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Advanced Numerical System Simulations for Navaids and Surveillance Radar - The Verification Problem

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ABSTRACT

More and more complex problems for navaids, landing systems, and radar systems can be solved today by system simulations using state-of-the-art numerical methods [2-6]. Generally the actual problems and objects are three-dimensional problems. These numerical methods are integrated into the simulation tool.

The simulations have to be carried out often in advance before the objects appear and before the building, etc., is constructed or before the aircraft appear on the airports. Other issues are the costs of such trials and operational and economical aspects, such as potential restrictions.

The problem of the verification and validation of the numerical results is imminent and has to be solved. Measurements for comparison seem to be the best way to verify the numerical results. It is obvious that this is not possible in the mentioned examples because the objects are not yet existent or the configuration is not yet existent. The classical method is to "validate the method" and to "validate the tool" by one or several measurements "at the beginning" for future use. It will be shown that this scheme has a number of problems.

First, the numerical methods themselves are not safe for all applications and all cases. The modeling is a further critical issue. The validation has been done for special cases which may be not really 3D but can be described by 2D methods and tools. "Worst case" assumptions and adoptions may not be correct and may not be adequate for a given practical problem, such as the parallel taxiway problem which is outlined.

Second, the measurements have often problems also and cannot be treated as generally correct or having sufficiently small errors [1]. This is in particular for ground checks and flight-checks in the related fields.

The validation problem is outlined by several state-of-the-art examples for navaids and radar systems. Objects are 3D cranes, control tower, A380 aircraft, and wind generators. Recommendations will be given.

INTRODUCTION

A typical situation for the simulation task is a given technical installation problem or a building plan which has to be approved and where actions have to be defined (Figure. 1). A typical "standard" way to resolve this task is to apply a commercial "tool" which has been "validated" before. Rough and often inadequate rules and recipes may be available to support the user for his task. The limitations of these "tools" are not clearly and uniquely defined, and the achievable accuracy seems to be justified by the previous "validation process". The user is mostly not aware of imminent problems or the consequences of the limitations. In many cases the users do not really know the mathematical and physical background and cannot appreciate the quality of the results achieved by the simulations. They trust in the effectiveness of the claimed validation and in the applicability of the available applied tools and methods for their actual problem.

On the other hand, state of the art numerical system simulations are discussed in this paper for actual field problems, i.e.,

- the effects of the new large aircraft A380 on the parallel taxiway affecting the ILS Localizer (ILS Instrument Landing system; Localizer azimuth guidance ILS subystem)
- the effects of wind generators on navigation systems (DVOR) and on ATC-radar.

MODELING, NUMERICAL METHODS, TOOLS

A system simulation process for navaids, landing systems, and radar systems consists typically of a number of consecutive steps (Figures 1 and 2). Three main steps can be defined (Figure 2):

1. System pre-processing
2. Simulation process; modeling of the object and of the scenario and application of the numerical methods
3. System post-processing; system (parameter) evaluation and application of specs and interpretation of the results

in the required operational coverage volume; transfer to consequences.

It should be anticipated that state-of-the-art-methods (SOTAM) and knowhow should be applied for all these safety critical applications discussed here. Other estimation methods for the scattering analysis, e.g., determination of scattering amplitudes by comparison of areas, are not discussed here due to their poor qualities and their non-SOTAM characteristics.

The SOTAM includes the application of the best available and most adequate numerical methods and system evaluation procedures. A further technical commercial strong argument for the use of SOTAMs and simulation procedures is the cost of measures and potential constraints to be imposed on the basis of basically potentially unreliable and inaccurate results.

A state-of-the-art system simulation includes all relevant factors in the system simulation process, such as

- 3D transmitting and/or receiving antenna-patterns
- Relevant tolerances
- Ground effects
- Receiver features, such as filtering and sampling
- Correct description of the signal processing (e.g. capture effect of the dual frequency ILS-Localizer).

It should be noted again that the so-called "system parameter" has to be evaluated as a result of the state-of-the-art system simulations, i.e.,

- DDM for ILS
- Angle error for MLS
- Range error for DME
- Bearing error for VOR/DVOR, TACAN
- Interrogation field strength and monopulse angle error for SSR Radar
- Shadowing, range, probability of detection (PoD) for the primary radar
- etc.

These system parameters have to be deduced from the scattering process of the object (of the model). The scattering process in itself is characterized by the scattering properties, i.e. the 3D scattering pattern in terms of amplitude and phase. Other sub-parameters like "field-fluctuations" or "field-distortions" have to be justified with regard to the relevance for the considered system. In most cases the system parameters are not directly linked to the "field fluctuations" and therefore these sub-parameters are more or less irrelevant. Two good examples are the DDM for the ILS and the monopulse error for monopulse radar. These system parameters depend on the ratio of 2 field quantities in some field point. If both sub-field-components undergo the same variations, the ratio may be practically constant.

In the simulation process, several general error sources are inherent:

- in the modeling process (e.g. data input errors).
- in the selection and application of the numerical methods. Even the best and highly proven numerical methods can have problems in certain situations.
- in both, interaction between modeling and numerical analysis
- in the system evaluation.

Detailed error sources include the following:

- The object is geometrically and electrically 3D, but the model is 2D. The results and consequences are case dependent and unpredictable. Figure 3 shows a tower crane example, and Figure 4 shows a highly 3D-control tower which will be constructed close to a CATIII runway. It is obvious that the simple plane metal strip is not an adequate model for the highly structured 3D crane. If one tries to model the tower by composed 2D-plates, it is widely open and arbitrary how to do that. Each of the 2D-models has quite different results for this risky application. Figures 5 and 6 show a comparison between the 3D-analysis and one selected 2D-analysis respectively. The differences are obvious. In the first case, the CATIII-specifications are easily met. This has been verified by ground measurements with excellent agreement. In the second case, the CATIII-spec is seriously violated and the tower would not be acceptable.

- All the electrically effective details of the object are not described in the model.

- The model is not adequate for the numerical method which is integrated into the tool (e.g. open wire structures and the application of physical optics based methods; asymptotic methods for small structures or open wire structures like cranes or high power line masts) and vice versa. Fig. 3 shows the 3D-model of widely used tower cranes, which are well suited for the analysis by the so-called "Method of Moments" due to their metallic wire structure. The approximate metal strip approximation is a very crude model for the application of the "physical optics" method. The quality of the achieved results by the latter inappropriate method is unpredictable [3,5].

- The numerical method itself is fast, but over-simple and not state of the art. Some tools use crudely simple versions of the physical optics method by modeling constant amplitudes and (linear) phases over the modeled often mostly rectangular plates. This is unrealistic due to several reasons: the antenna, the ground and near field effects.

- The rules for the numerical method are not processed, and limitations are not known or consequently applied.

- The approximations are not justified (e.g. neglecting the humped runway for ILS-Localizers, material characteristics by simple factors).

- The worst case concept may be often technically justified, but it is not generally applicable. It is not guaranteed that the anticipated worst case in 3D-situations is really the worst case. Instead, it is a potential risk.

General Modeling aspects; Arrays

It is decisively important to realize that the system simulation is solved for a "model" of the real object. Hence, the real object (terminal, hangar, crane, aircraft, windmill, etc.) has to be transferred into a "model" which is adapted to the numerical method used within the simulation process. The materials, the general shape and the surface structure of the real object have to be considered in the modeling process. The numerical method has to be selected acc. to the properties of the model (see the IHSS in Fig. 2). In the IHSS quite a number of numerical methods are integrated and the best suited one(s) is/are used and in case super-posed in the course of the analysis.

Each numerical method has its own rules and limitations. The model has to follow these rules (e.g., degree of subsectioning of a structure). On the other hand, the model determines the accuracy of the results, because in the simulation process the effects of the model are solved. If the model is not sufficiently equivalent to the real object in an electrical sense, then the numerical results are obviously questionable and strictly speaking worthless.

