SOTM terminals evaluation under realistic conditions

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***Index Terms*—SOTM, VMES, mobile VSAT, de-pointing measurement, LMS channel, Ka band, Ku band, motion profiles, FCC 25.226, ETSI EN 302977**

***Abstract*—The Vehicle-Mounted Earth Stations (VMES) operation requirements defined by the regulatory authorities are bounding for terminal manufacturers. Testing the VMES for these requirements (e.g., pointing accuracy and polarization alignment) is therefore a necessity. The disadvantages of involving operational satellites and having fixed separation between them in traditional test methods are overcome in the proposed Facility for Over-the-air Research and TEsting (FORTE). FORTE comprises an antenna tower and a laboratory building. A sensor array is mounted on the antenna tower with the center sensor emulating the satellite. In the laboratory building, the VMES is mounted on a motion emulator which can replay realistic motion profiles. In this contribution, the main components of FORTE are introduced and the performance of the de-pointing measurement system is verified. The tracking unit of the VMES may steer the antenna either mechanically or electronically to keep the pointing direction towards the target satellite. Measurements with antennas that have a fixed pattern (independent of the steering angle) as well as that have a variable pattern (dependent on the steering angle) are considered in this contribution.**

I. Introduction

The need to access communication services such as the Internet at all times and in all places has become an integral part of our private and professional lives. Especially at places without any terrestrial communication infrastructure, satellite based systems are the only solution. In this context, stationary Very Small Aperture Terminals (VSAT) are already commonly used. During the past years, operators learned that the inaccurate operation of VSAT frequently leads to a degradation of the quality of the offered communication services. A major reason for this degradation is a misalignment of VSAT, i.e., the so called *de-pointing* of the antenna, which has to be avoided in any case to minimize interference to adjacent satellites.

The increasing demand for mobile applications covering land, maritime, and aeronautical environments pushes the development of Vehicle-Mounted Earth Stations (VMES). For these applications, the mobility of the ground terminals represents a significant challenge in complying with the requirements in terms of pointing accuracy. In this context, operators and regulatory authorities are already aware of the need for testing VMES. For instance, in the US the Federal Communications Commission (FCC) [1] and in Europe the European Telecommunications Standards Institute (ETSI) [2] have defined requirements for VMES. These requirements are expressed, e.g., in terms of the pointing accuracy, the required polarization alignment (if non-circular antennas are used), Equivalent Isotropic Radiated Power (EIRP) spectral density limits, and the behavior of the terminal if the satellite signal is lost.

The Fraunhofer Institute for Integrated Circuits IIS in collaboration with Ilmenau University of Technology developed a Facility for Over-the-air Research and TEsting (FORTE) for Ku/Ka band terminals. FORTE can realistically and cost efficiently reproduce the operational environment of VMES regardless of the current weather conditions. It allows realistic testing and speeds up the development process of VMES, while lowering the risk of over-engineering new systems. This contribution presents the FORTE Facility and the accuracy of the de-pointing measurement system. For the latter the challenges when testing different antenna types are discussed.

In Section II, the structure and the main components of FORTE are presented. In Section III, the performance of the de-pointing measurement system w.r.t. different antenna types is discussed. Section IV summarizes the main features and outcomes introduced in this contribution.

II. FORTE

For system validation and quantitative performance evaluation of VMES, it is desirable to install and operate a test facility which allows for simple, repeatable, and realistic real-time measurements without the need for operational satellites. The Land Mobile Satellite (LMS) channel, the motion of the vehicle and the earth coordinates at which the functionality of the VMES is tested are emulated to reproduce the real world conditions. A tower of 50 m height located 100 m away from the VMES antenna is used to emulate the satellite. In this way, the far field condition can be guaranteed for apertures up to 90 cm diameter in Ka-band. The VMES is mounted on a motion emulator inside an anechoic chamber, having Line of Sight (LoS) through a RF transparent window towards the tower. In this way, FORTE enables the testing of the overall functionality of the VMES; including the antenna, Positioning, Acquisition, and Tracking (PAT) and the mechanical integration for different satellite elevations. In particular, the antenna sub-system can be tested independently both under movement and under the influence of the LMS channel. The operational environment of a VMES can be reproduced realistically with FORTE.

