

Validation of Planar Array of discrete beams used in Mobile Terminal for Satellite Communication

Gabriel Helbourn Bastos and A. Judson Braga

Abstract—Antenna arrays are very used in systems where the transmission's direction has to be decided automatically. In this project, a 16x16 square array using phase shifters capable of forming discrete beams and the beam distribution obtained according to requirements are analyzed. In addition to the beam functional analysis, the array is also analyzed by some restriction imposed by ANATEL. As a result, gain graphics are plotted for all pointing directions and the graphic of gain over the geostationary orbit is plotted along with the aforementioned restrictions.

Keywords—Antenna array, mobile terminal, satellite, discrete beams, ANATEL.

I. INTRODUCTION

Internet of things has stood out as a solution for several cases and preventing truckload thefts can be one of them. In most cases the cellular network is used to reach the HUB. Recent technologies such as connected cars allows communication with other vehicles for road safety applications, but instead of connecting them directly, satellite communication presents a lower risk of intermittency, since it allows communication even in remote areas.

Since the communication terminal is constantly in move, the pointing should be adjusted automatically, ensuring the greatest gain in the transmitting direction. In this work we are interested in the study of a class of architectures that uses a discrete and fixed number of beams, as they are popular and of lower cost, such as those based on Rotman Lens and Butler Matrix [2]. This way, the best beam is not necessarily pointing towards the satellite, but very close to it. The use of variable phase shifters (Analog Beamformer) or AD/DA converters (Digital Beamformer) at the end of each element has huge technical advantages [4], but still with great cost challenges for a large-scale market.

In Brazil, like other wireless communication, satellite communication is regulated by Agência Nacional de Telecomunicações (ANATEL). Thus, this project must comply with ANATEL's recommendations in order to operate in the Brazilian territory. For Ku band operations, the current resolution is Resolution No. 288, of January 21st, 2002. It defines operating conditions for geostationary satellites in Ku band with coverage over the national territory [5]. We choose the Ku band for our study due to its great availability nowadays.

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A. Project Specifications

In order to evaluate the beams and the obtained distribution, the initial design specifications must be determined, such as the array size, the scanning area, the useful beamwidth and the complexity of the system.

The array size and the complexity of the system are closely connected variables, since the larger the array, the more beams are needed to perform the same scan. In addition, due to automotive application, there is a limitation on the maximum antenna area occupied with a inter-element spacing of half wavelength. Therefore, in order to seek a solution that meets the requirements, a 16x16 square array was chosen as a middle ground.

Bearing in mind that Brazil has close commercial relations with MERCOSUR countries, it is important to guarantee an operation in most of South America. Thus, it was decided that the coverage area should be defined between the elevation angles equal to 0° and 45° , which allows transmitting near Buenos Aires. Also, the half power beamwidth (HPBW) of most eligible antennas is limited in such high frequency. Along with it, São Paulo corresponds to the highest data traffic in Brazil and where the main highways are located, and should therefore have priority in the beam allocation. In order to avoid sudden gain variations, we fix the useful gain to not vary more than 3 dB in relation to the maximum value of the beam.

Finally, a mobile terminal with enough power is considered, in such a way that the only object of study in this research is the beam formed by the antenna array and how they can be allocated. The simulations considered some specific scenarios and parameters, such as the use of a planar array with discrete shifters in the terminal, a geostationary satellite system in Ku band, and the use of the DVD-RCS2 standard [7].

In the remainder of this article, we present the gain resultant of a planar array in Section II. Section III presents the beam distribution and how it is obtained. The parameters that will be used during the transmission are calculated and defined in Section IV, and they are applied in Section V, where the terminal is evaluated around ANATEL's resolution. Finally, the conclusions end this paper in Section VI.

II. GAIN OF A PLANAR ARRAY

When combining antennas, the signal transmitted by an element interferes with the signal transmitted by another in a constructive or destructive way and the resultant electric field in far field can be found by summing the vectors of the electric field of each one. So, it is equivalent to the field generated by a single antenna multiplied by the array factor (AF), which depends on the array geometry and the excitation phase.

