RADOMES – LARGE SIZED COMPOSITE STRUCTURES WITH MULTI-DISCIPLINARY REQUIREMENTS FOR UNMANNED RECONNAISSANCE AIR PLATFORMS

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Abstract

High flying unmanned air vehicles (UAV) require the transmission of large data volumes via multiband / wideband satellite communication (SatCom).

The radome protects the antenna against a harsh environment and is a high performance component that has to fulfill requirements from several disciplines. The purpose of the presented work is to develop a technology to design, manufacture and qualify radomes fulfilling the requirements.

To identify the requirements and their prioritization is a first task. Most important is to understand and assure electromagnetic transmissivity. In principle there are three different candidates for a radome design, i.e. a monolithic, an A-Sandwich and a C-Sandwich shell structure. In a next step a suitable electromagnetic solution has to be transferred to a design that considers manufacturability, ensures structural integrity and all relevant criteria for certification. A thin wall A-Sandwich configuration is supposed to be the best selection and was evaluated in terms of transmissivity, manufacturing, damage tolerance, and lightning protection.

A building block approach with increasing complexity is established with tests on different coupons and with demonstrators to achieve a stepwise evolution of the technical maturity of the envisaged radome concept.

Promising results have been achieved within a collaborating framework of research institutes and industry and the work will continue to answer more specific questions to increase the technological readiness level (TRL).

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1. Introduction

Beside modern electronic equipment the data transmission from an UAV to geostationary satellites requires an antenna of a certain size which may drive the aircraft (A/C) configuration considerably. Usually the antenna is located in the front section of the air vehicle and needs a radome as an aerodynamic cover and as a protection against harmful environmental conditions and at the same time the radome should allow optimal electromagnetic (EM) transmissivity.

It is one of several tasks of the FFS R&T program (FFS = Fortschrittliche Flugzeug Strukturen, i.e Advanced Military Aerostructures, an established partnership between institutes and companies) to enhance radome technology which requires a multidisciplinary collaboration of Airbus Defence and Space, Airbus Group Innovations, DLR – Institute FA in Braunschweig and the DLR – Institute BT in Stuttgart, as well as of WIWeB (Wehrwissenschaftliches Institut für Werk- und Betriebsstoffe) in Erding.

2. Requirements

The radome requirements resulting from the A/C missions are shown as an overview in Figure 1.

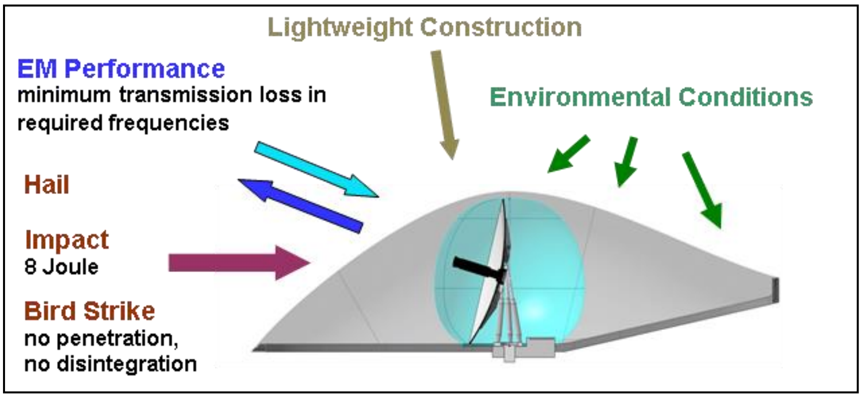

Figure 1. Radome requirements overview

In detail, the requirements may have different weighting or priorities.

Concerning the **EM performance**, the SatCom frequencies vary by mission or at least by the different operators. In principle, the established bands in operation by different satellites shall be usable:

Table 1. Rounded frequency band values

Band	Up Link	Down Link
Band 1 (X-band)	8.0 – 8.5 GHz	7.3 – 7.8 GHz
Band 2 (Ku-band)	14.0 – 14.5 GHz	10.7 – 12.7 GHz
Band 3 (Ka-band)	29.5 – 31.0 GHz	20.0 – 21.5 GHz

The radome losses shall be minimized and the ITU (International Telecommunication Union) regulation requirements especially concerning beamwidth and side lobe peaks shall be considered. If possible, the three frequency bands shall be covered by one radome.

