# APPLICATIONS OF HYBRID PHASED ARRAY ANTENNAS FOR MOBILE SATELLITE BROADBAND COMMUNICATION USER TERMINALS

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## ABSTRACT

This paper presents an overview of the results of the development of Ku-Band Low-Profile antennas for Mobile Satellite Communications. The antennas are based on a hybrid mechanical-electronic steerable array architecture. Different prototypes have been developed and demonstrated. We present the results for two receive-only antennas for satellite broadcasting applications and two Transmit-Receive antennas for broadband bi-directional communications. Both types of antennas are suitable for integration in ground vehicles and aircrafts.

## 1. INTRODUCTION

The demand for worldwide broadband mobile connectivity is growing constantly. This translates in an increasing request of mobile satellite terminals and the possibility to install them in any type of vehicle drives the requirement to build user terminal antennas with small size and height, reliable and at an affordable price. Typical antennas for mobile satellite broadband systems are based on fixed beam reflectors or Direct Radiating Apertures which are mechanically steered. These antennas are quite bulky and require heavy and expensive mechanical positioners that can stand high accelerations and speeds. On the other hand fully electronically steerable antennas offer an ideal solution for mobile applications, but they are still very expensive and they have not yet been applied to commercial systems.
In between these two extremes, JAST has developed a hybrid phased array antenna which steer the beam mechanically in azimuth and electronically in elevation and polarisation (see Figure 1). The combination of mechanical and electronic steering allow to design antennas with a low-profile form factor a very simple mechanical structure with a single axis of rotation and to reduce the number of active components by a square root factor with respect to fully electronically steerable antennas. Without requiring additional volume, the Antenna Control Unit (ACU) is embedded in the antenna structure.
These factors allow manufacturing user terminal antennas at a very competitive price, with high reliability and a form factor that is compatible with almost any type of vehicle.
Different types of antennas based on this architecture have been developed for different applications and are currently under industrialization for first commercial applications

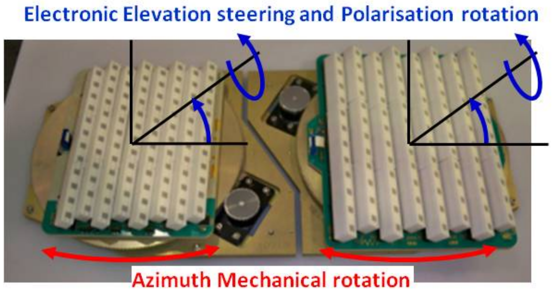


Figure 1. Hybrid phased array antenna.

## 2. ANTENNA ARCHITECTURE

A block diagram of the antenna structure is shown in Figure 2. The antenna is composed by four main subsystems, the radiating aperture, the Antenna Control Unit (ACU) and sensors, the power supply and the mechanical structure that allows the integration of the subsystems and the mechanical rotation in azimuth. The beam steering and polarization tracking is based on the information of attitude sensors (gyroscopes) onboard the antenna and a closed control loop on the quality of the received signal.
The antenna aperture includes the radiating elements, beam forming networks and RF electronic components for amplification and electronic beam steering.
The RF architectures of the Receive (Rx) and Transmit (Tx) aperture are shown respectively in Figure 3 and Figure 4. Both Rx and Tx chains integrate distributed amplification stages, respectively Low-noise and High-power. The Rx BFN includes LNAs also very close to the radiating element to maximize the signal to noise ratio. The pair of phase shifters integrated in each row of the antenna provides simultaneous control of polarisation angle and elevation beam steering, which is operated synchronously for Rx and Tx arrays. Each channel is connected through a rotary joint to the RF electronics (Up/Down converter) and then to the modem.
From this general architecture three different antenna

models have been developed for different applications. The details of these antennas and their performances are presented hereafter.

