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Modern Numerical Methods in the context of System Simulations for ATC-systems Examples, Results and Consequences

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ABSTRACT

The radio transmission and reception is the physical basis of all classical and modern navigation, landing and radar systems. Relevant objects in the radiation field can harm the intended electrical characteristics of these systems because the re-radiated components ("reflections", "scattering") at the objects interfere with the "wanted components". These potential interferences have to be predicted in advance before the new buildings are built or before the objects, such as the new aircraft A380 or the windturbines appear in the radiation field of the systems. Actions have to be derived from the predictions. The "system simulations" consist of some general tasks, namely the modeling, the numerical analysis and the evaluation of the system parameter. For each of these general tasks it has to be decided if a sufficient accuracy can be achieved at the end despite all the involved approximations. This has to be decided for every scenario. It will be shown that it is critical and insufficient to simplify the models and methods for reasons of speed, minimized effort and availability. Examples for different models and its numerical analysis will be shown. Also the aspect of "worst case analysis" is problematic. It is emphasized, that the methodology and the methods used in electromagnetics can be applied for these system simulations as well. The general rule is outlined that each method can be used only within its defined rules and limited applicability. It will be shown that a certain model and method can yield acceptable results for a certain scenario, but may yield totally wrong results in another one due to the approximations involved. For the case of the new Airbus A380 some principle test results on the modeling and scattering level and also on the ILS-DDM-level are presented using simple physical optics based methods and the advanced improved methods IPO, and finally the rigorous methods. In particular the limitations of the simple PO-methods are outlined by discussing the theoretical background.

INTRODUCTION

Many different types of classical and modern systems which are related to air traffic, are installed today on and around every major airport
• Navigation systems
• Landing systems
• Radar systems
• Communication systems.

These systems are operating with radio transmission and reception. The frequency range extends roughly from 500kHz to 15GHz. These systems on airports or enroute are working pretty well in the absence of scattering objects (scattering = reflections + diffraction). Depending on their characteristics major objects, such as hangars, terminals, large aircraft and windturbines, can distort these systems in an unspecified way. The forthcoming aircraft Airbus A380 (Fig. 1 and 2) is by far the largest civilian aircraft for regular air traffic. The latest largest windturbines have a height of the nacelle of up to about 110m and a total height of 150m. By their large conducting metallic bodies they have the capability of generating equivalently large scattering signals. This paper is dealing with the basics to evaluate the effects of an A380 and its adequate numerical analysis on the most common and standard landing system, i.e. the Instrument Landing System ILS, from the focused view point of the scattering. The ILS has the principle capabilities of "fully blind landing", called CATIII landing, where the autopilot is controlling even the rollout on the ground. Other aircraft which are taxiing on the ground are "distorting objects" for the ILS with respect to the landing aircraft. It is understandable that the large A380 is in discussion if its distorting capabilities on the ground would constitute a distorting threat for given airport layouts. This is in particular for the operationally very important parallel taxiways. It would be highly undesirable if the separation would have to be increased due to the potential distorting effects of the taxiing aircraft. Also, it is an important risky issue for the planning and layout of new airports or for extensions of existing airports. In order to safeguard the ILS signal, so-called "critical and sensitive areas" are defined which in turn depend on the scattering characteristics of the A380. It is obvious that larger safeguarding areas can have drastic effects on the operation and the capacity of an airport. Realistic definitions are thereof a vital issue. It is a safety issue in a sense that the analysis must be able to analyze all possible operational situations realistically and reliably. The systems are characterized by their main system parameter. In case of the ILS it is the guidance parameter DDM (Difference of Depth of Modulation) which controls the pilot in the cockpit or the autopilot in case of automatic landing. This system parameter is affected by the reflections and scattering of the mentioned objects. Every major building activity or the forthcoming appearance of the new large aircraft A380 on the airports have to be analyzed in advance due to its effects on the systems by advanced "system simulations". Because the effects are caused by "reflections" or "scattering" the analysis of the scattering properties of these objects is an integral part of the system simulations (Fig. 7 and 8).

SYSTEM SIMULATIONS

A system simulation consists of 3 major subsequent formal blocks or steps (Fig. 7 and 8)
• System pre-analysis/processing, setup
• Modeling, antenna and scattering analysis
• System post-processing.