As the weight of A/C components is of most concern, the radome mass shall be as low as possible. This will have an impact on the configuration choice, see Figure 2.

The component structure will be exposed to different **environmental conditions** which shall not deteriorate the structure:

- temperature variations (-55°C to 80°C),
- atmospheric and aerodynamic pressure,

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- humidity,
- rain, hail, lightning strike, icing conditions,
- solar radiation, etc.

Bird strike is the most challenging requirement from mechanical point of view. According to airworthiness certification regulations a 1kg bird impact shall not lead to a catastrophic failure. That means, penetration and disintegration of the radome shell is not allowed.

Damage Tolerance requirements do not allow impacts below 8 Joules to induce unallowable damage. The definition of the allowable damage is one of several challenges.

3. Principal Solutions

As EM transmission and its efficiency is a major radome task, first it is important to know the influence parameters and to understand the principles of the transmission of electromagnetic waves through materials in the context of radome designs.

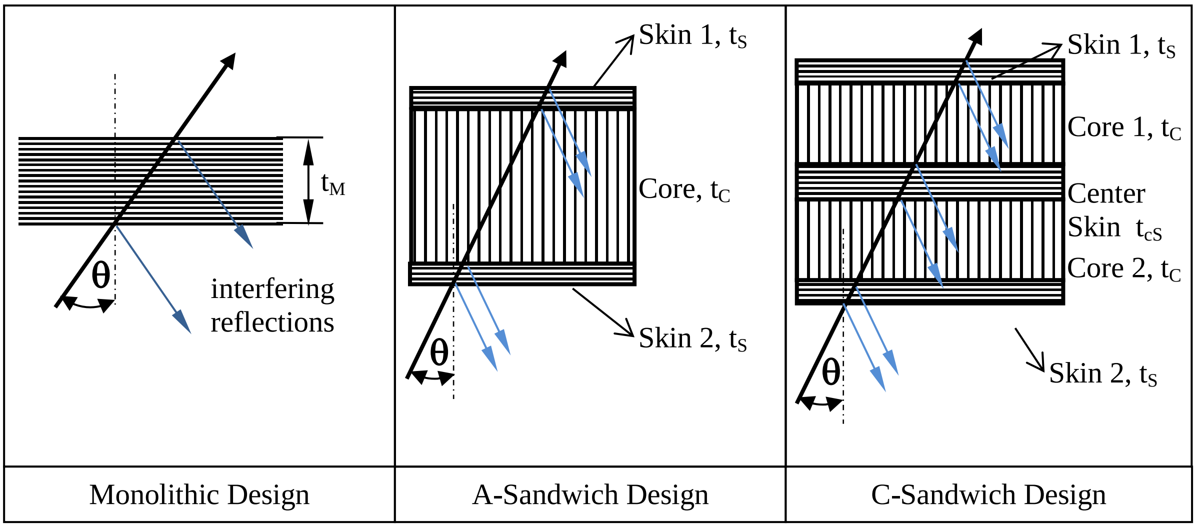
3.1. Influence Parameters

For this task a self-developed “Mathematica” code for EM calculations is used, based on the Fresnel equations which describe what fraction of the light is reflected or transmitted at the interface of two different planar, linear, non-magnetic, and homogeneous materials. The equations also describe the phase shift of the reflected light and assume, that the light is a plane wave. The Mathematica code allows the stacking of many material layers as a radome lay-up and considers the following parameters:

- The dielectric constants permittivity and loss, $\boldsymbol{\varepsilon_1}$ and $\boldsymbol{\varepsilon_2}$ in a complex formulation, for any non-conductive material layer,
- Layer thicknesses, **t**
- The frequency of the incident wave, **f** and **λ** as the corresponding wavelength,
- The incidence angle, **θ** , is the angle between the antenna central beam and the radome shell surface normal at the location of penetration.
- The polarization of the electromagnetic wave.