FORTE comprises the following components [3]:

- Channel emulators: emulate the fading characteristics caused by the propagation environment; especially blocking/shadowing [4] at Ku/Ka band and weather conditions independently for the uplink and downlink. Channels measured as well as simulated can be employed.
- Motion emulator: emulates mechanical disturbances that act upon a terminal mounted on different types of vehicles (e.g., trucks, cars, ships, etc.) under various conditions (e.g., highways, gravel road, rough sea, etc.). Both generic and measured motion profiles can be applied. For instance, measurements for typical scenarios of emergency aid organizations are available (see also [5] and [6]).
- Navigation emulator: provides arbitrary Global Positioning System (GPS) RF signals for a given set of real latitude and longitude coordinates, which may be necessary for antenna systems utilizing satellite navigation support.
- De-pointing measurement system: a cross shaped sensor array with five antennas is mounted on the antenna tower (see Figure 1). With this fundamental component of FORTE, the de-pointing angle in azimuth and elevation can be accurately determined.

This last component of FORTE is discussed in detail in the following sections. In this context, the performance of the antenna de-pointing measurement system is demonstrated.

III. Antenna de-pointing measurement system

To determine the VMES antenna de-pointing, a sensor array as shown in Figure 1 is used.

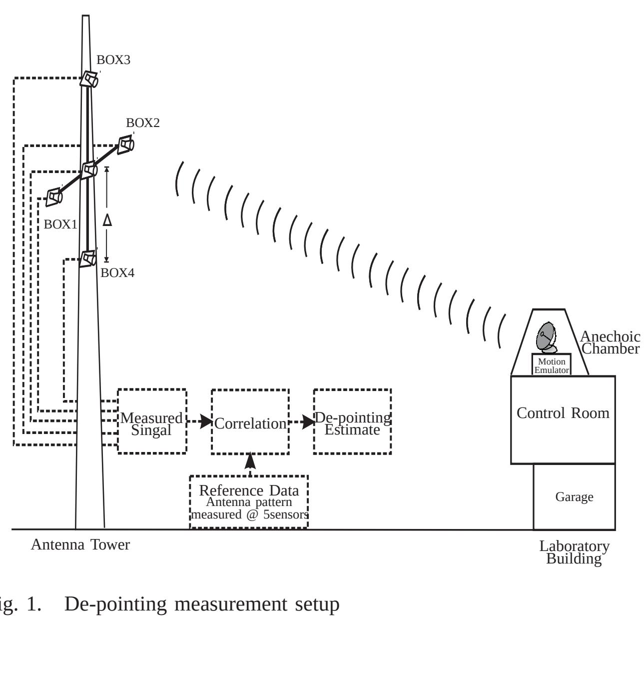


Fig. 1. De-pointing measurement setup

Each box on the tower contains an antenna for the required frequency (Ku/Ka band) and a power detector. The antenna de-pointing and the sensor positions are defined according to the coordinate system introduced in Figure 2.

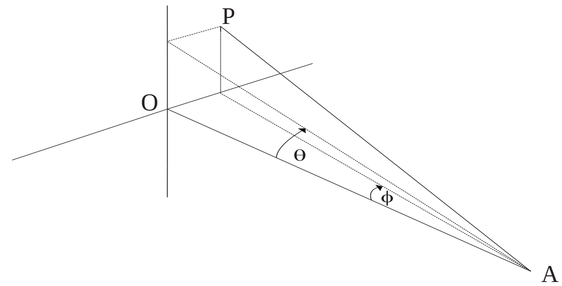


Fig. 2. Anetnna de-pointing coordinates. The sensor array is mounted such that the center sensor is located at the origin (point O)

The center sensor is assumed to be at the origin of the coordinate system (point O). The point A represents the position of the antenna and the point P represents the de-pointing direction of the antenna. The angle ϕ is the antenna de-pointing along the horizontal axis while the angle θ is the antenna de-pointing along the vertical axis. The separation between sensors 1 & 2 and between sensors 3 & 4 can be varied in the range $\in [1^\circ, 6^\circ]$, according to the beam-width of the terminal antenna, as explained in detail in Section III-A.

