Towards Structural Integration of Airborne Ku-band SatCom Antenna

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***Abstract*— The paper describes research towards a fully structurally integrated Ku-band SatCom antenna. This antenna covers the complete receive band for aeronautical earth stations and DVB-S broadcast in Ku band (10.7 – 12.75 GHz). The antenna front-end consists of 32 tiles where each tile has 8x8 Ku-band stacked patch antenna elements. Optical True Time Delays (TTDs) in an Optical Beam Forming Network (OBFN) enable a squint free beam steering over the whole band to geostationary satellites. The Ku-band antenna itself covers the whole frequency band in input impedance matching and radiation pattern. The performance of a Ku-band antenna tile will be discussed. A design is presented for the structural integration of 32 tiles and the associated optical beam forming networks into a fuselage panel of an aircraft.**

***Index Terms*— aircraft antennas , antenna arrays , array signal processing , satellite communication , structural integration, opto-elctronic beam forming**

I. INTRODUCTION

In aviation novel avionics communication systems are required for increasing flight safety and operational integrity, for optimizing economy of operations and for enhancing passenger services. An essential part of these communication systems is a so-called high-gain directional antenna, for example a dish antenna. Such a high-gain directional antenna has to be continuously steered to geostationary satellites. In the past Lufthansa installed mechanically steered dish antennas on top of the fuselage (see Figure 1), with a large protective radome.

Figure 1 Installation mechanically steerable dish antenna

The use of steerable dish antennas has a number of objections. The radome increases the aerodynamic drag and requires additional piercing of the aircraft skin as well as additional stiffeners in the fuselage structure. The radome was installed on a Lufthansa A340. Preliminary calculations reveal an increase of drag by 1.2 %. Furthermore, mechanical parts of the steering mechanism can break down and require regular maintenance.

The alternative to a steerable satellite dish is a panel with an integrated phased array antenna. Such an antenna consists of a number of tiles which in turn contains a number of Ku-band antenna elements. The tiles and antenna elements can be steered either using RF-phase shifters or broadband true time delays (electronic or opto-electronic delays) such that the bundle of the phased array antenna can be steered continuously during the flight in the direction of geostationary satellites. With respect to the required antenna performance (such as antenna gain and beam width), the angle between the normal of the tiles and the direction of antenna to satellite should not be too large (glancing angle of incidence). This can be achieved in two ways: 1. by tilting the antenna tiles towards the satellite, or 2. by placing two antenna panels on both sides of the fuselage such that the antenna with the lowest glancing angle is used for communication (see [1]).

II. TOWARDS STRUCTURALLY EMBEDDED ANTENNAS

The concept of tilting the antenna tiles leads to a hybrid approach, where multiple rows of Ku-band antenna tiles are placed on a rotating disk (electronic control in elevation, mechanical steering in azimuth direction). An example of a hybrid antenna is shown in Figure 2. These hybrid antennas must still be equipped with a radome and still have mechanically moveable parts. The height of the radome of hybrid antennas is lower than that of dish antennas, but these radomes still cause aerodynamic drag. From a technical point of view the most promising concept seems therefore the installation of two thin conformal panels with Ku-band antenna tiles on both sides of the fuselage. This concept can be achieved in two ways; (1) as an add-on panel (with minimal thickness) on the outer side of the fuselage (see Figure 3) or (2) by means of integration of tiles into the fuselage of the aircraft (see Figure 4).

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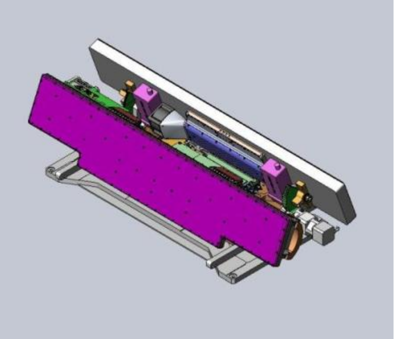