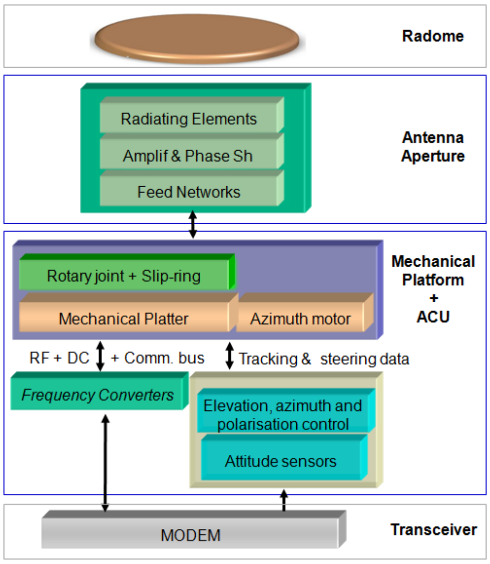

Figure 2. Antenna Architecture.

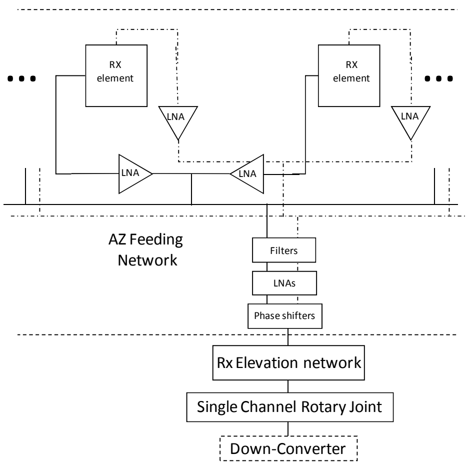

Figure 3. Antenna Rx chain structure.

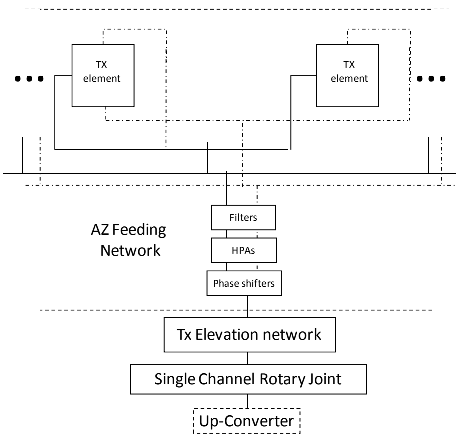

Figure 4. Antenna Tx chain structure.

## 3. RECEIVE-ONLY ANTENNA FOR TV/ MULTIMEDIA BROADCA-STING ON BOARD VEHICLES

The first model realised is a Rx-only antenna for reception of multimedia content from Ku-band broadcasting satellites on board vehicles. This model has been developed in the frame of the ESA co-funded activity HiSat [1]. The details of the antenna implementation have already been presented in previous papers (see [2] and [3]) and this paper presents last improvements and results.

The radiating aperture is based on a basic module of 8x12 elements. More modules can be arranged together to achieve different antenna sizes and level of performances to fulfill specific system requirements. This approach allows the flexibility to apply the design to different applications. Two different antennas with different size have been demonstrated for two different applications.

### 3.1. HiSat-30R small aperture Rx-only antenna

The first antenna model is based on a single module and fit in a package of 35 cm of diameter and 8 cm of height. The antenna has been fully validated in laboratory and an example of the measured far field patterns are shown in Figure 7 and Figure 8. As it can be observed from the Azimuth cut, the small dimension of the aperture generate a beamwidth of several degrees, The operational demonstration of the antenna has been realized in combination with the "Ku-mobile" system, developed by the Fraunhofer IIS in the frame of another ESA activity. The system uses spread spectrum and interference cancellation techniques to allow the reception of multimedia information from Ku-band satellites even with very small antennas. A custom integration has been required to interface the antenna with the Fraunhofer system. The ACU of the antenna has been customised to interface with the Ku-mobile receiver and use the C/N information to track the satellite position in a closed loop approach.

The antenna with the rest of the hardware set used for demonstration is shown in Figure 5.

