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ON THE USE OF GROUND ANTENNA ARRAYS FOR SATELLITE TRACKING: ARCHITECTURE, BEAMFORMING, CALIBRATION AND MEASUREMENTS

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Nowadays, ground stations which integrate the control segment of a satellite mission have as a common feature, the use of large reflector antennas for space communication. Apart from many advantages, large dishes pose a number of impairments regarding their mechanical complexity, low flexibility, and high cost. In the user segment, the use of planar arrays to substitute domestic reflectors will provide a more compact and easy to install antenna system and is an interesting solution e.g. for Satellite-On-The-Move (SOTM) systems.

Antenna arrays have several advantages over large dishes: the capability to track several satellites simultaneously, higher flexibility, lower production and maintenance cost, modularity and a more efficient use of the spectrum. In an antenna array, the computation of a close approach of the direction of arrival (DoA) and the correct performance of the beamformer depends on the calibration procedure implemented.

However, some issues must be considered during the design and implementation of a ground station antenna array: first of all, the architecture (geometry, number of antenna elements) and the beamforming process (optimization criteria, algorithm) must be selected according to the specifications of the system: gain requirements, interference cancellation capabilities, reference signal, complexity, etc. During implementation, deviations will appear as compared to the paper design due to the manufacturing process: sensor location deviations, and sensor gain and phase errors.

In the particular case of an active antenna array, due to the ageing of electronic components and temperature conditions, their gain and phase response will have a time-varying characteristic. As well, mutual coupling between antenna elements will modify the theoretical antenna pattern that depends on the position of the elements. Because of that, a calibration procedure must be defined in order to track these changes and compute an adequate beamforming solution. In case of very large arrays, it is also very important to select a calibration procedure with low complexity in order to compute the array parameters in real-time.

In this paper, we present the above issues applied to the design and calibration of a conformal active antenna array for tracking LEO satellites named GEODA (Geodesic Dome Array). It is formed by 30+30 triangular arrays of 1 m side. Its structure is based on the use of triangular subarrays of 45 double stacked circular patches with their own LNA and phase shifter. Special emphasis will be put on the calibration techniques and the associated measurements requirements. Results from simulations and measurements are presented.

I. INTRODUCTION

Stations integrating the earth segment of most space agencies are widely dispersed around the globe. As a common feature, earth stations make use of large antenna reflectors for downloading data from satellites. Depending on the mission, the antenna aperture must be increased in order to receive higher data rates.

However, the use of large dishes poses some problems when their diameters exceed certain limits. Reflector antennas are expensive and require the installation of a complex mechanical system to track the satellite in its orbit. This fact motivates the operation and maintenance costs are rather high. Moreover, the surface errors during the fabrication increase with the diameter and may affect the performance for high frequencies. On the other hand, these antennas can track one only satellite at a time, so that the efficiency of the earth segment is reduced[1].

As a consequence, other antenna technologies have been considered as an alternative to large reflectors. One alternative is the use of antenna arrays with beamforming[2]. Their main advantages over large dishes are the higher flexibility, which gives the possibility to track several satellites if the number of antenna elements is high, lower production and maintenance cost, modularity and a more efficient use of the spectrum.

Apart from large ground stations, antenna arrays have also been proposed as antenna solution for satellite on the move (SOTM) terminals in ground and aeronautical scenarios[3, 4], and also for the Deep Space Network[5].

Due to manufacturing, mutual coupling, temperature variations and component ageing, the operation of the manufactured antenna differs from the ideal one. The process for the estimation of actual array parameters is called calibration[6]. Thus, in order to compensate the performance degradation due to these errors, a calibration scheme must be implemented. Usually, the calibration tasks are divided in several processes depending on the specific errors to be compensated, as it will be explained later.

In particular, after active array manufacturing and before on-line operations, Off-line calibration process estimates the compensation or calibration parameters for a certain accuracy requirements extracted from measurements[7]. Thus, it is necessary to study which are the measurement requirements from the selected calibration schedule to get the desired accuracy of the estimated DoA.

On-site and on-line calibration processes deal with uplink calibration due to frequency change and compensation of dynamic errors such as component degradation, respectively.

The paper is organized as follows. Section II introduces the antenna array concept including the signal model for the analysis of gain and phase errors. Section III describes GEODA, an experimental antenna array for satellite tracking that is used as a baseline for the paper. Section IV explains the calibration requirements of an antenna array, and section V deals with the measurements that must be done to define a proper calibration procedure. Section VI shows the performance degradation of the array pattern in presence of errors by means of simulations and measurements. Finally, section VII draws the conclusions of this paper.