Numerical scattering analysis methods have to be used which are embedded into the simulation process. Many different kind of objects appear on the airports requiring different kind of suitable numerical methods and adapted models. Fig. 8 shows the detailed flow chart or the block diagram of such a highly sophisticated system simulation process, i.e. the IHSS "Integrated Hybrid System Simulations". The basic idea is to use the best available sophisticated numerical method in a hybrid superposition manner. The selection of the numerical method depends on the electrical size related to the wave-length and its constructional features, such as
• plane or curved surfaces.
• Wire type structures like tower cranes or sliding doors.

The different methods are well known in electromagnetics. They have different basic properties and features
• Rigorous and/or almost quasi-rigorous
• Approximate and asymptotic
• Ray-tracing, current integration
• Antenna and scattering analysis
• Wave propagation analysis in case of nonflat terrain.

Several basic tasks have to be executed at the end of the main central block (Fig. 7 and 8)
• Decision which of the available numerical methods should be applied
• Modeling of the 3D-object (e.g. A380)
• Scattering analysis itself.

Generally speaking as a "state-of-the-art"-simulation procedure, the best available and applicable numerical methods using the sufficiently accurate 3D-model of the object should be used in the system simulation process. This procedure guarantees inherently the most accurate results.

MODELLING AND WORST CASE PRINCIPLES

The basis task of a numerical model is to transfer the real detailed object to an approximate model which
• cooperates with the subsequent numerical method (patch model, wire grid model) and can be analyzed
• considers the electrically relevant details
• creates the sufficiently equivalent systemeffects of the object within the analysis
• works for all operationally relevant scenarios.

It must be realized that the numerical analysis evaluates the numerical model and not the real object. If the model is not realistic, the final results can never be better even when the subsequent numerical analysis is perfect. In other words, the "quality of the model" is crucial. If the object is a simple metallic cube, the cube model is perfect. But, the more the real object is structured and the more three-dimensional, the less simple modeling approximations are useful and acceptable. The application of approximate methods claimed to be worst case methods is very problematic due to a number of reasons. It is not proven to be the worst case and also the approximate method in itself may fail in certain cases and by that are not the worst case. The strongest argument against this general procedure is that the worst case results may pose unacceptable and costly restrictions on airports which are not necessary in an absolute sense.

Some other examples, such as

- highly three-dimensional control tower
- tower crane
- windturbines
- TV-tower

are discussed in the earlier publications[4-8] with respect to ILS, DVOR and MSSR-radar. All these cases have been modeled by adequate 3D-approaches in order to get realistic scattering.

SYSTEM SIMULATIONS AND SCATTERING ANALYSIS

The aircraft A380 is very large in terms of wavelength, but a highly three-dimensional conducting structure (Fig. 2). Its numerical analysis requires the correct calculation of the scattered fields. The basic of the numerical scattering analysis is the current which is induced on the object. So, the **correct current** is finally the decisive issue in the scattering analysis.

Several types of numerical methods which are integrated into the IHSS, could be applied[6]

- The asymptotic high-frequency GTD/UTD-methods (Geometrical/ Uniform Theory of Diffraction) have been ruled out due to the curved surfaces and basic caustic problems. and other reasons.
- The integral equation methods (method of moments MoM, multi-level fast multipole methods ML-FMM). The MoM is the only applicable rigorous method which is well established within the electromagnetic community[1,2]. However the large number of patches (Fig. 2) in particular for the ILS glidepath at about 330MHz prevents the general and routine use for systematic applications. Singular tests for comparison and validation purposes of the non-rigorous methods have been conducted. The basic MoM needs in any case the inversion of the scattering matrix which is an unfeasible computer effort when a systematic analysis is required.
- The improved physical optics IPO method which constitutes a major and decisive improvement of the basic physical optics PO. The basic physical optics PO which uses the Kirchhoff approximation (1)[1-3] for the unknown currents, has severe limitations and inaccuracies in certain situations[1], p.4-22[2,3]. The IPO is sufficiently accurate, but much slower than the former ones, but it is the preferred numerical method if applicable. Generally speaking it needs as much more time, as the ratio between the numbers of the rectangles or patches.