An array of objects (e.g., cranes, windmills, or aircraft) requires special consideration and treatment. The crucial point in these arrays is whether the individual contributions depend on the other members of the array. Basic electromagnetic theory reveals that the "superposition principle" is possible if the mutual coupling between the objects is negligible. That is the case in practically all realistic arrays of the mentioned objects. Multiple reflections between the array-objects, on the other hand, cannot be handled in a straightforward way by all of the numerical methods part of the IHSS-scheme (Fig. 2). Fortunately these multiple reflections are negligible in the very most practical cases of arrays. For example, the distance between windmills is roughly at minimum the triple of the diameter of the rotor circle. Modern windmills have a diameter of at least 80m. Hence, the distance between the windmills is at least 240m. That is about 90λ for the ILS-LOC- and VOR-frequencies and about 800λ for the SSR-frequencies. These are very large electrical numbers for which the mutual coupling is negligible.

VERIFICATION, VALIDATION OF NUMERICAL SYSTEM SIMULATIONS

Often the common procedure of system simu-lations is:

- development of a new numerical method or selection of a method.

- development of the related "new" tool where the numerical method is integrated.

- calculation of one known example.

- verification of that single or possibly several examples for all following examples by certain measurements or other reliable methods (if available).

- further use of the tool with almost no further validation procedures.

However, fundamental basics and experiences require a continuous and permanent verification process. A reasonable skepticism is appropriate for every simulated result. It is also clear that an initial detailed and intensive verification process is required in order to exclude programming and coding errors. Continuous improvements of the physical and mathematical core engine of a tool must also be realized, and these improvements and extensions must themselves be verified.

The verification and validation is mostly executed by comparison with measurements. This procedure assumes that the measurements are "correct" and useful as a reference. This assumption has to be carefully proven, because the measurements may have their own problems [1]. On the other hand, some of the measure-ment features are not a proof of the correct-ness of the numerical method. A good example for that is the DDM-scallop-structure of the ILS. The scallop structure depends solely on the relative geometry between the ILS-antenna, the scatterer, and the field points on the track (e.g. glidepath or the centerline). The scatter-ing characteristic determines "only" the spatial amplitude and the spatial envelope of the DDM-distortions.

The continuous verification and validation process can be performed by:

- plausibility and experience, minimizing the probability of wrong/erroneous results.

- crosscheck with other methods and other tools if available and possible.

- carefully and consequently following the rules and limitations of the applied method.
- Continuous comparison with available (reliable) measurements.

Each simulation result has to be checked, and should not be accepted automatically. It is obvious that this process is critical and needs a lot of knowhow and experience with the system to be treated. In case of "unexpected" results, a thorough verification procedure must be initiated. Even the best generally proven numerical methods can yield wrong results in certain situations.

Often borderline problems are analyzed where the rules and limitations are violated. Mostly, the users do not have other tools and tend to believe in computer results (numbers, tables, graphics).

CASE STUDIES

Some actual case studies are outlined below to illustrate the capabilities and the problems of system simulations.

ILS; A380-200 on parallel TWY

An imminent and increasing problem is the appearance of new widest body aircraft, the NLA Airbus A380 in a few years (Figure 7). The aircraft itself is already in an advanced R&D-status. The most impressive and relevant features of this aircraft are the large dimensions of the class F size. This is in particular the huge vertical tail fin, which has an upper maximum height of 24.1m. Even larger versions are being studied.

The effects of this aircraft have to be evaluated with regard in particular to CATIII ILS operation, taking into account the specifics of a given airport and ICAO Annex 10 issues. These specifics are:

- Characteristics of the currently installed ILS – in particular of the ILS-Localizer
- Actual operational system characteristics, i.e. the existing DDM system margin to the tolerance limits (the larger the existing distortions, the more stringent the requirements for the ILS-installations and the less additional distortions can be accepted)
- Characteristics of the layout of the airport - in particular the distances of the parallel taxiways to the centerline and of the taxi-ways in the back of the Localizers.

The layout of civilian airports is in most cases adapted to the requirements for the currently most challenging aircraft, i.e., the B747, and not yet to the requirements of the A380. Often the electrical challenges for the ILS are not considered or at least underestimated. Many airports have a limited space (Figure 8) and cannot be modified in the required way. A particular problem will be the definition of the safeguarding areas (critical, sensitive areas) and of the holding points.

A380; Simulations and numerical results

As part of a larger systematic study, some selective results are highlighted here:

1. the level of the threat by the A380
2. the need for an adequate simulation effort by using the suitable state-of-the-art methods, combined with the appropriate knowhow related to the physics, to the numerics, and to the ILS-system.

Figure 7 shows the numerical 3D-model of the A380 used for the numerical simulations. The model consists of a large number of metallic triangular patches which describe sufficiently the aircraft in a geometrical and electrical sense. Figure 8 shows a CATIII runway system with 3 parallel taxiways having 2 typical distances of about 260m and of 200m. The former is a very safe distance for the current aircraft, while the latter needs a closer look even today. It should be noted that the distances of the parallel taxiways must be larger for longer runways; also for ILS-LOC when the existing noise floor is not negligible. Therefore, a very long runway of about 4000m has been chosen in this synthetic case.

Figure 9 shows a selective numerical analysis for a tail-model of the A380 in a forward distance of 3500m to the wide aperture Localizer on TWY C of Fig. 8. It can be clearly seen that for one of the numerical methods the DDM-distortions exceed by far the CATIII specifications, while for the improved and rigorous ones used by NAVCOM Consult, the specifications are sufficiently met. The former method - a simple PO-physical optics method - is widely used elsewhere. For the distance of about 200m (TWY B in Fig. 2) the CATIII specifications hardly can be met. The numerical reason for these large discrepancies is that the derived currents on the tail fin are much too large for the case of the simple PO, due to the small subtended angle (Figure 10).

The remarkable consequence is that the TWY C would have to be closed for A380-aircraft under CATIII conditions when using the simple PO-methods instead of the advanced methods.

Wind Generators and DVOR/DME, Radar

VOR/DVOR and Wind Generators

Wind generators (WG, "windmills") are constructed more and more in major quantities as a single installation or in arrays ("windparks"). Often these objects are in the coverage volume of navigation stations or of radar of various types. Fig. 11 shows the layout of a large powerful windpark in Korea in some distance to a DVOR/DME/TACAN station. The related power line and masts can be seen also.

The analysis of the effects of these WG on the navigation and radar systems is of increasing interest. The different nature and function of the navigation systems and radar suggest that the simulation also must be quite different. However, the introduced IHSS (Figure 2) and its implemented features allow the adapted analysis. Extensions in the pre-processing part and in the final post-processing part had to be integrated.

The WG are highly 3D-structures and need an equivalent modeling (Figure 13). Mostly the shaft is a shaped metal tube. The cover of the generator house and the rotor blades are mostly made of glass-fibre material. The blades have an integrated metallic lightning protection system. However, the total structure has been modeled for the worst case to be fully metallic, i.e. by a large number of metallic triangles. This is to take into account rain, ice and wet snow conditions.

For the VOR/DVOR and the TACAN systems the scattered field components are superposed and processed appropriately, yielding the bearing errors. Figure 12 shows an example where the DVOR bearing error has been calculated on a horizontal plane at a height of 4100ft above the station.

Under these circumstances the total windpark was acceptable with some modifications. The different heights of the WG have been taken into account by the application of the so-called method of parabolic equation (Figure 2) in the discussed hybrid approach.

ATC-Radar and windgenerators

The effects of windmills on ATC radar (primary, secondary radar SSR) and their evaluation depend very much on the following:

- type of the radar (primary, secondary; 2D, 3D; range shadowing, probability of detec-tion PoD)
- features of the radiation characteristic
- characteristics and capabilities of the signal processing software and of the track algorithms
- mutual geometry relationship (distance, heights) between WG and radar
- size and materials (shaft concrete, metal tube, lattice; blade material etc.)
- signal processing and track algorithms (MTI/MTD, pulse compression; clutter detection and suppression capabilities; Doppler shift effects)
- definitions and specifications; treatment of "distortions" and interpretation.

The potential distortion effects on the two radar types are totally different due to the different principles. The SSR is not a real radar, but a transponder based two way automated communication system. The ground based "SSR radar" does not rely on the reflections from the target, but on active responses from the airborne transponder on a slightly different frequency.

WG effects on the range are not an issue for the SSR but for the primary radar. False interrogations may occur for close WG for the SSR in principle, but are not likely for realistic distances for terminal SSR. High and large WG will not be close to the airports. The WG will be seen by the primary radar due to its basic and inherent task "to see objects". It is a matter of judgement if that is a "distortion" in itself, although the WG will occupy a range cell of the 2D ATC primary radar at a well-known distance. Many WGs may produce a blanked dot pattern in the radar coverage.