II. ANTENNA ARRAYS. SIGNAL MODEL

II.I Architecture and operation

An antenna array is composed of several antenna elements forming a given geometry that can be linear, planar or conformal (3D). Each antenna has its own RF and IF stage, providing filtered and downconverted signals that are processed by the beamformer. A simplified scheme of the antenna array architecture is shown in Fig. 1.

The mission of the beamformer is the calculation of a weight vector to combine the received signals and obtain an array output signal that fulfils an optimization criterion. Typical optimization functions are the maximization of the received signal power by steering the beam towards the signal of interest, the minimization or interferences by placing pattern nulls in the direction of the undesired sources.

There are several options to calculate the beamforming vector depending on the type of reference used:

- Temporal reference: a known sequence d(t) must be transmitted by the desired source. This scheme is less flexible as the array receiver must be adapted to the particular communication signal. However, calibration requirements are normally less stringent than for spatial references schemes. An example of scheme based on time references applied to satellite tracking can be found in the literature[8];
- Spatial reference: in this case, the receiver must know the position or Direction of Arrival (DoA) of the sources prior to beamforming. This scheme typically applies to scenarios with a very low number of users with predefined trajectories as it happens with satellites. Calibration requirements are very strict in order to steer the beam in the appropriate direction;
- Blind reference: this scheme takes advantage of the properties of the received signals e.g. constant modulus to calculate the beamforming weights.

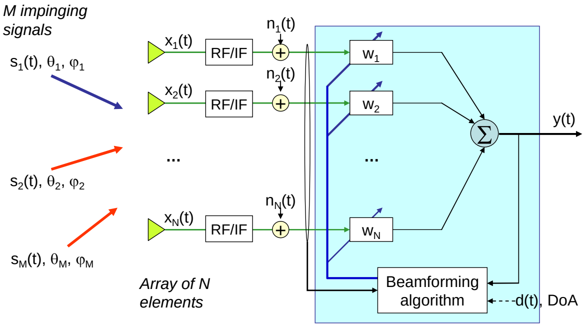

Fig. 1. Antenna array architecture.

II.II Signal model

Let us consider an array of N elements with M signal sources present in the scenario. We consider a spatial reference beamformer to track a given satellite in the presence of more sources (other satellites, signals). We assume the spacecraft trajectory is known. This hypothesis is valid if orbit propagators are used to generate the satellite trajectory e.g. using TLE files.

The received signal vector $\underline{x}(t)$ in the array can be expressed as

$$\underline{x}(t) = \sum_{m=1}^{M} s_m(t)\underline{a}_m + \underline{n}(t) \qquad [1]$$

where $s_m(t)$ is the received signal from the m-th source, $\underline{a}_m$ is the steering vector in the direction of the m-th source and $\underline{n}(t)$ is the noise vector component due to the receivers of the antenna array elements which which is assumed to be i.i.d zero-mean complex Gaussian with variance σ^2 per element.

The steering vector $\underline{a}_m$ depends on the antenna array geometry and the direction of the source, and can be written as

$$\underline{a}_m = \exp\left(-j\hat{r}_m \underline{\vec{r}}\right) \qquad [2]$$

where

$\hat{r}_m = \left(\sin\theta_m \cos\varphi_m, \sin\theta_m \sin\varphi_m, \cos\theta_m\right)$ is the unitary vector in the direction of the m-th source (θ_m, φ_m), and $\underline{\vec{r}}$ is a Nx1 vector representing the location of the antenna elements in the array.

Using matrix notation, the received signal vector can be expressed as

$$\underline{X} = \underline{\underline{A}}\underline{S} + \underline{N} \qquad [3]$$

where $\underline{X}$ and $\underline{N}$ are N-dimensional vectors, $\underline{S}$ is a vector of dimension M, and $\underline{\underline{A}}$ is an NxM matrix whose columns are the steering vectors of the array.

The model in [3] can be extended to include mutual coupling and gain and phase errors, obtaining a more accurate representation the received signal vector[9]

$$\underline{X} = \underline{\underline{C}}\,\underline{\underline{G}}\,\underline{\underline{\Phi}}\,\underline{\underline{A}}\underline{S} + \underline{N} \qquad [4]$$

where $\underline{\underline{C}}$ is a NxN representing the coupling matrix, $\underline{\underline{G}}$ and $\underline{\underline{\Phi}}$ are NxN diagonal matrices that representing the gain and phase errors, respectively.

