Characterization of Scatterers by their Energetic Dispersive and Anisotropic Behaviors in High-Resolution Radar Imagery

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SONDRA

OUTLINE

- **Conventional and Extended Radar Imaging Concept:**
  - Model of bright points scatterers,
  - Model of dispersive and anisotropic scatterers.

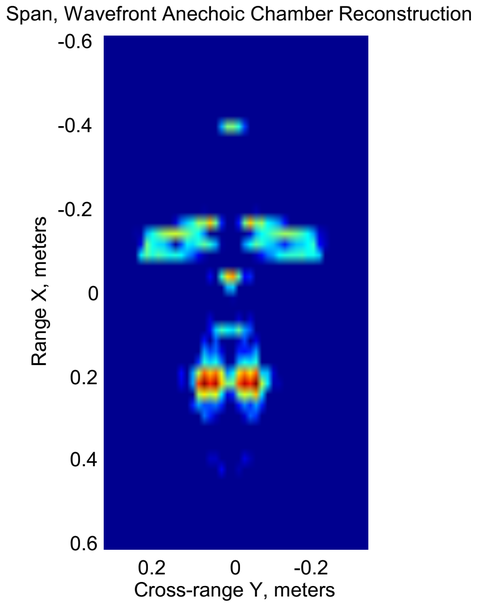
- **On the Use of Time-Frequency Distributions for Radar Imaging**
  - Concept of Hyperimages,
  - Physical interpretation of the energetic signatures in the hyperimage,
  - Physical interpretation of the polarimetric signatures in the hyperimage.

- **Physical Statistical Features Extraction in the Hyperimage**
  - Features extraction from marginals PDF,
  - Results on High-Resolution Laboratory radar imaging,
  - Physical interpretations of the statistical parameters.

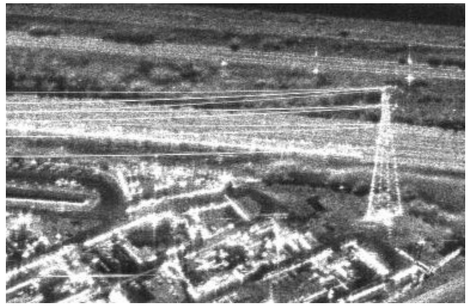
- **Conclusion.**

RADAR/SAR IMAGING

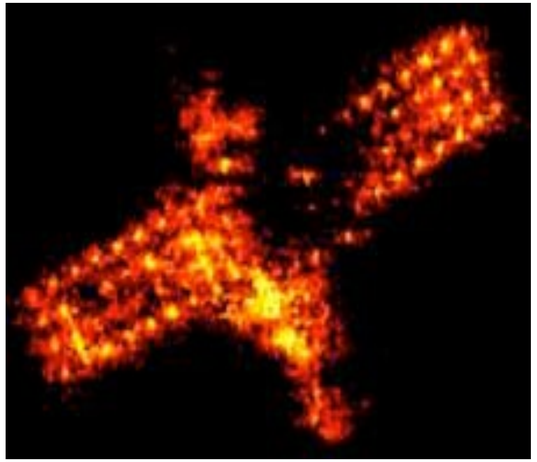
ONERA RAMSES Image



RAMSES Image



ONERA RAMSES Image



ONERA ISAR Image

Radar Imaging allows to build more and more detailed images:

- **Current use of very high bandwidth and long integration time (high azimuth bandwidth): very high spatial resolution,**
- **Application to surveillance (detection, change detection), classification, 3D reconstruction, EM analysis, …**

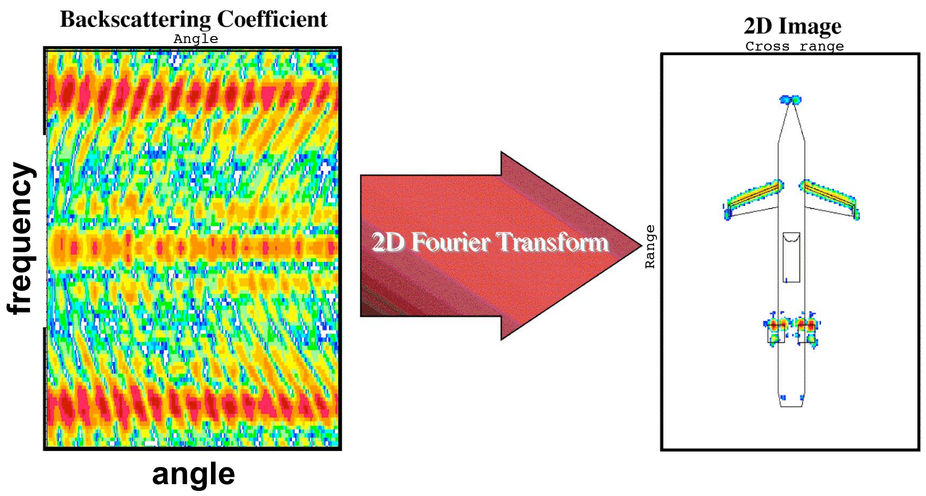
But it exists a strong limitation in the EM bright point model based on the hypotheses:

- **The bright points are considered as point-like, white (non-dispersive) and isotropic**

CONVENTIONAL PRINCIPLE OF RADAR/SAR IMAGING

Conventional Fourier Imaging (laboratory, SAR, ISAR):

- **makes assumptions of white and isotropic bright points,**
- **does not exploit the potential non-stationarity of the scatterers in angular and frequency domains.**



- Hypothesis of bright points model: all the reflecting elements of the scene localized in $\mathbf{r} = (x, y)^T$ and characterized by their spatial repartition function $A(\mathbf{r})$ have **the same behavior** for any wave vectors $\mathbf{k} = \dfrac{2\,f}{c}\,(\cos\theta, \sin\theta)^T$. The backscattering coefficient $H(\mathbf{k})$ acquired by the radar takes the form:

$$H(\mathbf{k}) = \int_{\mathcal{D}_\mathbf{r}} A(\mathbf{r})\, e^{-2\,i\,\pi\,\mathbf{k}^T\,\mathbf{r}}\, d\mathbf{r}$$

