

New improvements in HF ionospheric communication and direction finding systems

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- **INTRODUCTION and OBJECTIVES**
- **IONOSPHERIC PROPAGATION**
- **MODELLING OF IONOSPHERIC CHANNELS: THE HF SIGNALS**
- **EXPERIMENTAL RESULTS**
- **CONCLUSION**

- **Objectives :**

Study of new systems applied to HF (3-30 MHz), ground to ground links, with applications to:

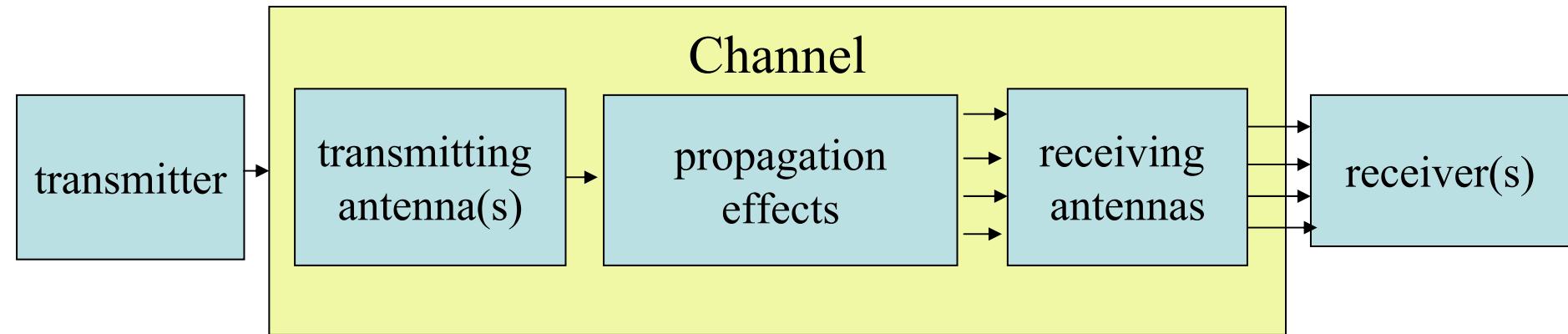
- ionospheric characterisation
- system simulators
- communications (transmitters et receivers)
- direction finding
- single site location (SSL)

Particularity : use of heterogeneous active antenna arrays with the objective of a:

- ***size reduction of the arrays,***
- ***good spatial sampling.***

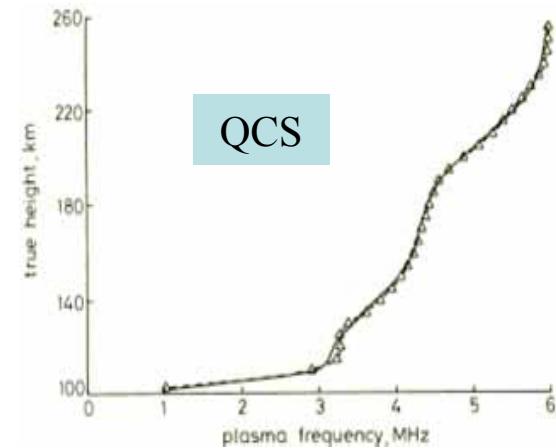
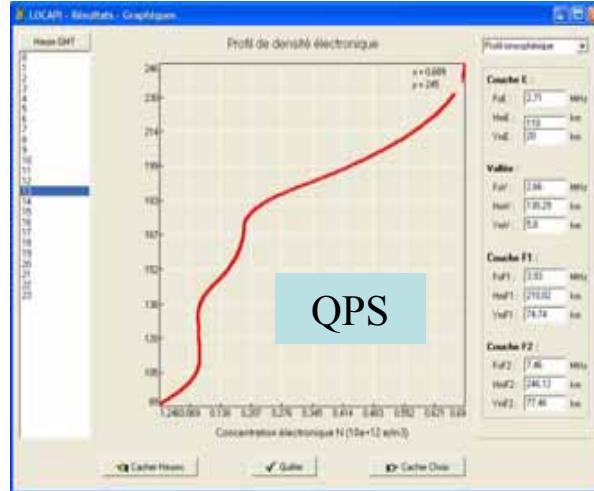
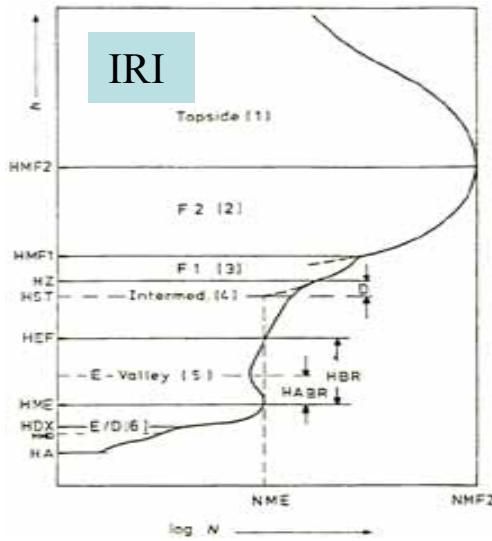
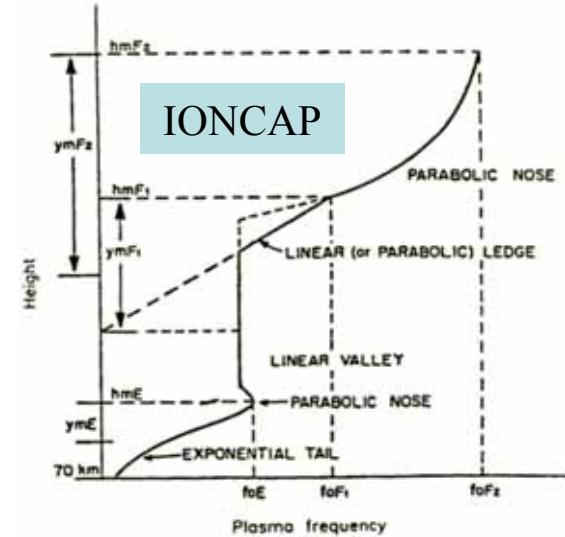
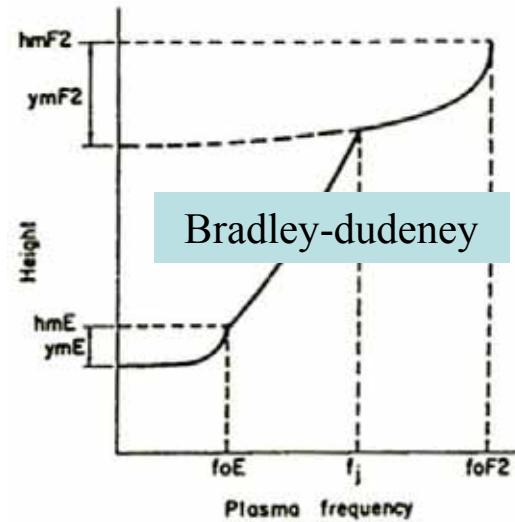
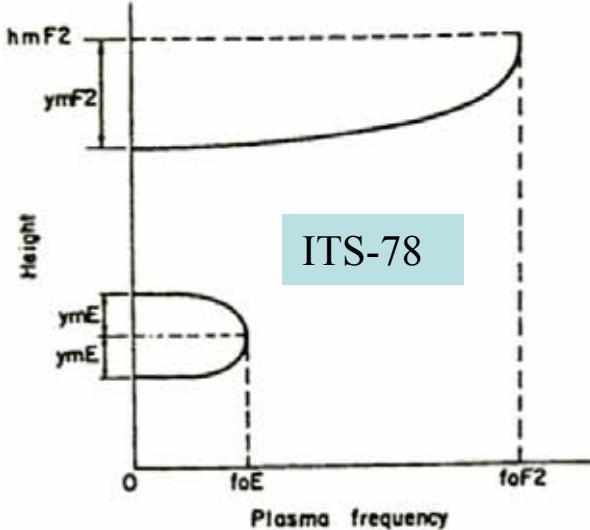
- To solve the problem it is necessary to introduce a model of signal allowing tests of systems. This model will include:
 - propagation effects (anisotropy,),
 - antenna effects.

Hypothesis : only one transmitted signal



- **INTRODUCTION and OBJECTIVES**
- **IONOSPHERIC PROPAGATION**
 - Ionospheric profiles
 - Forecast models
 - **LOCAPI software**
 - (Logiciel de calcul des prévisions ionosphériques)
 - **Applications of LOCAPI**
- **MODELLING OF IONOSPHERIC CHANNELS: THE HF SIGNALS**
- **EXPERIMENTAL RESULTS**
- **CONCLUSION**

Ionospheric profiles





The forecast software

Software	firm	Objective	Profile	Main output parameters
PRIME	COST 238	- To develop models of the ionosphere over Europe	DGR (latest version) (Di Giovanni and Radicella) (Rad95)	Complete work (see action 238 PRIME Final report, 1999)
ASAPS	IPS (Australia)	- Help to link establishment	Empirical model [Col92]	- Number of paths, - Angle of arrival, - Level of the signals.
VOACAP	NTIA/ITS (USA)	- Help to link establishment	IONCAP model [Spa95]	- Number of paths, - Angle of arrival, - Level of the signals, - Group path delay.
LOCAPI	IETR University of Rennes 1 (France)	- Help to link establishment - Accurate determination of parameters for a link - Single site location	Multi-quasiparabolic model [Bro96]	For each O and X mode: - Number of paths, - Angle of arrival, - Magnitudes of the signals, - Group path delay.

- Equations used in LOCAPI

D: distance transmitter-receiver

r₀: radius of the earth

r_{m_i}: radius corresponding to the maximum of the i layer

y_{m_i}: semithickness of the i layer

n(r): phase refractive index

(more generally the refractive index is defined for the two propagation modes O and X: n₊ and n₋)

N_e(r) : electron density profile

r: distance to the earth centre

r_t: distance between the centre of the earth and the reflection point

E : elevation of the incoming wave

c: light celerity

τ_g: group delay

$$N_e(r) = \sum_{i=1}^8 N_{m_i} \cdot \left[1 \pm \left(\frac{r - r_{m_i}}{y_{m_i}} \right) \cdot \left(\frac{r_{m_i} - y_{m_i}}{r} \right)^2 \right]$$

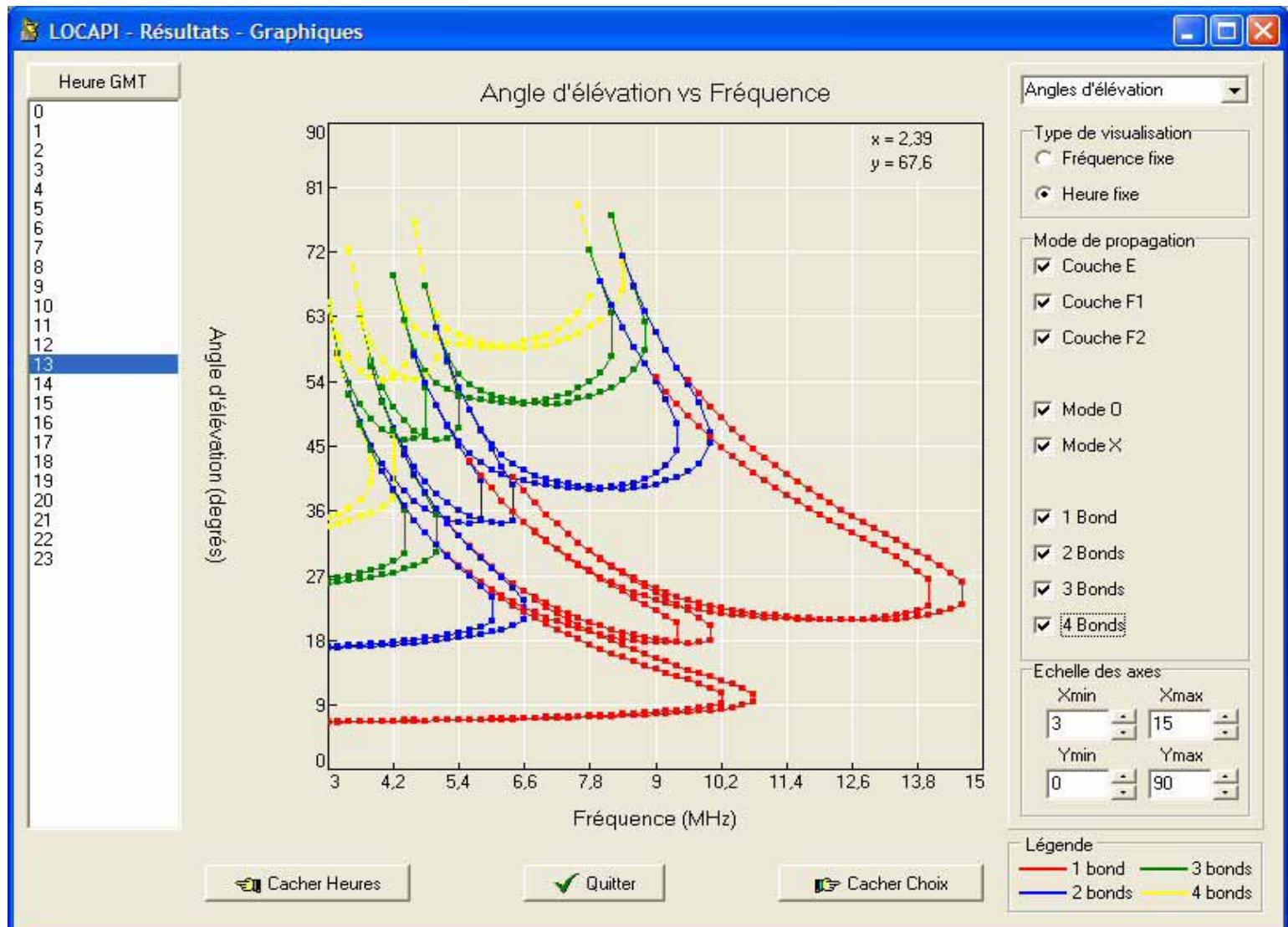
$$n^2(r) = 1 - \frac{80,62 \cdot N_e(r)}{f^2}$$

