Modeling and Manufacturing of a Series of Identical Antennas for a P-Band Ice Sounder

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***Abstract*— The most relevant aspects related to the modeling and manufacturing of the basic antennas of a P-Band ice sounder array are described. A robust basic element design insensitive to technological or construction tolerances and fulfilling electrical and very demanding mechanical specifications is presented. These goals have been attained after an exhaustive HFSS^{TM} simulation campaign, which has been efficiently performed with the help of a home made software tool, also presented here. After this campaign a series of 8 identical antennas, able to perfectly operate in the harsh arctic environment, has been absolutely in home manufactured at EPFL.**

I. INTRODUCTION

Nowadays, there is an increasing interest in the evaluation of the impact of meteorological phenomena on the Earth's surface. Within this frame, the European Space Agency (ESA) has launched within its "Living Planet" programme [1] the project POLARIS, an attempt to measure the thickness of the ice sheet as well as the shape of the bedrock in the Earth poles by means of new generation P-Band (435 MHz) synthetic aperture radars [2]. This project, led by the Technical University of Denmark, includes the development of the radar front-end formed by a linear array of 8 antenna elements.

The P-band ice sounder antenna will be installed in the underside of an aircraft fuselage as shown in Fig. 1. The main operational targets of the sounder system include: detecting bedrock through a 4 km layer of ice, allowing the simultaneous detection of deep and/or shallow ice layers and enabling ice anisotropy measurements. In order to attain these goals, the radar front-end must fulfill very demanding electric specifications, i.e.: 4 kW power handling and full polarimetric capabilities (allowing any polarization to be synthesized), as well as multiple phase center, to facilitate clutter suppression.

These requirements condition in turn the RF specifications of the individual radar antenna elements. A preliminary simulation of the system operation led to the specifications summarized in Table I for the electrical parameters of the individual antennas. However, in this problem the antenna design is not only determined by the electrical specification. The final system has to operate air-bound in the very harsh arctic environment (Fig. 1). This lead to a set of very stringent mechanical specifications, e.g.: resistance to high vibration, waterproofing, endurance to wide thermal cycles, size and weight restrictions and aerodynamic compatibility. All these requirements, together with ESA standards (reliability, safety, space-like qualification…) are indeed the most important elements in the antenna element design.

Fig. 1 Array installation on the belly of a Twin Otter aircraft.

The aforementioned specifications have led to the selection of a multilayer cavity backed double patch antenna design with dual lineal polarization, which has previously been demonstrated for a smaller radar [3]. Among all the analyzed options, this structure allows for a very good compromise between mechanical and electrical requirements.

TABLE I
INDIVIDUAL ANTENNA SPECIFICATIONS

Parameter	**Value**
[Min. Centre Max] frequencies	[390 435 475] MHz
Relative bandwidth	20% @ return loss
Polarisation	Dual linear
Return loss	<-15 dB
Cross polarisation	<-16 dB
Cross-coupling (both polarisations)	<-18 dB

Despite the narrow margin of parameter variation (the antenna element geometry was restricted and for some aspects even frozen, due to the aforesaid mechanical requirements) a big effort has been consecrated to analyze, model, optimize, manufacture and measure the basic antennas of the array. These individual cavity-backed patch elements will be integrated in the 4-meter/8-elements aluminum honeycomb structure of the new P-Band ice sounder front end (Fig. 1). A particular effort has been done to achieve a robust design, insensitive to technological or construction tolerances. Indeed, in this project the "best" design is not the one showing the best possible electrical performances but the less sensitive one simultaneously fulfilling all the mechanical specifications.

A combination of homemade and commercial softwares has been used to optimize the antennas. In particular, we have developed a software tool that can be combined with HFSS^{TM} to perform systematic optimization and sensitivity analysis. The capabilities of this software have allowed the efficient implementation of an extensive simulation campaign. As a result, and compared with the preliminary design [1], the final antennas posses optimal patches' dimensions, ports locations, substrate and foam thicknesses. All this has led to a lighter mechanically performing antenna, which exhibits the required EM performance. After attaining these objectives, a series of identical antennas have been manufactured in-house with the highest possible accuracy using the EPFL facilities. As it will be shown in this communication, the antennas obtained exhibit an impressive repeatability and the agreement with the theoretical predictions is excellent.

