DESIGN REVIEW OF A COMPACT AND LOW COST ELEMENTARY RADIATING CELL FOR SATELLITE BROADCASTING AUTOMOTIVE RECEIVING ARRAYS 33RD ESA ANTENNA WORKSHOP

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ABSTRACT

This communication presents a review of the developments carried out towards the electromagnetic modeling, design and practical implementation of the *basic building block* of a planar antenna for the reception of Ku-band satellite broadcasting services from user terminals on board automotive platforms.
The antenna is conceived as a low profile phased array with fully electronic beam steering and polarization tracking capabilities. This phased array is intended to address the market of low cost consumer applications, which imposes stringent structural and performance-to-price ratio requirements.
As will be shown next, these demanding requirements are going to drive the design of the array basic building block: the so-called *Elementary Radiating Cell* (ERC).

1. INTRODUCTION

The large capacity and the homogeneous continental coverage provided by satellite communication systems constitute an ideal platform for the provision of a wide range of low-cost broadband mobile communication services.
Currently, both vehicle manufacturers and end-users are increasing the demand of such services, that are mainly related to safety, telemetry & control, tolling, real-time driver information and entertainment.
The effort Direct Broadcasting Satellite (DBS) operators are making to improve the supply of these communication services contrasts, however, with the shortage of compact and cost-effective user interfaces to access them, which is actually limiting the expansion of such a promising market.
This shortage is related to the considerable engineering challenge that underlies the integration of the terminal antenna system into the targeted mobile platforms (touring cars, mainly).
Basically, the integration of DBS antennas in mobile platforms requires the capability of synthesizing and dynamically steering a beam that should be kept oriented towards the desired satellite along all the route of the vehicle. In the case of cars, the complexity of an antenna system providing such tracking capabilities, which is already paramount, must be made compatible with the particular structural and economical requirements imposed by the automotive industry. These latter requirements, that concern mainly aesthetics, comfort, dynamics, size and cost issues, are decisive for a successful penetration of the foreseen user interface into the automotive market. A typical application scenario is depicted in *Fig 1*.
Within this framework, the European Space Agency (ESA-ESTEC) has launched a project aiming to investigate the feasibility of such a satellite terminal for automotive consumer applications. The **NATALIA** (**N**ew **A**utomotive **T**racking **A**ntenna for **L**ow-cost **I**nnovative **A**pplications) project involves several key industrial partners in the sector of satellite R&D and consumer applications, led by IMST Germany, and the EPFL Laboratory of Electromagnetics and Acoustics (EPFL-LEMA).

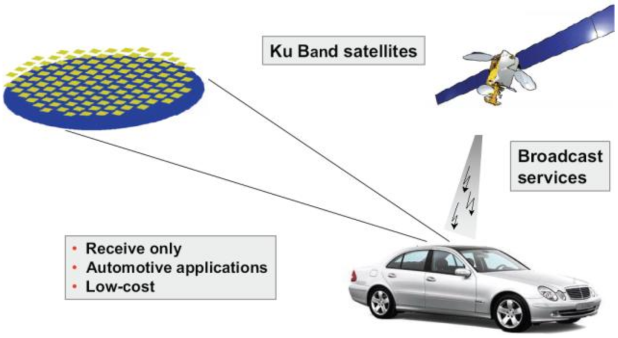

Figure 1. *Typical application scenario. From [1].*

2. SCOPE. THE NATALIA PROJECT

This section is a general description of some of the main topics addressed during the development of the NATALIA project and is based on a series of parent documents, where these topics, as well as many others, are discussed more in depth [1-3].
The NATALIA project is dealing with the strong compromise between **cost**, **performance** and **size** posed by both the *service* and the *market* for which the foreseen antenna terminal is addressed. The constraints

derived from this compromise are going to drive every stage of the design process summarized below.

At early stages of the viability survey, these constraints led to the rejection of mechanically based solutions to implement the beam steering and the polarization tracking capabilities required for the mobile reception of the satellite signal (in Europe, DBS carriers are linearly polarized). In fact, systems with mechanically moving parts are generally high-profile, bulky, and subject to G-forces. The alternative of a full electronic control of these pointing parameters is approached as a classic phased array design problem, that can provide low profile solutions, with no moving parts and high reliability.

The main building blocks of the NATALIA phased array concept are illustrated in *Fig. 2*. According to this diagram, the beam pointing and the polarization alignment are based on steering information provided by the *Receiver SubSystem*, that gathers all sensor information (GPS, gyro), to the antenna *Controller* at a certain update rate, that depends on the speed of the car as well as on the required pointing accuracy. Then, the *Controller* reconfigures the *Tracking Units* (TUs), that synthesize the array illumination, accordingly.

