

Performances of Conformal and Planar Arrays

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1 Introduction

Static and dynamic deformations can have a severe impact on the performance of conformal antennas on aircrafts and other vehicles. Therefore it is essential to study the different deformation and vibration mechanisms and their influence on the antenna's radiation pattern. This presentation gives an overview of different approaches concerning electromagnetic modelling of array antennas and investigations on antenna deformations presented in the scope of TG20 [1].

Various different tools for the electromagnetic analysis and modelling of conformal array antennas developed by the participating organisations are described in section 2. For both Computer Aided Design (CAD) and performance prediction of planar arrays efficient methods are available (also commercially). However, tools for the analysis of conformal arrays are still under development and subject to research. In the modelling of arbitrary geometries, numerical problems may arise especially for strongly curved surfaces or edges and arrays with large numbers of elements. Another important issue is the usability of the software tools and the calculation times for the analysis of a given geometry. The deformation of the antenna surface due to aerodynamic and acoustic loads has been assessed in [2].

Part 3 of the present paper is concerned with the analysis of conformal and planar arrays on both non-deformed and deformed structures. We assume that the deformations occurring inside an array antenna are known for a certain load profile. The resulting effects on the system (antenna parameters such as beam width, sidelobe level, pointing error etc.) are predicted by means of computational tools. The fourth section of the paper deals with the effects of deformations and vibrations on antenna signal processing techniques such as MTI, SAR-MTI, adaptive beamforming and multi-source direction finding. In a subsequent paper we discuss the suppression of deformations by means of mechanical sensors and actuators and compensation methods to improve performance by means of signal processing [3].

It is common for all presented methods that studies of deformation are based on generic load profiles, because few information is available about the real load in a (fighter) aircraft environment. Hopefully, this data might become available by future cooperation with aircraft manufacturers and/or military users for the validation of numerical and experimental results.

2 Development of electromagnetic analysis tools for conformal/planar arrays

2.1 Integral Equation Method Modelling for Arbitrarily Shaped Arrays

An electromagnetic full-wave modelling method for that kind of arrays is currently being developed at FGAN [4]. It consists of a combination of three techniques: The metal surfaces (PEC) will be modelled by a Boundary Element Method (BEM), which is based on a Method of Moments (MoM) solution of a Magnetic Field Integral Equation (MFIE). The complex antenna elements will be designed using the commercial general electromagnetic software MAFIA, that uses the Finite Differences Time Domain (FDTD) like Finite Integration Method (FIM). The exterior and the interior method will be coupled at the antenna elements' surfaces via a Mode-Matching (MM) technique leading to a hybrid BEM/MM/FIM technique (Figure 1).

A software modelling tool for arbitrarily shaped PEC bodies has been developed and verified. An extension of that tool in order to be able to take into account apertures in the metal surfaces has been implemented is currently being tested.

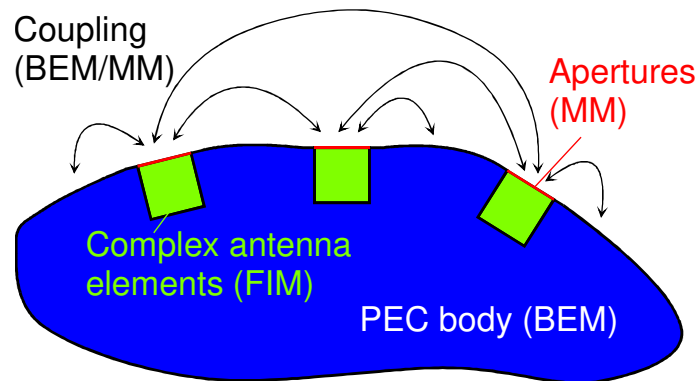


Figure 1 — Principle of hybrid BEM/MM/FIM

2.2 Analysis tools for conformal/planar arrays

Analysis tools are being developed at THALES Airborne Systems according two complementary methods:

- **exact solution of Maxwell's equations**

A digital algorithm based on the Finite Element method (FEM) is used to solve the Boundary Integral equation and has been developed for fifteen years in collaboration with French Ecole Polytechnique. It allows for the computation of the exact current distribution

- on a finite structure of arbitrary shape, made of homogeneous and isotropic materials in any arrangement
- on one element of a 1D or 2D infinite (planar or low curvature) antenna array [5]

Depending on the type of excitation (voltage generator, E/H/TEM/Hybrid modes, plane waves) impedance and S-parameters can be determined. In case of an active array, the active reflection coefficient may be computed. Using the computed currents, near and far fields can be computed as well as the Radar Cross Section (RCS). The tool provides exact electromagnetic analysis of radiating elements embedded into an antenna array which can be used in functional simulations. It has been validated over a large number of different structures and antennas.