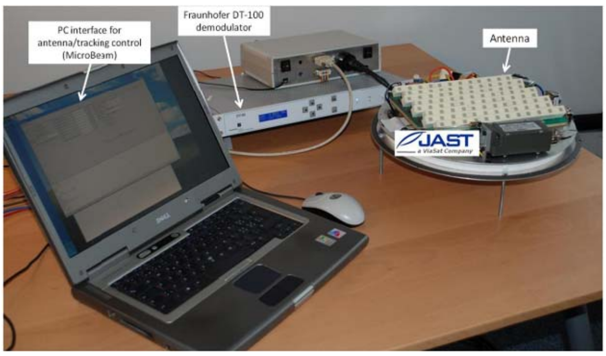

Figure 5. Testbed of HiSat-30R antenna.

The system has been installed in a car (see Figure 6) and has been demonstrated in several occasions in the frame of public events and with potential customers.

Figure 6. HiSat-30R antenna installed on car.

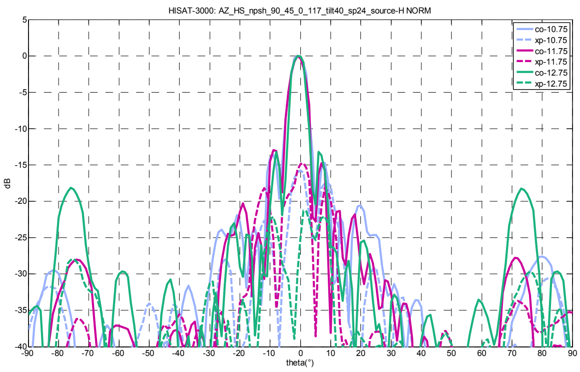


Figure 7. HiSat-30R radiation pattern. Azimuth cut for antenna pointing at an elevation of 45°.

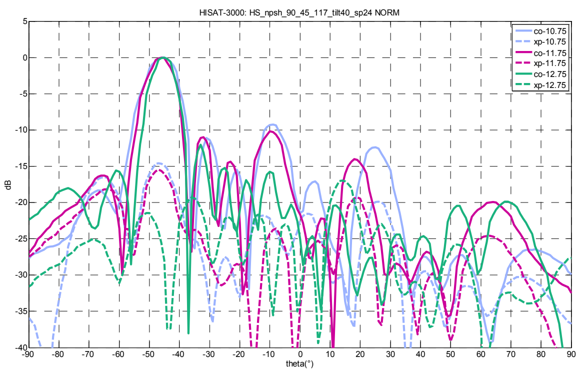


Figure 8. HiSat-30R radiation pattern. Elevation cut for antenna pointing at an elevation of 45°.

**3.2.** HiSat-60R large aperture Rx-only antenna

The second prototype realized is based on the combination of 4 modules placed in a 2x2 configuration (see Figure 9). The total aperture is approximately 55x45 cm and fit in a package of 70 cm of diameter and 9 cm of height. This size of aperture provides sufficient performances to be used with commercial DVB-S receivers.

In this case the control system has been customised attaching a DVB-S tuner directly to the ACU inside the antenna. The control software has been customised to use the satellite identification and the BER level in order to track a specific satellite position in a closed loop approach.

The radiation patterns of this antenna are shown in Figure 10 and Figure 11. We can observe that at high frequency the antenna presents some high sidelobes, however these are still about 20 dB lower than the main lobe and occur at angles that are close to the horizon, thus not critical for interferences from other satellites.

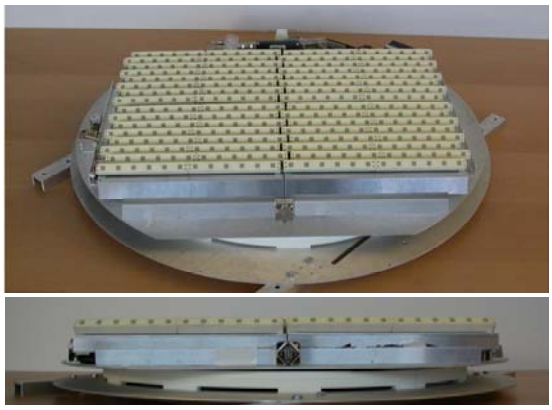

Figure 9. HiSat-60R antenna.

