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First experimental Results and Beamforming Features of Ground Antenna Implementing AESA Technology

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Abstract

This paper describes the last experimental results and studies of Safran telemetry ground antenna implementing Active Electronically Steerable Antenna (AESA) technology. Telemetry ground antennas play a key role in telemetry systems, by receiving data transmitted by the flying object and sending it to a ground system for data processing. The use of AESA technology allows for more precise targeting and tracking, making it ideal for high dynamic applications. The design presented in this paper is a 1-axis electronically steerable antenna, which is used for elevation axis while azimuth axis is mechanically driven. This S-band antenna is specifically intended for short to medium range telemetry and is able to handle high target dynamics. The paper presents the results achieved with a first prototype, at system level, with targets in real condition like rockets and LEO satellites. Moreover, beamforming shaping are likewise detailed in this paper in order to solve critical cases of propagation phenomena.

Key words: telemetry ground antenna, AESA, tracking, beamforming shaping.

1. Introduction : architecture and principles

To respond to short and medium range S-band telemetry applications, Safran began by developing a small ground station called Comtrack. The Comtrack antenna is a receive-only antenna with a gain of 21 dBi and a G/T of -2.5dB/K. This antenna has an automatic tracking function but only for azimuth axis and the half-power beamwidth in elevation is not considered large. Therefore, one other acquisition aid antenna has to complete the system to cover a certain number of missions. Taking into account the analysis of customer feedback and development advances in Active Electronically Scanned Antenna technologies, Safran decided to develop a new station enriched with new possibilities, while remaining transportable and economically relevant.

It is a new hybrid antenna, named Sparte e-100, with both mechanical rotation and electronic beam scanning, and which has a larger surface area as shown in Fig. 1. The antenna is equipped with a second degree of freedom on the radius diagram with an electronic elevation adjustment. The mechanical azimuth alignment is conserved in order to maintain 360° scanning. Note that the panel is tilted by 45°, which allows for an optimized coverage of 90° in elevation with an electronic offset of +/- 45°. Concerning the antenna array, a new elementary radiating element has been developed.

Fig. 1. Picture of Sparte e-100 ground station.

In order to achieve automatic tracking on both axes, the entire surface of the network is divided into four identical sub-networks named A, B, C and D as shown in Fig. 2. Automatic tracking is done according to the Single Channel Monopulse principle from the sigma and delta channels generated by specific circuit networks. We can thus express:

- Sigma channel :

$$\Sigma = A + B + C + D \quad (1)$$

- Delta channel for azimuth:

$$\Delta az = (A + C) - (B + D) \quad (2)$$

- Delta channel for elevation:

$$\Delta el = (A + B) - (C + D) \quad (3)$$

Each sub-array A, B, C or D is a matrix of 8 lines of 4 radiating elements excited according to two polarizations H and V. Each line of four elements includes low noise amplification and a phase shifter. Right and left circular polarizations, sigma and delta channel generation are obtained using a passive BFN (Beam Forming Network) in multilayer PCB technology designed by Safran with 3dB 0-90° hybrid couplers.

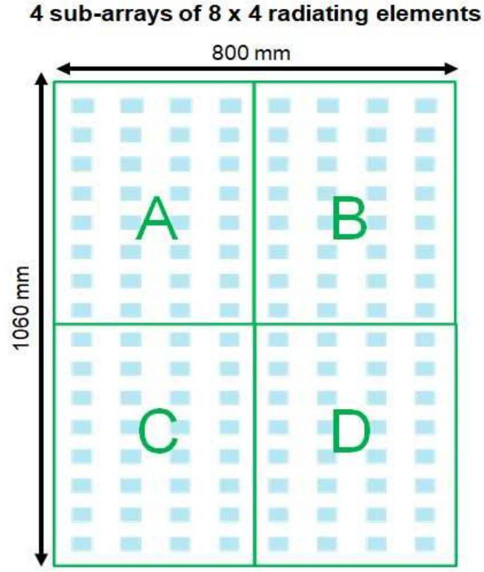

Fig. 2. Architecture of the complete array divided by four sub-arrays A, B, C and D.

Active RF modules designed by Safran for antenna feeds are used. These modules are equipped with a pre-filtered amplification stage, and generate the RHCP and LHCP circular polarizations for the sigma channels as well as the delta channels for the azimuth and elevation axes. The delta channels are phase shifted by a step of 90°, generally during one period of 2 ms, in order to obtain the four tracking error components Az+, El+, Az- and El+. Thus, there are two RF channels RHCP and LHCP after summation of delta and sigma including both telemetry data and tracking error information. The function of the RTR (Radio Telemetry Receiver) is used to demodulate the telemetry and tracking signals. Tracking errors are then processed by the ACU in order to adjust the beam orientation to the target in azimuth mechanically, and in elevation electronically: the synoptic of station is presented in Fig. 3 and performances in Tab.1.