It is obvious also that the numerical analysis of such kind of objects is time consuming and needs a lot of programming and computational effort. The application of approximate numerical methods, such as the simple physical optics PO, is based just on the well known Kirchhoff approximation[1] for the electrical surface current

$$I = 2\hat{n} \times H^i \quad (1)$$

From (1) the (scattered) electric PO-field

$$E^{PO} = E^i + \frac{jkZ_0}{4\pi} \iint_{S_{lit}} \hat{R}\times\hat{R}\times I \, \frac{e^{-jkR}}{R} \, dS' \quad (2)$$

results. From an assumed constant current amplitude on a rectangular plate the well known sinc-function

$$\sin c = \frac{\sin x}{x} \quad (3)$$

for the field-pattern results as a fast closed formula from (2). A constant current amplitude results from an incident plane wave - or approximately -from a source in electrically large distances. These basic PO-evaluations are widespread due to their simplicity and fast processing although known severe limitations and problems exist. These limitations and problems are well-known in electromagnetics and are taken into account[1,2,3] in applications. E.g., the simple PO is used for the calculation of the radiation pattern of reflector antennas - but only in the close angular vicinity of the main beam. Off the main beam the GTD/UTD is used due to the discussed reasons. However according to good engineering practice and principles of "state-of-the-art-solutions", the general accuracy should not be balanced against simplicity and speed. The accuracy of these "simple methods" is highly questionable for many operational relevant scenarios on top of the modeling issues. The problem with the simple PO-methods is that the expression for the assumed currents (1) is no more valid in certain situations, such as for the aircraft on the parallel taxiways on airports not too close to the Localizer. In this situation the impinging angle is small and grazing[1,2,3]. A series of modeling and numerical calculations for a sphere, cylinder and a representing square plate has been carried out (Fig. 3 to Fig. 6) for demonstration purposes. It can be clearly seen that for grazing angles the solution for the simple PO based on the simple Kirchhoff approximation (1) is seriously wrong, i.e. up to 20dB for small angles. The physical reason is that the real physical currents are no more constant and do not follow the simple Kirchhoff approximation as is well/known in electromagnetics. However on top of the mentioned current problem, the additional current problem applies that the hangars on airports and also aircraft A380 (Fig. 1 and 2) constitute large three-dimensional structures. The ILS-waves are horizontally polarized and create a deep minimum at the ground. By that the more elevated and more planar structure (tail fin) scatters a major part of the distorting fields. Often thereof, only the tailfin is considered for the scattering of the aircraft. However again, this assumption is completely wrong in certain situations. The total structure contributes significantly to the scattering depending on the scenario, such as when the aircraft is rolling on the runway or when the aircraft is crossing relatively close to the Localizer antenna. In certain situations the contributions from the aircraft structure (fuselage, wings, winglets) are the major ones. At the end it is tried sometimes to simplify the whole scattering problem A380 by one "(optimized) rectangular sheet" of a size to be determined (Fig. 1, Fig. 6). This extremely simplifying 2D-approach is in sharp contrast to the earlier described IHSS which is claimed to be a state-of-the-art 3D-procedure.

AIRCRAFT A380 ON AIRPORTS, ILS

The positions and the operational scenarios of A380 on airports are manifold (Fig. 7 and 8). The parallel taxiway is only one of the important ones. The operation of the ILS has to be protected by "safeguarding areas" and "holding lines" which the aircraft may not enter or cross during the landing of another aircraft. Increased separations on the glidepath may be consequences also. For the definition of the size of the safeguarding areas the distortion effects of the aircraft by scattering have to be evaluated. The important lateral size depends on many factors, such as the antennas, the existing distortions, the terrain structure like humped runways. If the scattering from a structure is too large, either realistically or virtually, these related safeguarding areas are unacceptably large. The operational and/or economical consequences are manifold

- reduction of capacity of the airport
- requirements for increased space, i.e. in case enlargement of the distances of runways and/or parallel taxiways
- etc.

A serious safety issue would occur if the simulated scattering is too small compared with the real effects.

