

Shielded Aircraft Windows to Protect Radio Altimeters in the Presence of Wireless Avionics Intra-Communication

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Abstract—Wireless Avionics Intra-Communications in the frequency range of 4.2 to 4.4 GHz is an upcoming solution to replace the cabling of part of the data network in aircraft with a wireless alternative. This solution shares its frequency band with the radio altimeter and is therefore subject to limitations on the transmitted power to ensure compatibility with flight critical equipment of the aircraft. This paper presents simulation results on the effectiveness of shielded aircraft windows to protect radio altimeters in the presence of wireless avionics intra-communication. A propagation model is developed to simulate how shielded cabin windows affect the EIRP of WAIC transmitters within the cabin of an aircraft. Simulation with this model show that a reduction in EIRP of roughly 15 dB can be expected when electromagnetic coating is applied to the passenger windows. These results can be used in the design of robust WAIC network solutions that are compatible with legacy aircraft equipment.

Keywords—wireless avionics intra-communications, shielded windows, radio altimeter, electromagnetic compatibility, electromagnetic propagation simulation

I. INTRODUCTION

Aviation industry experiences an everlasting quest for weight reduction, with the intent to suppress fuel burn and emission of greenhouse gasses, as well as decreasing operational cost. This has led to a trend of electrification of many on-board systems, which is reinforced by the current developments around sustainable aviation. Inherently, such developments imply drastic increases in the weight and complexity of data networks on-board modern aircraft.

The Horizon 2020 project ADENEAS (Advanced Data and power Electrical Network Architectures and Systems) targets the development of technologies that enable development of a safe, light, self-configuring, autonomous and modular power and data distribution network scalable to all aircraft sizes. One of the targeted enabling technologies involves Wireless Avionics Intra-Communications (WAIC), in which wireless technologies are used to replace conventional cabling in parts of the data network, with the intent to decrease the weight of an Electrical Wiring Interconnection System (EWIS).

Two of the major challenges in the deployment of wireless technologies for avionics functions on-board aircraft are reliability and compatibility with legacy aircraft equipment. WAIC working groups have established frequency allocation for deployment in aircraft [1] [2], allowing the use of wireless

technologies in the frequency range 4.2 – 4.4 GHz. One of the most sensitive and critical on-board legacy equipment that shares the same frequency band is the radio altimeter [3]. Requirements have to be set on performance characteristics of WAIC, for instance transmit power, to prevent disturbing the radio altimeter at all times. EUROCAE WG-96 on wireless on-board avionics networks is working on appropriate Minimum Operational Standards (MOPS) and Minimum Aviation System Performance Standards (MASPS) that should guide the development of safe WAIC.

Considerations include to limit the Effective Isotropic Radiated Power (EIRP) of the aircraft in which WAIC is in operation. This quantity concerns a combination of WAIC transmit power and potential fuselage attenuation.

Measurements of in-cabin wireless networks have been done on wireless connectivity for personal passenger devices such as in [4] and [5], or focusing on in-flight entertainment systems in [6]. Prediction models have also been developed for in-cabin wireless devices such as [7] and [8]. These wireless solutions do not share a frequency band with sensitive on-board equipment.

This paper discusses the benefits of using EM shielded windows for on-board WAIC systems. To that extent, multilayer properties of shielded windows with and without appropriate shielding are extracted from simulations with the in-house developed software Layer. These properties are subsequently used in propagation simulations with Altair Winprop of transmitters in the cabin of an aircraft fuselage. Differences in EIRP with and without shielded windows are compared to draw conclusions on possible increase in allowed transmit power when WAIC is combined with shielded windows.

The following section introduces properties of shielded windows, including build-up of layers as well as simulation of electromagnetic characteristics. Thereafter, section 0 discusses the EM propagation simulation model created in Winprop. Section IV will discuss simulation results, after which Section V will give the conclusions.

II. PROPERTIES OF SHIELDED AIRCRAFT WINDOWS

To incorporate effects of shielded windows in propagation simulations with Altair WinProp, either transmission and reflection coefficients, or permittivity and permeability values of the material are required. This section introduces these for both a typical conventional configuration and for shielded aircraft windows. The conventional configuration is used for

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comparison of results, but also as base for the shielded window design.

A. Typical aircraft window assembly

A typical window model that is common in conventional aircraft is shown in Fig. 1 [9]. It is a multilayer structure comprised of an outer pane, middle pane and scratch pane, separated by air gaps. The panes are modelled as polymethyl methacrylate (PMMA) which is a polymer, commonly used for aircraft widows [10].