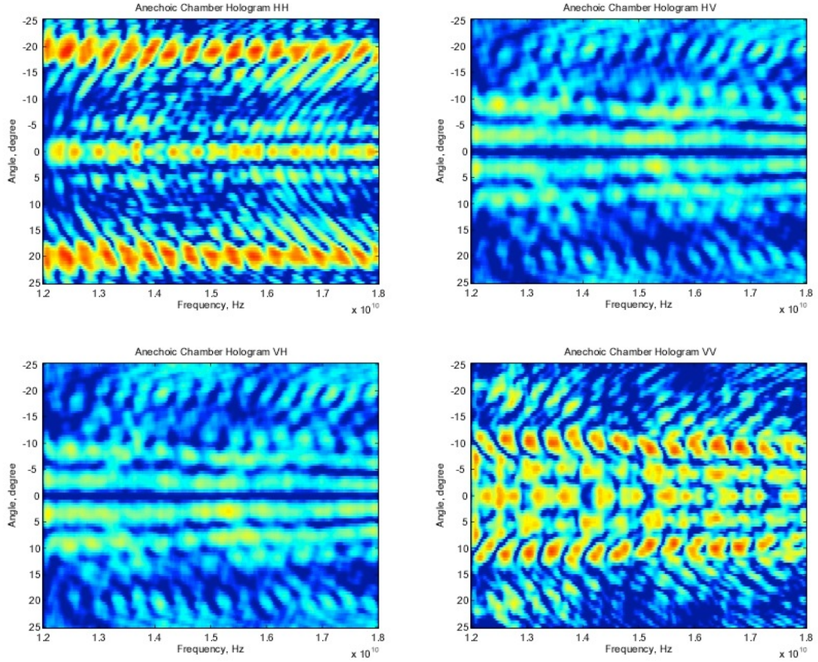
- The construction of the radar image $A(\mathbf{r})$ is then given by the inverse classical Fourier transform of the backscattering coefficient $H(\mathbf{k})$:

$$A(\mathbf{r}) = \int_{\mathcal{D}_\mathbf{k}} H(\mathbf{k})\, e^{2\,i\,\pi\,\mathbf{k}^T\,\mathbf{r}}\, d\mathbf{k}$$

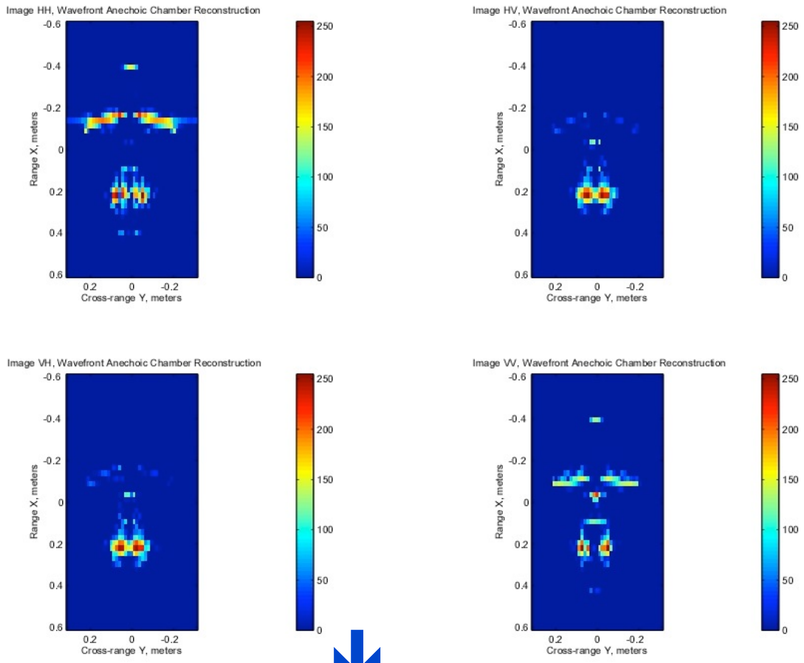
CLASSICAL POLARIMETRIC RADAR IMAGING

Example of laboratory radar imaging

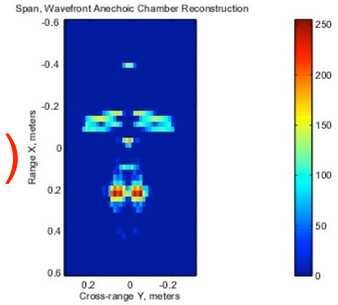
Polarimetric Hologram



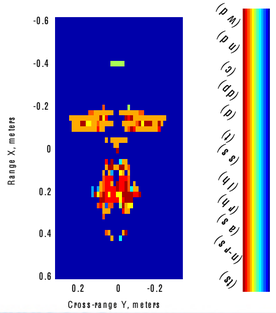
Polarimetric Image



→ Energetic Image (Span)

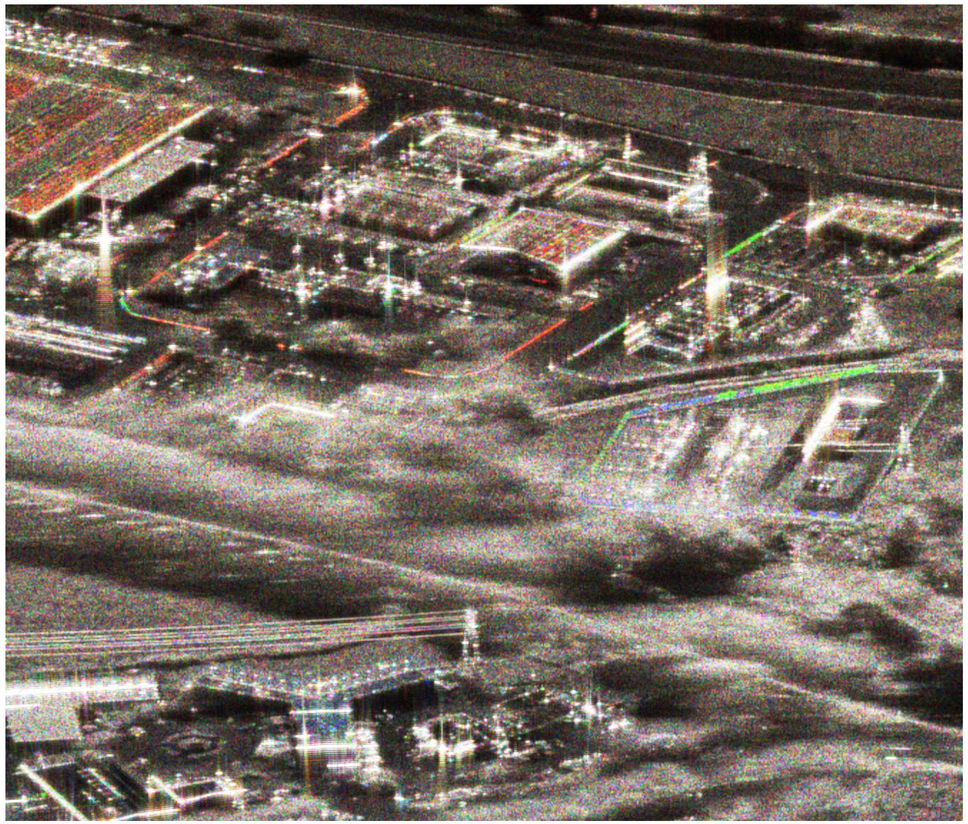


Polarimetric decompositions (Cameron, Krogager,…)