D = 2.r₀².cos²(E).
One hop $\int_{r_0}^{r_t} \frac{dr}{r \sqrt{n^2(r).r^2 - r_0^2 \cdot \cos^2(E)}}.$

$$n(r_t).r_t = r_0 \cdot \cos(E)$$

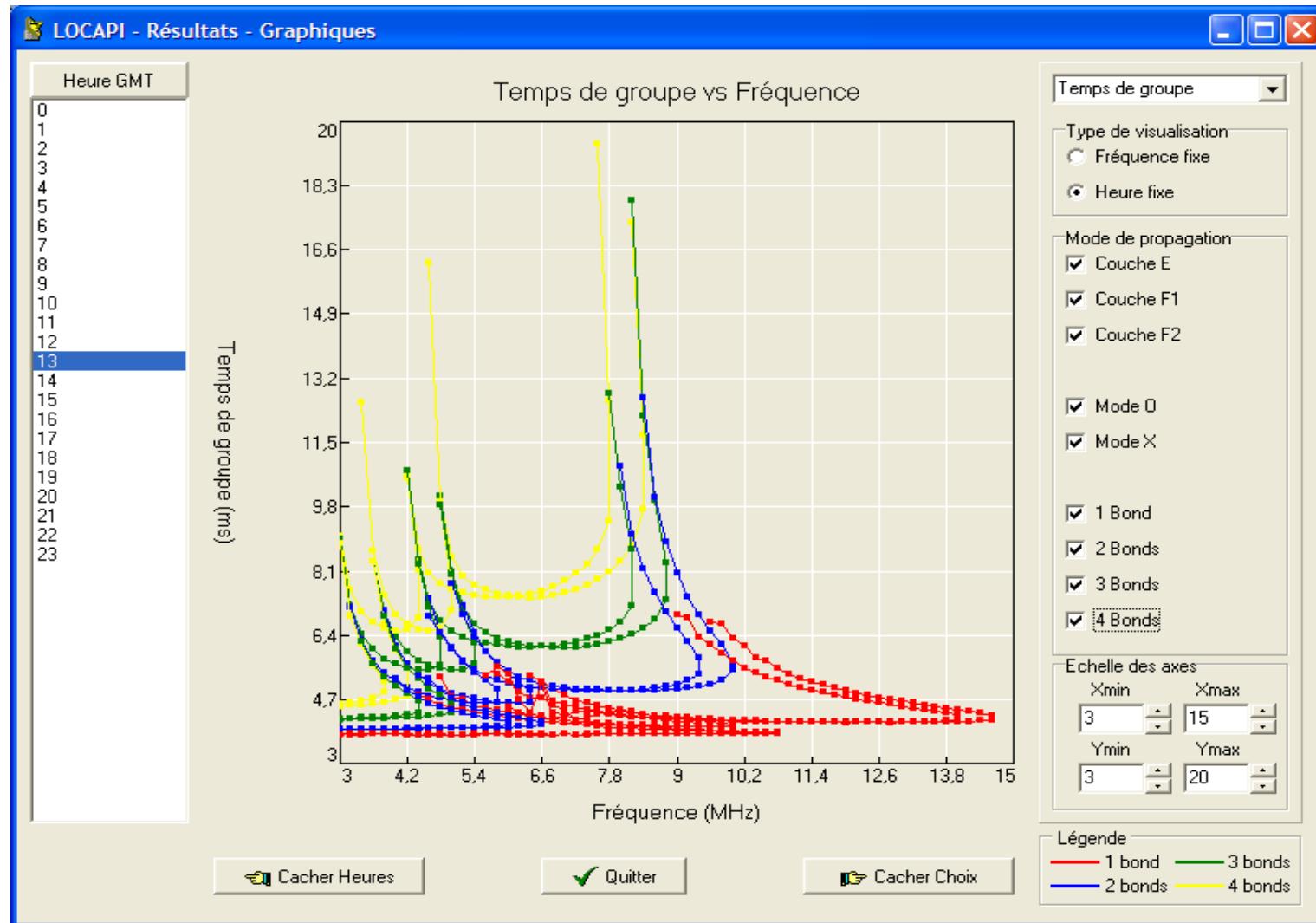
$$\tau_g = \frac{2}{c} \cdot \int_{r_0}^{r_t} \frac{r \cdot dr}{\sqrt{n^2(r).r^2 - r_0^2 \cdot \cos^2(E)}}$$

Locapi software: results (Elevation vs frequency)



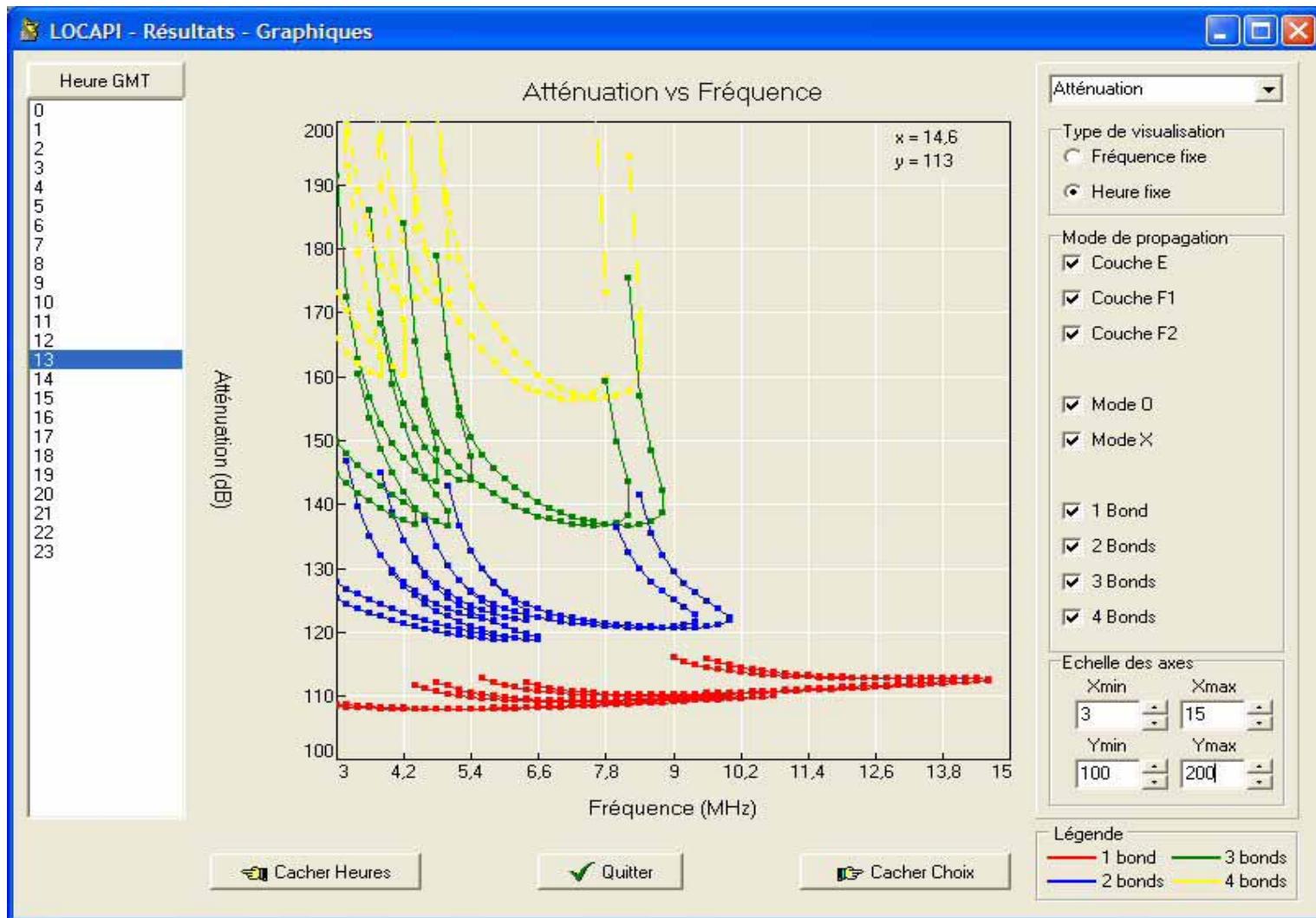
link Rome-Paris, january 2005

Locapi software: results (group delay vs frequency)



link Rome-Paris, january 2005

Locapi software: results (attenuation vs frequency)

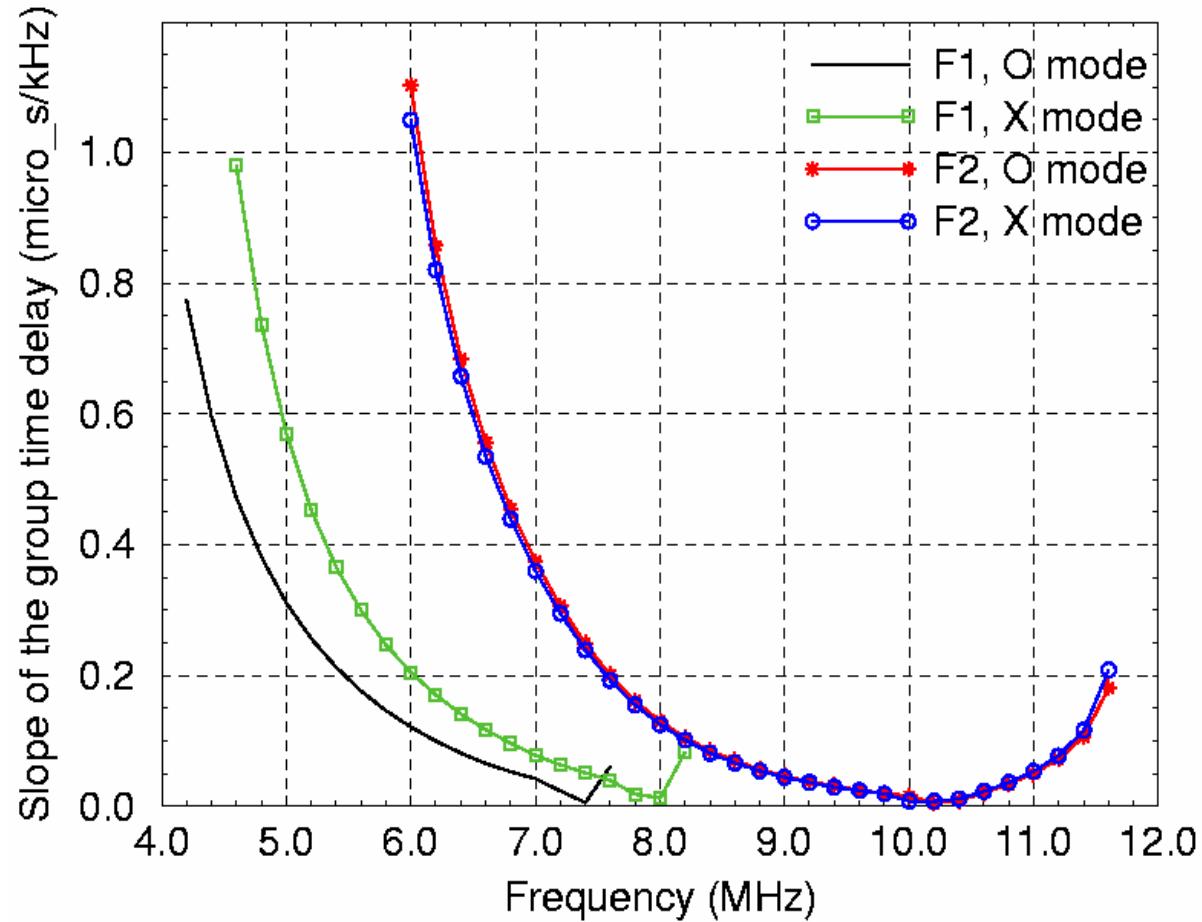


link Rome-Paris, january 2005

- LOCAPi applications

Known variable	Calculus	Application	Note
n(r) and D known (fixed frequency)	Determination of the E angle(s)	Direction finding	Several angles can be obtained
E and D known (fixed frequency)	Determination of n(r)	Electron density profile determination	Updating profile, need of complementary informations
n(r) and E (and azimuth) known (fixed frequency)	Determination of D	Location of transmitters (SSL)	difficulty: determination of the number of hops (dispersivity)
n(r) and E known (variable frequency)	Group delay τ_g versus frequency and slope of the group time delay/f (SGTDF)	Dispersion bandwidth determination	

Locapi software: results (help to the determination of the dispersion bandwidth)



Variation of the SGDF versus frequency (Valensole (5.59°E – 43.5°N) – Monterfil (2°W – 48.03°N), 12h00 UT, 02/1998).

$$SGTDF = \frac{\partial \tau_g}{\partial \omega_0} = K \text{ in } s/(rad/s)$$

$$2\pi \cdot B \cdot K < T_s / 2$$

$$T_s \sim 1/B$$

B modulation bandwidth, T_s symbol duration

$$4\pi \cdot B^2 \cdot K < 1 \text{ (Sunde 1961)}$$

for a simple digital amplitude modulation

Carrier frequency (MHz)	K (SGTDF)		Dispersion bandwidth B (kHz) (Minimum)
	μs/kHz	s/Hz	
8	0,2	0,2 10^{-9}	20
9	0,05	0,05 10^{-9}	40
10	0,02	0,02 10^{-9}	63

- **INTRODUCTION and OBJECTIVES**
- **IONOSPHERIC PROPAGATION**
- **MODELLING OF IONOSPHERIC CHANNELS: THE HF SIGNALS**
 - **Scalar models**
 - **Vectorial models**
 - **The antenna functions**
 - **Examples of results**
 - **Software for system simulations**
- **EXPERIMENTAL RESULTS**
- **CONCLUSION**

- **The scalar models (SISO: single input, single output)**

- Watterson
- Vogler and Hoffmeyer
-
- DRM (Digital Radio Mondiale)

Drawback:

in these models:

- anisotropy and antennas effects are not taken into account,
- a single magnetoionic component is usually simulated,
- a limited number of propagation modes are allowed

- **The vectorial models (SIMO, and MIMO, multiple input, multiple output)**
 - are based on a deterministic scalar model
 - take into account the effects of:
 - antenna(s)
 - polarisation and anisotropy of the ionospheric medium

So the channel includes the antennas

- **Scalar signal for one mode**

Transmitted signal

$$e(t) = m(t)e^{j\omega_0 t}$$

Received signal

$$s_{rk}(t) = A_k \ m(t - \tau_{gk}) e^{j\omega_{rk}(t - \tau_{pk})} + n_k(t)$$

$$\omega_{rk} = \omega_0 + \Delta\omega_{rk}$$

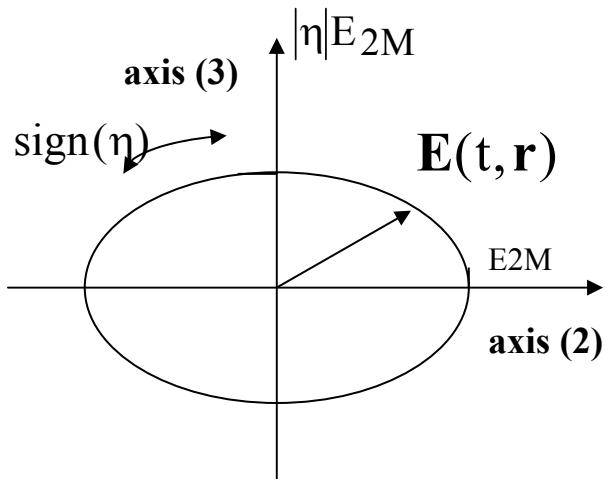
$$\Delta\omega_{rk} = 2\pi \{ \Delta f_{ok} + a E_k \cos(2\pi t/T + \Psi_k) \}$$

