NATALIA: A SATCOM PHASED ARRAY IN KU-BAND

ESA/ESTEC, NOORDWIJK, THE NETHERLANDS
3-5 OCTOBER 2012

R. Baggen (1), S. Vaccaro (2), D. Llorens del Río (2), J. Padilla (2), R. Torres Sánchez (3)

(1) IMST, Carl-Friedrich-Gauss-Str. 2-4, 47475 Kamp-Lintfort, Germany. Email: baggen@imst.de
(2) JAST, PSE-EPFL BAT: C, CH-1015 Lausanne, Switzerland. Email: stefano.vaccaro@jast.ch, dll@jast.ch, jose.padilla@jast.ch
(3) LEMA-EPFL, Station 11, CH-1015 Lausanne, Switzerland. Email: roberto.torres@epfl.ch

ABSTRACT

This article presents the prototype of an electronically steerable receive-only array antenna realised within the ESA-project NATALIA. This project is funded under contract number 18612/04/NL/US. The antenna is conceived for the reception of mobile satellite services in Ku-band and its design targets the market of automotive applications. The design of the prototype is based on an innovative polarisation agile phased array concept and exhibits an excellent RF-performance as well as a very compact envelope.

1. INTRODUCTION

Phased array technology for mobile satellite telecommunication (satcom) applications is an increasingly interesting and growing commercial market for mobile satellite terminals. Such systems, either for maritime, aeronautical or land mobile applications, must be able to receive satellite broadcasting services on-the-move. Current and future multimedia services (general and/or customised broad-casting news) push the development of small compact terminals to the edge of cost effectiveness.

Conventional mobile antenna systems that are commercially available, normally track the satellite by means of (partly) mechanical steering: the antenna is in general mounted on a two-axis steering system adjusting the orientation of the antenna in such a way that the antenna beam is continuously pointing towards the satellite. Such systems with mechanically moving parts are however heavy and/or bulky, subject to g-forces and maintenance intensive. The internal momentum of mechanically steered antennas can be detrimental to their tracking accuracy, especially when operating on-the-move.

These properties are not very appealing to the automotive market, where car aesthetics are ever so important. Far more favourable are the fully electronically steerable solutions that can be extremely low-profile, possess fast, almost instantaneous and accurate pointing capability, and generate no sound..However, the major limitations of this type of arrays is that their practical feasibility, as well as their final price, depend strongly on the complexity of the antenna system, that can be very high, and the count of electronic components, potentially very large too. The key design challenge is therefore to accomplish an extremely cost-effective design, with an excellent balance between performance, size, reliability and cost.

The NATALIA project (New Automotive Tracking Antenna for Low-cost Innovative Applications), funded by the ESA (contract number 18612/04/NL/US), focuses on the realisation of a compact cost-effective receive-only full electronically steerable antenna for automotive platforms in Ku-band. The consortium is composed of partners from Switzerland, Luxembourg, and Germany (Fig. 1).

Figure 1. NATALIA Consortium.

First, the motivation and the concept behind the satcom system are presented. This is followed by an overview of the design process, with emphasis on the main challenges encountered during this process and the solutions to these challenges. Thereafter, the realisation of the NATALIA antenna is described, focusing on the general buildup and its key components. Next, the overall performance of the antenna prototype is illustrated. With this aim, a small selection of the measured far fields will be shown. This article concludes with an assessment of the success of the NATALIA project and an illustration of the future steps towards the development of a commercial product based on the antenna prototype described in this article.

2. DESIGN OVERVIEW

Mobile satcom designs in Ku-band face two major challenges:

1. One has to adjust the polarisation besides pointing the antenna beam, because most satellite services in Europe use linear polarised signals. This results in a highly complex polarisation agile design that proves to be quite a challenge, surely when considering a cost-effective realisation.
2. A line-of-sight connection between satellite and terminal, required for adequate signal reception, can never be guaranteed during normal operation due to blockage by buildings, trees, bridges, tunnels, trucks, etc. This implies that real-time reception for such applications is actually only possible for a limited time, thus one can speak at most of *near real-time* reception.