3.2. Radome Designs

For radomes different design options exist. The basic design principles are shown in Figure 2, [1].



Monolithic Design | A-Sandwich Design | C-Sandwich Design

Figure 2. Radome principle designs

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To find an electromagnetic solution for a required frequency is relatively simple for the **monolithic design** because there is only one design parameter (laminate thickness t_M) when assuming the best available material, a prescribed angle of incidence and a given polarization.

The **A-Sandwich** (A-SW) configuration has two design parameters, namely core thickness (t_C) and skin thickness (t_S). Usually t_S is very thin compared to the wavelength (λ) of interest and fulfills the thin wall condition ($t_S <$ ca. $1/20\ \lambda$). That means the skins have a negligible influence on transparency and the core may be seen as a lightweight monolithic configuration. But configurations with thicker skins can be found which may be of interest for higher frequency bands.

The **C-Sandwich** (C-SW) has even more design parameters (Figure 2) and the challenge is to find suitable configurations.

3.3. Electromagnetic Behavior

From the EM transmissivity point of view, materials with low dielectric values ε_1 and ε_2 are favorable. For the project typical values for quartz glass in epoxy resin are selected for the monolithic part (skins) of the designs and the sandwich cores are represented by honeycomb or foams.

Typical values:	Glass / epoxy:	$\boldsymbol{\varepsilon_1}$ ca. 3,2 – 3,7 and $\boldsymbol{\varepsilon_2}$ ca. 0,02 – 0,08
	Honeycomb, foam:	$\boldsymbol{\varepsilon_1}$ ca. 1,1 – 1,2 and $\boldsymbol{\varepsilon_2}$ ca. 0,001 – 0,01

Diagram 1 in Figure 3 shows possible solutions for the monolithic laminate thickness in a transmissivity-t_M-f contour-plot for $\boldsymbol{\theta = 0°}$. Three solutions are indicated for each of the required frequency bands by red bars in the light colored diagram areas for good transmissivity. The frequency bands (down-link and up-link, Table 1) are indicated by transparent columns in all diagrams.

Diagram 2 can be seen as a cross-section of Diagram 1 for the band 3 solution (t_M = 8mm). Transmissivity (T [dB]) is shown for $\boldsymbol{\theta = 0°}$ (red curve) but also for $\boldsymbol{\theta = 40°}$ (green curve) and for $\boldsymbol{\theta = 60°}$ (black curve). The green and black curves have their peeks at the same frequencies as the red curve. This is only the case when $\boldsymbol{t_M}$ is adapted to the angle of incidence $\boldsymbol{\theta}$. Consequently the radome has to be tapered, i.e. $\boldsymbol{t_M}$ is a function of $\boldsymbol{\theta}$ and $\boldsymbol{\theta}$ is a function of the radome surface location.

Diagram 3 in Figure 3 is similar to Diagram 2, but calculated for a A-SW configuration with thin wall cover sheets. The contour plot is very similar to Diagram 1 and the only design parameter $\boldsymbol{t_C}$ = ca 14mm for $\boldsymbol{\theta}$ = 0° shows acceptable transmission for all 3 bands. This solution is called the A1-configuration. The curves shown in Diagram 3 stand for $\boldsymbol{\theta}$ = 0°, 20°, 40°, 50° and 60°. The curves for high angles of incidence show a severe decrease in transparency at the edge of the frequency bands. An adaptation of $\boldsymbol{t_C}$ to improve e.g. transparency for the band 2 up-link results in unacceptable transparencies for band 3.