B. Shielded aircraft window

Although PMMA has many advantages like being light weight and having good optical transmittance, the material performs poorly with respect to electromagnetic (EM) shielding. PMMA has a low permittivity, $\epsilon_r = 2.7$, and loss tangent, $\tan \delta = 0.005$, which allows good propagation of EM energy with limited attenuation. When it comes to the application of WAIC, lower transmission is desired, which can be obtained by applying a thin conductive coating to the PMMA surface, e.g. Indium Tin Oxide (ITO). ITO is an attractive candidate due to the unique combination of high electrical conductivity and high optical transmittance in the visual region of the electromagnetic spectrum [11].

The effect of an additional conducting film on the transmission through a multilayer PMMA based window was studied using the simulation tool Layer. Layer is a MATLAB-based research tool, developed internally at NLR, and is used for the simulation of infinitely large, flat, multilayer structures. It is based on a transmission line transfer matrix method and calculates reflection and transmission coefficients using material properties and layer thicknesses [12]. Within Layer, the conductive film is included in the aircraft window model as an additional layer characterized by a specific sheet resistivity which was set to be $15 \Omega/\text{sq}$. As the airplane window model consists of three separate PMMA panes, the conductive film could be applied at six different positions. The shielding effectiveness of applying the conducting film at each position is calculated and compared.

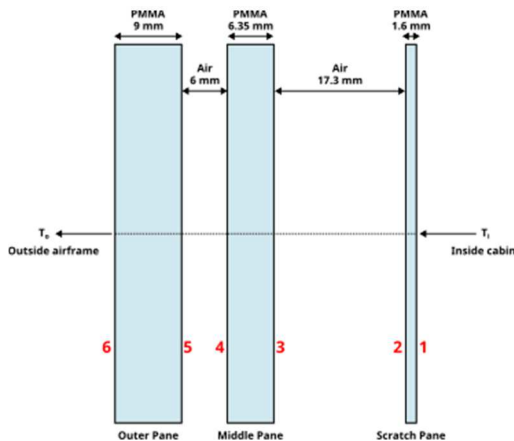


Fig. 1. Aircraft window model based on a typical multilayer assembly. The red numbers indicate the six different interfaces at which a conductive film for shielding can be applied.

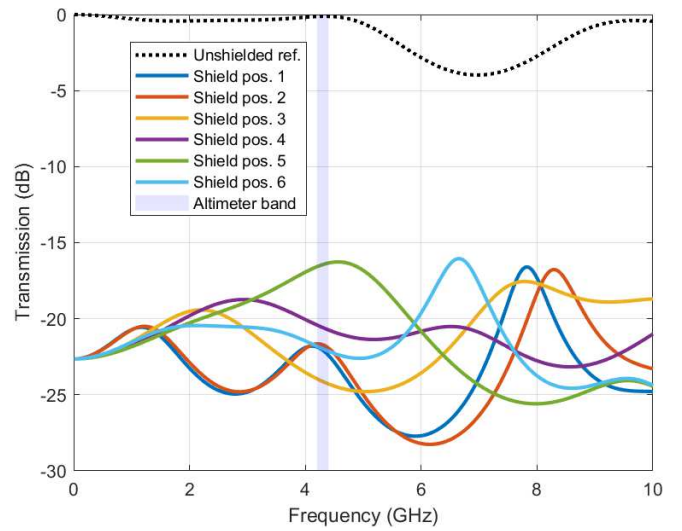


Fig. 2. Transmission of unshielded (dotted line) and six different shielded window configurations. The numbers in the legend refer to the interfaces labeled in Fig. 1.

C. Attenuation simulation results

The simulation results are shown in Fig. 2 in which the transmission through various airplane window configurations is plotted as a function of frequency. The solid curves represent the transmission through shielded windows, with the conducting film applied at different positions. The dotted curve represents the transmission through an unshielded window for comparison. The shaded blue area indicates the WAIC frequency range, i.e. 4.2 MHz to 4.4 MHz. The results confirm that shielding can be accomplished using a conductive film, as the average transmission through the shielded windows is found to be approximately 20 dB lower compared to the unshielded window. Additionally, the figure illustrates that the position of the conducting film has a significant impact on shielding performance. At 6.5 GHz, the transmission can be decreased by more than 10 dB by placing the conductive film at position 2 instead of position 6. When considering WAIC frequencies, and the protection of the radio altimeter, the conductive film is most effective when applied at position 3 which results in a transmission of approximately -24 dB at 4.3 GHz.