Point #2 cannot be solved by relying solely on the reconfiguration capabilities of the antenna design, as in case of point #1, but requires an overall system solution. The system concept is depicted in Figure 1.

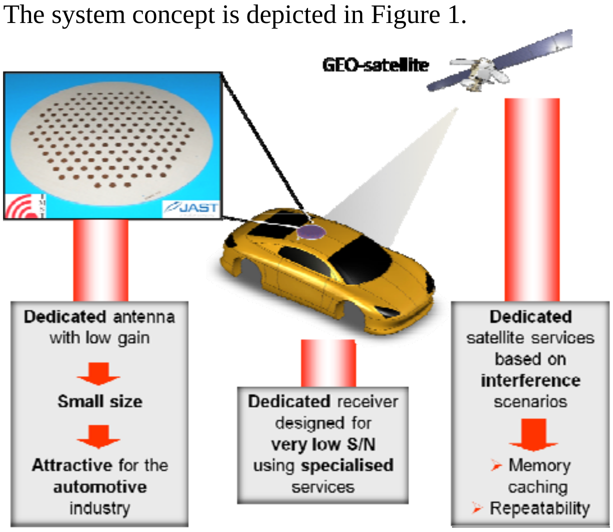

Figure 1. The NATALIA-concept: dedicated antenna & receiver (modem) & satellite services.

As one can observe in Figure 1, the complete system consists not only of an antenna front-end as envisaged here, but also of a dedicated receiver & dedicated satellite services that have been investigated and developed in a separate ESA-funded project. This aspect is quite important because without such services and a customised receiver/modem, the NATALIA antenna concept cannot become a commercial successful product.

The services and the receiver are designed to handle the blocking/interference scenarios that an automotive terminal experiences: multimedia contents are transmitted on an interleaving basis, repeated at certain intervals and stored in the modem memory of the car, which compensates for certain blockage periods. This also allows the user to 'customise' the information she/he wants to hear ('dedicated news').

Point #1 is of course the main focus of the NATALIA project.

The key requirements to be satisfied for the NATALIA front-end have been established after elaborate discussions with the car industry and service providers:

⇒ Operating frequency: 10.7 GHz – 12.75 GHz
⇒ Operation mode: Rx-only
⇒ Polarisation: linear
⇒ G/T: > -6 dB/K (Figure-of-Merit)
⇒ Cross polarisation discrimination: > 15 dB
⇒ Antenna size: 20 cm in diameter for Europe
⇒ Scan range: 20°- 60°in elevation from horizon, 0°-360° in azimuth
⇒ Size (~ 20cm Ø x 3cm thick) & weight (< 5kg).

Various concepts and RF-topologies for achieving simultaneously beam steering and agile polarisation have been evaluated with respect to complexity/cost, performance and size: RF-phase shifters in (M)MIC technology, and various configurations of beam forming and switching networks in combination with different antenna layouts [1]. On one side, this investigation revealed that only a full phased array approach, i.e. using a single RF-phase shifting control per antenna element, can deliver the desired beam scanning performance. On the other hand, one of the major bottlenecks of this antenna, the polarisation agility, has been investigated extensively, and different approaches have been analysed. This has resulted in a special beam steering concept in which the beam pointing and the polarisation adjustment are combined using <u>only</u> two RF-phase shifting devices (MMIC's) per array element [2,3,4]. This concept has been patented by JAST.

Moreover, the complete RF-design (antenna elements included) has to cover the complete Rx-band being 2 GHz wide, surely not a trivial task.

Since the number of electrical components is in general very high for a phased array concept, another important factor is the packaging density of the electronic components. At the same time, however, the front-end has to be also of 'small compact size'. Therefore, (M)MIC phase shifter devices have been investigated and a survey of off-the-shelf components of MMIC-components has been performed. This resulted in a GaAs MMIC customised design (called corechip, hereafter) that combines Low Noise Amplifier (LNA), phase shifter and digital steering logic.

