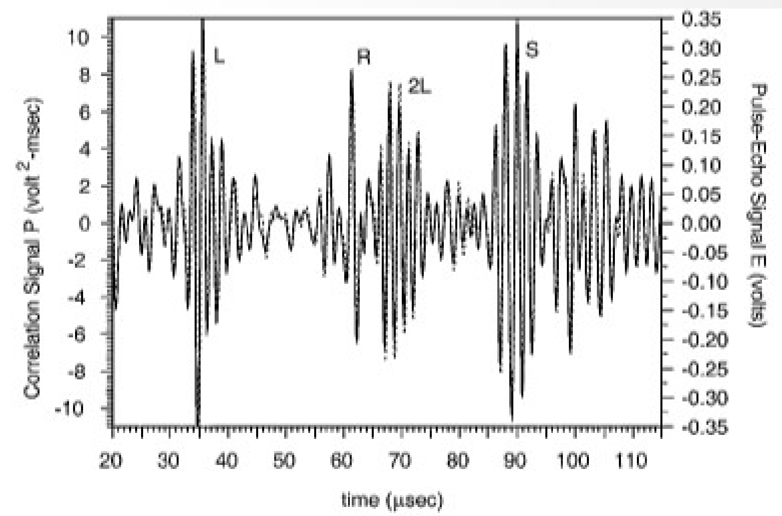


FIG. 2. Comparison of the noise autocorrelation function *P* (solid line) and the direct pulse/echo signal *E* (dotted line). They

Elastic waves

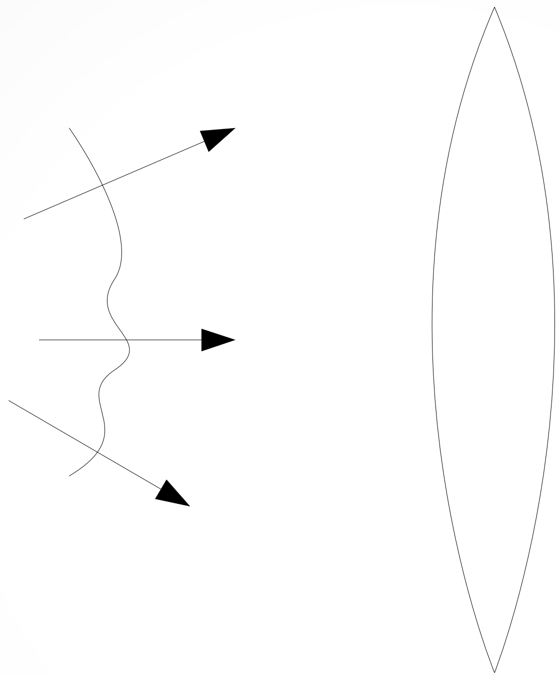
Passive measurement

Im G(A,A) recovered from thermal phonons

IR camera

Thermographic camera

$\lambda \sim$ 9 – 14 μm



Hot system emits thermal radiation

Lens

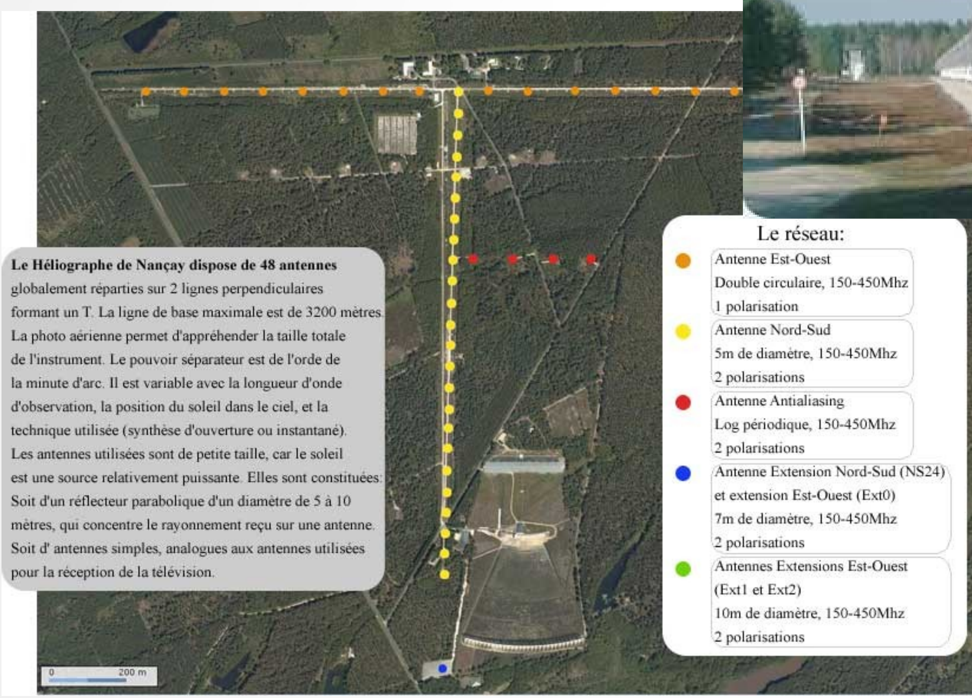
Mean intensity distribution

Source: NASA

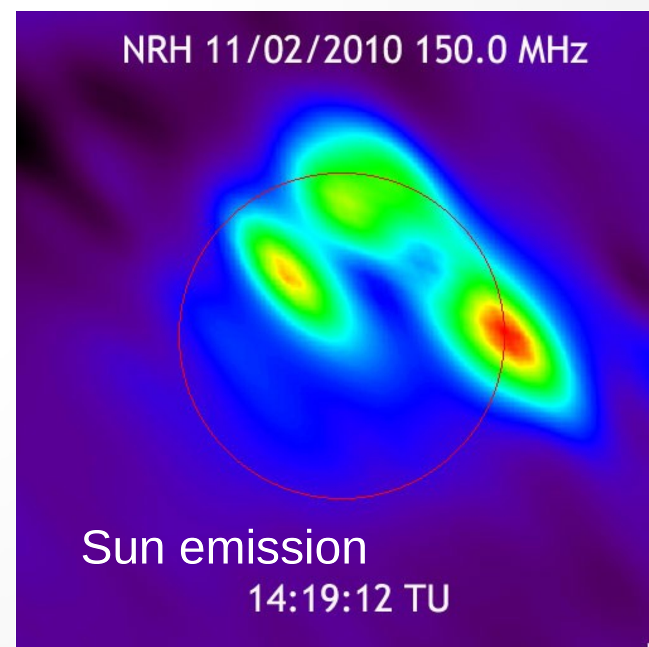
Interferometric arrays

: 47 antennas, frequencies : 150 - 450 MHz

Radio telescope



Beamforming



Source : Station de Radioastronomie de Nançay

Black body radiation

Black body radiation at temperature T

Planck's law

$$B(T,\nu)=\frac{2h\nu^3}{c^2}\frac{1}{\exp\left(\frac{h\nu}{k_bT}\right)}$$

Spectral radiance (W/m²/sr/Hz)

