Design and Optimization of Multi-Faceted Reflectarrays for Satellite Applications

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***Abstract*—The design and optimization of multi-faceted reflectarrays for satellite applications are presented. The objective of this work is to investigate the performance of a multi-faceted reflectarray designed using a direct optimization technique. To this end, a single-layer multi-faceted reflectarray, that produces a contoured beam for a European coverage in a bandwidth of 17% has been designed. The performance is compared to that of a planar reflectarray as well as a shaped reflector. In the considered frequency range, the co-polar minimum directivity within the coverage of the multi-faceted reflectarray surpasses that of its planar counterpart with more than 1 dB. Compared to the shaped reflector, the difference between the co-polar minimum directivity of the multi-faceted reflectarray and the shaped reflector is only 0.3 dB. To improve the cross-polar radiation of the multi-faceted reflectarray, cross-polar suppression is included in the optimization and the minimum cross polar discrimination of the optimized reflectarray is improved with 2.3 dB without any degradation of the co-polar radiation.**

***Index Terms*—reflectarrays, contoured beam, optimization, shaped reflectors, satellite applications**

I. Introduction

Printed reflectarrays usually consist of a flat surface. They are light, easy and cheap to manufacture, and provide a way to realize low-cost high-gain antennas for space applications. They are therefore of great interest for satellite manufactures and space agencies and are the subject of increasing research and development activities [1]–[4].

To ensure high gain, the electrical size of the printed reflectarrays must be large, and an accurate yet efficient design procedure is therefore a challenging task. The conventional approach for the design of printed reflectarrays is based on a phase-only optimization technique [4]. Although this technique is efficient, a direct optimization technique, where all the array elements are simultaneously optimized, may produce more optimal designs. Such a direct optimization technique was presented in [5], where several contoured beam reflectarrays were designed and they exhibited superior performance compared to similar designs obtained using the phase-only optimization technique.

Although printed reflectarrays possess several attractive features in terms of the manufacturing process, they have not yet gained widespread acceptance for space applications, and conventional shaped reflectors are still the preferred choice for this purpose. This is presumably due to several reasons, one of them being the inherent narrow bandwidth of the printed reflectarray, which is controlled by the bandwidth of the printed elements and the differential spatial phase delay from the feed [6]. Many solutions have been proposed in the literature to alleviate the bandwidth issue, one of them being the use of advanced broadband elements [7] in conjunction with a multi-faceted reflectarray, as suggested in, e.g. [8], [9] and demonstrated in [10]. In this latter work, the reflectarray is designed using a phase-only optimization technique, which may result in sub-optimal designs, and the presented design did not reach the performance of a shaped reflector. The use of a direct optimization technique, e.g., the one presented in [5], may on the other hand produce designs with enhanced performance.

The objective of this paper is to demonstrate the capability of optimizing a multi-faceted reflectarray using a direct optimization technique. To this end, a single-layer offset multi-faceted reflectarray, that produces a contoured beam for a European coverage, is designed and the performance is compared to that of a corresponding planar design and an equivalent sized shaped reflector.

