ABSTRACT

Among different solutions for mobile antenna systems, phased array antenna in general, cannot be considered as low cost especially in case if two-axis main beam scan is applied. Despite of this drawback regarding possible commercial application, this approach still remains attractive due to possibility to provide very low contour, high system agility, lower antenna aperture noise temperature and global coverage avoiding equator problem. This paper presents a flexible concept that among similar known solutions can be described as a cost effective. The antenna only receive terminal has been fully in house developed for trials on workbench platform that has to provide similar in flight motions for outdoor trials. The antenna terminal composed of 768 dual polarized elements operating in the range 10.95-12.75GHz is ready for an extensive anechoic chamber and field test campaign.

1. RATIONALE FOR A USE OF PHASED ARRAY IN SATCOM-ON-THE-MOVE (SOTM) APPLICATIONS

From functionality point of view, an active electronically scanned array system (AESA) presents an attractive solution for establishing a two-ways satellite link from a mobile platform. The major drawback that doesn’t allow this solution is spread in commercial applications, is the fact that pure phased array technology is still, despite of putting the decades of engineering efforts, far from a low or at least medium cost solution. It can be stated, on base of prices of commercially available counterparts based on pure mechanical or combined electromechanical systems. Therefore, employment of such system of higher cost could be justified for an airborne application where the wind drag reduction, agility and reliability are essential. An AESA system inherently poses possibility to offer order of magnitude better accomplishment of all aforementioned factors, but together with elevated costs, difficulties in design, fabrication and testing.

Moreover, design of an AESA system for a SOTM application, faces with some requirements that this system usually applied as radar is not required to accomplish, such as polarization tracking (polarization diversity) and fulfillment of pattern shape regulations [1]. As an example, following analysis demonstrates some strong points of using this concept.

The selected antenna structure consists of 768 dual polarized elements arranged on a triangular lattice across an octagonal aperture. This antenna configuration offers a high degree of radiation symmetry which together with the full electronic pointing system increases the antenna coverage area regarding off-axis EIRP. Comparing this antenna configuration with traditional uniform lattices, it can be seen how in the case of uniform lattices with mechanical pointing systems the displacement along the equator increases the main lobe width, which provokes the off-axis regulation non-fulfilment. On the Fig. 1 are depicted the apertures taken into consideration.

![Figure 1. Octogonal aperture with triangular lattice element distribution and clasic rectangular panel with rectangular element distribution.](image-url)
On the fig. 2 is depicted a comparative analysis between following antenna structures:

- Octagonal Aperture, Triangular Lattice and two-axis electronic scan.
- Rectangular Aperture, Uniform Lattice and two-axis mechanical scan.

The presented results show the EIRP over geostationary arc when the antenna is moving 30º west along equator with regard to the target satellite. As can be seen in the Fig. 2, the radiation pattern of the octagonal aperture almost doesn’t change when the antenna moves along longitude. On the contrary, main lobe width of the mechanical pointing rectangular aperture gets wider and also its side-lobe magnitude increases. This fact provokes that the traditional rectangular configurations can’t operate along equator and low latitudes; meanwhile the proposed solution offers a wider coverage area.

In practice, rectangular panel antenna with one dimension rather extended could have increased its geographical coverage if some smooth amplitude taper is applied, but equator problem still remains. At the same time AESA with simple uniform distribution could satisfy regulations in bigger geographic area. The reference values for EIRP, employed in calculations, were taken according the EIRP values of the terminals available on the market (ViaSat, Starling).

### 1.1. Rationale for reaching a cost effective solution

As it was pointed out, generally speaking an AESA system is high cost solution. In order to briefly justify this, it would be possible to list following reasons [2]:

- Wide scan angle range implies that radiating element should be placed at inter-element distances near to half wavelength resulting in a very limited volume for RF front-end, associated control and power supply electronic circuit integration.
- Especially in case of transmitting antenna, dissipation problem arises as very serious,
- Calibration process could be very large and complex.