Boltzmann constant

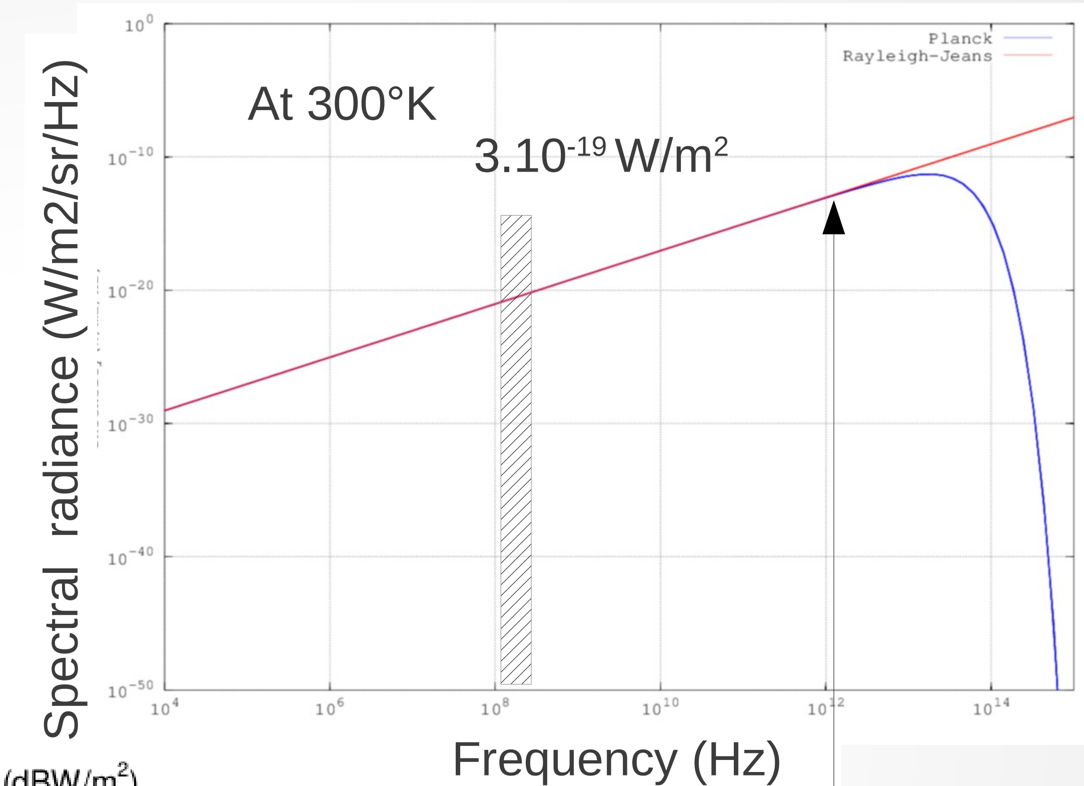
$$h\nu \ll kT \quad B(T)\approx\frac{2k_bT\nu^2}{c^2}$$

Rayleigh-Jeans classical limit

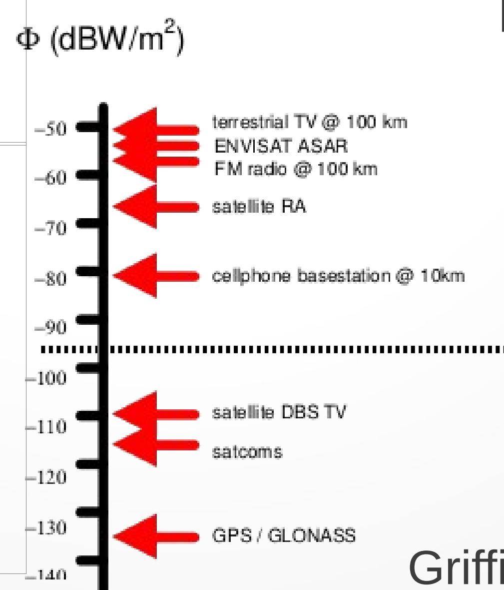
$$I(T)\approx\frac{8\pi k_bT\nu^2}{c^2}\delta\nu$$

T=300K Δf=10MHz, ν=2GHz

→ I(T)=-103 dBW/m2



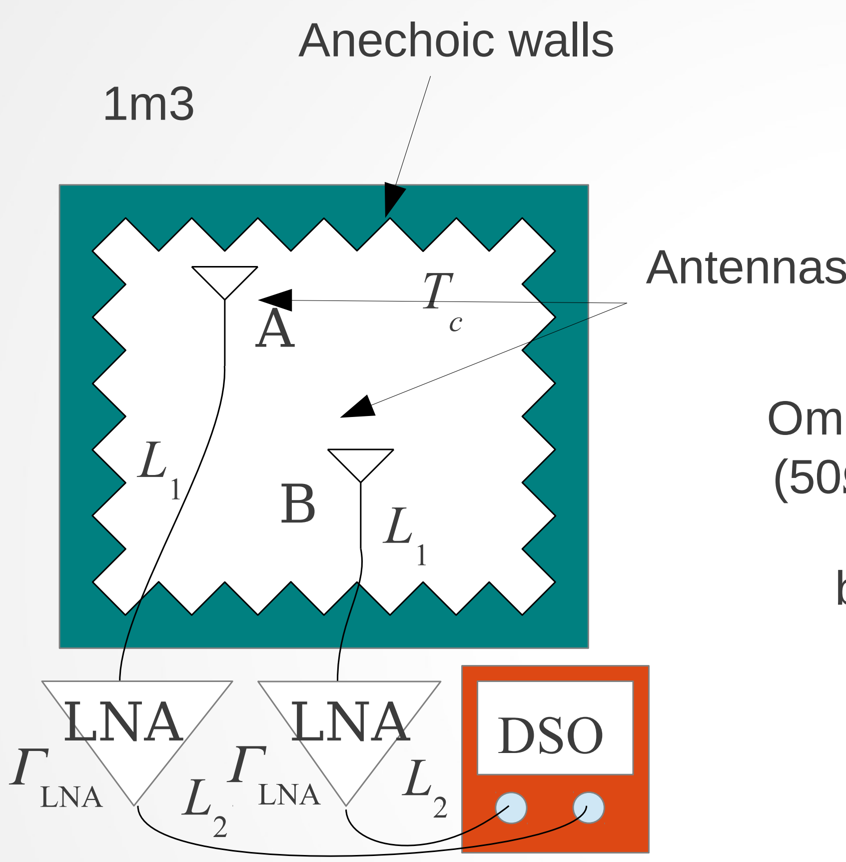
ν ~ 6.62THz (λ ~ 45µm)