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II. ANTENNA DESCRIPTION

As aforementioned, among all the analyzed possibilities the best option, which sets a good compromise between mechanical and electrical specification, is a multilayer double patch cavity backed antenna, whose geometry is shown in Fig. 2 and described below. The variables used in this description are the quantities to determine for the final design.

The cavity's dimensions are L_c x L_c x H_c and the material is aluminum 6061-T6, because of its low density, good electrical conductivity and resistance to corrosion. The aluminum sheet thickness is 1.6 mm, which is a compromise between rigidity and weight. The cavity is crowned by an aluminum "T" frame, with an upper arm of length L_t . The basic antennas are screwed to the honeycomb structure through this arm, so that the rigidity and the safeness of the whole system are improved.

The multilayer structure, shielded by the cavity, consists of two foam layers, whose dimensions are L_c x L_c x H_{f1} (bottom) and L_c x L_c x H_{f2} (upper), and two substrate layers with sizes L_c x L_c x 1.52 mm (bottom) and L_c x L_c x 3.04 mm (upper). The upper substrate is twice as thick as the first one to protect the antenna against the environment. The foam material is ROHACELL 51, whereas the substrate is ROGERS RO4003C, inasmuch as it is the only adequate substrate to operate within the mechanical, thermal and dimensional stability constrains.

An active patch with dimensions L_{p1} x L_{p1}, which is coupled by two W_{ep} x L_{ep} excitation patches trough a gap of size d_{ep} , is hold by the first substrate. On its turn, a pin of diameter D_p is used to connect these excitation patches to a Huber+Suhner type 23_N-50-0-23/133_NE connector, with SUCOPLATE body plating and gold plated copper beryllium alloy centre contact. The two ports on the antenna are attacked by coaxial cables through these connectors. A second L_{p2} x L_{p2} parasitic patch is placed between the second foam layer and the upper substrate.