D. Equivalent single layer structure

The next step is to implement the optimal shielded window configuration in the Altair WinProp simulation software. Unfortunately, Altair WinProp does not support the implementation of multilayer structures [13]. This issue is solved by defining an equivalent single layer model with artificial material properties. The material properties should be chosen such that the propagation properties of the single layer model are identical to the propagation properties of the shielded multilayer structure at normal incidence and at the frequency of interest.

The single layer model is defined by the following parameters: layer thickness t , relative permittivity ϵ_r , relative permeability μ_r and electrical conductivity σ . For this study, the material is assumed to be non-magnetic, i.e. $\mu_r = 1$, and the layer thickness is set to be $t = 15$ mm. The goal is to fit the permittivity and conductivity using the propagation properties of the multilayer structure as input. Instead of fitting the transmission, reflection and absorption separately, the three were combined into a single objective function f :

$$f(\sigma, \epsilon_r) = \sqrt{(T_S(\sigma, \epsilon_r) - T_M)^2 + (R_S(\sigma, \epsilon_r) - R_M)^2 + (A_S(\sigma, \epsilon_r) - A_M)^2} \quad (1)$$

This is the 2-norm of the difference between the transmitted (T), reflected (R) and absorbed (A) power of the multilayer structure and the transmitted, reflected and absorbed power of the single layer structure for a specific combination of σ and ϵ_r . The subscripts S and M denote the single layer model and the multilayer model, respectively. The objective function was minimized at 4.3 GHz. Using this approach, the relative permittivity and conductivity of the artificial material were found to be $\epsilon_r = 505$ and $\sigma = 7.1$ S/m respectively. Note that a material with a permittivity of 505 is unrealistic, however the intent of the single layer model is to reflect transmission and reflection properties, not to represent physical material. The high permittivity is simply an artifact caused by the fact that the propagation properties of a complex multilayer structure should be mimicked by a single dielectric.

The propagation properties of the equivalent single layer structure with optimized properties ($\epsilon_r = 505$, $\sigma = 7.1$ S/m) were calculated and compared to the propagation properties of the shielded multilayer structure. The results are shown in Fig. 3. As designed, the propagation properties of both models are found to match at 4.3 GHz. It should be noted that the material properties of the single layer structure were fitted to the multilayer structure propagation properties at normal incidence. This means that, in general, the propagation properties of both models do not exactly match at oblique angles of incidence. After analysis this error was found to increase with the angle of incidence, and was found to be limited by approximately 3 dB for all angles.

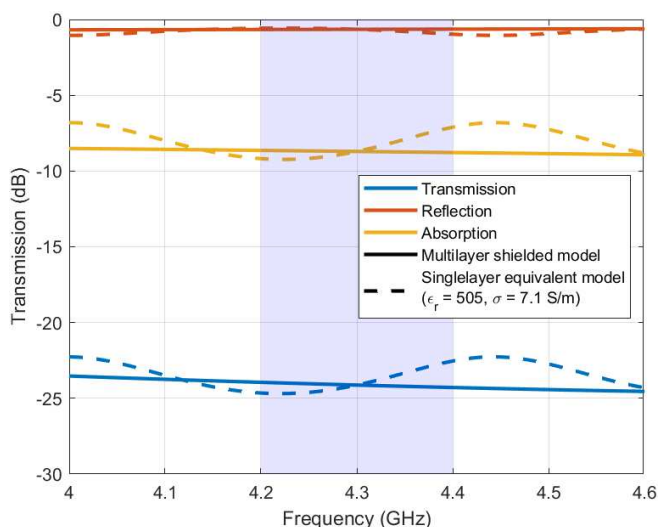


Fig. 3. Propagation coefficients of the shielded multilayer airplane window model (solid line) compared to the equivalent single layer model (dashed line)



Fig. 4. Aircraft CAD model used for the propagation simulations

III. SIMULATION OF EM PROPAGATION IN AN AIRCRAFT FUSELAGE

Propagation of the electromagnetic fields in and around an aircraft have been simulated with Altair WinProp (part of Altair Feko [13]). WinProp uses a Standard Ray Tracing (SRT) solver to simulate propagation in structures much larger than the wavelength. Electromagnetic full-wave solvers, such as finite element methods and method of moments solvers, would require large amounts of time and memory for such simulations. An SRT solver gives a significant improvement in terms of those requirements for computation time and memory. This section introduces the computer-aided design (CAD) model used in the simulations and the setup of the simulations in WinProp.