- **functional simulation**

The functional simulator comprises a description of the antenna according to a generic arrangement of radiating elements, different stages of active modules and RF distributors. All antenna parts are described by functional models obtained through exact simulations (Antenna design, Circuit simulators etc.) or through approximate electromagnetic modelling. In addition to the description of the antenna, other parameters such as frequency, dispersion models on different inputs, temperature models, failure models can be taken into account.

Ongoing developments include application to conformal arrays and amplitude/phase distribution synthesis on strongly curved antennas for wide angle coverage.

3 Calculation of directivity function of conformal and planar arrays with or without vibrations and deformations

3.1 Antenna Model for Conformal Array Performance Prediction

A physical modelling method for the calculation of characteristic high-frequency electromagnetic parameters of small conformal arrays has been developed at FGAN [6]. The antenna array model is based on the interaction between special antenna elements composed of electrically small dipoles and loop antennas. It allows for the calculation of approximate mutual coupling effects inside the antenna array. While some system aspects (such as subarray structures, T/R-module quantization, bandwidth, driving point impedance etc.) are taken into account, the numerical complexity of exact EM modelling software (e.g. integral equation methods) is avoided.

Embedded element characteristics can be calculated by the antenna modelling tools. The predicted element patterns exhibit certain features due to coupling influences (e.g. ripple, narrowing) which can also be found in measurements. Other antenna parameters may be calculated using the antenna model described above. Where available, results have been compared to measured data for validation.

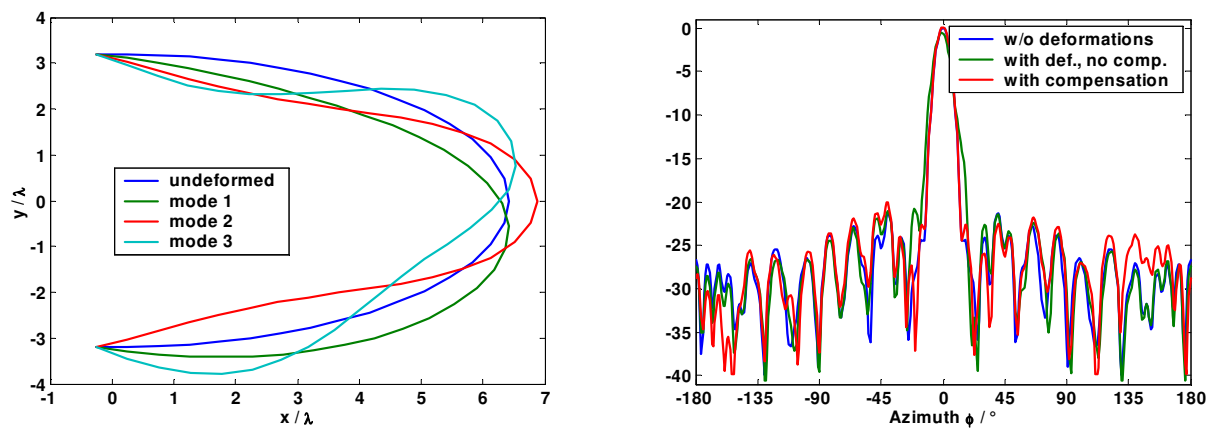


Figure 2 — Vibration modes of an elliptical cylinder and deformed array radiation pattern

Of special interest with respect to SMART antenna structures are investigations on the array bandwidth of conformal arrays and on influences of static deformations [7]. Static deformations of the array may occur in airborne applications and can cause element dislocation and disorientation. As an effect, the resulting array far field pattern is distorted. In both cases compensation is (at least partially) possible using adapted array coefficients (see Figure 2).

3.2 Electromagnetic analysis of conformal phased array antennas

Conformal phased array antennas on fighter aircraft are subject to unsteady aerodynamic loads. Mechanical forces and these aerodynamic loads will cause deformation of the antenna aperture. As a consequence, the positions and slopes of the elements of the phased array antenna change (see also [2]), which in turn will change the antenna's radiation pattern: the main beam direction can change and the beam width and/or side lobe level can increase.