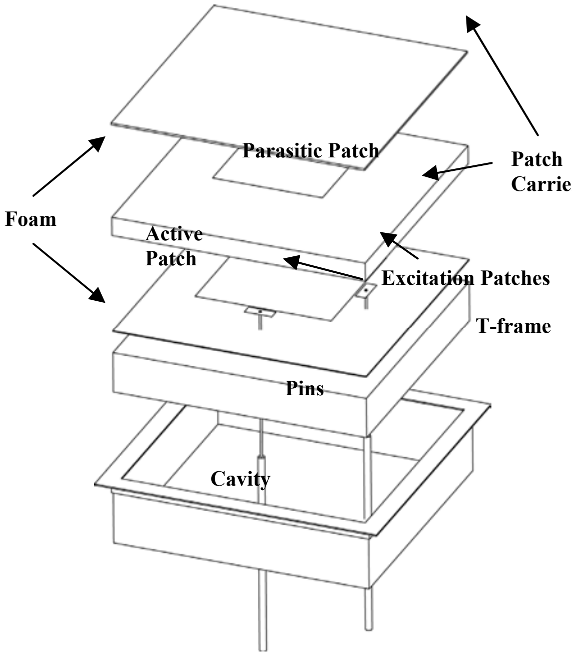


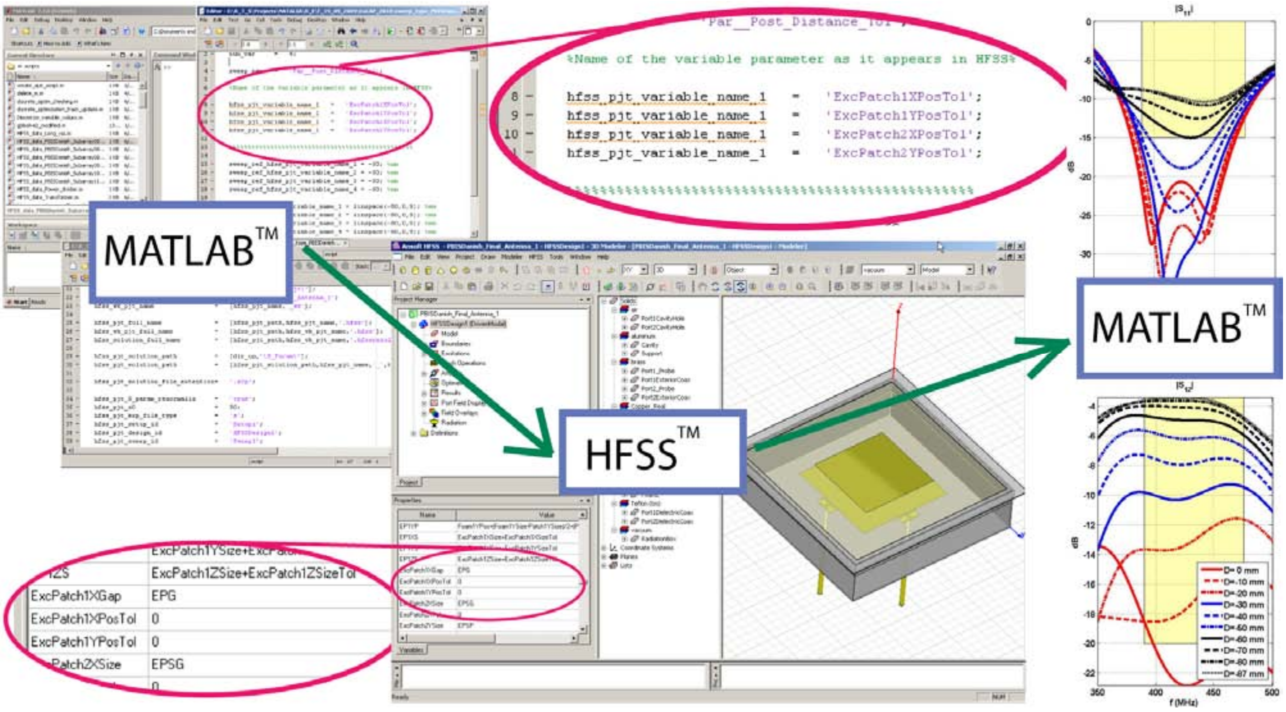
Fig. 2 Antenna description.

III. SIMULATION AND OPTIMIZATION PROCEDURE

In the design of the antenna element shown in Fig. 2, a theoretical model of the electromagnetic problem (EM) is defined with the help a commercial software tool (Ansoft HFSS^{TM}) and the accuracy of this model verified by the fabrication and measurement of several preliminary prototypes, the so called 'model calibration'. On the basis of this mature theoretical model and as a support for the parametric studies, optimization and fine tuning carried out during the design of the antenna element, HFSS interfaces a high level programming language (MATLAB^{TM}).

Such interface allows for the full customization and efficient automation of the aforementioned tasks, which involve intensive EM simulation and data processing. In particular, the interface used for this design is conceived to provide the user with the possibility to widely exploit both the computational and graphical capabilities of the EM software tool as well as the vast potential of modern high level programming languages.

This appealing property is achieved by minimizing the data to exchange between HFSS and MATLAB to a couple of sets of numerical values. The first set, the input one, corresponds to certain pre-defined and adjustable physical parameters of the EM model whose impact in the behavior of the model is to be monitored. The output set comprises the numerical values quantifying the forenamed impact, in a convenient pre-defined format. A schema showing the data flow between the two software tools is depicted in Fig. 3.



