Using Roughness Textures in Target Modelling - Impact on ISAR Images Calculations of the ZSU 23-4

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1. ABSTRACT

Tools for electromagnetic simulation, such as SPECRAY EM / FERMAT, make RCS and ISAR image computations down to millimetre wavelength possible from the CAD of targets. The higher the frequency is, the greater the influence of the precision and the realism of the CAD models on results are. In millimetre wavelength, whatever the precision of the CAD, the roughness of surface and the flatness of sheets of construction of terrestrial military vehicles cannot be reproduced by the geometry. Nevertheless, a realistic prediction of RCS can be carried out by taking into account the statistical surface qualities, which are superposed, on the deterministic effects of the geometry of the CAD. The calculations carried out on the CAD 600 and 80 kfacets of the ZSU 23-4 illustrate these effects, without degrading the efficiency of computations.

2. THE ELECTROMAGNETIC COMPUTER CODE FERMAT

The SPECRAY EM software includes several tools for the generation, management of physically textured databases, the edition of scenarios relating to a given sensor, the post-processing and visualisation of the output data and an EM core, FERMAT. FERMAT deals with the electromagnetic calculations of the interactions between EM wave and the observed scene.

The FERMAT software has been developed by the Electromagnetism and Radar Department of ONERA within the framework of a project dedicated to electromagnetic (EM) modelling. This computer code capitalises the results of research activities in high frequency scattering methods. A unique tool is currently available for studies dealing with radar analysis, antennas radiation, EM inter-system compatibility and propagation applications. This numerical simulation tool has the ambition to calculate scattered EM fields at high frequencies (i.e. the size of objects is supposed large compared to the wavelength), in a virtual 3 D, geometrical and physical complex environment including natural and man made objects. EM fields calculations either on a surface or in a volume could be carried out according to specific applications.

FERMAT associates various techniques and tools.

Virtual 3D, geometrical data bases, composed of a great number of elements, landscapes and objects such as vehicles, buildings, ..., are modelled by thousands of plane geometrical faces and associated management tools. Specific features and textures relative to electromagnetic scattering are provided for each face.

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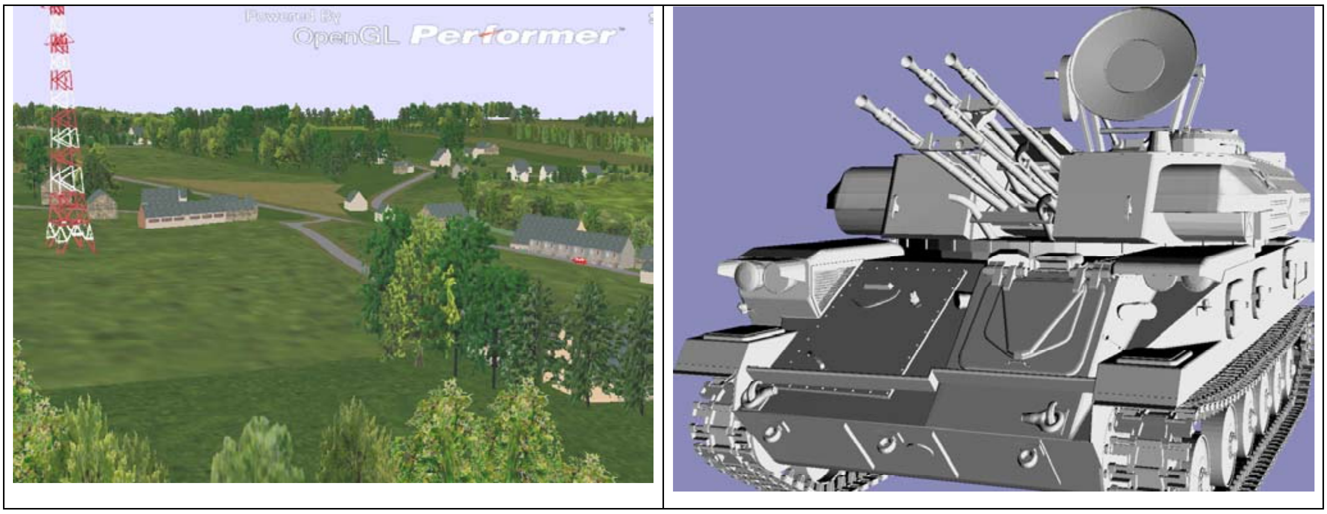


Figure 1: Examples of natural and man made databases

A geometrical Shooting and Bouncing Rays (SBR) technique has been optimised in order to calculate the intersections between rays from the transmitter towards the database and back to a receiving point. EM models of propagation, reflection, diffraction and an operating strategy (thanks to SBR) which allows unified calculation for the near or far EM scattered fields from the scenes. These models are the formulations of Geometrical Optics (GO), Physical Optics (PO), Uniform Theory of Diffraction (UTD) and Equivalent Current Method (ECM). Again, these models, judiciously coupled with the SBR technique make the computation time slightly dependent on the complexity of the treated virtual scene.

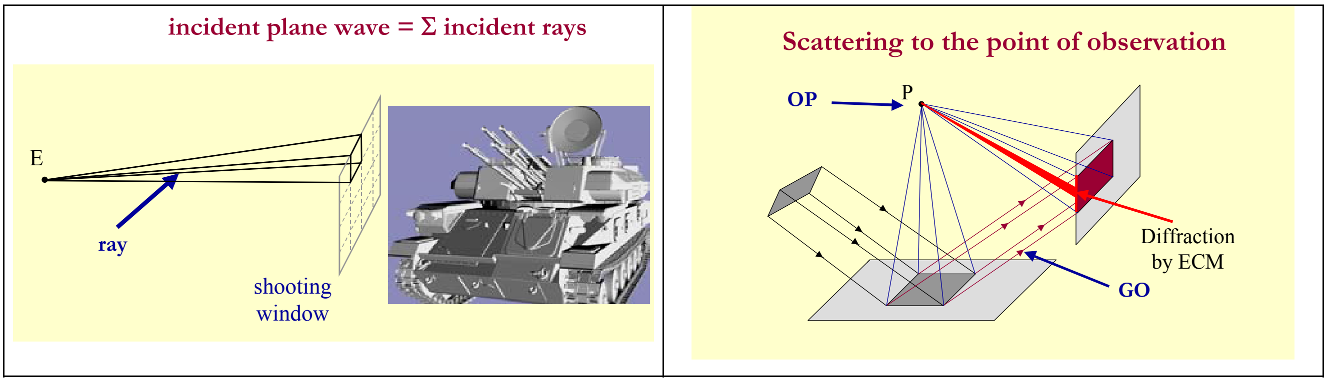
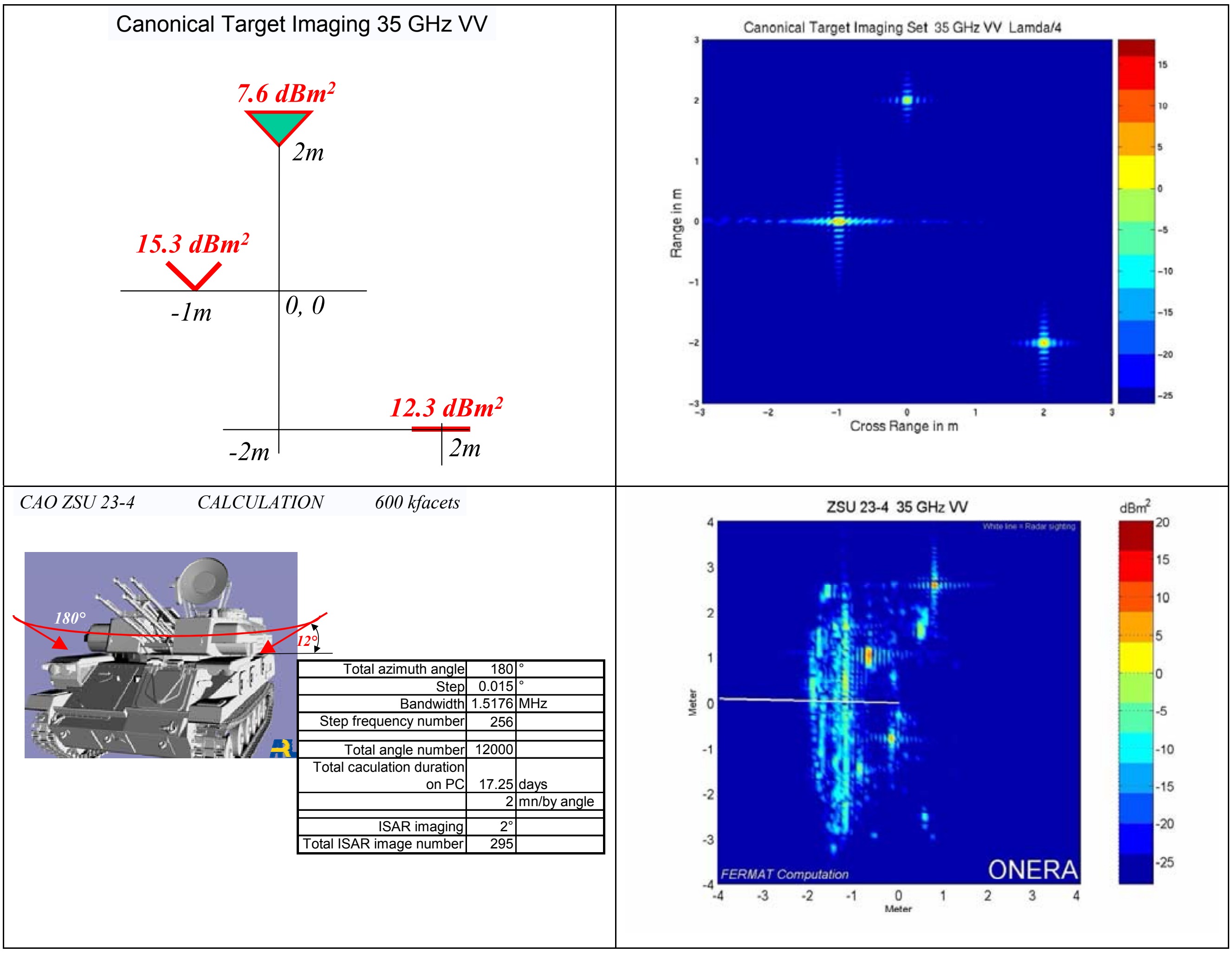


Figure 2: Coupling of SBR technique and EM asymptotic methods

Generation and management scenarios tools has been developed to simultaneously simulate, for example, motions of a radar sensor and displacements of mobiles in the landscape according to the type of field calculations. Outputs and visualisation tools have been adapted to investigated applications.



Total azimuth angle	180	°
Step	0.015	°
Bandwidth	1.5176	MHz
Step frequency number	256	
Total angle number	12000	
Total caculation duration on PC	17.25	days
	2	mn/by angle
ISAR imaging	2°	
Total ISAR image number	295	

Figure 3: Examples of ISAR images from the canonical target set and the ZSU 23-4

The strength of FERMAT is that it is developed, under an agreement of partnership between ONERA and OKTAL SE. This company brings its competencies in the management and exploitation of databases, and the control of the SBR technique.

The validation mainly consisted in comparison with the EM models calculated either with other reference methods or with measurements on simple object known as canonical and allowing evaluating the various EM interactions. These comparisons took place during specialised national and international "workshops".

3. ROUGHNESS CHARACTERISTICS

3.1. Introduction

In previous investigation related to millimetre wavelength modelling, under-meshing of objects had led to peaks of scattering in the specular direction (very high values RCS that do not correspond to predicted or known values from real targets). A disturbance of height on the object facets was introduced to correct this effect, by attenuating it. The technique consisted in plating a texture (space height function) of random height on the smooth facets of the under-meshed target. We expected that the technique also made possible to take into account the presence of real roughness and non-flatness of real surfaces giving results superimposing random effects on the coherent scattering.

ONERA, OKTAL SE and CELAR completed a work of expertise, in millimetre wavelength, to validate those first ideas in a context representative of the requirements. Measurements on a VAB vehicle (made on CELAR STRADI set up in Rennes, France) and computation (by FERMAT) on a CAD file of this same vehicle equipped with a texture of roughness have been compared. The principal conclusions were a better agreement between the predictions and the importance of the presence roughness texture on the surface of the object. Through this expertise, ONERA proved that the method is well adapted to simulation of radar behaviour radar in millimetre wavelength.

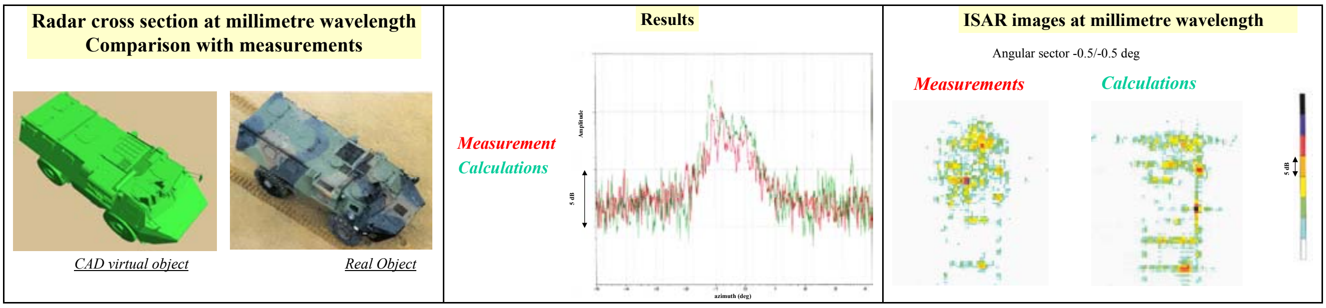


Figure 4: Previous results in using roughness texture on a recovery vehicle

3.2. Profile parameters

Generally, a surface roughness is characterised by the root mean square σ of its height distribution relating to wavelength and by the space correlation length Lc of an extracted profile from this surface. The interaction of EM waves and the surface presents a coherent part in the specular direction and a scattering part in the other directions. According to appropriate bibliography, the calculation of the specular component does not require the knowledge of correlation length. However, this one is necessary an evaluation of the scattering component.

A surface is known as smooth when the product $k\sigma < 0.2 \text{ or } \frac{\sigma}{\lambda} < 0.03$.

A surface is known as rough when the product $k\sigma > 1 \text{ or } \frac{\sigma}{\lambda} > 0.16$ with $k = \frac{2\pi}{\lambda}$

According to Rayleigh [Ulaby and Al 82], the coherent component is present for $\frac{\sigma}{\lambda} < 0.25$.

Other characterisation criteria using the correlation length will be specified thereafter. Kirchhoff approximation [Ulaby and Al 82] led to an expression of the attenuation of the coherent scattering (specular reflection) in the form known as the modified Fresnel reflection coefficient:

$$R = R_{th} \cdot exp(-2k^2 \quad \sigma^2 \quad cos^2(\theta_i))$$

Note: Thereafter, we will use the term of "bump" to indicate the texture of height disturbance. The texture of bump represents a random profile variation of height according to a given statistical distribution.

An example of profile of 512 x 256 points is presented on figure 4:

- height values could take 256 values,
- height RMS is 38.

The ratio of 15% (38/256) will remain constant for this texture. The peak-to-peak value and the length of the motif (of 512 points) would be the two parameters that have to be tuned according to a given wavelength

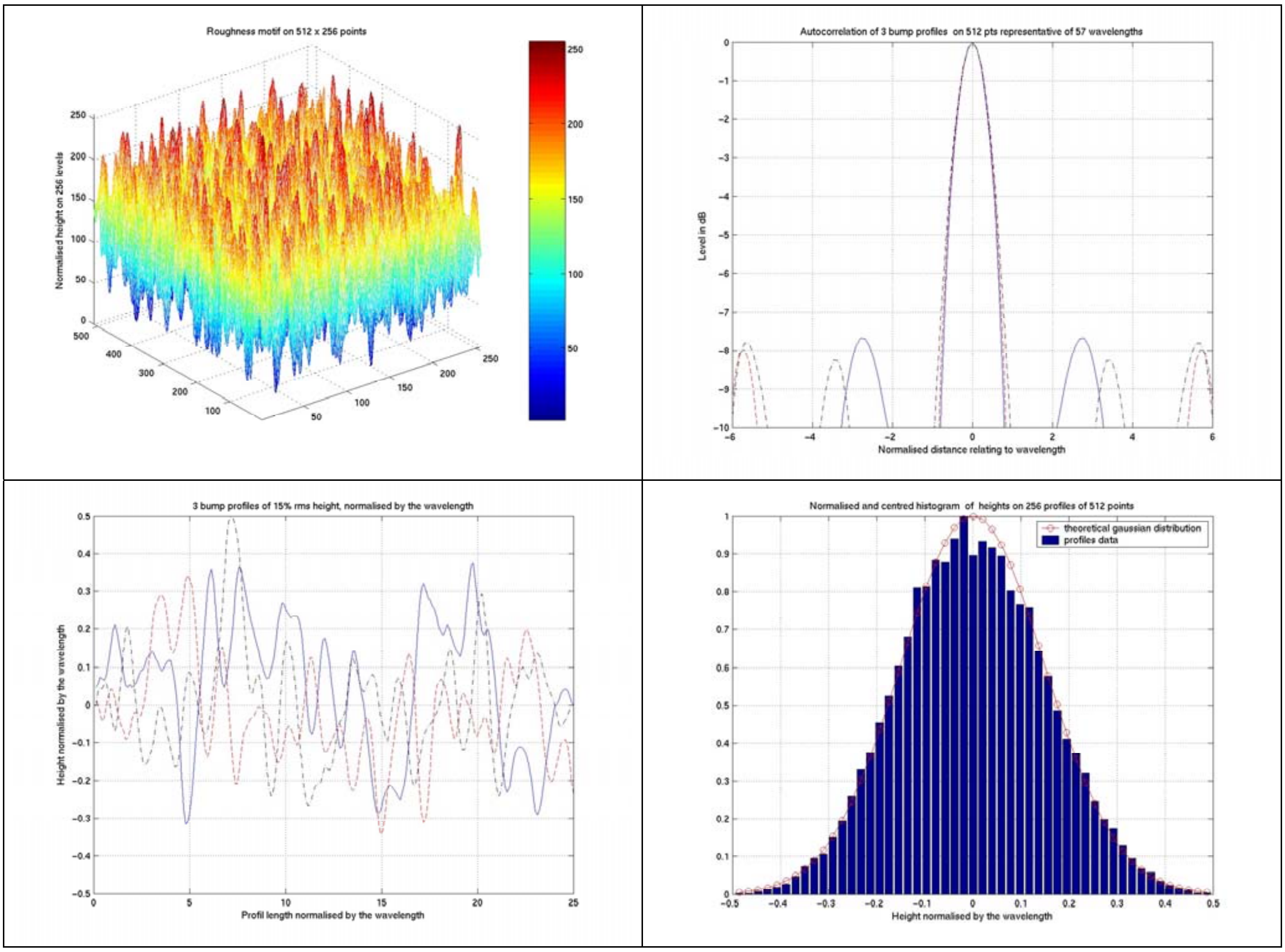


Figure 5: Statistical profile parameters

The density of the irregularities of a surface is described by the autocorrelation function that evaluates the degree of covering between a profile and its shifted image of a distance R.
It is defined by $\rho(R) = \sigma^2 C(R)$ where $C(R)$ is the function standardised autocorrelation function or coefficient of correlation and σ is the RMS height of roughness.
Most of profile modelling generally admits that

- $C(R) = exp(-(R/L_c)^2)$ for a Gaussian function and
- $C(R) = exp(-(R/L_c))$ for an exponential function where L_c is the correlation length , defined as the distance for which the coefficient of correlation is equal to 1/e or –4.3 dB.