The main problem for the primary radar is the return signal characteristics and its radar processing. Rotating WG may be integrated into a track in special cases. If the blades are stationary, the return signal is part of the clutter with no frequency shift. When the blades are rotating, the return signal has a typical and unique symmetric Doppler spectrum, together with a strong stationary component which can be identified uniquely in principle. It is also different from the Doppler spectrum of helicopters. If the signal processing and the track algorithms have the capabilities for the identification, no false tracks should be generated in general. Unfortunately many radar are not prepared for WG which came up primarily in the last decade.

The shadowing for an ATC primary radar in the back of a WG has a typical characteristic (Fig. 14). Directly in the back of the WG there is a non-negligible shadowing. In operationally important distances the field in the back recovers more as the distance between the radar and the WG increases. This behavior is plausible and can be explained physically. By that plausibility, by fundamental theoretical considerations, and by parallel calculations with other methods, it can be taken as validated. Scaled measurements are difficult to conduct realistically despite the dielectric materials.

SUMMARY AND CONSEQUENCES

Numerical system simulations are carried out by numerical methods and by complex tools for increasingly complex scenarios. The real objects are often highly three-dimensional and of different structures. It has been explained that the state-of-the-art approach is a three-dimensional one where the suitable numerical methods are integrated into one hybrid simulation tool. However, often 2D methods and tools are used.

It has been outlined that the classical approach, to validate the method and tool at the beginning and to take the tool in the future as validated, is insufficient and critical. It has been shown that the verification and validation have to be treated as a continuous process. This is done by the following strongly recommended practices:

- Use state of the art 3D numerical methods.
- Try to simulate as realistically and accurately as possible.
- Realize that anticipated "worst-case approaches" can completely fail.
- Accept that these state-of-the-art methods and this adequate treatment require a lot of modeling effort and CPU-power in contrast to the simple and fast 2D-approximations.
- Be aware that even the best available numerical methods require rules and have limitations, and can fail in certain situations. This holds also for the "exact methods".
- Use state of the art modeling techniques.
- Verify each numerical result in principle.
- Apply the appropriate knowhow in the field of numerical math and the related systems for plausibility checks.
- Realize that the measurements may have errors also.
- Be skeptical in principle for every numerically achieved result.
- Try to cross-check with other methods or tools in case of "surprising and un-expected results".

Some examples have been outlined where the necessity of the 3D-approach is evident, i.e., the 3D-structures - e.g. tower cranes, control towers, and aircraft.

Practically speaking, every simulation result should be verified in principle and should not be taken as correct and accurate per se. Several practical examples are described and some related numerical results have been shown:

- for an A380 aircraft on parallel taxiways. This problem is connected with the definition of the safeguarding areas (critical and sensitive areas, holding lines). It has been shown that the threat by A380-aircraft is real for the CATIII-ILS even for the best available systems when the A380 is taxiing on parallel taxiways up to more than 250m from centerline, and if an independent CATIII operation must be conducted. It has been shown also that the application of in-sufficient methods, which are not state-of-the-art, can result in operational restrictions on taxiways which are not physical and not necessary. A practical example has been presented.
- for windgenerators and large windparks close to DVOR/DME/TACAN navigation and ATC-radar stations. The availability of suitable methods and tools allow their reliable numerical treatment.

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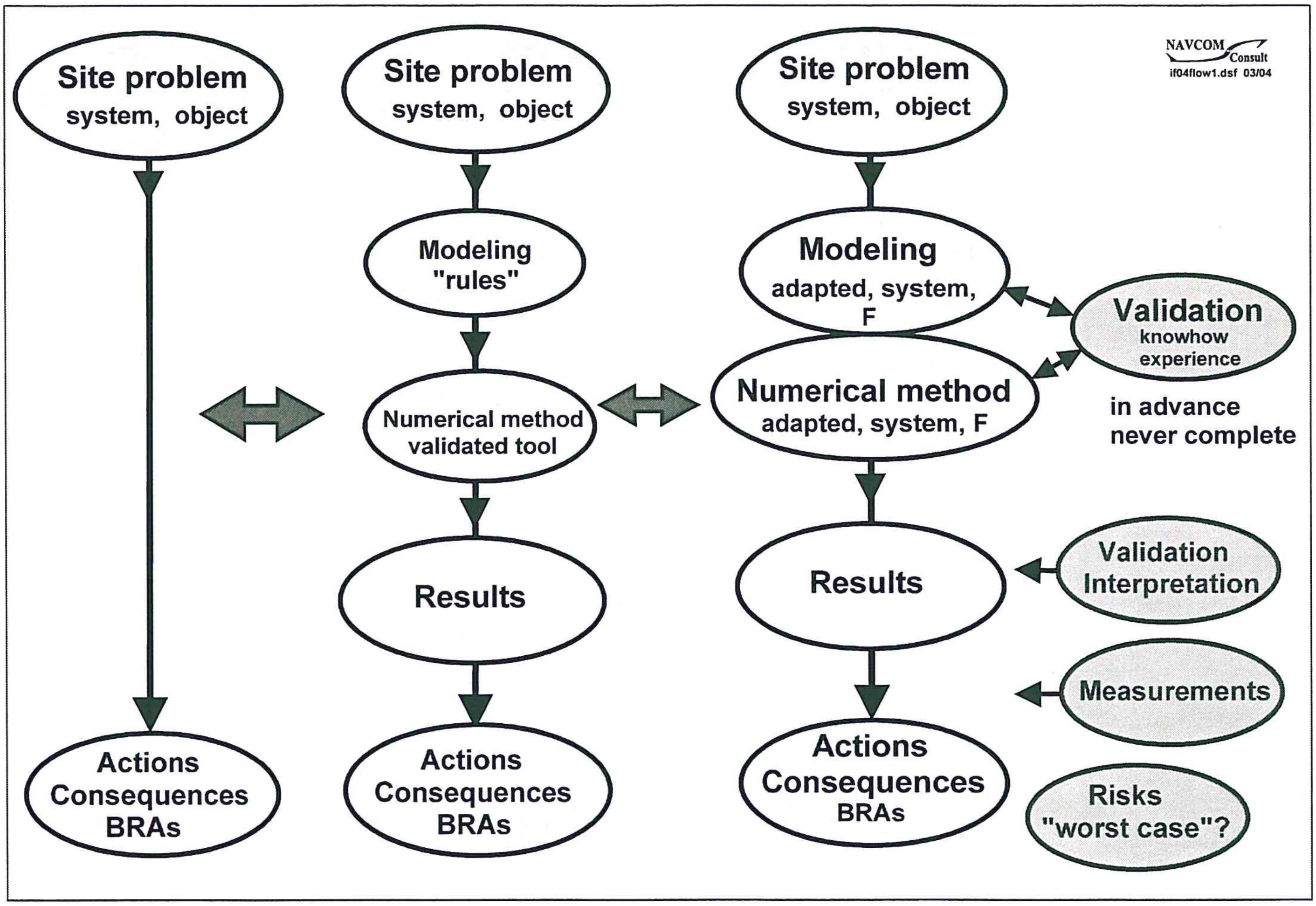

Figure 1: General process flow of the original task and situation (left), of simplified system and simulation treatment (middle) and of advanced state of the art system simulations (right)