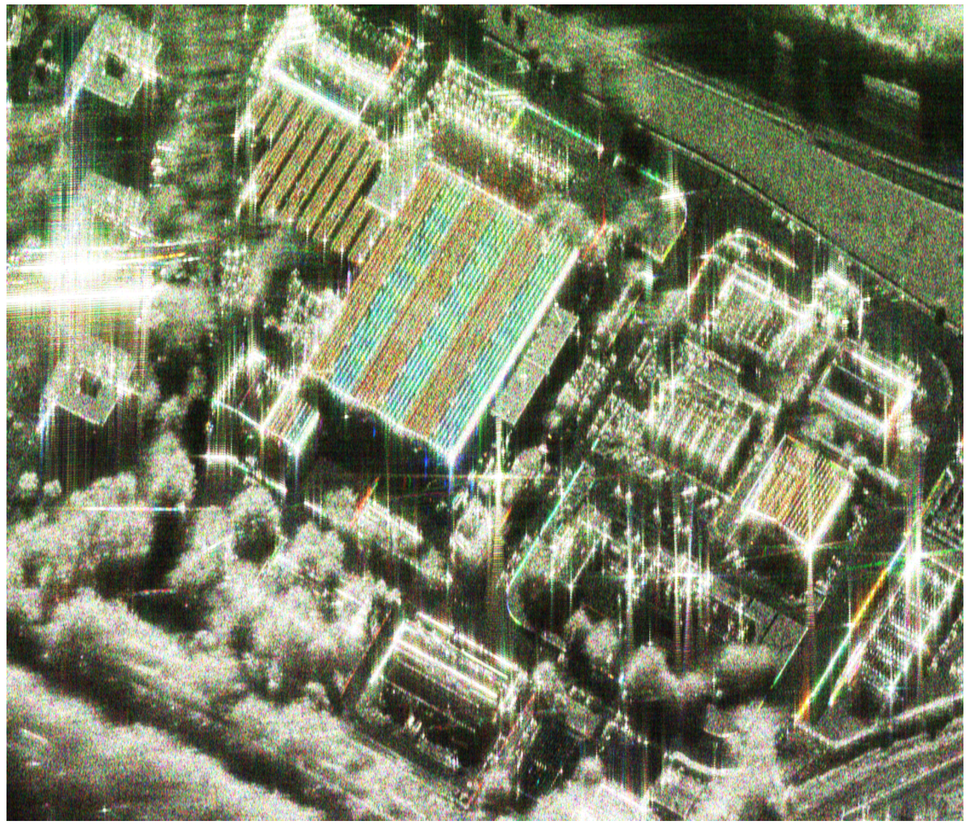


EXAMPLE OF TRUE PHYSICAL BEHAVIOR OF SCATTERERS IN SAR IMAGING

elevation 30°



elevation 50°



Sub-band 1 Sub-band 2 Sub-band 3

Scatterers have different behaviors with respect to the frequency and illumination direction

TIME-FREQUENCY ANALYSIS FOR RADAR/SAR IMAGING

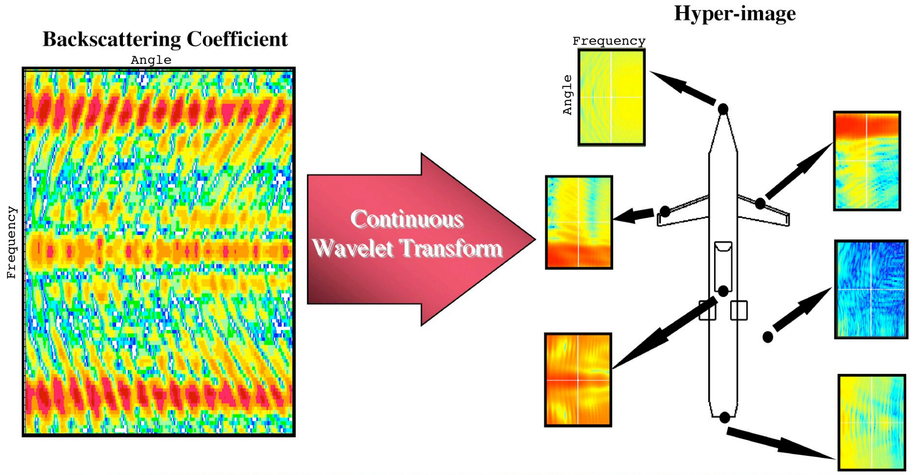
Time-Frequency Analysis allows to highlight the coloration and anisotropy properties of monodimensionnal Radar/SAR scatterers by characterizing each pixel of the image with a vector of information related to angular or/and frequency behaviors [*Bertrand et al. 94*, *Ovarlez et al. 03*, *Duquenoy et al. 10*].

The hyperimage is defined as a linear Time-Frequency decomposition of the backscattering coefficient $H(\mathbf{k})$:

$$A(\mathbf{r},\mathbf{k}) = \int_{\mathcal{D}_{\mathbf{u}}} H(\mathbf{u})\, \phi^H(\mathbf{u},\mathbf{k},\mathbf{r})\, e^{2\,i\,\pi\,\mathbf{u}^T\,\mathbf{r}}\, d\mathbf{u}$$

where $\phi(.)$ is an analyzing kernel acting on a mother wavelet $\phi_0(.)$ by given groups of transformation:

- group of translation in frequency domain and in angular domain: 2D short-time Fourier transform in angular and frequency domain,
- group of dilation in frequency domain and translation in angular domain: 2D wavelet transform in angular and frequency domain.