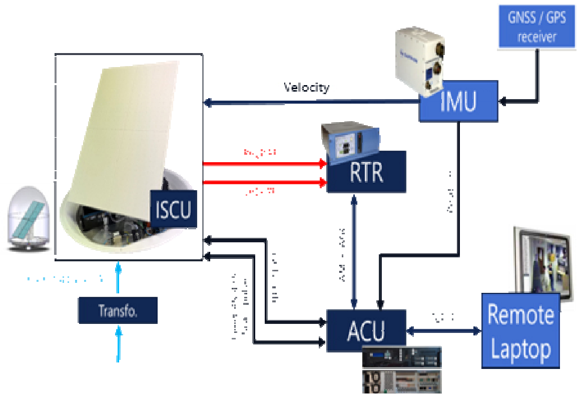

Fig. 3. Synoptic of Sparte e-100 ground station.

Bandwidth	2.2-2.4 GHz
Gain	27 dBi
G/T El 45°	6 dB/K
Beamwidth 3dB	Az 8° / El 6°
Tracking Accuracy	+/- 0,5°
Azimuth Velocity	30°/s
Azimuth Acceleration	30°/s²

Tab. 1: Main performances of Sparte e-100

2. Antenna experimental results in anechoic chamber

Several antenna prototypes have been manufactured. Before validating the 4x8 sub-array with the active elements, it was necessary to validate the radiating elements without the active components, such their Sii parameters adaptation and the radiation patterns in the H and V polarizations. Furthermore, this made it possible to know the efficiency of the radiating element and the losses of the power lines up to the input of the low noise amplifiers.

Firstly, a single sub-array was validated on the following points: routing of power supplies and phase shifter controls, radiation and function efficiency diagrams, and S parameters. One of the difficulties is to be able to evaluate the gain AESA because the presence of active elements with additional gain and losses. This gain measurement is done indirectly by measuring microwave lines with the same characteristics as those between the radiating elements. It is important to note that a correct consistency has to be established between gain measurements in the room and G/T measurements carried out outdoors.

Secondly, a complete set of the antenna with four subarrays was validated with the sigma/delta recombination and polarization formation circuit RHCP and LHCP: Fig. 4 and Tab. 2 show radiation patterns and directivities of sigma RHCP and LHCP channels. The single channel monopulse tracking function could also be tested: some examples of radiation patterns of both sigma and delta channel are given in Fig. 5 and Fig 6; the tracking slopes in Fig. 7. The tests were carried out in one of the anechoic chambers of Safran Data Systems. These results show a good agreement between measurement and expected performances as demonstrated in [1] and [2].

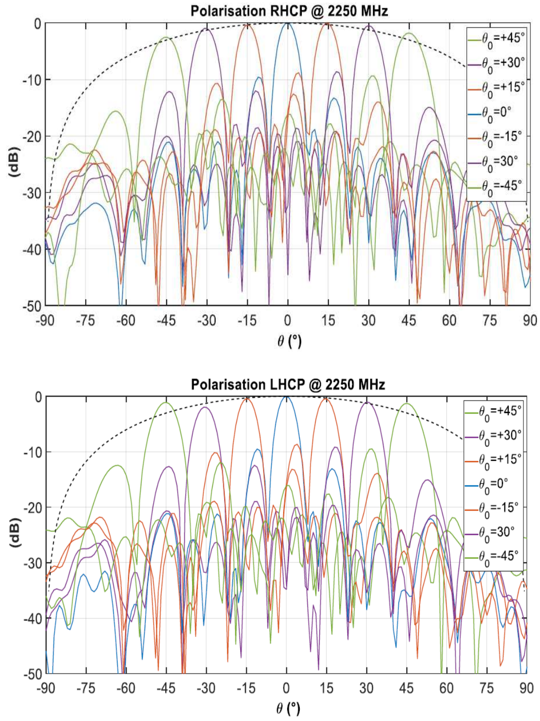

Fig. 4. Measures of sigma radiation patterns θ=-45, -30, -15, 0, +15, +30 and +45° @2250MHz.