Griffiths

Thermal noise at microwave range can be measured

Experimental set-up

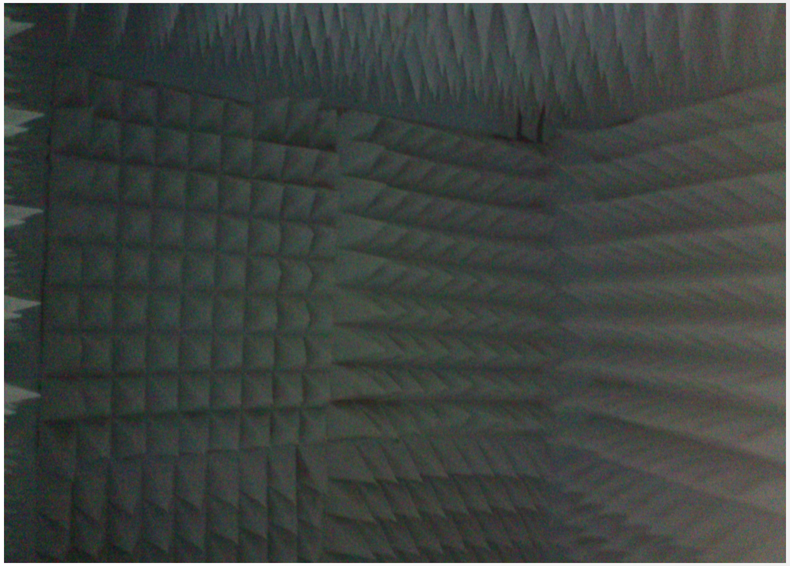


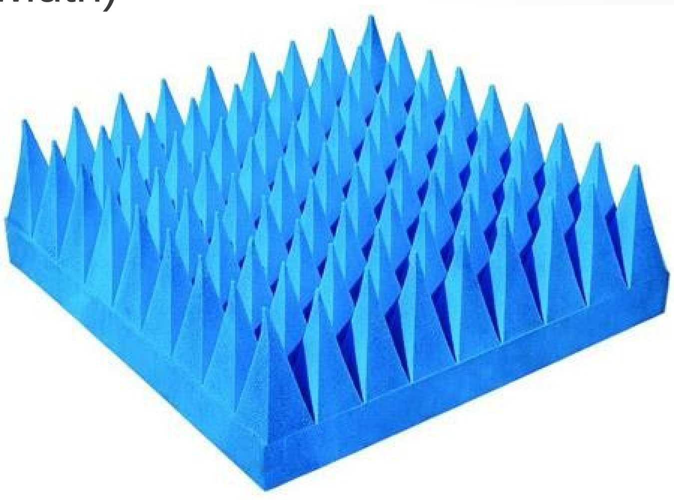
$$\Gamma_{LNA}=10^4(40\pm1.5\,dB)$$

1-5GHz

NF=1.5dB

Omnidirectionnal
(50Ω,2.5dBi gain
1-5GHz
bandwidth)





Absorbing material

Absorbing cavity ↔ blackbody

THE REVIEW OF SCIENTIFIC INSTRUMENTS VOLUME 17, NUMBER 7 JULY, 1946

The Measurement of Thermal Radiation at Microwave Frequencies

R. H. Dicke*
*Radiation Laboratory, Massachusetts Institute of Technology, Cambridge, Massachusetts***

(Received April 15, 1946)

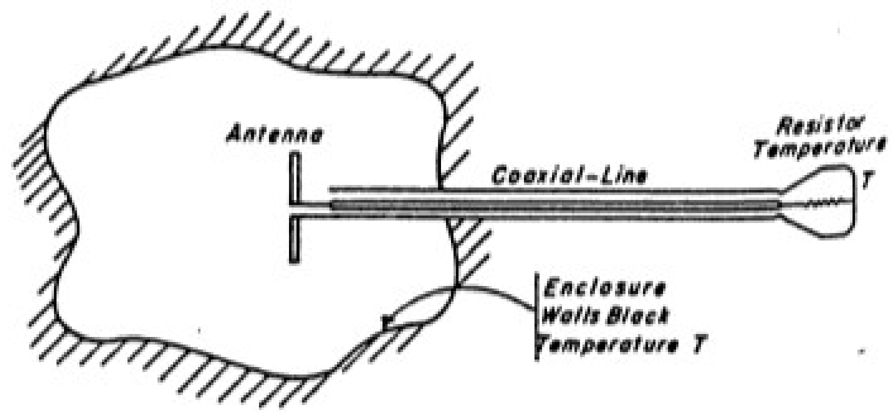


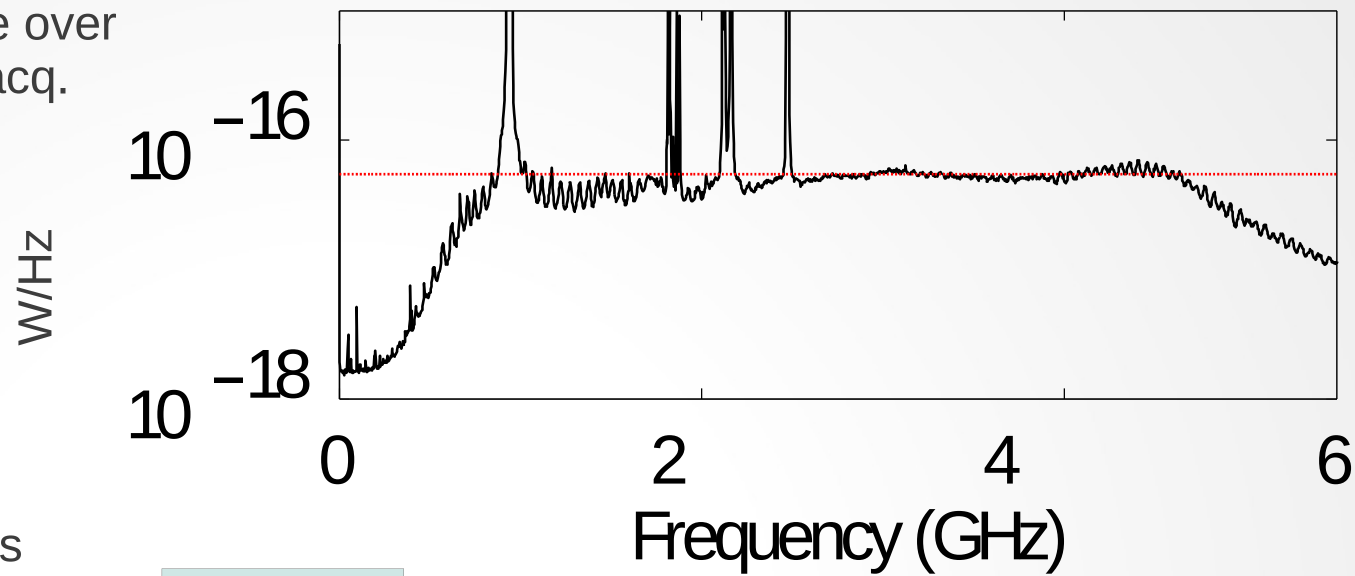
Fig. 1. Antenna system in black enclosure.

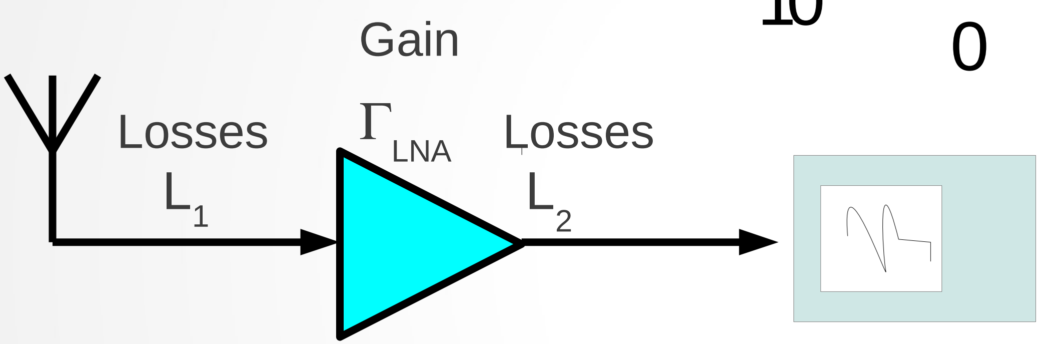
Perfect blackbody cavity : at thermal equilibrium power spectral density(PSD) $=k_b T$

Power spectral density in the cavity

$$N = \frac{\langle |U(\omega)|^2 \rangle}{Z_0}$$

Average over 40000 acq.