L_c gives an estimate of the size of the irregularities of surface. Correlation length of several profiles was calculated and is presented on previous figure. It is important to remind that this length of correlation does not depend on the direction chosen on the profile.

A standardised and centred histogram on 256 profiles of 512 points extracted from this texture of bump is presented on the figure according to. It shows the Gaussian and isotropic behaviour of the distribution heights on this texture.

3.3. Roughness effects on canonical objects

The roughness previously described is used to measure its impact on the RCS of simple canonical objects such as plate planes, dihedral, trihedral and canonical scene (from SET 069). The length of the motif (of 512 points) is 1 m and calculations have been carried out at 34 GHz. Typical results according to the height of the texture of roughness are presented on the figure 6.

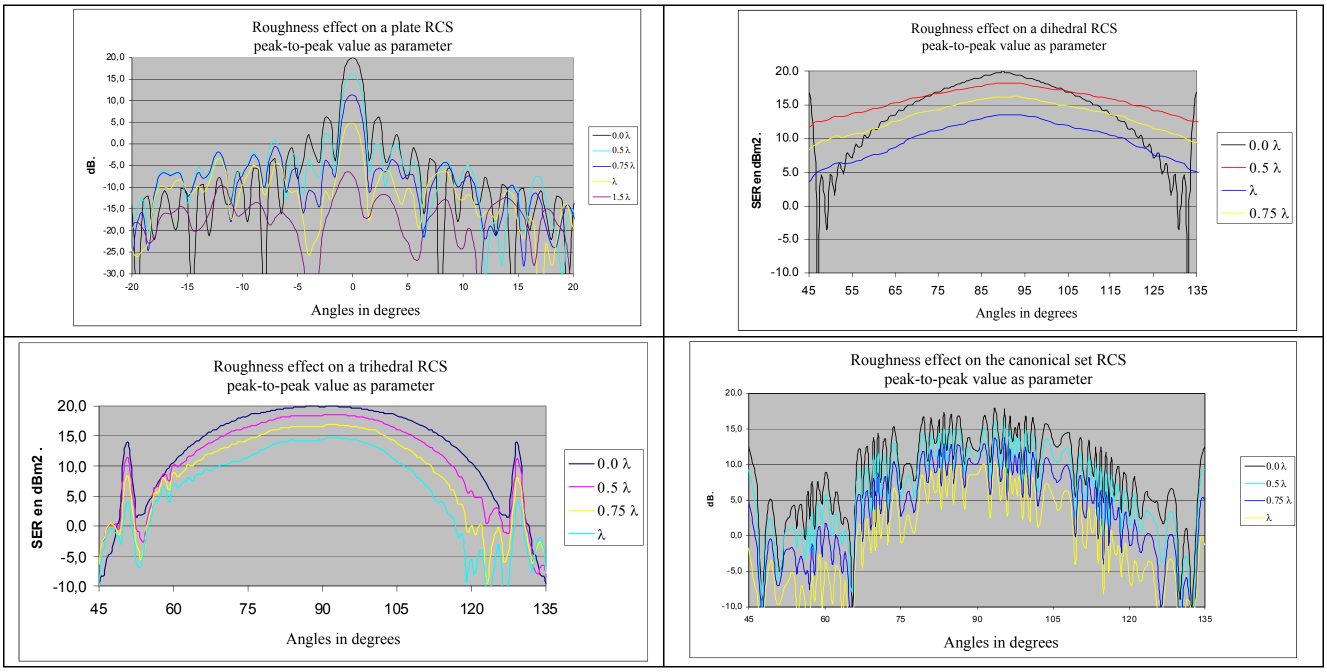


Figure 6: Roughness effect on RCS of canonical targets

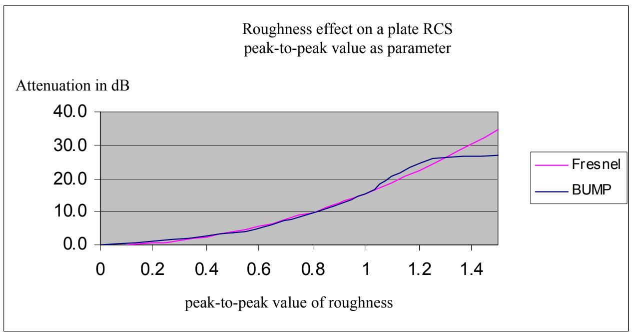
On this figure, attenuation on the maximum RCS is observed. As an example, for a peak-to-peak roughness value of one wavelength λ, following values could be noted:

- -15 dB for the plate,
- -8 dB for the dihedral,
- -5 dB for the trihedral.

Less attenuation is observed in the backscattering direction for the dihedral and the trihedral even though multiple interactions are involved. In fact, the increase of the angle of incidence on the constitutive plates of each object decreases the effect of the roughness in agreement with the modified Fresnel coefficient reminded above. It is important to note that at the same time, the sidelobes level is globally increasing.

Bump texture effect and modified Fresnel formulations

$$R = R_{th} \cdot exp(-2k^2 \quad \sigma^2 \quad cos^2(\theta_i))$$



3.4. Results on the ZSU 23-4 60 kfacets

On figure 8, from left to right we respectively have a photo and 2 pictures from the 600 kfacets and 60 kfacets CAD files. It is important to note that in terms of EM interactions at Ka band, the 2 pictures do not really represent the same object, particularly concerning the caterpillar tracks.

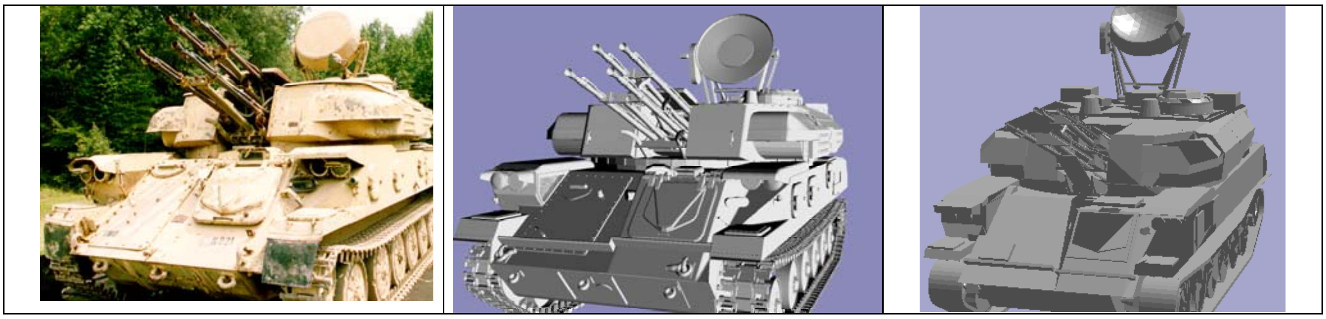


Figure 8: Representation of the ZSU 23-4

After analysis and adjustment of the effects on the canonical objects, it was decided to apply previous texture to the 60 kfacets CAD file of the ZSU 23-4. First results are presented below on figures 9 and 10.

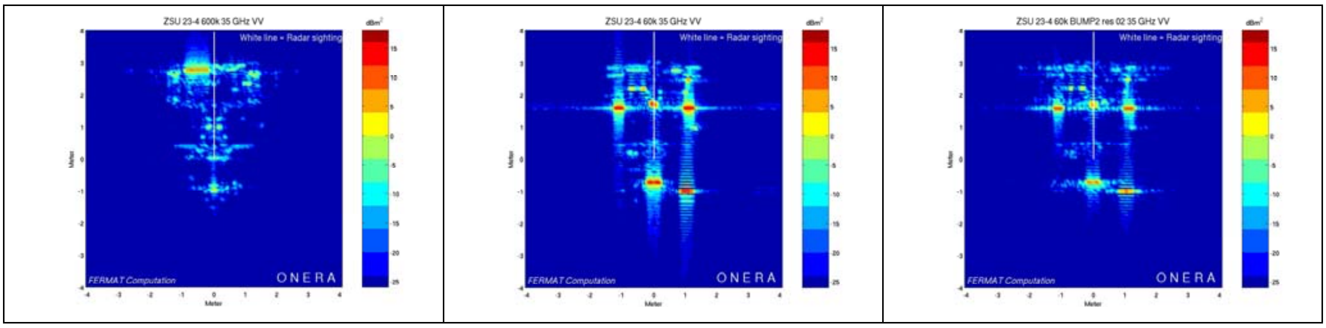


Figure 8: ISAR images with and without roughness texture

Concerning the ISAR images, high returns from specular effects are present on the central image and the distribution of scatterers is different. RCS investigation has been carried out from these images.

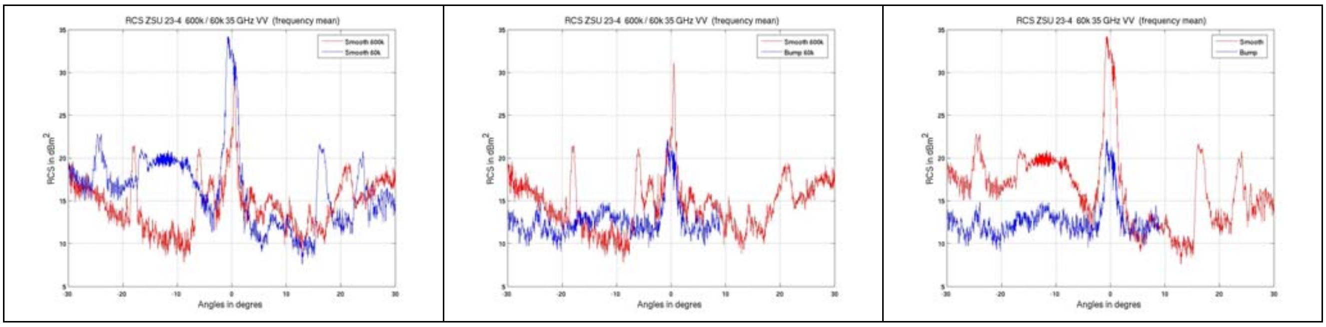


Figure 9: RCS of smooth or with roughness texture

Figure 9 presents the RCS behaviour from each target. Smooth configurations of 600 kfacets and 60 kfacets models are really different. Comparison between results from smooth and rough 60 kfacets CAD file shows reduction of principal peaks. CAD files. It is more difficult to compare results from rough 60 kfacets and smooth 600 kfacets.

4. ONGOING WORK - CONCLUSION

The principal shortcoming of a RCS calculation in MMW is the too significant value of "specular" backscattering due to unsatisfactory available CAD files compared to the real targets. FERMAT has the potential to take into account roughness texture thanks to the adaptive antialiasing. From these first experiments of roughness modelling, it appeared the results are satisfying compared to available measurements.

Comparison on global RCS (frequency averaged) and ISAR images on measurement references from SET 069 data pool and other available measurements from DCE/CELAR will be carried on. Statistical analyses on

ISAR images evaluated in terms of peak values, mean values, quadratic mean will be assessed and could allow an adjustment, on a given class of vehicle, of the random part of the scattering process.

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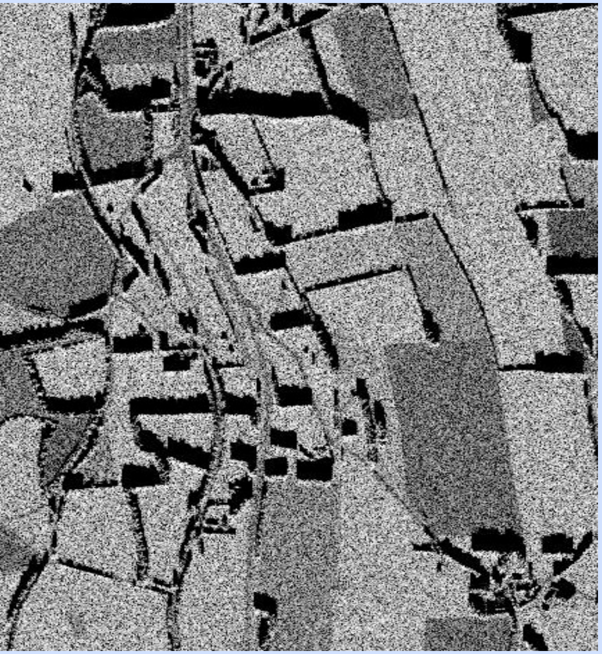
Modelling Outline



Shooting and bouncing rays technique
+
electromagnetism formulations
+
atmospheric propagation

Scenario
+
Radar Sensor Model

Virtual environment and targets geometrical 3D data base completed by specific scattering coefficients

Scientific ambition

- **Near field or far field** high frequency scattering from **metallic or dielectric materials** including reflection, transmission or diffraction of electromagnetic wave interaction.
- Taking into account the **statistical surface roughness (natural or artificial)**
- **Asymptotic formulations of** Maxwell's equations and **shooting and bouncing rays** technique coupling.

FERMAT: physical approach of EM Modelling

FERMAT
asymptotic modelling
in near or/and far field interaction
of an EM wave and
its environment
(up to mm wavelength)

Antenna on structure
Far field

Target RCS
Far field

RADAR and SAR Sensors
Far field and ambiguity function

External EMC
Near field

ONERA-OKTAL SE Partnership

- **ONERA/DEMR**
  - **Electromagnetic models**
  - **Material databases.**
  - **EM expertise especially for RADAR.**
- **OKTAL SE**
  - **Geometrical 3D databases**
  - **Ray tracing technique**
  - **Software development**

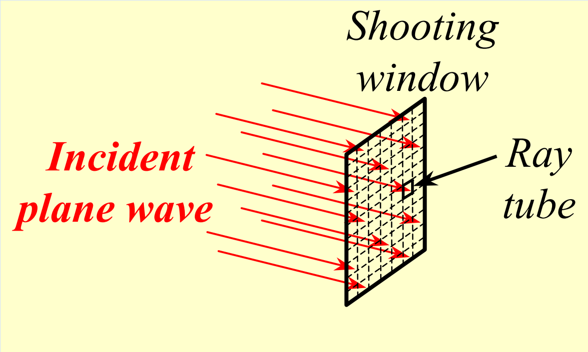
Materials and surfaces classification in the database

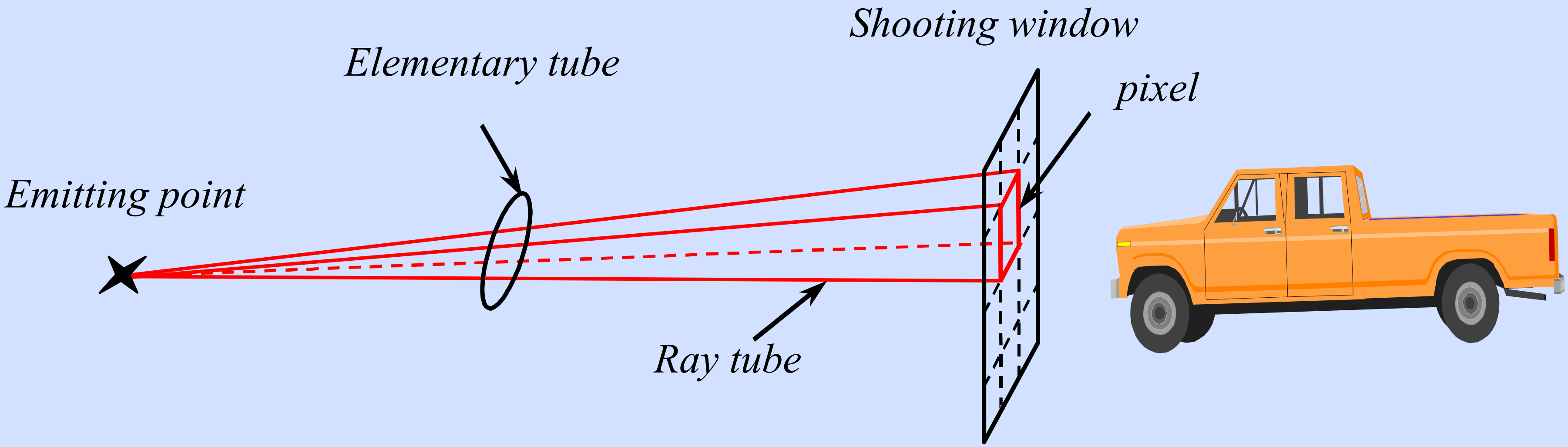
- **Dielectric materials** (characterised by: ε, ε', σ, thickness)
- **Metallic materials** (characterised by infinite conductivity)
- **Natural surfaces** classification in 30 sub-classes (characterised by backscattering coefficient average depending on incidence angle and related statistical fluctuations through a density of probability)
- **Surface roughness** by RMS height and correlation length characterisation

Shooting and Bouncing Rays

General Principle

- ***SBR : Optimised technique*** *to explore geometrical data base, validated in optical domain*
- ***Set of rays*** *representing an incident plane wave*





Electromagnetic Models : asymptotic methods of rays and current on dielectric or metallic surfaces