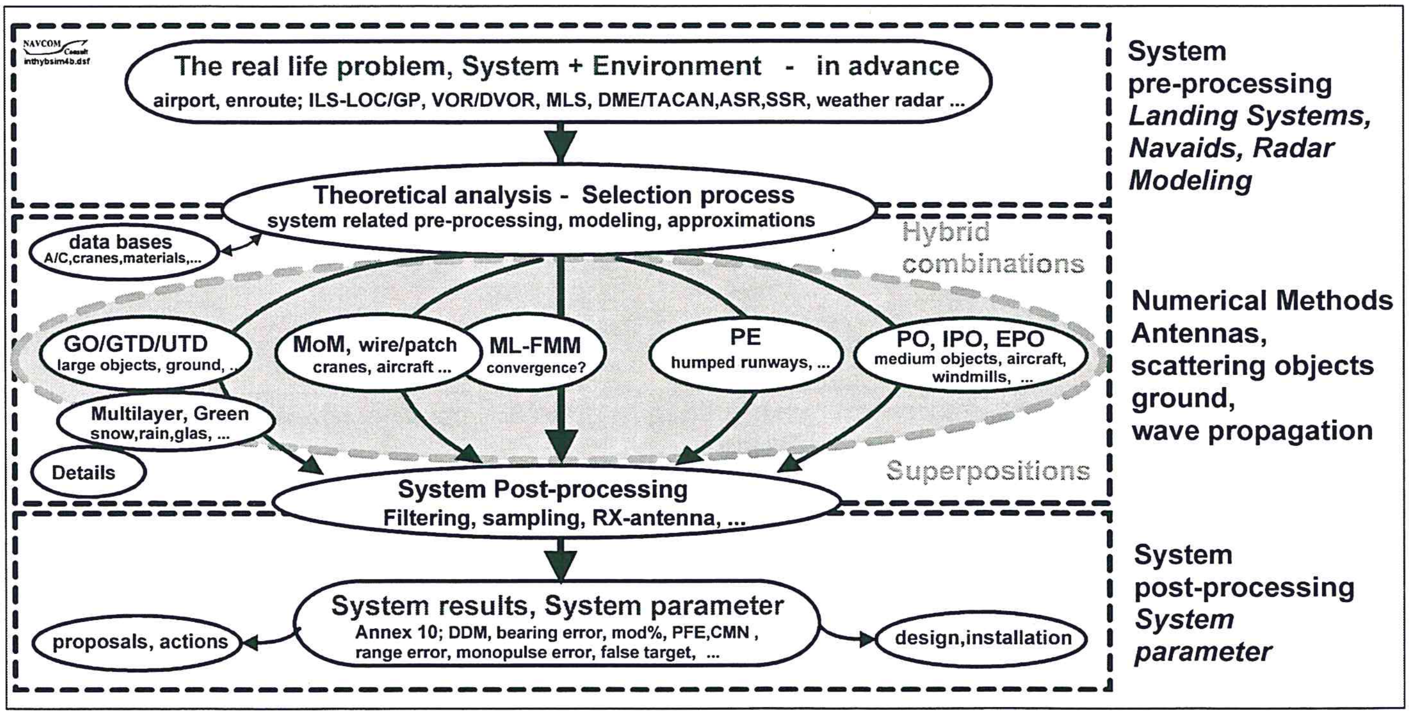

Figure 2.: Detailed process flow of the advanced IHSS ("Integrated Hybrid System Simulation")

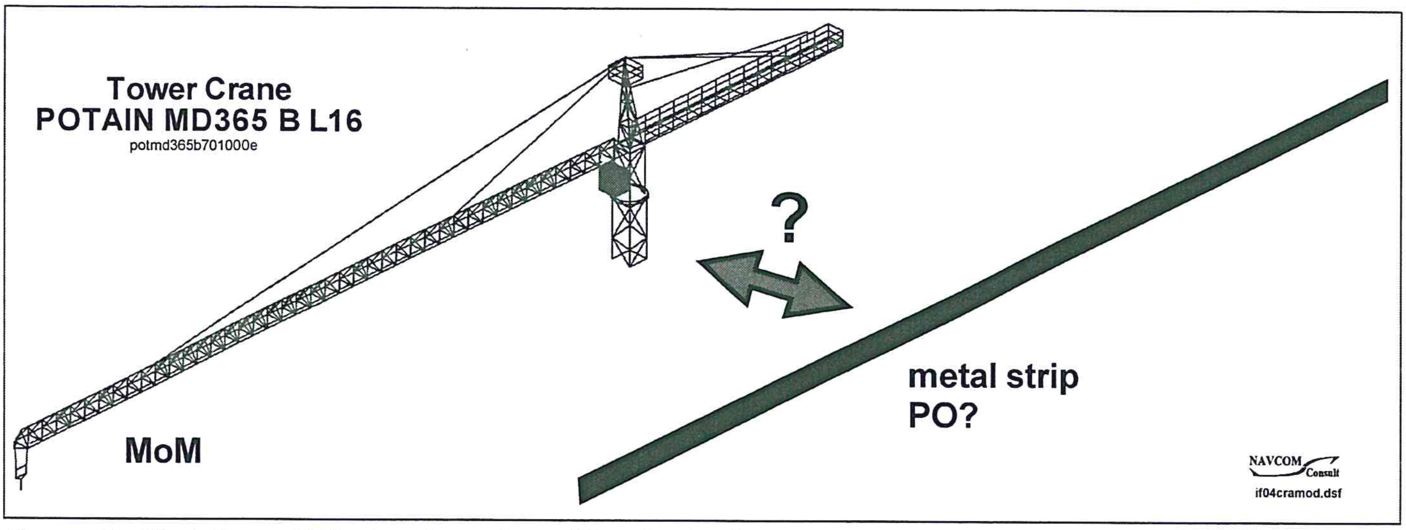

Figure 3: Modeling of 3D-structures by a 2D substitution; tower crane by a metallic strip?

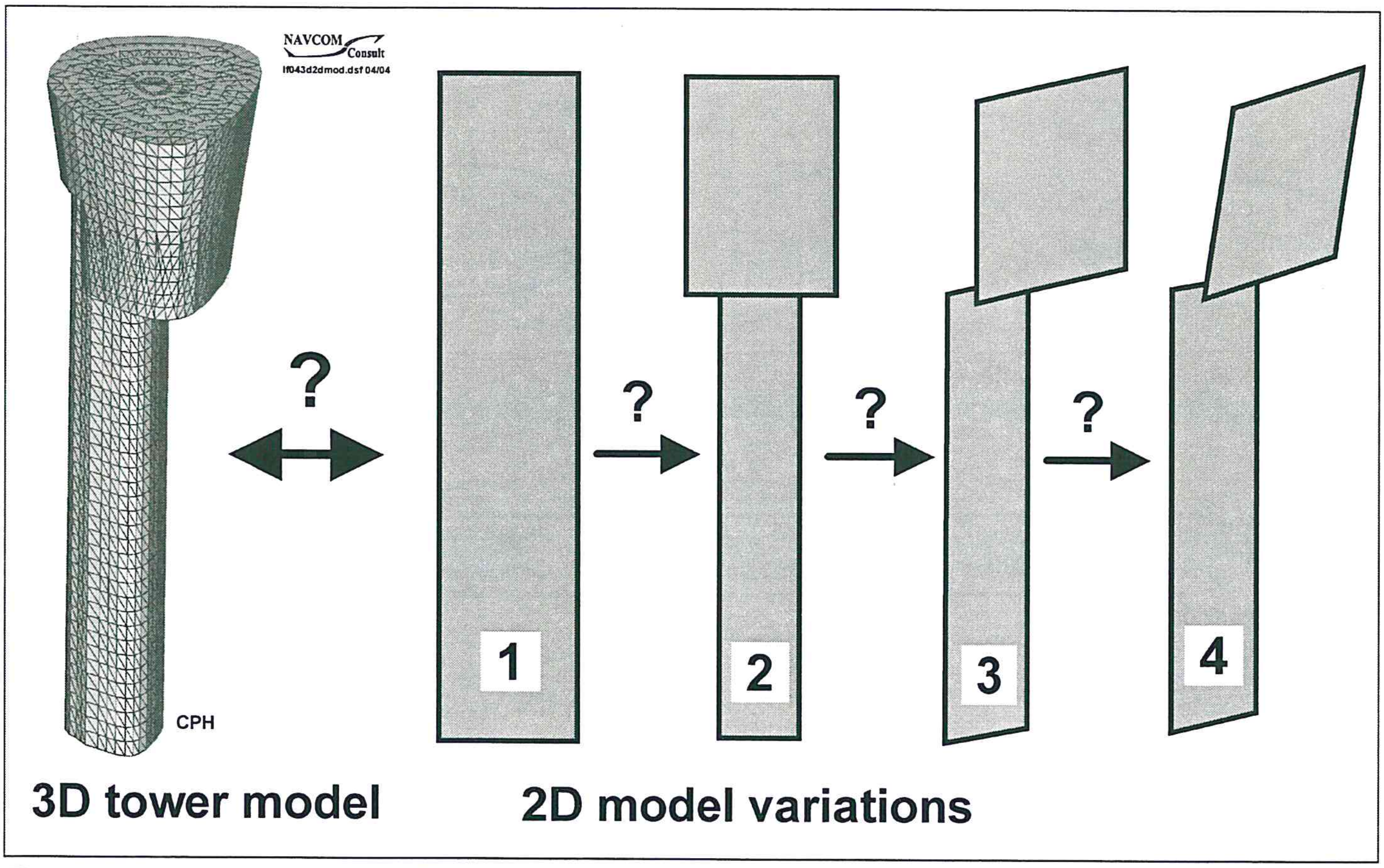

Figure 4: Modeling of a highly 3D control tower (left) by various 2D representations (right);
Each 2D-model has of course quite different results.