The National Aerospace Laboratory NLR has developed a computational model for predicting the radiation pattern of a conformal phased array antenna on structurally deformed aircraft structures. The model has been described in detail in [8]. The mutual coupling between the patch element in the phased array has been neglected. Imperfections of antenna elements have been modelled by introducing a correction factor in the beam-forming. This factor is related to measured data of transmission parameters of the antenna elements. The computational model has been validated by comparing results of computations with data of measurements on the NLR Antenna Test Range. The computational model is applied to assess the distortion of the radiation pattern of a C-band phased array antenna, flush-mounted on the skin of a reconnaissance pod.

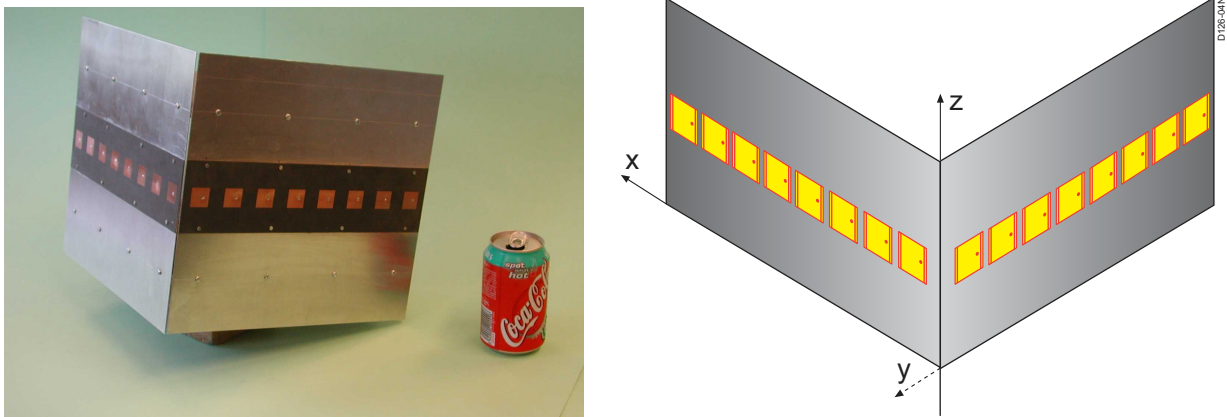


Figure 3 — Geometry of C-band phased array of 16 microstrip patch antennas mounted on a dihedral corner

3.2.1 Computation and measurements of radiation patterns of phased array antennas

For the validation of the computational modelling NLR has designed a C-band phased array antenna on the exterior of a corner structure (see Figure 3), consisting of two aluminium plates. Each plate supports a substrate with 8 patch antenna elements. Beam-forming and amplitude tapering have been applied to generate a directive antenna. The distortion of the antenna is simulated by means of a prescribed steady deformation of one of the plates. The first distorted structure has a concave plate; the second structure has a convex one (see Figure 4). Computations and measurements have been performed for both non-deformed and deformed antennas. The radiation patterns are shown in Figure 5 to Figure 7. For the non-deformed geometry a good agreement is observed in Figure 5. Only one side lobe near 125 degrees is not predicted by the computations, which may be due to measurement errors in the transmission parameters. A good agreement is also observed for the concave shaped antenna (see Figure 6), except in the region from 25 to 50 degrees. Here the measurements predict a higher level, which is probably due to spurious double reflections and mutual coupling between the patch elements on the concave plate. For the convex shaped antenna the correlation between computations and measurements is fair (see Figure 7). For this case, however, some discrepancies are observed which are probably due to measurement errors in the transmission parameters and neglecting mutual coupling between the patch elements.