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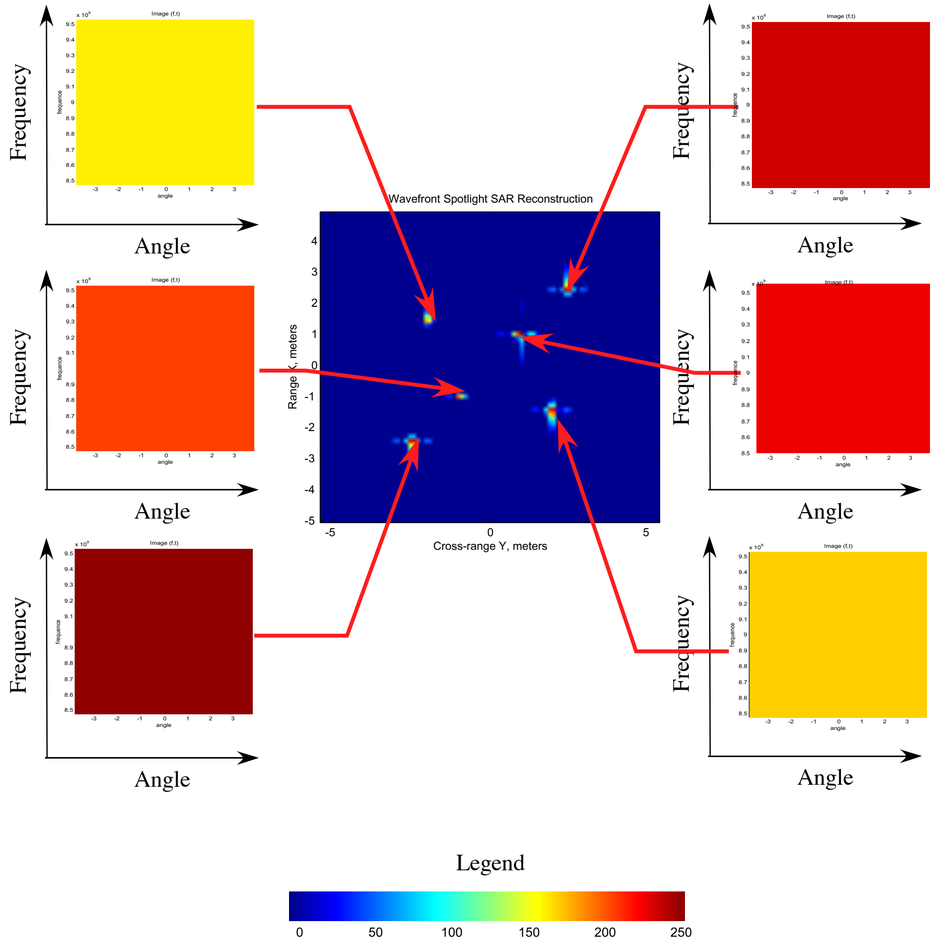
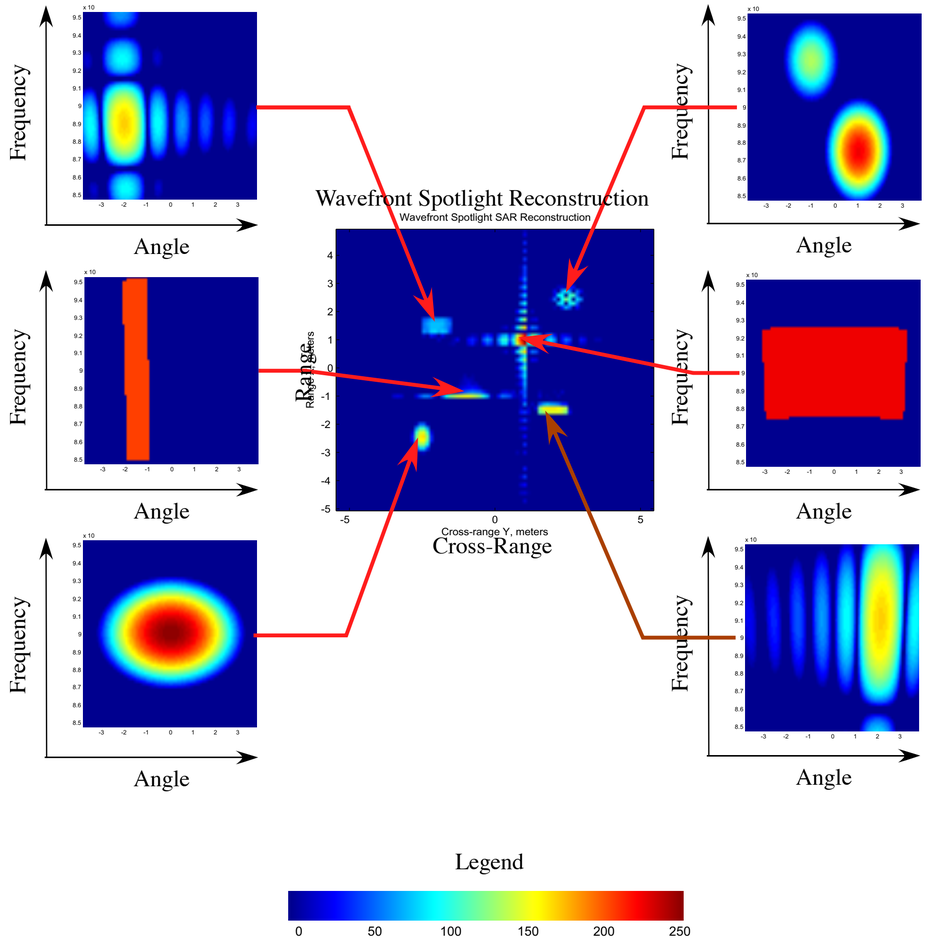
COMPARISON BETWEEN THE TWO MODELS

Example of theoretical model of isotropic and white scatterers



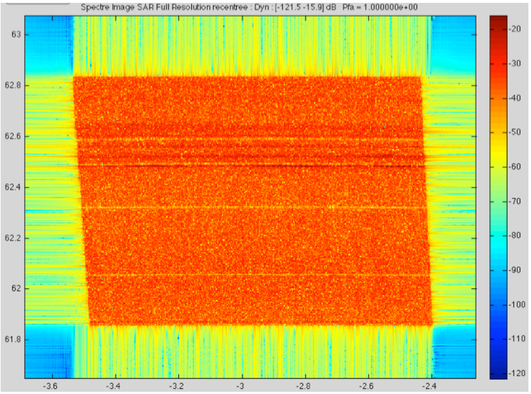
Example of theoretical model of anisotropic and dispersive scatterers

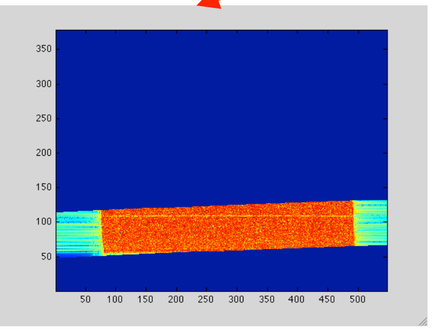


SAR BACKSCATTERING DECOMPOSITION ONTO SUB-BANDS AND SUB-LOOKS USING TIME-FREQUENCY ANALYSIS

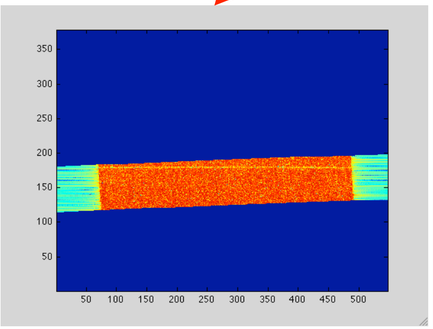
Backscattering coefficient $H(\mathbf{k})$

with $\mathbf{k} = \dfrac{2f}{c}\left(\cos\theta, \sin\theta\right)^T)$

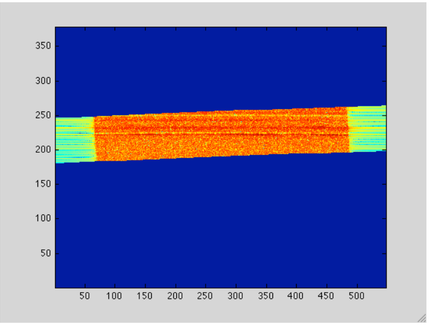




Sub-band 1

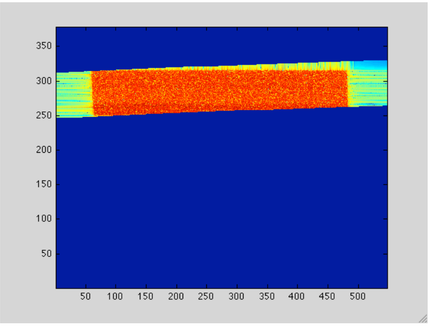


Sub-band 2



Sub-band 3

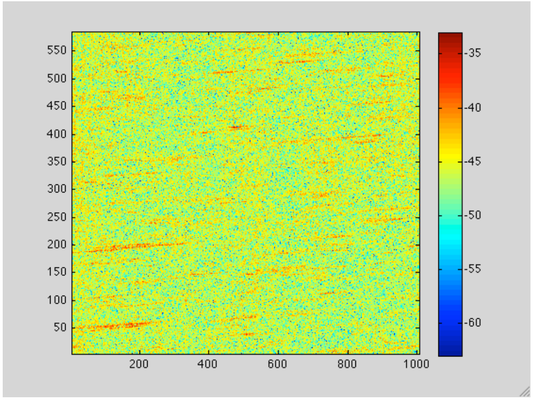
...