From previous atmospheric gravity waves measurements

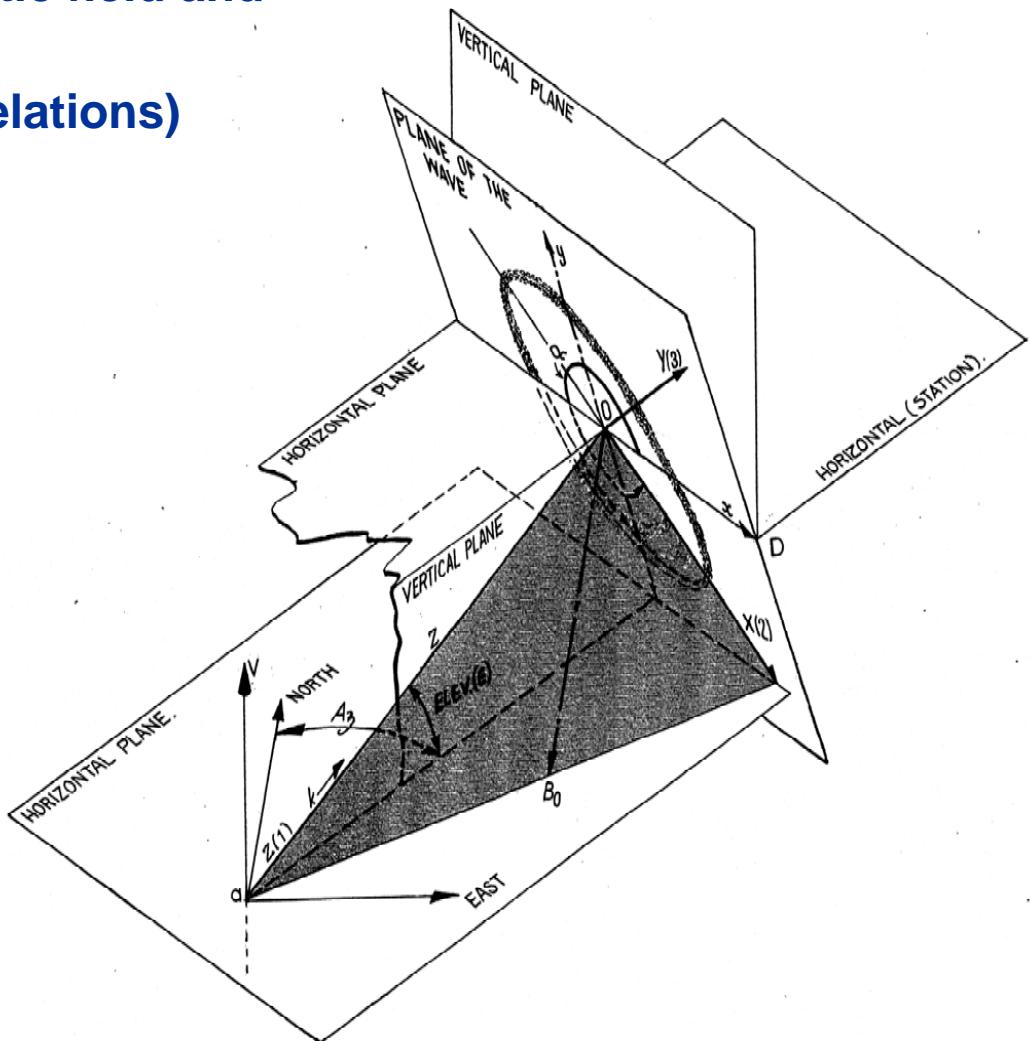
where A_k is the attenuation related to the kth mode,
 τ_{gk} is the group delay corresponding to the kth mode,
 ω_{rk} is the received angular frequency including the Doppler shift,
 τ_{pk} represents the phase delay for the considered mode
 $n_k(t)$ represents the observed noise for the mode
 E_k : is the elevation angle of the mode
T: typical period of an atmospheric gravity wave (15 mn for example)
 Ψ_k : relative phase

Modelling of ionospheric channels: the HF signals

- Relation between electromagnetic field and signal
(Maxwell equations + Budden relations)

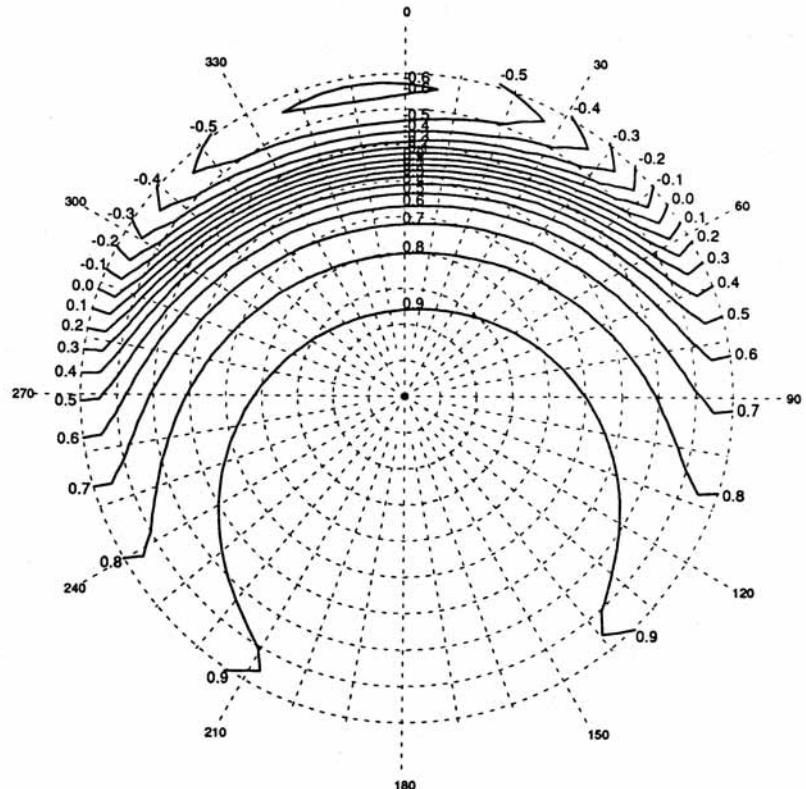


Definition of the polarization ratio η



Modelling of ionospheric channels: the HF signals

- Polarisation chart for Paris (France) at a frequency of 6 MHz (*from Bertel et al 1989*)
- When $\eta = 0$ the polarisation equations show that the two modes are linearly polarised, the O mode lies along axis (2) and the X mode lies along axis (3).
- When η is comprised between 1 and 0,9 the polarisation can be considered as quasi-circular



Modelling of ionospheric channels: the HF signals

- Relation between electromagnetic field and signal (for one antenna)

$$\mathbf{E}(\mathbf{t}, \mathbf{r}) = \begin{pmatrix} 0 \\ 1 \\ \mathbf{j}\eta \end{pmatrix} \mathbf{s}_r(\mathbf{t}, \mathbf{r})$$

$$s_r(t) = A_m(t - \tau_g) e^{j\omega_r k(t - \tau_p)} + n(t)$$

$$\mathbf{x}_r(\mathbf{t}) = \mathbf{V} \cdot \mathbf{R}(\theta) \mathbf{Q}(\alpha) \begin{pmatrix} 0 \\ 1 \\ \mathbf{j}\eta \end{pmatrix} \mathbf{s}_r(\mathbf{t})$$

$\mathbf{V}[1,3], \mathbf{R}[3,3], \mathbf{Q}[3,3]$

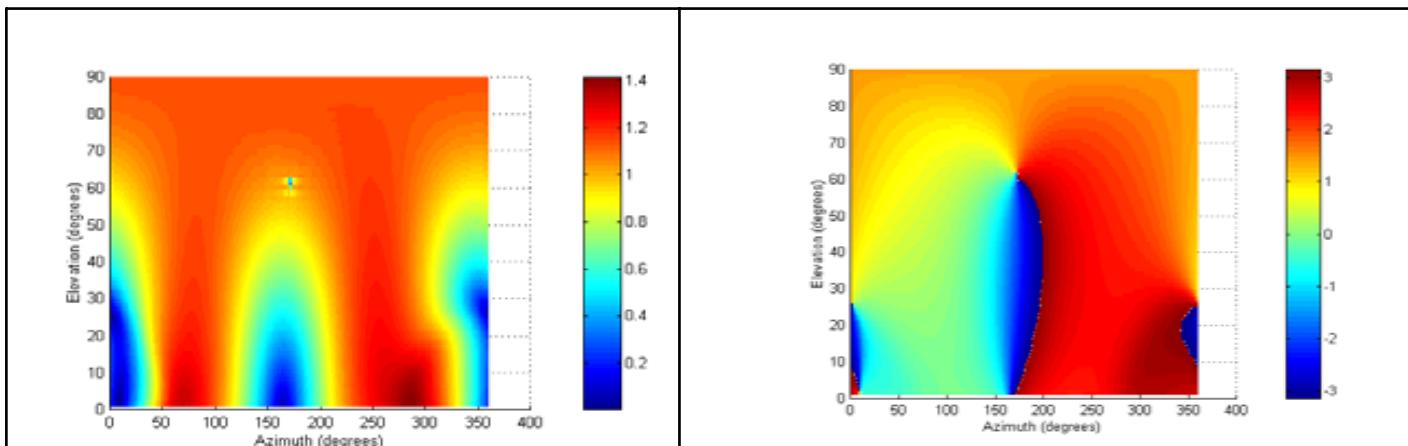
$$\mathbf{x}_r(\mathbf{t}) = \mathbf{F}(\theta) \mathbf{s}_r(\mathbf{t})$$

$\theta(EI, Az)$

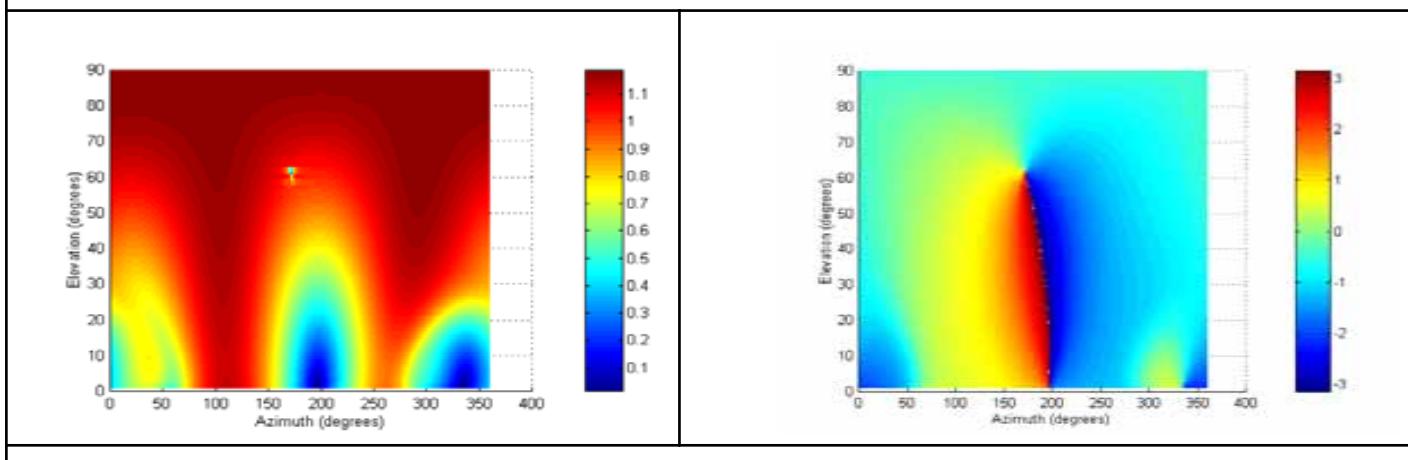
$F(\theta)$ is a complex function of :

- the antenna type and ground effect
- the polarisation of the incoming wave
- the mode (O or X) of the incoming wave

- Theoretical Fik antenna functions (use of NEC2)

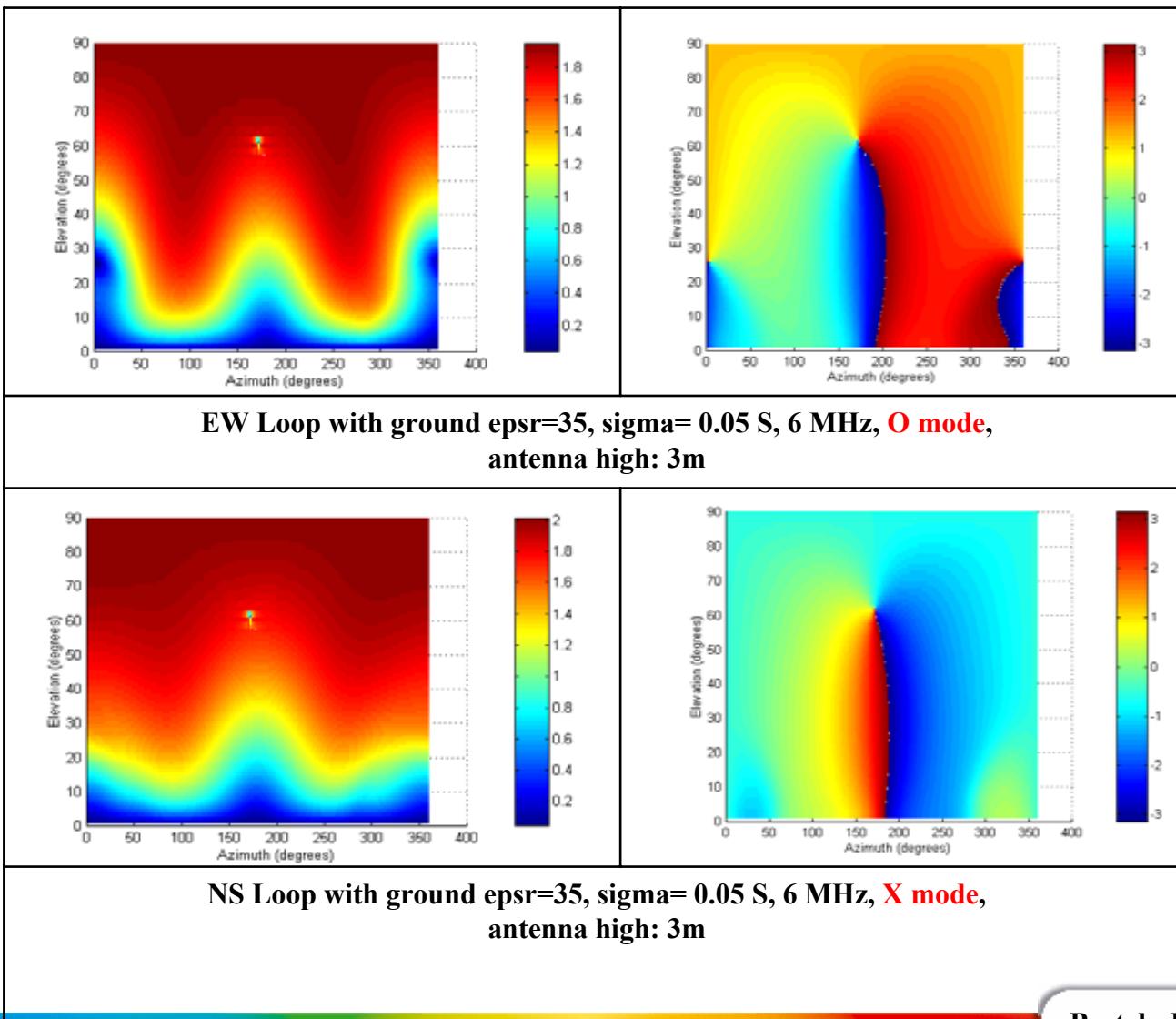


EW Loop, free space, 6 MHz, **O mode**, relative amplitude, angles in radians



EW Loop, free space, 6 MHz, **X mode**, relative amplitude, angles in radians

- Theoretical Fik antenna functions (use of NEC2)