Figure 2 Hybrid antenna of Panasonic

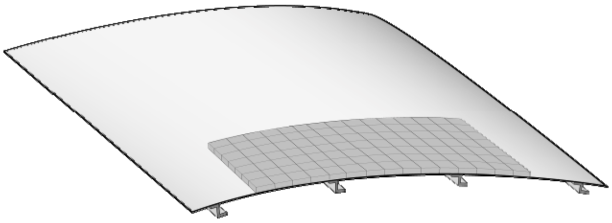

Figure 3 Faceted antenna array add-on fuselage

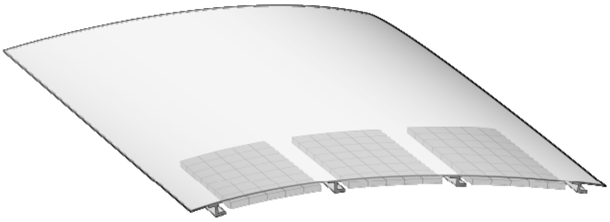

Figure 4 Faceted array, embedded in fuselage behind transparent RF skin

III. KU-BAND ANTENNA TILES

The development of the Ku-band phased array has been described in [2] and [3]. The array consists of several hundreds of broadband antenna elements. The beam direction of this phased array antenna is controlled with Optical Beam Forming Networks (OBFN). The research and development of this array antenna has been has been carried out in the EU FP7 project SANDRA (Seamless Aeronautical Networking through integration of Data links, Radios, and Antennas). The architecture of the SANDRA Ku-band antenna consists of 32 tiles of 64 Ku-band antenna elements, where each tile has its own OBFN. Details on the architecture have been presented in [2],[3] .The dimensions of a single tile are 9x9 cm^2 with a height of approximately 3 cm. Each Ku-band antenna tile contains three main sub-modules: antenna front end, board with electro-optical interface and a 16x1 OBFN. The goal is to develop antenna tiles with sufficient structural integrity in order to integrate these tiles into a pressurized fuselage panel so that loads on electronic components are minimised. Such a structurally integrated antenna will satisfy new ARINC 791 standards for Ku and Ka airborne SATCOM, which require the placement of advanced electronics inside pressurised aircraft structures (see [5]).

A. CAD geometry

The CAD geometry of a single Ku-band antenna tile (as developed in EC project SANDRA) is displayed in Figure 5. The front end of this tile has 8x8 Ku-band stacked patch antennas.

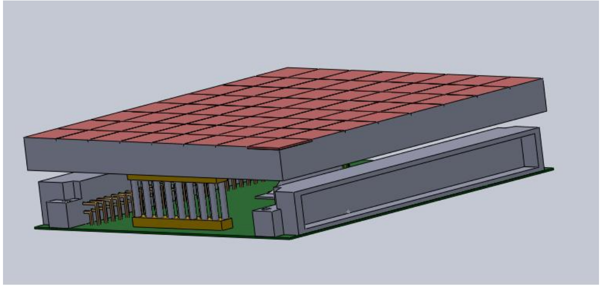

Figure 5 Geometry of Ku-band antenna tile with antenna front-end, Optical beam forming and Electro-optical conversion

The design of SANDRA Ku-band antenna tiles needs to be optimised to balance required mechanical strength, antenna properties and cooling of electronic components. The thickness of the tiles needs to be minimized for structural integration. The structural design of the fuselage panel has to satisfy challenging antenna integration requirements. But, also the design of the Ku-band antenna array has to comply with structural strength and has to take into account geometrical structural constraints.

B. Antenna measurments

A prototype of the antenna front end has been manufactured. The S-parameters of the measurements are shown in Figure 7 and Figure 8.

E1	E2	E3	E4
E5	E6	E7	E8
E9	E10	E11	E12
E13	E14	E15	E16

Figure 6 Layout of the 4x4 antenna array.

In Figure 7 the return loss (S11) has been measured of the individual antenna elements of a 4x4 element array embedded in a tile with the size of an 8x8 element array (Figure 6). Each antenna element has two outputs with orthogonal polarisation. Only one output has been measured, the other output was terminated with a 50 ohm load. The behaviour of the centre elements (E6, E7, E10 and E11) and the edge elements is quite similar. The requirement is to have a minimum return loss of -10 dB in the frequency range 10.7 GHz to 12.75 GHz. Although simulations show that this requirement can be met over the whole band, this is not fully achieved yet in this prototype. More prototypes are currently being made to find the parameters responsible for this deviation.

In Figure 8 the results are shown of the mutual coupling measured between the antenna elements. The measurements show that coupling in one plane (E6-E7, E10-E11) is smaller than in the other plane (E6-E10). The coupling in the diagonal directions is the smallest (E6-E11), as could be expected.