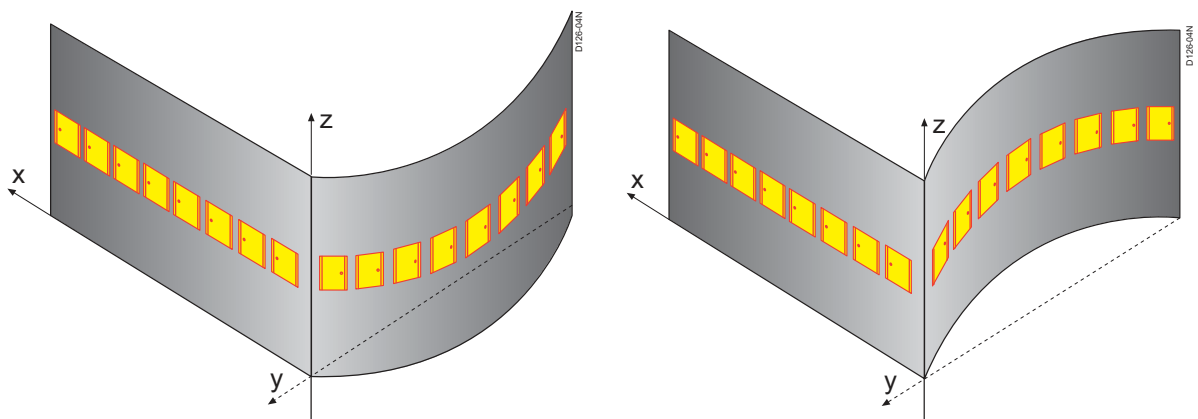


Figure 4 — Geometry of a deformed (a. concave shaped; b. convex shaped) C-band phased array of 16 microstrip patch antennas mounted on a dihedral corner

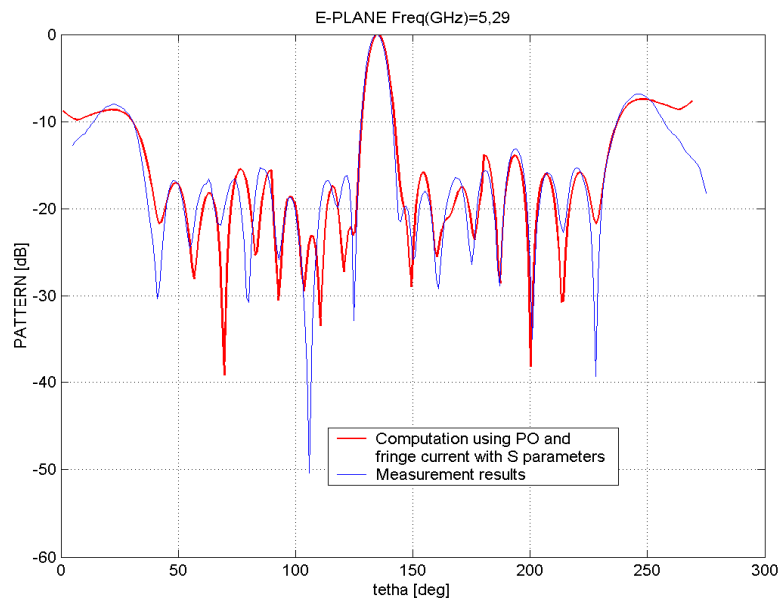


Figure 5 — Radiation pattern of rectangular C-band phased array antenna.
Comparison between computations and antenna measurements

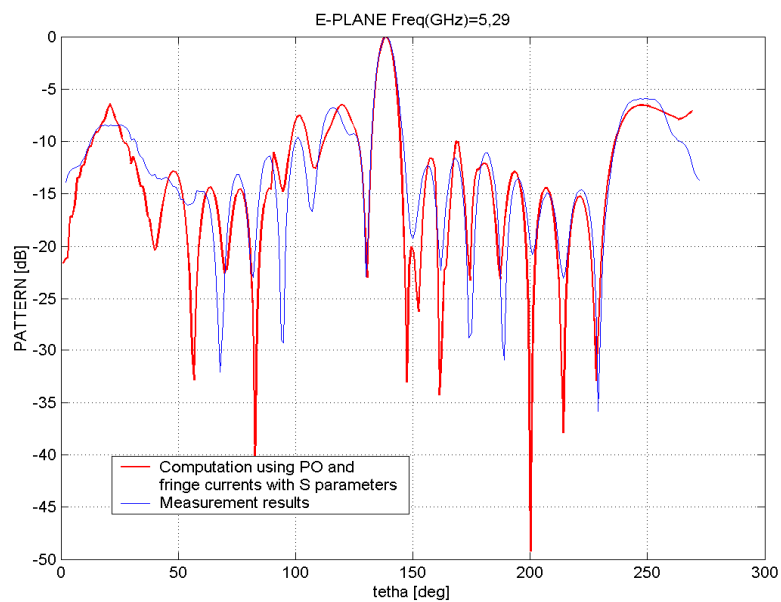


Figure 6 — Radiation pattern of concave shaped C-band phased array antenna.
Comparison between computations and measurements