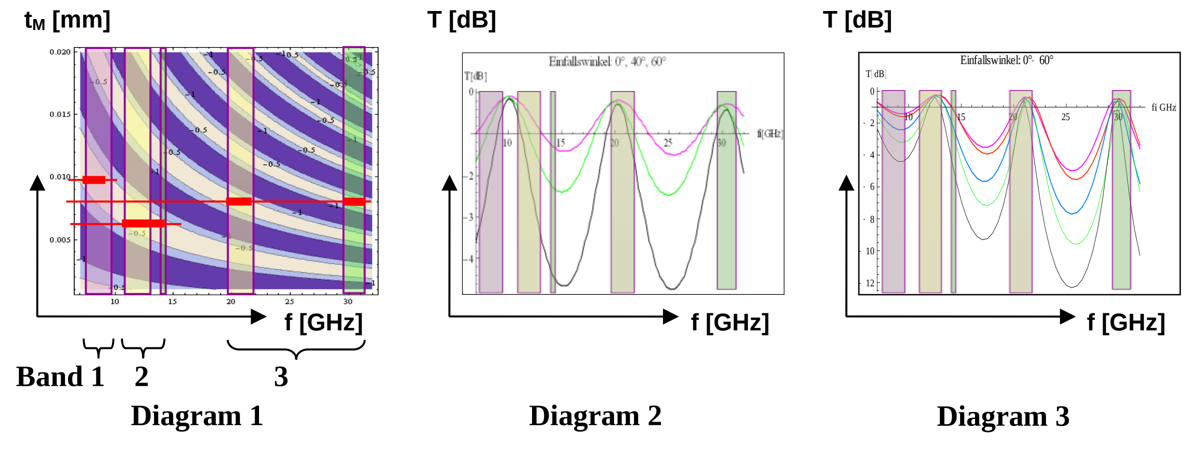

Figure 3. Monolithic and A-Sandwich calculated transmissivity examples

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Diagram 1 in Figure 4 shows a contour plot with a good solution in band 3 (A2 – configuration) for an A-SW with thick coversheets ($\mathbf{t_S}$ ca. 2.2mm) for **θ = 0°**.
Diagram 2 shows transmissivity over **f** for the core thickness indicated in Diagram 1 ($\mathbf{t_C}$ = 5,5mm). Note the possibility of increased up-link bandwidth. The curves show transmissivity for **θ = 0°, θ = 20°, θ = 40** and for **θ = 60°** (black curve).
Diagram 3 in Figure 4 shows the transmissivity for a C-SW configuration (in this case C1). The curves stand for **θ** = 0°, 20°, 40° and 60°. The C1 configuration promises excellent transmission properties in a bandwidth comprising band 1 and 2 for all relevant angles of incidence. Relevant thicknesses for C1 are: t_S = 1mm; t_{cS} = 2,0 – 2,4mm; t_C = 4-5mm (denomination in Figure 2).

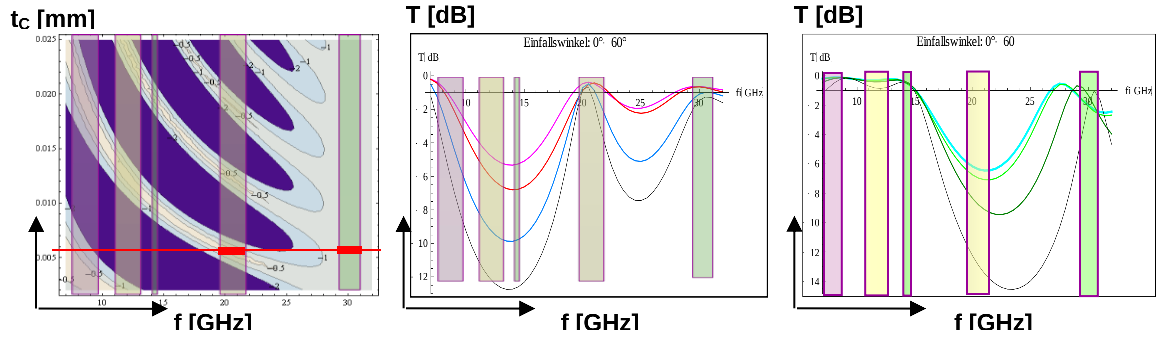

Diagram 1 **Diagram 2** **Diagram 3**

Figure 4. A-Sandwich (A2) and C-Sandwich (C1) transmissivity examples (diagram 3 for C1)

A weight evaluation of different configurations is shown in Figure 5. The EM transmission quality of the found solutions is not represented.