Fig. 12 shows a layout of a major international airport. The position of an A380 is marked inmidst the runways and taxiways. Parallel runways and parallel taxiways are typical on air-ports and operationally very important. The aircraft is illuminated under a very small angle of 4.2° (Fig. 12) and under a very small subtended angle and area. This situation is known to be critical. The A380 is modeled in 3D by a large number of triangular metallic patches (Fig. 1 and 2; ca. 37000 for 110MHz) for the rigorous approaches. The model must be as realistic as possible, and as realistic as needed, having in mind that the scattering analysis is made for the model. The model should be applicable also for all operational scenarios to be analyzed (Fig. 11). This includes both ILS subsystems, the Localizer as well as the glidepath. The surface current distribution is shown for the tail test sample here (Fig. 10). Here as well as for the total aircraft[6] typical details can be interpreted, such as increased current amplitudes at the rims and the standing wave behaviour.

NUMERICAL RESULTS AND EFFECTS

Fig. 9 shows best agreement between simulations and measurements for an example for the Localizer DDM-distortions caused by the metallic glideslope mast. Fig. 13 shows for comparison test purposes the ILS-DDM-guidance parameter for 4 different distances to the runway-centerline (100m, 150m, 200m, 250m) of a rectangular test plate representing the tailfin for the 2 numerical methods, the MoM and the most simple PO. The DDM is almost proportional to the scattering amplitude of the plate. Very large differences can be observed up to a factor of about 10 which would have negative operational and economical consequences for the airports by having largely increased safeguarding areas. In fact it would threaten the operation of A380 on airport often during CATIII conditions seriously. The technical reason for these large differences are the wrong surface currents (Fig. 10) for the simple PO-approach compared to the MoM or the improved PO (IPO) yielding much too large scattering amplitudes. The currents are wrong by the amplitude level as well as by the distribution. The Kirchhoff approximation does not hold for the currents and completely fails for these operationally important situations. As a result of the advanced simulations, the parallel taxiways in Fig. 12 are safe for CATIII in filtered condition.

VALIDATION, VERIFICATION, MEASUREMENTS; CALIBRATION; RECOMMENDATIONS

Numerical simulations have to be verified and validated. This is complicated and difficult in the case of complex system simulations which use embedded numerical scattering analysis. One "obviously proven" method is to compare simulations and measurements. The problem in this case is the complexity of the measurements and the impacts of many partially unknown or unconsidered parameters (e.g. sampling, filtering, dynamic behaviour of receivers, sensor antennas). Often the measurements are performed by flight check or ground checks. The measurement conditions for these two types of measurements are much less defined compared to regular antenna test ranges which are designed for highly precise measurement under well controlled conditions. By that the system measurement uncertainties are much higher than in the antenna case. On the other hand the rigorous numerical methods, such as the method of moments MoM, have been verified and validated as a rigorous state-of-the-art-method itself by a vast number of cases in the last 30 years around the globe, by measurements and R&D-products. By that, the MoM is treated as a reference method for approximate methods or less rigorous methods. However, it is required to apply for this MoM-method a set of rules and boundary conditions within its range of applicability. However, the simulations have to assume a number of not precisely known factors, such as the setting of the antenna and the real antenna pattern, which are influenced by tolerances and by potential errors in the antenna networks. Attempts have been made to "calibrate" the simple PO-methods by comparing measured and simulated results for "known cases" and by deriving "correction factors" for unknown cases. The aim is to use simple "corrected" flat rectangles as a representation for a much more complicated 3D-structure (e.g A380). This is technically unjustified and strongly not recommended due to several reasons

- The "correction factor" is not a constant but would be a multi-dimensional factor or function depending on many parameters and scenarios
- The accuracy for unknown cases and uncorrected scenarios is unpredictable and can be very much in error depending on the scenario.
- It is simply not a state-of-the-art procedure despite the availability of powerful and rigorous or quasi-rigorous numerical 3D-methods.

In conclusion, both measured and simulated results suffer from errors and it is often difficult to judge which of the results is better and more accurate. It can be stated also, that all verifications on the system level for an approximate method (simple PO) are also validations for the improved methods (IPO, MoM). It is the theoretical and physical background that the results of improvements will be more accurate than the basis. If not, the improvements would be obsolete. This statement seems to contradict cases where the presented measurements seem to validate cases where the models are very crude and where the numerical methods are also basic approximations. As outlined before, the basic numerical methods are fairly accurate for certain characteristics (e.g. scallop behaviour) for a certain model in certain situations (e.g. simple PO in almost perpendicular incidence and where the scattering mechanism is fairly modelled by a plate). However, these cases are in no way a validation for all scenarios. The results of the problems of the basic PO are in such a way well established in electromagnetics that measurements on the systems level (e.g. DDMon airports) can in no way disqualify these basic results of the pitfalls of the simple PO. Other reasons must be found in case.