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'Par__Post_Distance_Tol';

%Name of the variable parameter as it appears in HFSS%

hfss_pjt_variable_name_1    =   'ExcPatch1XPosTol';
hfss_pjt_variable_name_1    =   'ExcPatch1YPosTol';
hfss_pjt_variable_name_1    =   'ExcPatch2XPosTol';
hfss_pjt_variable_name_1    =   'ExcPatch2YPosTol';

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
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ZS	ExcPatch1ZSize+ExcPatch1ZSizeTol
ExcPatch1XGap	EPG
ExcPatch1XPosTol	0
ExcPatch1YPosTol	0
PatchZXSize	EPSG

Fig. 3 Exemplary flow control of MATLAB™-HFSS™ interface.

Therefore, it is up to the designer to conveniently define and parameterise a robust EM model, to calibrate it and to optimize its computational efficiency. For all these activities, the designer has the powerful user interface of HFSS fully available. While for the definition of the way the input/output data to/from each simulation are to be processed, the designer can rely on all the coding amenities provided by MATLAB.

The price to pay is, moreover, related to another virtue of this particular interface: its flexibility. Thus, in addition to the activities above described (which are inherent to any design process), the user must configure the interface, which is fully coded in MATLAB, in accordance with the parameterization of the EM model in question. Out of each particular parameterization, the remaining characteristics of the EM model (nature, complexity, frequency of operation) are transparent for both the interface and the data processing routines, which can be reused for many different analysis/design problems without or with minor modifications. As an example of its versatility, this approach has been successfully applied to other challenging antenna and circuit designs up to Ku-band [4], [5].

On the one hand, the parametric capabilities of this home-made software were used to study the impact of the industrial tolerances on the antenna EM performance, as well as, to set the dimensions of the cavity, the foam, the “T” profiles and the pins. On the other hand, its optimization capabilities took an important role to determine the size of the patches and the distance between the excitation patches and the resonant patch. After an exhaustive simulation campaign, the final dimensions of the antenna were set to the values gathered in Table II.

TABLE II
ANTENNA FINAL GEOMETRICAL VALUES

Parameter	Value
L_c	400 mm
H_c	100 mm
L_t	30 mm
H_{f1}	65 mm
H_{f2}	30 mm
L_{p1}	215 mm
L_{p2}	173.5 mm
W_{ep}	43.5 mm
L_{ep}	16.5 mm
d_{ep}	3 mm
D_p	3 mm

IV. MANUFACTURING PROCEDURE AND MEASUREMENTS

This section is devoted to describe the most relevant aspects related to the manufacturing process, which has entirely been done at EPFL facilities, of a series of 8 identical antennas described in Section II and with the dimensions from table II. The process explained here was set having the following goals in mind: best possible reproducibility from element to element, minimal weight, maximal RF screening, vibration endurance and water and snow resistance.

According to the aforesaid objectives, the cavity was built through the assembly of separate plates by welding. This choice provides lightweight construction, excellent RF shielding and waterproofing, since among other facts, neither screws nor additional profiles are needed to assemble the plates forming the box. These plates were provided after being cut by means of a computer-controlled laser and assembled

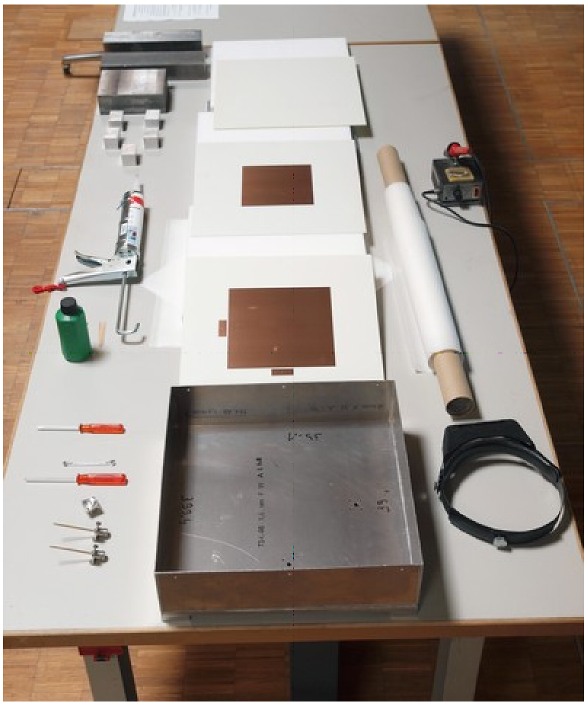

Fig. 4 Elements needed to built a single array element.