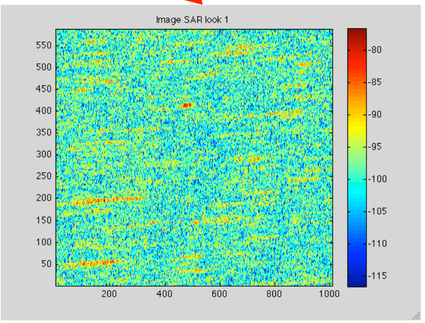


Sub-band N

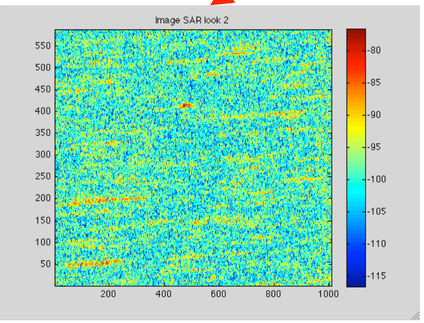
SAR BACKSCATTERING DECOMPOSITION ONTO SUB-BANDS AND SUB-LOOKS USING TIME-FREQUENCY ANALYSIS

High Resolution SAR Image

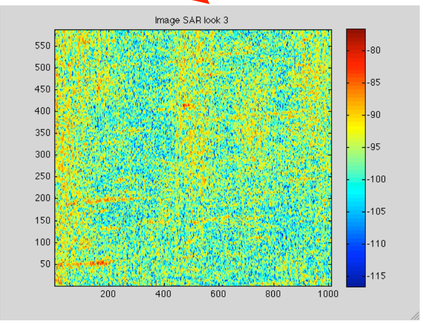




SAR Image Sub-image 1

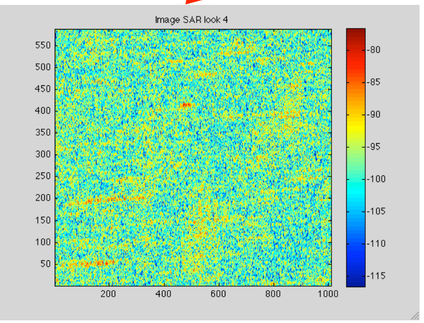


SAR Image Sub-image 2



SAR Image Sub-image 3

…



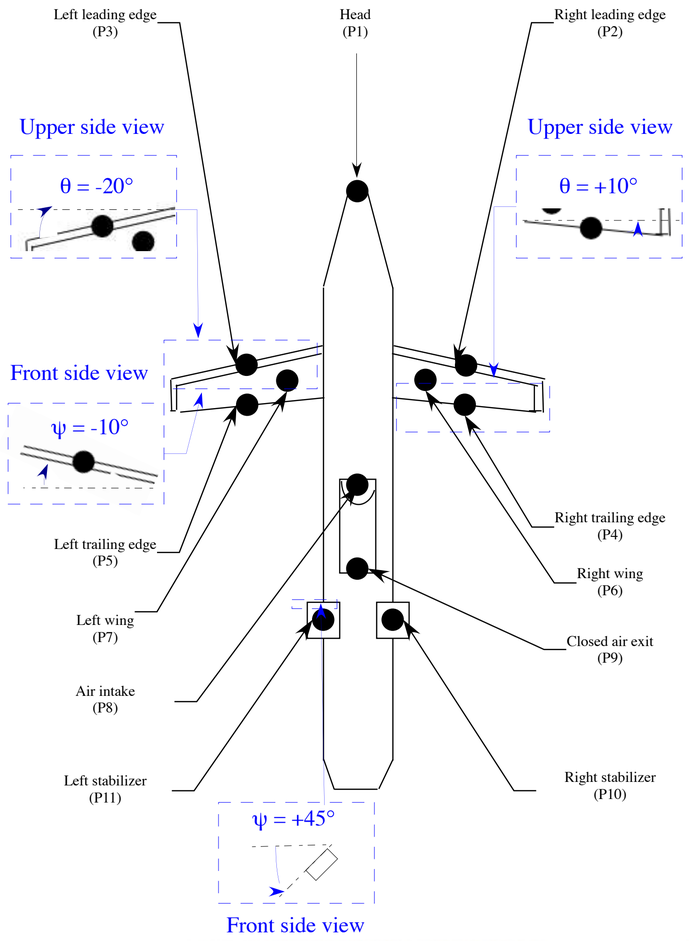
SAR Image Sub-images N

Each pixel characterizes a in-phase N-vector of information related to dispersion and anisotropy

EXAMPLE OF TIME-FREQUENCY USE FOR RADAR IMAGING

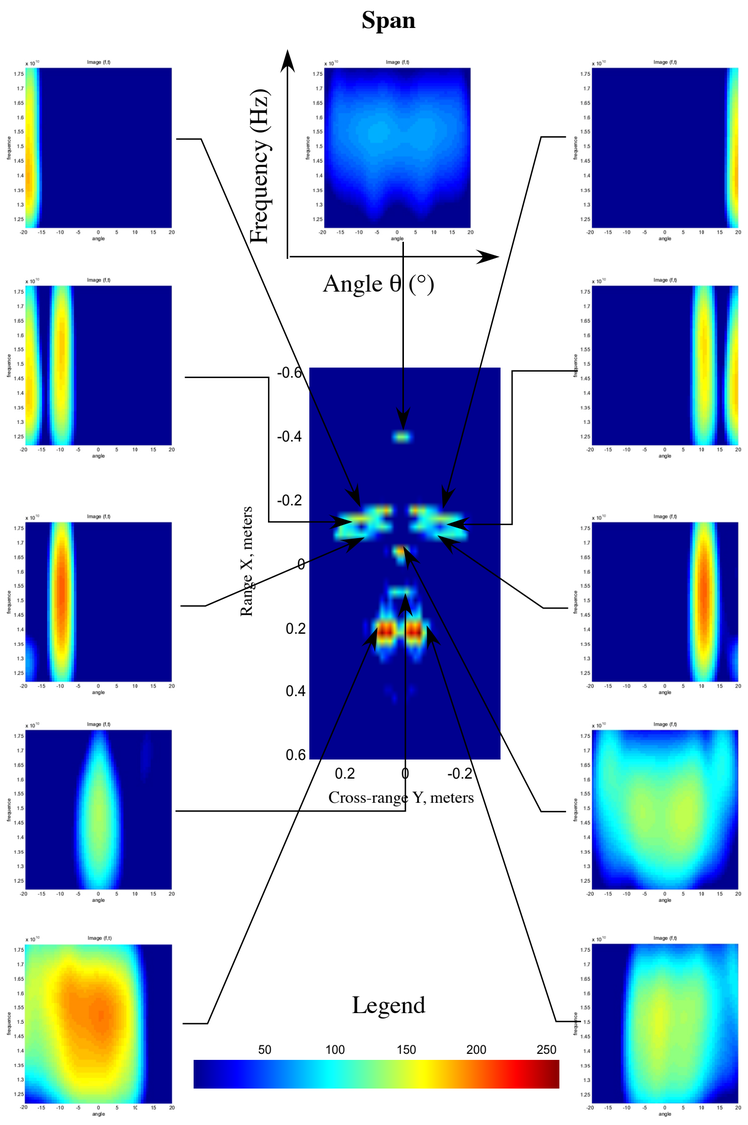
Polarimetric Radar Imaging in laboratory