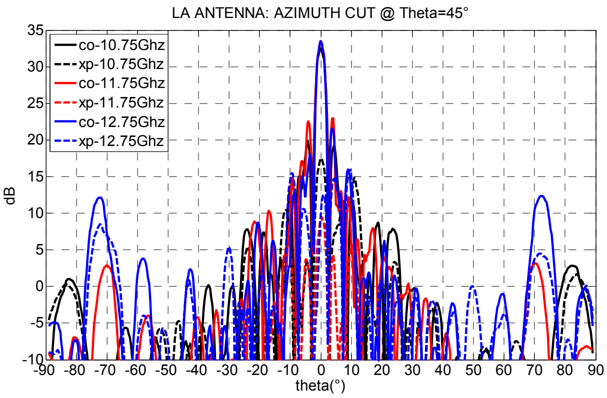


Figure 10. HiSat-60R radiation pattern. Azimuth cut for antenna pointing at an elevation of 45°.

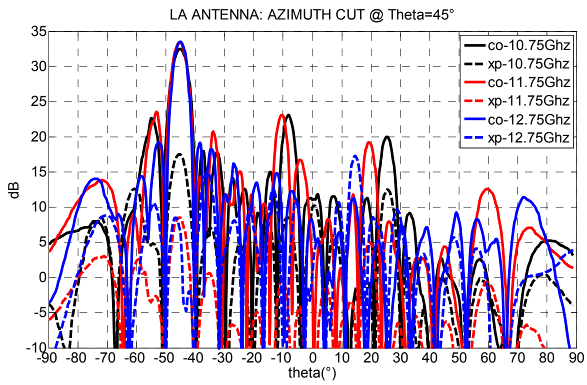


Figure 11. HiSat-60R radiation pattern. Elevation cut for antenna pointing at an elevation of 45°.

Also in this case the antenna has been installed in a car (see Figure 12) and field trialled to validate the tracking system and the other functionalities in operational conditions.

Figure 12. HiSat-60R antenna installed on car for field trials.

A sample of the level of received signal during mobile operations is shown in Figure 13. Apart for zones where the antenna reception was affected by blockage (buildings, trees and electrical poles), the Signal to Noise Ration (SNR) shows a very stable behaviour with respect to the azimuth and elevation variations.

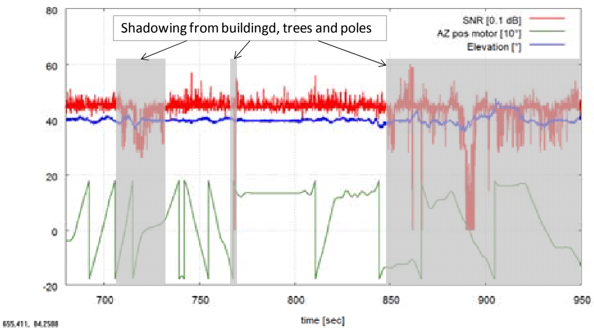


Figure 13. HiSat-60R. Sample SNR and sensor response during operation.

The main specifications of the HiSat-30R and HiSat-60R antennas are listed in Table 1. Currently the commercialisation of the HiSat-60R model is under evaluation with some potential customers. Based on market research, the HiSat-60 antenna presents some unique interesting features for application to SatTV terminals for vans, motorhomes and trucks.

## 4. DUAL APERTURE TX/RX ANTENNA FOR BROADBAND COMMUNICATIONS

To fulfill applications requiring bidirectional communications, a Tx aperture has been developed and used in combination with the Rx aperture to implement a dual–aperture bi-directional antenna.
The Tx aperture is based on the architecture shown in Figure 4 and cover the Ku-Tx band (14.0-14.5 GHz). The physical implementation is very similar to the Rx aperture, but special care has been applied to the integration and cooling of the power amplifiers.
The mechanical structure is composed of two plates rotating simultaneously. The ACU of the antenna is split into two parts integrated respectively in the two plates.