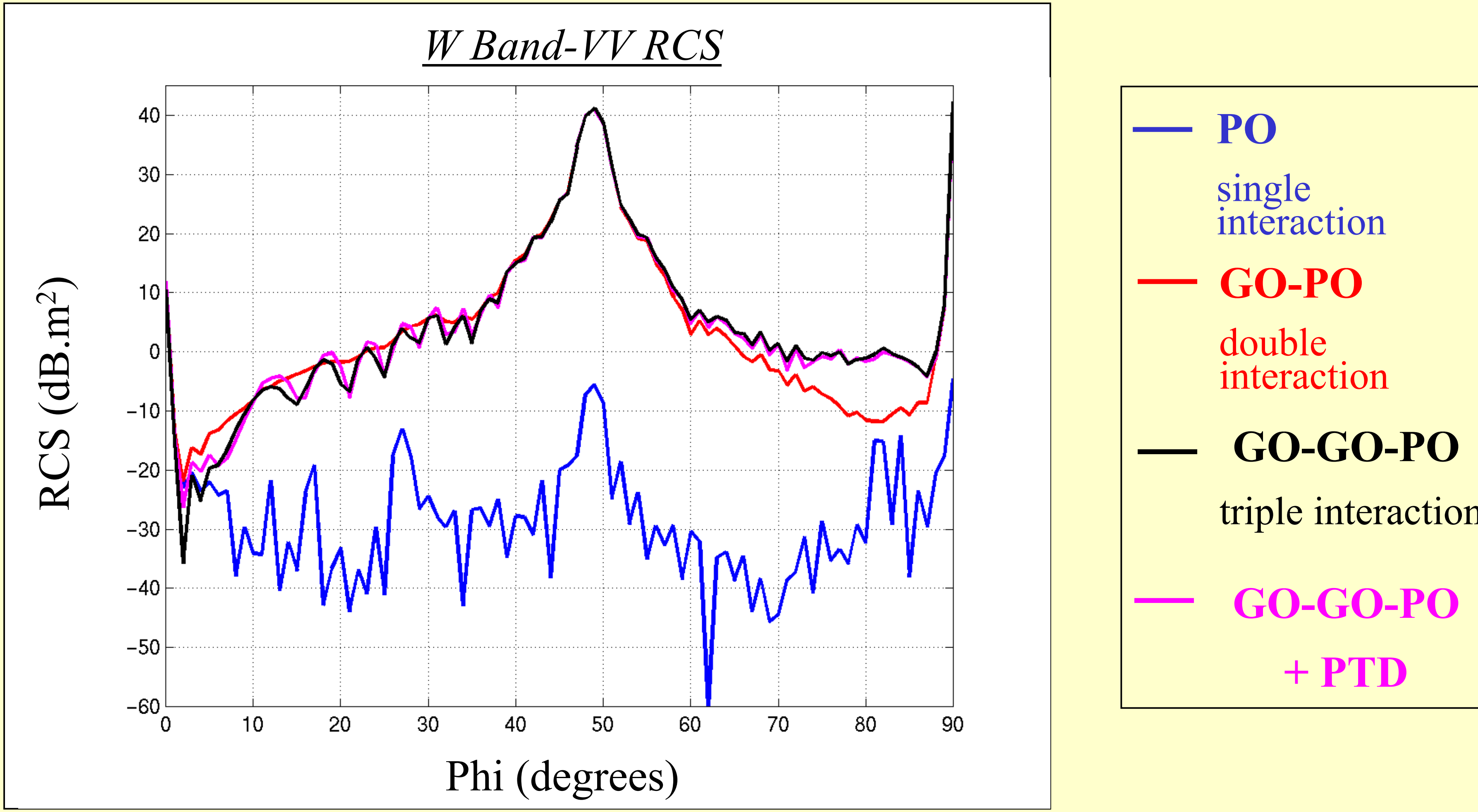
- Geometrical Optics **GO**: coupling, and forward scattering (multiple interactions) , very near field
- Physical Optics **PO:** scattering to observation (mono or bistatic configuration)
- Uniform Theory of Diffraction **UTD:** (near field edge diffraction)
- Equivalent Currents Method **ECM:** (edge diffraction to observation)

Examples and Results on Various Data Base

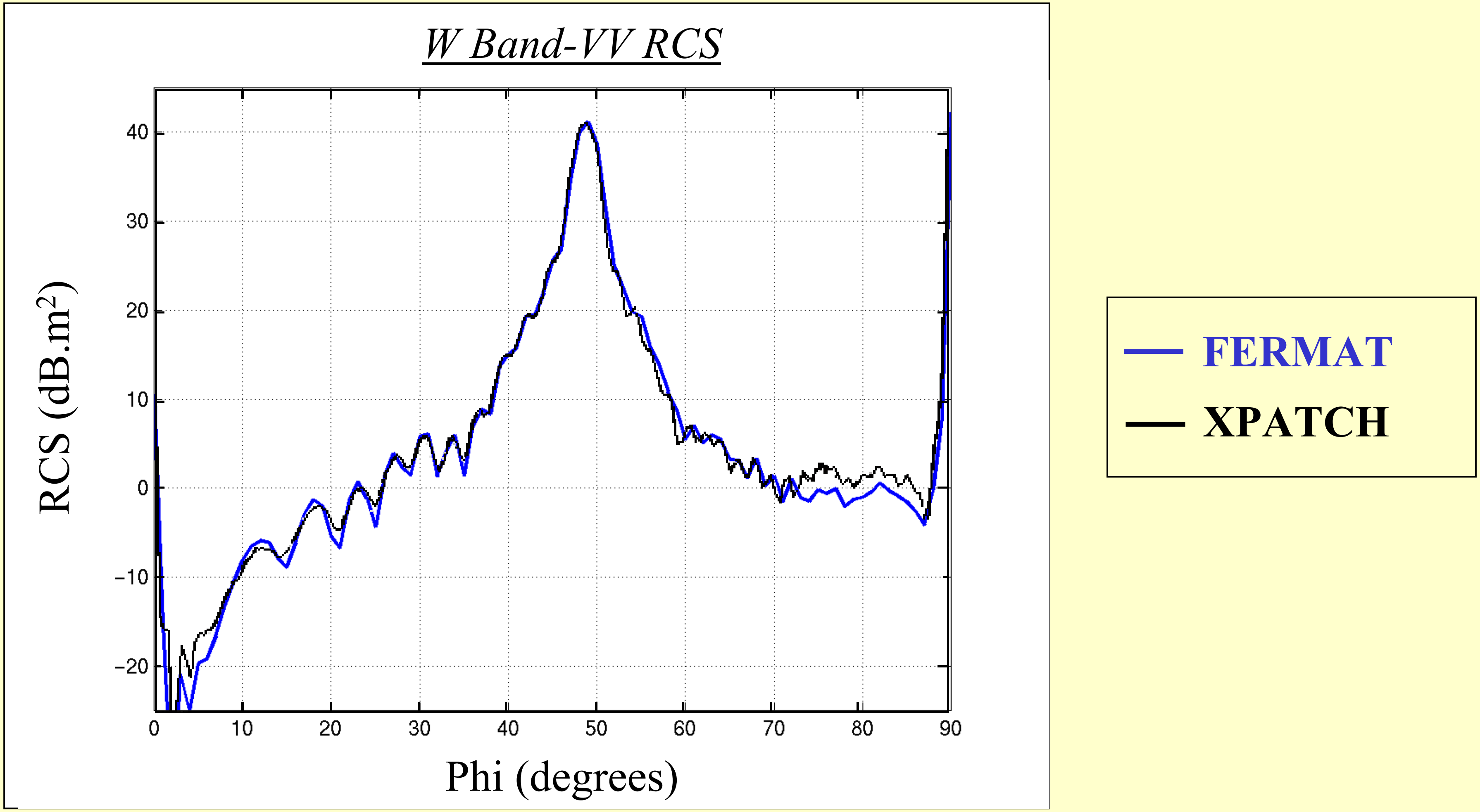
Radar Signature Prediction

- Tilted Trihedral Corner (dimensions ~ 140 cm x 60 cm x 20 cm)
- Polished aluminum full-scale canonical target
- 10 GHz RCS data published
- Workshop on 19 February 2003 in ONERA Salon de Provence at 9, 34, 94 GHz

Tilted trihedron W-Band RCS at 10° depression:
Interaction decomposition

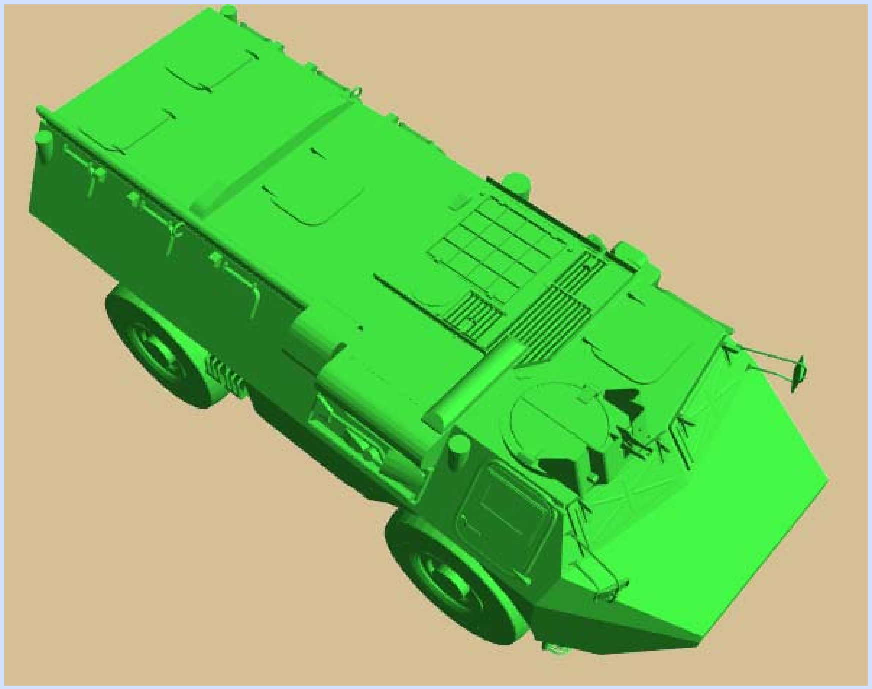


Tilted trihedron W-Band RCS at 10° depression: Validation



Radar Cross Section Results on VAB (Véhicule de l'Avant Blindé) Repair and Recovery Vehicle