A. CAD model

The simulations in this paper were performed with a modified CAD model of an existing aircraft. The resulting model is shown in Fig. 4. The fuselage of the model includes elements that are most relevant for the propagational behavior of the WAIC signals, i.e. the cabin and cockpit windows, as well as the wings. Details that do not affect the propagation simulations, such as protruding antennas and sensors on the exterior of the fuselage, were omitted for simplicity of the model. The interior of the aircraft is filled with chairs and a cabin floor as shown in Fig. 5. Chairs are included in the model since they have a significant role in the distortion of the radio propagation in the cabin. Due to the properties of the chairs they will absorb part of the energy that is transmitted in the cabin. Passengers are also expected to affect the field distribution in the cabin. However, in view of the added complexity, these have been omitted in this paper. The intention is to include the effects of passengers, both static in their seats as well as moving in the cabin, in future work.

One of the advantages of the SRT solver is that the size of the mesh elements can be chosen independent of the frequencies of interest. The main importance is that the geometry is represented well. Therefore, in general, this method requires less mesh elements, which results in a significant reduction of computational effort and time.

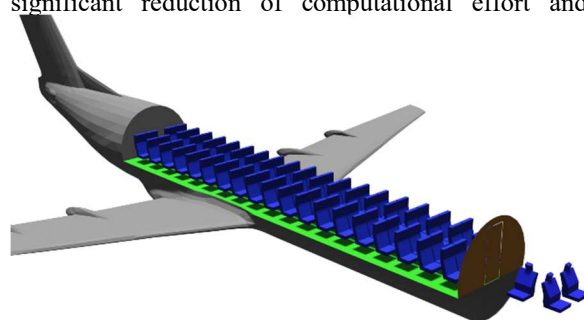


Fig. 5. Interior of the aircraft CAD model.

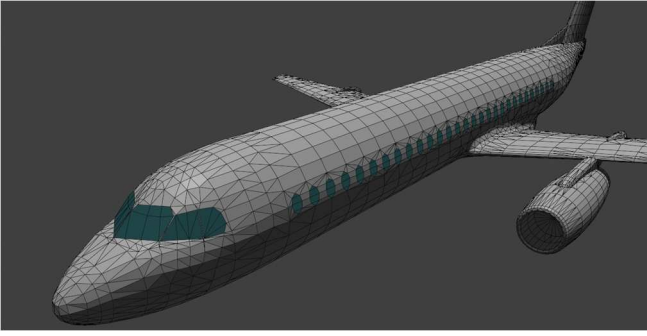


Fig. 6. Mesh elements for aircraft CAD model

The mesh elements of the model are chosen as coarse as possible without compromising the overall shape of the aircraft. This resulted in a mesh with 10039 elements. The corresponding mesh is shown in Fig. 6. Areas that require a higher level of detail, e.g. the cockpit, have smaller mesh elements to ensure that the model accurately represent the geometry of the aircraft.

B. Simulation setup

The effect of the aircraft fuselage on the radiated power of a transmitter was determined by simulating a 0 dBm EIRP omnidirectional transmitter in the fuselage and computing the field strength of the transmitter in a sphere of 5 km centred around the transmitter. The transmitter is positioned at one of the six positions (A1 to A6) in the cabin shown in Fig. 7. The radiated power was then derived from the field strength. The radiated power depends on the angle of emission and takes into account attenuation introduced by aircraft fuselage. The radiated power is computed for all directions around the aircraft. EIRP is then defined as the maximum radiated power over all computed angles.

The effectiveness of an ITO coating on the cabin windows was studied comparing a simulation model in which an ITO coating was applied with a reference model in which no coating was applied on the cabin windows. In the case including ITO the equivalent single layer structure with ($\epsilon_r = 505$, $\sigma = 7.1$ S/m) was applied to replicate the behaviour of an ITO coated cabin window. The reference model uses acrylic as material for the cabin windows.

IV. SIMULATION RESULTS

The simulated radiated power of transmitter inside the fuselage is shown in Fig. 8. The transmitter was placed in the cargo area in the front of the aircraft (position A1 in Fig. 7). The radiated power outside of the fuselage is largest along the sides of the aircraft and weakest in the direction of the tail of the aircraft. This is caused by the windows along the sides of the aircraft. Moreover, the fuselage shows a focussing (or beamforming) effect on the radiated power of the transmitter which can increase the radiated power at some angles above the transmitted 0 dBm.