After beamforming, the array output is calculated as

$$Y = \underline{W}^H \underline{X} \qquad [5]$$

where $\underline{W}$ is the beamforming vector. Under a beamsteering approach for an ideal array without errors, $\underline{W}$ is a Nx1 vector that compensates the phases of the steering vector in the DoA of interest.

It is important to note that beam steering is not capable of controlling the impact of interference sources on system performance as other schemes do[2].

III. AN EXAMPLE OF ANTENNA ARRAY: GEODA

III.I Architecture

For this contribution the AUT is a triangular active array which is a part of one conformal adaptive antenna based on multiple triangular active arrays as geodesic antenna array (GEODA).It is specified for satellite tracking at 1.7 GHZ, including multimission and multibeam scenarios[10]. Its geometry is a half dodecahedron geodesic dome with a diameter of 2.4 m placed over a cylindrical structure of 1.5 m height. Both geometrical structure parts are conformed by 30 active triangular active arrays (panels), as presented in Fig. 2.

Each triangular active array is composed by 45 elements as double stacked circular patches with their own RF circuit. There are 15 sub-arrays (cells) with 3 elements. In total there are 45×(30+30)=2700 radiating elements each with its active RF section.

As a first approach, the manufacturing of one triangular panel has been carried out and it has been used for defining the measurements and calibration procedures.

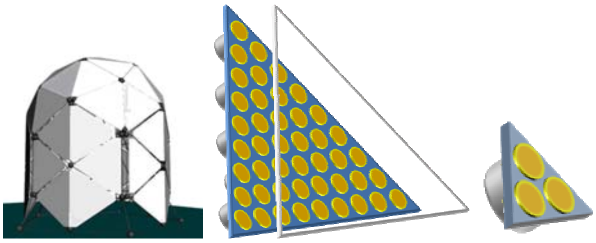

Fig. 2. GEODA: 3D dodecahedron geodesic dome and cylindrical structure shaped by triangular panels (left), triangular active array of 45 elements (center) and cell sub-array of 3 elements (right).

The RF circuit of each cell as shown in Fig. 3 has one hybrid coupler with a 25 dB coupler for test signals added for calibration purposes, an LNA with 3 states (on, off, bypass) and one phase shifter with 6 states per patch. The outputs of the 3 patches are combined into one signal using a Wilkinson combiner, and finally this signal is amplified with another LNA at the output of the cell.

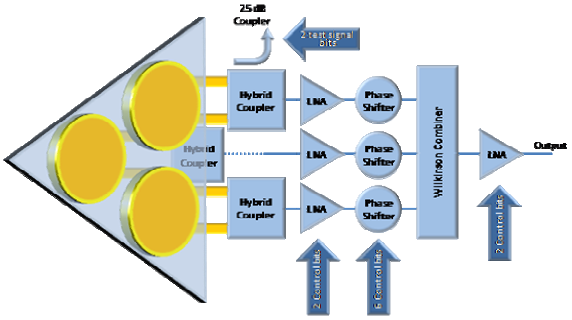

Fig. 3. GEODA: Cell sub-array and RF circuit.

Each cell provides a combined signal, consequently each panel provides 15 pre-beamformed outputs that are sent to the 15 to 1 signal combiner, and finally the signal goes through the RF receiver for IF conversion (27.5 MHz).

In GEODA, beamforming is performed under a hierarchical scheme; first, impinging signals are combined using an analog beamformer implemented with the 45 phase shifters of one triangular panel; second, the outputs of the panels are fed to a digital beamformer.

III.II Control System

The control system has two main parts: the hardware structure and the control system software. A multi-layer architecture has been implemented for the hardware structure (Fig. 4). The first layer is based on one embedded microcontroller per cell to control the phase shifter, LNA and coupler switch for the test signal of the RF circuit. The second layer has the panel microcontroller which addresses the control data to each cell. The third layer consists on the work station PC which operates with the control software. The work station is connected to the microcontroller of the panel by a USB port, and the microcontroller of the panel is connected to the 15 microcontrollers of each cell by I2C bus. The goal of the I2C bus solution is to isolate the 15 I2C bus ports and to control the capacitance level of the wire connections. For the I2C bus solution four PCA9516A chips from Philips have been used.