In a preliminary measurement, the received power at the five sensors is measured for different known antenna de-pointing directions while the tracking system of the antenna is disabled. This data serves as reference for the de-pointing estimation, in which the motion emulator replays a certain motion profile while the tracking system of the antenna is active. At this point, the estimation is carried out in three steps (see Figure 1):

1) measure the received signal at the 5 sensors of the VMES
2) calculate the correlation between the measured signal and the reference data
3) the antenna de-pointing estimate results from the maximum of the correlation

A. Optimum sensor positions

The optimum sensor positions that yield the best estimation accuracy will be derived in the following. The estimation accuracy depends on three parameters:

- the position of the 4 outer sensors
- the available Signal-to-Noise-Ratio (SNR) at the power detectors
- the 3 dB beam-width of the antenna

The SNR and the 3 dB beam-width of the antenna are fixed parameters since they result from the transmit EIRP of the antenna and the fixed beam of the antenna. Therefore, the positions of the sensors are the only variable parameters that can be adjusted to improve the de-pointing estimation accuracy. In the following, the optimum positions of the sensors are derived for the highest possible de-pointing estimation accuracy w.r.t. the SNR and the 3 dB beam-width of the antenna. Antenna patterns with different 3 dB beam-widths are simulated and the de-pointing estimation accuracy is calculated based on Monte Carlo simulations w.r.t. the positions of the sensors and the SNR. The simulation results lead to an empirical equation for the optimum positions of the sensors with:

$$\Delta \approx (a \cdot \rho^3 + b \cdot \rho^2 + c \cdot \rho + d) \cdot w, \tag{1}$$

where

- Δ is the distance of the outer sensor to the centered sensor along horizontal as well as vertical axes (see Figure 1)
- ρ is the SNR in dB
- w is the 3 dB beam-width of the antenna in degrees
- with the polynomial coefficients $a = -1.3 \cdot 10^{-06}$, $b = 1.8 \cdot 10^{-04}$, $c = -7.2 \cdot 10^{-03}$ and $d = 0.709$

The maximum achievable estimation accuracy corresponding to the optimum sensor positions are plotted in Figure 3. It

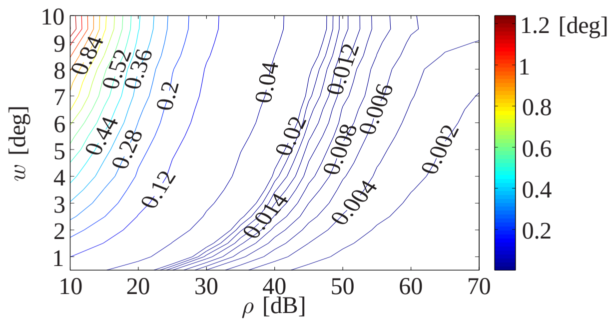


Fig. 3. Estimation accuracy for the optimum sensor positions Δ [deg] w.r.t. antenna-beam width and SNR

can be seen that for a certain antenna beam-width, better estimation accuracy can be achieved by increasing the SNR. Assuming that the sensor positions can be adjusted freely, the maximum accuracy as shown in Figure 3 can be achieved. However, the adjustment of the sensors can be very time consuming in practice. If one wanted to test subsequently various terminals with different antenna beam-widths, it would be preferable to keep the sensors at fixed positions for all tests. By defining a minimum de-pointing estimation accuracy (e.g., $0.05°$) that has to be achieved in any case, a region w.r.t. sensor position and antenna beam-width can be defined achieving at least the minimum accuracy at a certain SNR. According to Figure 4, the sensor position can be chosen in a wider range.

B. De-pointing Measurement Results

To demonstrate the performance of the de-pointing measurement system, measurements with different antenna types are carried at FORTE.