For a planar array arranged along the XY plane, with M elements arranged along the X axis and N elements along the Y axis, the AF varies according to the elevation (θ) and azimuth angle (ϕ) and can be written as [1]:

$$AF(\theta, \phi) = \left[\frac{\sin(\frac{M\psi_x}{2})}{\sin(\frac{\psi_x}{2})} \right] \left[\frac{\sin(\frac{N\psi_y}{2})}{\sin(\frac{\psi_y}{2})} \right], \quad (1)$$

where

$$\begin{aligned} \psi_x &= kd_x \sin \theta \cos \phi + \beta_x \\ \psi_y &= kd_y \sin \theta \sin \phi + \beta_y \end{aligned} \quad (2)$$

In the equation, k represents the wave number, d_x and d_y represent the distance between each element in the X and Y planes, respectively, and finally, β_x and β_y represent the progressive phase between the elements on the X and Y axes, respectively. Spacing equal to half the wavelength will be considered on both axes.

Considering a high radiation efficiency, the gain can be approximated by its directivity. Therefore, the total gain of the array formed by isotropic antennas is [1]:

$$G(\theta, \phi) = \frac{4\pi |AF(\theta, \phi)|^2}{\int_0^{2\pi} \int_0^\pi |AF(\theta, \phi)|^2 \cdot \sin \theta \, d\theta \, d\phi}. \quad (3)$$

Using integration methods, it is possible to simplify the expression by relating it to the directivity of linear arrays (D_x in the X axis and D_y in the Y axis). This simplification is valid for a large array with isotropic elements and pointing close to the zenith angle. Under these circumstances, the array gain can be written according to:

$$G(\theta, \phi) = \pi \cos \theta \cdot D_x(\theta, \phi) \cdot D_y(\theta, \phi). \quad (4)$$

In order to generalize (4), the numerical integration presented in (3) was performed for elevation angles between 0° and 45° at a step of 5° . Although (4) defines directivity only for small elevation angles, the difference between the results obtained by each method was less than 0.25 dB. Therefore, the gain will be calculated according to (4).

III. BEAM DISTRIBUTION

The phase shifter is an important component for analog beamformers, as the progressive phase between the radiators is responsible for the beamforming. However, simpler and more accessible phase shifters, such as the Rotman Lens and Butler's matrix, have limitations in their behavior. This type of shifter is capable of generating a discrete number of phase-shifts and, consequently, a discrete number of beams.

Following the initial design determinations, the half power beamwidth must be respected. In this way, each beam is delimited by a set of points, which form an ellipse perpendicular to the beam. Figure 1 represents this set of points for different beams. When projecting these points in the XY plane, the shape turns into a circle whose center is in the projection of the maximum point of the beam.

In order to provide symmetry in the distribution and reduce complexity of Rotman lens or Butler matrix [2], it was decided to allocate the beams in a matrix format. For this shape, only

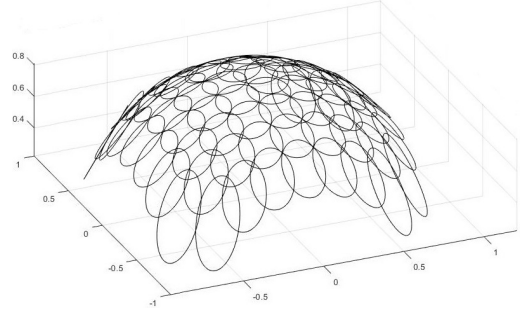


Fig. 1. Three-dimensional view of the half power regions of the beams.

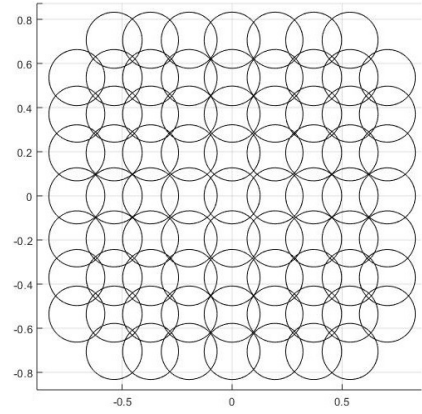


Fig. 2. Top view of the half power regions of the beams.

32 lenses have to be used in a 16×16 array and, for others shapes, more lens would have to be combined. Thus, the projection of the beam must form the rows and columns of the matrix, as can be seen in Figure 2.