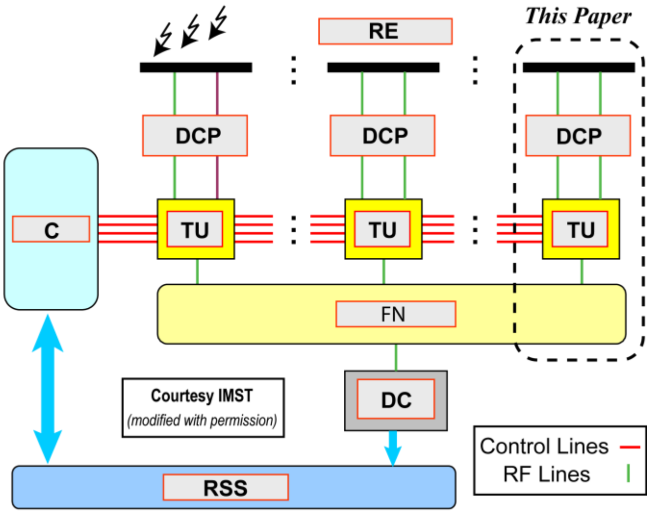

Figure 2. *Block diagram of the NATALIA array concept. The acronyms* ***RE***, ***DCP***, ***TU***, ***C***, ***FN***, ***DC***, ***RSS*** *and* ***RF*** *stand for* ***Radiating Element***, ***Dual Circular Polarization***, ***Tracking Unit***, ***Controller***, ***Feeding Network***, ***Down-Converter***, ***Receiver SubSystem*** *and* ***Radio Frequency***, *respectively.*

The phased array alternative suffers, however, from the potentially high costs associated to both the **complexity of its implementation** and the **number of active components** (typically GaAs Monolithic Microwave Integrated Circuits -MMICs) required. Generally, these are major obstacles to a broad diffusion of phased array technology in the consumer market and constitute, in fact, the main design challenges addressed by the NATALIA phased array concept.

2.1. The Tracking Unit

With regard to the issue of the **active components count**, the NATALIA concept tries to optimize the compromise between their number, their complexity and their diversity by merging the amplification, the beam steering and the polarization tracking capabilities within a couple of twin active components. This combination of functionalities takes place at *Radiating Element* (RE) level, inside the TU, and constitutes the so-called *Combined Phase Shifter* (CPS) scheme. The incorporation into the CPS scheme of a convenient sequential rotation of the REs over the array aperture enables a further simplification of the logic within the active components, with the consequent impact on their size and cost, as well as an important relaxation of the performance requirements at RE level, see [3].

2.2. Implementation of the Antenna Aperture

Despite all these simplifications, the **practical implementation** of the NATALIA concept remains rather complex, especially within the aforementioned constraints of size, cost and performance. This practical implementation concerns basically the *array topology*, the *manufacturing technology* and the *interconnections architecture*. For the first part, an in depth study of different array topologies reveals the convenience, for the present application, of a planar array with its elements arranged in the basis of a densely populated triangular grid, as illustrated in *Fig. 3*.

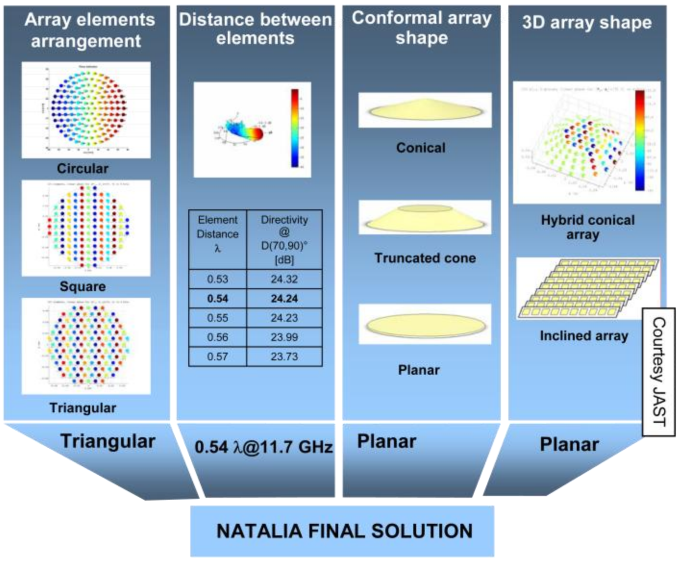

Figure 3. *NATALIA array topology alternatives and final solution.*

With respect to the *manufacturing technology*, standard Printed Circuit Board (PCB) prevails mainly due to its compatibility with large production volumes, its high yield, its maturity as well as its inherent suitability for low cost, low profile, compact and sturdy architectures.

In spite of the apparently direct mapping of the planar array topology into a multilayer PCB structure, it is at this point that a careful choice of both the *interconnections architecture* and the particular fabrication processes must be carried out in order to minimize certain fundamental risks, namely:

- the high potential complexity associated to the interconnection and control of the elements of the array, which may either severely restrict the technical viability of the whole antenna, or downgrade its performance below acceptable limits,
- the intrinsic performance limitations at microwave frequencies, with regard to other special purpose technologies (such as coaxial or waveguide), of both circuital and radiating components when implemented in standard PCB technology without high-end materials, and
- the considerable impact the PCB processing details (i.e.: the number of processes and their sequence) may have on the fabrication tolerances, the yield, the performance and the cost of the antenna terminal.