- Signal models

G_{lk} is related to a transmitting antenna l and the mode k, F_{ik} to the receiving antenna i and the same mode, only one transmitted signal

MIMO systems with space diversity

$$X_{rl} = \sum_{k=1}^{ns} G_{lk} e^{j\gamma_{lk}} F_{ik} e^{j\delta_{ik}} s_{rk}(t) + n_i(t)$$

MIMO systems without space diversity

$$X_{rl} = \sum_{k=1}^{ns} G_{lk} F_{ik} s_{rk}(t) + n_i(t)$$

SISO systems

$$X_r = \sum_{k=1}^{ns} d_k s_{rk}(t) + n_i(t) \quad \text{Scalar model}$$

$$X_{rl} = \sum_{k=1}^{ns} G_{lk} F_{ik} e^{j\delta_{ik}} s_{rk}(t) + n_i(t)$$

$$X_{ri} = \sum_{k=1}^{ns} c_k F_{ik} e^{j\delta_{ik}} s_{rk}(t) + n_i(t)$$

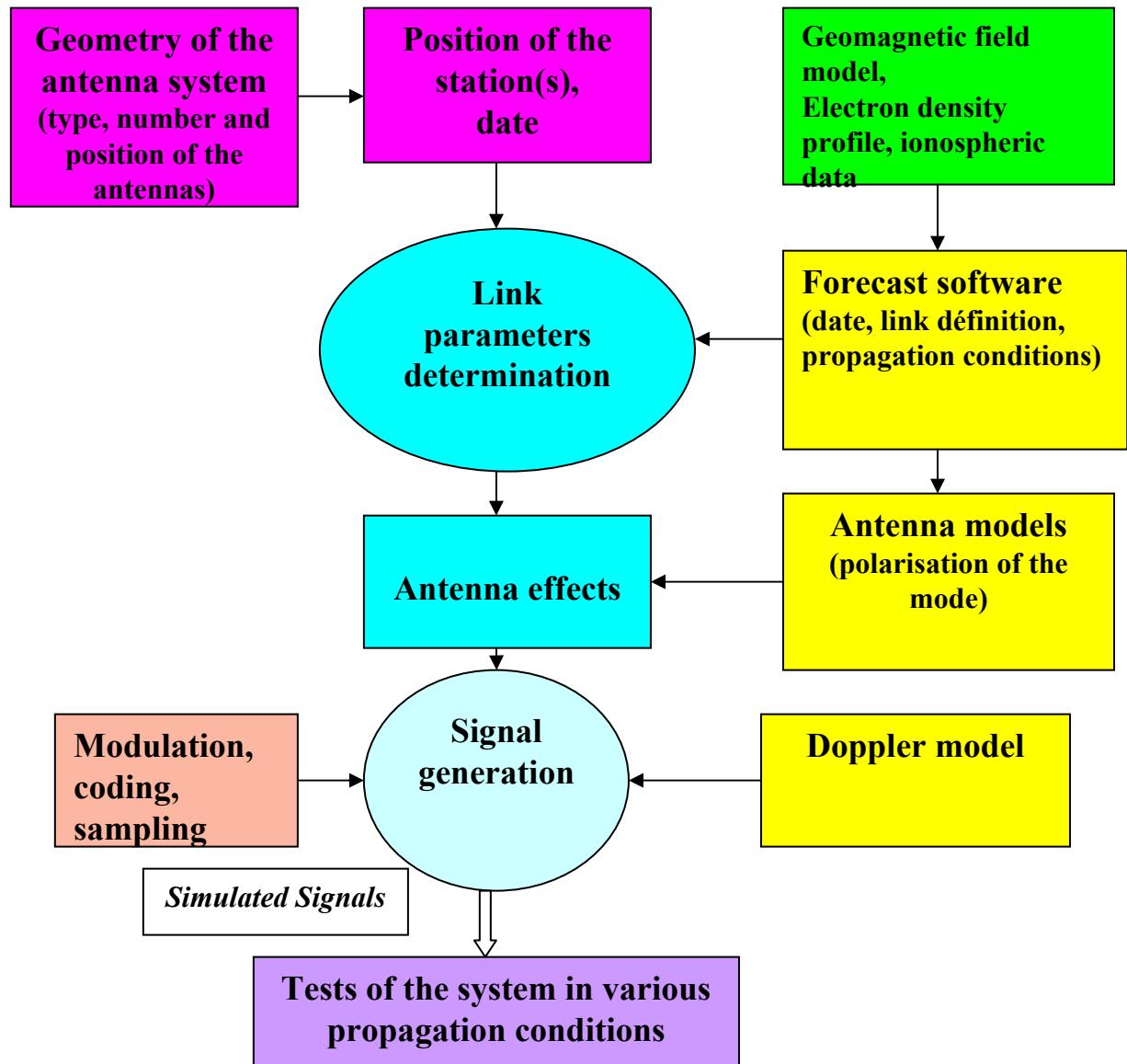
SIMO systems with space diversity

Collocated antennas without space diversity

$$X_i = \sum_{k=1}^{ns} c_k F_{ik} s_{rk}(t) + n_i(t)$$

d_k and c_k are complex constants, γ and δ are the phase differences related to the k mode and the location of the antennas in the arrays

HF System Simulator



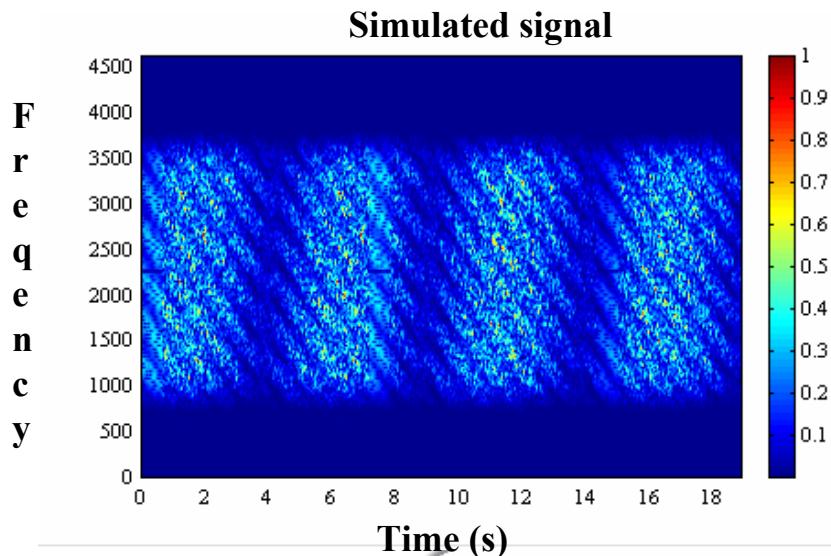
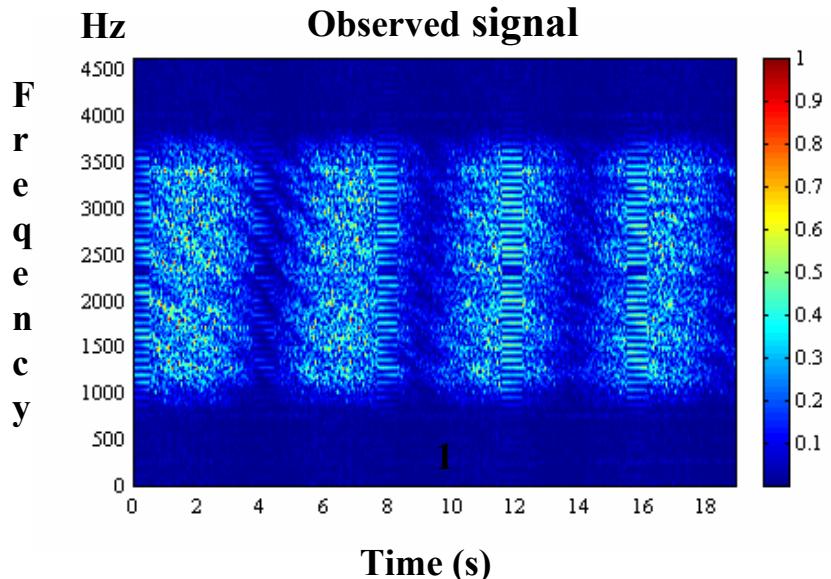
Modelling of ionospheric channels: the HF signals

- The instantaneous power spectral density DSPT(t,f) can be determined from the observed signals by the expression:

$$\text{DSPT}(t,f) = E\{ |X(t,f)|^2 \}$$

Figures from Bisiaux (PHD 2001)

Link : Poitiers Monterfil



Modelling of ionospheric channels: the HF signals

Time-frequency analysis of the second signal
(received by V_{EW} and V_{NS} active vertical
loops antennas) with IF of 2250 Hz

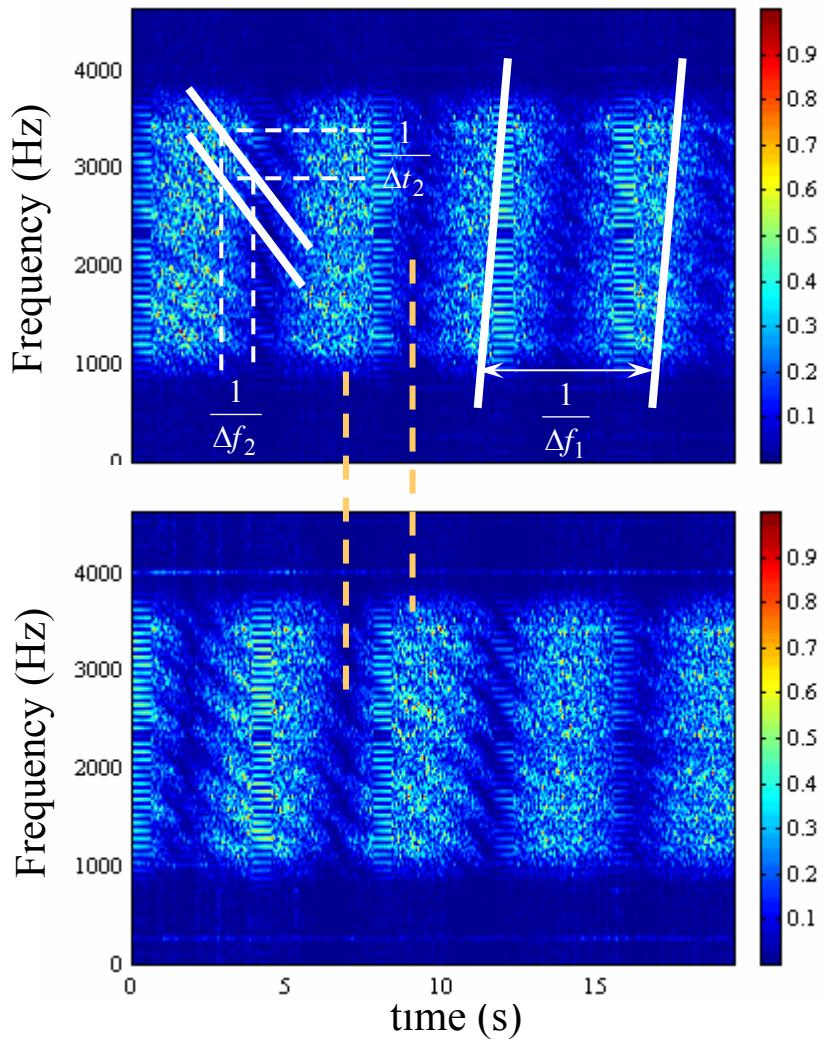
O and X modes identified

(from : Bisiaux et Bertel, AAS, 2001)