The final system architecture is shown in Fig. 3 and the antenna aperture in Fig. 4: the array is planar and composed out of 156 dual polarised microstrip stacked patches arranged in a hexagonal grid. Both received orthogonal (linear) signals (V & H) are for each patch first converted into two circularly polarised components (left- and right-handed) via a 90° hybrid coupler and fed into a combined phase shifting unit (the corechips). These corechips constitute the tracking unit, which performs the beam pointing and polarisation adjustment simultaneously. The output RF-signals from all tracking units are again linearly polarised and combined in a corporate feeding network. The summed RF-signal is then routed to the down-converter, whose output (an L-band signal), is the input for the aforementioned dedicated receiver system, which interfaces with the microcontroller governing the phase shifters.

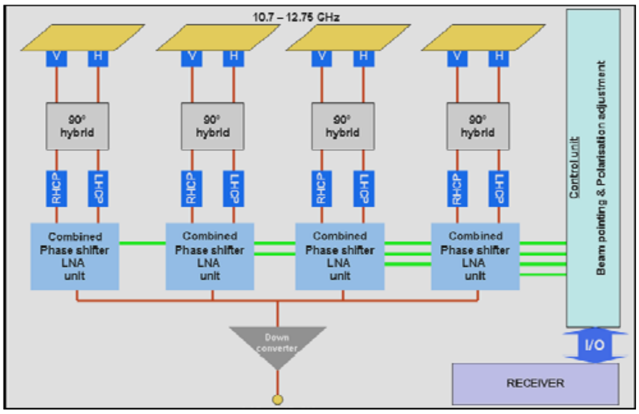

Figure 2. Schematic overview of the NATALIA topology.

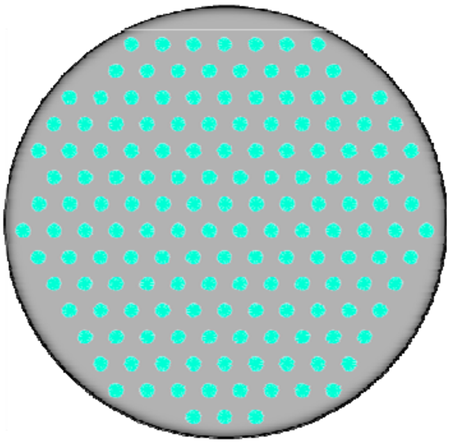

Figure 4. Antenna aperture.

Key components of the complete buildup are a highly optimised antenna aperture, a multilayer Printed Circuit Board (PCB) including various circuits like RF-feeding network, designed for mass production, and a dedicated MMIC-component that is the core element responsible for the beam steering of the array.

3. ANTENNA PROTOTYPE

The antenna has been implemented as a planar structure using standard multilayer PCB technology (Fig. 5). The combination of a compact planar PCB build-up and dedicated MMIC-components allows for an antenna that at the same time can be compact and cost-effective. The complete buildup is composed of 3 PCB's:

- Antenna PCB containing only the stacked patches.
- Core PCB that contains the feeding topology for the antenna elements (156 elements), the beam forming network, DC feeding network, digital steering network, 312 MMIC's, 3 Mini SMP-connectors, and 3 DC/Digital connectors.
- External PCB containing 3 Mini SMP-connectors, 3 DC/Digital connectors, 3-to-1 RF-combiner, DC Power converters, serial PC-connection, power connector, microcontroller & memory, down-converter (not yet installed for the prototype), RF-output port, and two mini fans.

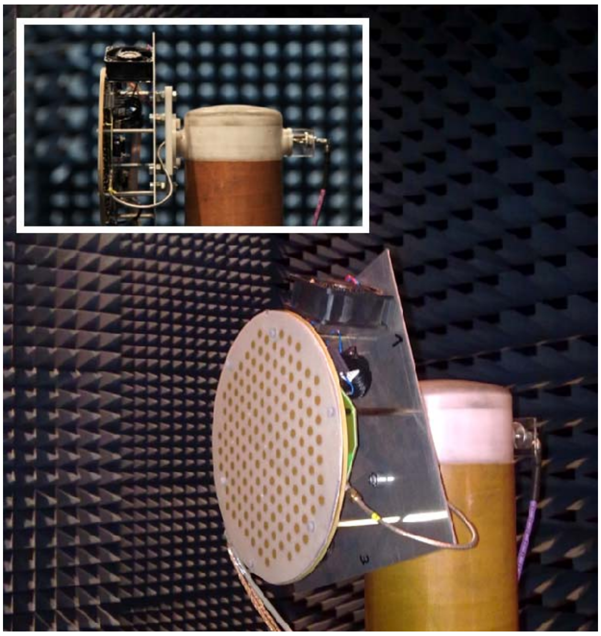

Figure 3. Prototype under test.