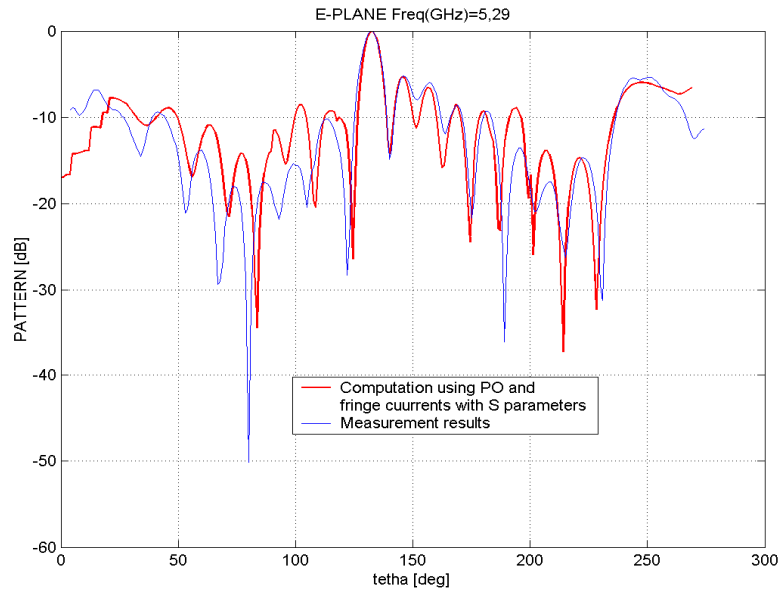


Figure 7 — Radiation pattern of convex shaped C-band phased array antenna. Comparison between computations and measurements

It must be noticed that the radiation patterns of the non-deformed and the deformed antennas cannot be compared with each other, because the non-deformed plates of the deformed structures have been rotated 180 degrees. Therefore, the directions of the radiating slots of the non-deformed and the deformed antennas are different.

3.2.2 Application to a Side-looking airborne radar antenna

The effects of deformations on the antenna performance are shown for the case of a C-band Side-looking airborne radar (SLAR) antenna, designed on the surface of a reconnaissance pod. The excitation of the patch elements has been designed to form a SLAR application, with beam elevation defined at 45° w.r.t. nadir, corresponding with 135° with respect to zenith. ($\theta=0^\circ$ is towards zenith, $\theta=180^\circ$ is towards nadir opposite to zenith, the ϕ -plane is the horizontal plane with $\phi=0^\circ$ being the flight direction). The radiation pattern of this antenna is shown in Figure 8.

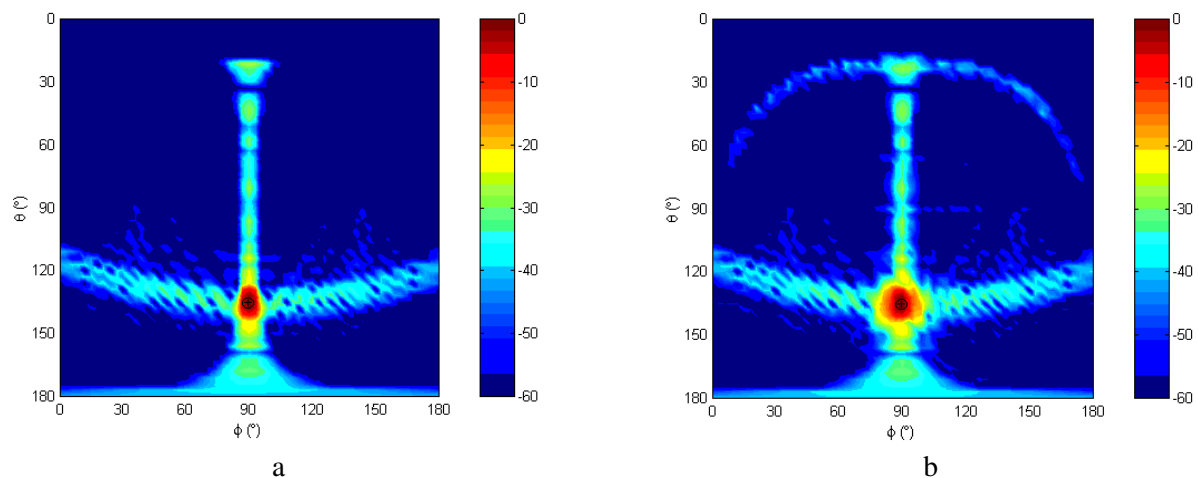


Figure 8 — 3-D radiation pattern of SLAR antenna
a) non-deformed
b) surface deformed by a vibration mode with resonance frequency of 229.62 Hz