4 main sources of noise :

- N_a : microwave noise
- N_{lna} : Low noise amplifier
- N_c : Losses in coaxial cables
- N_s : Noise of the scope

$$N_a = \epsilon k_B T_c L_1 L_2 \Gamma_{LNA}$$

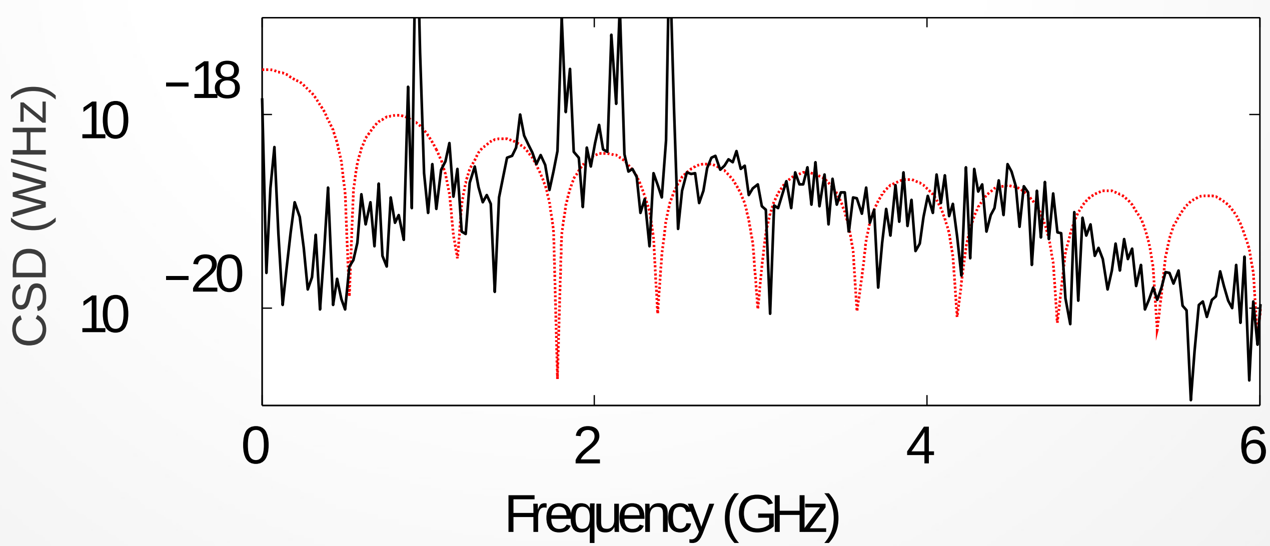
$$N_{LNA} = k_B T_{LNA} L_2 \Gamma_{LNA}$$

$$N_c = k_B T_c (1/L_1 - 1) L_1 L_2 \Gamma_{LNA}$$

$$N = N_a + N_{LNA} + N_c + N_s$$

Process

- 50,000 acquisitions of 40ns long signals for each channel
- Fourier transform over the 2x50,000 acquisitions
- $C_{AB}(\omega)$ cross-spectral density is estimated from the average of the product of the 50,000 Fourier transforms

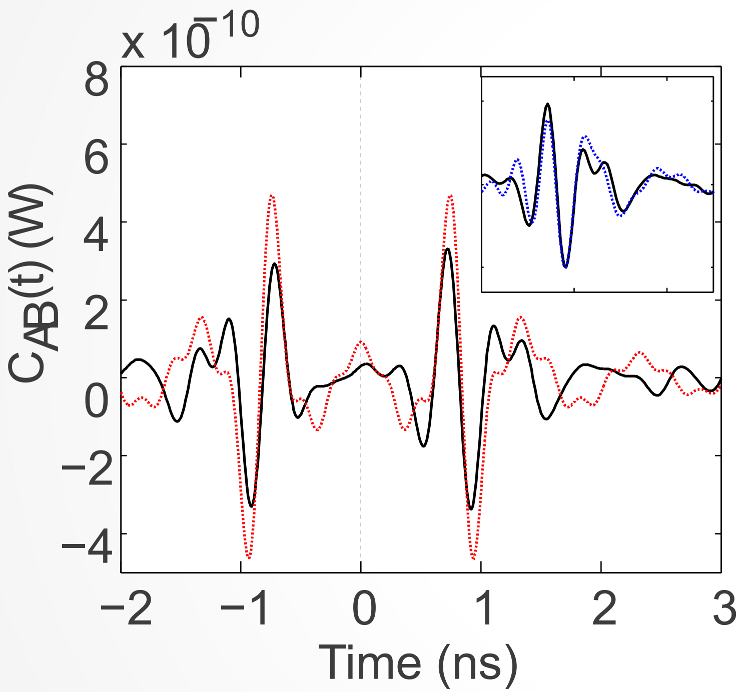


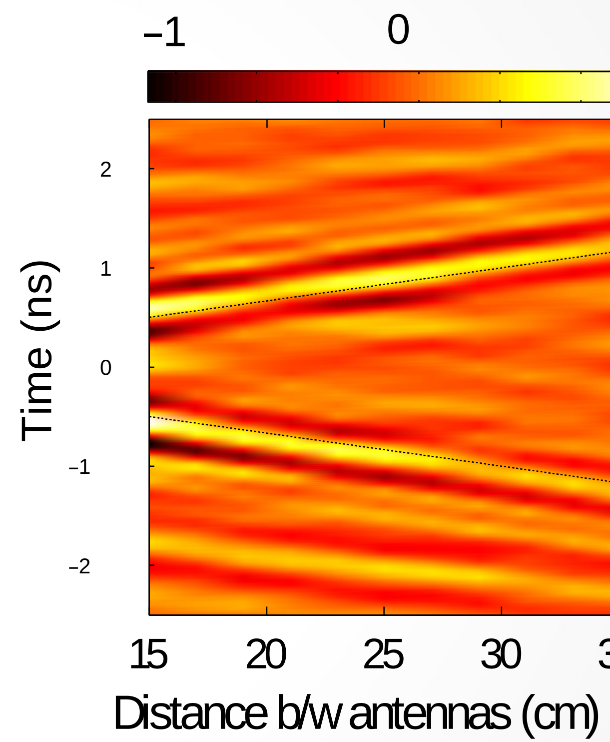
cross-correlations

Suppression of strong contributions (artificial noise sources) > a few kT

Fourier transform of the cross-spectral density ↔ cross-correlation

Cross-correlations





t=cR

Cross-correlations

FD theorem

Active direct measure of transient response

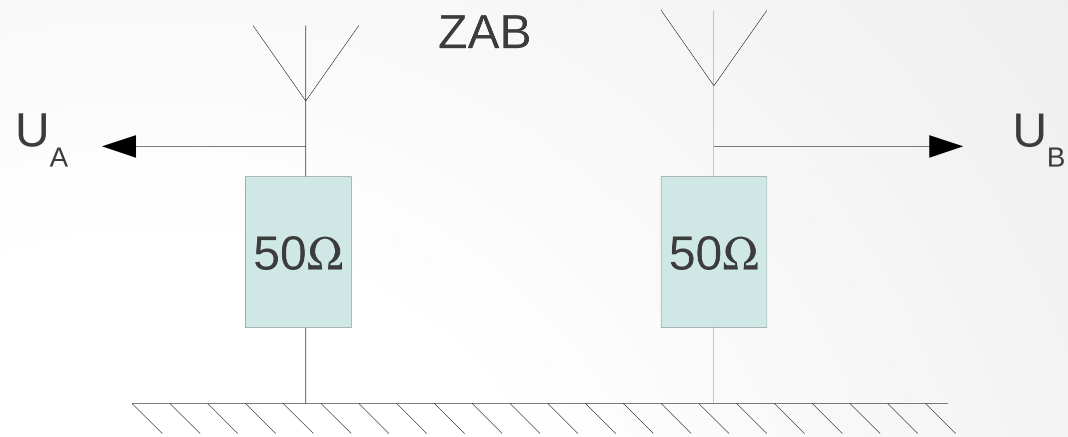
c ~ 3e8 m/s

→ Recovering of the Green's function

Theoretical correlations

From the scope point of view : electrical problem

Modeling with impedances (linear system)