An estimation of the differential doppler shifts
and the differential group delays can be
extracted from these figures (Salous et Bertel,
PSIP,1999)

$$\Delta t_1 = 0.04 \text{ ms} \quad \Delta f_1 = 0.2 \text{ Hz}$$

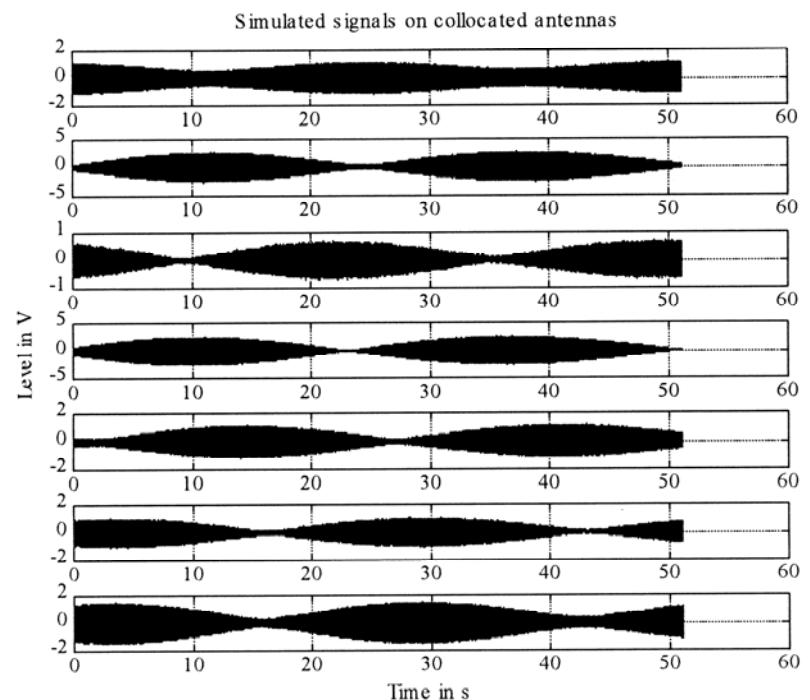
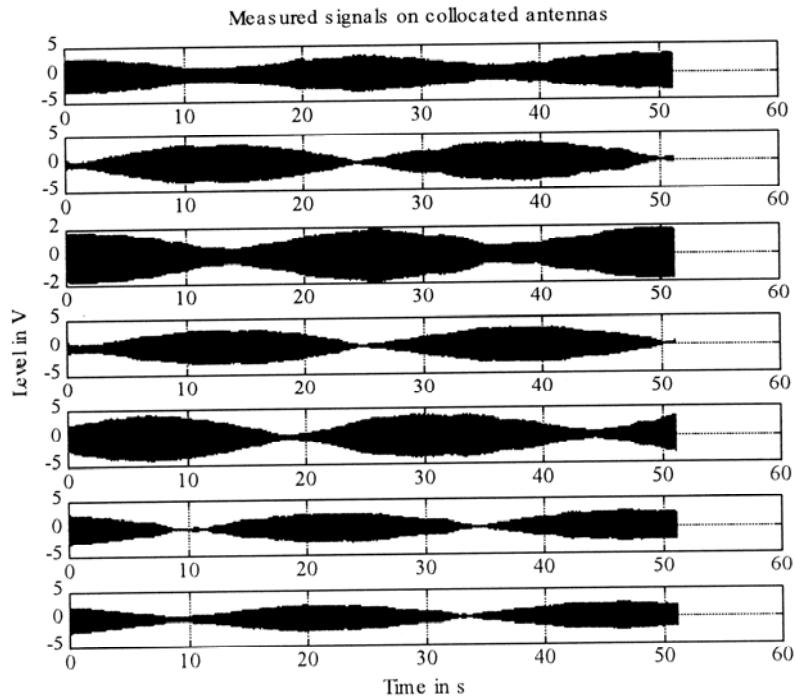
$$\Delta t_2 = 2.2 \text{ ms} \quad \Delta f_2 = -1 \text{ Hz}$$



Link : Poitiers Monterfil

Comparison between observed and simulated signals

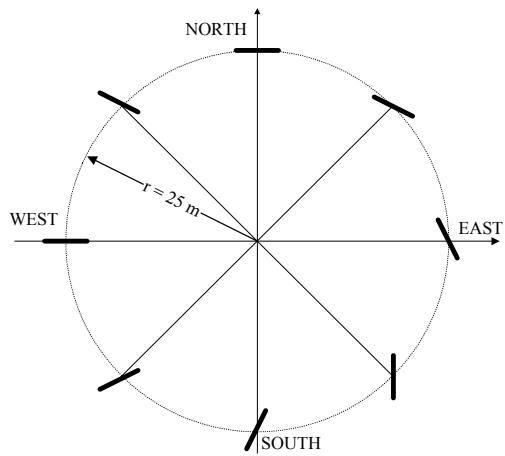
(from Le Meins et al, AAS, Monticello 1999)



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- **IONOSPHERIC PROPAGATION**
- **MODELLING OF IONOSPHERIC CHANNELS: THE HF SIGNALS**
- **EXPERIMENTAL RESULTS**
 - Description of used antenna arrays
 - HF transmission
 - DRM
 - Trilion (transmission d'images par liaisons ionosphériques)
 - Direction finding
 - Single site localisation
- **CONCLUSION**

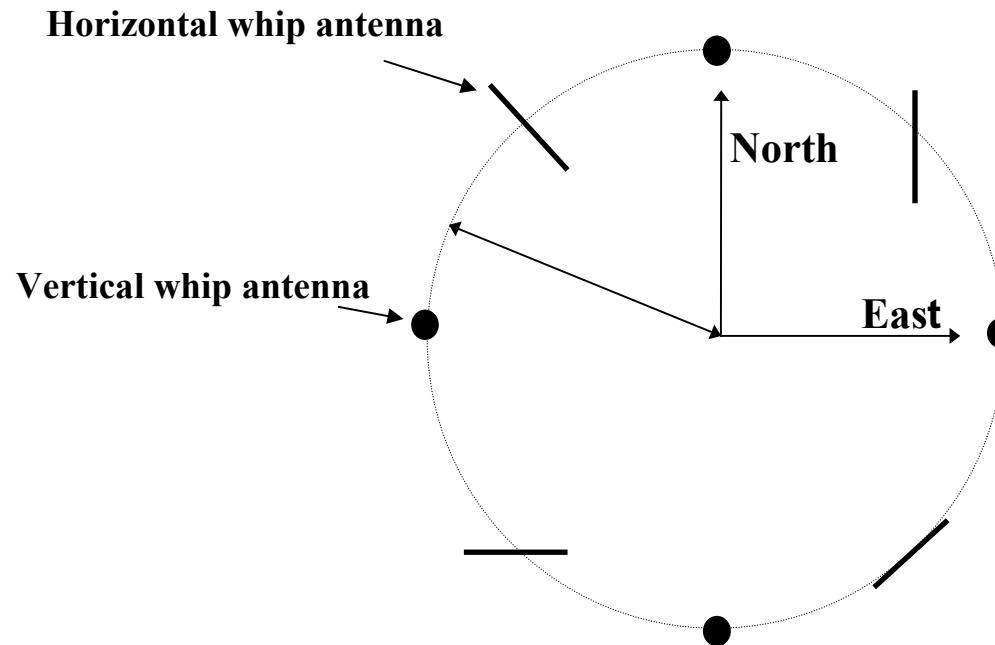
First array:

eight **active** loops, with
different orientations, equally
spaced around a circle with a
radius of 25 m



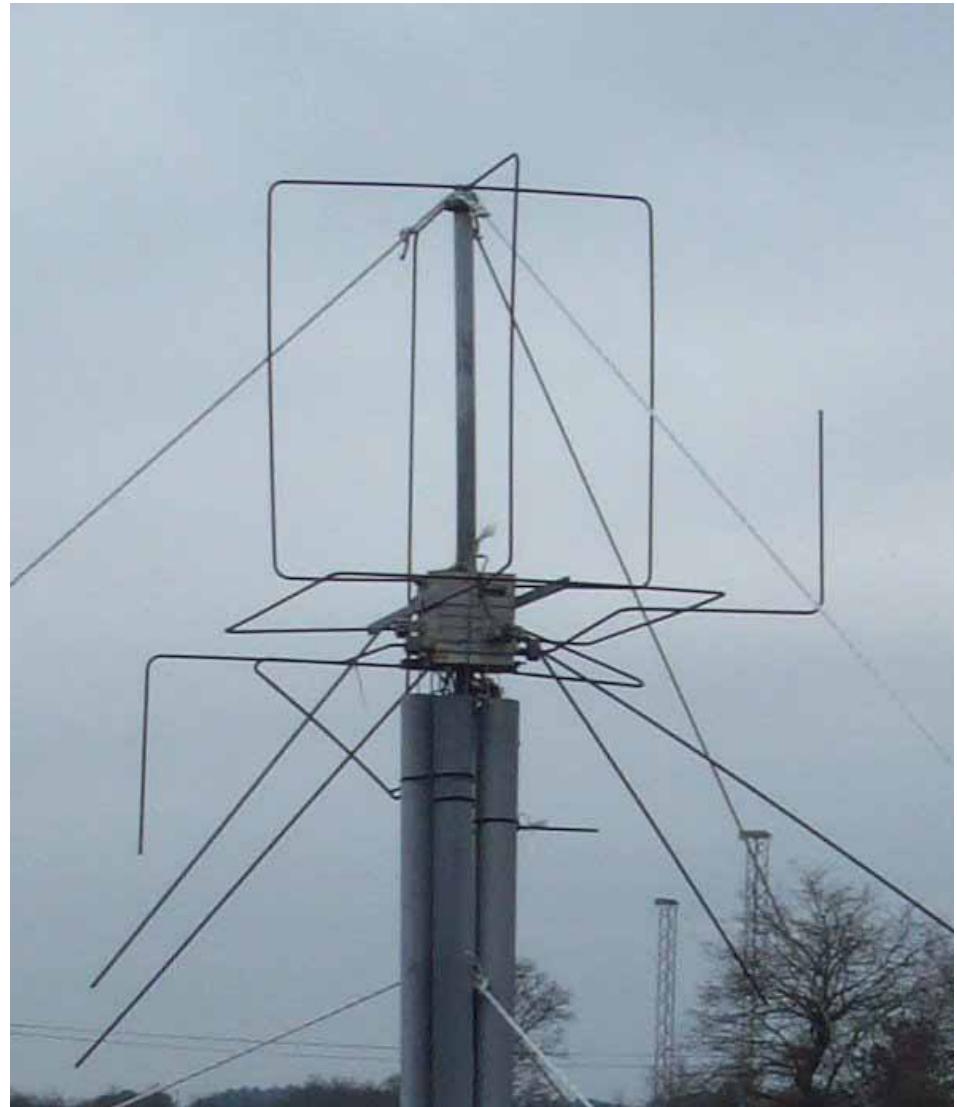
Antenna arrays description

- **Second array (*from Erhel et al, 2004*)**



Third array: the collocated sensor

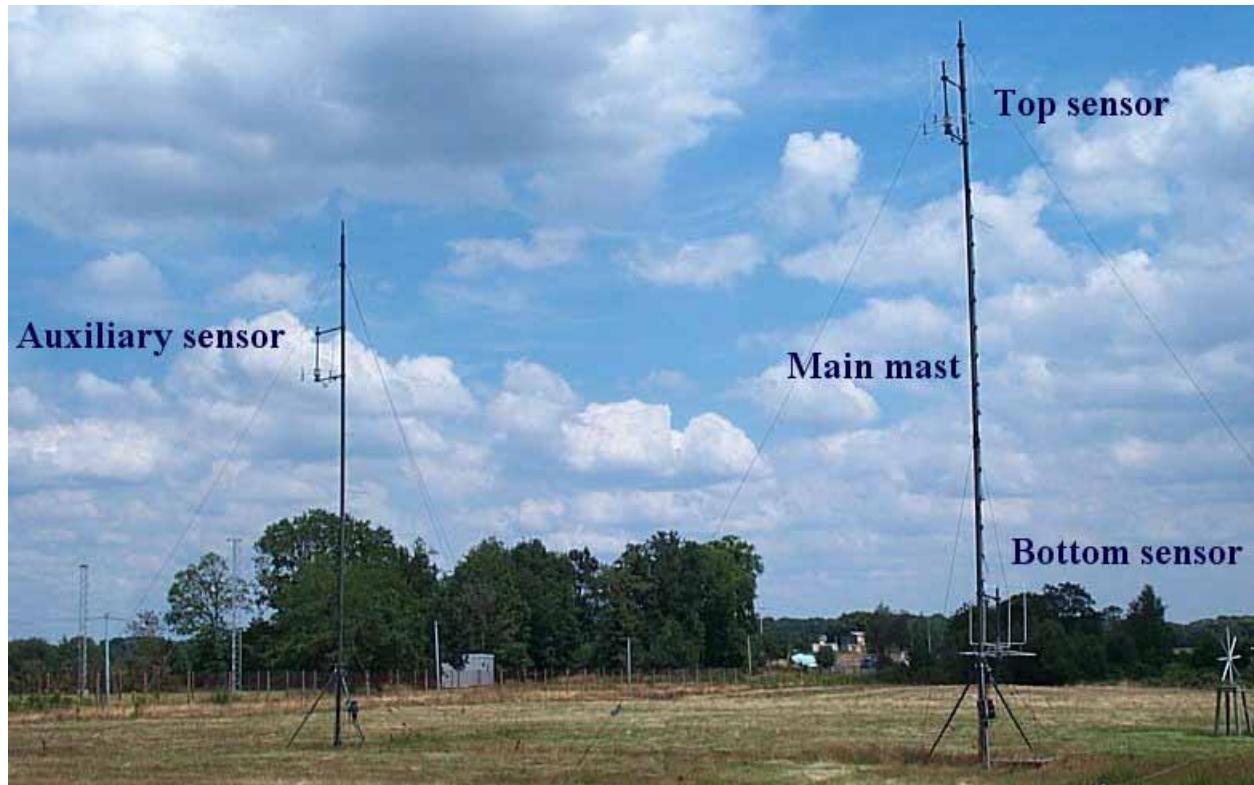
2 crossed vertical loops,
1 horizontal loop,
1 XYZ loop,
2 V dipoles,
1 vertical dipole
1 XYZ dipole



Patent: PCT FR00/03544

Antenna arrays description

Fourth array: *The last array uses three sets of sensors (Le Bouter, PHD 2004)*



Operational systems

Society and (Bandwidth)	Norm	Bite rate	Modulation	Particularity	BER (objective)
(3 KHz)	Standard militaire STANAG 5066 annexe G	9600 b/s	QAM 64	SISO system	10^{-3}
Harris (USA) (3 kHz)	Military standard MIL-STD-188-110B	9600 b/s (maximum)	QAM 64	With coding and interleaving SISO system	10^{-3}
Consortium DRM (4,5 to 10 or 20 kHz)	ETSI EN 302 245-2	26 kb/s 12 kb/s useful	COFDM+QAM (4, 16, 64) (subcarriers)	SISO system	10^{-4}
IETR, University of Rennes (3, 6, 9 or 12 kHz)	TESTS (TRILLION Project, image transmission)	9600 b/s up to 40 kb/s	QAM 16, QAM 64	Use of collocated or multi antennas for the receiving system, no interleaving or coding SIMO system	10^{-3}

The Digital Radio Mondiale has been set up for digital transmission in the broadcasting bands below 30 MHz. According to the robustness mode of propagation (A to D), for a coding rate of 0,6 and a QAM 64 modulation used, the bit rates are comprise between 8,7kb/s and 56kb/s; for a QAM16 modulation they are comprise between 6 kb/s and 38,8 kb/s in function of the spectrum occupancy (4,5 kHz to 20 kHz).