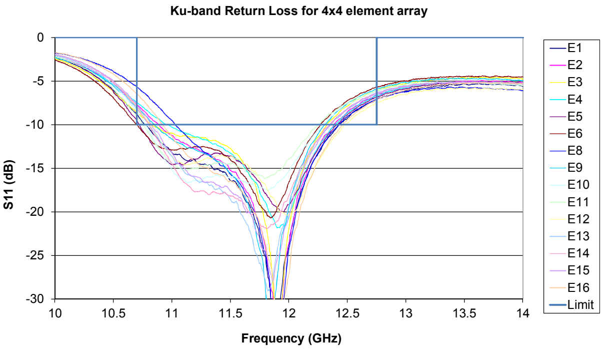

Figure 7 Return loss measurement of individual antenna elements of 4x4 antenna array.

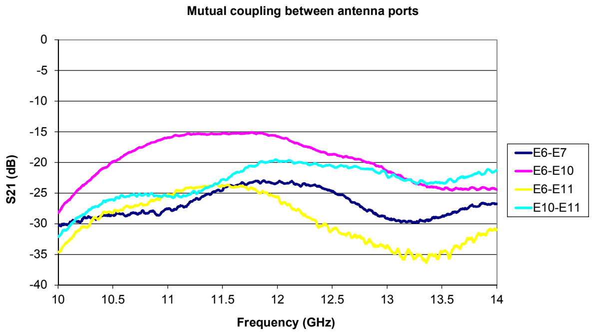

Figure 8 Mutual coupling between antenna ports (measurements).

C. *OBFN measurements*

The performance of the OBFN chip is measured by the setup shown in Figure 9 (see [4]). Light from a 1550 nm distributed feedback (DFB) laser is modulated using a Mach-Zehnder modulator (MZM) and coupled into the OBFN chip. The radio frequency (RF) signal (with a frequency of 50 MHz) is supplied from a vector network analyzer (VNA). The VNA is synchronized with the laser controller that controls the injection current of the laser. As the VNA starts triggering the injection current of the laser is ramped up resulting in a linear increase of the laser frequency. The result is then a double sideband with carrier modulation of the laser where the carrier frequency is linearly increasing and the sidebands are 50 MHz apart from the carrier. This swept frequency propagates through the optical chip and then detected by the photodetector. The output of the RF photodetector is fed to the other port (port 2) of the VNA. In this way the magnitude and phase responses of the RF to RF transfer of the OBFN chip can be measured.

In Figure 10 we show how the integrated delay line can be used to provide different values of group delay to the signal. The amount of time delay of the ODL unit can be varied with continuity by means of tuning the resonance frequencies and the coupling factor (hence the Q-factor) of the Optical ring resonators (ORRs) of the chip (see [4]). By properly cascading the ORRs (i.e. adding their delay response) in principle a large and wideband true time delay can be achieved. A delay of 600 ps (18 cm in free space) with a bandwidth of 2 GHz has been measured for a cascade of six ORRs.

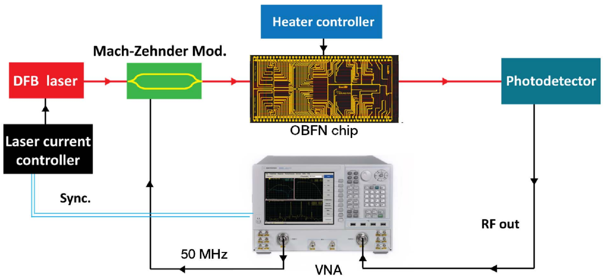

Figure 9 Schematic of the measurement setup for characterizing the ring resonator and the optical sideband filter responses.

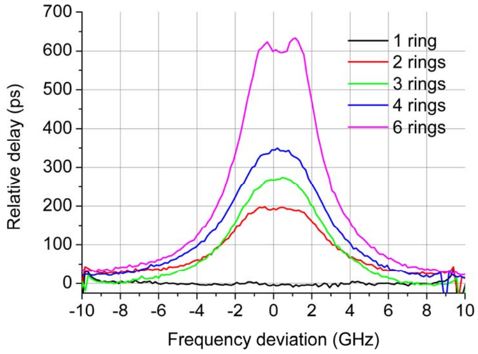

Figure 10. Measured delay response of a cascade ring resonators on the OBFN chip. The different traces correspond to different number of rings cascaded.

IV. STRUCTURAL INTEGRATION

The Ku-band antenna tiles need to be integrated into a pressurized fuselage panel. A promising concept for structural integration of Ku-band antenna tiles is a stiffened panel with glass-fibre skin and quadrangular cell pattern (see Figure 11). The dimensions of the cells correspond to the size of the antenna tiles. This concept has great benefits: no aerodynamic resistance, no movable parts, the electronics of the antenna are inside the fuselage (in the cabin pressure) and the quadrangular grid can be used for mechanical stiffening of the skin and for embedding of the antenna tiles.