The success of this choice relies on the wide experience of the industrial partners in both system design and PCB technology as well as on intensive interaction with several leading PCB manufacturers. The resulting PCB buildup, whose preliminary overview is depicted in *Fig. 4*, has been optimized in order to be easy to implement and inexpensive. In particular, the configuration of the vertical interconnections has been designed to allow the manufacturing of the PCB in one single press and one single metallization (plating) processes.

2.3. The Elementary Radiating Cell

Once the system architecture and the fabrication technology are properly settled, a more convenient redefinition of the main building blocks of the antenna sub-system can be addressed. The definition of these blocks will enable the identification and solution of further design compromises and, thus, prepare the way for their integration in the foreseen antenna array. These building blocks are defined as follows:

- the ***Elementary Radiating Cell*** (ERC), which comprises the dual circularly polarized radiating element, in the upper side of the PCB buildup, and, by extension, all the components of the TU that are embedded in the PCB core. These components are:
  i) the interconnections between the RE and the TU. As illustrated in *Fig. 4*, these interconnections are the couple of twin vias that cross most of the buildup to reach the inputs of the TU-MMICs, which are located in the bottom microstrip layer. These vias are implemented as *through vias* and will be referred hereafter as *Long Vias*.
  ii) The *Power Combiner* that connects the outputs of the TU-MMICs to the Feeding Network, as shown in *Fig. 4*. According to this figure, the Feeding Network is located in an intermediate stripline-like layer. This layer is reached by the Power Combiner using a *blind via*.

  As will be seen throughout this paper, the **integration** of the ERC within the *PCB buildup* and the *array lattice* are two issues of major relevance for the design of this building block.

- Each ***MMIC*** is a customized design that integrates a Low Noise Amplifier and a reconfigurable Phase Shifter. This component constitutes the heart of the TU and is expected to represent more than 80 % of the antenna terminal cost price. Its design and

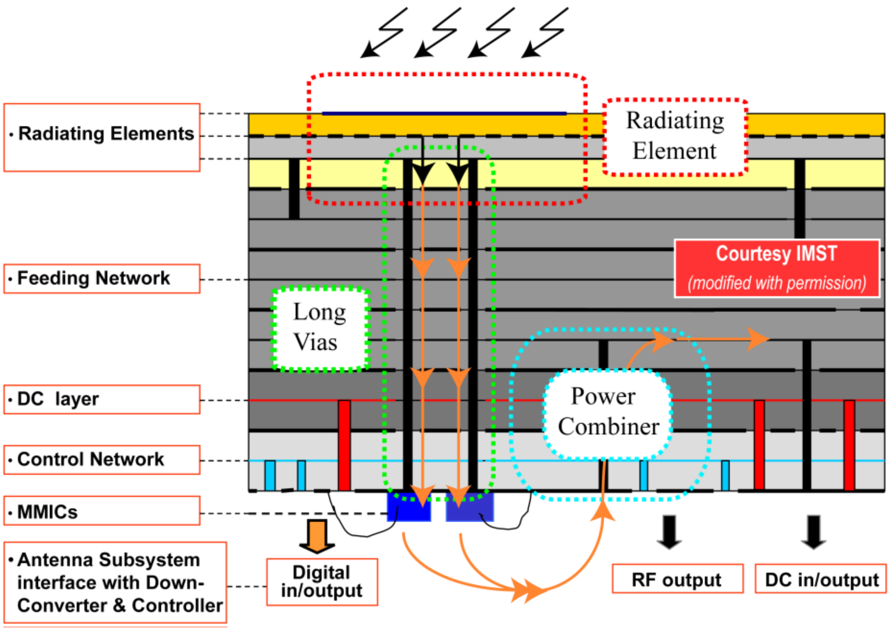

Figure 4. *Preliminary NATALIA PCB buildup overview (not to scale).*

prototyping are carried out in parallel with those of the ERC to mitigate the impact of the long delays required for the completion of each foundry run. Besides, to cope with the high cost of each run, the number of iterations is minimized.

- The ***Feeding Network*** is conceived as a passive corporate network connecting the output of all TUs to the input of the *Down-Converter* (recall *Fig. 2*). In addition to the minimization of its transmission loss, another important design constraint is related to the situation of this network within the PCB buildup. In fact, since the network is mostly accommodated in the intermediate layers of the buildup, its routing must be compatible with the distribution over the array aperture of the through vias used for the implementation of the cells (e.g.: the Long Vias). According to *Fig. 4,* this last constraint is also present in the routing of the *Control Network*. In fact, the density of vias over the antenna aperture is expected to be so high that it is advisable not to start the routing of these two networks until the design of the ERC as well as the arrangement of its replicas within the array aperture (i.e. the sequential rotation) are frozen.