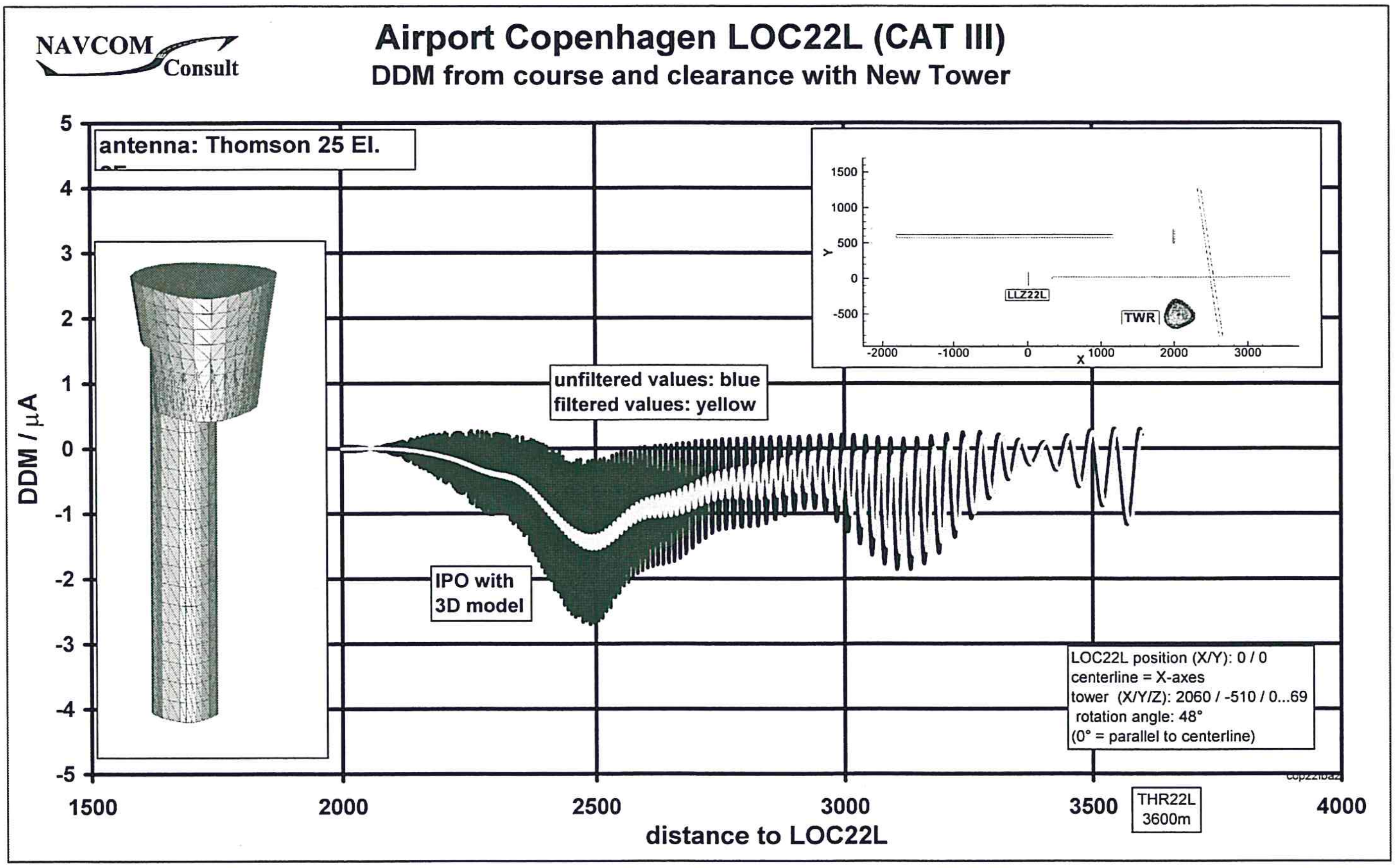

Figure 5: Numerically calculated DDM-distortions of a new highly 3D control tower for CATIII application on centerline; un-filtered raw data and ICAO and ICAO filtered; tower model fully metallized.

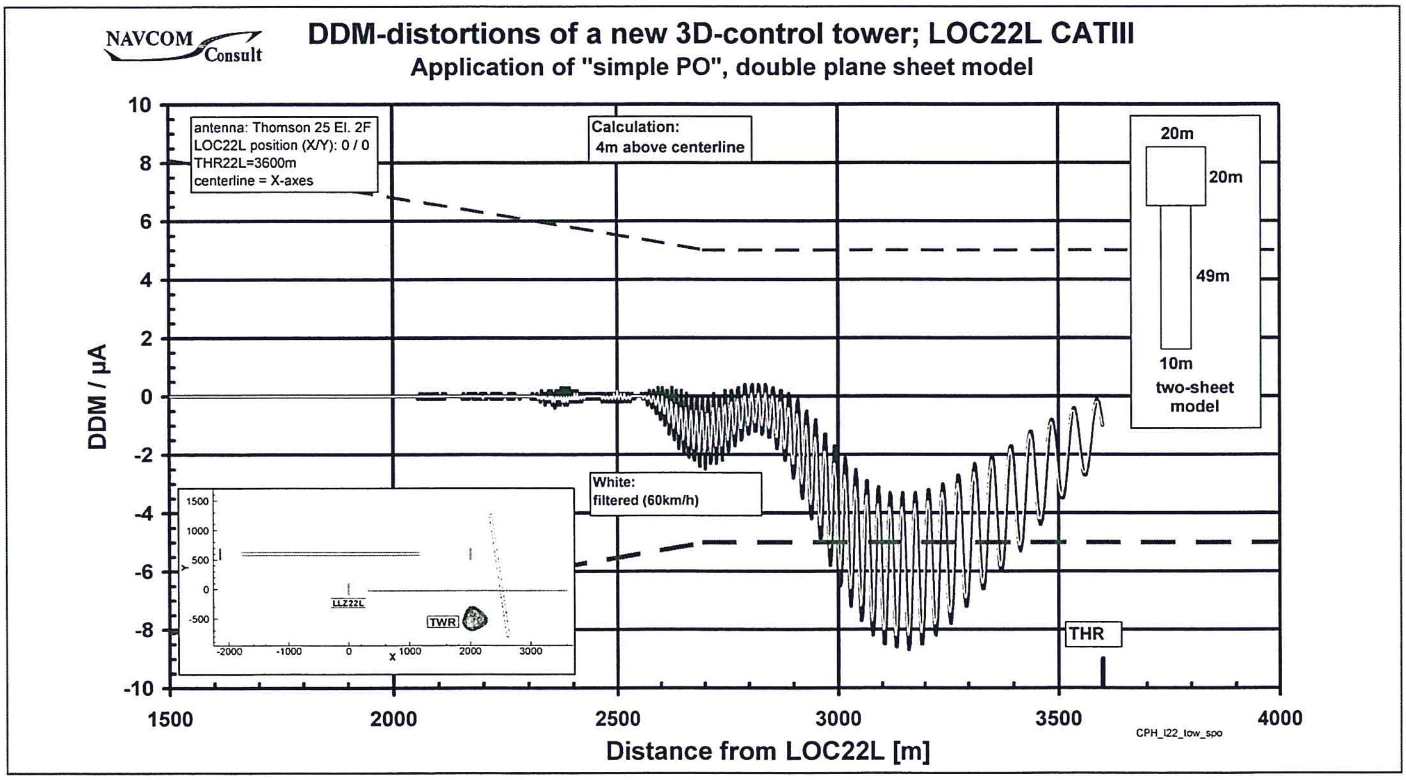

Figure 6: DDM-distortion by the 3D-tower acc. Fig. 4, but calculated by a simplified 2D double plate representation and simplified PO-method acc. Fig 5. Note the different vertical DDM-scale between the Figures.