Theta(°)	Directivity (dBi) Simulation	Directivity (dBi) Measurement
-45	27	25.7
-30	27.8	26.5
-15	28.3	26.9
0	28.5	27.2
+15	28.3	26.9
+30	27.8	26.5
+45	27	25.7

Tab. 2: Directivities by simulation and measurement.

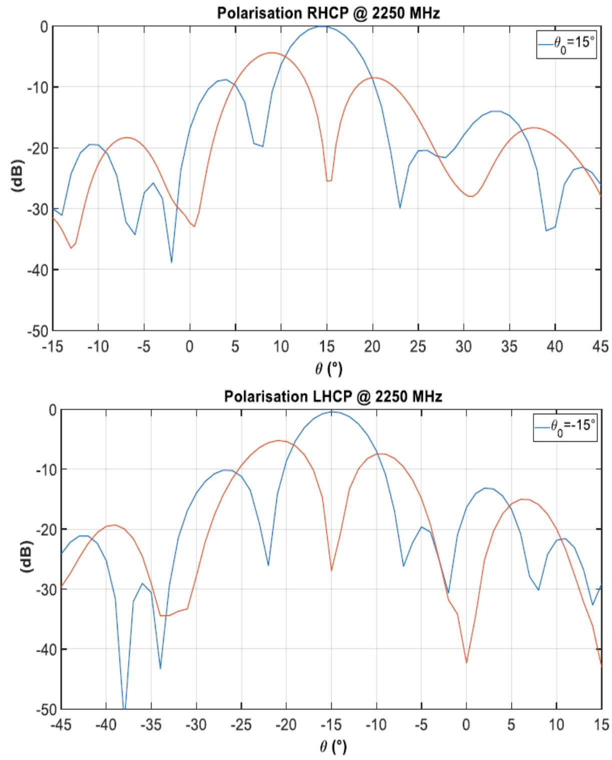

Fig. 5. Examples of sigma & delta radiation patterns RHCP θ=+15° & LHCP θ=-15° @2250MHz.

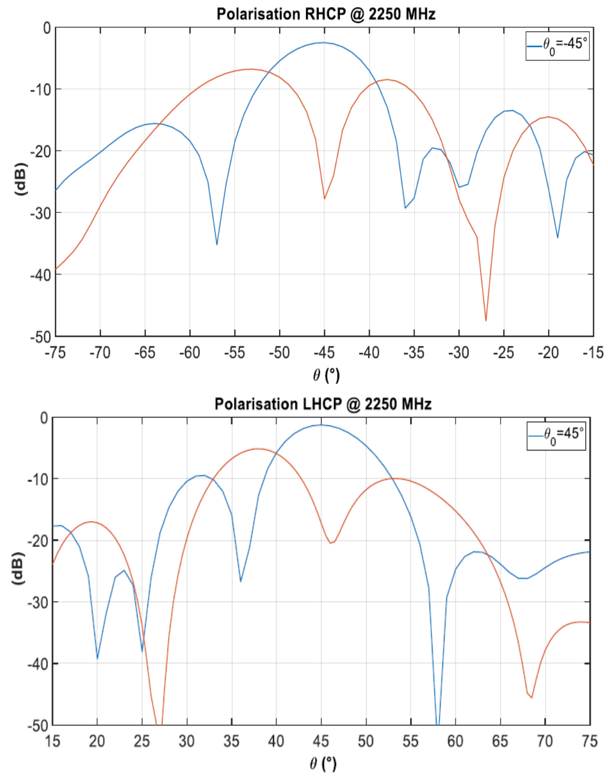

Fig. 6. Examples of sigma & delta radiation patterns RHCP θ=-45° & LHCP θ=+45° @2250MHz.

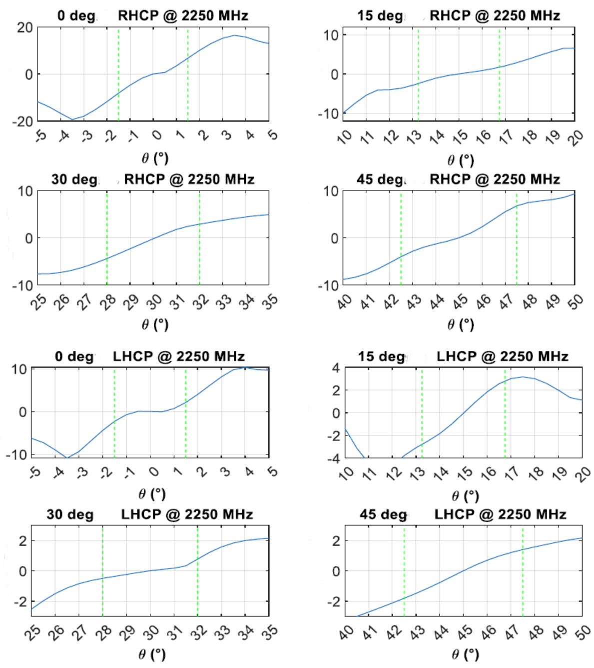

Fig. 7. Tracking slopes from delta / sigma measured @ 2250MHz.