3. ERC DESIGN PROCESS

Due to the cross-cutting nature of the array basic building block, the understanding of the tradeoffs that underlie the design of the ERC calls, in the first place, for a basic knowledge of the whole antenna solution, at both functional and technological levels. The design requirements of the ERC and the NATALIA array are summarized in *Tab. 1*. A more detailed description of the role of the ERC as well as of its design guidelines will then provide a deeper overview of the remaining components of the array antenna and highlight design issues that are not evident at this stage.

According to the practical implementation of the array antenna, the design of the ERC is conceived from the point of view of its **integration** into the antenna *PCB buildup* and into the *array grid*. These two levels of integration (*'horizontal'* and *'vertical'*) are not independent, but strongly interrelated and deeply affecting the electromagnetic (EM) performance of the cell. As will be shown throughout the present section, this conceptual division contributes, on one side, to highlight the compromise between the integration of the element and its EM performance that underlies the design of the ERC. On the other hand, such a division provides the basis to the design process itself, which is approached as an **iterative process**. This process tries to optimize the intimate relation between performance and integration by aiming sequentially to each one of the two levels of integration involved. These iterations should converge, ideally, on the best EM performance that is compatible with all the integration constraints.

3.1. Integration into the Antenna Buildup (1^{st})

The first design iteration concerns, basically, the **feeding of the Radiating Element**.

The RE is based on the microstrip patch antenna concept and, given the fabrication technology and the performance requirements, the so-called *Aperture Coupled* feeding [4] is considered to be the most advantageous choice. This feeding scheme provides a convenient isolation between the mechanisms involved in the feeding and the radiation of the RE. Combined with further design refinements, like the use of *Inverted Patches* [5] and *Dog-Bone* shaped coupling apertures (slots) [6], this isolation enables important performance enhancements of the basic microstrip patch antenna. The integration of such an RE into a buildup like that of *Fig. 4* demands, however, the introduction of an additional shielding layer to prevent undesired interactions between the element feeding and the remaining components of the array, which are embedded in the lower layers of the PCB stack. This shielding is accomplished with the insertion of an additional ground plane in the *lower* part of the element buildup, which leads to the definition of a sort of stripline structure, as illustrated in *Fig. 5*.

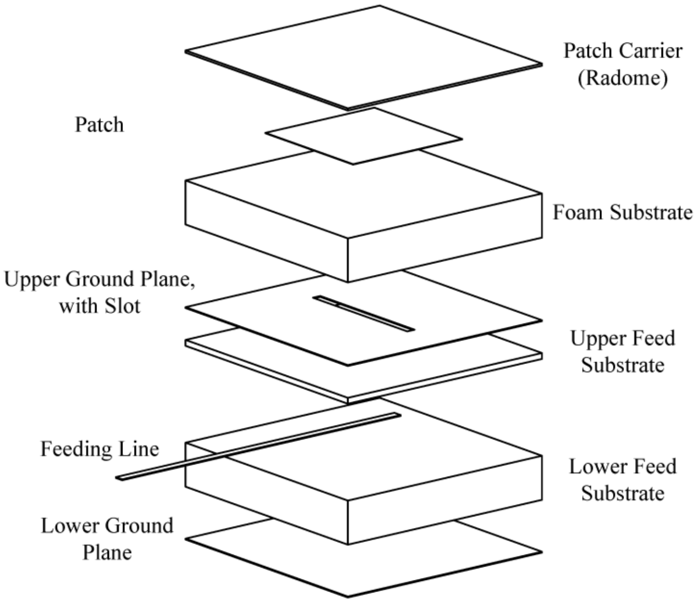

Figure 5. *Preliminary buildup of an Aperture Coupled RE with improved feeding shield.*

The use of a stripline for the excitation of the RE requires special attention to mitigate the power leakage due to parasitic modes propagating in the resulting triplate structure, like the *Parallel Plate Waveguide Modes* (PPWMs). These modes can be excited by asymmetries in the triplate, like the slot in the upper ground plane of *Fig. 5*, and the most harmful PPWM is typically the fundamental mode, that tends to create a difference of potential between the *Upper* and the

Table 1. *Design Requirements for the Array antenna and the ERC. From [2]. The symbols & acronyms* ***G/T****,* $\boldsymbol{\eta_{rad.}}$*,* $\boldsymbol{S_{ii}}$*,* ***XPD*** *and* ***AR*** *stand for* ***Gain over noise Temperature****,* ***Radiation Efficiency****,* ***Impedance Matching****,* ***Cross-Polarization Rejection*** *and* ***Axial Ratio****, respectively.*