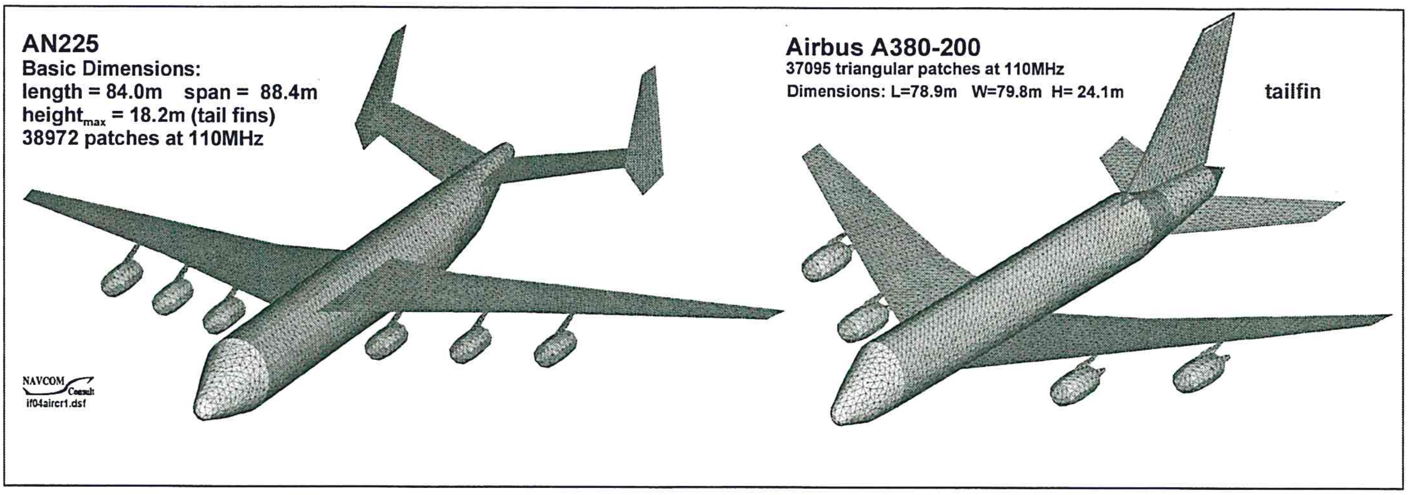

Figure 7: Numerical 3D-models of very large aircraft (AN225 larger than class F left; A380 class F right); less triangles than modeled are displayed

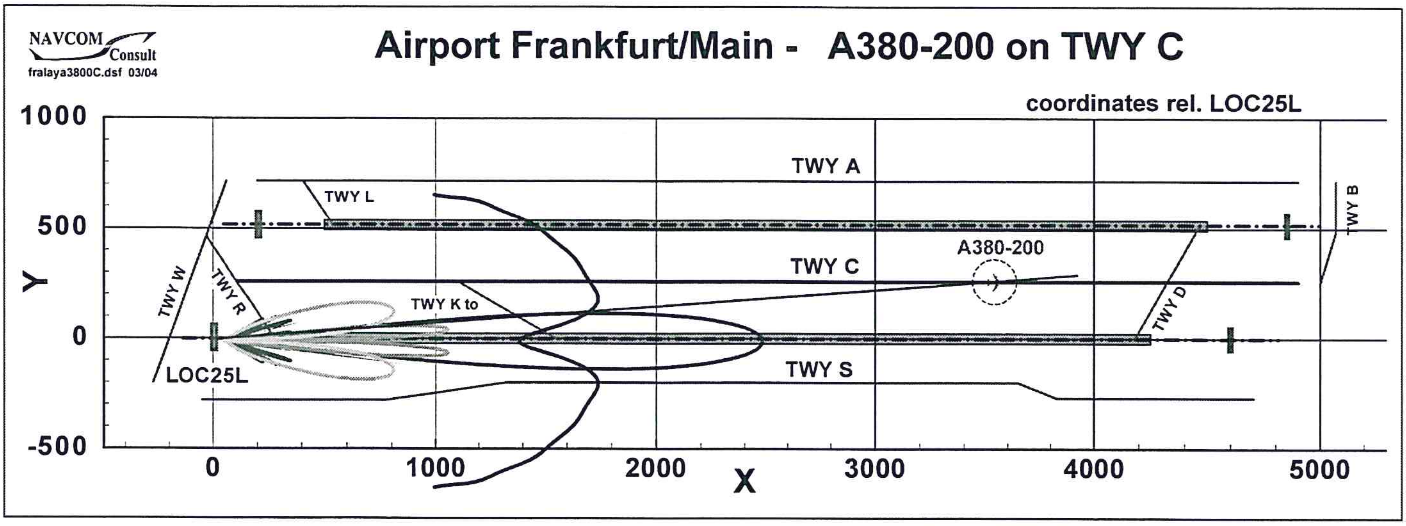

Figure 8: Partial layout of Frankfurt airport; parallel runways and taxiways

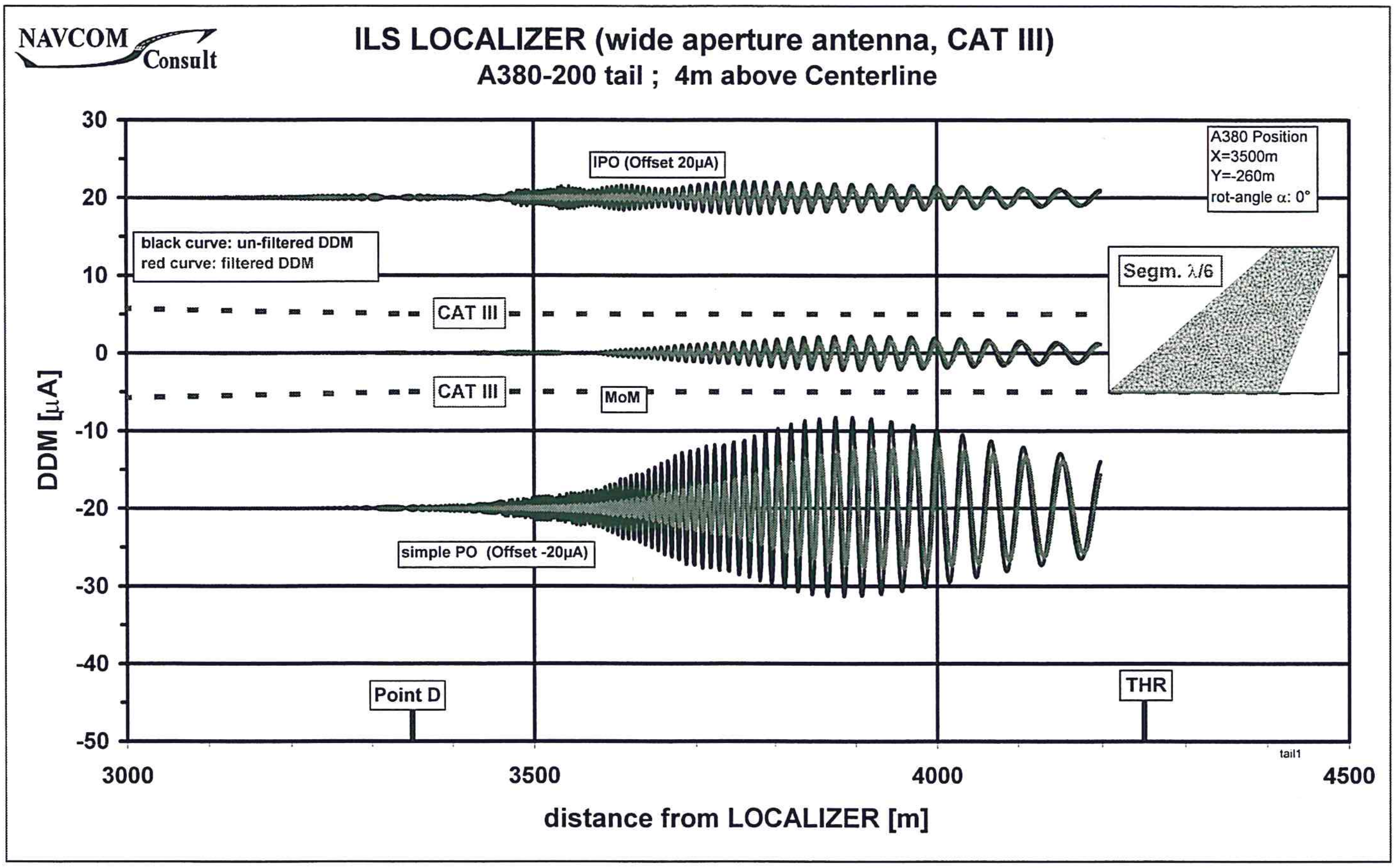

Figure 9: Numerically calculated DDM-distortions created by an A380 on a parallel TWY; different numerical methods. The exceedingly large DDM-distortions are obtained with a simple PO-method