DRM robustness modes

Robustness mode	Typical propagation conditions	Preferred frequency bands
A	Ground-wave channels, with minor fading	LF, MF
B	Time- and frequency-selective channels, with longer delay spread	MF, HF
C	As robustness mode B, but with higher Doppler spread	Only HF
D	As robustness mode B, but with severe delay and Doppler spread	Only HF

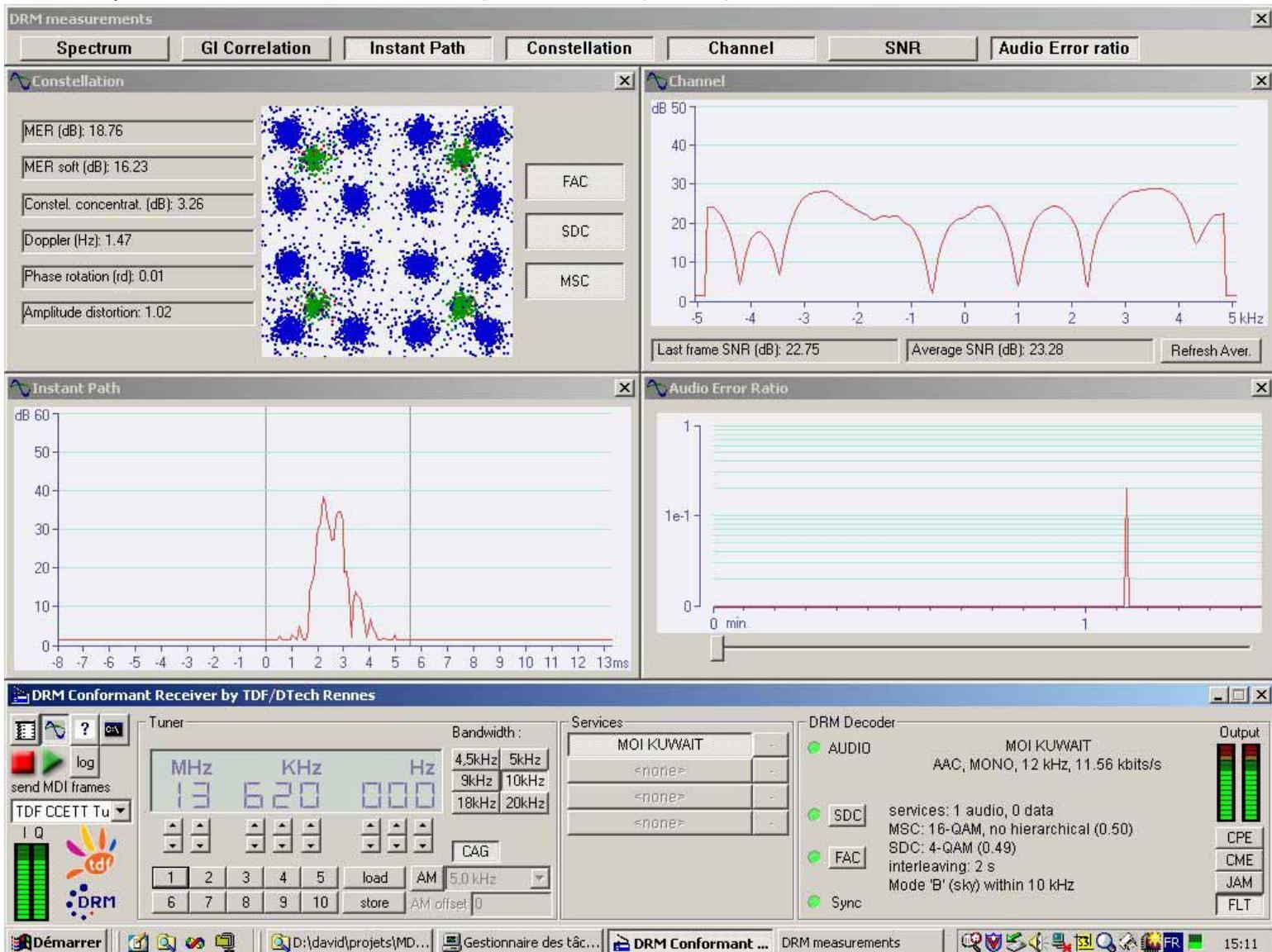
Bandwidths for DRM robustness mode combinations (kHz)

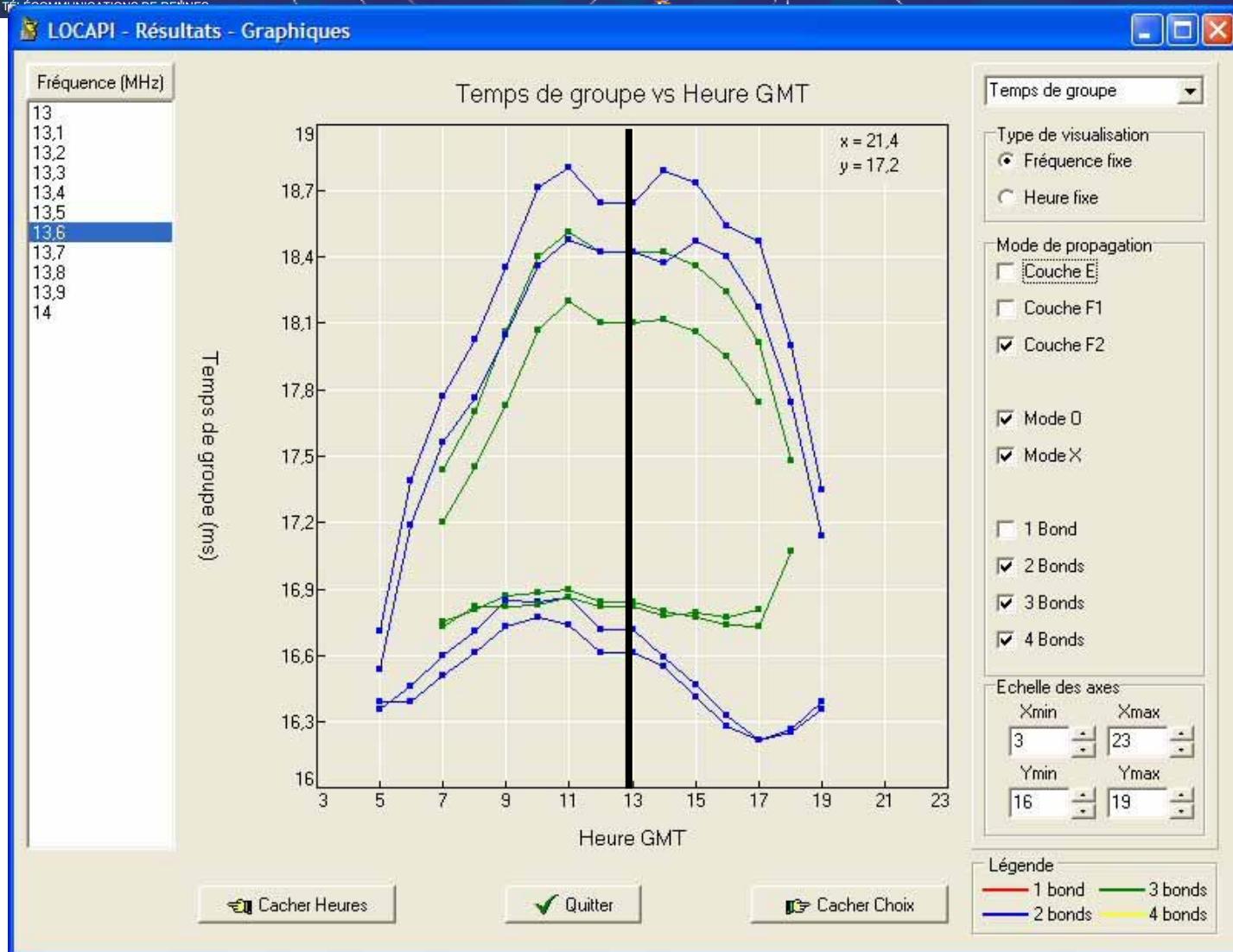
Robustness mode	Spectrum occupancy type			
	0	1	2	3
A	4.208	4.708	8.542	9.542
B	4.266	4.828	8.578	9.703
C	-	-	-	9.477
D	-	-	-	9.536
Nominal bandwidth (kHz)	4.5	5	9	10

From ETSI ES 2001 980 V2.1.1

Digital Radio Mondiale (DRM)

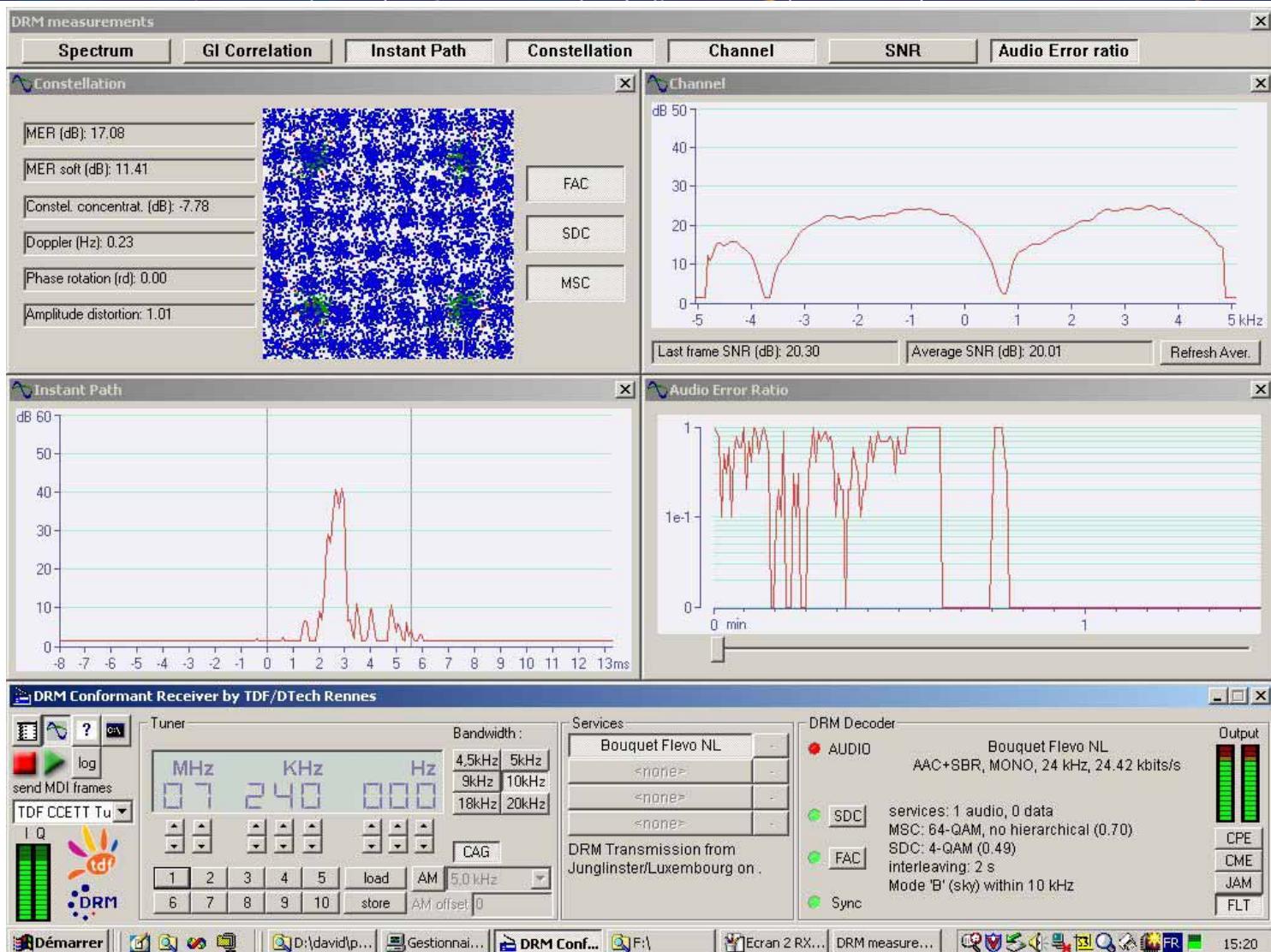
From TDF Rennes, Link: Kuwait-Rennes, 30/09/05, 13h, 13.620 MHz





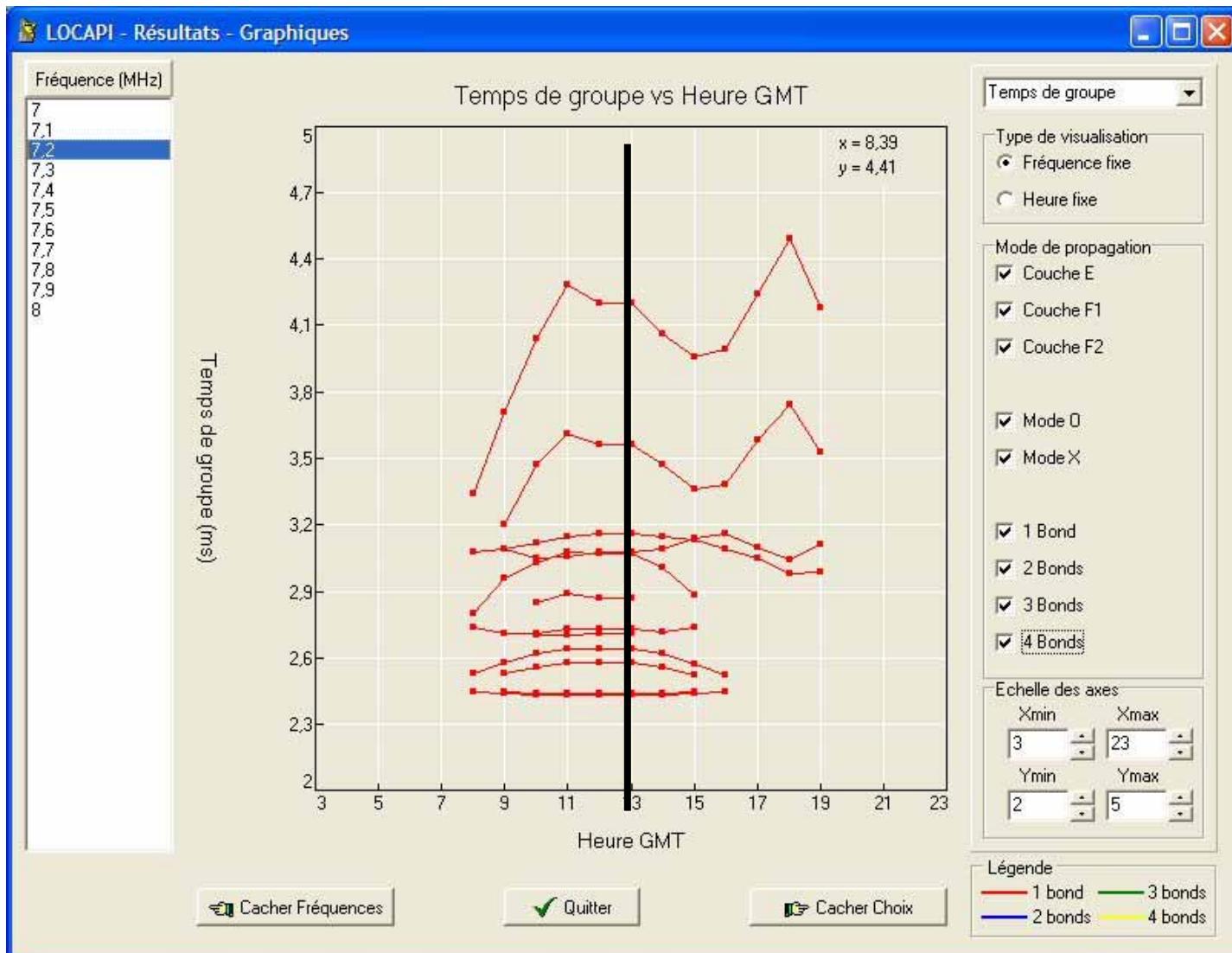
Link Kuwait Rennes, LOCAPI simulation

Digital Radio Mondiale (DRM)