The distortion of the radiation pattern has been analysed for a typical vibration mode with prescribed amplitude of 7 mm, which results from the analysis of [2]. This amplitude corresponds with an eighth of wavelength of the C-band antenna. Notice that the frequency of the electromagnetic field is much higher than the frequency of the vibrating structure. As a consequence, for the electromagnetic analysis the displacement of the antenna surface (due to the vibration) can be considered as a quasi-steady deformation. The electromagnetic field responds instantaneously to the deformation. The steady deformation can be considered as an instantaneous exposure of a vibrating antenna surface. For this steady deformed antenna surface the distorted radiation pattern has been computed according to the prescribed amplitude of $\lambda/8$. The results are displayed in Figure 8b. A comparison between Figure 8a and Figure 8b reveals that the beam-width of the antenna array will increase slightly, while the side lobe levels near the main beam increase significantly. Figure 8b can be interpreted as a snapshot of the radiation pattern of the SLAR antenna, at maximum deformation for the specific vibration mode.

4 Expected effects of vibrations and deformations on antenna functions

4.1 Overview of antenna functions :

A smart antenna will most probably be shared between various functions, such as radar, telecommunications, navigation, Electronic Support Measures and Electronic Counter Measures. To achieve these functions with a single antenna, it will be a broadband system.

Each function will use a different set of algorithms applied to the element signals. The table below give a possible repartition of algorithms being used for some of the above mentioned functions:

	Radar	Telecom.	ESM	ECM
Beamforming	X	X		X
Beamforming with low sidelobes	X	X		
Moving Target Indicator (MTI)	X			
Synthetic Aperture Radar (SAR)	X			
SAR-MTI	X			
Adaptive beamforming (probably with low sidelobes)	X	X		
Interferometry			X	
High Resolution Direction Finding (HR DF)			X	

The present work at ONERA gives a short description of each of the above algorithms, (beamforming was deeply presented above, interferometry was not investigated) and to infer the impact of vibrations and deformations.

4.2 Dynamic and static deformations effects on a linear array

The aim of this contribution by ONERA is to study the effects of generic deformations on 3 classical antenna functions for radar or electronic warfare:

- Adaptive beamforming, (for jammers cancelation),
- MTI processing, (moving target indicator),
- High resolution DOA finding (Direction of Arrival).

The first two cases are radar functions, the last one is used in passive mode.

Results of simulations clearly show temporal effects of vibrations / deformations on antenna performances. We define „static situation“ as a situation in which the antenna does not move too much during the time needed to process the signals and get a detection.

For adaptive beamforming, static effects are not too important : in simulations with only one jammer, the jammer is correctly nulled. Static effects are important only when both jammer nulling and low sidelobes are desired. In this case, effects are similar to those already described: shift of the mainbeam, rise of sidelobes etc. Vibrations further degrade antenna performances : they produce a sort of angular spreading of the jammer. Consequences of this effect will be : broadening of the null, difficulties when cancelling a large

number of jammers, possibly, difficulties in canceling a main lobe jammer. On the figure below, a linear antenna was supposed placed on the wing of a plane. Three kinds of vertical deformations were simulated :

- a curvature, supposed static ;
- a wing flapping, that could be due to turbulence for example ;
- sensors vibrations.

As the level of vibration increases (low vibration amplitude on the left, strong amplitude on the right), the width of the null canceling the jammer at 32° widens.

Adaptive BeamForming

Dynamic

1st case

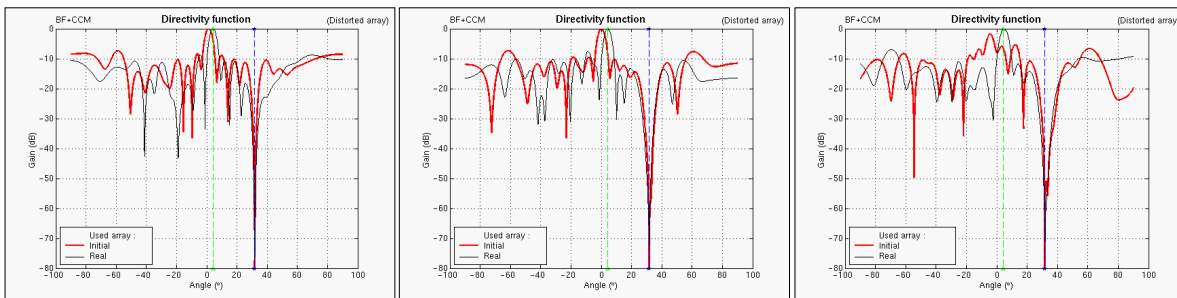
MAX_Curv $\approx \lambda/3$
MAX_Slop $\approx \lambda/26$
MAX_Vibr $\approx \lambda/66$