		Array	**ERC** (Isolated)
Electrical Performance	**Frequency Band**	10.7-12.75 GHz (Bandwidth ≈ 18 %)	
	Scan	360° in Azimuth 20- 70° in El.	—
	Power Efficiency	G/T ≥ -6 dB/K	$\eta_{rad.}$ ≥ 80% S_{ii} ≤ -10 dB
	Directivity	≥ 20 dB	Moderate (~ 5-7 dB)
	Polarization	Lineal XPD ≥ 15 dB	Dual Circular AR ≤ 6-8 dB
Cost -effectiveness	Simplest and Cheapest PCB processing: • single press & • single plating.		
	No high-end materials.		
Aesthetics – Mechanical	**Small**	≤ 1-2 cm thick ≤ 20 cm diameter	≤ 1 cm thick ≤ 1.64 cm^2 area
	Robust	No mechanical parts.	

Lower ground planes. An effective technique to diminish this power leakage is, in fact, to insert shorting pins between both ground planes, in the vicinities of the slot. Alternatively, the coupling between the feeding line and the patch can be enhanced if the line and the slotted ground plane are moved nearer, leading to an asymmetric stripline structure. As proposed in [7], the combination of these two measures can contribute notably to the improvement of the RE feeding mechanism and, consequently, of its *Radiation Efficiency* (enhancements of up to 50 % have been observed in simulations), among others.
The proof of concept of the feeding architecture proposed for the NATALIA RE is provided by the successful implementation and measurement of an aperture coupled element with asymmetric stripline feeding [8], which concludes this initial design iteration.

3.2. Integration into the Array Lattice (1st)

This stage focuses on the implementation details of the Dual Circularly Polarized Radiating Element (DCPRE). These details are going to determine the way both the DCPRE and the ERC are embedded into each other and into the array lattice, respectively.
For the present application, the preferred design alternative to implement the DCPRE is based on the combination of a Dual Linearly Polarized Radiating Element (DLPRE) and a 3 dB-quadrature coupler. In turn, the DLPRE operation is provided by the simultaneous excitation of the couple of orthogonal modes that can resonate lengthwise and widthwise to the patch cavity. As illustrated in *Fig. 6* (and, later, in *Fig. 7*), these modes are excited through a pair of transversal *Dog-Bone* slots. This excitation architecture, in which the feeding lines lie on the same metallization plane and the slots are arranged in a *T-shaped* configuration, provides a favorable tradeoff between the performance of the RE, the structural simplicity of its buildup and the area occupied by its feeding circuitry (slots, feeding lines & shorting pins).

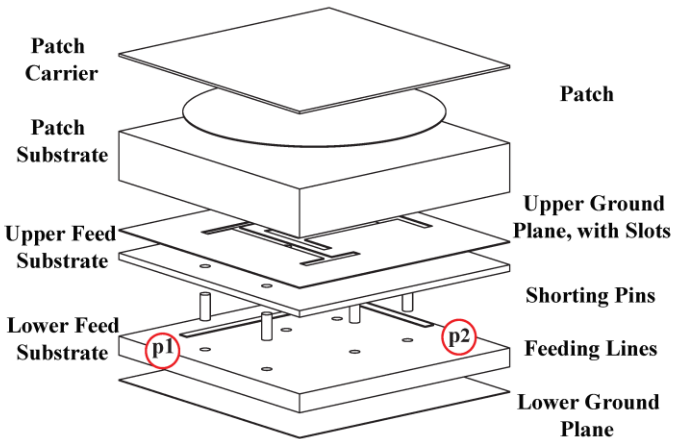

Figure 6. *Buildup of the Aperture Coupled DLPRE.*

The PCB area taken up by the DLPRE feeding is an important design issue, since it determines, in the end, the feasibility of the ERC integration into the array lattice. This area can also condition the way the quadrature coupler (a branch-line hybrid, here), is connected to the DLPRE and, therefore, the footprint of the resulting DCPRE. In this case, such area is so large that the possibility of deploying the arms of the hybrid around the DLPRE feeding circuitry, which would lead to a convenient radial growth of its layout, has to be discarded in favor of the lineal connection scheme depicted in *Fig. 7*. Less efficient in terms of area consumption, this lineal connection already suggests a *rectangular shape* for the final footprint of the ERC.

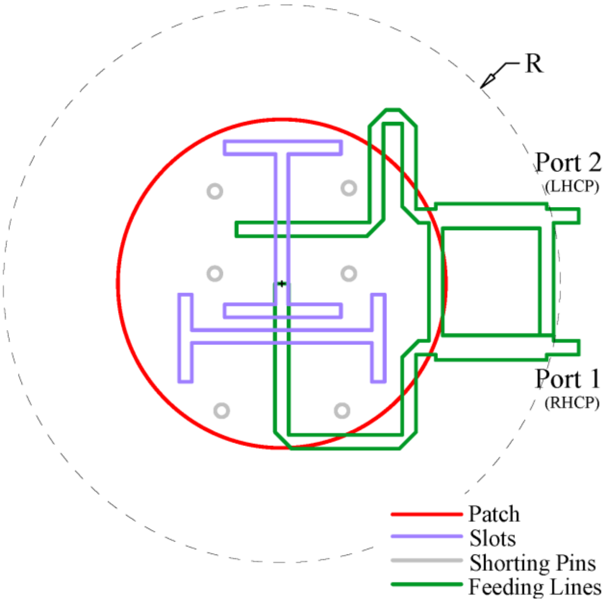

Figure 7. *Layout outline of the DCPRE.* ***L(R)HCP*** *stands for* ***Left (Right) Hand Circular Polarization****.*