The GaAs-foundry technology of OMMIC in Paris was used for all MMIC-foundry runs. OMMIC offers several foundry processes, some of them capable of integrating not only RF-circuitry but also digital logic circuits. Combining digital logic, LNA and phase shifter within a single MMIC will reduce considerably the final cost of the antenna frontend and allows for maximal integration density. The final design of the corechip is shown in Fig. 6. It measures only 2.12 mm by 2.43 mm and is probably one of the smallest MMIC's of its kind. It contains the following circuits: a two-stage LNA (cascaded with the phase shifter), 4-bit phase shifter (180°, 90°, 45°, and 22.5°), 5-bit shift register, 4-bit latch, and digital input/output buffers. This component has been added to the portfolio of OMMIC [5] and is nowadays commercially available in two versions: bare die or packaged (QFN). It is one of the smallest of its kind on the market [6].

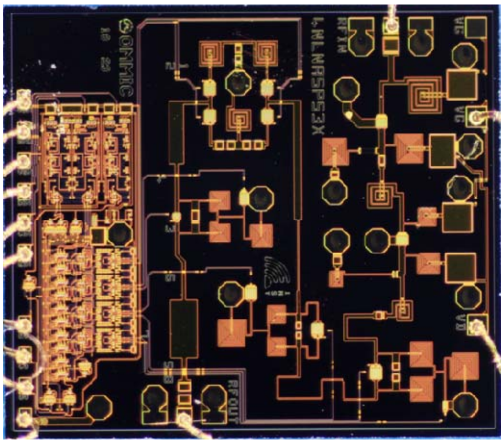

Figure 6. GaAs Corechip.

The Antenna & Core PCB buildup is extremely compact with a diameter of 21 cm and a height below 3 cm. A glance of the radiating element within the antenna aperture and the PCB buildup, including hybrid coupler, long via and the footprint of the corechip, are depicted in Fig. 7 [7,8].

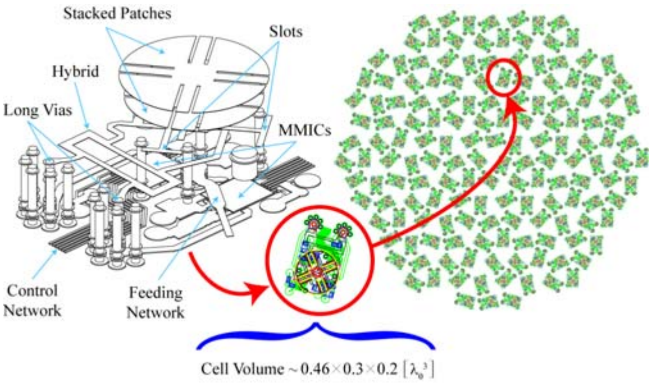

Figure 7. Radiating element within the antenna aperture.

The Antenna PCB is mounted on the Core PCB with screws and this complete piece is mounted onto the External PCB with help of 6 distance holders. The RF-signal is routed from the Core PCB to the External PCB via 3 mini SMP connectors and the DC/digital signals via 3 power connectors. All connections to the external world are performed via the External PCB (DC, digital input, RF-output). The prototype is mounted on a metal plate fixture for testing purposes (Fig. 5). An overview of the separate pieces of the antenna is depicted in Fig. 8. An external dedicated calibration/diagnostic system has been developed that can be used to debug the antenna for possible error in the phase shifters or for quality control during production.

The Core PCB consists of over 9 layers, and contains the slot and 90° hybrid coupler feeding the individual patches as well as both the RF and DC feeding networks. The layout for the MMICs and digital network is on the backside of the Core PCB. The Antenna PCB and Core PCB are screwed together.