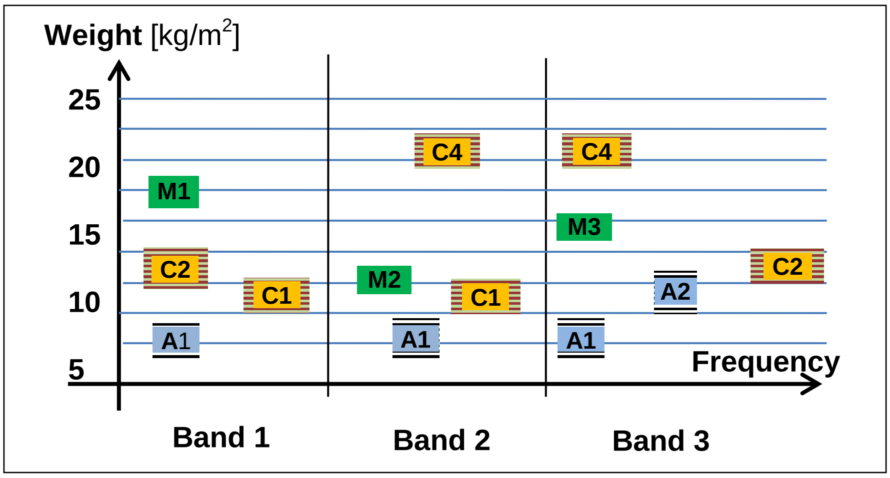

Figure 5. Weight distribution of different radome configurations

The different solutions have a great weight variation. If the monolithic versions (M1, M2 and M3, see Diagram 1 in Figure 3) are rejected partly because of excess weight, the C4 configuration is not an option. Figure 5 also indicates that except A1 no solution is found with acceptable transmissivity in all

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three frequency bands. But this has to be checked with more precise calculation tools and validation experiments.

From the electromagnetic point of view the C1 configuration is a very good alternative for band 1and band 2. This has also been confirmed by EM-measurements on a specimen manufactured by DLR-FA in Braunschweig.

4. Investigations of Major Aspects

The A1 configuration seems to be the only radome design that works (with restrictions in terms of transmissivity) at the same time in all three frequency bands. Nevertheless A1 has the potential to be adapted better for band 2 or band 1 if band 3 would be excluded due to unfulfilled requirements. In that case more than one radome type has to be used to serve all three frequency bands. Therefore A1 is selected as the basis for the analysis of component characteristics not only belonging to EM transparency. Damage tolerance, lightning protection and 3-D electromagnetic calculations were identified as important aspects necessary to comply with aircraft requirements. Therefore specimens for impact testing and lightning protection have been manufactured at DLR-BT in Stuttgart.

4.1. **Impact Behavior**

Different levels of impact tests have been performed and analyzed.

A1-configuration sandwich coupons (100mm x 150mm) have been built for Compression After Impact (CAI) testing according to the Airbus standard. First, the specimens have been impacted and evaluated for remaining indentation and for internal damage by different NDT-methods. In a second step CAI residual strength has been determined.

The results of the test program are summarized in Figure 6. The two diagrams show the indentation depth for any tested specimen and their CAI-strength. The different test parameters may be identified by the mark's color, size and shape:

- Specimen conditioning at 70°C 85% r.h. is differentiated by color. Red marks symbolize conditioned specimens and blue marks stand for unconditioned specimens.
- Impactor of 25mm and 16mm sphere diameter were used and are characterized in the diagram by big or small marks.
- Air tightness after impact was tested in a warm water bath and tight specimens are marked by a closed symbol (circle or square in opposite to a cross) .
- Material: in addition to the baseline configuration with quartz-glass-epoxy prepreg cover sheets and 48 kg/m^3 Nomex honeycomb, specimens with Rohacell HERO 71 foam core and infiltrated S2-glass-epoxy were tested as an alternative material and processing configuration. These specimens may be identified by the "Imp-u-RH-71" mark in the legend.