Table 1. RX-only Specifications.

| **RX-only HYBRID PHASED ARRAY** | | | |
|---|---|---|---|
| **Parameter** | | **Specification** | |
| | | **HiSat-30R** | **HiSat-60R** |
| G/T | @ 20° elev | > 2.0 dB/°K | > 8.0 dB/°K |
| | @ 45° elev | > 5.0 dB/°K | > 11.0 dB/°K |
| RX Frequency Band | | 10.7 to 12.75 GHz | |
| Polarization | | Linear with electronic polarization tracking | |
| Cross Polarization Rejection | | > 15 dB | |
| Scanning Range | | 360° in Azimuth<br>20° to 90° in Elevation | |
| Antenna diameter | | < 35cm | < 70 cm |
| Antenna Thickness | | < 8 cm | < 9 cm |
| | | (including radome and mechanical platform) | |

The two parts of the ACU are connected together in a master/slave configuration. The Rx aperture acts as master and ensures that the antenna is pointing correctly to the satellite. The Tx aperture is controlled as a slave and will point the beam in the same direction.
The first realized prototype of the dual aperture antenna is shown in Figure 1.
The dual aperture architecture allows the flexibility to design different aperture sizes for Tx and Rx depending on the specific application needs. As example a second version of this antenna with a larger Rx aperture for increased G/T performances is currently under realisation to fulfill the requirement of a specific application (see Figure 14).

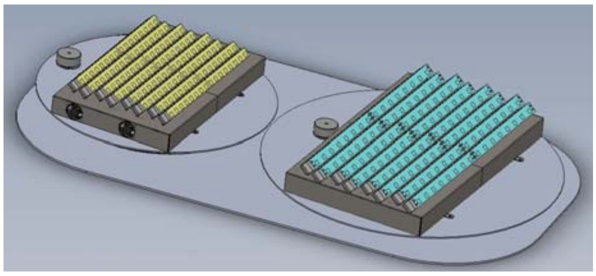

Figure 14. HiSat-35TR antenna model.

The main targeted application of this type of antennas is for installation on the fuselage of small aircrafts and small jets to allow in-flight broadband connectivity. The typical hardware set to be installed in the aircraft and the possible installation of the antenna on a small piston engine aircraft is shown in Figure 15.
This type of installation can allow worldwide broadband connectivity when used in the ViaSat Yonder® network (see coverage in Figure 16).
The reference specifications of the HiSat-30TR antenna are listed in Table 2.

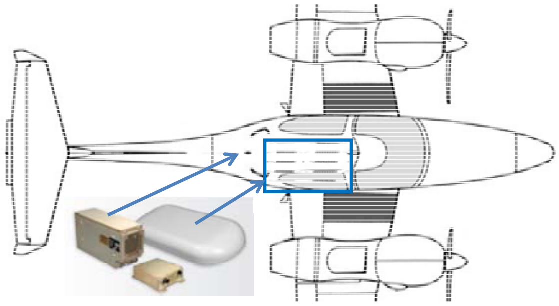

Figure 15. Possible installation of the HiSat-30TR antenna on a small aircraft.

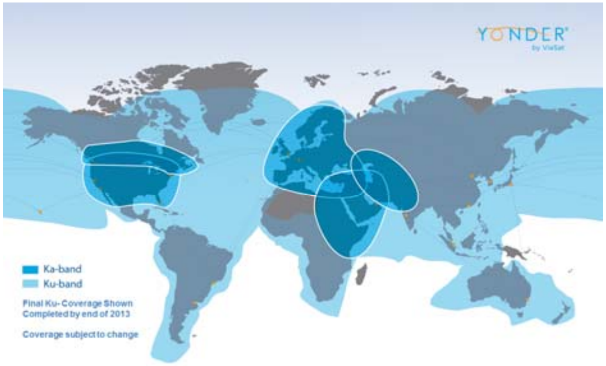


Figure 16. ViaSat Yonder® coverage.