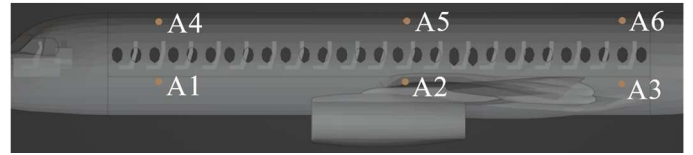


Fig. 7. Location of the WAIC transmitters inside the fuselage.

When ITO shielding is applied to the cabin windows, an overall reduction in radiated power is observed. The reduction in radiated power is not uniform in all directions around the aircraft, rather, the reduction in radiated power is most notable along the sides of the aircraft where the windows are. The reduction of radiated power along the sides of the aircraft is about 20 dB, which corresponds well with the transmission and reflection results of the multilayer model described in section II.C. Radiated power in the direction of the cabin or tail of the aircraft are practically unaffected by the ITO shielding on the cabin windows.

The simulated radiated power can be extended to a full sphere around the aircraft. The results of these simulations are shown in Fig. 9 for the reference aircraft with no shielding and in Fig. 10 for an aircraft with ITO shielding on the cabin windows.

The radiated power results in Fig. 9 show a strong contribution to the total radiated power by radiation through the cabin windows. The regularly spaced pattern and the oval shape of the cabin windows are clearly visible in the results (see for instance at roughly 0 degrees azimuth and 25 degrees elevation). The angular positions of the windows in the results correspond with line of sight transmission of the WAIC transmitter, which is placed below the cabin windows. A comparison of the results in Fig. 9 to Fig. 10 shows an overall reduction of the contribution to radiated power by the cabin windows. The reduction of radiated power through the cabin window is roughly 20 dB.

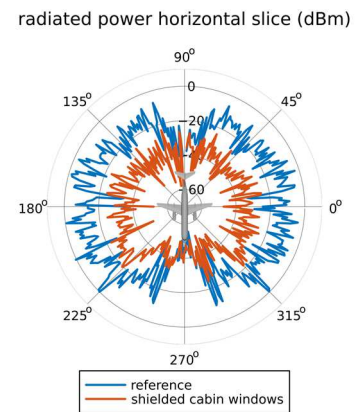


Fig. 8. Simulated radiated power for reference case (blue) and case with shielded windows (red) in the horizontal plane of transmitter. Cockpit of the aircraft is located at 270 degrees.

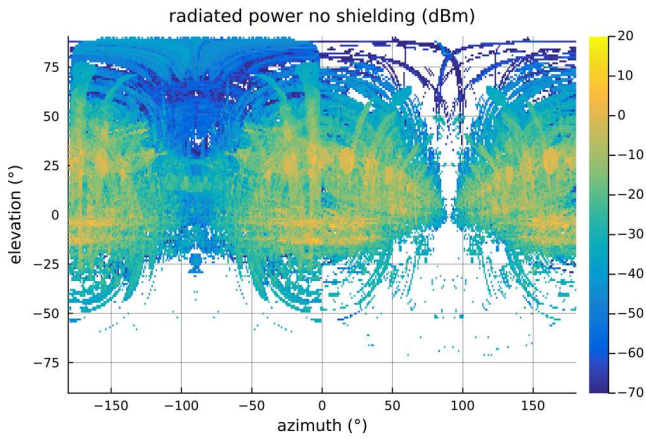


Fig. 9. Radiated power of transmitter in aircraft with no ITO shielding on cabin windows. Cockpit is directed at -90 azimuth and 0 elevation. The tail of the aircraft is directed at 90 degrees azimuth and 0 degrees elevation. WAIC transmitter is set at 0 dBm EIRP.

The results in Fig. 9 and Fig. 10 can be used to derive the EIRP of the WAIC transmitter after interactions of the radio waves with the fuselage of the aircraft. This is done by finding the maximum value of the radiated power. The EIRP of the non-shielded model was found to be 10.8 dBm. The positive sign of the EIRP implies that the fuselage has a focusing effect on the radiation pattern of WAIC antennas placed within the fuselage. The EIRP of the shielded model is -12.0 dBm.

A. Placement of the WAIC transmitter

The effect of the fuselage on the radiated power and EIRP of the WAIC transmitter depends on the placement of the transmitter. This was simulated by placing a transmitter at several key locations in the fuselage. The locations represent the most likely position of the WAIC gateways in the fuselage, which will be either in the crown of the fuselage, or beneath the cabin floor. Furthermore, transmitters were placed in the front, centre and back of the fuselage. The transmitter locations are shown in Fig. 6.