2nd case

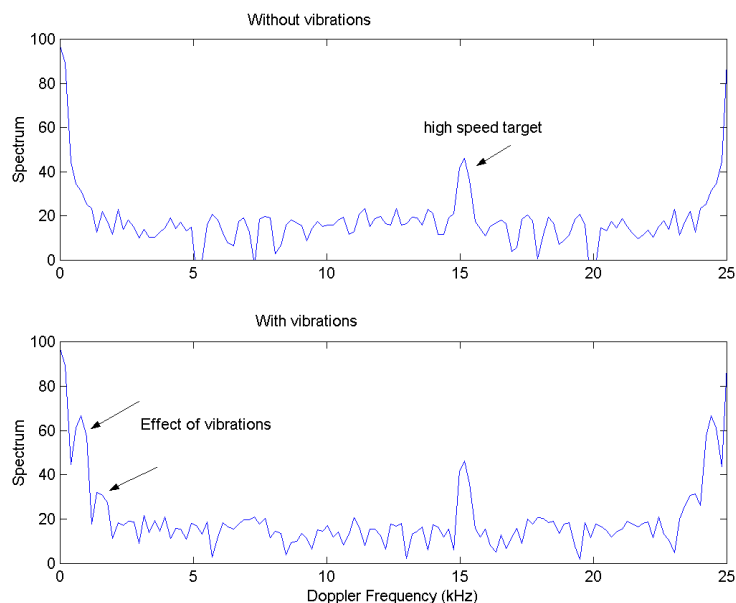
MAX_Curv = 0.75λ
MAX_Slop $\approx \lambda/13$
MAX_Vibr $\approx \lambda/33$

3rd case

MAX_Curv = 1.5λ
MAX_Slop $\approx \lambda/6$
MAX_Vibr $\approx \lambda/16$



MTI processing is sensitive to time effects as well : if one thinks of a rigid antenna, a sinusoidal vibration will produce a frequency modulation which will split the doppler line at frequency F_0 into several lines, at frequencies : $F_0 + k F_{vib}$, where F_{vib} is the frequency of the vibration. Thus again, an important parameter is the vibration frequency compared with the inverse of integration time. Main effects are : false alarms at low speeds, or lack of detection at low speeds if one widens the notch filter used to cancel fixed echoes. It must be emphasized that even moderate level vibrations may impact on the results, as shown on the figure below :



Scenario :

- Carrier frequency = 10 GHz ($\lambda = 3$ cm)
- Pulse Repetition Frequency = 25 kHz
- Vibration frequency : 758 Hz
- Vibration amplitude : $\lambda/100$ or 0.03 cm

Such a sensitivity to vibration can be explained by the fact that the MTI processor has to cancel clutter returns of very large amplitude. No extended simulations was run on GMTI processor. However, it seems likely that analog problems will be encountered with even more unfavourable consequences since slower targets are searched in this case (ground vehicles).

The MUSIC algorithm is sensitive to both static and dynamic effects : static deformations are known to affect these methods, because the wave front must be known with precision. However, vibrations will again spread the signals in space, possibly leading to errors in estimating of the number of sources (sources are split into 2 or more peaks). Effects are : loss of detection and of angular resolution, angular bias (deformations), and spreading of the sources, errors in estimation of the number of sources.

4.3 Influence of deformations on SAGE based compensation algorithms

In this contribution by the K.U.Leuven, we investigate a technique derived from the Maximum Likelihood (ML) principle, which allows for high-resolution determination of the propagation delay, the azimuthal incidence angle and the complex amplitude. The Space-Alternating Generalised Expectation Maximisation (SAGE) algorithm updates the parameters sequentially by replacing the high dimensional optimisation process necessary to compute the estimates of the parameters, by several separate, low dimensional maximisation procedures, which are performed sequentially [9]. The effects of unknown antenna sensor positions (for instance due to modal vibrations [2]) on the accuracy of the parameter estimation are explained. In this work, a two-dimensional example will be used, while a full three-dimensional investigation is reported in [10].