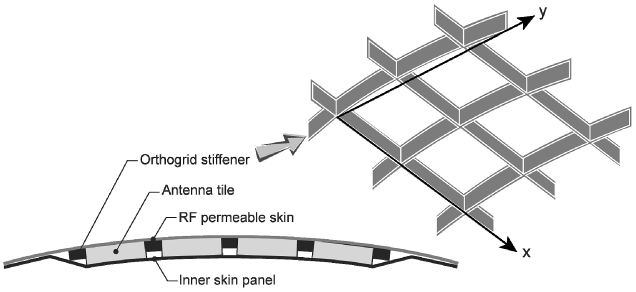

Figure 11 Schematic view of ortho-grid stiffened panel with embedded Ku-band antenna tiles

The dimensions of the cells of the quadrangular grid correspond with the sizes of the Ku-band antenna tiles. The outer skin needs to have appropriate electromagnetic properties for transmission of Ku-band radio waves. Other challenges for the design of the structurally integrated antenna are:

- The heat produced by embedded antennas has to be exchanged.
- The skin needs protection against lightning.
- The electrical connection for antennas requires cables and connectors for transmitting power and RF signals.
- Because of maintainability, the antenna tiles should be replaceable.
- The integrated stiffeners have to be as narrow as possible, because the gaps between antenna tiles have a negative effect on the RF performance of the Ku-band antenna array.
- The panel with integrated antenna requires air worthiness certification.

A. Thermal aspects

The structural integration of antennas in fuselage panels requires special measures for cooling of electronic components of antenna tiles. For instance, one Ku-band antenna tile needs about 40 to 60 Watt power while the materials inside the tiles have a low thermal conductivity. Therefore, thermal aspects need to be addressed early in the design phase of the Ku-band antenna tiles. Preferred options to cool the electronic RF-components are integrated heat pipes and heat sink areas, which are connected via thermal vias [6]. This approach is applied in active phased array radar systems. With respect to the extremely high integration density of the RF-components within the PCB-buildup of a tile, it is necessary to design a cooling strategy that has the least impact on the RF-performance. Transferring the heat away from the antenna tiles requires a compromise between RF-performance and adequate cooling. For example, it is likely not possible to introduce too many thermal vias within the RF-buildup of the PCB, hence vias will have to be used for both thermal and RF. Heat transfer from antenna tiles to the outer aircraft skin can be realised by thermosyphons or micro-pumped cooling loops [7]. The development of breadboards is required to show the concept feasibility.

B. Lightning aspects

The protection of antenna electronics against HIRF and lightning strikes needs to be addressed. In the case of lightning, voltage transients induced by single strike, multiple strike and multiple burst lightning will be considered. The challenge is to divert lightning strokes over the outer skin of the integrated antenna and to provide adequate protection for antenna electronics. CAE lightning simulations will be performed on aircraft level with the aim to evaluate the indirect effects of the lightning strikes to the integrated antenna tiles. The simulations will provide design guidelines for the placement of narrow lightning strips on the outer glass skin of the fuselage panel with integrated Ku-band antenna tiles. Lightning protection measures will be evaluated to assess benefits at A/C level. Simulations will be based on the international applicable standards and guidelines documents such as EASA, RTCA/DO and MIL standards, etc. On the level of integrated antennas, research will be performed to provide protection of the low impedance interfaces (e.g. power, serial and discrete lines) in a small volume as close to the external connector(s) as possible, whilst minimising capacitance, so as to not adversely affect signal rise and fall times. Combinations of Transient Voltage Suppressor (transorbs), series forward bias diodes and series resistors will be considered.

C. Cabling aspects

The communication network for the 32 antenna tiles is distributed along the edges of the orthogrid using optical fibres. This results in a low loss, firm, light weight, low cost, immune to EMI data link. It also enables the control of the individual tiles by using bidirectional optical communication via the same optical fibre, which is already massively used in fibre-to-the-home systems. A similar fibre optic distribution network can also be installed inside the aircraft to distribute signal to the satellite receiver and antenna control unit. The power network for the 32 tiles can also be distributed along the edges of the orthogrid. The positioning of a distributed power and communication network along the edges of the orthogrid will reduce the required wiring for the Ku-band antenna tiles. Without this network each tile would require at least 3 interface cables.

D. Maintainability

The structure of the orthogrid has unique possibilities to put and to replace antenna tiles. The backside of the orthogrid has to be supported by a removable back skin, which can be realised by using special adhesives. Removing the back-skin will provide access to the antenna tiles, so that they can be replaced as modules.