The interface layer between Antenna & Core PCBs is at the level of the slots (aperture coupled microstrip patches [9]), which has the advantage that no galvanic connection between the Antenna PCB and Core PCB is required; hence, to screw the two PCBs together involves no special manufacturing step.

The steering of the antenna beam of the prototype is performed via a microcontroller mounted on the External PCB. This PCB communicates with a PC via a serial bus interface. For prototyping & evaluation purposes, a dedicated graphical user interface has been developed. This is an easy-to-use program that runs on a standard PC. It loads the desired phase settings given in a file (lookup table), via the microcontroller on the External PCB into the corechips on the command of the user. Later on, the lookup tables will be stored directly in the memory of the microcontroller.

The design of the Antenna, Core and External PCBs has been optimised as much as possible for mass production at this stage. Minimising the number of PCB layers (number of layers), the number of RF-components, and most important, using only the appropriate mass volume PCB process steps, contributes to a realiable and cost-effective solution.

The overall cost of the terminal is, besides the manufacturing costs of the Antenna, Core and External PCBs, for the larger part determined by the prices of the MMIC-components. As pointed out before, a customised development has been performed. For a consumer market where the number of products can be very large, MMIC-components can become relatively low in fabrication costs. For such high volumes, wafer surface becomes the dominant cost factor; hence not the design itself but its size is the critical parameter with respect to costs. Therefore, the MMIC-development focused on a highly compact design in order to arrive at the smallest chip size possible (Fig. 6).

This, together with the use of mass market PCB manufacturing techniques, is the first essential step towards a cost-effective front-end and a successful market introduction.

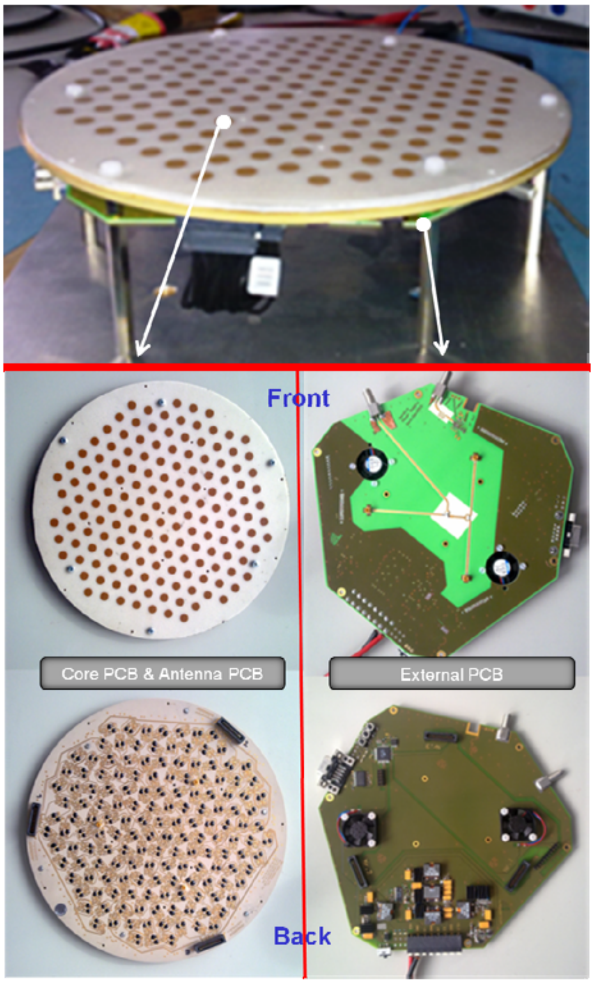

Figure 8. Buildup prototype.

4. ANTENNA MEASUREMENTS

The antenna has been extensively measured with respect to far field patterns, scanning performance, polarisation agility, G/T, spurious modes, and thermal behaviour. In this section, samples of the measured far field patterns are presented. The patterns have been determined in the anechoic chamber of IMST via far and near field setups (Fig. 9). The gain shown in all plots is the active gain, which includes the antenna gain, corechip LNA gain, losses in feeding network, transitions, etc.