Radar cross section at millimetre wavelength
Comparison with measurements

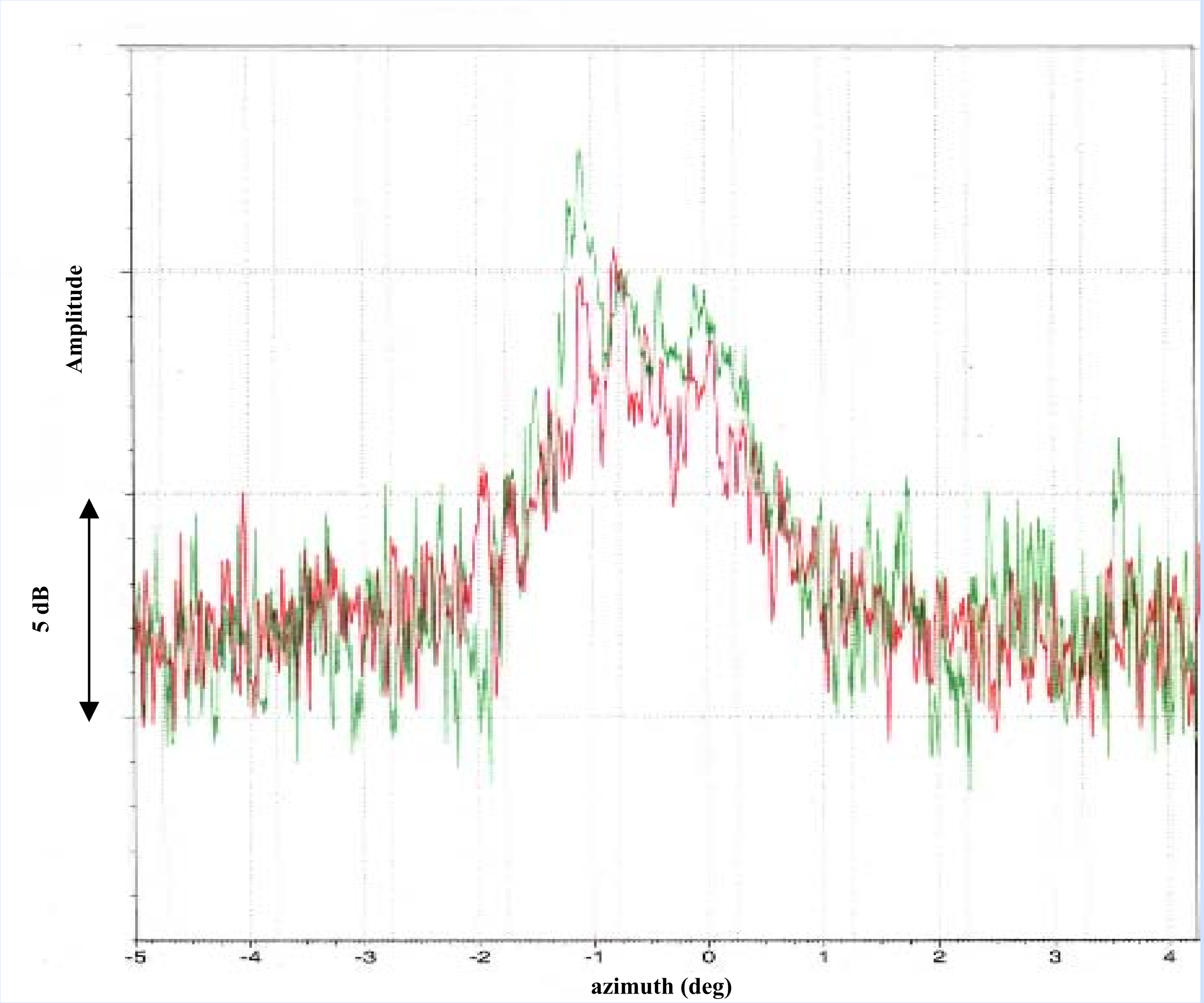


CAD virtual object *Real Object*

Results

Measurement

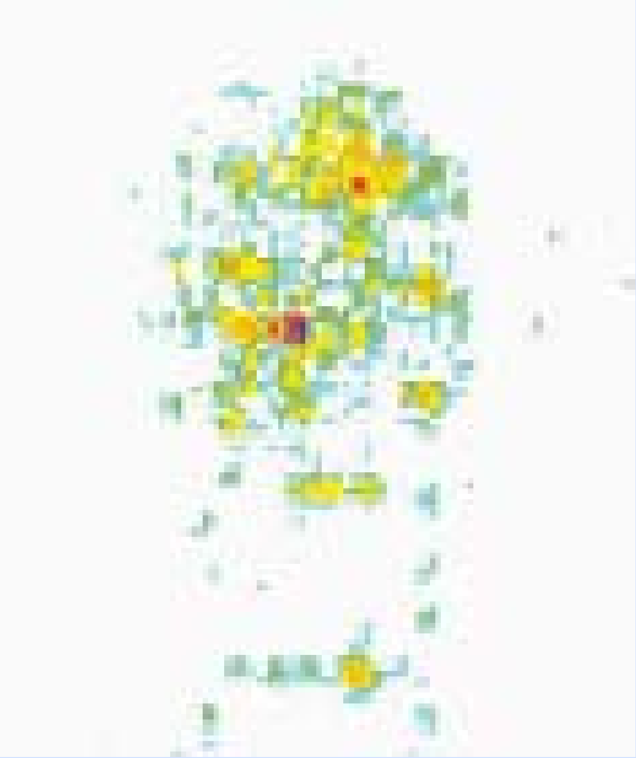
Calculations



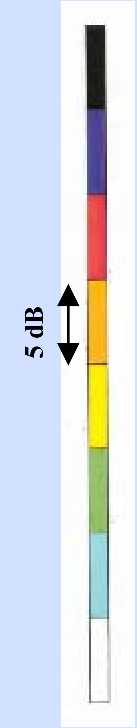
ISAR images at millimetre wavelength

Angular sector -0.5/-0.5 deg

Measurements



Calculations



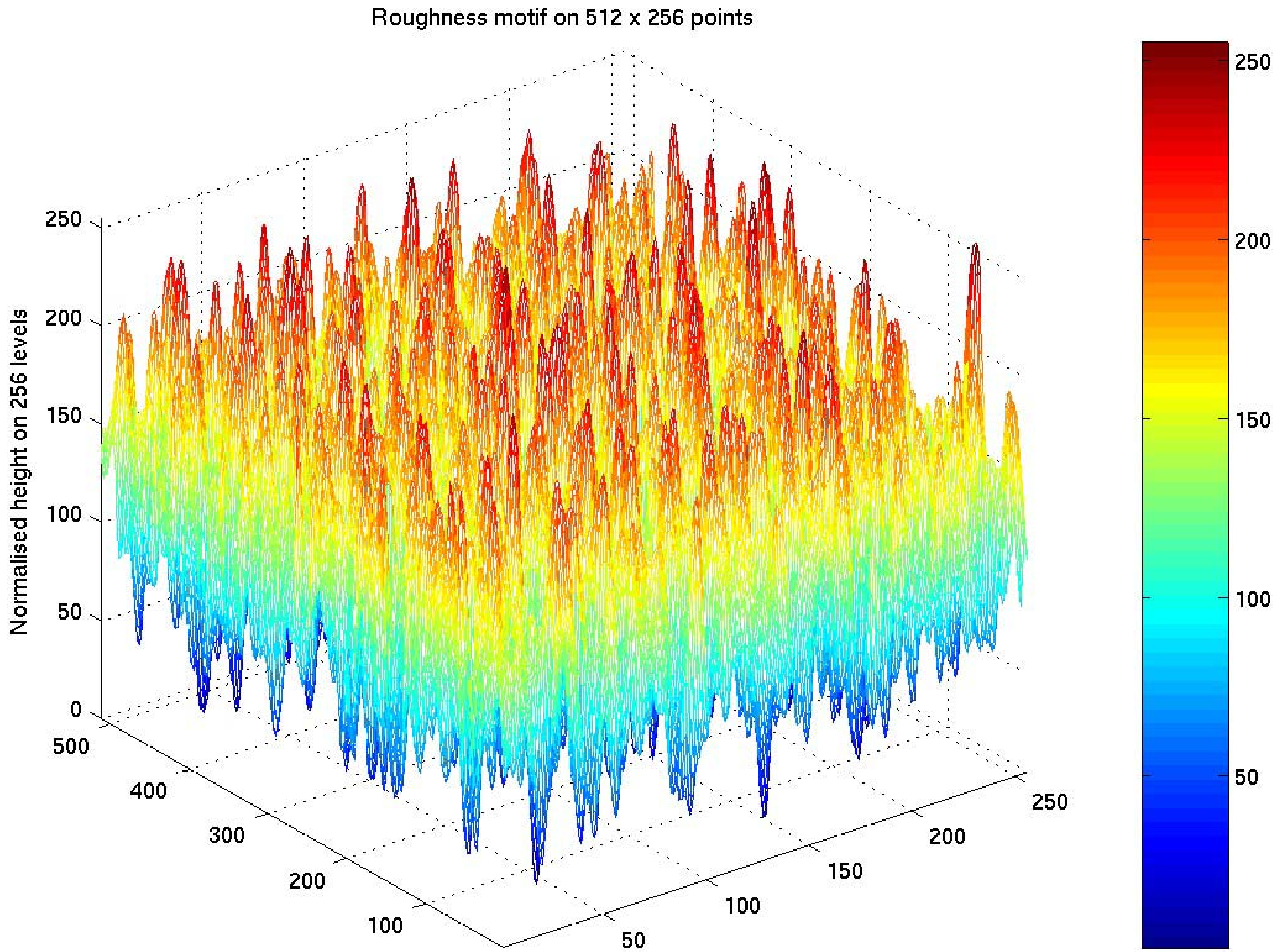
Profile Statistical Parameters

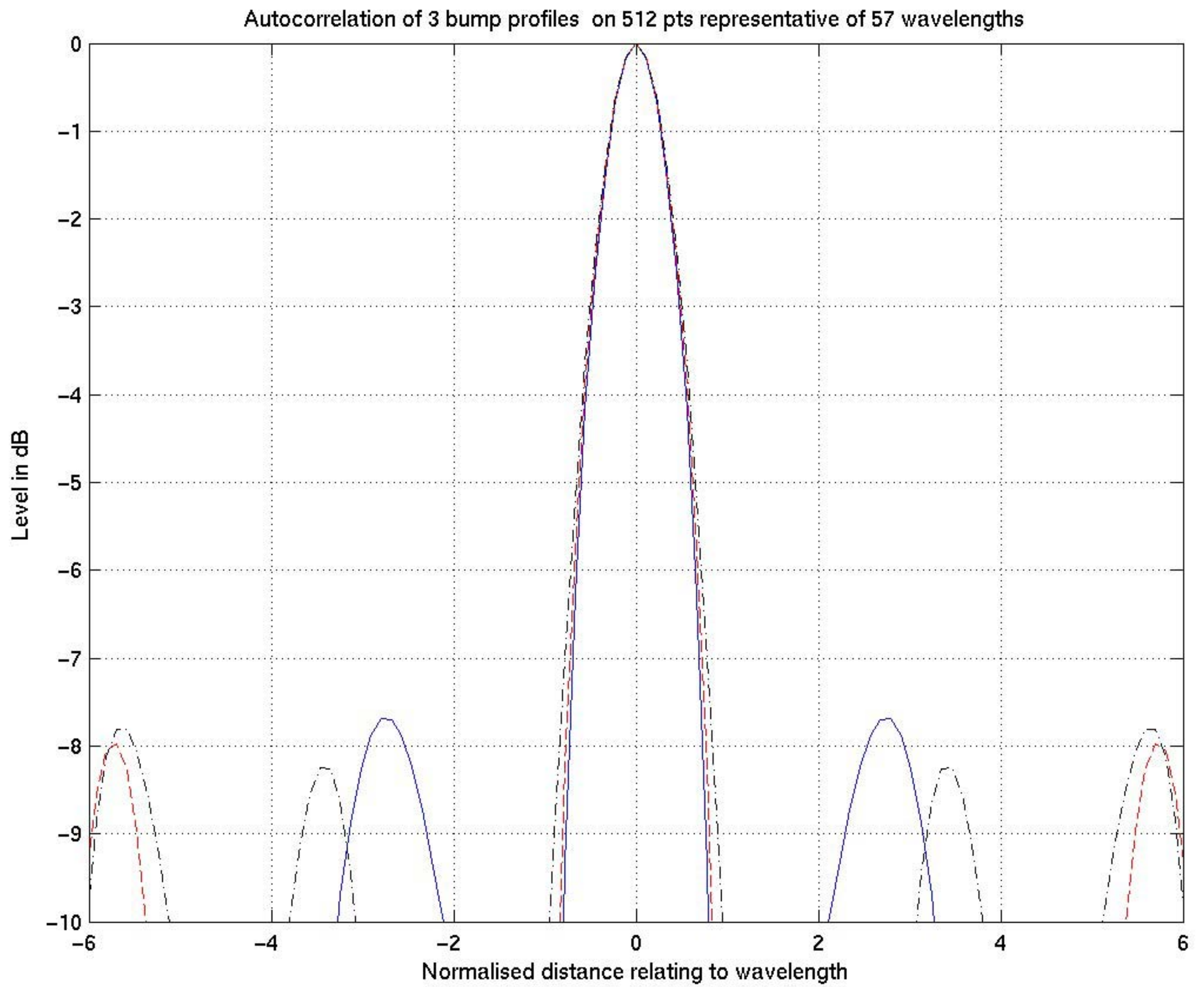
Gaussian distribution of the heights, characterised by:

- 256 levels (8 bits)
- An extended area of 1 m^2

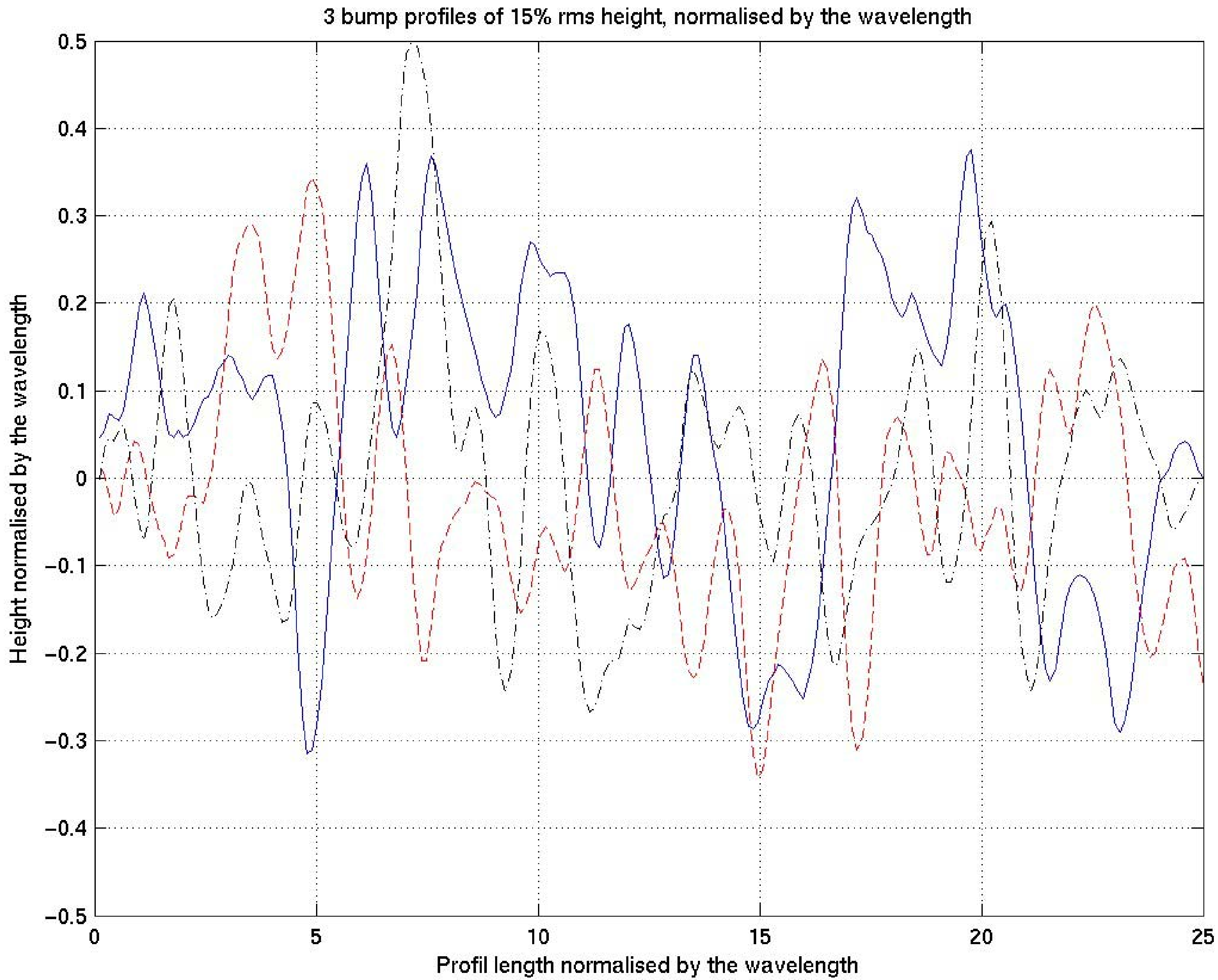
Adjustment of:

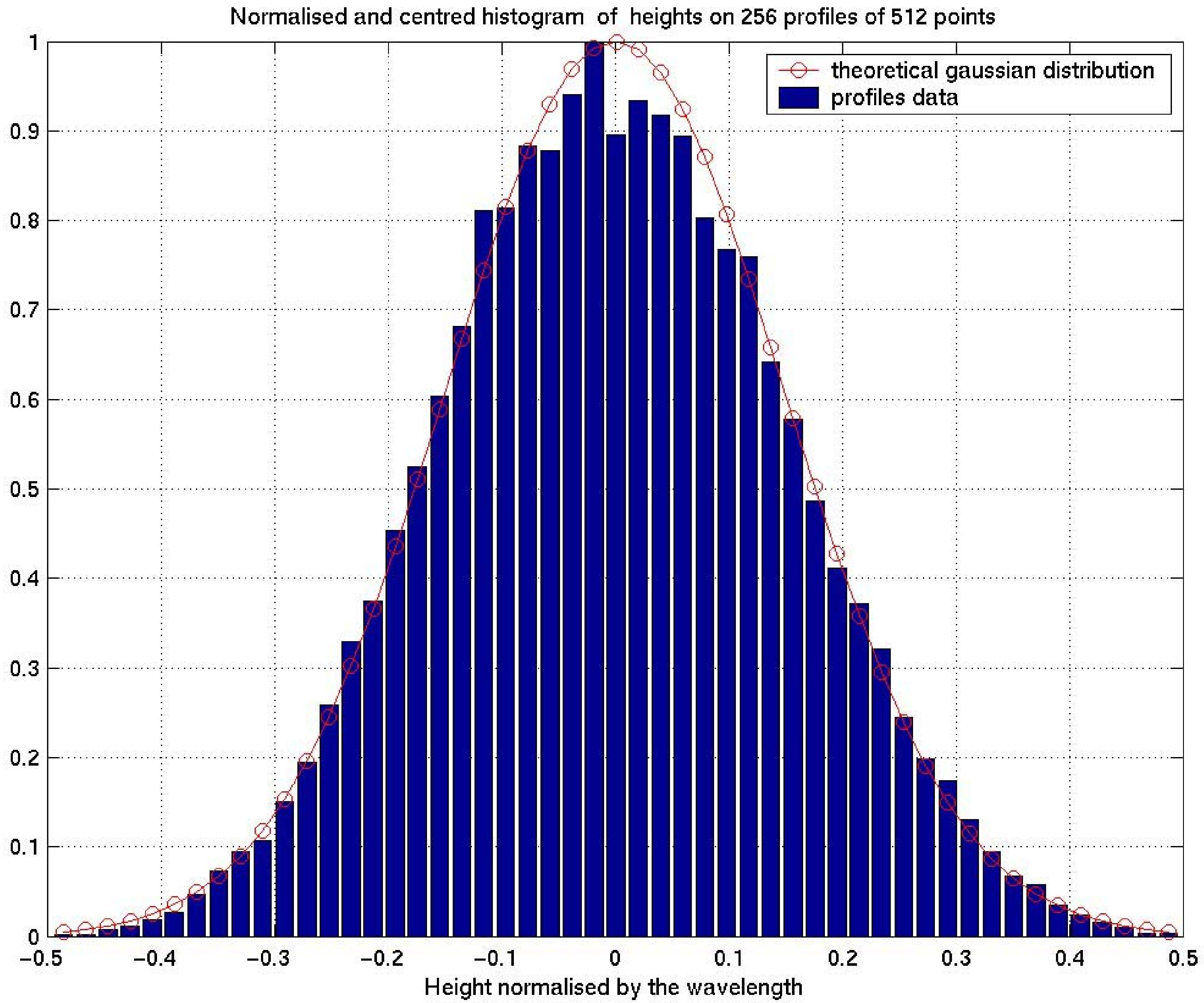
- rms height
- correlation length
- antialing parameters


Roughness motif on 512 x 256 points
Normalised height on 256 levels
250
200
150
100
50
0
500
400
300
200
100
50
100
150
200
250
250
200
150
100
50



Autocorrelation of 3 bump profiles on 512 pts representative of 57 wavelengths
Level in dB
0
−1
−2
−3
−4
−5
−6
−7
−8
−9
−10
−6
−4
−2
0
2
4
6
Normalised distance relating to wavelength


3 bump profiles of 15% rms height, normalised by the wavelength
Height normalised by the wavelength
Profil length normalised by the wavelength
0.5
0.4
0.3
0.2
0.1
0
−0.1
−0.2
−0.3
−0.4
−0.5
0
5
10
15
20
25


Normalised and centred histogram of heights on 256 profiles of 512 points
theoretical gaussian distribution
profiles data
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
−0.5
−0.4
−0.3
−0.2
−0.1
0
0.1
0.2
0.3
0.4
0.5
Height normalised by the wavelength

Available data and measurement on ground vehicles :

➔ Data pool group SET 069

- ARL
  - ZSU CAD 600 kfacets and 60 kfacets
  - T72 measurements
- ZSU 23-4 FGAN ISAR measurements
- T72 FGAN measurements

➔ Specific measurements on rough plates

➔ Others ...

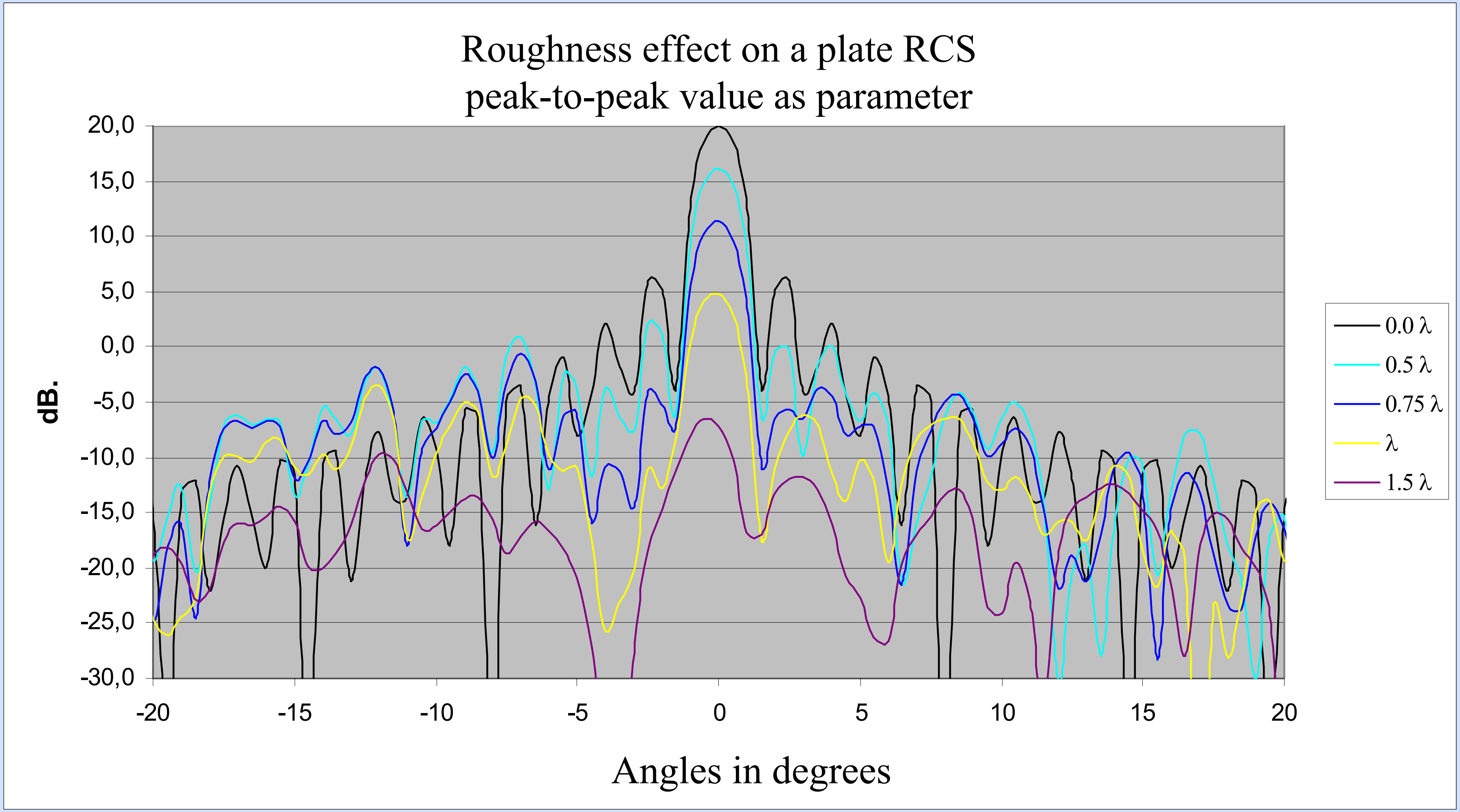
First analysis of roughness effect on ground vehicles :