Fluctuation dissipation theorem applied to **U=ZI**

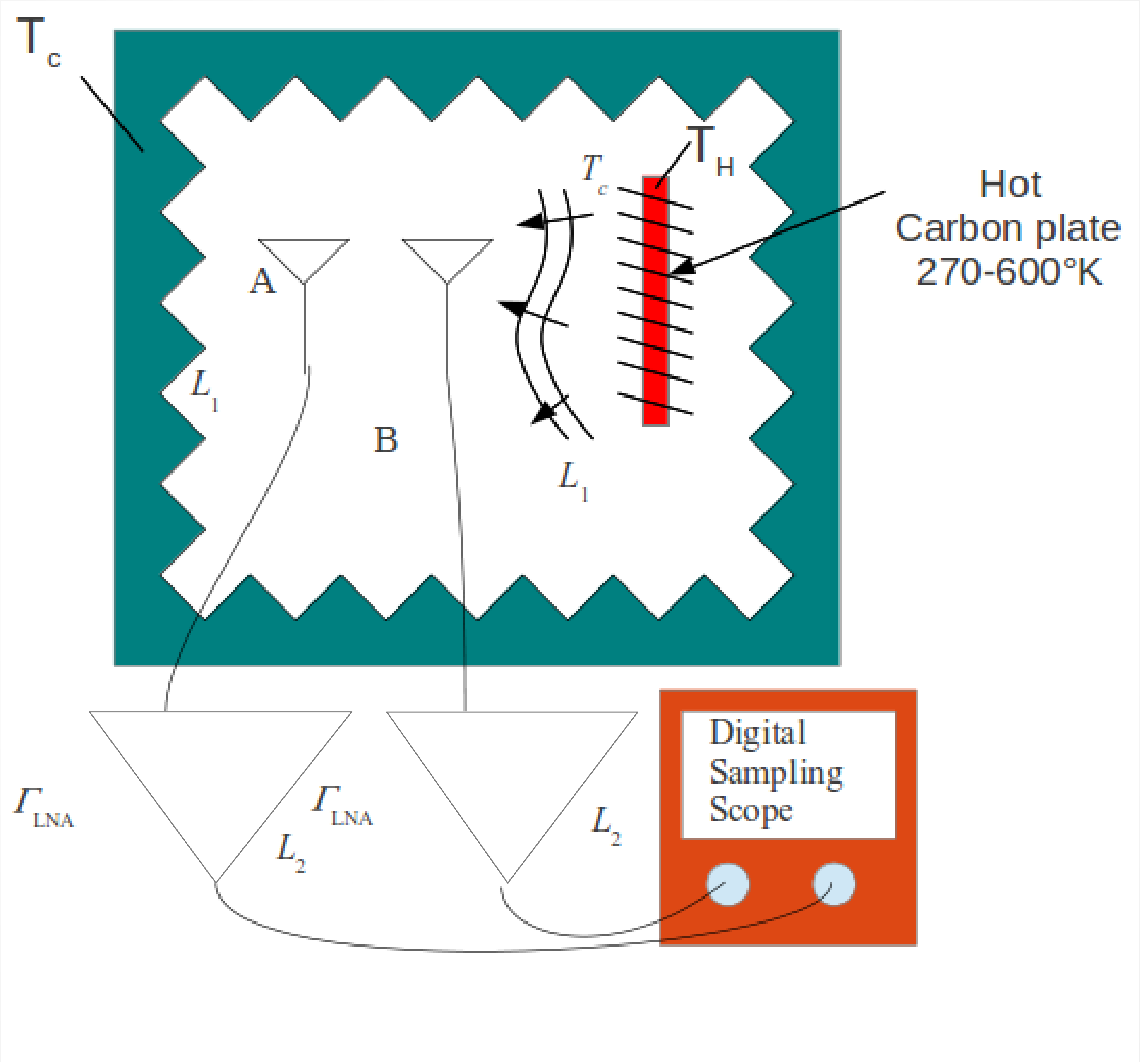
$$C_{AB}(\omega)=\frac{\langle U_A U_B^* \rangle}{Z_0}=k\,T\,\frac{2\Re(Z_{AB})}{Z_0}$$

In case of dipole like antennas that are adapted (Z_{AA}~Z_0), it comes

$$C_{AB}(\omega)=\alpha\Gamma_{LNA}L_1L_2\epsilon k_B T_c\frac{3}{2}\left(\sin(k_0d)\left(\frac{1}{k_0d}-\frac{1}{(k_0d)^3}\right)+\cos(k_0d)\frac{1}{(k_0d)^2}\right)$$