Fig. 10 shows the scanning ability of the antenna for both CP (co-polar) and XP (cross-polar). It is clearly visible that scanning performance of the antenna is excellent. Other measurements (not shown here) show that the hexagonal array provides a good overall performance for different azimuth cuts. Further analysis of the measurements reveals excellent cross polarisation discrimination behaviour. At centre frequency, the cross-polarisation discrimination is larger than 20 dB in average with a worst case value of 17 dB at some specific pointing directions.

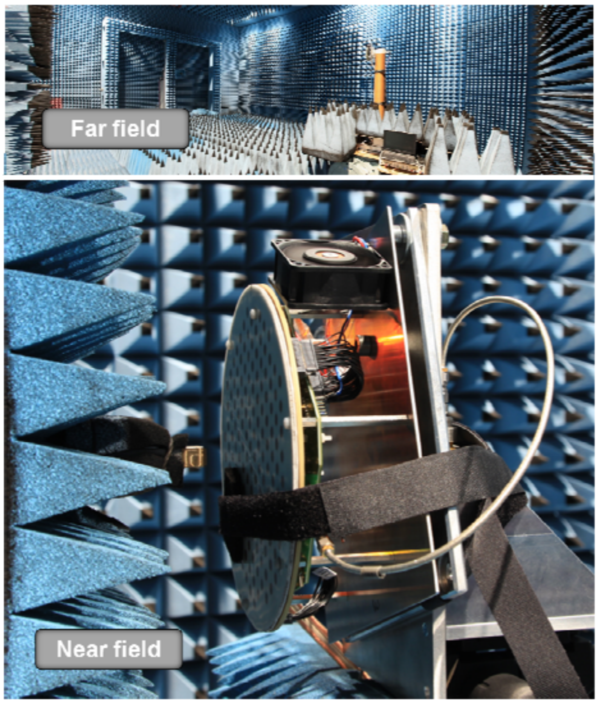

Figure 9. Measurement setups.

Fig. 11 and 12 illustrate the polarisation agility: the beam is pointed into a fixed direction and the polarisation is changed in regular intervals. These plots confirm the excellent performance of the antenna in this aspect. Also, the cross-polarisation discrimination is for all these cases again larger than 20 dB in average.

Near field scans have also been performed to verify the far field measurements and determine the 3D far field diagrams. Several 3D-radiation patterns are shown in Fig. 13 and 14. The findings of these measurements confirm the results of the far field measurements.

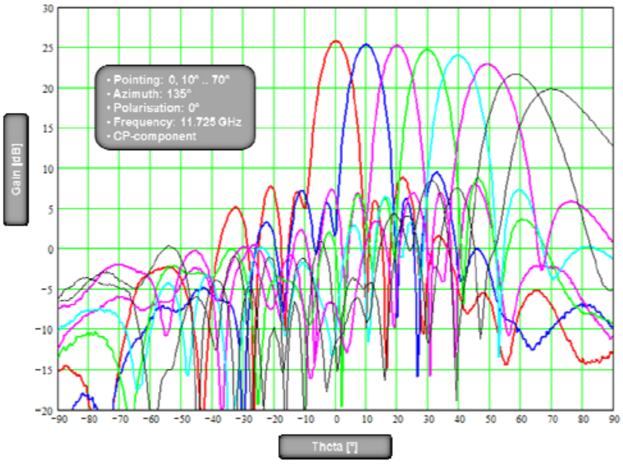

Figure 10a. Beam pointing in a fixed azimuth plane, CP-component.

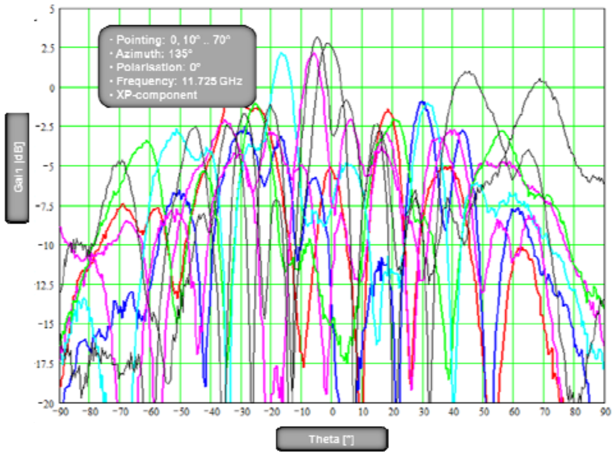

Figure 10b. Beam pointing in a fixed azimuth plane, XP-component.