3. Outdoor static and dynamic results

A second part of validation consists of validating the station system parameters. These tests proceed in two phases. The first phase consists of making adjustments to the servo control, software and RF on a static target. Safran teams has performed following:

• carry out the integration of the electronic beam steering functions in the ACU,

• ensure the tracking function on a fixed target in the far field: adjustments of gains and phases, calibration on the Az and El axes. See the homing tests (Fig. 8),

• validate the G/T measure on Sun to ensure the good value of figure of merit.

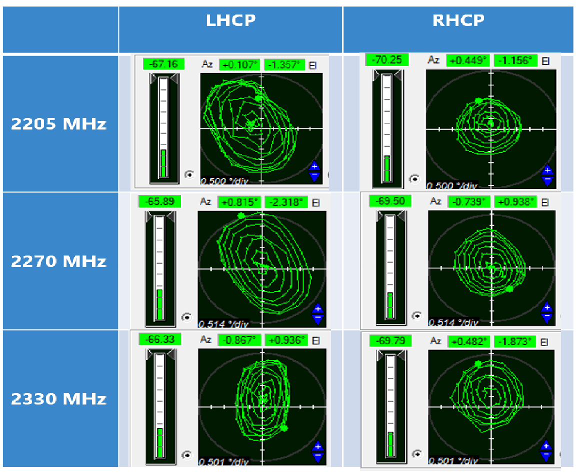

Fig. 8. Tracking homing tests for three frequencies.

The second phase consists of testing in dynamic mode on moving targets. The tests were carried out on satellites and on a rocket. Here are the main tests carried out in the factory or on site:

• Measurement of G/T on Sun (Fig. 9)

• C/N measurements and tracking tests on LEO satellites: Pleiades 1B, Pleiades 1A, Jason 3, Spot 6 and Calipso.

• Measurements of Eb/N0 on satellites (CNES).

G/T measurements are summarized in Fig. 9 for the both polarizations (LHCP and RHCP) and measured at 2350 MHz and 2250 MHz. Note that these performances are observed for an antenna of 1m² and the angle El = 0° corresponds to the beam towards the horizon. These measurements show the capacity of the 1m² antenna to reach a mean G/T of 5.9 dB/K.

TEST Type	Date dd/mm/yyyy	Time UTC	Channel Signal-polar	Sun noise (dBm)	Sky noise @ Sun EL (dBm)	Sky noise @ 0 EL (dBm)	Y factor, measured (dB)
Validation	13/06/20223	14:26:00	TM LHCP	-58,20	-65,30	-65,00	7,10
Validation	15/06/20223	15:48:00	TM LHCP	-57,90	-65,00	-64,32	7,10

TEST Type	Date dd/mm/yyyy	Time UTC	Channel Signal-polar	Sun noise (dBm)	Sky noise @ Sun EL (dBm)	Sky noise @ 0 EL (dBm)	Y factor, measured (dB)
Validation	13/06/20223	14:23:00	TM RHCP	-58,20	-65,20	-64,90	7,00
Validation	15/06/20223	16:00:00	TRK RHCP	-57,60	-64,80	-64,12	7,20

LHCP

Frequency (MHz)	Sun EL (°)	Sun Radio Flux W/m²/Hz	Antenna Beam width θ3dB (°)	A (dB)	K1 -	K2 -	K4 -	S = K1*K2*K4 *Freq -	G/T @ 0 EL (dB/°K)
2250,00	65,00	0,00	7,22	0,036	0,99	1,00	1,0	1,85E-20	**6,09**
2350,00	65,20	0,00	6,91	0,036	0,99	1,00	1,0	2,01E-20	**5,73**
									5,91

RHCP

Frequency (MHz)	Sun EL (°)	Sun Radio Flux W/m²/Hz	Antenna Beam width θ3dB (°)	A (dB)	K1 -	K2 -	K4 -	S = K1*K2*K4 *Freq -	G/T @ 0 EL (dB/°K)
2250,00	65,00	0,00	7,22	0,036	0,99	1,00	1,0	1,85E-20	**5,97**
2350,00	65,20	0,00	6,91	0,036	0,99	1,00	1,0	2,01E-20	**5,86**

Fig. 9. Measurements of G/T level.