Analysed Target: a "*Cyrano*" scaled model



Anechoic room geometry

PHYSICAL INTERPRETATION OF THE ENERGETIC SIGNATURES IN THE HYPERIMAGE



Extended Span Results ([12,18] GHz, [-25,25]°)

Head: isotropic and non-dispersive signature

- Sphere geometry.

Leading and trailing edges: directive response, orientation on the horizontal plane

- Diffraction phenomena.

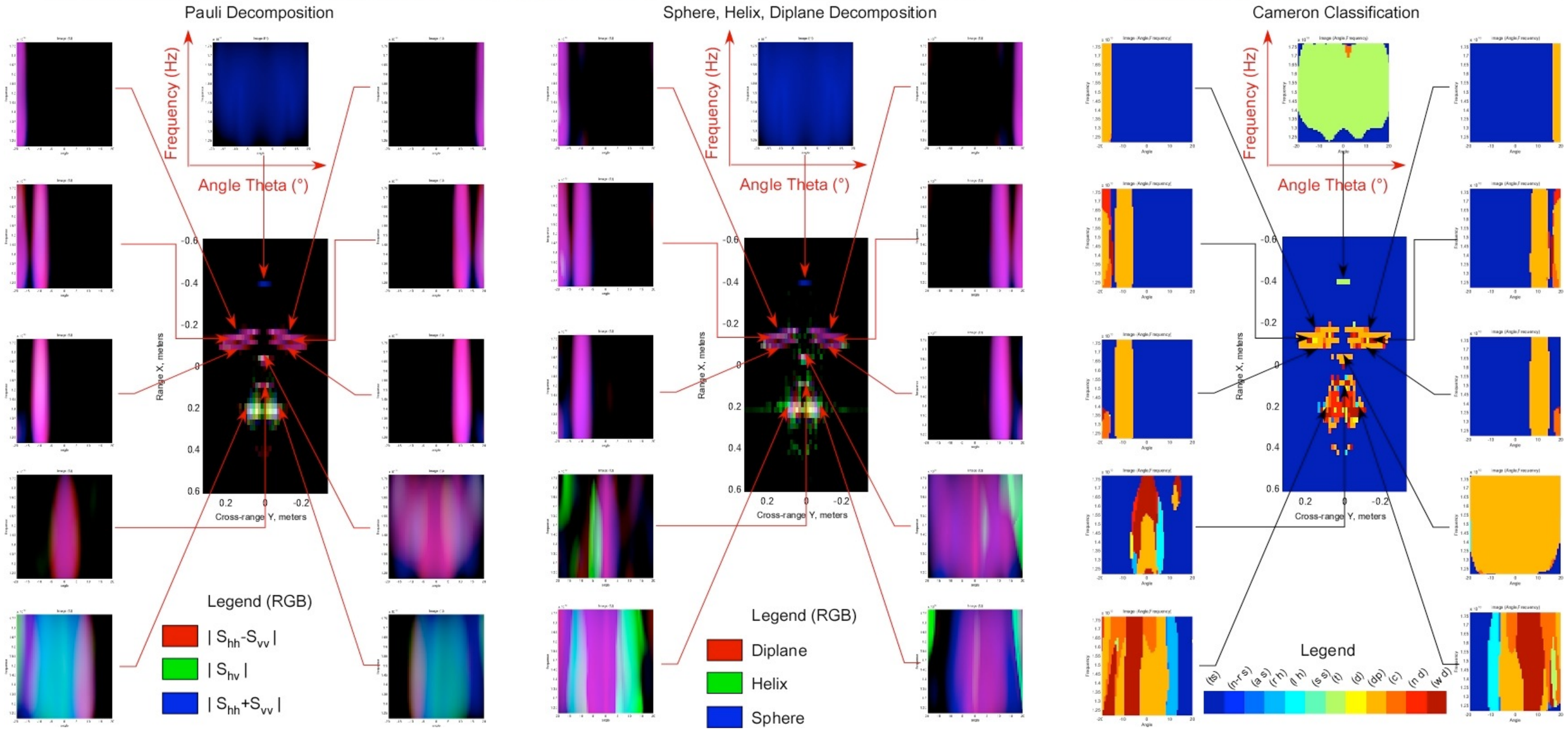
Wings: mix of the contributions between leading and trailing edges

- Heisenberg incertitude.

Closed air intake: directive response, wave guide phenomena

- Specular reflection.

PHYSICAL INTERPRETATION OF THE POLARIMETRIC SIGNATURES IN THE HYPERIMAGE



FEATURES EXTRACTION IN THE HYPERIMAGE

How to reduce this huge quantity of informations ?

Sinclair Matrix

$$[S](\mathbf{r}) = \begin{bmatrix} I_{\mathrm{Hh}}(\mathbf{r}) & I_{\mathrm{Hv}}(\mathbf{r}) \\ I_{\mathrm{Vh}}(\mathbf{r}) & I_{\mathrm{Vv}}(\mathbf{r}) \end{bmatrix}$$

→ **Multi-Dimensional Time-Frequency Analysis (STFT or CWT)**

→ **Hyper-Scattering Matrix**

$$[S](\mathbf{r};\mathbf{k}) = \begin{bmatrix} I_{\mathrm{Hh}}(\mathbf{r};\mathbf{k}) & I_{\mathrm{Hv}}(\mathbf{r};\mathbf{k}) \\ I_{\mathrm{Vh}}(\mathbf{r};\mathbf{k}) & I_{\mathrm{Vv}}(\mathbf{r};\mathbf{k}) \end{bmatrix}$$

→ **Extended Span Computation**

→ **Extended Span**

$$P(\mathbf{r},\mathbf{k}) = \left|I_{\mathrm{Hh}}(\mathbf{r},\mathbf{k})\right|^2 + \left|I_{\mathrm{Hv}}(\mathbf{r},\mathbf{k})\right|^2 + \left|I_{\mathrm{Vh}}(\mathbf{r},\mathbf{k})\right|^2 + \left|I_{\mathrm{Vv}}(\mathbf{r},\mathbf{k})\right|^2$$

→ **Computation of the Marginal Density in frequency**

$$P_f(\mathbf{r}, f) = \frac{\int_\theta P(\mathbf{r},\mathbf{k})\, d\theta}{\int P(\mathbf{r},\mathbf{k})\, d\mathbf{k}}.$$