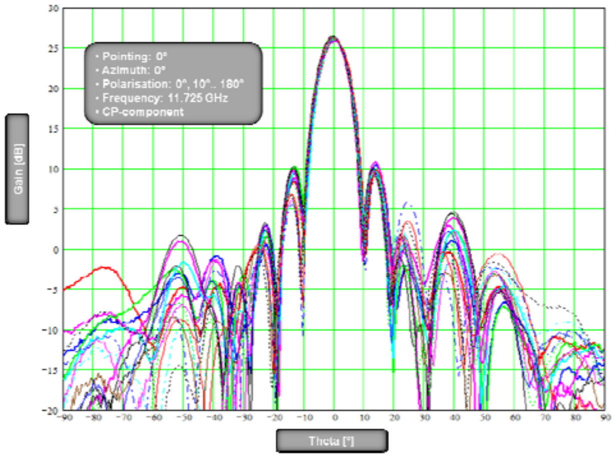

Figure 11. Polarisation adjustment in steps of 10° for pointing at boresight.

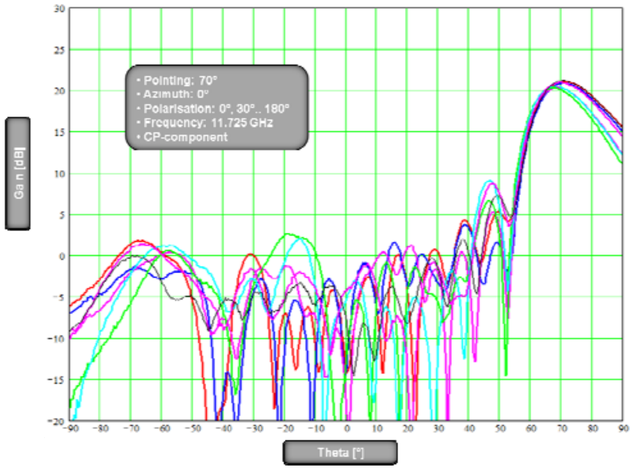

Figure 12. Polarisation adjustment in steps of 30° for pointing at 70° from boresight.

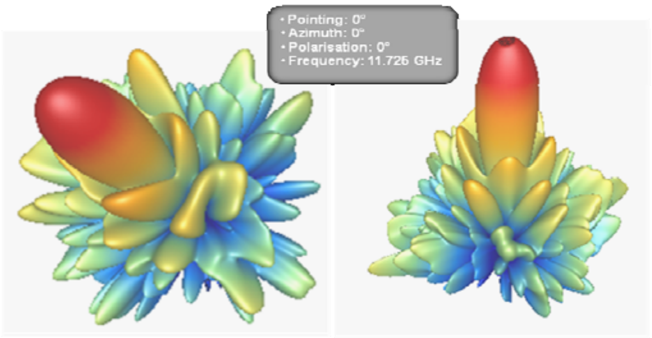

Figure 13. 3D CP-Pattern for pointing at boresight.

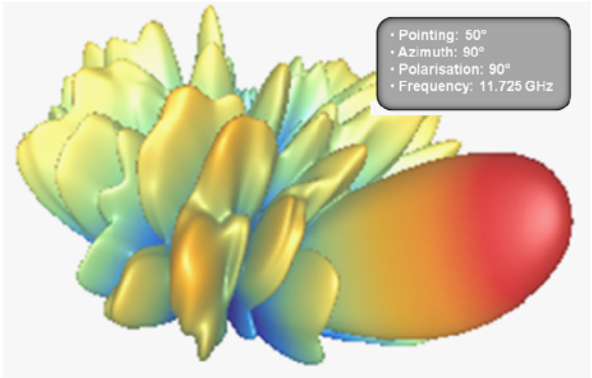

Figure 14. 3D CP-Pattern for pointing at 50° from boresight.