These aforementioned facts were identified as major contributors to the overall high price of such system, taking in account that number of radiating elements for a SOTM application could reach up to 2500 elements. A proper selection of technology to employ in design and fabrication would lead partially to cost effective solution. In relation with this, a complete printed multilayer antenna panel seems to be very attractive solution, especially in combination with MMIC. In practice, fabrication of a large multilayer board is facing with tolerances that become more critical at higher frequencies as well as quality of buried lines and via-s. This could be overcome by implementing some modular approach reducing the maximum multilayer board size. Despite of this, prices of available GaAs MMIC still do not permit to lower drastically overall antenna cost. Cheaper MMIC-s, based on SiGe technology, still do not exhibit usable performances with respect to the noise figure and RF power. Employment of SiGe technology results in considerable antenna oversizing for the same G/T and EIRP. The historical heritage from radar development leads to a vertical unit integration approach as a less risky with variety of possibilities for major problems solutions.

### 1.2. Common or separated panels

A common transmitting and receiving panel seems to be more attractive solution due to the fact that occupies less volume in comparison with terminal based on separated antennas. A common panel means also a common wider broadband element to design and need to efficiently couple transmitting and receiving RF chain on it, together with filtering section. All these facts make even more complex design and fabrication, decreasing already reduced volume available for integration. On the other hand, separated transmitting panel permits optimization of radiation properties, in order to accomplish pattern mask regulations, while on the receiving side independently can be reduced noise and associated losses obtaining maximum G/T.

As an example, a receiving antenna array terminal that has to provide nominal G/T of 10dB/K at Ku band in case of common aperture, assuming optimistically only

![Fig. 2.EIRP over geostationary arc when antenna is moving along Equator. Top figure: Octagonal aperture with triangular lattice. Bottom figure: Rectangular aperture with uniform lattice.](image-url)
0.5dB diplexer loss, has to include approximately 250 extra radiating elements than separated antenna array in order to conserve same G/T value.

2. BUILDING BLOCK CONCEPT

The principal aim of the project was to develop and test a fully integrated and functional engineering model of receiving AESA. Complete terminal implementation is done using COTS components, while during the design phase were performed research activities with objective of defining a preferable MMIC architecture for possible future implementation and cost estimation. Further in the paper will be discusses a bit more the use of COTS component vs. MMIC, with emphasis on the overall price and dimensions.

This concept is based on modules that can fit one into the other, providing RF signal flow without using expensive connectors. The modules can also be resized with no additional engineering efforts, in order to provide different terminal sizes without having impact on its overall height. The implemented concept is completely valid for transmitting antenna array case.

The major applied concept advantages can be summed up as following:

- Full linear polarization tracking performed at radiating element level without the need to additional polarization transformer block
- Fully integrated antenna front-end without using any RF connector
- Low cost IF combining network based on commercial available circuit
- Low cost LO distribution network at RF level
- Scan range within a cone of +/-70 degrees with respect to vertical
- Phased shift control performed by using DDS at IF level
- Developed fast (instantaneous) calibration procedure for one beam pointing angle.
- Building blocks modular approach permits different antenna sizes with minor hardware changes while the terminal height is conserved
- Interface with aircraft inertial system without need for additional pointing acquisition system (PAT).

The next set of figures shows in more clear way the applied concept. Fig. 3 gives a cross-section block diagram view of the concept where can be identified the major blocks that comprises antenna array. The contact between the RF front-end and top and bottom panels is provided by printed exciters and mechanical guidelines. The excitors integrated with RF chain in the same board enter into the corresponding cavities filled with dielectric materials on the top and bottom panel.
On the Fig. 6 are presented two different artistic views on the complete Ku only Rx AESA terminal.

2.1. Radiating element

Linear polarization tracking is performed by combining two circular polarized waves with opposite sense. The frequency invariant phase shift between them results in polarization rotation. The advantage of this approach is that it is not necessary to implement any polarization rotation block, because wave rotation is performed directly at the radiating element level. Also, it is quite suitable for transmitting antenna case, where it is not necessary to change amplitudes of the RF chains.

![Figure 7. Dual CP radiating element concept](image)

On the Fig. 7 is depicted the concept of the employed radiating element and on the Fig. 8 its real implementation into array panel. Some of the radiating elements are filled with C-Stock dielectric material. The whole panel is made of aluminum as one peace by electro erosion treatment.

![Figure 8. Radiating element implementation into array panel](image)

On the next set of figures are presented experimental results from the breadboard making phase. The fig. 9 shows the linear polarized co-polar and cross-polar measured radiation pattern. It can be observed that it was achieved very smooth elevation gain roll-off, which is quite suitable for total electronic scan operation. On the fig. 10 is presented achieved satisfactory matching within operational range.