Good fitting with the experimental results

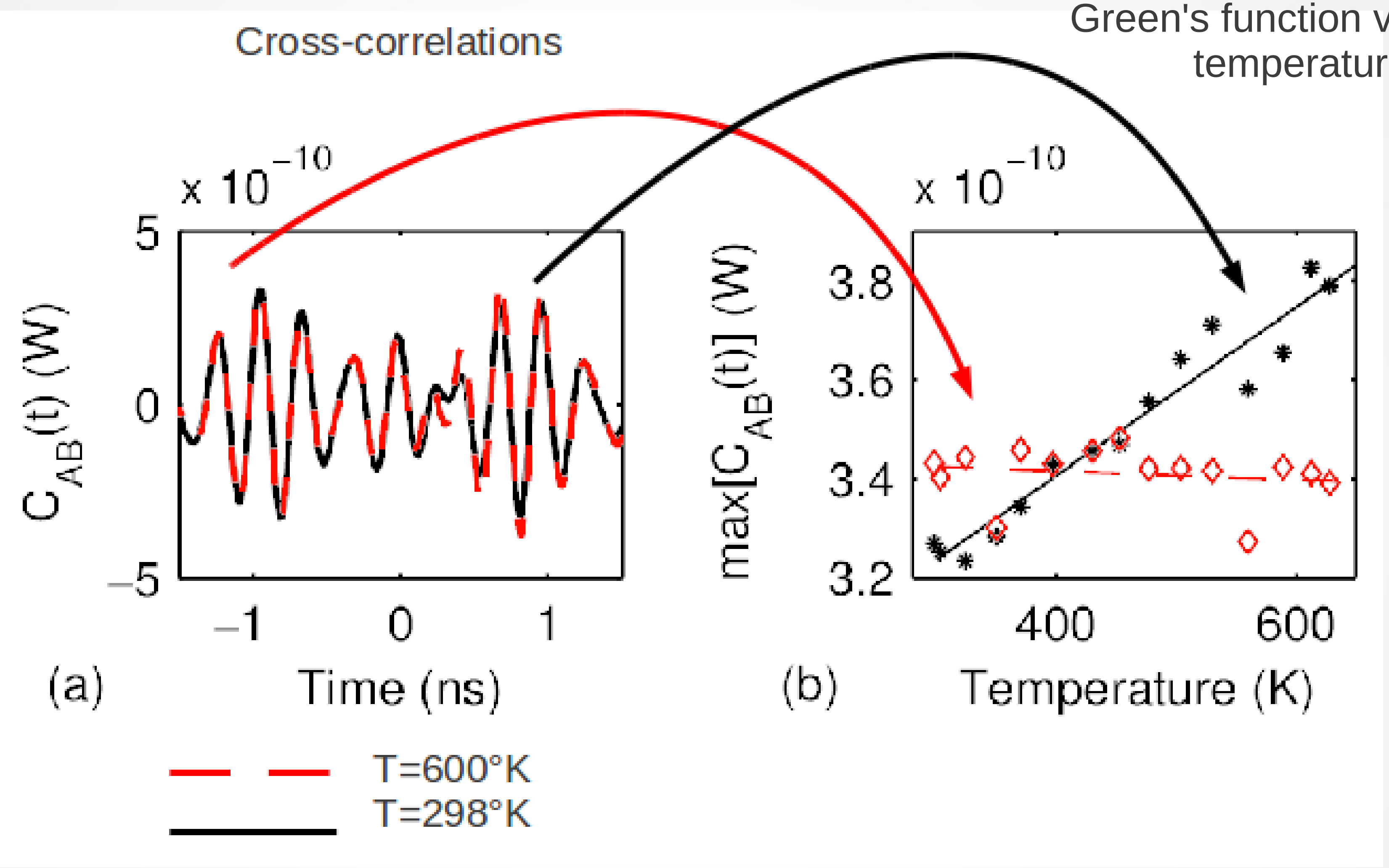
Hot source



T c
T H
T c
Hot
Carbon plate
270-600°K
A
B
L 1
L 1
Γ LNA
Γ LNA
L 2
L 2
Digital
Sampling
Scope

Measurement results

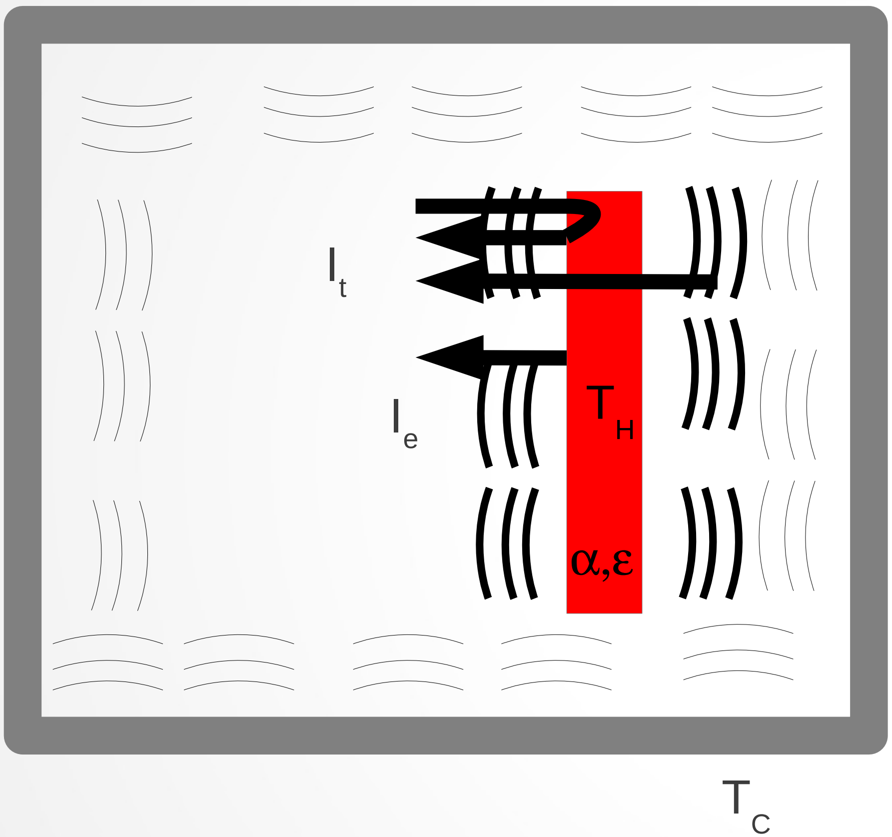
Maximum amplitude of the causal and anticausal Green's function vs. Plate temperature



Causal response increases with temperature because the heater increase the thermal flux in one direction

Result interpretation

A perfect absorber is a perfect black body



Absorptivity
α

Emissivity
ε

$$I = I_t + I_e$$

$$I \propto (1-\alpha) k_b T_c + \epsilon k_b T_H$$

But $\varepsilon = \alpha$ (Kirchoff's law)