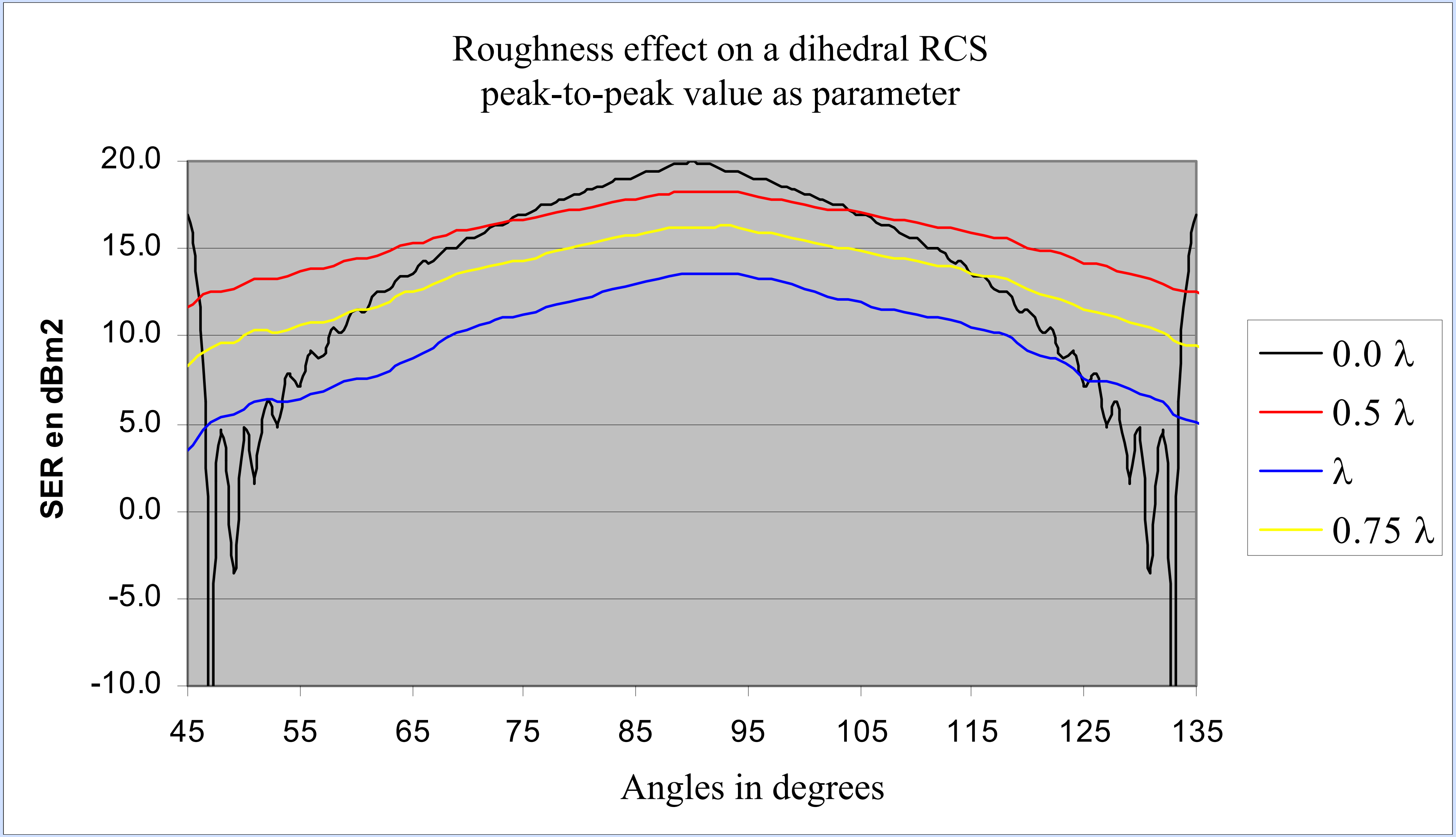
➔ Based on previous investigations on:

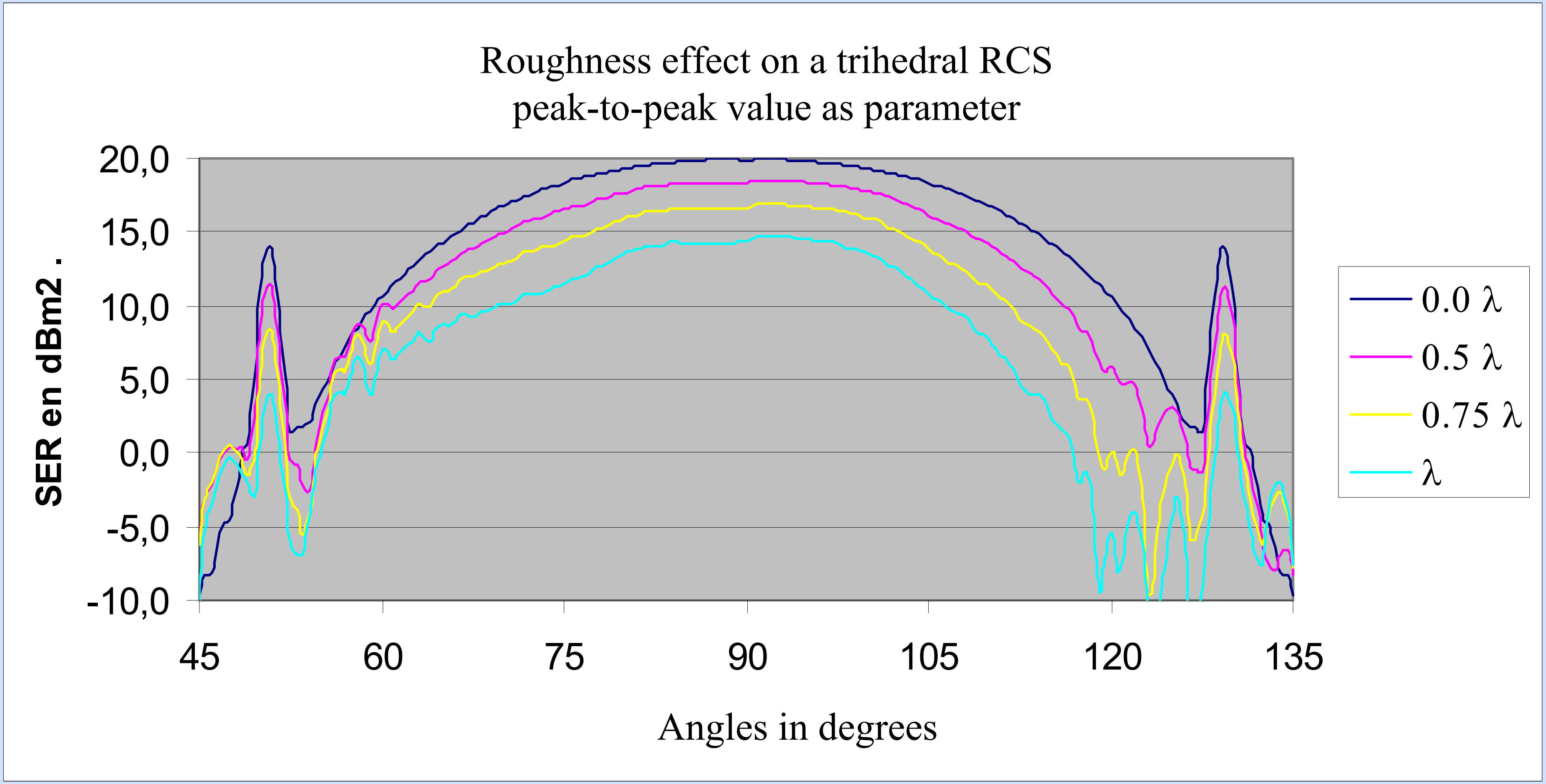
- a VAB (Véhicule de l'Avant Blindé) Repair and Recovery Vehicle
- the use of bump texture in IR applications

➔ Specific roughness analysis on canonical objects (plates, dihedral, trihedral, test scene)

➔ First applications on the ZSU CAD 60 kfacets

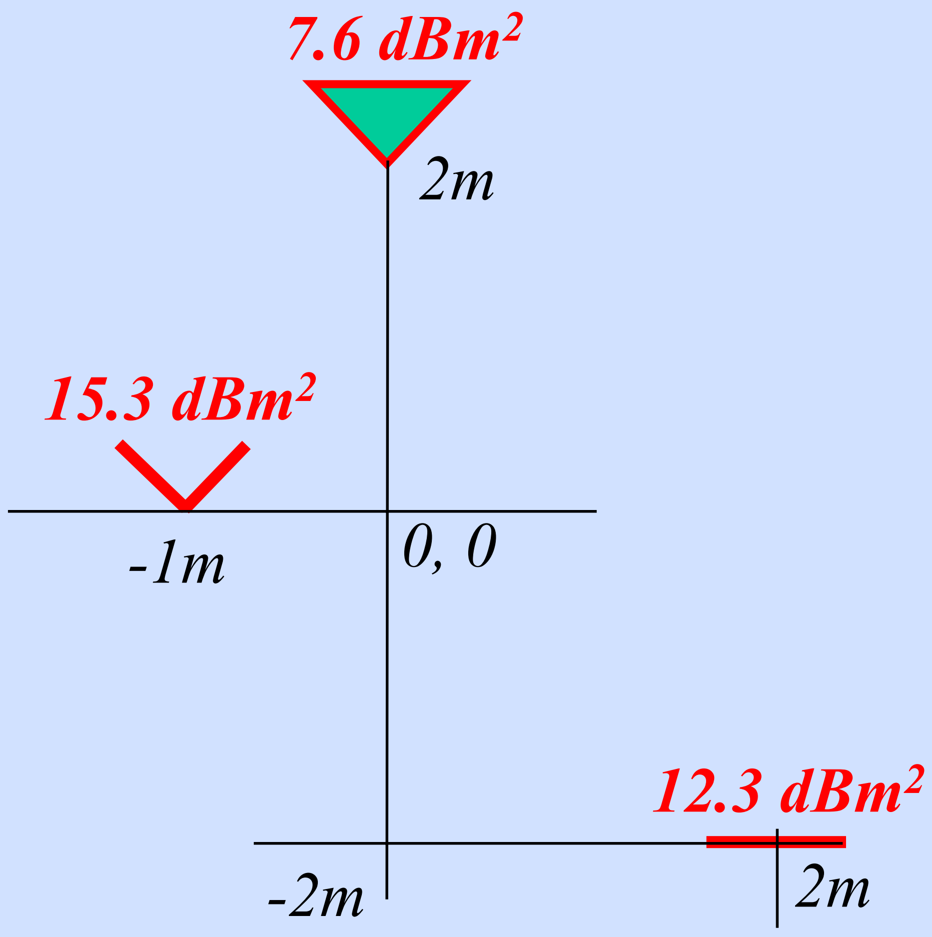

Roughness effect on a plate RCS
peak-to-peak value as parameter
20,0
15,0
10,0
5,0
0,0
-5,0
-10,0
-15,0
-20,0
-25,0
-30,0
dB.
-20
-15
-10
-5
0
5
10
15
20
Angles in degrees
0.0 λ
0.5 λ
0.75 λ
λ
1.5 λ

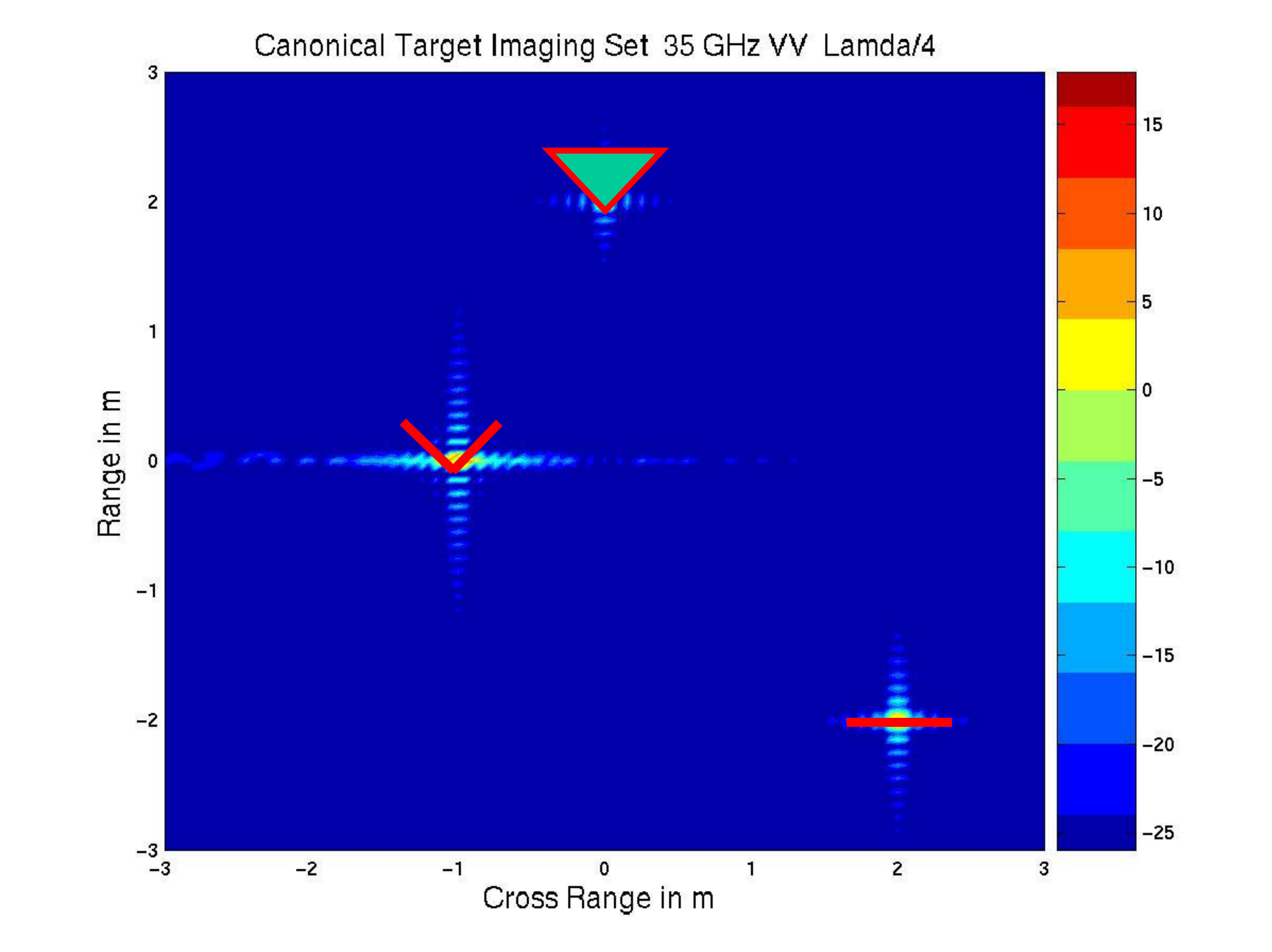

Roughness effect on a dihedral RCS
peak-to-peak value as parameter
20.0
15.0
10.0
5.0
0.0
-5.0
-10.0
SER en dBm2
45
55
65
75
85
95
105
115
125
135
Angles in degrees
0.0 λ
0.5 λ
λ
0.75 λ



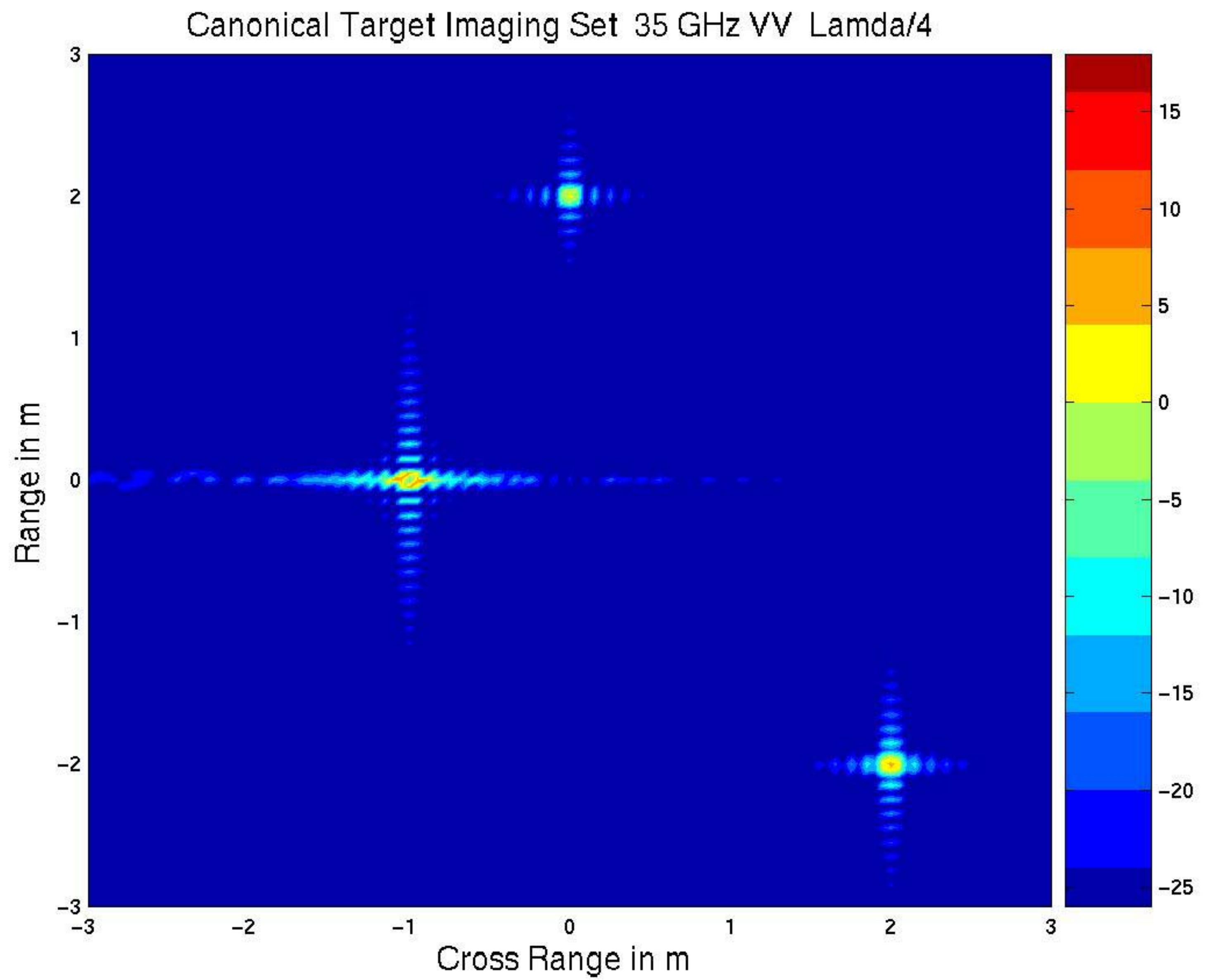
Roughness effect on a trihedral RCS
peak-to-peak value as parameter
SER en dBm2 .
20,0
15,0
10,0
5,0
0,0
-5,0
-10,0
45
60
75
90
105
120
135
Angles in degrees
0.0 λ
0.5 λ
0.75 λ
λ