5. CONCLUSION AND PERSPECTIVES

This paper has presented an overview of the design process of the NATALIA array antenna, some of the main design challenges encountered during this process, as well as some of the measurement results that have validated the antenna concept and its practical realisation. In particular, the success of this validation is supported by the high quality of the measurement results which confirm the performance expectations and fulfil the key design requirements.

The antenna buildup is already designed for a major part with respect to costs (mass production) and size. Still, further optimisation of the buildup is however unavoidable to arrive at a fully competitive solution in terms of costs, and to move to the next stage; the production model, as illustrated in Fig. 15.

6. ACKNOWLEDGEMENTS

The authors wish to thank the ESA for funding and supporting the NATALIA project, under contract number 18612/04/NL/US.

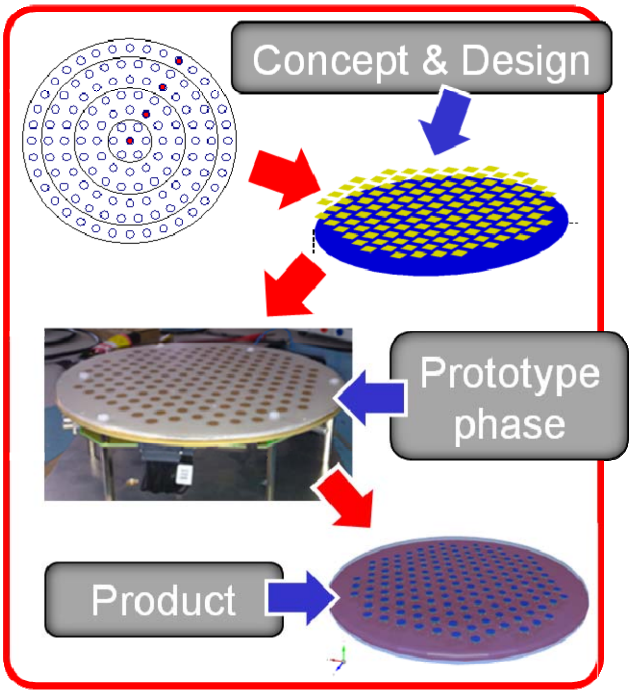

Figure 15. Development trajectory.

7. REFERENCES

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

[2] Vaccaro S., Llorens del Río D., Torres Sánchez R., Baggen R., *Low cost phased array for mobile Ku-band satellite terminal*, 4th European Conference on Antennas and Propagation EuCAP, Barcelona, Spain, April 2010.

[3] Baggen, L., Vaccaro, S., Llorens del Rio, D., Langgartner, G., *Compact phased arrays for mobile terminals*, International Semiconductor Conference CAS, October 2010.

[4] Baggen R., Vaccaro S., Llorens del Río D, Torres-Sánchez R., *First prototyping of a compact mobile Ku-band satellite terminal*, 4th European Conference on Antennas and Propagation EuCAP, Barcelona, Spain, April 2010.

[5] www.ommic.com

[6] Langgartner G., Baggen R., Vaccaro S., Smith D., *Dedicated GaAs Corechip for Mobile Satellite Ku-Band Terminals*, 32nd ESA Antenna Workshop, ESTEC, Noordwijk, Netherlands, October 2010.

[7] Torres Sánchez R., Mosig J. R., Vaccaro S., Llorens del Río D., *A compact and low cost elementary radiating cell for satellite broadcasting automotive receiving arrays*, 28th Progress in Electromagnetics Research Symposium PIERS, Cambridge, USA, July 2010.

[8] Torres Sánchez R., Mosig J. R., Vaccaro S., Llorens del Río D., *Design review of a compact and low cost elementary radiating cell for satellite broadcasting automotive receiving arrays*, 33rd ESA Antenna Workshop, ESTEC, Noordwijk, Netherlands, October 2011.

[9] Pozar, D. M., *Microstrip antenna aperture -coupled to a microstripline*. Electronic Letters, vol. 21, no. 2, pp. 49–50. 1985.