→ **Frequency Signature**

$$P_f(\mathbf{r}, f)$$

→ **Computation of the Marginal Density in angle**

$$P_\theta(\mathbf{r}, \theta) = \frac{\int_f P(\mathbf{r},\mathbf{k})\, df}{\int P(\mathbf{r},\mathbf{k})\, d\mathbf{k}}.$$

→ **Angle Signature**

$$P_\theta(\mathbf{r}, \theta)$$

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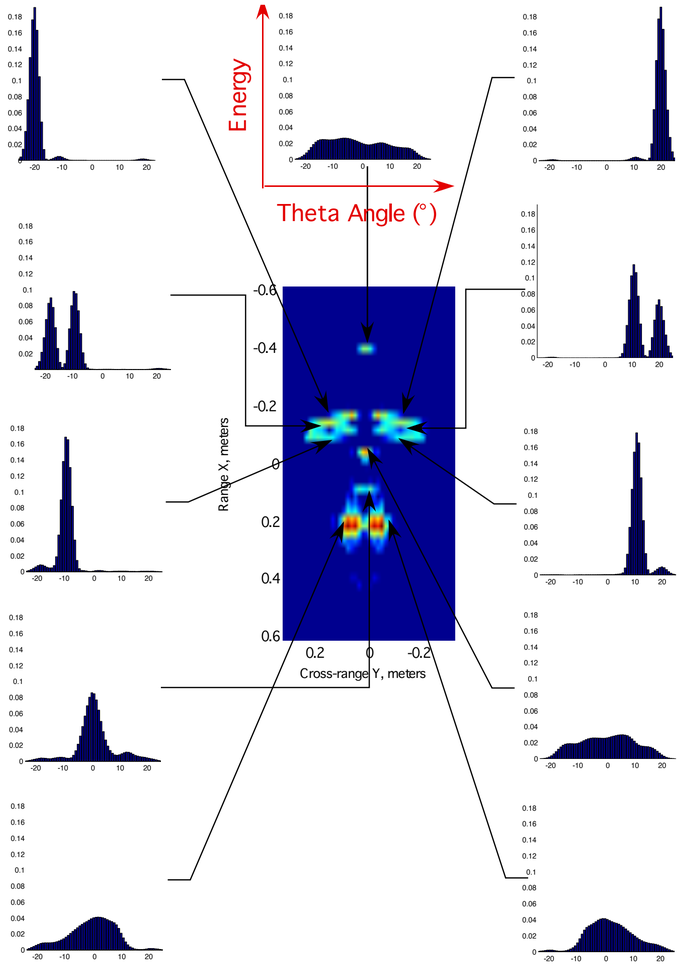
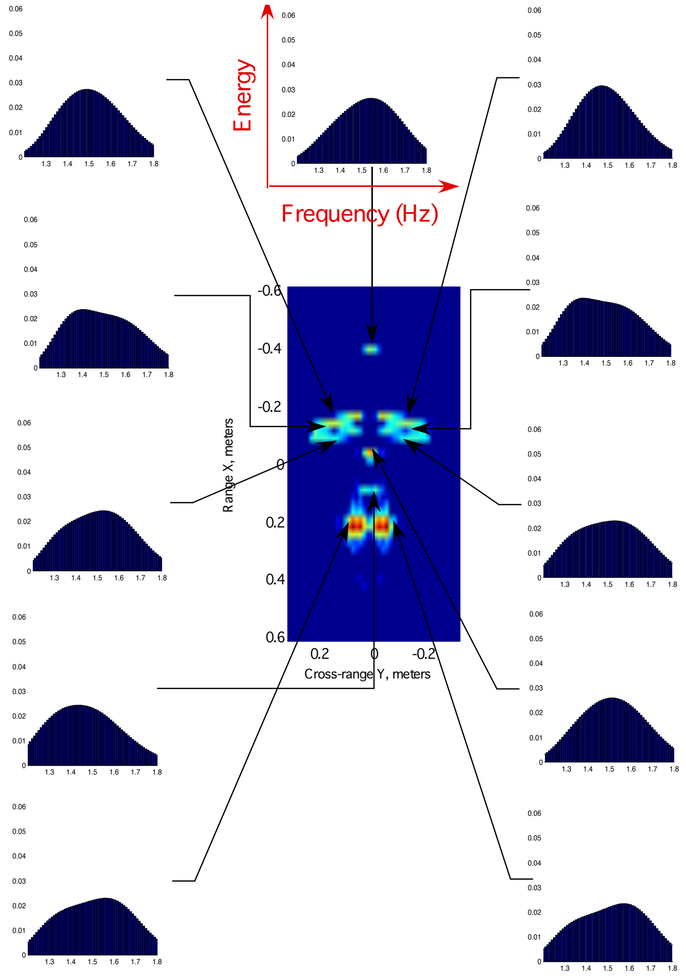
FEATURES EXTRACTION IN THE HYPERIMAGE

Synthesis of information using Marginal PDF

Angular domain



Frequency domain



FEATURES EXTRACTION IN THE HYPERIMAGE

Marginal density

$P_q(\mathbf{r};q) \quad q=\theta \text{ or } q=f$

Computation of the Average Value

$$\mu_q(\mathbf{r}) = \int_q q \cdot P_q(\mathbf{r},q) \cdot dq$$

Computation of the Standard Deviation

$$\sigma_q(\mathbf{r}) = \left[\int_q (q-\mu_q(\mathbf{r}))^2 \cdot P_q(\mathbf{r},q) \cdot dq\right]^{\frac{1}{2}}$$

Computation of the Entropy

$$Ent_q(\mathbf{r}) = -\int_q P_q(\mathbf{r},q) \cdot \log(P_q(\mathbf{r},q)) \cdot dq$$

Computation of the Skewness

$$Skw_q(\mathbf{r}) = \frac{1}{\sigma_q(\mathbf{r})^3} \int_q (q-\mu_q(\mathbf{r}))^3 \cdot P_q(\mathbf{r},q) \cdot dq$$

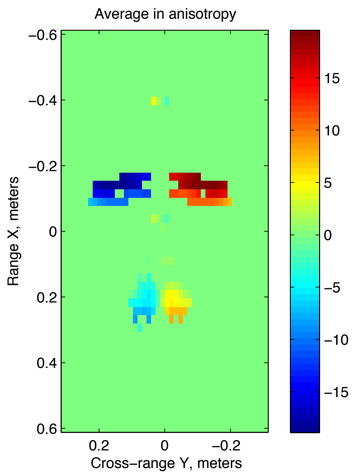
Computation of the Kurtosis

$$Kurt_q(\mathbf{r}) = \frac{1}{\sigma_q(\mathbf{r})^4} \int_q (q-\mu_q(\mathbf{r}))^4 \cdot P_q(\mathbf{r},q) \cdot dq$$