TABLE I. REDUCTION OF RADIATED POWER AND EIRP DUE TO ITO SHIELDING ON CABIN WINDOWS.

Transmitter position	EIRP reference (dBm)	EIRP shielded (dBm)	Average reduction in radiated power (dB)
A1	10.8	-12.0	17.0
A2	12.9	-4.7	20.0
A3	11.7	-3.2	21.2
A4	7.1	-2.3	18.7
A5	11.8	-0.2	20.2
A6	10.5	0.0	20.2

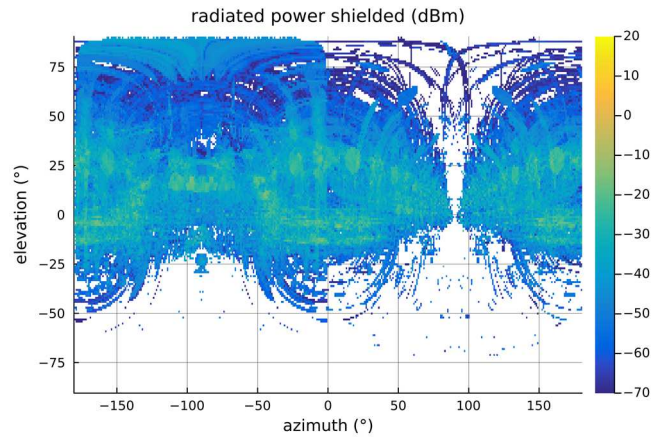


Fig. 10. Radiated power of transmitter in aircraft with ITO shielding on cabin windows. Cockpit is directed at -90 azimuth and 0 elevation. The tail of the aircraft is directed at 90 degrees azimuth and 0 degrees elevation. WAIC transmitter is set at 0 dBm EIRP.

The EIRP for the transmitters was determined by finding the maximum of the simulated directional radiated power. The resulting EIRP values for both the non-shielded and shielded cases are shown in TABLE I, together with the average radiated power reduction over all simulated angles. These results show that, on average, a reduction of 20 dB can be expected for the radiated power of the transmitter regardless of the position of the transmitter. Note that the reduction in radiated power is computed by subtracting the radiated power of the shielded case from the radiated power of the non-shielded case, for each angle. The maximum radiated power for each case might however be at different angles. Therefore, the reduction in radiated power does not directly translate into the same reduction in EIRP. These simulations have been repeated at the edges of the WAIC frequency band at 4.2 and 4.4 GHz. The results at the edges of the band are similar to the centre band results.

When no shielding is applied to the cabin windows, the EIRP of WAIC transmitters in the cabin increases by roughly 10 dB due to interactions with the fuselage. However, with EM shielding applied, the EIRP of the transmitters decreases by roughly 5 dB. The net effect of the EM shield on the EIRP of the WAIC transmitters is about 15 dB, which is 5 dB less than the overall reduction expected from the multilayer simulations. The reason for this discrepancy is that line of sight transmission through the cabin windows are the main contributors to EIRP for the reference model, but not for the shielded model. The EM shielded model reduces the transmission through the cabin windows, but increases the power reflected by the windows. These reflections can, in some cases, slightly increase the radiated power for non-line of sight propagation paths.

V. CONCLUSIONS

The effectiveness of ITO coated cabin windows in reducing radiated power of aircraft in presence of on-board WAIC transmitters is determined. It can be concluded that that transmission through shielded windows is 20 dB lower compared to unshielded window. Moreover, it can be concluded that the position of the coating within the layer build-up of the cabin window has a significant effect on the shielding performance.

The shielded multi-layer cabin window has been simplified to artificial single layer material with $\epsilon_r = 505$, $\sigma = 7.1$ S/m, which is unrealistic for a single layer material, but accurately reproduces the behavior of the multilayer shielded cabin window in WinProp.

A Standard Ray Tracing solver was used to determine the effectiveness of coated cabin windows as a means to reduce the EIRP of WAIC transmitters. These simulations were performed using a simplified aircraft model with chairs on the inside of the cabin. The simulation results show that EM coating on the cabin windows reduces the transmitted power, on average, by about 20 dB. The reduction in average radiated power does not directly lead to a reduction of 20 dB in EIRP. Instead, EM shielded windows reduce the EIRP of a WAIC transmitter in an aircraft by 9 to 23 dB depending on the placement of the transmitter.

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