In satellite tracking, the terminal tries to keep the antenna always pointed towards the target satellite. This is achieved by either mechanically or electronically steering the antenna to have its main beam in the direction of the satellite. For most of the mechanically steerable antennas, the antenna pattern characteristics remain fixed and do not change from one steering angle to another. However, for electronically steerable antennas and some of the mechanically steerable antennas the pattern characteristics are changing when steering

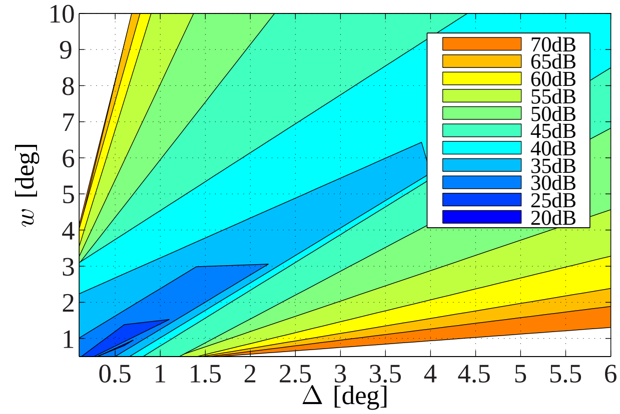


Fig. 4. Regions with estimation accuracy better than $0.05°$

towards another direction. This represents a concrete challenge for the antenna de-pointing estimation technique proposed in section III (see Figure 1). The estimation is based on calculating the correlation between the measured signal and the reference data. If the dependency of antenna pattern characteristics w.r.t. the steering direction is not accounted for, de-pointing estimation will be inaccurate.

In the following, measurements with two different antennas are performed at FORTE. In section III-B1, measurements using a terminal with a mechanically steerable reflector antenna which has a fixed beam pattern for all steering directions are analyzed. In section III-B2, a terminal with a mechanically steerable antenna is inspected whereby the construction of the terminal results in antenna pattern characteristics which is dependent on the steering angle. The effect of this dependency on the de-pointing estimation results is discussed.

The following parameters are used for the measurements:

1) Antennas with fixed beam pattern: A measurement with a Ka-band antenna which has a fixed beam is performed. Other setup components are adjusted according to Table I. The

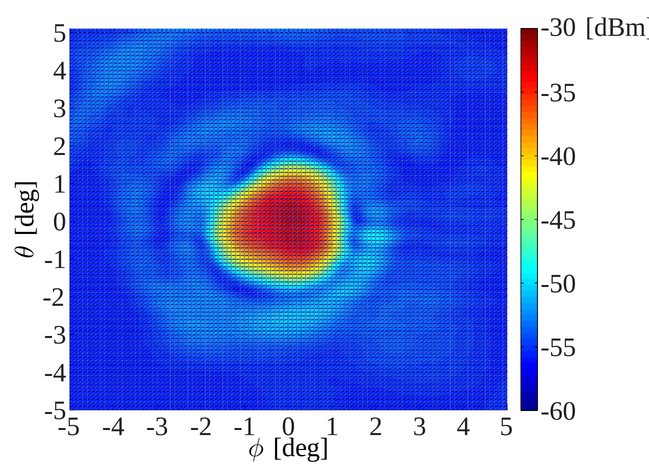


Fig. 5. Received power (2D pattern) of the Ka-band antenna with a fixed beam pattern

received power at the center sensor while rotating the DUT (using the motion emulator) in a 2D (horizontal-vertical) grid

TABLE I
THE SETUP PARAMETERS FOR THE MEASUREMENTS DESCRIBED IN SECTIONS III-B1 AND III-B2

	Ka-band antenna	**Ku-band antenna**
Frequency	Ka-band (27.5 - 31 GHz)	Ku-band (11.5 - 14.5 GHz)
w	1° both in azimuth and elevation	between 1.5° and 2° in azimuth and between and 4.8° and 5.8° in elevation depending on the elevation steering angle
Δ	1°	1°
Maximum receive SNR	30 dB	35 dB

is shown in Figure 5. The values shown in Figure 5 represent the received power at the antenna tower and are proportional to the antenna gain of the DUT.

The performance of the system can be analyzed rotating the DUT around the horizontal (one-dimensional, ϕ angle) and horizontal&vertical axes (2D, ϕ angle and θ angle) (see Figure 2). The motion profiles are sine functions with a fixed amplitude, frequency and phase. During the movement, the DUT tracking mode has been switched off, which means that the estimated de-pointing should exactly correspond to the excitation induced by the motion emulator.