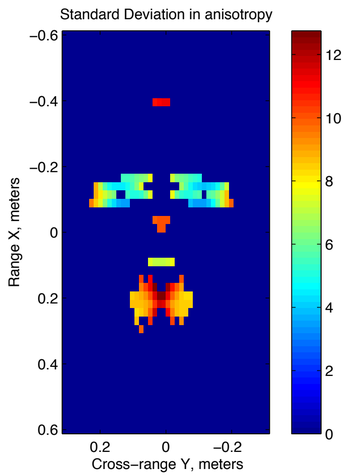
STATISTICAL ANALYSIS OF SIGNATURES IN ANGULAR DOMAIN

Anisotropy results on High-Resolution Laboratory Radar Imaging

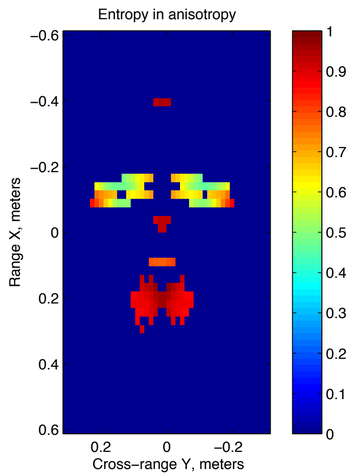
Mean



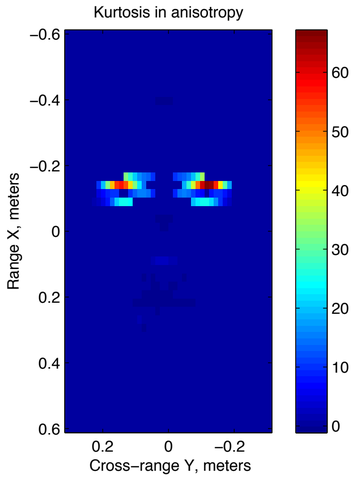
Standard deviation



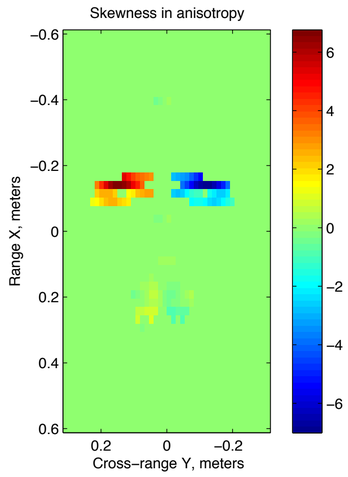
Entropy



Kurtosis



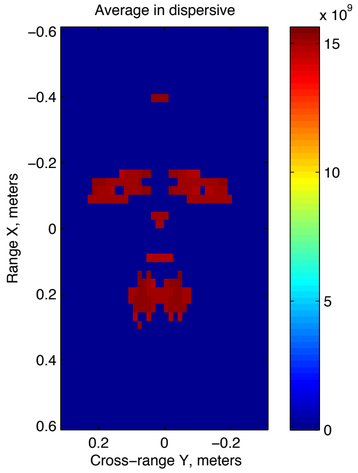
Skewness



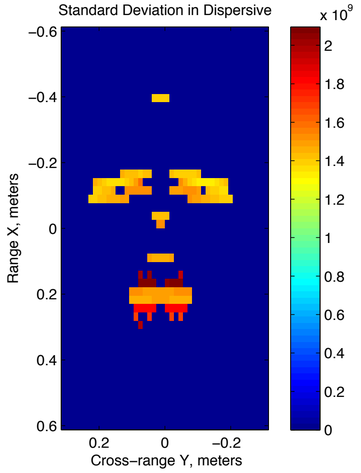
STATISTICAL ANALYSIS OF SIGNATURES IN FREQUENCY DOMAIN

Dispersion results for High-Resolution Laboratory Radar Imaging

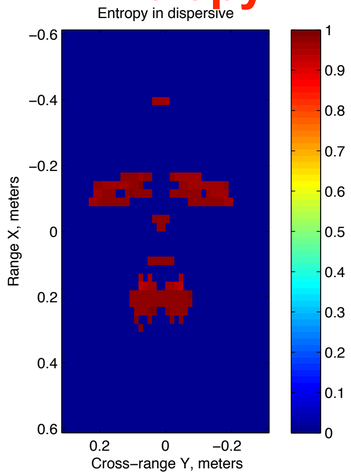
Mean



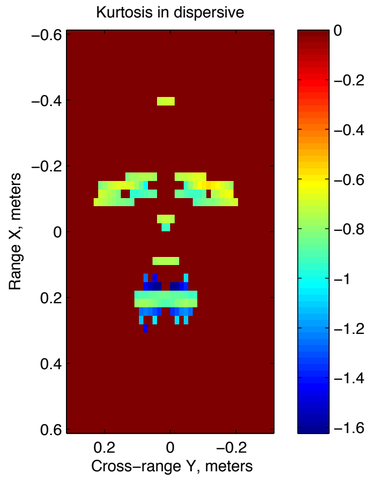
Standard deviation



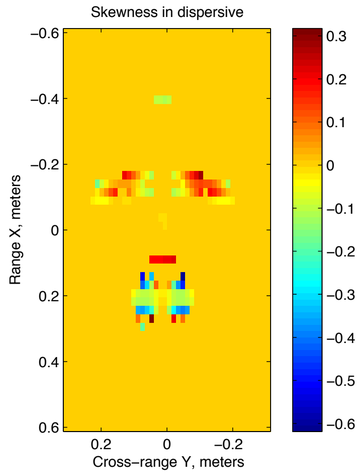
Entropy



Kurtosis



Skewness



PHYSICAL INTERPRETATION OF SOME FEATURES

	Angular Domain		Frequency Domain	
Target & Scatterer	Directive response (energy focused in one direction)	Isotropic response (energy spreads in all direction)	Resonant response (energy centered in one frequency)	Non-dispersive response (energy spreads over all the frequency range)
Mean	Average value is focusing on a direction		Average value corresponds to a resonant frequency	
Standard Deviation	Low Value	High value	Low Value	High value
Entropy	Tends to 0	Tends to 1	Tends to 0	Tends to 1
Excess Kurtosis	Kurt>0	Kurt<0	Kurt>0	Kurt<0

Synthesis of the statistic results in azimuth:

- Standard deviation, Entropy and Kurtosis allow to detect directive response,
- For the directive response, the mean value can indicate the orientation of a scatterer,
- Mean value and skewness cannot be used for Automatic Target Recognition or features extraction.

Synthesis of the statistic results in frequency:

- The only efficient statistical parameter can be the Skewness in frequency domain (but not for dispersive or resonant scatterer) .

CONCLUSIONS AND PERSPECTIVES

CONCLUSIONS

- Time-Frequency tool applied on full-resolution radar image allows to exploit more degrees of freedom and allows to understand physical behaviors and properties of the scatterers in ISAR, SAR or Radar Imaging in laboratory

- Extraction of statistical features in the hyperimages information allows to discriminate target behavior

PERSPECTIVES

- ATR Applications in High-Resolution Synthetic Aperture Radar (SAR) Imaging,
- ATR Applications in Circular SAR Imaging,
- Potential application of this Time-Frequency schemes for deriving Adaptive Detection tests (AMF, Kelly, ANMF, coherence tests, etc.) in mono-dimensional SAR images, detection of moving target, refocusing moving target, etc.