As a starting point, the angles on the reference axis, which will be considered in azimuth equal to 0° must be defined. To determine the beams pointing to this azimuth, the first guess is to allocate them so that the border of one is adjacent to the neighbor. However, as can be seen in Figure 2, it was decided to add an overlap between them in order to avoid regions whose gain is below of what was initially expected.

Thus, the equation (5) determines the final relation to obtain the next beam (θ_{i+1}) based on the previous one (θ_i) and the HPBW on the elevation plane ($HPBW_{elev}$).

$$\theta_{i+1} = \theta_i + \frac{HPBW_{elev_i} + HPBW_{elev_{i+1}}}{2} - \delta_i. \quad (5)$$

The intensity of the overlap (δ) can be variable and determined according to the need or interest, favoring coverage at certain elevation angles. In addition, as the calculation of the next elevation angle depended on their HPBW, it is necessary to use computational tools in order to converge the result to the final value.

As mentioned above, the matrix relation guarantees symmetry between the quadrants. Thus, the elevation angles determined for $\phi = 0^\circ$ are the same for 90° , 180° and 270° . Knowing that the matrix elements are the projections of the beams in the XY plane, the coordinates of the other beams are defined by those of the beams on the axis. Therefore, it

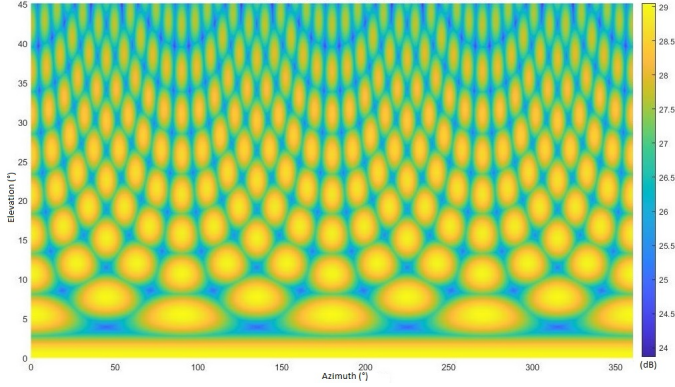


Fig. 3. Antenna gain for all pointing directions for a 16 x 16 planar array.

is possible to establish trigonometric relationships in order to obtain the elevation and azimuth angle for all.

Once beams with an elevation angle greater than 45° are not needed, they can be discarded and the total coverage is obtained with 233 beams. Bearing in mind that the system is multibeam, the beam with the highest gain must be chosen for the transmission or reception of the message. So, Figure 3 presents the result of maximum gain for a square array with 256 elements, in which beam shifting is considered.

The array resultant gain remains between 23.87 dB and 29.05 dB, exceeding the initial limit of 3 dB. However, this determination is only related to adjacent beams and the main cause of this difference is the scan loss of planar arrays and not due to the areas not covered by the overlaps. This is a result of the fact that the gain decreases as the elevation angle increases ($\cos(\theta)$ in (4)).

As stated, those areas where the overlap is not sufficient to meet the initial restrictions exist, but they do not make the project unfeasible. A small deflection in vehicle orientation can cause the terminal to point again with a larger relative gain beam. Despite this dynamism, in order to evaluate those possible alarming areas, Figure 4 presents the map of Brazil with the largest areas highlighted, considering the geostationary satellite at 65° West. These zones can be defined only by the elevation angle necessary for pointing in each geographical position. The azimuth angle can not be considered because it depends on the orientation of each vehicle.

As shown in Figure 4, these areas are located neither in the big Brazilian capitals nor in the South American capitals. These are cities of greater traffic and, therefore, cannot be inoperative. That said, areas where the EIRP may not reach the minimum value will be reduced to less populated areas with less traffic.

IV. TRANSMITTING PARAMETERS

The DVB-RCS2 [7] specification establishes some references for a return link, transmission from the terminal to the HUB. It works with multiple time division access (TDMA) and presents different waveforms, each with its own characteristics. Although the terminal has no limitation on transmission power, it is not desired to work with high powers. Thus, the most suitable waveform for the project is number 42, which

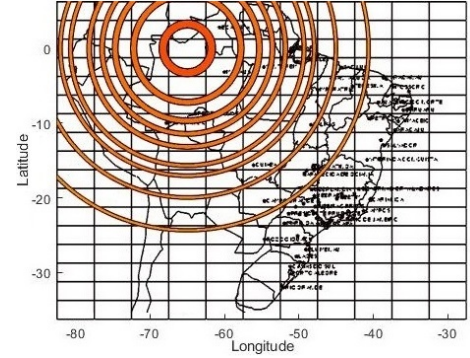


Fig. 4. Brazilian map with highlighted geographic areas where the gain may be less than expected.

promises to operate with an E_s/N_o ratio equal to -3.81 dB and BPSK modulation [7]. Waveform 42 does not provide high data rate, but enough for security applications, such as text messaging and remote control.