$$I \propto (1-\epsilon) k_b T_c + \epsilon k_b T_H$$

estimation from reflection – transmission measurement

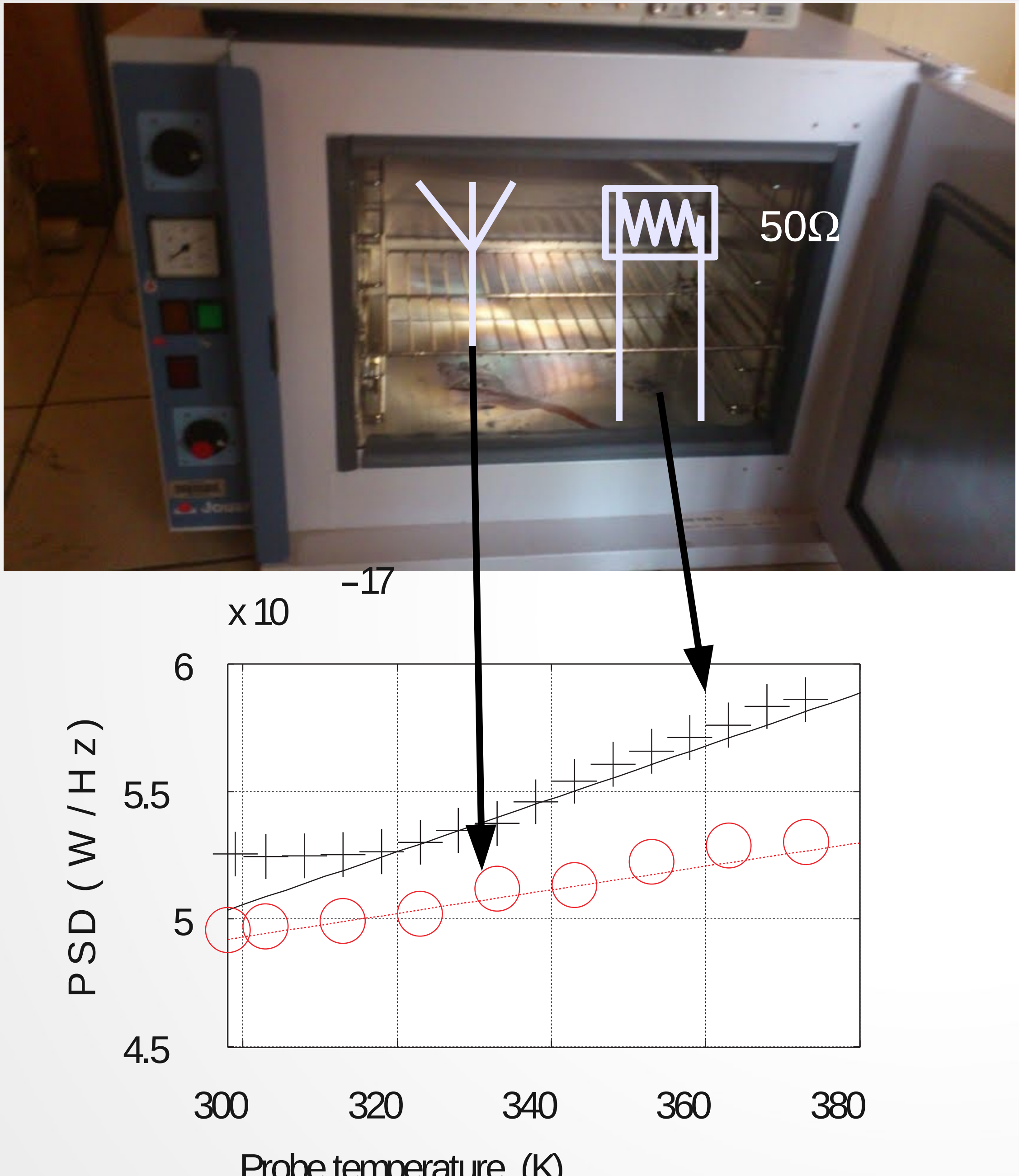
$$\alpha = 0.15$$

$$\epsilon = 0.13$$

Measured from cross-correlation slope vs. frequency

Good estimation of the emissivity

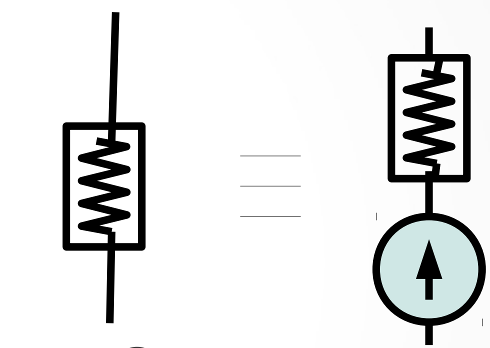
Power spectrum density in an oven



T ~ 300 → 400°K

Power spectrum density of
- an omnidirectionnal antenna
- of a 50Ω resistance

Resistance model



Johnson–Nyquist noise

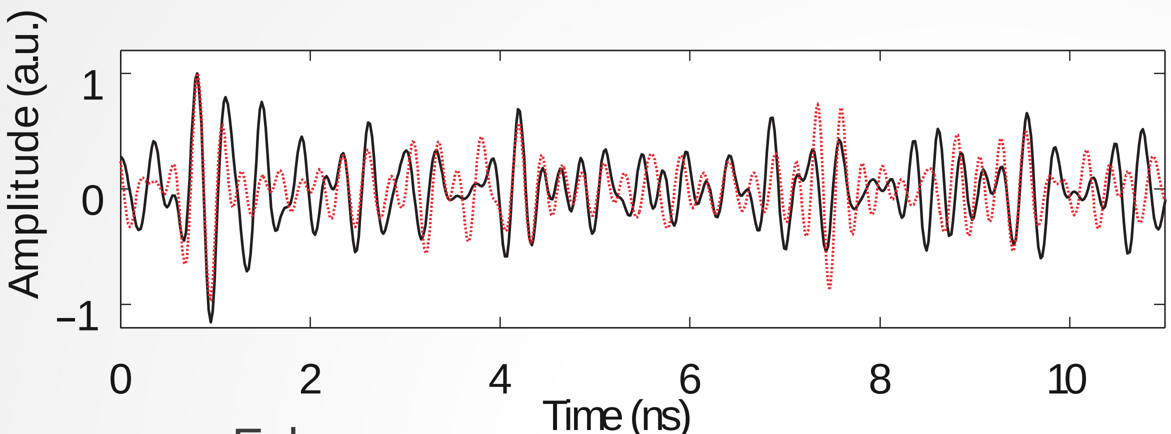
PSD of resistor = k_b T_{OVEN}

PSD of cavity = ε k_b T_{OVEN}

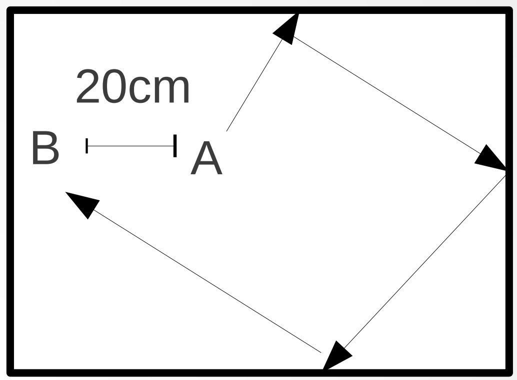
ε=0.55 due to cavity losses

Cross-correlations in an oven

Cross-correlations between 2 antennas



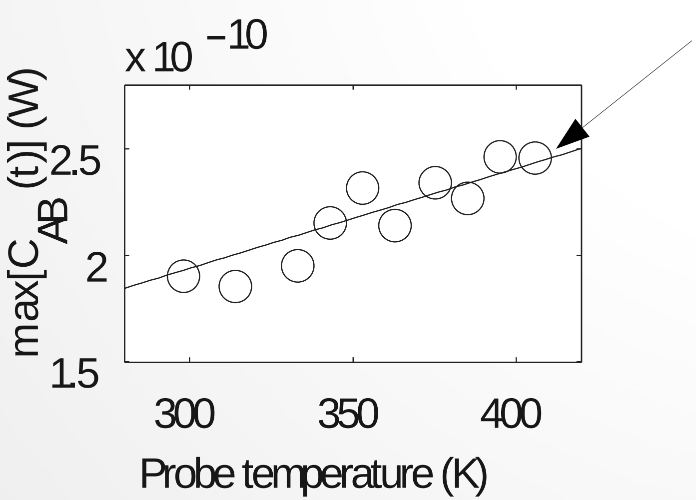
Echoes



Oven is a reverberation cavity