Table 2. Dual aperture TX/RX-only Specifications.

| HiSat-30TR antenna | | |
|---|---|---|
| **Parameter** | | **Specification** |
| RX Frequency Band | | 10.70 to 12.75 GHz |
| TX Frequency Band | | 14.00 to 14.50 GHz |
| G/T | @ 20° elev | > 2.0 dB/°K |
| | @ 45° elev | > 5.0 dB/°K |
| EIRP | @ 20° elev | > 28.5 dB/°K |
| | @ 45° elev | > 31.5 dB/°K |
| Polarization | | Linear with electronic polarization tracking |
| Cross Polarization Rejection | | > 15 dB |
| Scanning Range | | 360° in Azimuth<br>20° to 90° in Elevation |
| Antenna diameter | | ≈ 40 x 70 cm |
| Antenna Thickness | | < 9 cm<br>(including radome and mechanical platform) |

## 5. SINGLE APERTURE TX/RX ANTENNA FOR BROADBAND COMMUNICATIONS

For applications on platforms with a limited footprint, a dual aperture antenna can require too much surface and it can be impossible to install. To overcome this problem we have developed a version of the hybrid array that integrates in the same surface both Rx and Tx functions [4]. The Rx and Tx elements are interleaved in the same surface and the entire radiating aperture is used for both bands. The elements are interleaved with spacing in the transversal axis lower than half wavelength at the highest frequency of the system band (i.e. 14.5 GHz) (see Figure 17).

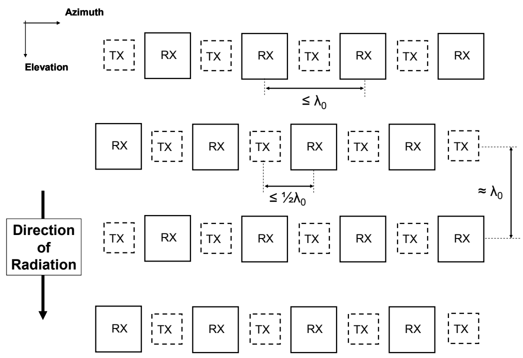


Figure 17. TX/RX array elements distribution.

The architecture of the antenna, shown in Figure 18, is very similar to that of the dual aperture antenna, but combined together on a single platter and using a dual channel rotary joint to transfer the signal from the rotating to the static part.

Due to the tight integration of the two channels, this antenna has required the customisation of the radiators, the insertion of a rejection filter in front of the first LNA and the limitation of maximum power that can be radiated in full duplex mode. The consequences of these modifications are a narrower Rx bandwidth and lower G/T and EIRP levels than the dual aperture antenna. However, considering that this model uses half of the surface, the aperture efficiency is very similar and the more compact shape provides an interesting solution for user terminals with very limited footprint.

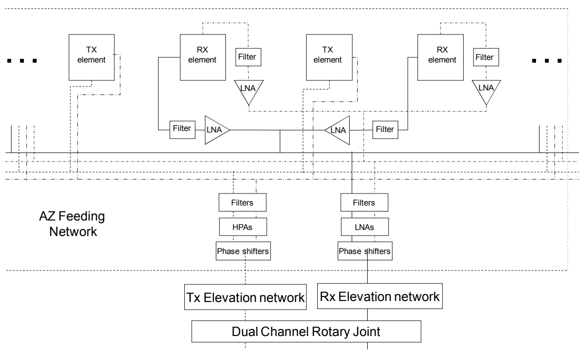


Figure 18. SatMax antenna architecture.

Also in this case the aperture is divided in sub-array modules. The size of the module is 16x8 cm. A picture of the assembled sub-array is shown in Figure 19. Each module contains four rows, which are inclined at an optimum angle to maximise the radiation efficiency at low elevation angles.

Each row has 16 elements 8 Rx and 8 Tx respectively. Tx elements are implemented in a lower layer and cannot be seen in the pictures.

Figure 19. TX/RX 8x4 elements passive Sub-Array.