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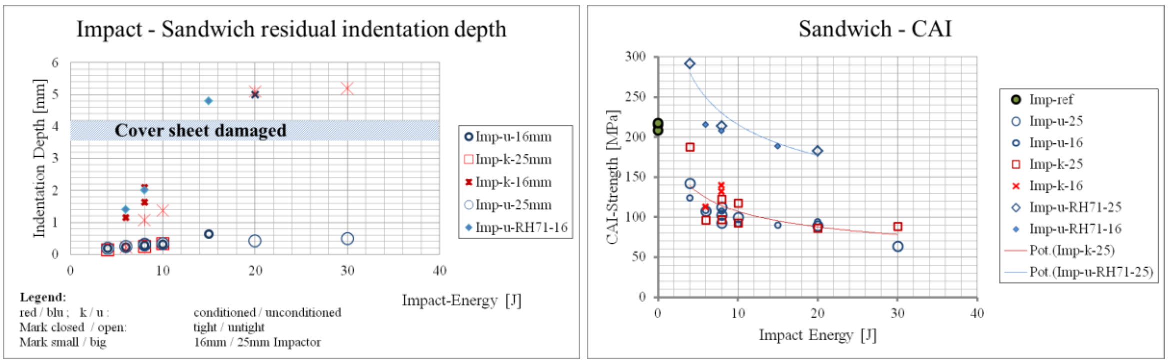

Figure 6. Indentation depth and CAI-strength

The intention of the indentation depth measurement is to identify the BVID (Barely Visible Impact Damage) threshold impact energy as an indicator for inspection necessity. As can be seen in the left diagram of Figure 6, the indentation depth of several specimens, even at high energies remain below 1mm which is defined as the criteria for visibility.

At the same time NDT (Non Destructive Testing) analysis by µ-CT and ultrasonic testing show some core damage which is not visible from the outside, see upper specimen in Figure 7.

According to the Damage Tolerance philosophy, a structure with an undetectable damage shall withstand ultimate loads till end of life of the aircraft. The CAI-tests, right hand diagram of Figure 6, indicate a strength reduction of 50% to 70% which may be acceptable if the component has the according reserve factors.

Nevertheless it has to be shown that damage is not growing and there are no other deteriorating influences like water ingress which may be caused by untight cover sheets.

Hail impact tests in the style of [2] with respect to hail stone sizes and impact patterns have been performed at the IABG Lichtenau test range on unconditioned flat (300 mm x 300 mm, 600 mm x 600 mm) and cylindrical (approx. 500 mm x 500 mm, outer radius: 550 mm) specimens and with different grain sizes (Table 2) at an impact angle of 40° versus the surface normal of the specimens. From outside no damage could be observed, even at the higher energies. But µ-CT and ultrasonic inspections, see Figure 8, revealed core damages similar to the CAI-specimens.

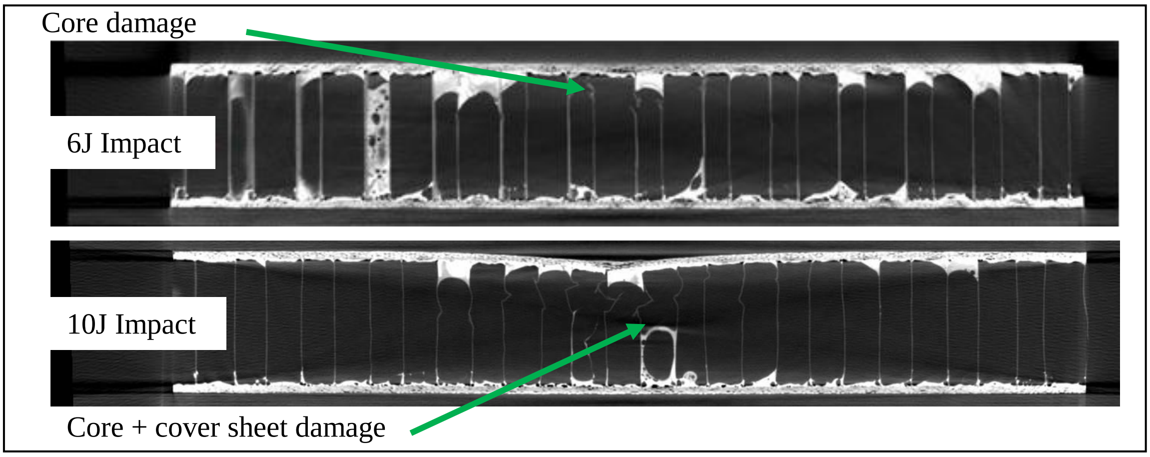

Figure 7. Cross sectional µ-CT images, showing the damages of two conditioned impact specimens