with techniques tailored to weld aluminum in the EPFL workshop. Therefore, accurate dimensions (inner aperture: 400x400 ± 0.3 mm; depth: 100 ± 0.1 mm) with minimal wall deformation were achieved. The frames closing the boxes are realized with "T" profiles, which were milled to an unsymmetrical shape to be adapted to the simulated dimensions and adjusted to its corresponding box dimensions. Four profiles are use to built a frame by welding the angles. Then 12 holes for "Cherry Max" rivets are drilled in both the frame and the box. The manufacturing of cavity finishes by also drilling the holes for the "N" connectors through a special in home-made setup to ensure accuracy and repeatability in their positioning. This setup is also used to drill the holes in the foam plates, thus ensuring perfect alignment of these holes with the pin position.

The manufacturing of the "N" connectors' extensions is also a critical step. This extension was realized from brass at EPFL mechanical workshop and carefully mounted by ensuring both reliable electrical contact and mechanical strength. The end of the pin extension is provided with a screw and a washer, which are pre-tinned and will be secured during the soldering operation to the print, so that perfect mechanical and electrical junction is assured.

The multilayer structure requires the assembly of prints and foam. On the one hand, the process to produce the prints include substrate cleaning, photoresist coating with RISTON film, UV insolation of the coated substrates, photoresist development, copper etching, stripping, drying with hot air, cutting the prints with diamond saw and drilling the holes for extension pin connections. The highest possible accuracy was maintained during all operations, carefully controlling all parameters. For instance, the patch alignment is better than ±0.1 mm relative to the external dimensions of the print, and the holes positioning is better than ±0.05 mm. On the other hand, the foam was, at first, sawed to approximately 410x410 mm. Each square was then milled on a CNC machine to the correct thickness using a diamond tool rotating at high speed. A special structure was designed to maintain the foam plates on the CNC machine without excessive pressure. Pairs of 40/25 mm thick plates were adjusted together, so that their total thickness is 65 mm with the highest possible accuracy. Special care was taken with the 30 mm plate thickness, as this dimension is critical for the coupling between patches. A group of three foam plates (40, 25 & 30 mm) was assigned to a given box, and their 400x400 mm dimension adjusted using a diamond saw to the exact actual inner dimension of the box, so as to leave no void inside the box when assembled. Finally, two 3 mm holes for the pin extensions have been drilled in the 40 and 25 mm thick foam plates.

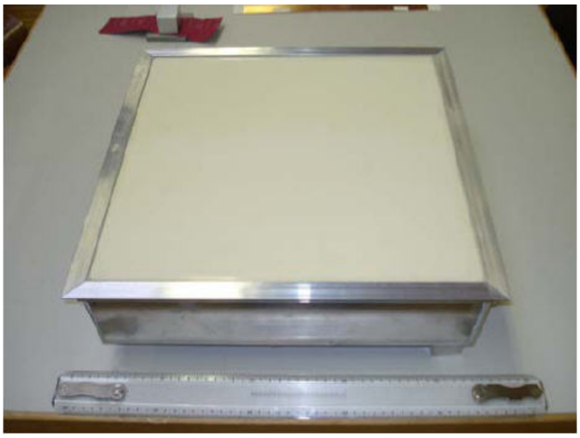

Fig. 5 A finished single array element.

All the described components, illustrated in Fig. 4, were assembled following a building brick principle and placing a film of glue between the layers. This film was also placed around each foam plate, which implies that the sides of the plate will adhere to the inner sides of the box, thus reinforcing the whole structure. In order to polymerize the films of glue, the assembled antenna was put into an oven and "baked" under pressure for two hours at 150°C. It has to be pointed out, that during the "baking" process, the foam plates will slightly extend in the X and Y directions, eliminating any eventual void between the foam and the inner faces of the box.