CONCLUSION AND CONSEQUENCES

The scheme of system simulations and the hybrid integration of sophisticated scattering analysis methods have been outlined. The modeling of real objects for simulations pur-poses has been outlined. The main affecting steps in the simulation process have been discussed Test examples for simple structures and for an aircraft A380 have been presented where the simple PO-method using the simple straightforward Kirchhoff approximation completely fails for the test cases and for the ILS and in an analog sense also for other systems. The technical reason is that the presumptions for the Kirchhoff approximation for the surface currents are violated. It is well/known in electromagnetics that the Kirchhoff approximation is wrong for grazing angles of incidence. The general result is that simple PO-methods overestimate the scattering in the analyzed cases of parallel taxiways much too much and yield much too large safeguarding areas - prohibitive and very negative for the introduction of the A380 on international airports. The correction scheme by improving the "simple PO" by "calibrating measurements" is technically unjustified and practically impossible due to some outlined technical and basic procedural reasons. Some more ex-amples and the detailed consequences for the airports with respect to the safeguarding areas are shown and discussed on the conference itself.

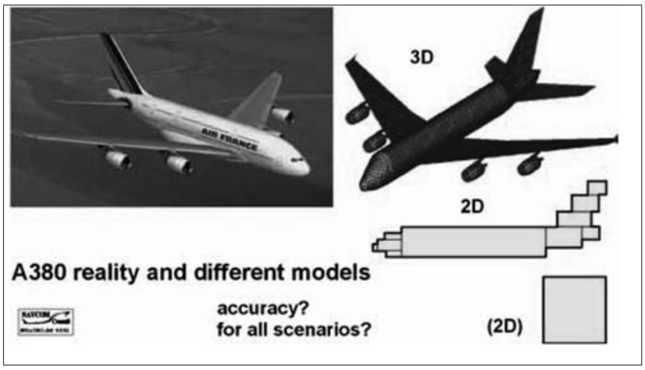

Fig.1: Real object of A380 and different modeling approaches.

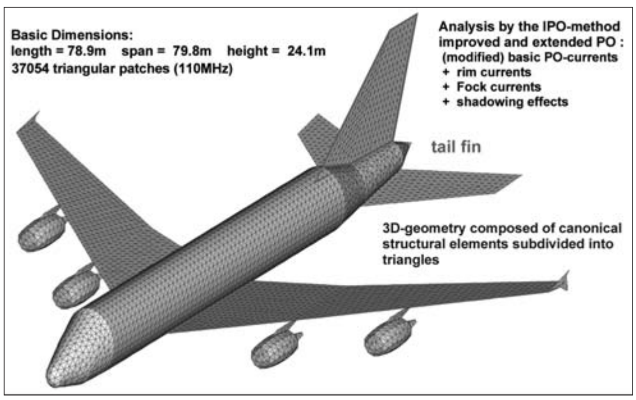

Fig. 2: A380 numerical 3D-model, scattering object.

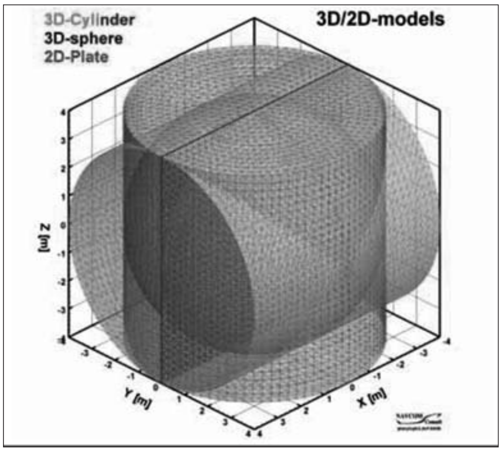

Fig. 3: Three different basic test models having the same overall dimension of 8m; sphere, cylinder vertical and horizontal, square plate.