With regard to the dimensions of this rectangular shape, an upper bound for them is determined taking into account:

i) the possibility of implementing one, at least, of the required sequential rotation schemes without collision of the ERC footprints (see *Fig. 8*) and
ii) the feasibility of the subsequent routing of the Feeding & Control Networks.

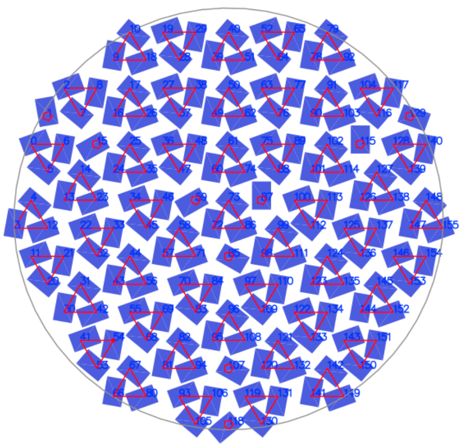

Figure 8. *NATALIA array aperture with an exemplary sequential rotation. The rotation is applied to an ERC with rectangular shape and dimensions: $0.46\lambda_o x 0.3\lambda_o$. From [3].*

Such an upper bound, that is found to be close to $0.46\lambda_o$ $x\ 0.3\ \lambda_o$, reveals that the dimensions of the DCPRE layout displayed in *Fig. 7* are not compatible with the integration of the ERC into the array lattice. Further design iterations are thus conducted to reduce the dimensions of the DCPRE, which results in the miniaturized layout shown in *Fig. 9*.

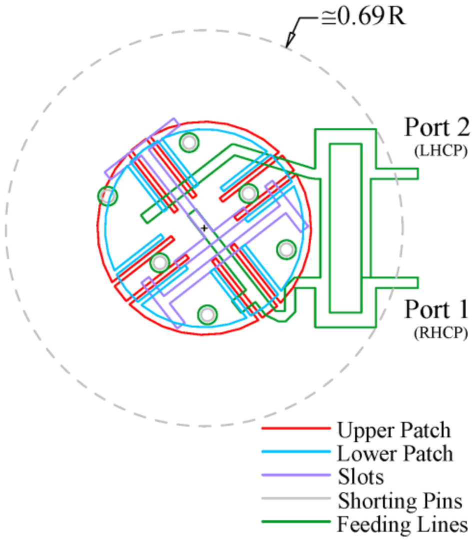

Figure 9. *Layout outline of the miniaturized DCPRE.*

The most salient features of this miniaturized layout are the rotation of the DLPRE with respect to the hybrid and the squeezing, in the horizontal dimension, of the latter. A more detailed comparison of the layouts in *Fig. 7* and *Fig. 9* would reveal that the rotation of the DLPRE, and the consequent reduction of the lengths of the meanders in the lines feeding it, is made possible by a movement of the shorting pins and the 'horizontal' slot of the RE towards the patch center. In practice, this movement, that includes a shortening of the 'horizontal' slot, has a considerable impact on the performance of the element and, as it will be discussed next, the measures to compensate for such an impact concern, basically, the RE buildup.

3.3. Integration into the Antenna Buildup (2nd)

The main effect of the aforementioned layout modifications is a weakening of the coupling between the feeding lines and the patch of the DLPRE. Here, the preferred approach to compensate for this weakening is, in principle, the reduction of the distance between patch and slots by using a thinner patch substrate. And, in order to prevent the bandwidth drop associated with this reduction of the volume occupied by the RE, an additional resonating patch is introduced in its buildup.

This design step, that is based on the *Stacked Patches* technique [9], explains the presence, in the layout of *Fig. 9*, of the couple of patches that are labeled as *Upper* & *Lower* and enables, at the expense of an increased structural complexity, further improvements of the RE performance. In fact, besides the expected recovery in terms of Radiation Efficiency and Impedance bandwidth, the *Stacked Patches* technique is also found to facilitate:

i) the enhancement of the Symmetry of the DLPRE Radiation Pattern, with the consequent amelioration of the DCPRE Axial Ratio (AR), and

ii) the mitigation of an eventual Directivity excess, with regard to the upper bound imposed by the array lattice, at (isolated) element level.
Beyond the potential scan loss at low elevation angles, such a directivity excess would bode pronounced mutual coupling phenomena between the array elements. The strengthening of these element interactions would then put into question the validity of the simplified design approach followed here, which does not take these phenomena into account [10, Ch. 3].