Finally, the weatherproofing of the antenna element is assured by applying a special rubber material (PR-1422 A2), which withstands temperatures for -55°C to +135°C, on the radome, top and upper edges of the box. Then the "T" frame is put in place and secured using 12 "Cherry Max" aluminum rivets. The PR-1442 will then slowly dry, attaining its final characteristics after a few days, but remaining elastic even under severe temperature conditions. The presence of this rubber on the top sides of the box reinforces the whole structure, acting as cement between the box sides and the sides of the "T" profiles. The final result can be appreciated in Fig. 5.

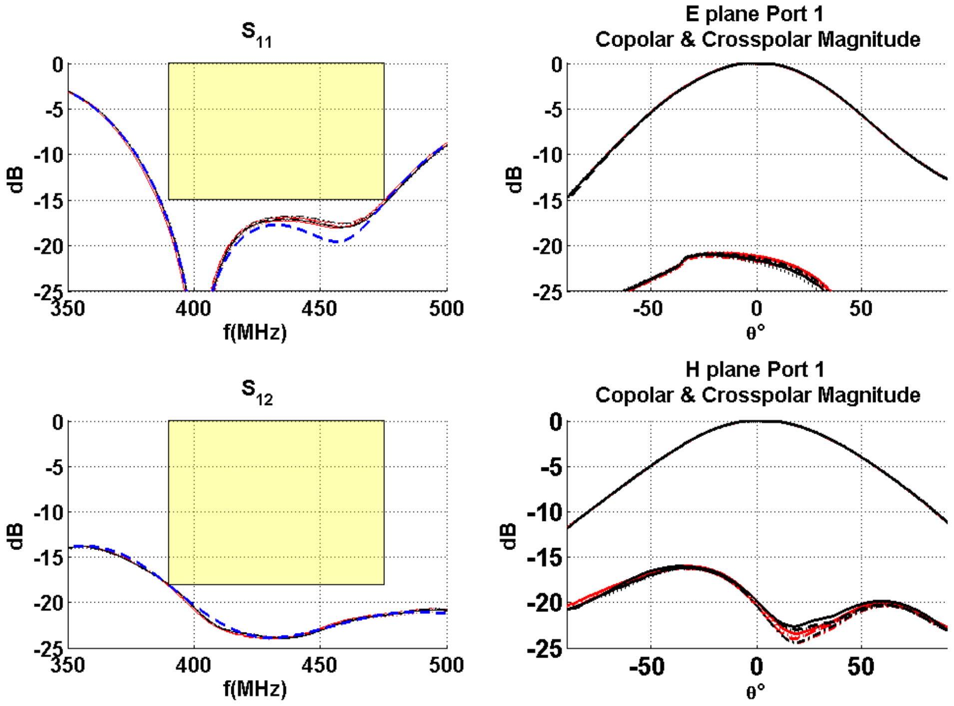

Fig. 6 EM performance of the antenna series: A1(——), A2(— — —), A3(· — · —),A4(·········), A5(——), A6(— — —), A7(· — · —),A8(·········), Simulation (——).

A series of 8 antennas was built following the described procedure. Each element was measured in the LEMA-EPFL facilities. The final results are presented in Fig. 6, where the excellent level of similarity between elements attained can be appreciated. Also in this figure, it can be observed that all antennas fulfill the required specifications, as well as a very good agreement between the results predicted by simulation and measurements.

V. CONCLUSIONS

LEMA-EPFL has successfully modeled, built and measured the basic antenna elements for the P-Band ice sounder array. The modeling process has been efficiently implemented with the help a home made software tool, which interfaces HFSS. As a result of this process, an optimized and mechanically enhanced antenna, with respect to previous designs, has been obtained. A series of 8 antennas has been in-house manufactured with very high precision techniques, attaining and excellent degree of similarity between replicas and also an excellent agreement with the theoretical predictions. The whole series fulfils the EM specifications together with the very demanding mechanical specifications, which are required to operate within the harsh arctic environment.

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