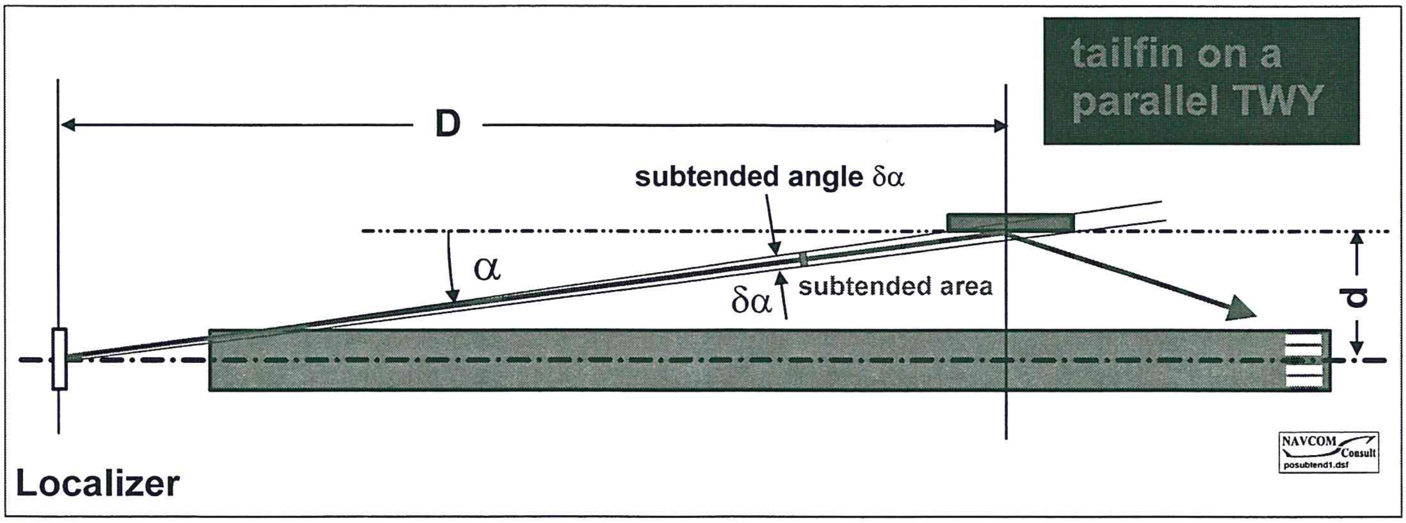

Figure 10: Visualization of a particularly critical case for "simple PO-methods"; small subtended angles of the object appearing for aircraft on parallel TWY

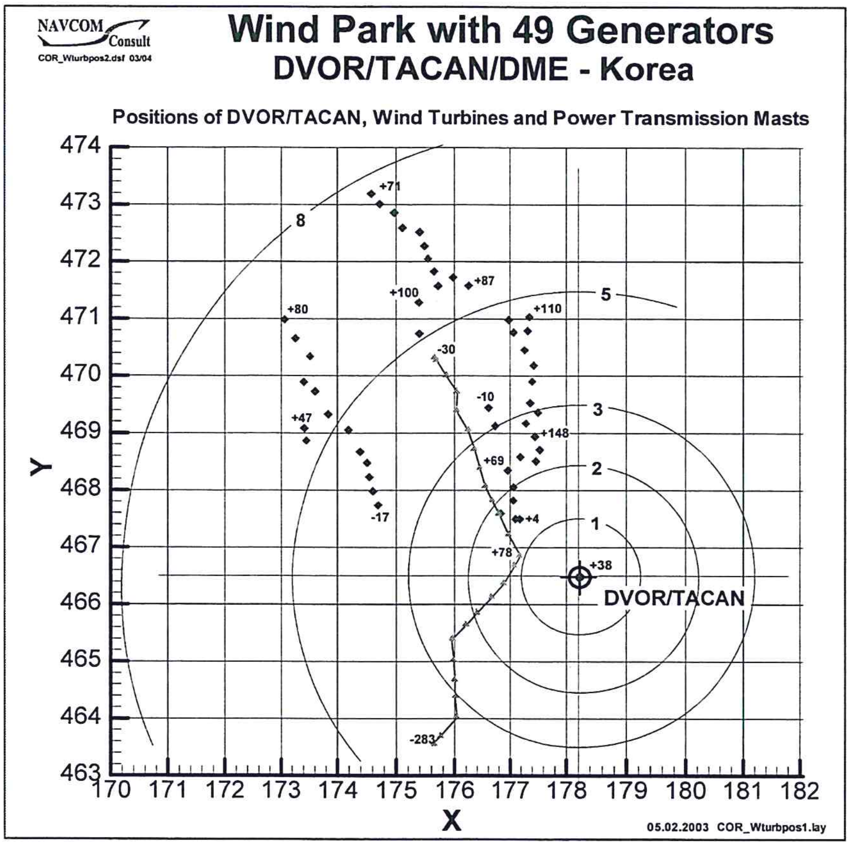

Figure 11: Original configuration of a large windpark and the associated power-line close to an enroute DVOR/TACAN station

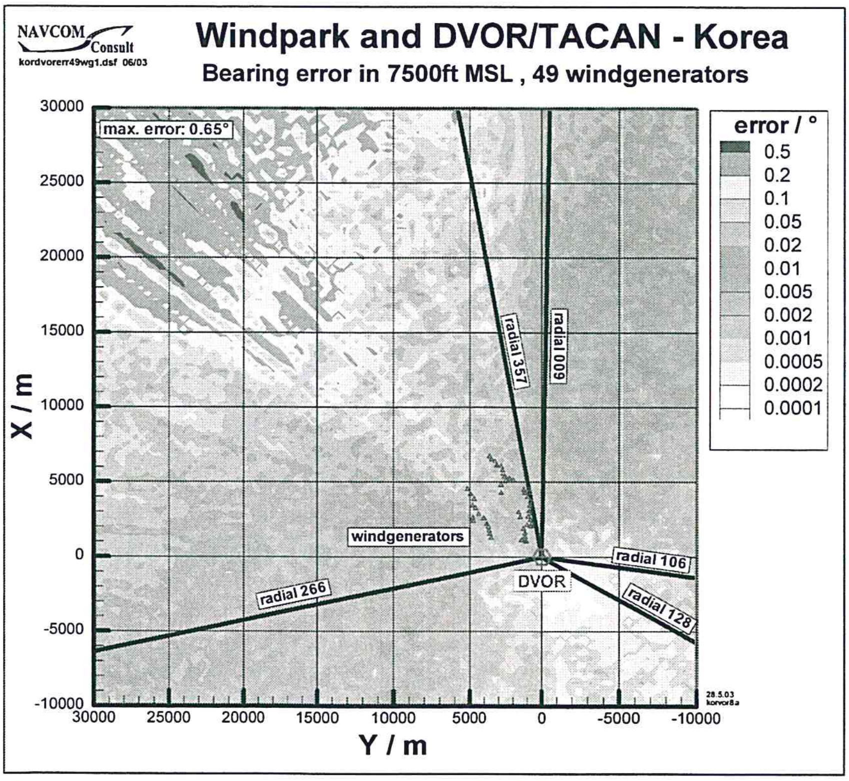

Figure 12: Numerically calculated DVOR bearing errors on a horizontal plane in a height of 4100ft, for a windpark of 49 windgenerators.