As an example, the antenna moves according to Equation (2)

$$\phi(t) = \alpha_\phi \cdot \sin(2\pi f_\phi t + \psi_\phi), \tag{2}$$

where the antenna de-pointing follows a sine function along the horizontal axis only (with amplitude α_ϕ, frequency f_ϕ and phase ψ_ϕ). In this example: $\alpha_\phi = 0.2^\circ$, $f_\phi = 0.1\,\mathrm{Hz}$ and $\psi_\phi = 0^\circ$. The maximum SNR at the power detectors is 35 dB. The Root Mean Square Error (RMSE) and the standard deviation of the estimation results by means of the confidence interval are shown in Figure 6. The RMSE is represented by the blue line and the confidence interval (i.e. standard deviation) is represented using the red bars. The RMSE and the confidence interval are calculated for at least 100 realizations at each de-pointing angle ϕ.

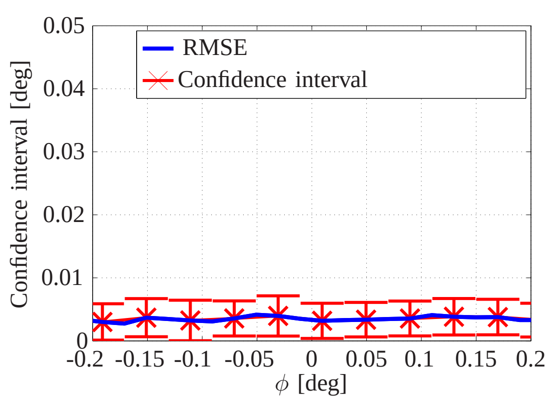
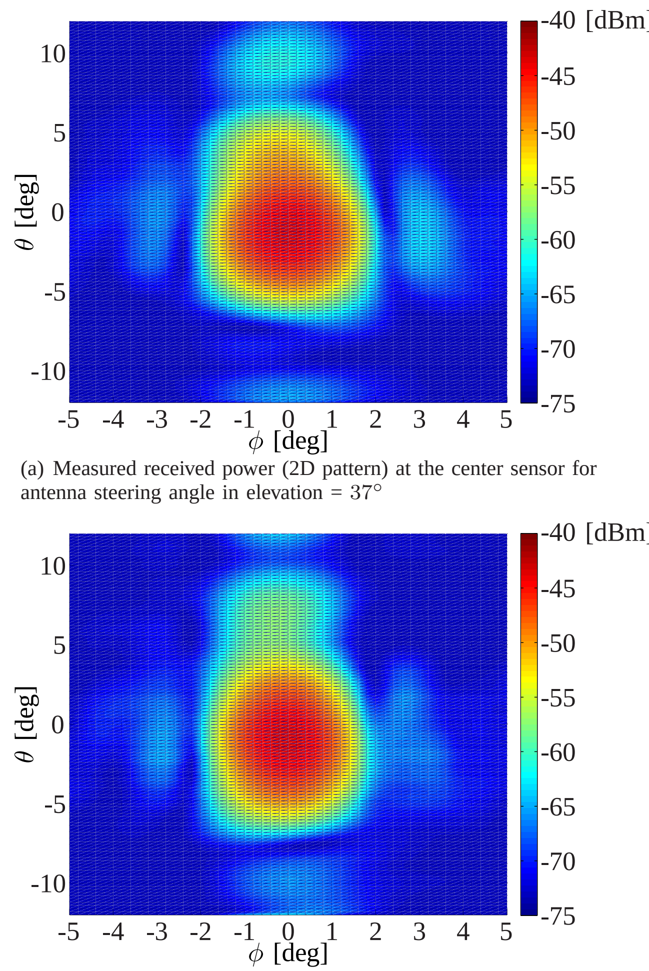


Fig. 6. RMSE and confidence interval for the estimation results when having a sine motion excitation ($f = 0.1\,\mathrm{Hz}$) along the horizontal axis with $\alpha_\phi = 0.2^\circ$

From Figure 6 it can be seen that the estimation accuracy is in the order of 0.005° on average.

2) Antennas with variable beam pattern: In a second measurement a terminal with a Ku-band antenna is used as DUT. The setup components are adjusted according to Table I. The terminal has a mechanically steerable reflector antenna. Due to the structure of the terminal, the pattern characteristics of the antenna change w.r.t. the elevation steering angle. The Tx-patterns of the antenna as measured for two different elevation steering angles are shown in Figure 7.