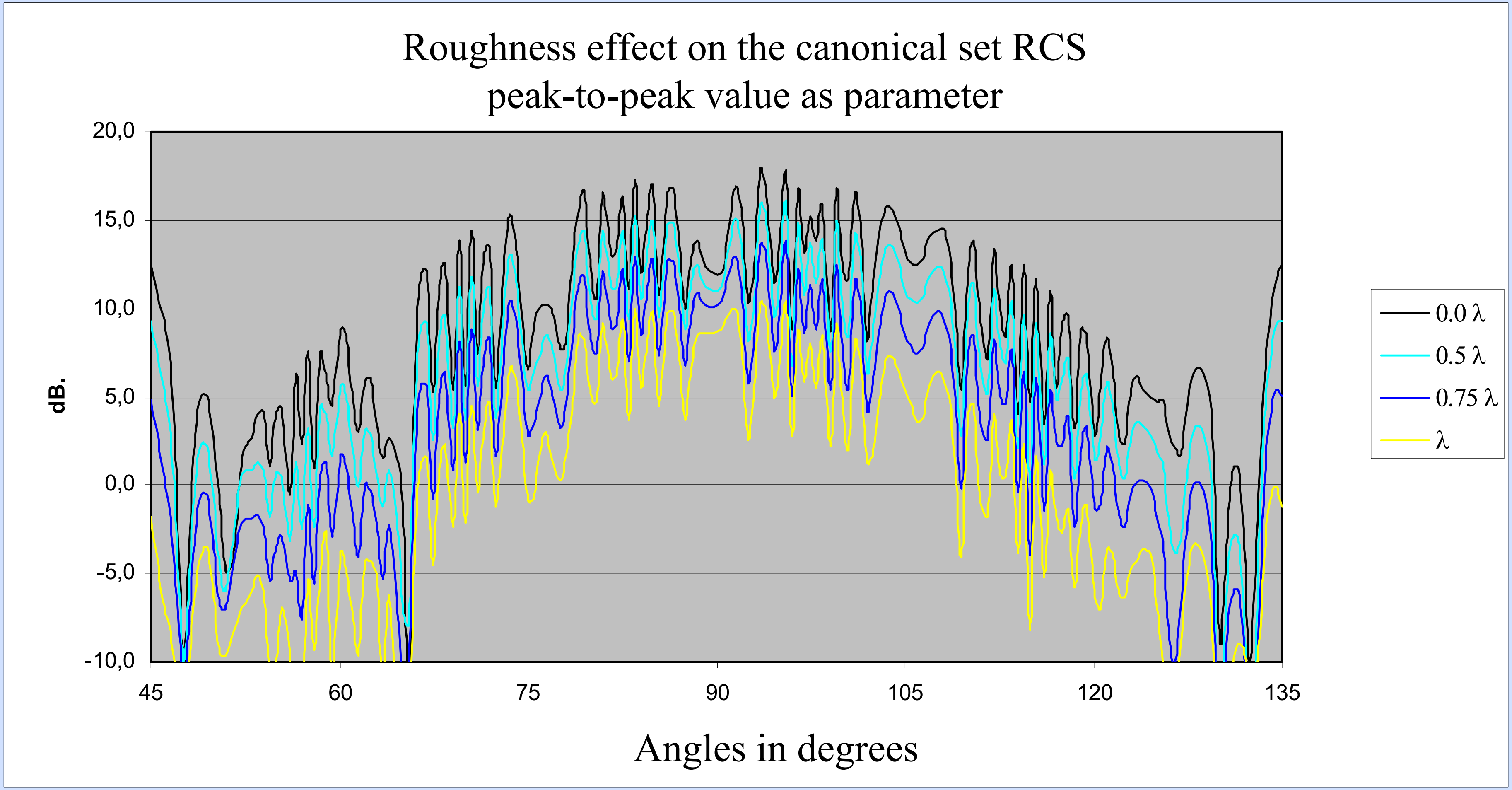
Canonical Target Imaging 35 GHz VV



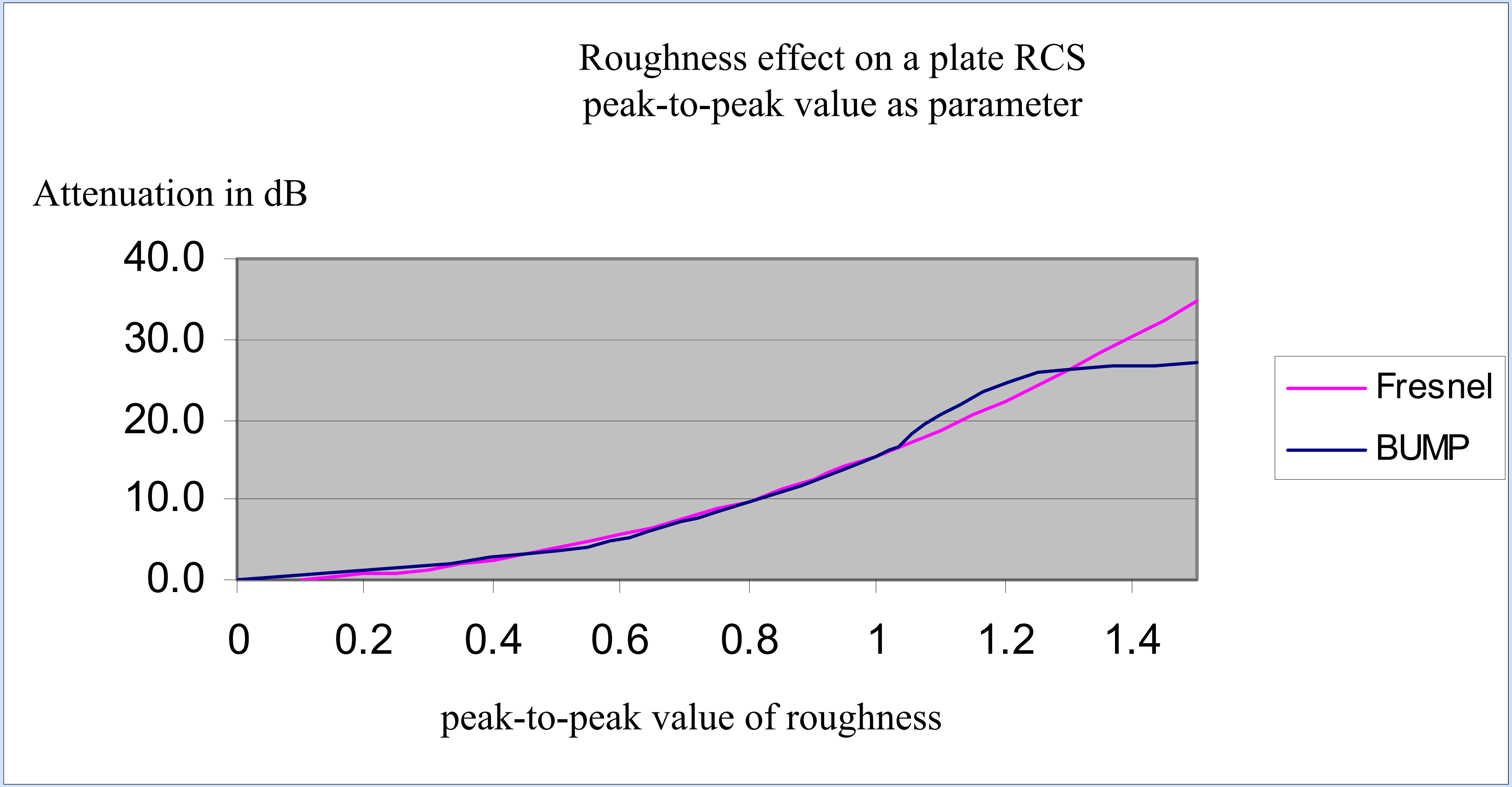


Canonical Target Imaging Set 35 GHz VV Lamda/4
Range in m
Cross Range in m
3
2
1
0
−1
−2
−3
15
10
5
−5
−10
−15
−20
−25


Canonical Target Imaging Set 35 GHz VV Lamda/4
Range in m
Cross Range in m
3
2
1
0
−1
−2
−3
−3
−2
−1
0
1
2
3
15
10
5
0
−5
−10
−15
−20
−25


Roughness effect on the canonical set RCS
peak-to-peak value as parameter
20,0
15,0
10,0
5,0
0,0
-5,0
-10,0
dB.
45
60
75
90
105
120
135
Angles in degrees
0.0 λ
0.5 λ
0.75 λ
λ

Bump texture effect and modified Fresnel formulations ($R_{//,\perp}$*exp[-2*($2\pi\sigma\cos(\theta)/\lambda)^2$]



Evaluation tools (metric comparison)

Evaluation and comparison tools worked on:

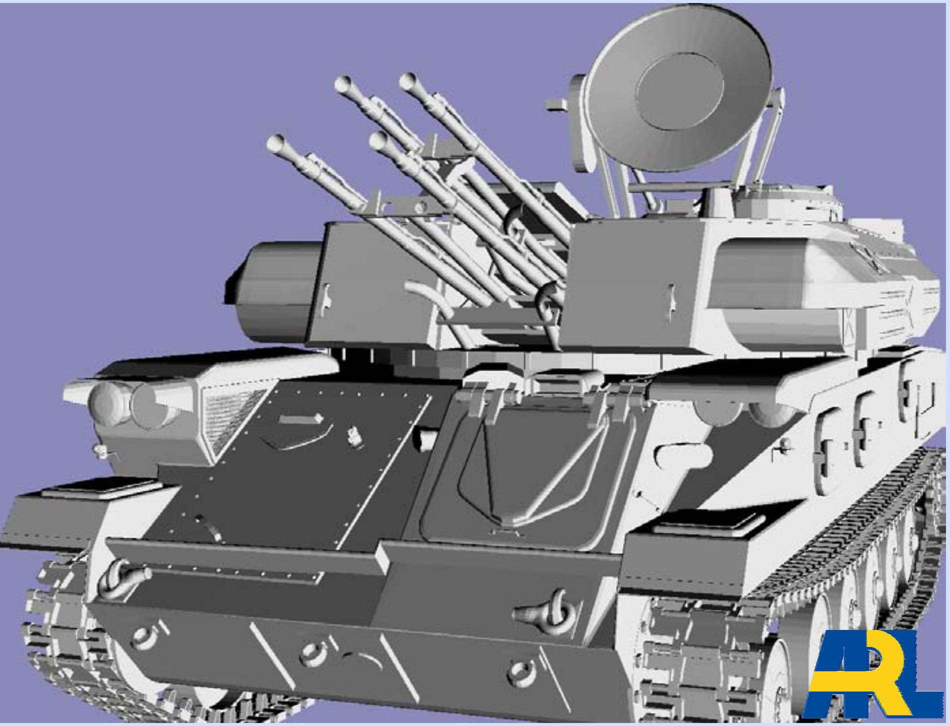
➔ Statistical evaluation of ISAR images

- peak values,
- mean value,
- quadratic mean,

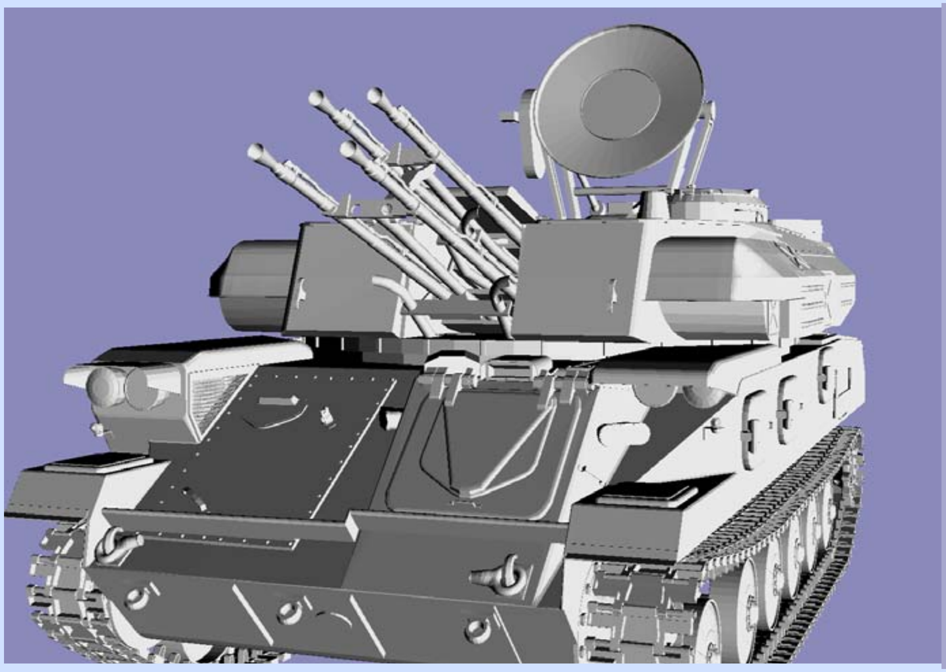
➔ Comparison on global RCS (frequency averaged)

➔ Measurements references from SET 069 data pool and other available measurements from DECE/CELAR.