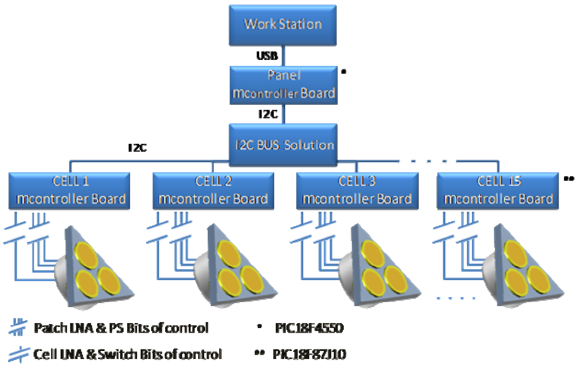

Fig. 4. Hardware architecture of the Control System.

The control software has been developed to manage AUT for satellite tracking, anechoic chamber measurement, S_{21} measurement of the RF circuit, and S_{21} measurement with the test signal for RF network and circuits calibration.

IV. CALIBRATION REQUIREMENTS

Antenna array calibration aims at compensating manufacturing and other errors that make the performance of the antenna array differ from the ideal situation. As a consequence of the presence of errors, the magnitude and phase response of antenna elements change and the synthesized array pattern is degraded and causes gain loss, sidelobe increase and erroneous estimation of direction of arrival.

These errors can be classified as

1) Static errors: manufacturing of antenna elements leads to gain and phase variations, manufacturing and installation of the supporting structure implying location errors, and errors due to mutual coupling;
2) Dynamic errors: temperature variations, element ageing, and errors in gain and phase of active components.

As a general remark, it must be emphasized that antenna calibration is usually understood as a task performed in reception. This is due to the fact that antenna array parameters can be extracted from received signals using different techniques. However, if the antenna array is to be used also as a transmitting station, a calibration procedure must be applied before transmission.

Calibration in transmission is not an easy task to perform. The most common approach is to extract the information from measurements of the received signals[11, 12].

The calibration procedures of an antenna array can be divided in three groups (Table I):

- Task 1. Off-line calibration (reception): it aims at compensating the static errors. The measurements are performed in anechoic chamber before the final antenna installation.
- Task 2: On-line calibration (reception): the scope of this task is to compensate the dynamic errors. The compensation is done after antenna installation with the use of calibration signals and self-calibration algorithms. As on-line calibration is performed during antenna operation, it must be transparent to beamforming procedures.
- Task 3. On-site calibration (transmission): it compensates the errors due to the different frequencies used in transmission and reception. This task requires measurements in anechoic chamber at different frequencies and the generation of calibration tables e.g. based on phase center variation with frequency.

Procedure	Errors	Test in
Off-Line	Static (mutual coupling, location, gain, phase)	Anechoic Chamber and Laboratory
On-Site	Change in operating frequency	Anechoic Chamber
On-line	Dynamic due to component ageing and temperature variations	Operating Emplacement

Table I. Calibration procedures for an active antenna array.

V. MEASUREMENTS

V.I Measurement steps

Prior to calibration, a number of measurements tasks must be carried with a two-fold objective: (a) selection of an appropriate calibration technique and (b) estimation of antenna array parameters and compensation matrices.

The first test to be performed aims at aiding in the selection of the most appropriate calibration technique. These initial tests measure the S coupling parameters evaluate the mutual coupling between antenna elements and the impact of phase and gain errors.

These measurements are carried out manually as it requires the load of the antenna array ports. The number of measurements can be reduced depending on the symmetry of the array geometry.

After initial tests, measurements are post-processed and the most appropriate calibration technique is then selected in order to minimize the impact of manufacturing and other errors.

In the particular case of GEODA, it was concluded that the array pattern degradation is more sensitive to phase errors than to gain and sensor location errors. The mainbeam loss due to location errors after integration and fabrication is nearly zero due to the good manufacturing accuracy. Thus, a calibration technique for the compensation of phase errors must be selected[13, 14].

Once the calibration technique is selected and prior to apply the calibration process to the array, an exhaustive measurement campaign must be carried out to characterize the antenna array behaviour.