Though certain functional limitations of the RE, like those concerning its AR, are expected to be compensated at array level (once the overall performance improvements provided by the foreseen sequential rotation are effectively exploited [11]), the reduced inter-element spacing required by the broad scan capabilities of the foreseen array stresses the aforementioned 'directivity excess / mutual coupling' issue. The next design iteration is going to concentrate on this issue.

3.4. Integration into the Array Lattice (2nd)

The integration of the ERC into the densely populated aperture of the NATALIA array does not only concern the mechanical insertion of the elements and their isolated performance, but also the EM interactions between neighboring cells.

As stated above, the simplification of the element design process calls, in the first instance, for a reduction of the inter-element mutual coupling. The technique used here to attain such a reduction relies on the ***miniaturization*** of the patches, whose diameter is conveniently scaled-down by slitting their perimeter [12, 13], as it can be noted in *Fig. 9*. In fact, the impact of this miniaturization on the spacing between the radiating edges of the patch(es) is twofold:

i) *at element level*, this spacing is reduced, which is compatible with a **lower element directivity**, while

ii) *at array level*, this spacing is increased, which leads, typically, to a **mutual coupling diminution**.

The design of the miniaturized RE concludes with the successful assessment of its performance, both theoretically and empirically [10, Ch. 3-4].

3.5. Final Integration steps

Once the design of the DCPRE is complete, the final development steps are devoted to the integration of the *Long Vias* and the *Power Combiner* within the ERC footprint and the PCB buildup.

Detailed 3-D views of the Long Via and the Power Combiner are shown in *Fig. 10* and *Fig. 11*. In addition to the electrical operation, the design of these components and their placement within the ERC footprint is determined, to a large extent, by the stiff competition for the layout area that is established in the interface between the cell and the MMICs. According to *Fig. 4*, such interface is located in the microstrip layer of the PCB core. In this layer, the ERC and the MMICs, with all their biasing components, must share the available footprint area with the part of the Control Network that programs and interconnects the MMICs [10, Ch. 3].

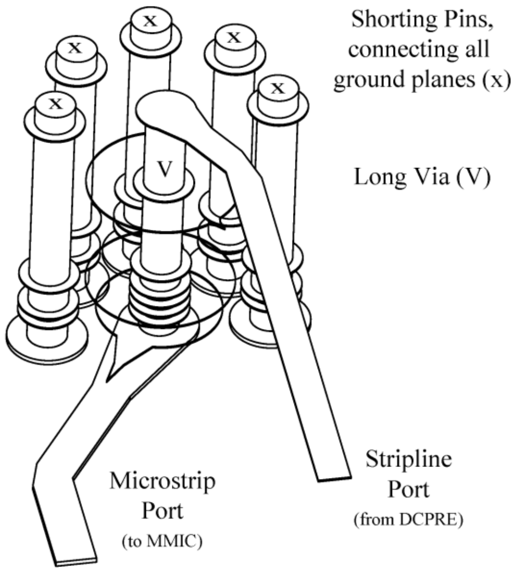

Figure 10. *Long Via. Detailed 3-D view of the metallizations and the clearances as they would lie within the antenna buildup. For the sake of clarity, the substrates and the ground planes in the buildup have been removed.*

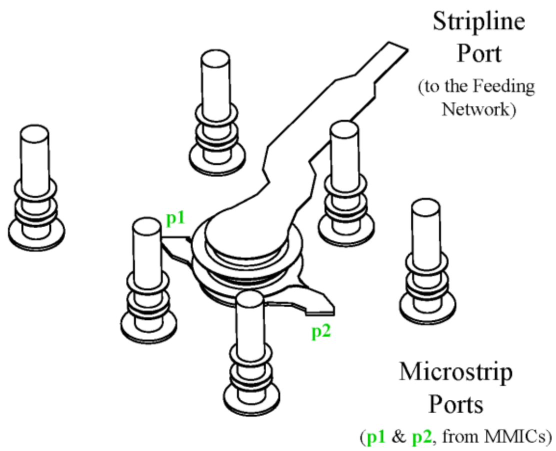

Figure 11. *Power Combiner, with $\lambda_o/4$ impedance transformer in the stripline layer. Note the bigger diameter of the signal via (blind), compared to the shorting pins of the RE (through vias).*

The completion of these integration steps results, finally, in an ERC that fulfills the technological and the structural requirements specified for the targeted antenna solution, and provides a very satisfying EM performance [10, Ch. 4],[14]. The structure of this ERC is depicted in *Fig. 12.*