Maximum correlation versus temperature

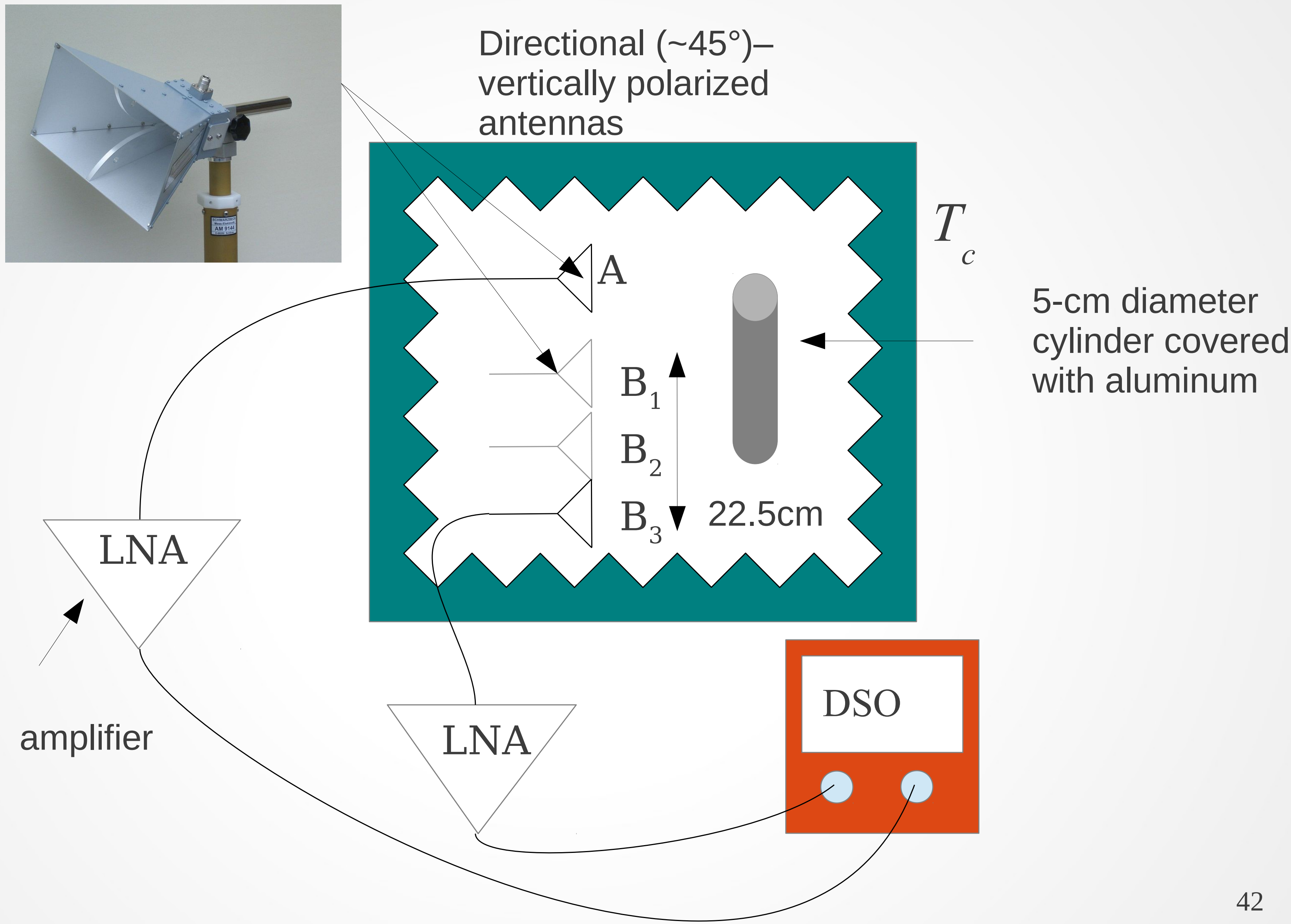
$$C_{AB} \propto \left(T_0 + \epsilon \left[T_{\mathrm{OVEN}} - T_0 \right] \right)$$



The cavity is leaky (some energy is radiated outside it) → $\varepsilon < 1$

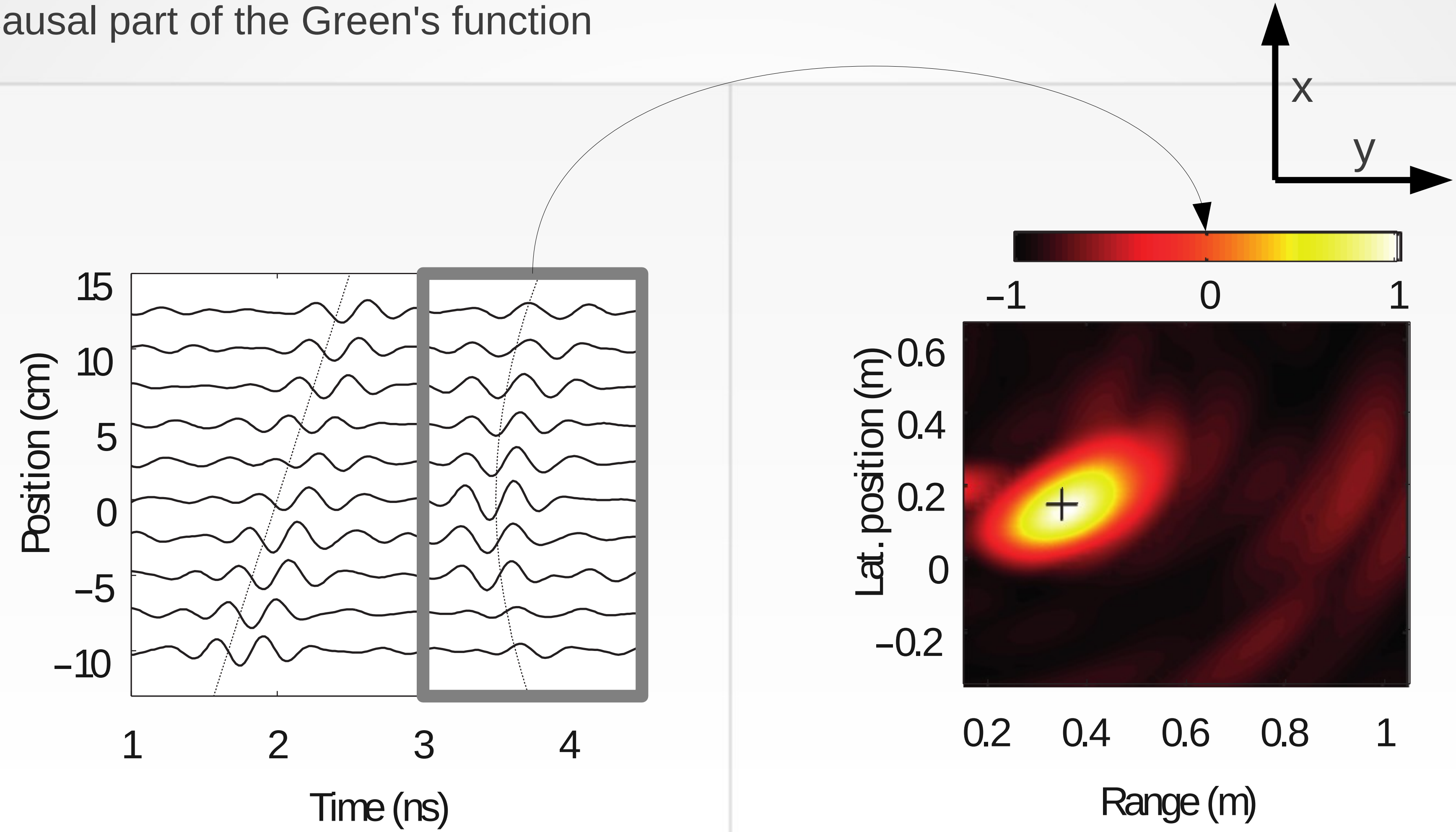
ε=0.6

Application to imaging



Imaging from thermal noise

Causal part of the Green's function



$$I(x,y) = \left| \sum_{positions} C_{ref,j}\left(t - \sqrt{(y - j\,\delta x)^2 + x^2}/c\right) \right|$$

Antenna B steps

Conclusions

- Green's function recovering with electromagnetic waves from
  - Artificial noise
  - Thermal noise
- Fluctuation dissipation theorem
- Black body thermal emission
- Non-uniform temperature → asymmetric pulse reconstruction
- Green's function in hot reverberating media

- Main application : detection / imaging