The radiators have been designed with a T-shape in order to decrease the Tx to Rx coupling [5]. In addition, the elements of the same type are staggered from one row to another to minimise blockage effects and grating lobes. More details about the antenna element and aperture design are provided in [5, 6].

A passive breadboard of the Tx/Rx sub-array has been built to measure the radiation patterns of the Tx/Rx aperture and verify the antenna performances. The measured sub-array has 4 rows of 8 elements each (4 Rx and 4 Tx), i.e. half the size of the final antenna module and it has a fixed beam pointing at an elevation of 45°. Figure 20 and Figure 21 present Azimuth and Elevation Cuts of the Rx Horizontal polarization.

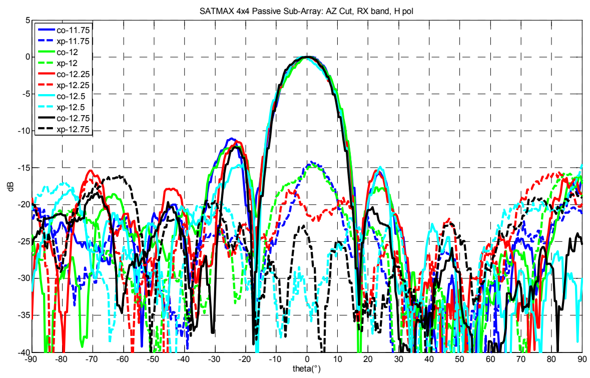


Figure 20. TX/RX 8x4 elements passive Sub-Array: Azimuth cut, Receive band, Horizontal polarisation.

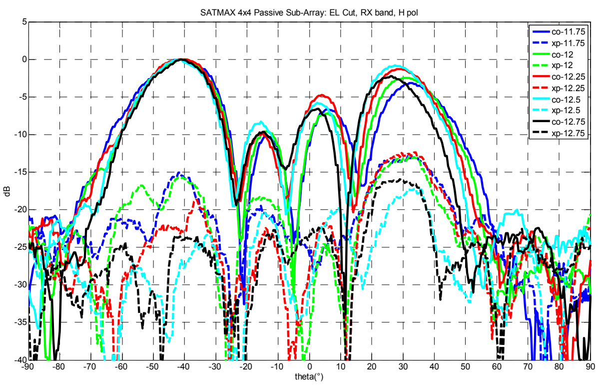


Figure 21. TX/RX 8x4 elements passive Sub-Array: Elevation cut, Receive band, Horizontal polarisation

Even for such small array, which is affected by some intrinsic asymmetries, the side-lobes remain belos -12 dB and the cross-polar level is lower than -15 dB for all frequencies.

Figure 22and Figure 23 show the pattern cuts of the TX sub-array for the horizontal polarization. Also in the Tx band, the results are correct and the cross-polar level remains below -18 dB.

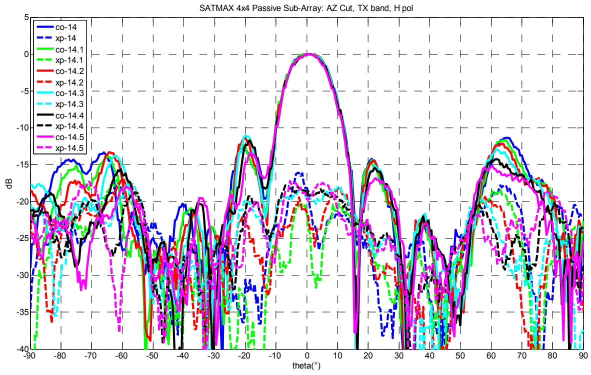


Figure 22. TX/RX 8x4 elements passive Sub-Array: Azimuth cut, Transmit band, Horizontal polarisation.