In the same way that the beam distribution prioritizes São Paulo, the minimum power must be calculated with the parameters of that city. The transmission power (P_T) can be obtained by the equation (6), using known parameters, such as Boltzmann constant (k_B), losses involved in the transmission (L), the transmission gain (G_T), and the satellite figure of merit (G_R/T) according to the satellite specifications [6].

$$\frac{E_s}{N_o} R_s = P_T G_T \frac{G_R}{T} \frac{1}{k_B} L. \quad (6)$$

On the other hand, the transmission symbol rate (R_s) is fixed and must be defined for the whole system.

Knowing the directly proportional relationship between the transmission rate and the bandwidth occupied by the signal, the choice of R_s should be based on the desired bandwidth for the channel. Working with a high bandwidth requires a higher transmission power, because the noise power is also greater. In contrast, narrow bands are more vulnerable to some phenomena such as the Doppler effect.

It was then decided to use a transmission bit rate equal to 250 kbps per channel, resulting in a bandwidth equal to 300 kHz for a factor of *roll-off* equal to 0.2. As mentioned above, this is the transmission rate of a time division system for multiple users. The number of users per frame and the transmission bit rate of each user can be decided respecting the parameters of the waveform number 42.

Once the transmission rate is defined, the power can be calculated according to (6) with the parameters for São Paulo presented in Table I. The transmission gain was obtained from the proposed distribution and the pointing angle calculated considering that the array is oriented to the north. Only the loss in free space is considered because the other losses are negligible, most of the time. The required power is -4.82 dBW.

TABLE I
PARAMETERS IN DECIBEL FOR CALCULATING THE TRANSMISSION POWER.

E_s/N_o	R_s	G_T	G/T	k_B	L
-3.81	53.98	28.19	5.5	-228.6	-207.3

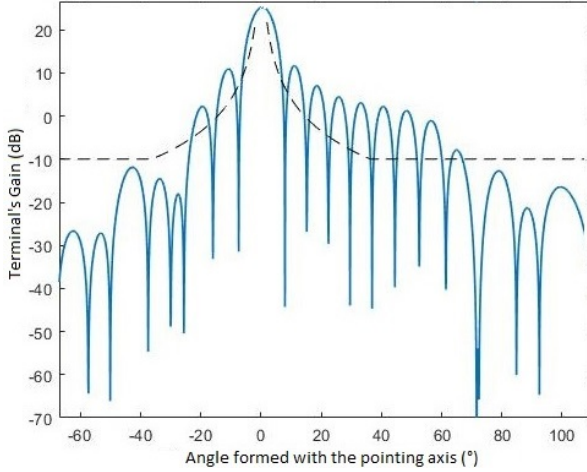


Fig. 5. Gain of a 16x16 antenna array for a transmission from São Paulo to a geostationary satellite at 65° West.

V. ANATEL REGULATIONS

The ANATEL resolution n° 288 [5] is responsible for restricting communication in Ku band. The purpose of the regulation is to reduce the level of interference on neighboring satellites or other terminals. The criteria, which involves the formation of the beam, refer to the gain of the antenna and the EIRP of the transmission. Other criteria are also presented in the resolution in the parameters and technical criteria section.

A. Radiation Mask

The topic 4.1.1. item V of the list attached to ANATEL resolution n° 288 defines the gain limit of the side lobes for a transmitting earth station. The equation (7) shows the limit imposed on the terminal's gain. The angle γ is the angle formed by the desired point (satellite) and any other point in the geostationary belt.

$$G(\gamma) = \begin{cases} 29 - 25 \cdot \log_{10}(\gamma) & 1, 9^\circ \leq \gamma < 36^\circ, \\ -10 & 36^\circ \leq \gamma < 180^\circ. \end{cases} \quad (7)$$

The terminal gain for all points of the geostationary line was plotted for a pointing from São Paulo. ANATEL's mask was plotted with the radiation diagram in order to evaluate the terminal. Figure 5 shows that the 16x16 array is not capable of operating according to restrictions.