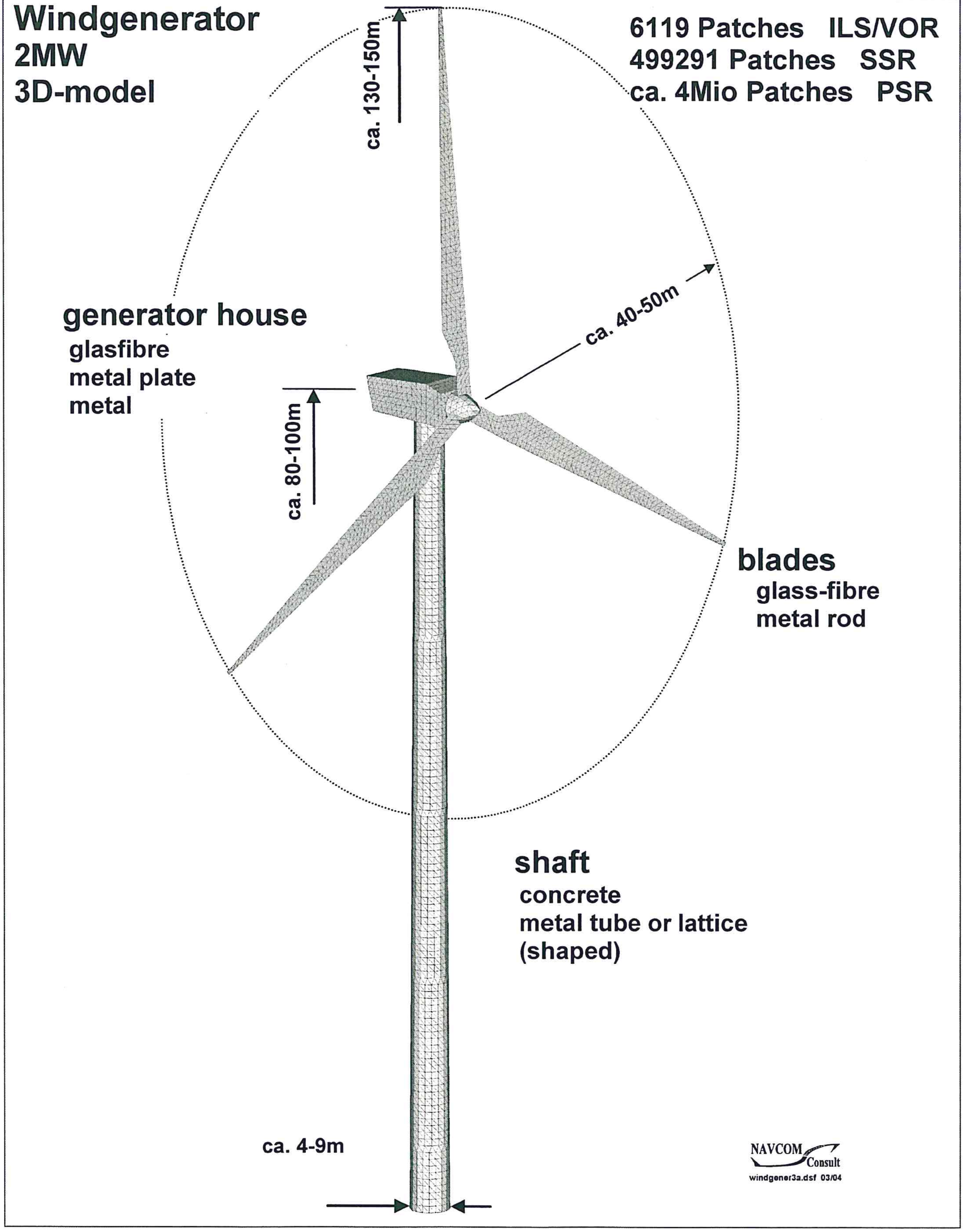

Figure 13: Numerical 3D model of a high power windgenerator assumed to be fully metallized consisting of a large number of metallic triangles; Model displayed in this figure is for far less triangles.

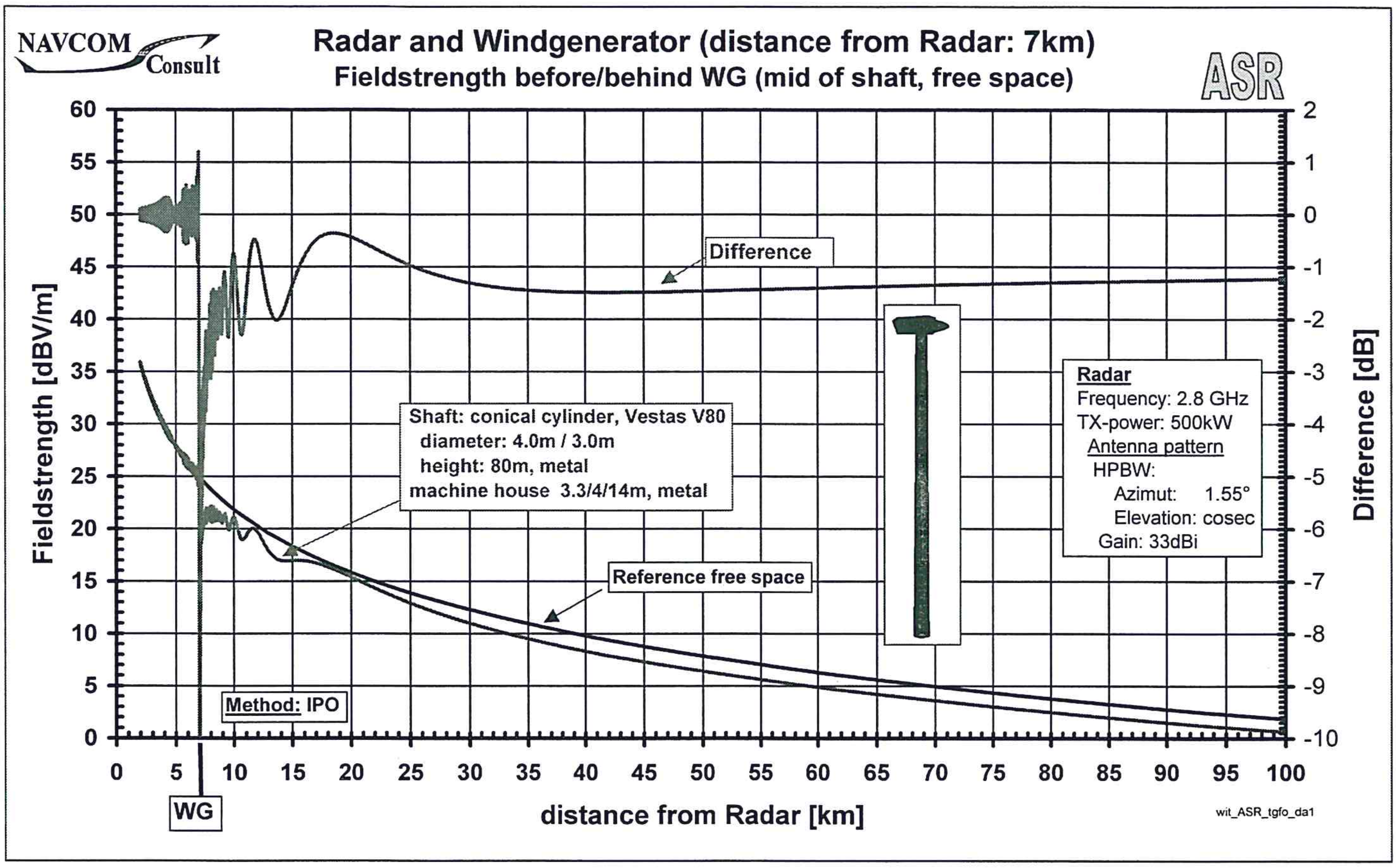

Figure 14: Numerical calculation of the fieldstrength on a line exactly through the WG (stationary part) from the phase center of the radar; apparent shadowing directly in the back of the WG; recovering field for larger distances.