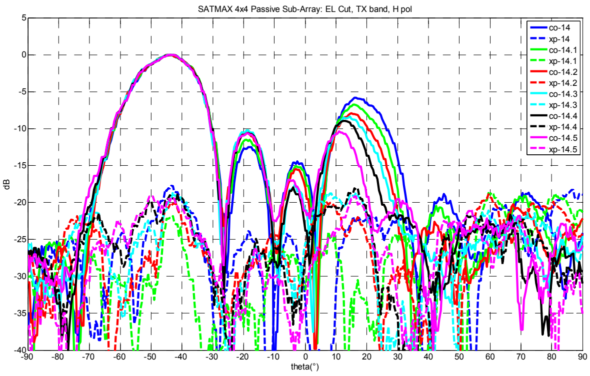


Figure 23. TX/RX 8x4 elements passive Sub-Array: Elevation cut, Transmit band, Horizontal polarisation.

The complete antenna is composed by 6 modules assembled in a cross shape. A picture of the first prototype assembled is shown in Figure 24.

The expected specifications of the antenna based on the available measurements and models are summarised in Table 3. The validation is currently in progress and more results will be presented in the future.

As for the dual-aperture antenna, the targeted applications for this antenna are in the field of broadband connectivity for small aircrafts and land-mobile vehicles.

## 6. CONCLUSIONS

In this paper we have presented three models of antennas suitable for satellite communications on the move. The antennas are based on an original design allowing electronic beam steering in a large elevation range and full range polarisation tracking, while a mechanically rotating platform ensures full azimuth coverage. The electronic beam steering allow to build antennas with a very low height, mechanically robust and particularly resistant to acceleration thanks to the single axis of rotation and the absence of suspended masses.

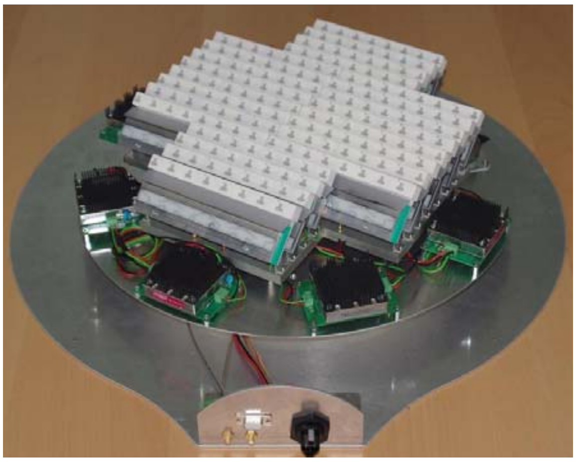

Figure 24. First prototype of the SatMax antenna currently under validation.

Table 3. Single Aperture TX/RX Antenna estimated Specifications.

| TX/RX HYBRID PHASED ARRAY | |
|---|---|
| **Parameter** | **Specification** |
| G/T | > 0.0 dB/°K @ 20° elev.<br>> 3.0 dB/°K @ 45° elev. |
| EIRP | > 25.5 dBW @ 20° elev.<br>> 28.5 dBW @ 45° elev. |
| RX Frequency Band | 11.7 to 12.75 GHz |
| TX Frequency Band | 14 GHz to 14.5 GHz |
| Polarization | Linear with electronic polarization tracking |
| Cross Polarization Rejection | > 15 dB |
| Scanning Range | 360° in Azimuth<br>20° to 70° in Elevation |
| Antenna diameter | 38 cm |
| Antenna Thickness | 15 cm<br>(including radome and mechanical platform) |

The radiating apertures have been designed with a modular approach that provides the flexibility to build antennas of different size to fit the requirements of different platforms or different performance levels.
A custom antenna tracking system has also been developed and is fully integrated in the antenna structure.
Two of the antenna models have been fully validated and successfully demonstrated in operational conditions. The third antenna is currently under validation and complete results will be soon available.
The development of pre-production units is currently in progress in parallel with the commercial applications.

## 7. ACKNOWLEDGEMENTS

The presented results have been obtained also thanks to the support of the European Space Agency and of the Swiss Space Office.
The conception, design and implementation of the Antenna Control Unit has been developed in collaboration with the company MicroBeam (Yverdon, Switzerland).

## 8. REFERENCES

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