The same procedure was done for different locations in Brazil and in none of them did the radiation diagram obey the limits. Arrays with more elements were studied and, for the main lobe to follow the recommendations, the number of elements in a row would have to triple. In addition to size being an obstacle to this adaptation, the secondary lobes also prevent approval.

B. Interference in neighboring satellites

The topic 4.1.1. item VI of the list attached to resolution n° 288 of ANATEL gives an alternative for not complying with item V. There are two possibilities for operation: coordinate the use with satellite networks close to the satellite of interest and reduce the transmitted power in a way that

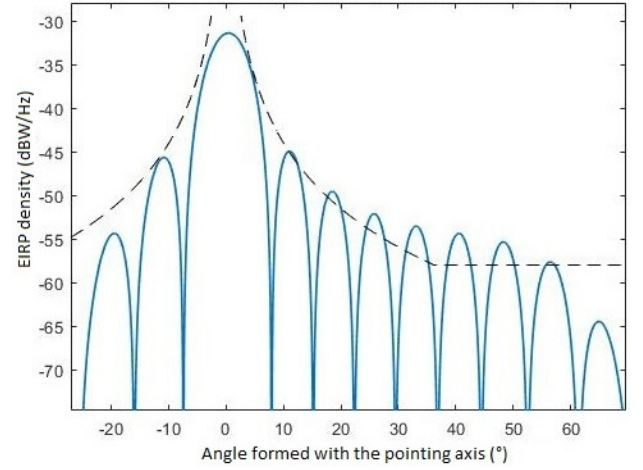


Fig. 6. EIRP density transmitted in 16x16 antenna array for a transmission from São Paulo to a geostationary satellite at 65° West.

the off-axis EIRP density meets the requirements of item VII. The equation (8) defines the limit imposed in item VII for the density of EIRP in transmission (dBW/Hz) so that an earth station can operate without the need to coordinate the use.

$$d_{EIRP}(\gamma) = \begin{cases} -19 - 25 \cdot \log_{10}(\gamma) & 1, 9^\circ \leq \gamma < 36^\circ, \\ -58 & 36^\circ \leq \gamma < 180^\circ. \end{cases} \quad (8)$$

To calculate the transmitter's EIRP density, the transmission EIRP (calculated by the power obtained in section IV and the antenna gain) was divided by the channel bandwidth (also defined in section IV). In a given channel, only one terminal is able to transmit (TDMA) at that frequency range. Therefore, the total EIRP is equivalent to the minimum operating power associated with the gain of the terminal.

Similarly, the EIRP density graphic as a function of the pointing angle was also plotted with the imposed limits, as can be seen in Figure 6. It is possible to notice that the terminal also does not meet this restriction because of some side lobes above the minimum level. For the pointing presented, the biggest difference between the obtained and the restraint is 3.61 dB. However, the same procedure was performed for other pairs of latitude and longitude in the Brazilian territory and this difference can reach up to 7.34 dB.

Figure 7 shows the density of EIRP for several locations in Brazil and the large amplitude of the secondary lobes are the main causes of the non-adequacy of the beam. In addition, it is also possible to notice that, in several positions, the main lobe does not meet the restrictions because it is out of relation to the maximum gain, caused by the use of discrete beams that not always points to the satellite.

C. Compliance with the Standard

Some changes are necessary for the terminal to meet the requirements and be authorized to operate. These changes should aim at decreasing the density of transmitted EIRP. The main method for this decrease would be to increase the system's bandwidth. However, increasing the bandwidth requires an increase in transmission power to maintain the same E_s/N_o ratio. The equation (9) presents this relation for