(a) Measured received power (2D pattern) at the center sensor for antenna steering angle in elevation = 37°

(b) Measured received power (2D pattern) at the center sensor for antenna steering angle in elevation = 32°

Fig. 7. Received power (2D pattern) of the Ku-band antenna with a variable beam pattern at two different steering angles in elevation

For de-pointing estimation evaluation, the antenna was moved in 2D diagonal track around 37° in elevation. During the movement, the antenna tracking mode has been switched off. To show the effect of pattern change on the de-pointing estimation performance, the following was considered:

1) The reference data measured for antenna elevation steering angle = 37° is applied for estimation to the measurement with an antenna elevation steering angle of 37°
2) The reference data measured for antenna elevation steering angle = 32° is applied for estimation to the measurement with an antenna elevation steering angle of 37°

Figure 8, depicts the motion excitation as well as the estimation results for the two cases.

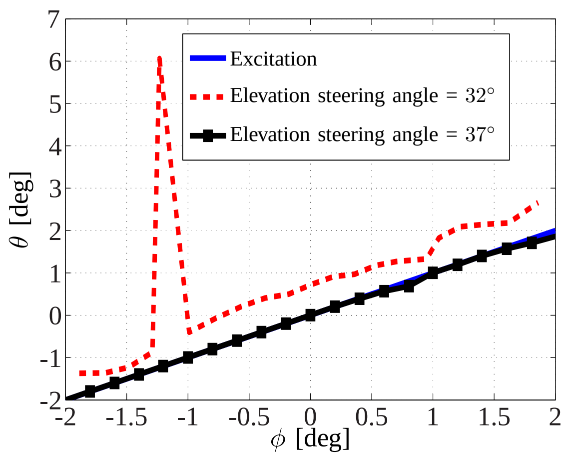


Fig. 8. De-pointing estimation results using the reference data for antenna elevation steering angle = 37° to estimate a motion with an antenna elevation steering angle of 37° (black line with squares) and De-pointing estimation results using the reference data for antenna elevation steering angle = 32° to estimate the same motion excitation (red dashed line)

The results in Figure 8 show that when using the reference data for antenna elevation steering angle = 37° to estimate the measurement with an antenna elevation steering angle of 37° (the black line with squares). the RMSE in azimuth is in the order of $0.002°$ with an accuracy of $0.001°$. For elevation, the RMSE is in the order of and $0.03°$ with an accuracy of $0.02°$. The estimation accuracy is lower for elevation compared to azimuth because the beam pattern is wider in elevation than in azimuth (see Figure 7).

However, using the reference data for antenna elevation steering angle = 32° to estimate the measurement with an antenna elevation steering angle of 37° leads to a biased estimation of the de-pointing (the red dashed line). The RMSE is in the range of $0.1°$ with an accuracy of $0.008°$ for azimuth and $0.9°$ with an accuracy of $0.05°$ for elevation. The bias in the estimation violates the estimation performance requirements. Furthermore, some outliers with wrong estimation results can be observed.

Measuring the full beam pattern for every steering angle of an antenna with a variable beam pattern represents the main challenge in evaluating their performance. It is desirable to minimize the time and cost needed to measure antenna patterns. In future extensions of this work a fast and efficient methodology of measuring the antenna pattern with the lowest possible number of measurements is to be explored.

The results discussed above primarily validate the performance of FORTE and approves its usage for VMES performance testing and validation.

IV. Conclusion

In this contribution FORTE is described. The de-pointing estimation accuracy is analyzed and evaluated by measurements. Measurements using antennas with pattern characteristics which are either dependent or independent of the antenna steering angle are performed. The advantages of FORTE and especially the demonstrated de-pointing measurement system compared to system verification with operational satellites can be clearly identified as follows:

- With the proposed sensor array, the de-pointing angle can be determined without involving operational satellites
- The distance between the sensors can be adjusted w.r.t. beam-widths, which results in a higher estimation accuracy of the de-pointing angle
- De-pointing measurements in azimuth and elevation in contrast to azimuth only are available, which is relevant in case of asymmetric antenna characteristics as in case of low profile antennas
- Measuring the reference data includes far field radiation pattern measurement (far field condition applies for aperture sizes of up to 90 cm)
- Real operational Geostationary Earth Orbit (GEO) satellites can also be used for testing
- Cost-efficient and available at all times

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