In the following, measurements of Eb/No are realized for some satellites passes. Eb/No is a normalized signal-to-noise, or the ratio of energy per bit to noise density, and depends on C/N and G/T of the system. This measurement allows to evaluate the capacity of the station to receive a correct level of modulated signals. This can be linked to the BER (Bit Error Rate) which gives the number of bits altered by noise, interference, distortion or bit synchronization errors.

Many satellite passes and test configurations have been realized and, for this paper, only 2 satellite passes with their configuration are presented. The configurations used for these passes are presented in Tab. 3 and implemented in a RTR.

Satellite	JASON 3	Pleiades 1A
Frequency	2 215.92 MHz	2 269.2 MHz
Rate	3 355 444 bits/s	941 176 bits/s
Modulation	QPSK	QPSK
Polarization	LHCP	LHCP

Tab. 3. Configuration of JASON 3 and Pleiades 1A.

First, the measurements for JASON 3 satellite passes are presented using a RTR. Sparte e-100 is able to track Jason 3 satellite (Fig. 10) with an error of 0.05° rms in azimuth and 0.07° rms in elevation in auto-tracking mode. Then, Fig. 11 shows its capacity of receiving modulated signals with a maximum Eb/N0 of 7dB.

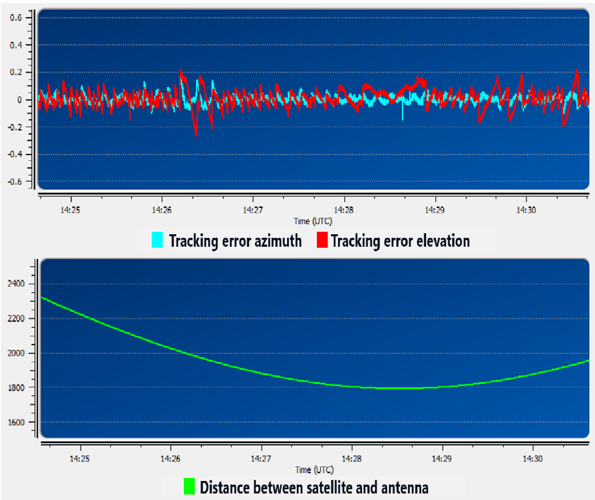

Fig. 10. Tracking tests with Jason 3 Satellite.

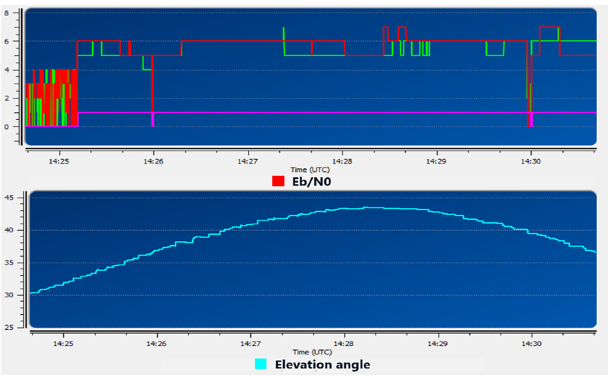

Fig. 11. Eb/No evaluation and elevation with Jason 3 Satellite.

The following figures show the results for Pleiades satellite, version 1A. Tracking errors are plotted in Fig.12 and present an error between -0.5° and 0.5° in azimuth and in elevation during the tracking mode. These values are higher than the tracking errors seen with Jason 3, but the antenna still offers very good tracking capability. During Pleiades tracking, the antenna is able to reach a maximum Eb/N0 of 14 dB (Fig. 13).

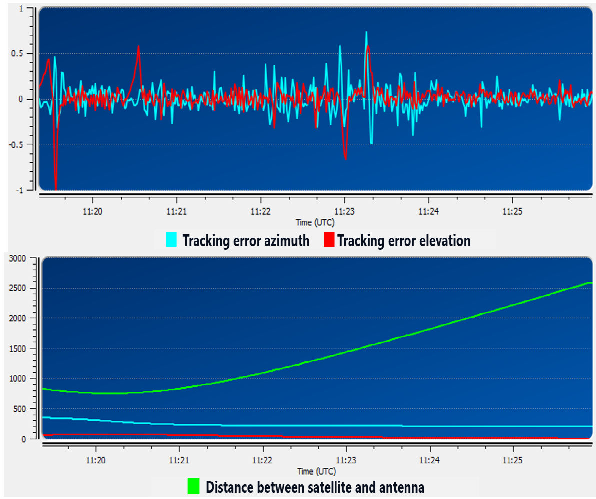

Fig. 12. Tracking tests with Pleiades Satellite.