![Figure 9. Linear polarized co-polar and cross-polar measured radiation pattern of the single element](image)

![Figure 10. Measured $S_{11}$ at one CP radiating element port](image)

2.2. AESA computed radiation properties

AESA radiation scan properties prediction is performed using embedded single element radiation pattern obtained from analysis of an element surrounded by other ones in an infinite large array. On the Fig. 11 is shown the computed typical results of the main beam scan expected radiation properties.

It can be denoted that the main beam scan range reach 70 degree angle without appearance of significant level of side and grating lobes.

![Figure 11. Computed prediction of the AESA main beam scan radiation properties](image)
2.3. RF block

On the Fig. 12 is depicted the RF front-end conceptual block diagram. LNA stage is realized by discrete GaAs transistor. Manufacturer declared noise figure is below 0.4dB at 12 GHz. Price of one unit is 0.3€. These performances couldn’t be obtained with any MMIC amplifier including GaAs and SiGe circuits – GaAs MMIC have high price and SiGe circuits have noise figure 1dB higher.

Lower noise figure is available with die transistors but (in order to achieve comparable transistor price) high serial production of antenna units has to be guaranteed. As a second LNA stages, IQ demodulator, and LO amplifier, SiGe MMIC can decrease antenna price (in the future) but MMIC development cost and time should be compensated by the high serial production.

![Figure 12. RF front-end block diagram](image)

In order to decrease sensitivity of the antenna performances from production process and component tolerances, fast calibration process is enabled. Received signal is down converted by IQ demodulator and microwave filter is omitted. Phase shift is performed by the second LO signal. Second LO signal is generated by DDS circuits. Phase of the second LO signal is controlled by the digital words. During the normal operation process second IF signals are summed by passive power combiners. During the calibration process 5MHz reference is applied at the combiner outputs and divided between all Rx elements. Received signal and 5MHz references is guided to phase detector and phase of DDS is adjusted in such a way that phases between reference and received signals are 0 degree. Phases of DDS signal are memorized together with beam position and operating frequency. Calibration process is performed simultaneously and independently at all radiating elements, which means that EM coupling between elements is included.

The next set of photos at Fig. 13 shows different steps within the process of RF front-end fabrication prior integration into array.

![Figure 13. Blocks of 5 elements RF chains fabricated (top), Laboratory workbench for RF block checking (middle), RF block ready for integration (bottom).](image)

2.4. LO distribution and capturing system

LO signal reaches each RF front-end through near-field transmitting and capturing sub-system, consisting of an open waveguide array depicted on Fig. 14 and bottom linear polarized panel array with identical element distribution as the top antenna array panel (Fig 14, bottom)
The principal role of this system is to “pitch” a sufficient portion of the LO power to saturate LO amplifier and to provide sufficient level for mixer at each antenna RF front-end.

Figure 14. LO distribution and capturing sub-system. Bottom view of open waveguide array (top figure) and bottom capturing panel (bottom on the left), which has the same distribution of elements as top antenna panel (bottom on the right).

Figure 15. Experimental adjustment of the LO distribution system. Proximity of the open waveguides and bottom panel, provides a strong coupling and significant field variation in the space between them. Due to the fact that margin of input power for LO amplifier to be kept in saturation is about 20dB, at the same time, this value is permitted value of variation of captured power at each bottom panel output. Besides simulation it was confirmed experimentally on the workbench with near-field probe connected with amplifier, which is presented on the Fig. 15. The total RF power introduced into open waveguide array was 25dBm.

2.5. Phase shifting and calibration sub-system

In order to avoid high price of Ku band phase shifter, received signal is down converted to IF frequency and further processing is performed by low frequency cheap components. Price of Ku band phase shifter is one order higher than price of Ku band frequency mixer. Losses introduced by Ku band phase shifter are in the same order as the losses of frequency mixer. LO signal is generated by common oscillator and price of LO generator is divided between 1500 elements.

Figure 16. Phase shifting and calibration sub-system

In the case that Ku band phase shifters are applied, proposed calibration method should employ Ku band phase detector. Ku band reference signal has to approach all radiating elements in the same phase. Price of Ku band detector and temperature sensitivity of the components significantly decrease reliability of this method. For that reason calibration process is performed at IF frequency. Prices of the components are very low and complete processing could be incorporated in integrated circuit realized by mature silicon technology. Phase detector is realized by classic D flip flop and other components (amplifiers and switches) don’t overcome prices of few cents. Phase shifts are performed by cheap DDS circuit with two order higher resolution than any other digital phase shifter. DDS are easily controlled and calibrated by microcontroller that could be common component for all receiver chains belonging to one linear sub-array. All DDS, phase detectors and microcontroller belonging to one sub-array could be replaced by unique FPGA simplifying the hardware significantly. On the Fig. 16 is shown complete phase-shifting and calibration sub-system.