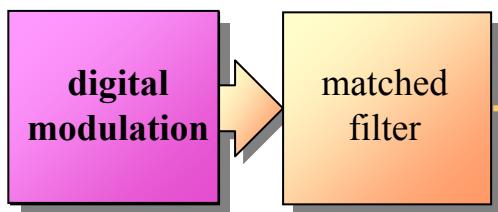
From TDF Rennes, Link: Flevo (NL)-Rennes, 30/09/05, 13h, 07.240 MHz

Digital Radio Mondiale (DRM)

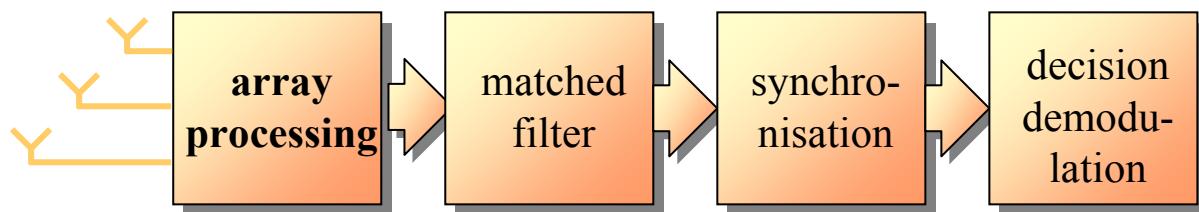


Link Flevo Rennes, LOCAPI simulation

transmitter

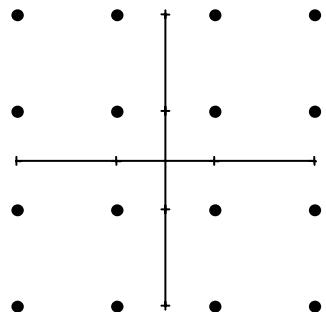


receiver

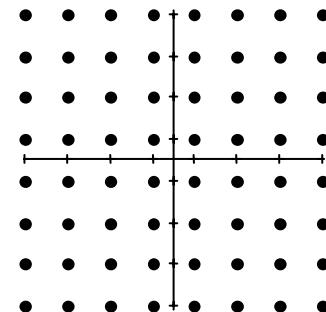


QAM (Quadrature Amplitude Modulation)

CONSTELLATION

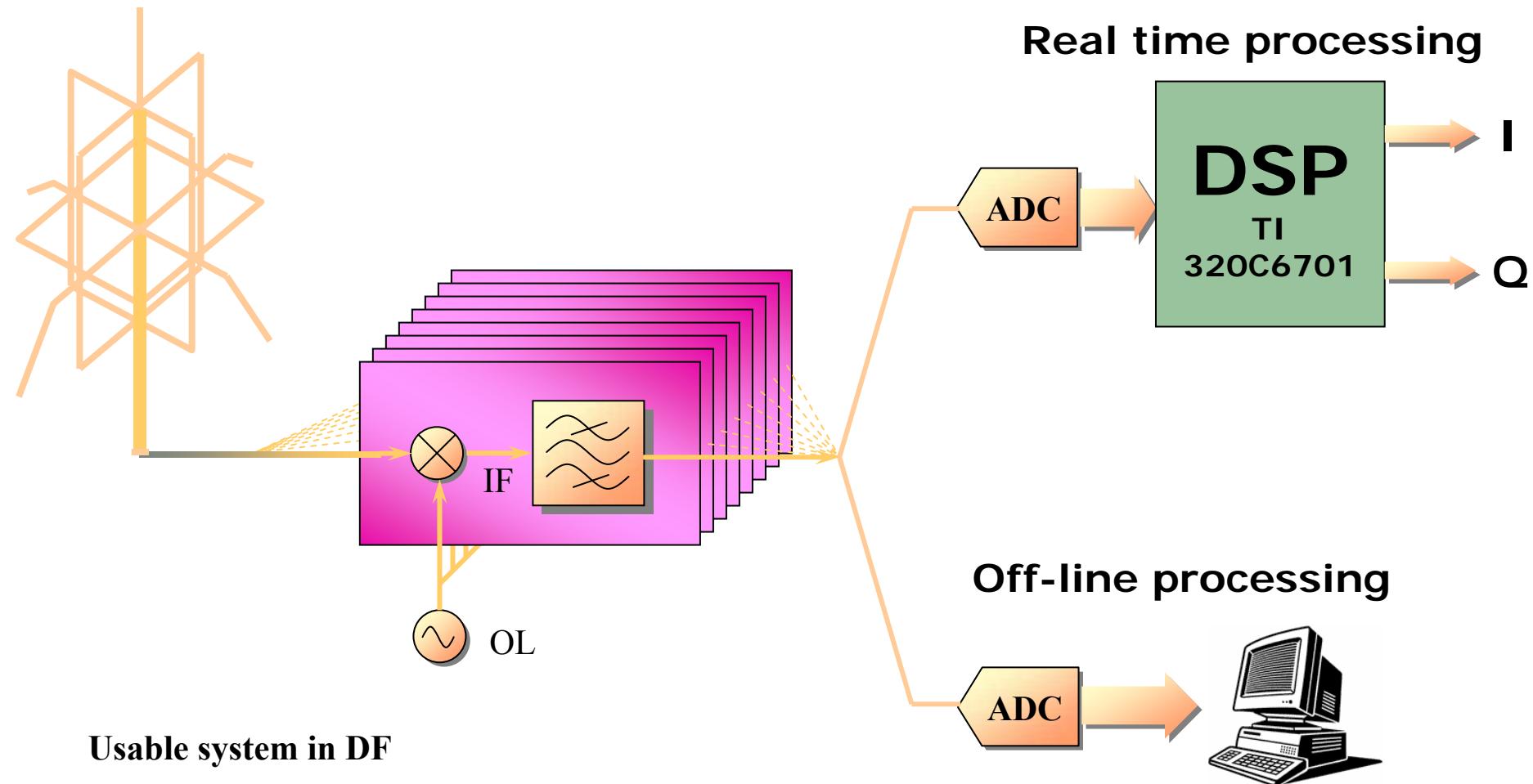


QAM-16



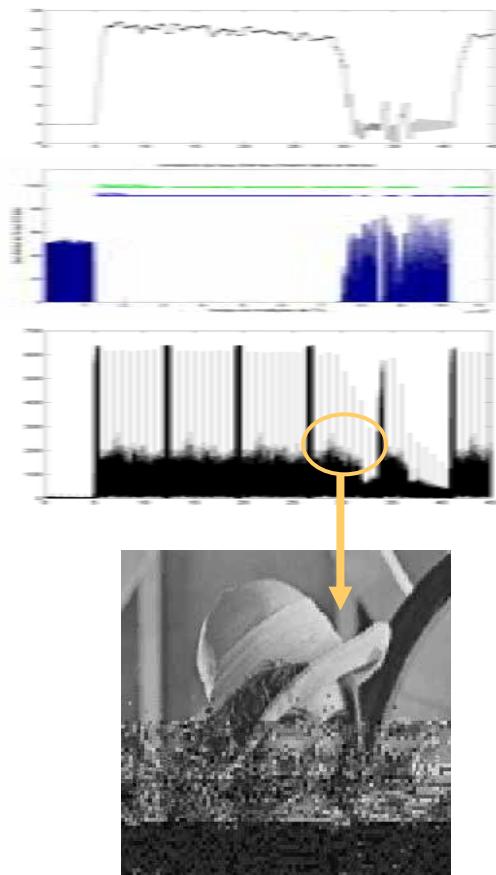
QAM-64

From Perrine et al, 2005, IES, Alexandria, 2005

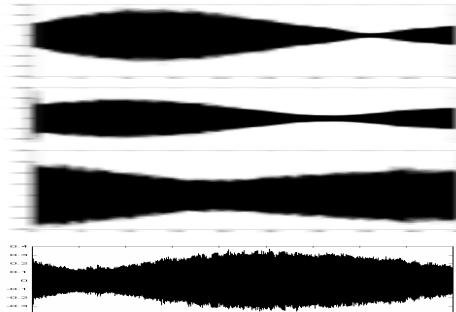


From Perrine et al, 2005, IES, Alexandria, 2005

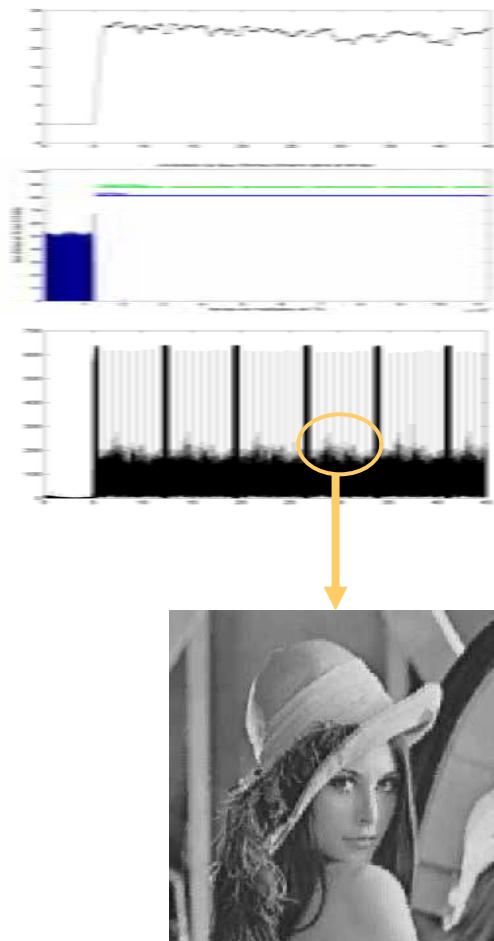
Results obtained using 3 antennas



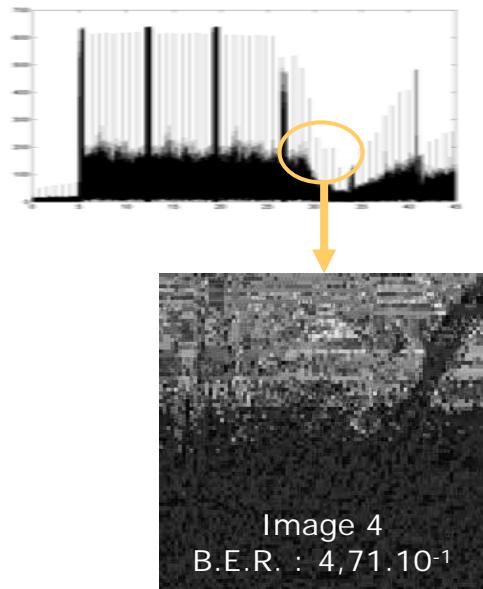
From Perrine et al, ECPS, 2005



Results obtained using 4 antennas



Results obtained using 2 antennas



Efficiency: typical examples of results (University of Rennes) obtained with antenna diversity

Modulation	QAM 16 (Valensole Monterfil)	QAM 64
Bandwidth		
3 kHz	9 700 b/s (LMS) 10 000 b/s (CMA) BER<3. 10-4 SNR: 3-30 dB SNR/bit after filtering : 18 dB	14 500 b/s (LMS) Poitiers Monterfil BER< 1,25 10-3 7,767 MHz SNR: 20 dB
6 kHz	19 400 b/s (LMS) 20 000b/s (CMA) BER<2,3 10-4	
9 kHz	29 100 b/s (LMS) 30 000 b/s BER< 2,3 10-3 8,847 MHz	43 344 b/s (LMS) Valensole Monterfil BER< 1,44 10-5
12 kHz	38 800b/s (LMS) 40 000b/s (CMA) BER 1,96 10-3 8,847 MHz	43 344 b/s (LMS) Valensole Monterfil BER< 1,88 10-4

Measurements parameters:

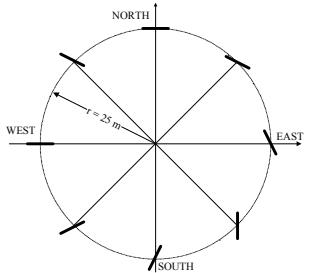
- **Array system: number and type of antennas, size and geometry of the array**
- **Duration of signal acquisition: from some milliseconds to several tens of seconds**
- **Bandwidth of the signal: carrier frequency, narrow band or wide band**
- **Type and duration method of the processing (real time or off-line processing)**
- **Utilization of other statistical processing**

Data:

- **Number of paths and/or modes, type of the mode (polarisation),**
- **Estimation of angles of arrival (azimuth, elevation)**
- **Typical error estimation**
- **Location of the transmitter if a particular software (like ray tracing) is available**