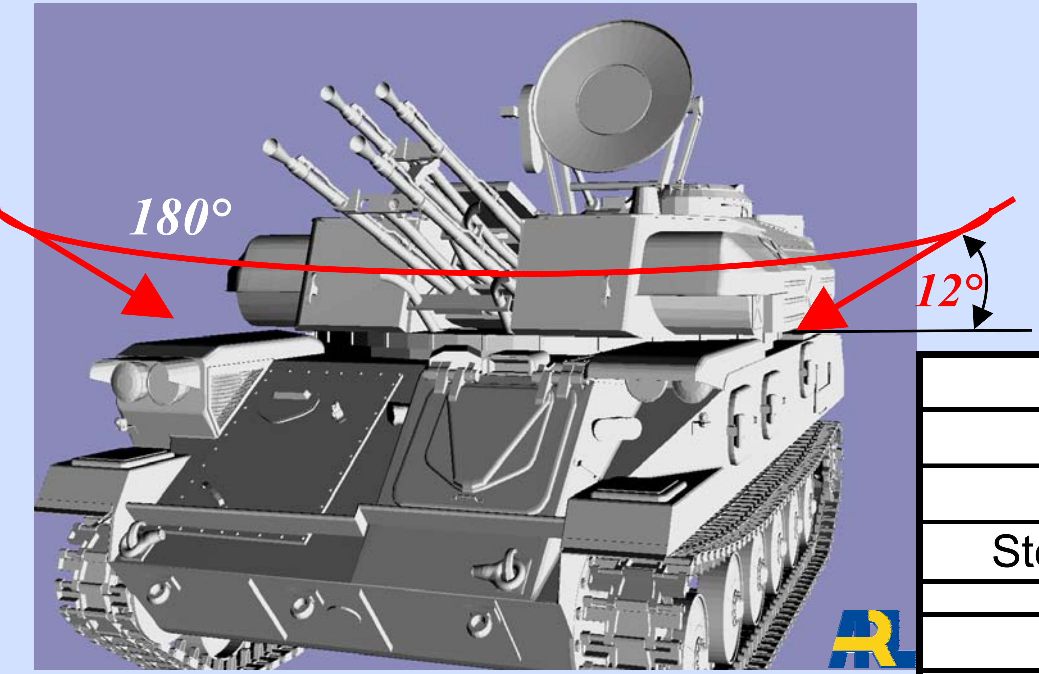
ZSU 23-4 600 kfacets



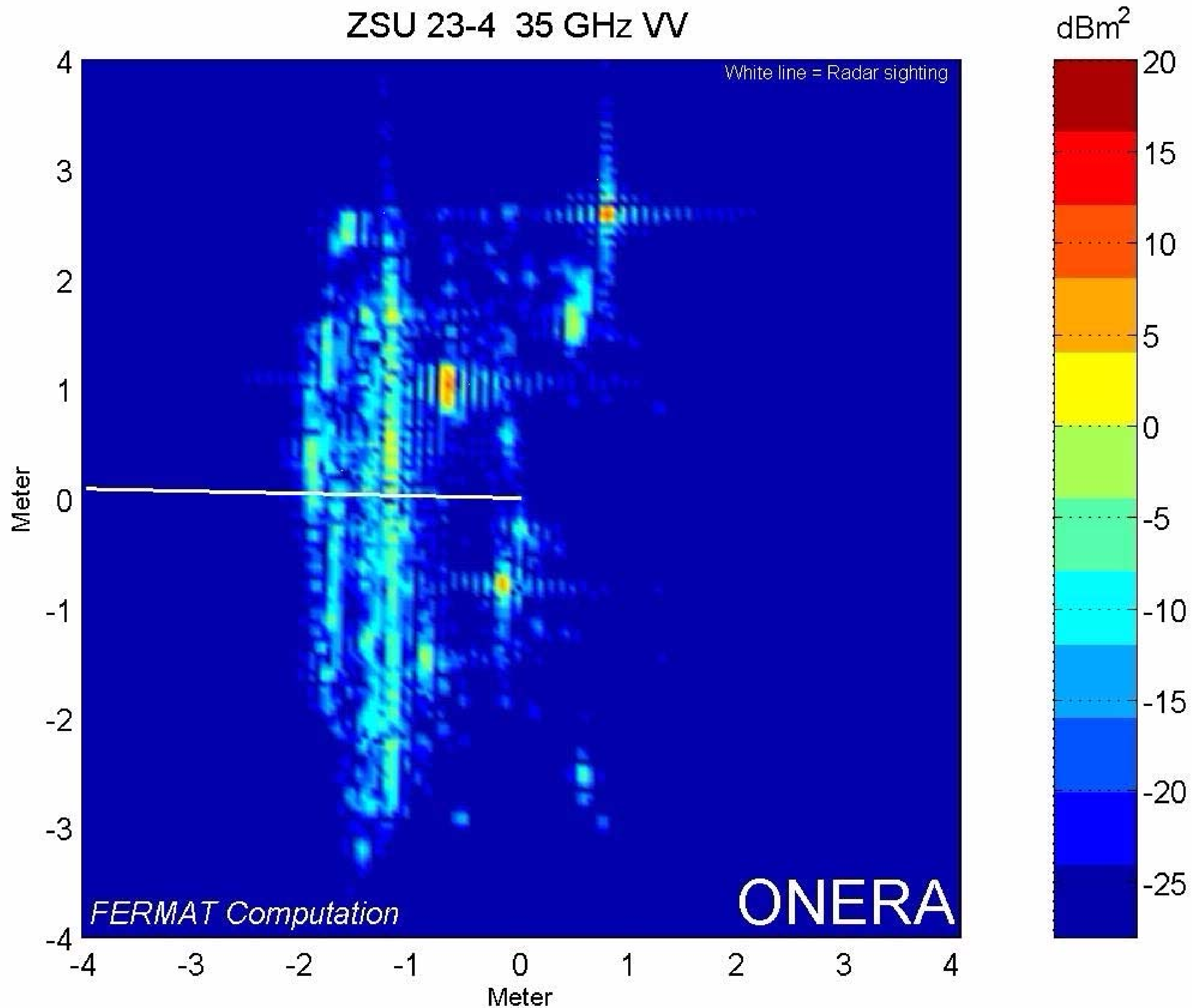
ZSU 23-4 600 and 60 kfacets



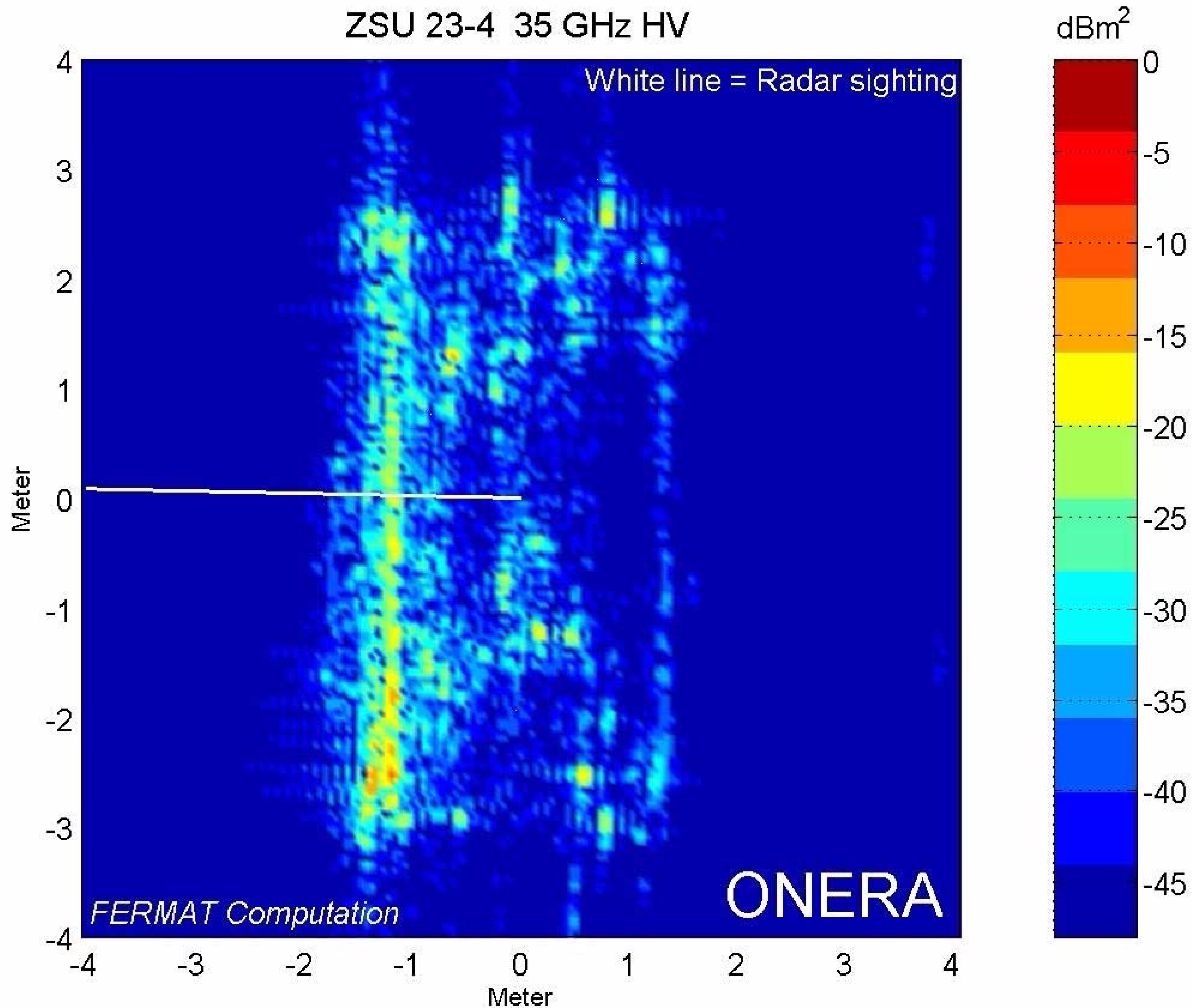
CAO ZSU 23-4 CALCULATION 600 kfacets

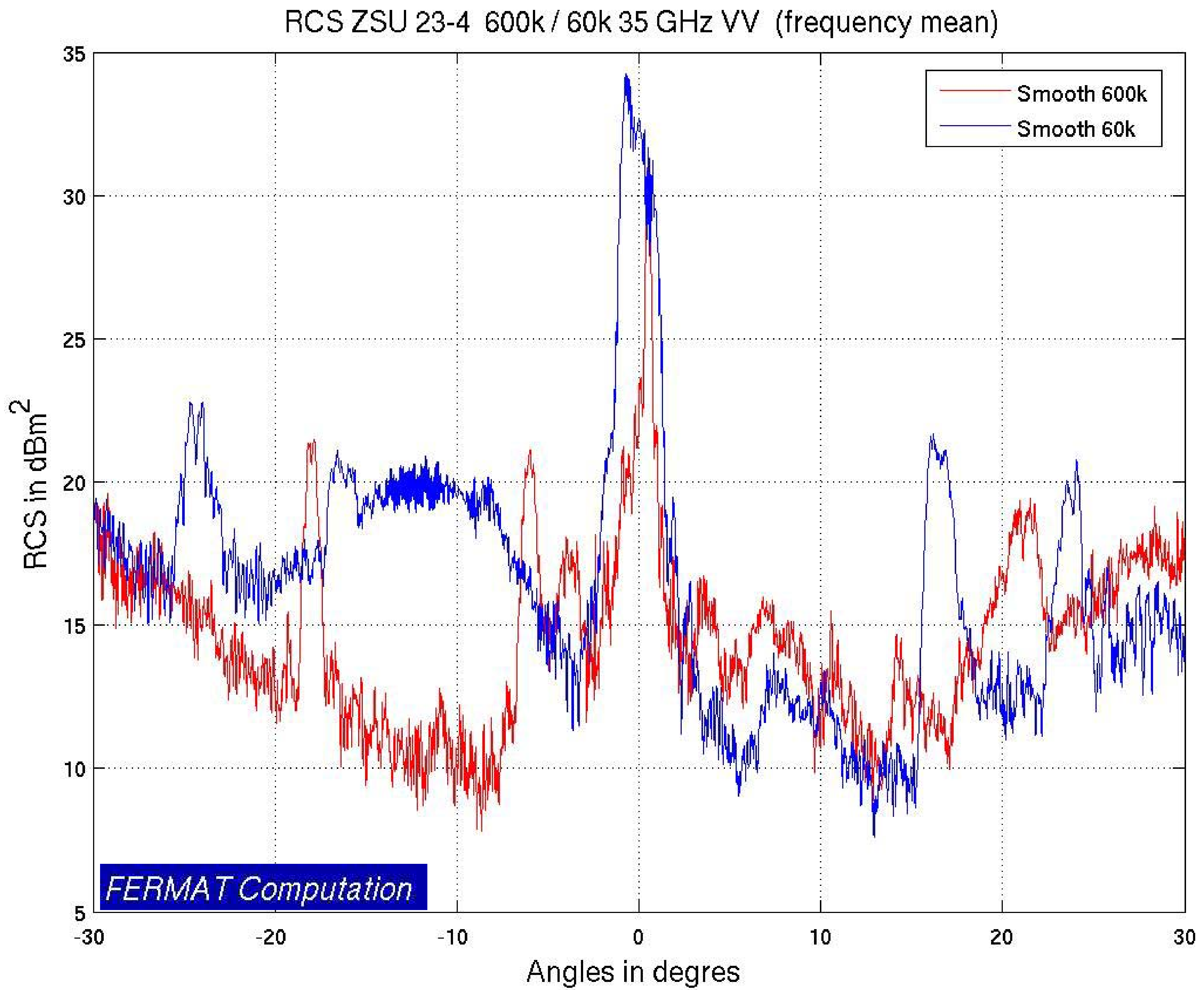


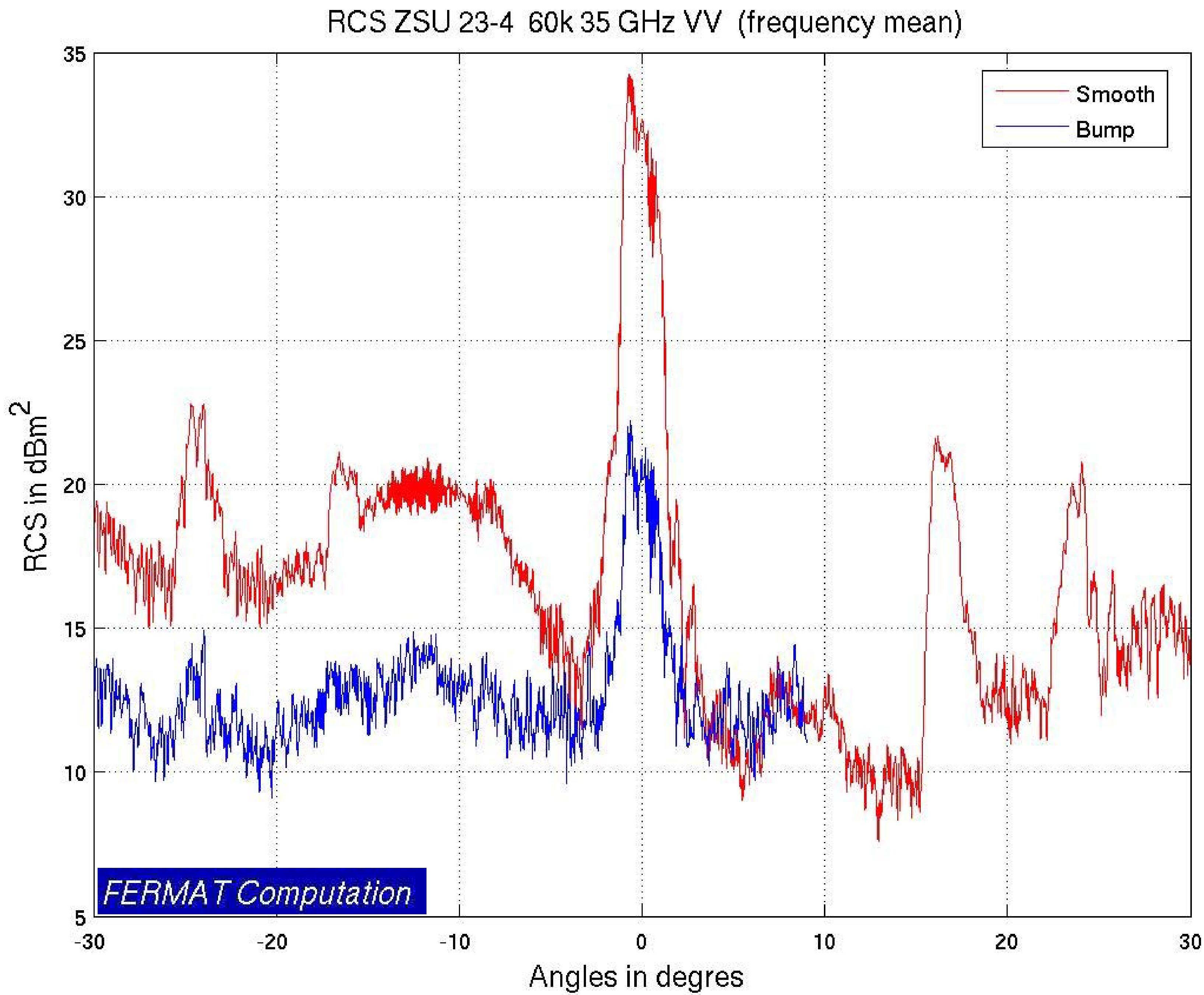
Total azimuth angle	180	°
Step	0.015	°
Bandwidth	1.5176	MHz
Step frequency number	256	
Total angle number	12000	
Total caculation duration on PC	17.25	days
	2	mn/by angle
ISAR imaging	2°	
Total ISAR image number	295	

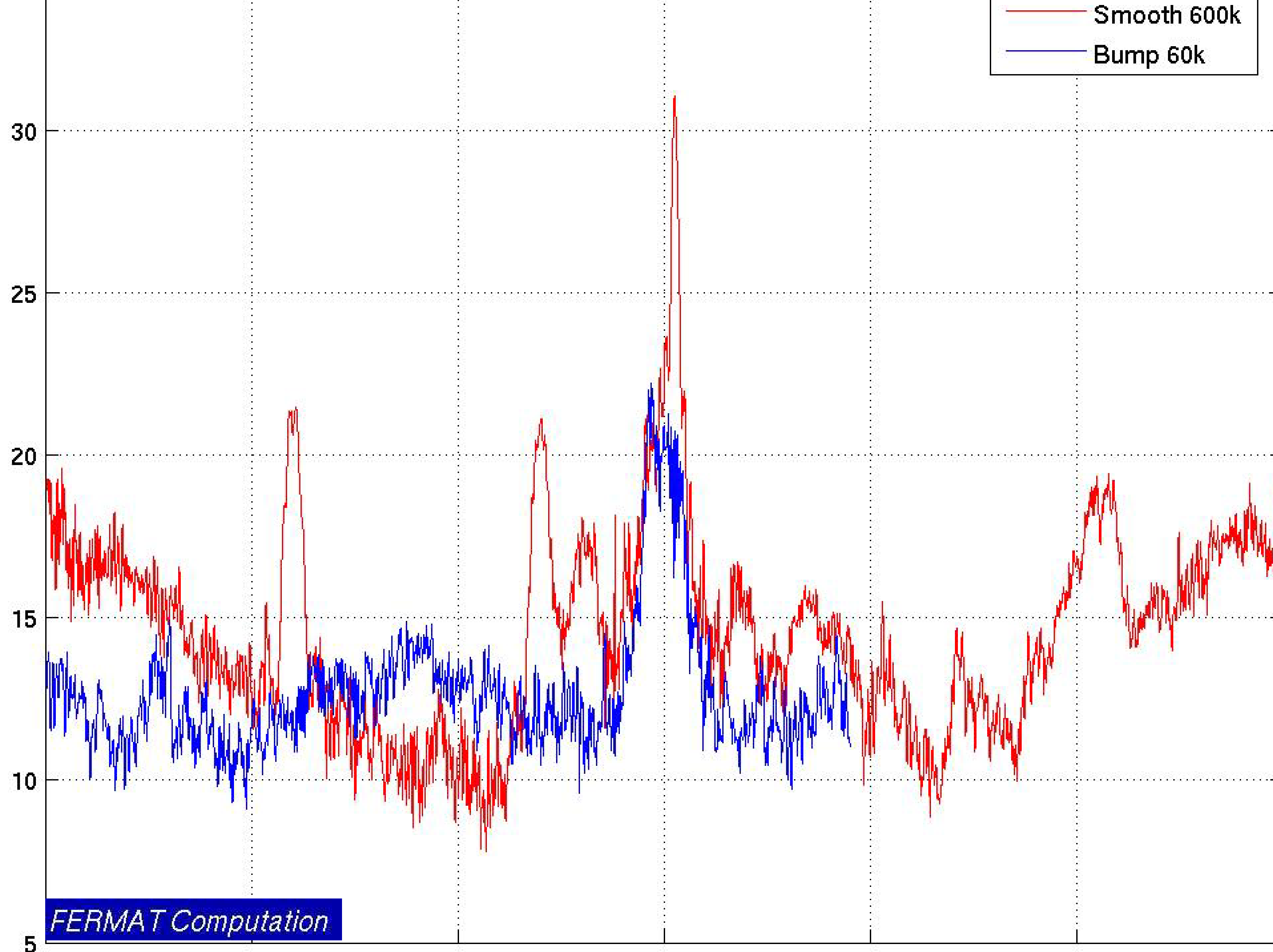


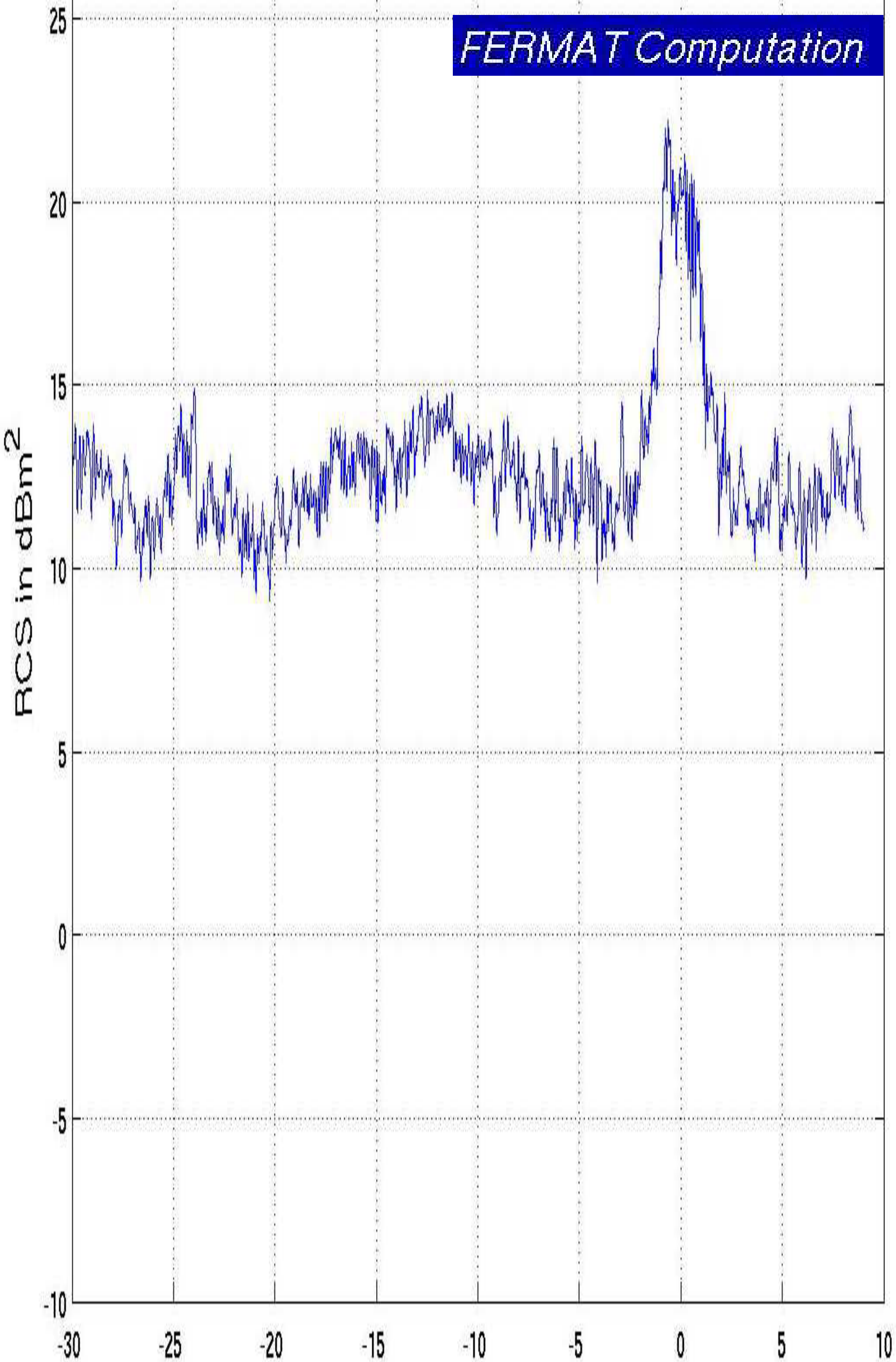
ZSU 23-4 35 GHz VV
dBm2
White line = Radar sighting
Meter
Meter
FERMAT Computation
ONERA
20
15
10
5
0
-5
-10
-15
-20
-25
4
3
2
1
0
-1
-2
-3
-4