3. BREADBOARD EXPERIMENTAL RESULTS

In order to prove selected AESA concept it has been fabricated a small breadboard model consisting of seven radiating elements presented on the Fig. 17.
4. EXPECTED PERFORMANCES ON BASE OF BREADBOARD MEASUREMENTS AND DESIGN

The following table (Tab.1) summarizes the expected performances of the complete antenna.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>G/T</td>
<td>8dB/K</td>
<td>In bore sight</td>
</tr>
<tr>
<td>Scan Range</td>
<td>Within a cone of +/-70 degrees wrt. Vertical</td>
<td>Without appearance of high grating lobe level</td>
</tr>
<tr>
<td>Polarization</td>
<td>Full linear polarization tracking</td>
<td>XPD&gt;25dB Terminal works also with both sense of CP</td>
</tr>
<tr>
<td>Frequency Range</td>
<td>10.95-12.75GHz</td>
<td></td>
</tr>
<tr>
<td>Instantaneous bandwidth</td>
<td>4MHz</td>
<td>Extendable with minor hardware changes</td>
</tr>
<tr>
<td>Overall Dimensions</td>
<td>Diameter: 48cm Height: 26cm</td>
<td>Height below 15cm in case of using MMIC</td>
</tr>
<tr>
<td>Power consumption</td>
<td>1440W</td>
<td></td>
</tr>
</tbody>
</table>

Table 1. Expected performances of the complete AESA

5. BUILDING BLOCK ANTENNA ASSEMBLY

As it is has been explained, RF front-ends jointly with phase shifting and calibration boards form rows of different lengths depending of corresponding number of radiating elements within projected octagonal aperture.

Figure 17.7 elements breadboard phased array and trials in TTI anechoic chamber.

Figure 18. Measured pattern for 45 degrees main beam scan at 11GHz for horizontal (top diagram) and vertical polarization.

An extensive test campaign served to refine calibration process, control software and to prove taken calibration and polarization rotation concept. On the diagrams at Fig. 18 are presented as typical, results of measured patterns while main beam is scanned towards 45 degree for horizontal and vertical polarization.

Figure 19. RF front-ends and phase-shifting board placement on bottom panel.

Its placement into top panel is performed by simple mechanical guidelines (Fig.19). The next step is mounting of lateral shelter walls, and spatial cable distribution for IF outputs, clock distribution etc (Fig.20 top). On the middle photograph is depicted placement of bottom antenna panel using specially designed manual elevator accessory. Finally, the bottom
waveguide LO distribution system is attached (bottom photograph).

![Figure 20. Placing of the shelter wall and cables distributing (top); bottom panel placing (middle); bottom waveguide LO system attaching.](image)

The filling of the circular cavities with dielectric material on the top antenna panel is performed at the end of assembly, which is shown on the Fig. 21. On the Fig. 21 is presented complete assembled array with appropriate cooling system.

![Figure 21. View on the assembled antenna aperture.](image)

6. CONCLUSIONES REGARDING COST EFECTIVNES OF THE CONCEPT

It has been presented a novel concept of fabrication of an AESA that was guided with idea to reduce as much as possible fabrication cost, offering a system capable for the use in SOTM applications. The system, after laboratory tests is prepared for an extensive trial campaign that will include tests on the aircraft test bed. At this point it is necessary to review current fabrication cost based on COTS components and possible MMIC (Tab. 2).

<table>
<thead>
<tr>
<th>Cost per element including associated mechanical parts fabrication and mounting</th>
<th>COTS</th>
<th>MMIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost of antenna panels fabrication, associated mechanical and waveguide parts, power supply block</td>
<td>50€</td>
<td>130€</td>
</tr>
</tbody>
</table>

It can be concluded that COTS approach provides significantly lower fabrication cost at the expense of the overall terminal height of 26cm. The employment of more expensive MMIC-s would lead to significantly lower profile terminal below 15cm.

7. REFERENCES