The measurement procedure is sequential as follows:

1) S_{21} parameter measurement of the RF circuits: this test measures each RF branch for each radiating element and polarization connecting the vector network analyzer (VNA) to each polarization feed port of the RF circuit.
2) RF circuit and network measurement: characterization and to obtain the compensation matrix for both static and dynamic errors in on-line operation;
3) Anechoic chamber measurements: the radiation pattern of the antenna elements for different configurations and the array radiation pattern for several pointing directions are measured. Afterwards, measured patterns are post-processed to compute pattern distortions, pointing losses and compensation matrices from each calibration technique procedure.

The measurement setup in anechoic chamber is shown in Fig. 5. It is important to mention that an intensive work must be done in order to integrate the software that controls the positioning system, array operation (beamforming) and measurement equipment.

Finally, it is important to mention that a calibration model for transmission can be obtained measuring the antenna array in anechoic chamber with different probe positions and in several frequencies.

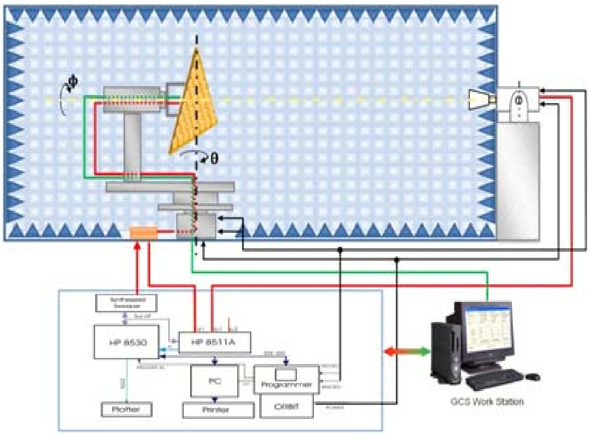

Fig. 5. Measurement setup in anechoic chamber.

V.II Measurement automation and cost

As in the case of GEODA, the number of required measurements and time required are very large and costly. Because of that, the automation of measurements is a way to reduce time and associated costs.

Of the four measurement steps, automation can be introduced in 2, 3 and 4. The most significant time savings with automation comes from the anechoic chamber tests[15]. This reduction is especially important as the costs associated with these measurements are the most expensive and resource demanding (equipment, technician staff, measurement time). Moreover, thanks to the remote operation of the measurement system, we have reduced required time in 296 hours.

VI. PERFORMANCE RESULTS

VI. I Simulation assumptions

The scope of the simulation is to show the impact of different error sources on the performance of the synthesized beam.

In the simulations, the following assumptions apply:

1) Noise due to receiver is negligible
2) Only one user is present in the scenario
3) Gain, phase and location errors are simulated randomly.

Antenna array geometry is one panel of GEODA, with 45 elements. Beamforming weights are quantified using 6-states phase shifters.

We assume that the desired Direction of Arrival is θ_0=45°, φ_0=225°, so that beamforming weights are calculated and quantified for that angular position.

For comparison purposes, Fig. 6 shows the ideal (without errors) array pattern. It can be seen that a maximum of the antenna array pattern appears in the location of the DoA.

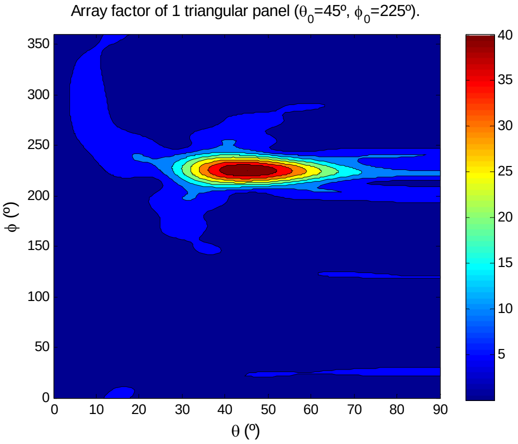

Fig. 6. Ideal array pattern for θ_0=45°, φ_0=225° (natural units).

VI.II Location errors

For these simulations, location errors are modelled by introducing a zero-mean uniform random variation in the position of elements in x and y dimensions. Two variances are selected: λ/16 and λ/8. Errors in the position are equivalent to phase errors.

Next figures show the impact of phase errors on antenna pattern. Two effects can be seen in the synthesized pattern comparing with Fig. 6: first, side lobe levels increase; second, the beam steering is deviated from the desired DoA.