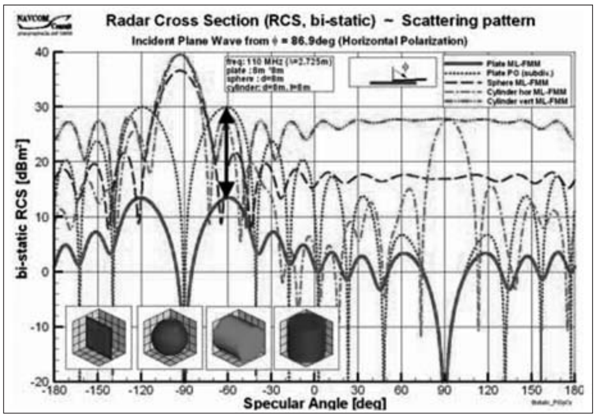

Fig. 4: RCS Radar Cross Section (corresponds to scattering pattern) of the models in Fig. 3 calculated by the rigorous MoM (ML-FMM) and also by simple PO for the plate (red dashed).

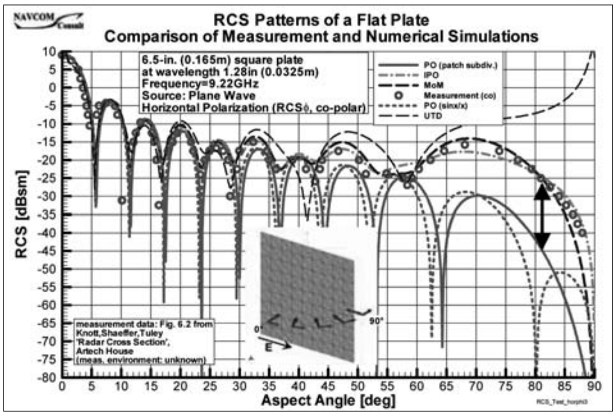

Fig. 5: RCS Radar Cross Section (corresponds to scattering pattern) of a square metallic plate; lab measurements (circles) compared with different numerical methods.

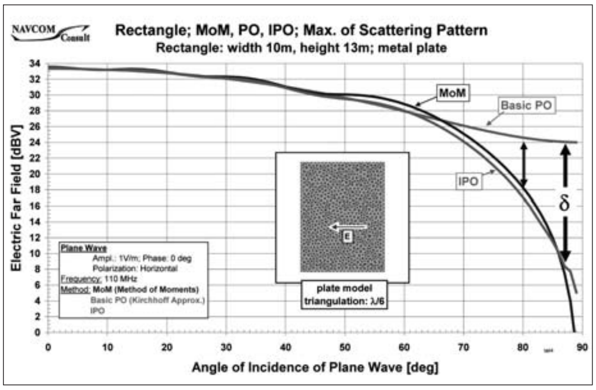

Fig. 6: Maximum of the scattering pattern of a flat metallic rectangle excited by a plane wave of variable angle of incidence; horizontal polarisation; size of the envelope size of the tail of the A380; comparison of the rigorous MoM, basic PO and the IPO.

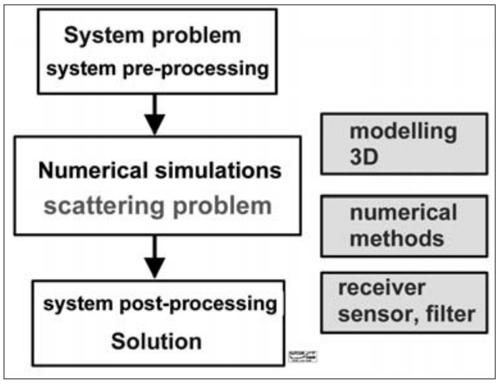

Fig. 7: (left) Basic scheme of the system simulations.

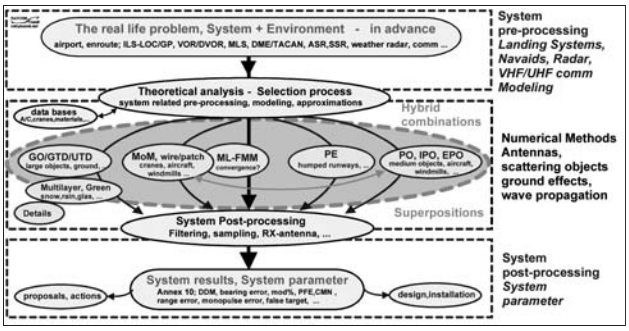

Fig. 8: (below) Detailed scheme of the IHSS (Integrated Hybrid System Simulations).