E. RF performance

The integrated stiffeners will cause gaps between the antenna tiles. These gaps will generate likely side lobes in the antenna radiation pattern. The effects of gaps on the level of the side lobes need to be investigated by means of simulations. Furthermore, the radiation pattern of the Ku-band antenna can be influenced by the embedded lightning strips above the stiffeners.

F. Air worthiness certification

The air worthiness certification of a pressurised orthogrid stiffened panel with embedded antenna tiles is considered as a critical challenge. The recommended approach is to get the certification stepwise. Consider first a small modification of the fuselage panel and increase the complexity by steps. Therefore, the feasibility of the concept is first investigated for the integration of one tile in a fuselage door. NLR has available two spare emergency exit doors of its Fairchild Metro laboratory aircraft. The dimensions of these doors are approximately 20x28 inches. The doors are located on both sides of the fuselage above the wings. The aim is to integrate two antenna tiles of size 9x9 cm in this door. The positioning of the antennas is shown in Figure 12. The outer surface of this door is replaced by an electromagnetic transparent skin with appropriate orthogrid stiffened cells. The space between the inner and outer surfaces of the door is limited, because the already present stiffeners and the handle assembly need to be maintained.

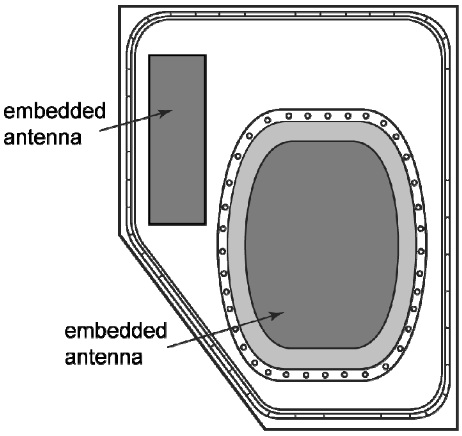

Figure 12 Outbound view of modified emergency exit door with two embedded antennas behind transparent RF skin

The first step is to consider just the integration of one antenna tile in glass window of a fuselage door. This requires only the replacement of the glass window by a composite stiffened panel of the size of the window. The second step is to replace part of the aluminium skin of a door by an appropriate panel with embedded antenna tiles. The emergency exit door is part of the pressurised cabin of NLR's METRO research aircraft. The modification of the door is considered as a major modification which requires certification by the Dutch Human Environment and Transport Inspectorate (ILT). This inspectorate ensures that aircraft comply with airworthiness and environmental protection standards. Compliance is achieved through certification of the modified door by NLR's Design Organization for Research Aircraft (RADO), which has privileges to undertake aviation activities. RADO will draft a certification plan and a certification report, which have to be approved by ILT. Furthermore, ILT will witness structural tests to verify compliance. For the certification a range of structural tests are foreseen: from coupon tests for determining strength of building components to air pressurised test for determining the strength of the entire door.

V. ROADMAP

The short-term research activities follow from the proposed solutions to tackle the challenges as discussed in the previous section.

1) Thermal management of integrated Ku-band antenna. Thermal modelling and simulations of feasible solutions, and development of breadboards to demonstrate concepts.

2) RF design activities

Computational electromagnetic models for the structurally integrated antenna are developed with the aim to study the effects of gaps between the Ku-band antenna tiles and the effects of narrow lightning strips on the outer skin between Ku-band antenna tiles. CAE lightning simulations are performed on aircraft level. Research needs to be performed to provide protection of the electronic components of the integrated antenna.

3) Mechanical design activities

Mechanical models have to be developed for the CAD geometry of Ku-band antenna tiles (see Figure 5) with the aim to verify the mechanical strength in relation to pressurised conditions. In case the strength is insufficient the design of the tile has to be reconsidered.

4) Integrated antennas in emergency exit door

The redesign of the emergency exit door is focused on the installation of miniaturised UHF communication antenna tiles. A UHF antenna is considered here instead of a single Ku-band antenna tile since its mechanical and RF requirements are less severe. Topics to be addressed are: the design and manufacturing of a planar UHF antenna of size 9x9cm by the approach of 0, the development of composite panels with orthogrid stiffened cells (these panels replace parts of skin of the emergency exit door), the certification of the modified exit door including structural tests, and flight trials.

On the longer term the results of the above activities are the input for the development of a pressurised orthogrid stiffened fuselage panel for the structural integration of 32 integrated Ku-band antenna tiles with optical beam forming network for the continuous steering of the antenna beam.

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