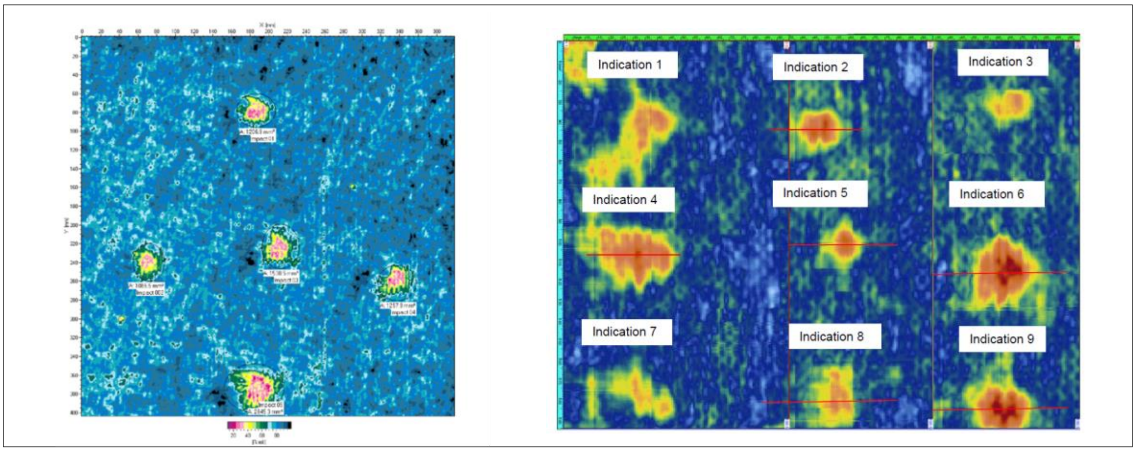

Figure 8. Ultrasonic C-images with indications, showing surface indentations caused by hail impact of hailstones with diameters of 50mm (left side) and 25mm (right side)

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Table 2. Hail test parameters

Hail diameter [mm]	13	25	50
Mean mass [g]	1,1	7,5	60,2
Mean impact velocity [m/s]	80	80	80
E_{tot} [J]	3,39	24,1	192,7
E_{perp} [J]	1,99	14,1	113,1

4.2. EM 3-D Analysis

As described in chapter 3, thickness design of the sandwich layers is performed with simplified models assuming plane surfaces and plane waves. The method is good enough for selecting the design candidates and to get an overview of the EM performance, but for realistic conclusions it is necessary to consider the real radome geometry and an adequate antenna diagram. First calculations with the appropriate complex 3-D-software indicate, that there will be challenges with the band 3 frequencies to meet the ITU regulations because of increased side lobes.
If this will be confirmed, it is not possible to operate one radome at all three frequency bands. Then A1 still has the potential to be adapted e.g. for band two in order to increase transmissivity in the up-link band.

4.3. Lightning Protection

Lightning strike protection shall prevent an electric breakdown of the radome shell which would lead to the damage of the antenna and other components. The task implies knowledge about the material and sandwich design behavior under high voltage. A first step was the measurement of dielectric strength on 300mm x 300mm specimens. In a second step, envisaged divertor stripes were analyzed to evaluate ignition voltage and to estimate the maximum possible length that can be used on the radome.

5. Summary and Outlook

Radomes as large sized composite structures with ambitious multidisciplinary requirements were successfully elaborated in a collaborating network of institutes and industry. Electromagnetic transmission calculations were performed to find suitable solutions. The selection of an A-sandwich configuration with adequate materials and a suitable manufacturing process allowed the production of specimens for an extensive test program. The influence of impact / hail on damage tolerance could be evaluated, as well as electromagnetic transmission and lightning strike parameters. The tests confirmed in principle the A-sandwich selection even if there are still challenges at the higher frequency bands.
The next steps will prove the transferability of the achieved results on large double curved shells.

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