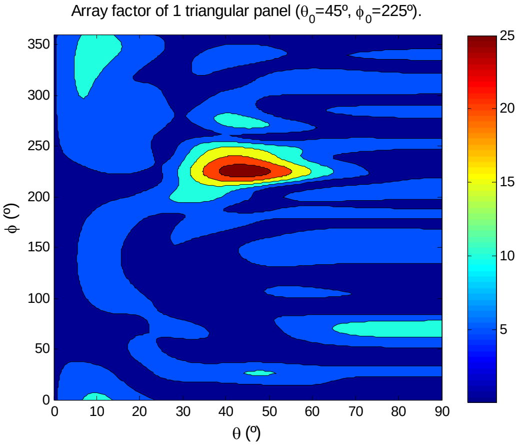

Fig. 7. Array pattern for θ_0=45°, φ_0=225° with location errors (σ^2=λ/16) (natural units).

VI.III Measurement results

Fig. 9 shows how the pointing losses change as a function of the pointing direction. These results have been obtained from measurements in anechoic chamber by selecting different spatial directions and selecting appropriate beam steering weights. It can be seen that as the beam is steered out of the broadside direction, pointing losses increases.

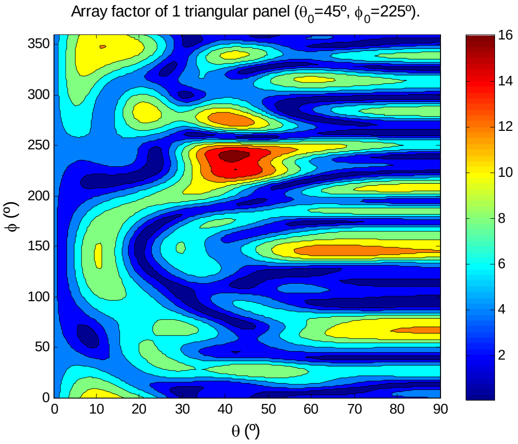

Fig. 8. Array pattern for θ_0=45°, φ_0=225° with location errors (σ^2=λ/8) (natural units).

As well, Fig. 9 provides information about the maximum angular exploration range of the array which gives system information e.g. time of visibility.

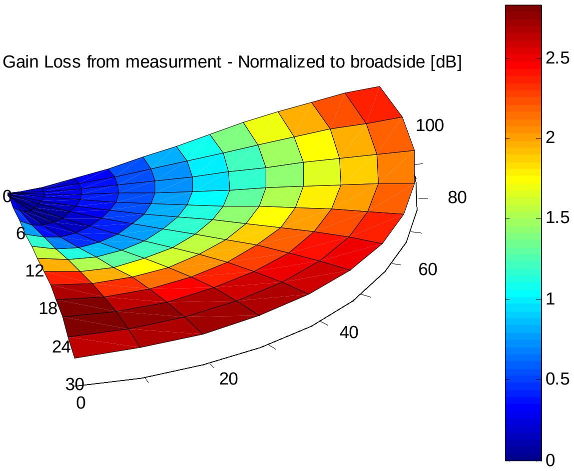

Fig. 9. Measured beam pointing losses in anechoic chamber (radial dimension: θ; angular dimension: φ). Colorbar represents the normalized loss in dB respect to broadside.

VII. CONCLUSIONS

In this paper, we have presented the impairments associated with the use of antenna arrays for satellite tracking. Although a potential technology for increasing the efficiency of current ground segment, aspects such as calibration must be considered.

In the absence of an appropriate calibration technique and procedure, errors due to manufacturing and to component ageing and temperature variations, will lead to degraded antenna patterns that will re.

Associated to calibration, the measurement step for GEODA (Geodesic Dome Array) has been presented.

For such a large antenna, it has been shown that the automation of tests implies a reduction in time and costs, mainly from measurements in anechoic chamber.

Simulation results have been presented to show the impact of gain and phase errors in the antenna array. In the absence of calibration, gain loss and sidelobe increase can make the antenna system reduce its performance and even not comply with specified pattern masks.

A number of challenges are today under study and are presented as emerging research topics: first, the use of antenna arrays as multibeam stations for the simultaneous tracking of several satellites requires the application of complex resource assignment algorithms in terms of frequency management and subarray formation.

Second, the development of transmission/reception arrays implies the design of complex calibration techniques for the proper antenna array operation as well as novel antenna array architectures. As a continuation of GEODA, a follow-on project named as GRUA (Ground Uplink Array) is on-going in ETSIT-UPM with the scope of implementing a transmission/reception antenna array for satellite tracking[16].

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