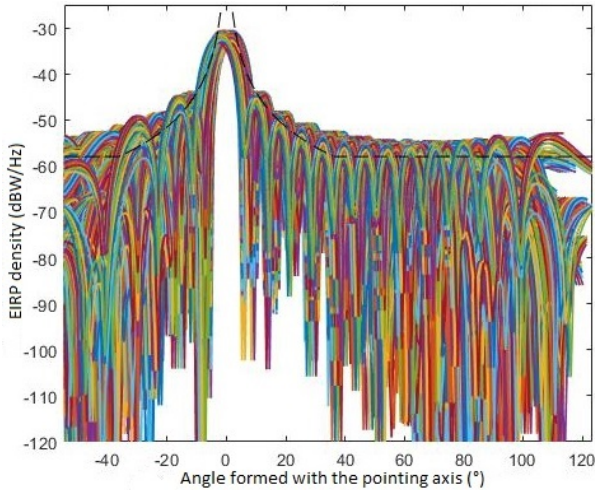


Fig. 7. EIRP density transmitted in 16x16 antenna array for different locations in Brazil to a geostationary satellite at 65° West.

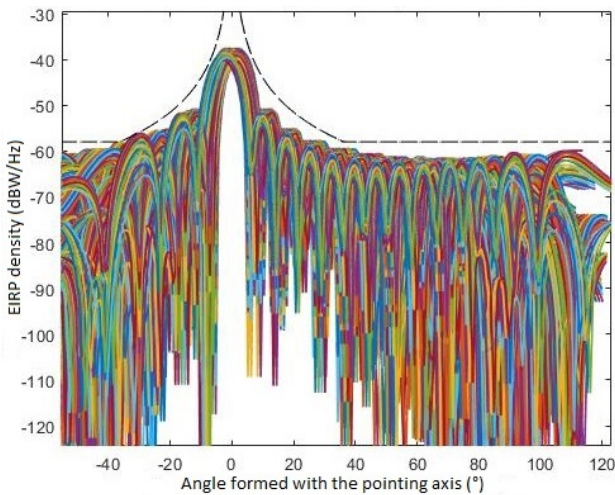


Fig. 8. EIRP density transmitted in 16x16 antenna array with spread spectrum for different locations in Brazil to a geostationary satellite at 65° West.

a system with modulation BPSK, in which the bandwidth is only determined by the transmission rate.

$$\frac{E_s}{N_o} \frac{1}{1 + \alpha} = d_{EIRP} \frac{G_R}{T} \frac{1}{k_B} L. \quad (9)$$

In order to decouple the bandwidth from the minimum power, the spread spectrum technique is used, because it does not affect the SNR. For the signal to meet the standard, the spread must have a processing gain approximately equal to 5. Figure 8 presents the result of spreading the spectrum. This would solve the problem, but it also has consequences for the system, since the increase in bandwidth decreases the number of channels per transponder.

Other alternatives are also possible and, in order to maximize use, they must be adopted together. To reduce the impact of the main lobe, the coverage area must be reduced, so that the number of beams would be the same and they would be closer. Thus, the maximum value of the beam would be nearer the pointing axis. Secondary lobes are also obstacles to approval and, therefore, in addition to the phase, amplitude control in

the antenna excitation must be performed. These two methods combined can reduce interference in neighboring satellites, enabling the approval of the terminal without impacting the number of users that the system supports.

VI. CONCLUSION

The proposed distribution for the discrete beams meets the initial requirements, even with the large proposed coverage area. To ensure that there is communication for elevation angles up to 45°, a minimum of 233 beams are defined. Bearing in mind that one of the requirements is to respect the half power beamwidth, the beams are positioned overlapping, avoiding regions with partial coverage.

On the other hand, analyzing the beams formed by the array, the result is not so satisfactory. Since the main lobe is very large and the secondary ones are expressive, the terminal does not meet ANATEL standards. The project as a whole does not become unfeasible due to this, but it is necessary to make some adaptations. These adaptations are positive, but result in some disadvantage in the system.

The first one is the spread spectrum of the signal, which decreases the spectral density of EIRP without changing the SNR of the system. This is the simplest choice and allows an increase in transmission power for less favorable situations, but it also provides the greatest impact on users. By increasing the bandwidth of a channel, fewer channels will be allocated on a transponder and, consequently, fewer users will be served.

The second adaptation is the control of the amplitudes of the antennas, which impacts on the reduction of the secondary lobes. On the other hand, this is a costly solution as it requires amplifiers and/or attenuators. Finally, the last adaptation involves changing the initial project definitions. Reducing the coverage area allows the beams to be closer without changing the total amount of beams. This provides greater gains and decreases the angular error in relation to the desired pointing.

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