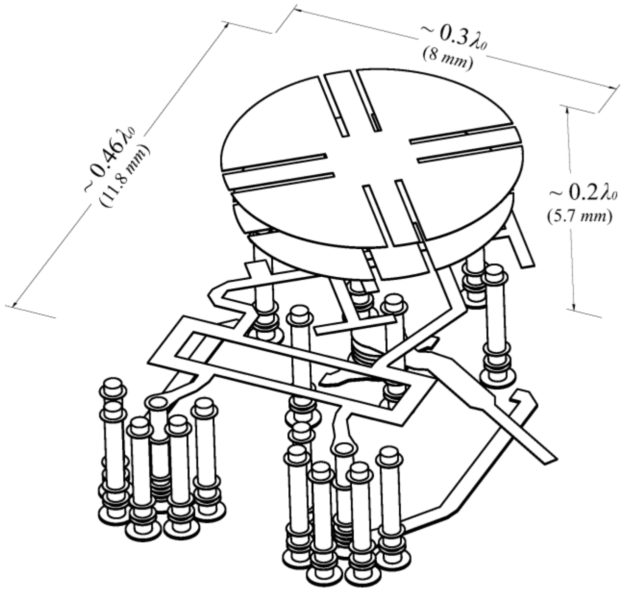

Figure 12. *ERC. Detailed 3-D view with dimensions. From [14].*

4. CONCLUSION

This paper contains an overview of the design of an innovative antenna element at Ku-Band for a low-profile phased array antenna. The design of the antenna element is done in the framework of an industrial project that is aiming to address the increasing demand of mobile satellite terminals for consumer applications.

In this framework, the conciliation of conflicting design requirements (that are related to the cost, the size and the EM performance of the antenna array) has driven the optimization of known concepts and structures up to an unprecedented degree of sophistication. At antenna element level, this optimization focuses on the integration of the element within both the array lattice and the antenna PCB buildup.

5. REFERENCES

1. Baggen, R., Vaccaro, S. & Llorens del Río, D. (2007). Design considerations for compact mobile Ku-band satellite terminals. *In 2nd European Conference on Antennas and Propagation, EuCAP 2007*. Edinburgh, UK.

2. ESA, (2003). Patch Antenna for Mobile Receive Only Terminals. Appendix 1: Statement of Work. *Invitation To Tender AO/1-4482/03/NL/US.*

3. Llorens del Río, D., Tiezzi, F. & Vaccaro, S. (2010). Sub-array polarization control using rotated dual polarized radiating elements. *US Patent 20 100 253 585.*

4. Pozar, D. M., (1985). Microstrip antenna aperture-coupled to a microstripline. *Electron. Lett.,* vol. 21, no. 2, pp. 49–50.

5. Zürcher, J.-F., (1988). The SSFIP: A global concept for high performance broadband planar antennas. *Electron. Lett.,* vol. 24, no. 23, pp. 1433–1435.

6. Pozar, D. M., & Targonski, S. D., (1991). Improved coupling for aperture-coupled microstrip antennas. *Electron. Lett.,* vol. 27, no. 13, pp. 1129–1131.

7. Brachat, P. & Baracco, J. M., (1995). Dual-polarization slot-coupled printed antennas fed by stripline. *IEEE Trans. Antennas Propagat.,* vol. 43, no. 7, pp. 738–742.

8. Torres-Sánchez, R., Vaccaro, S. & Mosig, J. R. (2008). Compact and low cost radiating element for automotive satellite broadcasting reception arrays. *In 30th Antenna Workshop of the European Space Agency*. ESA/ESTEC, Noordwijk, The Netherlands.

9. Targonski, S. D., Waterhouse, R. & Pozar, D. M., (1998). Design of wide-band aperture-stacked patch microstrip antennas, *IEEE Trans. Antennas Propagat.,* vol. 46, no. 5, pp. 1245–1251.

10. Torres-Sánchez, R. (2011). *Analysis and Design of a planar Radiating Element for Automotive Satellite Broadcasting Reception Systems*. EPFL Ph.D. dissertation, no. 5123. Lausanne, Switzerland.

11. James, J. R. & Hall, P. S., Editors. (1989). *Handbook of microstrip antennas*. P. Peregrinus on behalf of the Institution of Electrical Engineers, London, UK, Ch. 13.

12. Huang, J. (2001). Miniaturized UHF microstrip antenna for a Mars mission. *In Antennas and Propagation Society International Symposium 2001*. IEEE, vol. 4, pp. 486 –489.

13. Torres-Sánchez, R., Mosig, J. R., Vaccaro, S. & Llorens del Río, D. (2009). On the design of a compact and low cost radiating element for satellite broadcasting automotive receiving arrays. *In 33rd Annual Antenna Applications Symposium.* Monticello (IL), USA.

14. Torres-Sánchez, R., Mosig, J. R., Vaccaro, S. & Llorens del Río, D. (2010). A compact and low cost elementary radiating cell for satellite broadcasting automotive receiving arrays. *In Progress in Electromagnetics Research Symposium, PIERS 2010.* Cambridge (MA), USA.