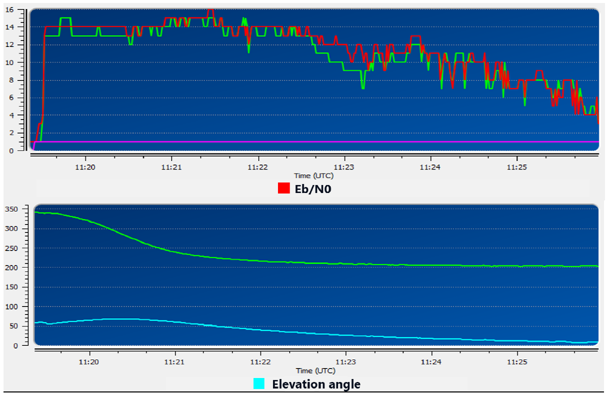

Fig. 13. Eb/N0 evaluation vs elevation with Pleiades Satellite.

All the link budget parts impact Eb/N0 levels as climatic conditions and ephemeris, this can explain the difference of Eb/N0. For both cases, these results validate the capacity of receiving modulated signals.

It is possible to get the value of G/T thanks to this formula, obtained in the literature [3]:

$$\left(\frac{G}{T}\right)_{dB/k} = \left(\frac{Eb}{N0}\right) + (R)_{dB} - (flux)_{dBW/m^2} + (k)_{dB/K/Hz} - 10\log\left(\frac{\lambda^2}{4\pi}\right)$$

The corresponding computations for both passes are presented in Tab. 4.

Satellites crossing			Satellite -		
Date	Satellite	Cortex	Frequency (MHz)	lambda (m)	flux (dBW/m2)
08/12/2023	Jason 3	RTR Safran	2215,92	0,14	-134
22/12/2023	Pléiades	RTR Safran	2269,2	0,13	-133

Ground Station link			G/T comparison	
lambda^2/4pi	R (bit/s)	Measured Eb/N0	Measured G/T (El=0°) (dB/K)	Computed G/T (dB/K)
-28,36	3355444	7	5,91	6,02
-28,57	941176	14	5,91	6,70

Tab. 4. Computations of G/T with measured Eb/N0.

Many conclusions can be done thanks to these computations. First, they allow to estimate the minimum flux level received by the antenna. Then, this method (measurements of Eb/N0 and computations of G/T) is less time-consuming than experimental measurements of G/T on sun. In this context, it is important to have a good knowledge of flux levels to avoid computation errors of G/T.

For Jason 3 and Pleiades, the estimated flux levels are respectively -134 dBW/m² and -133 dBW/m² at the antenna input. These computations give the sensitivity of the antenna with a given G/T in tracking conditions and for different satellite links.

About the performances achieved with rocket, one demonstration done in November 2023 has given excellent results, but the details cannot be communicated for confidentiality purpose.

4. Conclusion and tracking with possible beamforming shaping features.

The results achieved in factory and during demonstrations with the CNES or other Customers show that the Sparte e-100 is close to a production prototype. The hybrid technology is a very good trade-off between technical performances and cost. The dimensioning of the antenna, the hybridization of the mechanical and electronic axes and its good sensitivity are well suited to launcher or micro-launchers missions, and more generally for applications which require only one beam. It should also be noted that in principle it is a by-design scalable antenna: it is indeed possible to assemble more than 4 sub-arrays or tiles for higher gains and G/T.

Note that in the context of multi-contact applications, Safran Data Systems is oriented more towards developments of analog-digital AESA, digitization of each analogical channel from sub-array or digitization of the analogical channel from each antenna. These developments are possible, if the frequencies allow it from an economic point of view towards full Digital Beam Forming network antennas.

To conclude for improvement of Sparte e-100, considering the propagation difficulties experienced during missions, such as multi-path effects and possible saturation of the amplification stages, it seems interesting to exploit the real-time agility and shaping capacity of the beam to reduce these undesirable effects. Thus, Safran Data Systems currently study advanced processing algorithms of beam shaping. This concern the opening of the beam in elevation and possibly the use of information given independently by the four sub-arrays (A, B, C, D) mentioned above.

5. Acknowledgments

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