Radio direction finding techniques

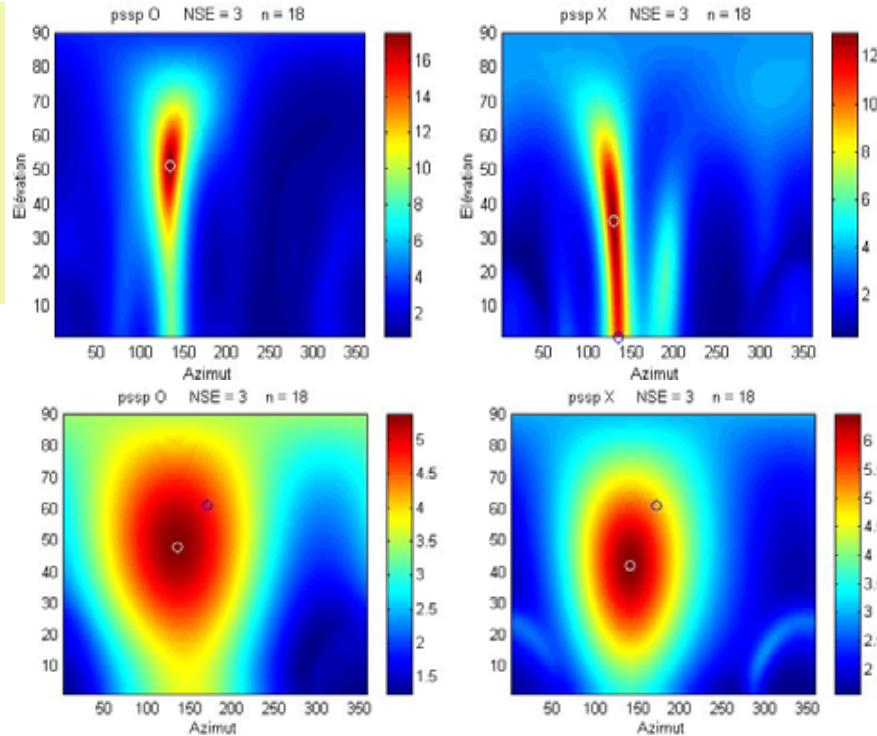
1



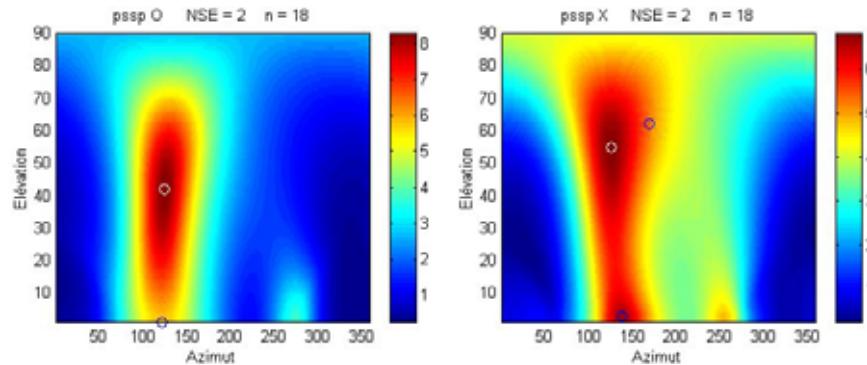
Position determination of the maximum(a) of the pseudo-spectrum(a), use of MUSIC modified algorithm



3



4



Radio direction finding techniques

Rough arrival
angles
measurements

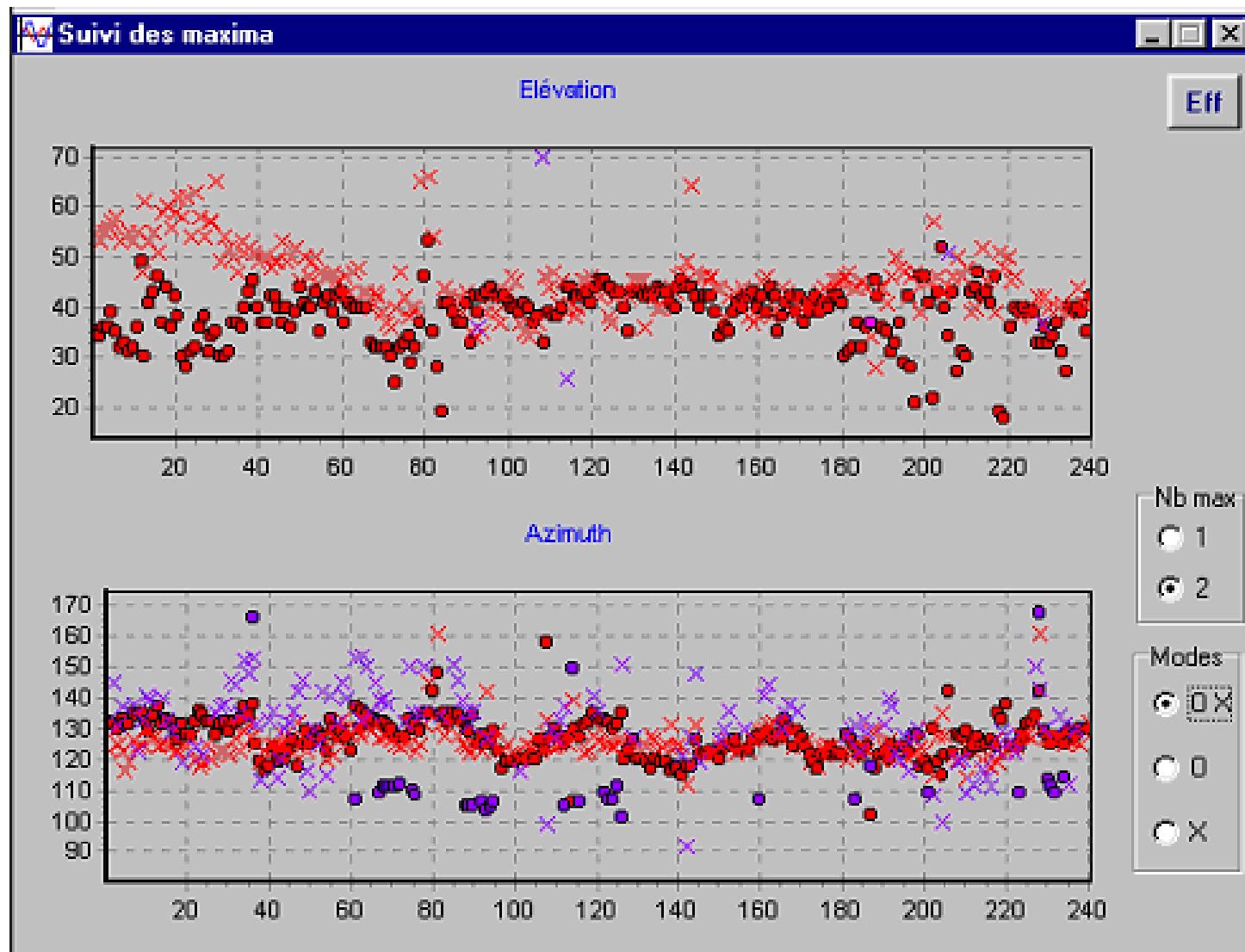
Link Valensole-
Monterfil (753 km)

Night (27-28 may
2004)

Time in mn

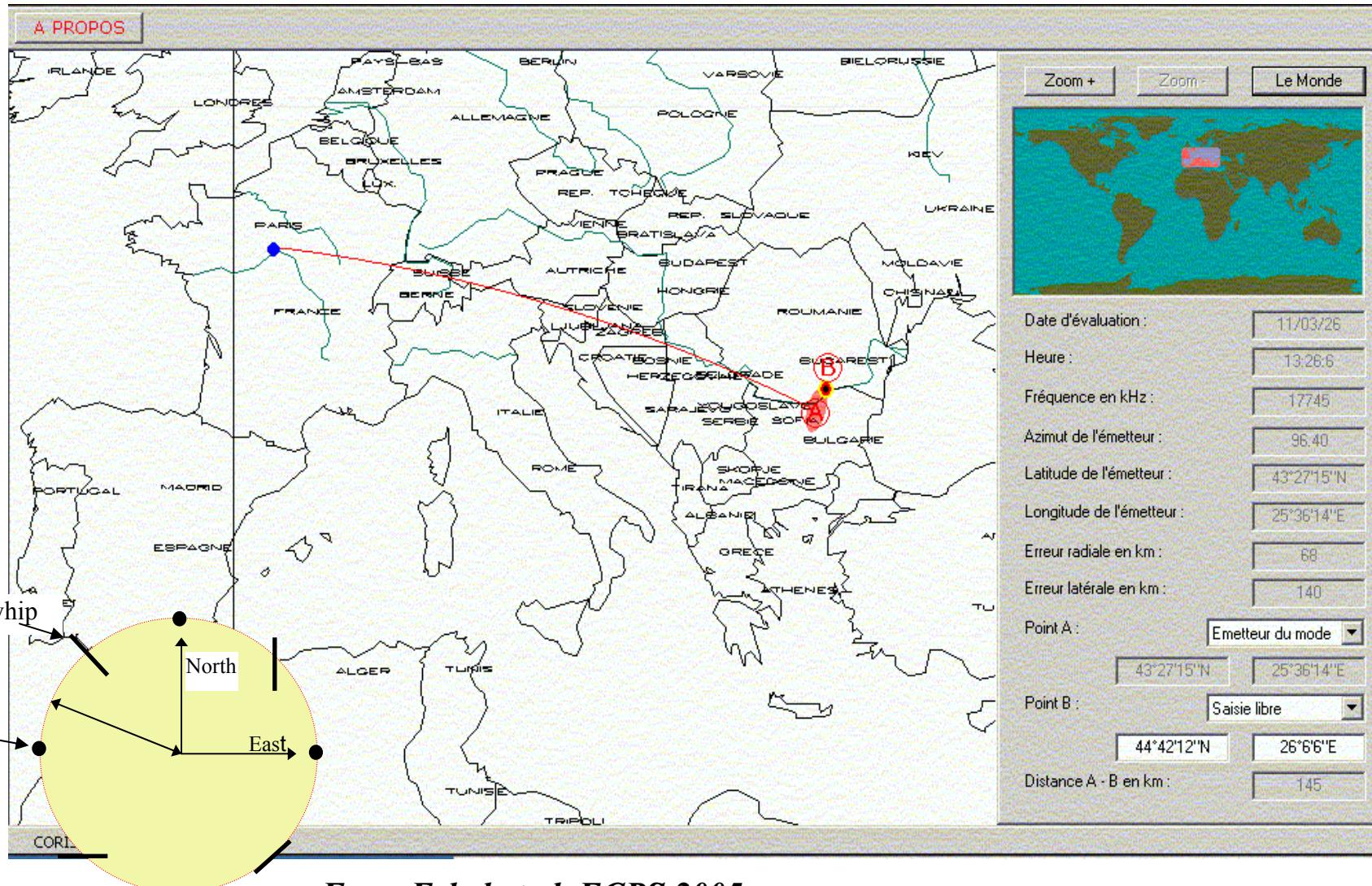
Angles in degrees

6,640 MHz



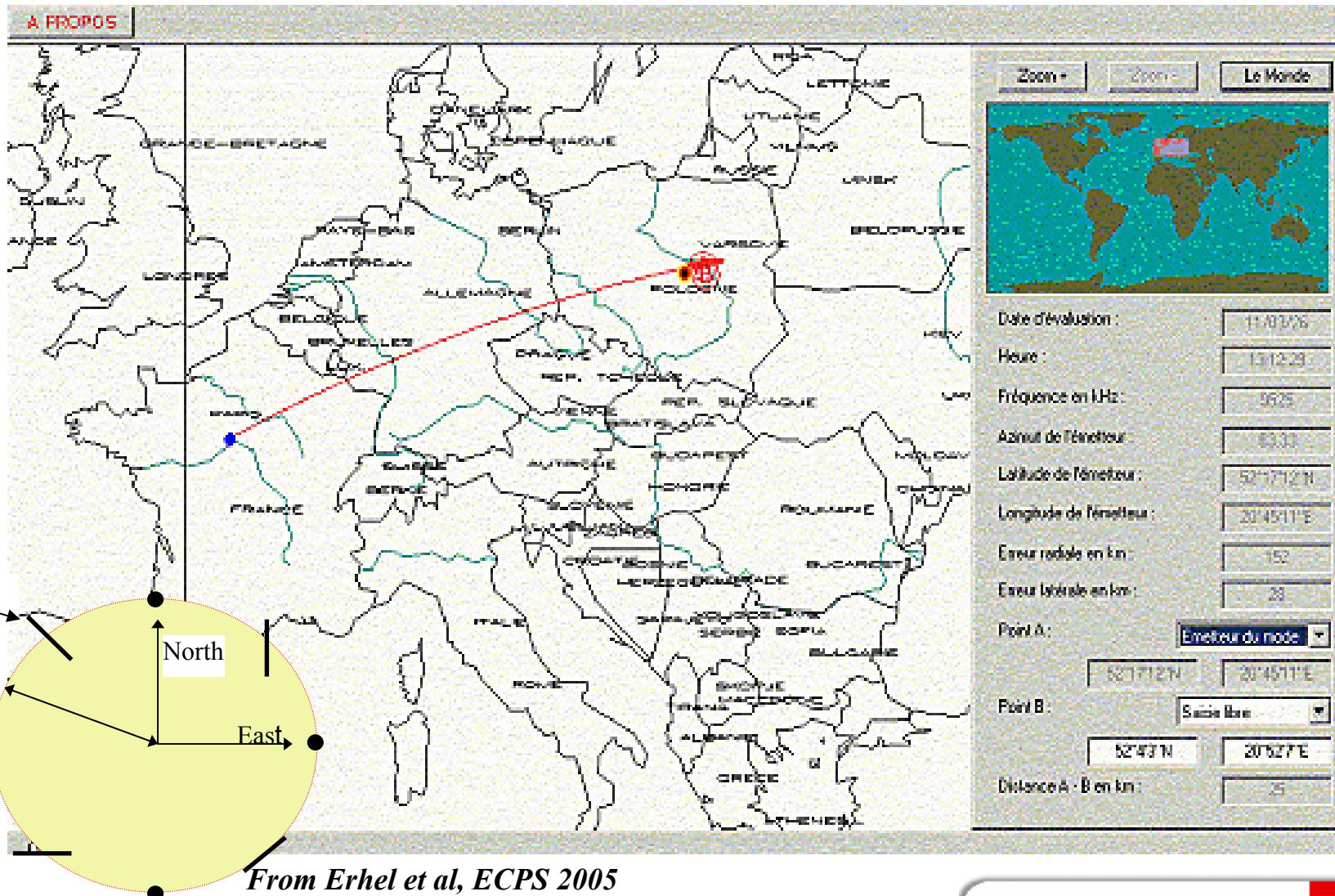
Radio direction finding techniques

Direction finding and localisation (array number 2, use of PRIME)



Radio direction finding techniques

Direction finding and localisation (array number 2, use of PRIME)



- A good knowledge of the ionospheric mechanisms contributes to improve the systems used in the HF band
- Antenna diversity brings array processing into a N-dimensional level instead of the usual 2 spatial dimensions
 - sensitive to polarization (2 new parameters)
 - increases the diversity range
 - able to separate signals coming from the same direction as long as they have different polarisation properties
- Space diversity is no longer required; compact arrays made of collocated antennas can be used (smaller systems)
- Efficient improvement of HF transmissions (throughput and BER)
- Improvement of direction finding systems with new applications (updating profile)