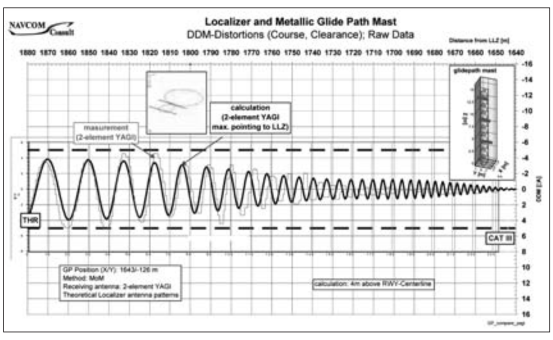

Fig. 9: DDM distortions of a lattice type glideslope mast (raw data); system simulations by using MoM compared to ground measurements.

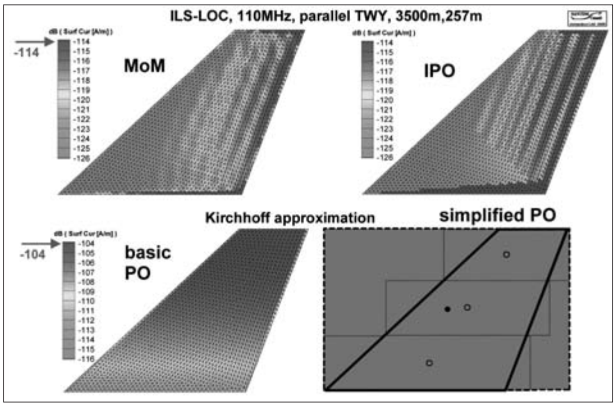

Fig. 10: Currents induced on a tail/fin like metal plate; different numerical methods: rigorous MoM, improved physical optics IPO, basic PO (uses Kirchhoff but for small patches), simplified PO (assumes constant current on the representing rectangle).

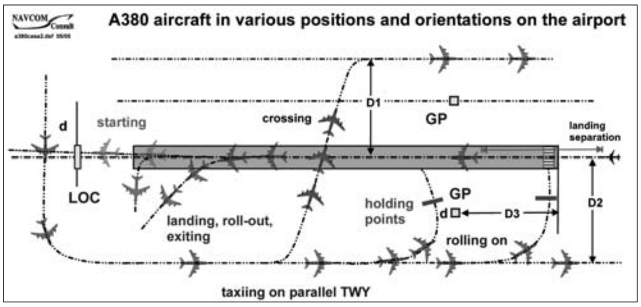

Fig. 11: Aircraft on different positions and scenarios on the airports.

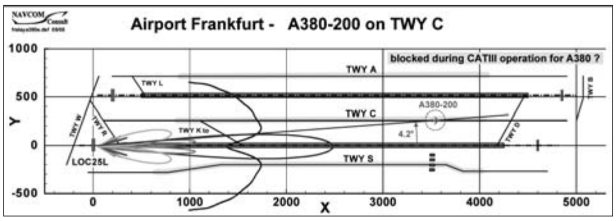

Fig. 12: Real example of a major international airport and the vital problems to be solved due to the appearance of the A380 under CATIII-conditions.

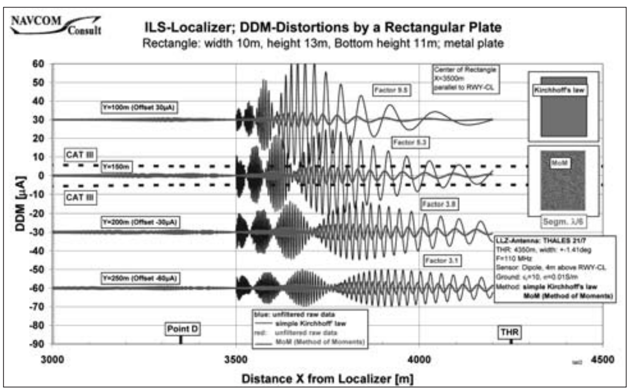

Fig. 13: DDM-distortions for a metal plate on a parallel taxiway of increasing distances from 100m to 250m in a grazing situation; comparison of Kirchhoff-law/based PO with the rigorous MoM ; The size approaches the rectangular envelope of the tail-fin of an A380.

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