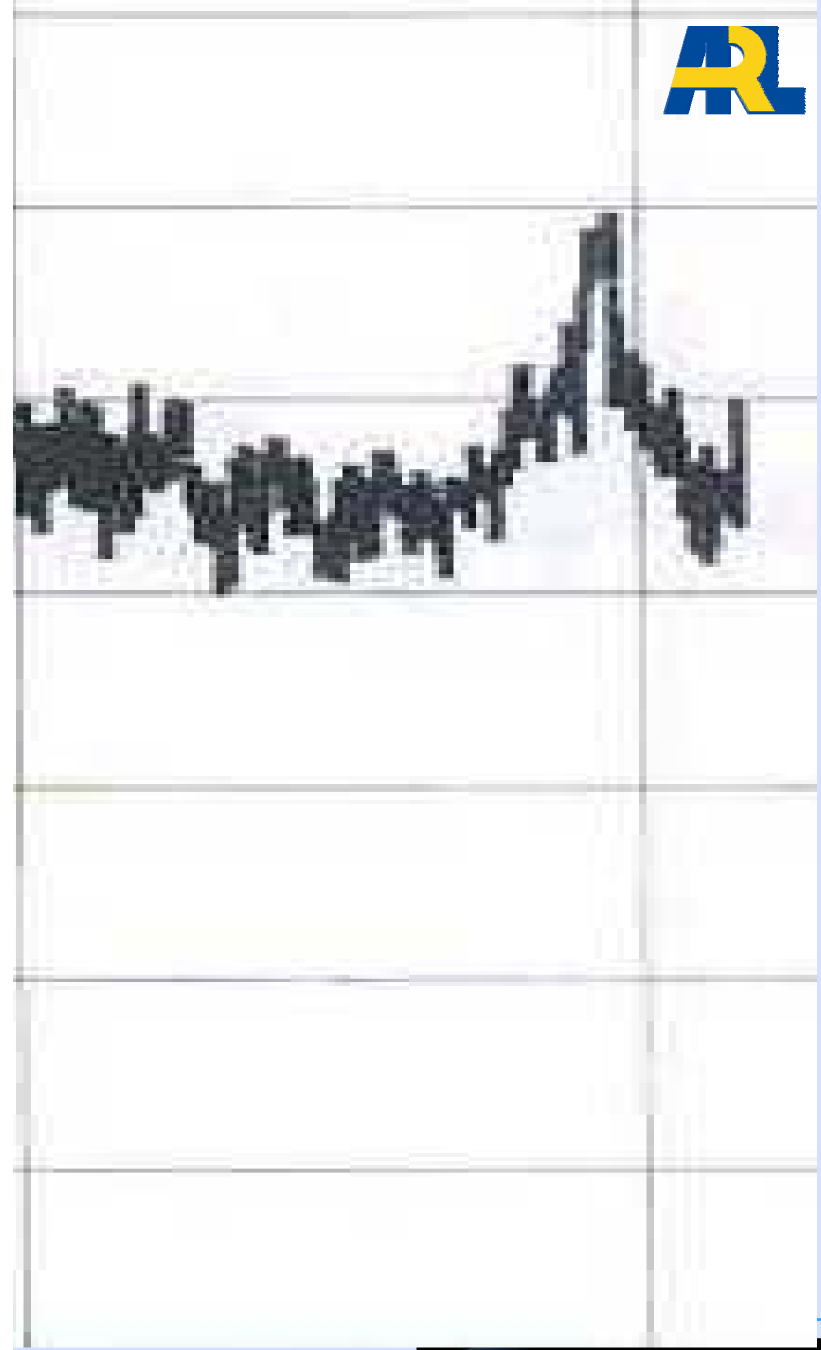

ZSU 23-4 35 GHz HV
dBm2
White line = Radar sighting
FERMAT Computation
ONERA
Meter
Meter
4
3
2
1
0
-1
-2
-3
-4
-4
-3
-2
-1
0
1
2
3
4
0
-5
-10
-15
-20
-25
-30
-35
-40
-45


RCS ZSU 23-4 600k / 60k 35 GHz VV (frequency mean)
Smooth 600k
Smooth 60k
RCS in dBm^2
Angles in degres
FERMAT Computation
35
30
25
20
15
10
5
-30
-20
-10
0
10
20
30

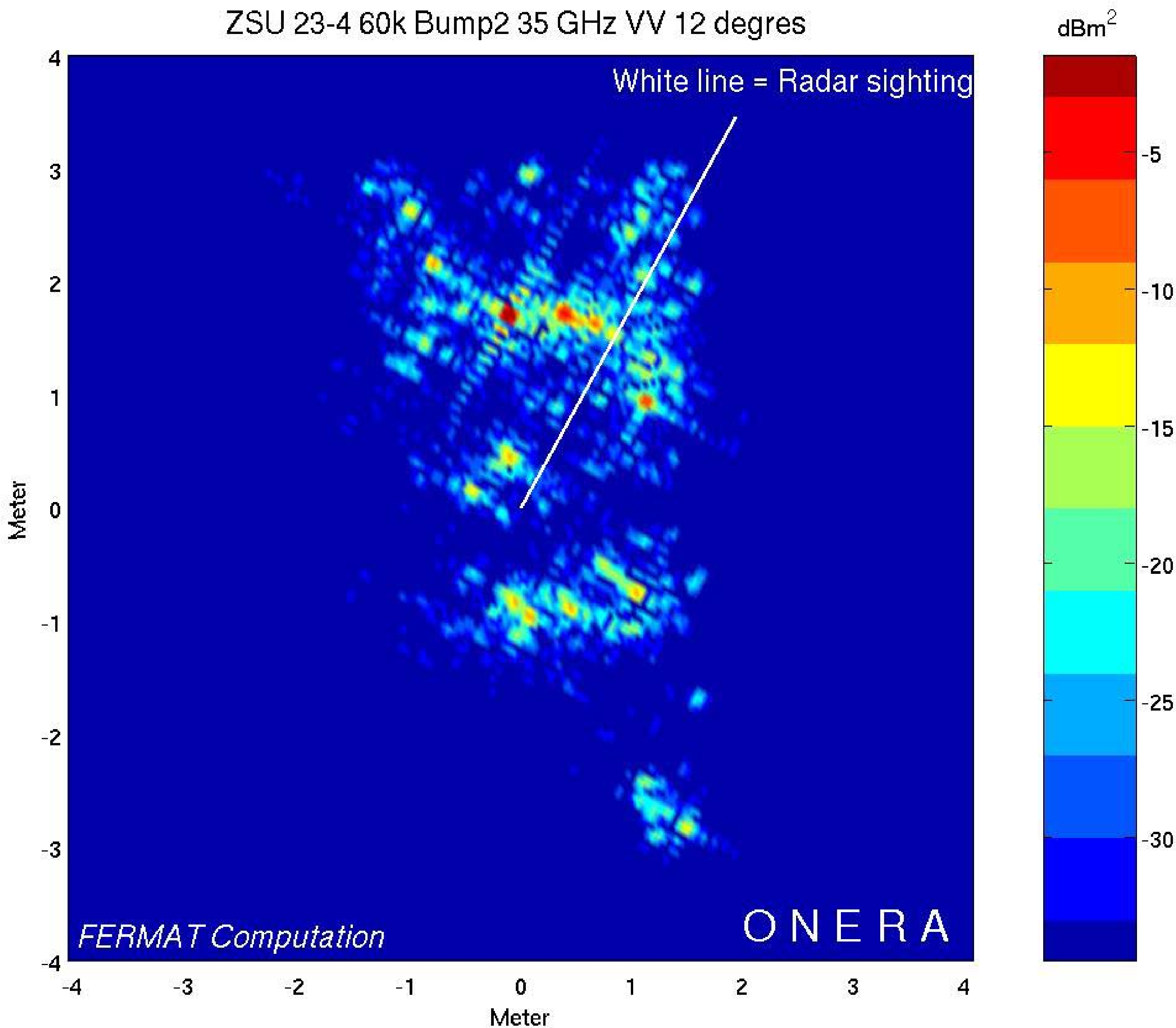

RCS ZSU 23-4 60k 35 GHz VV (frequency mean)
Smooth
Bump
RCS in dBm^2
Angles in degres
FERMAT Computation
35
30
25
20
15
10
5
-30
-20
-10
0
10
20
30


Smooth 600k
Bump 60k
30
25
20
15
10
5
FERMAT Computation

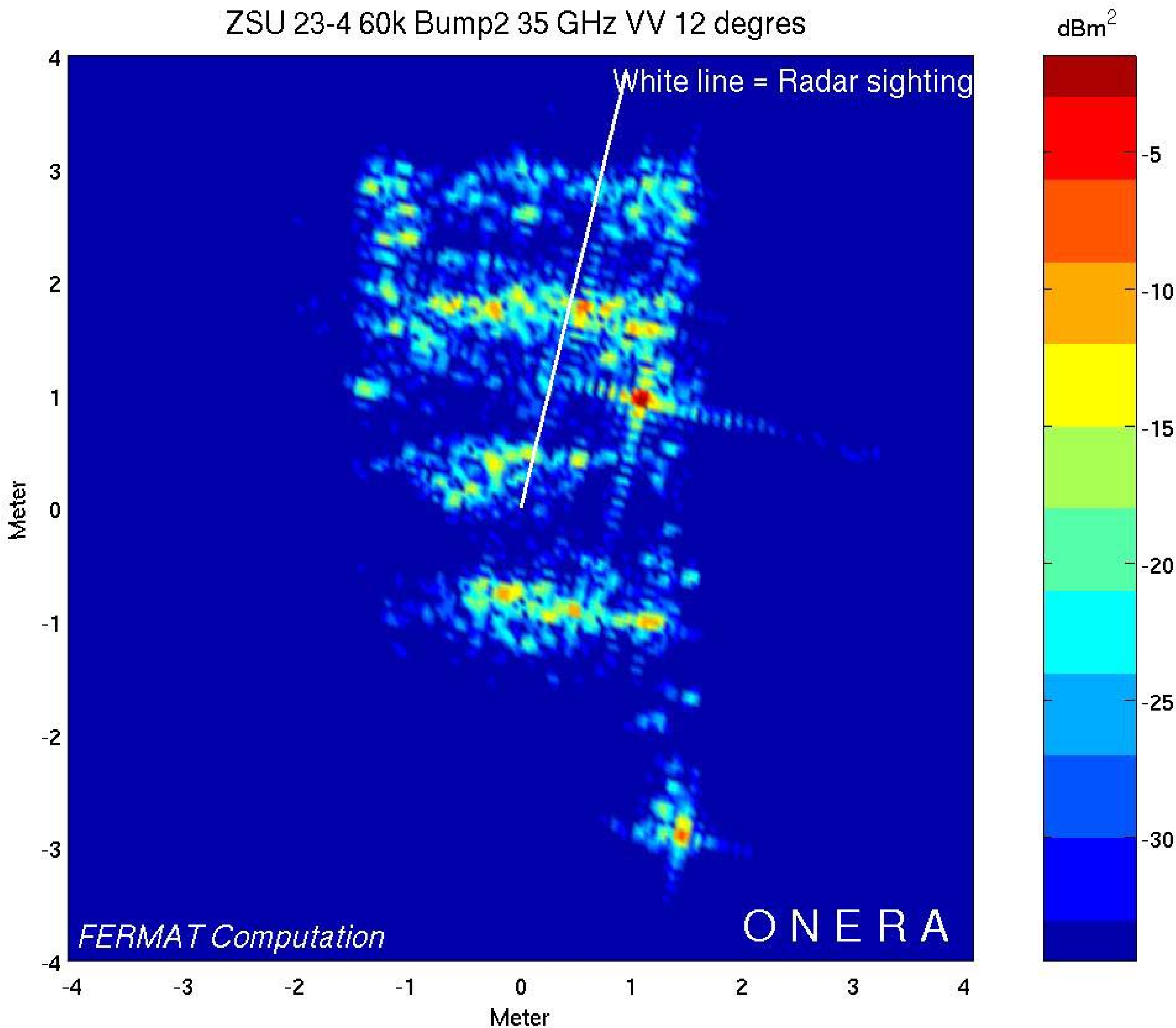

FERMAT Computation
RCS in dBm2
25
20
15
10
5
0
-5
-10
-30
-25
-20
-15
-10
-5
0
5
10

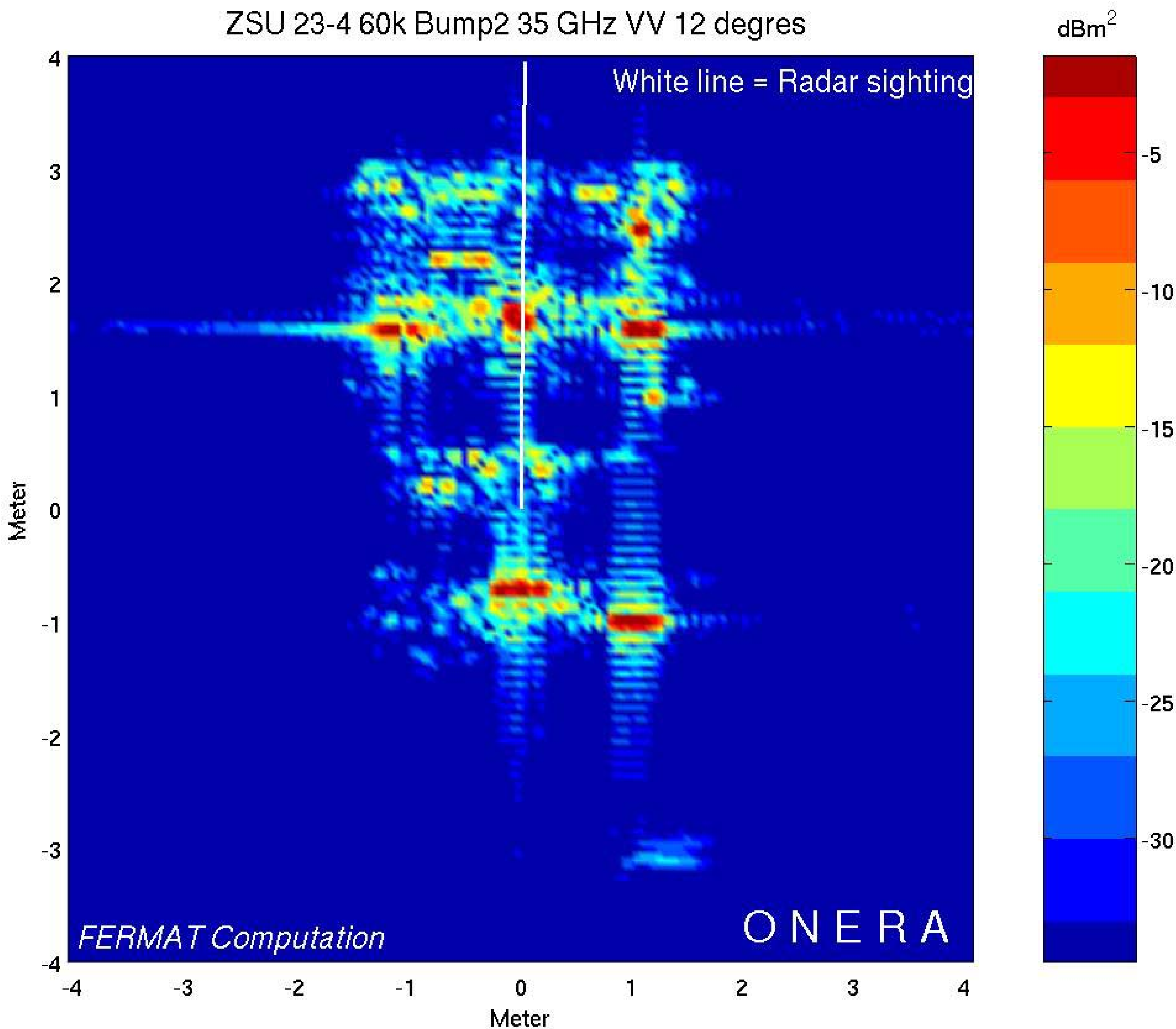


ment



ZSU 23-4 60k Bump2 35 GHz VV 12 degres
dBm2
White line = Radar sighting
FERMAT Computation
ONERA
Meter
Meter
-5
-10
-15
-20
-25
-30
4
3
2
1
0
-1
-2
-3
-4


ZSU 23-4 60k Bump2 35 GHz VV 12 degres
dBm^2
White line = Radar sighting
FERMAT Computation
ONERA
Meter
Meter
4
3
2
1
0
-1
-2
-3
-4
-4
-3
-2
-1
0
1
2
3
4
-5
-10
-15
-20
-25
-30


ZSU 23-4 60k Bump2 35 GHz VV 12 degres
dBm^2
White line = Radar sighting
FERMAT Computation
ONERA
Meter
Meter
4
3
2
1
0
-1
-2
-3
-4
-4
-3
-2
-1
0
1
2
3
4
-5
-10
-15
-20
-25
-30

Conclusion on the methodology

➔ From the first experiment of modelling of the VAB it appeared that with the principal shortcoming of a RCS calculation in MMW is the too significant value of "specular" compared to a diffuse scattering.

➔ Statistical analyses on ISAR images evaluated in terms of:

- peak values,
- mean value,
- quadratic mean,

can allow an adjustment, on a given class of vehicle, of the random part of the scattering process.

Comparison on global RCS (frequency averaged)

➔ Measurements references from SET 069 data pool and other available measurements from DCE/CELAR will be used.