4.3.1 Simulations

One possible mode (Figure 9, left, order 2) shows both the exact positions, indicated as dots on a full line, and the two extreme positions, plotted as dots on dashed-dotted lines. The corresponding centres of gravity are shown with asterisks, and the dotted lines indicate the directions of the mobile targets (for the 3 different configurations another angle is obtained). The results of the two extreme positions are plotted in 3 different lines and the references (with fixed or undistorted antennas) are shown in full line in Figure 9 (centre: delay; right: azimuth angle).

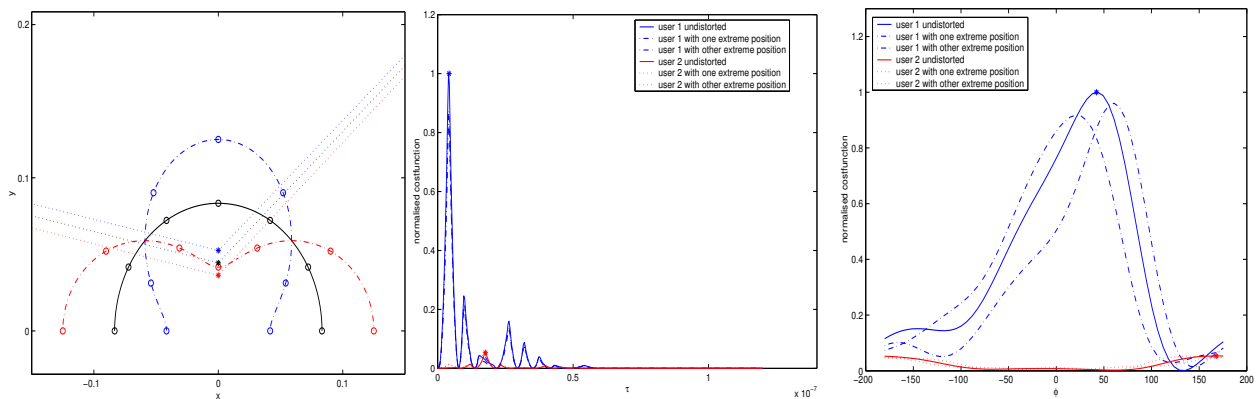


Figure 9 - Geometry ($R = \lambda/4$), delay and azimuth for the mode of order 2

As we expect, the oscillations have no significant influence on the estimation of the time delay. For the azimuth angle, the oscillation results in different centres of gravity, resulting in other directions of the mobile targets. The SAGE algorithm adapts the steering vector consequently, leading to an angular error with respect to the exact position.

4.3.2 Interpretation

Here, the deviation in angle $\Delta\phi$ is plotted as function of the relative deviation in radius $\Delta R/R$ (Figure 10). We notice a nearly linear behaviour of the angular error as function of the amplitude deviation of the oscillation. For example 10% oscillation amplitude leads in this case to an angular error of 2° .

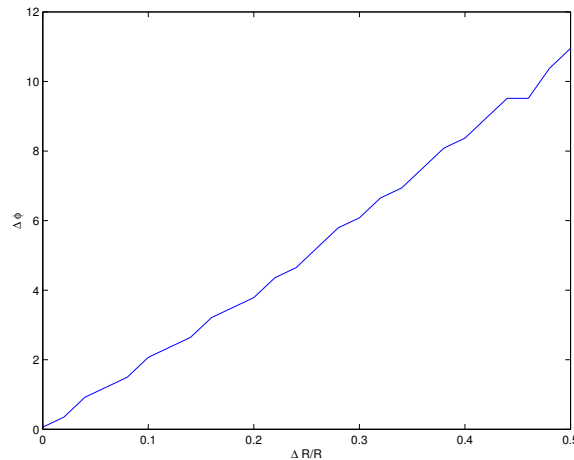


Figure 10 - Angular error (in degrees) as function of the relative oscillation amplitude.

To summarise, one can conclude that even with high oscillation amplitudes, the distance can be estimated very accurately. In contrast, the angular accuracy depends linearly on the sensor position error. The results demonstrate that the SAGE algorithm is a powerful tool that could be successfully used to correct vibrations and deformations and to estimate the accuracy in case the vibrations are not exactly known.

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