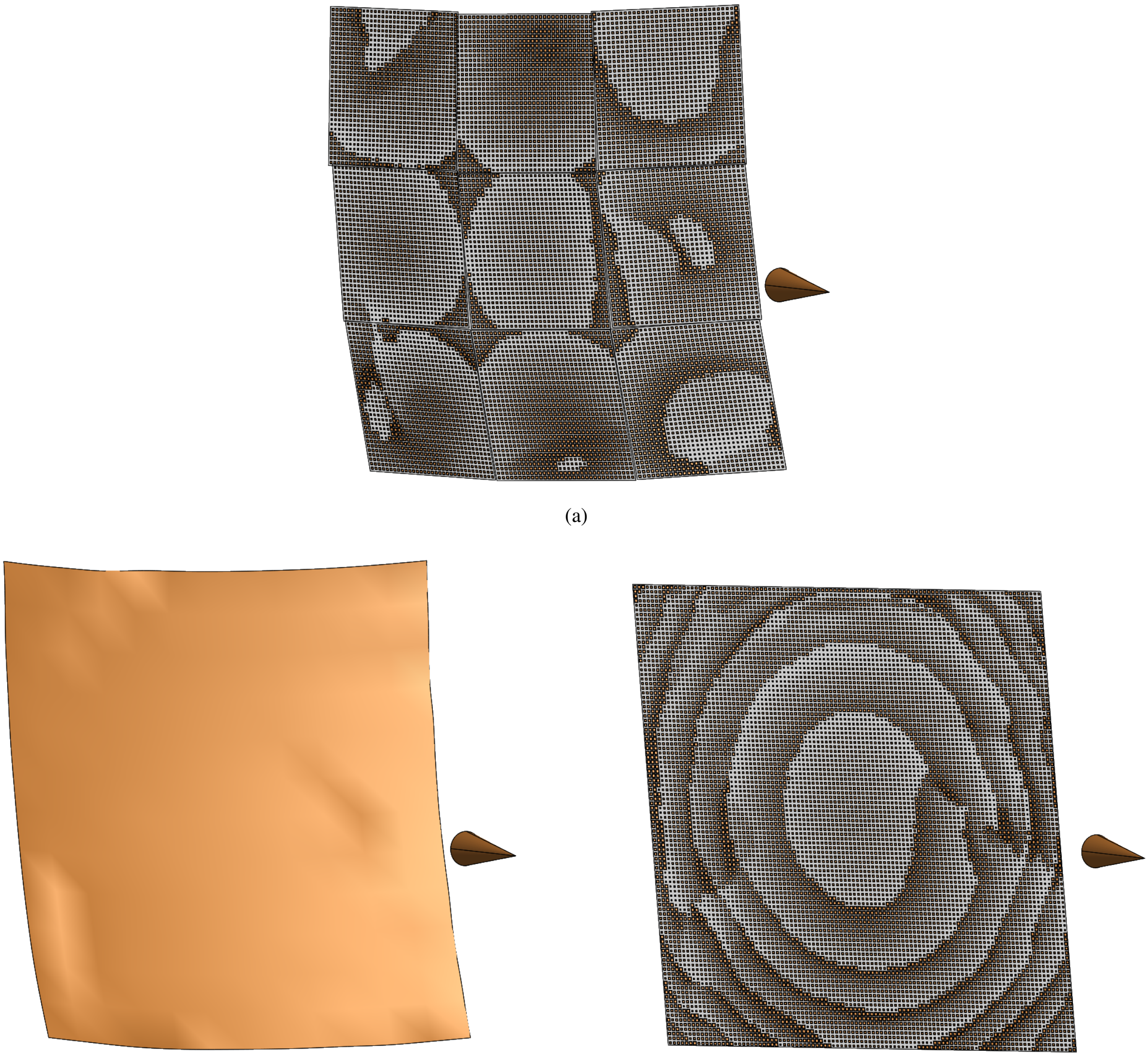
This paper is organized as follows. Section II describes the design of the multi-faceted reflectarray. Numerical results of the antennas are provided in Section III. In Section IV, future works are suggested, and conclusions are given in Section V.

II. Reflectarray Design

The direct optimization technique from [5] has been extended to allow the optimization of multi-faceted reflectarrays. The analysis in the direct optimization technique is based on a spectral domain method of moments assuming local periodicity and has proven to be both efficient and accurate. The optimization engine uses a gradient-based method for non-linear minimax optimization and is the same algorithm that is used in TICRA's software POS [11], which is considered by the antenna community to be the de-facto-standard software tool for the design of shaped reflectors. For more details on the analysis and optimization in the direct optimization technique, the reader is referred to [5].

A. Reflectarray Configuration

The configuration of the multi-faceted reflectarray is depicted in Fig. 1a. The reflectarray is composed of 9 flat panels, each with a dimension of $0.33 \times 0.33\,\mathrm{m}^2$. The panels are arranged such that they imitate the surface of a rectangular paraboloidal reflector. The reflectarray consists of 9801 elements and is optimized to radiate a contoured beam for a European coverage in H-polarization within the frequency range



(a)

(b)

(c)

Fig. 1. Configuration of (a) the multi-faceted reflectarray, (b) the shaped reflector, and (c) the planar reflectarray.

$11 - 13\,\mathrm{GHz}$ (17% bandwidth). At the center frequency, the dimension of the multi-faceted reflectarray is approximately $40 \times 40\,\lambda_0^2$, where λ_0 is the free-space wavelength. The feed is a linearly polarized Gaussian beam with a taper of $-12\,\mathrm{dB}$ at $26.6°$.

Square panels are used in the current design, however, other shaped panels can also be utilized if, e.g., an elliptical rim is desired for the multi-faceted structure.

B. *Reflectarray Element*

To obtain broadband performance, the reflectarray elements should be carefully selected. The phase curve of the scattering coefficients as function of the geometrical parameters should be slow and almost parallel at different frequencies [12]. In previous studies [13], [14], the square loop/patch combination element has shown to possess good phase response properties. This is shown in Fig. 2, where the phase response for normal plane wave incidence as a function of L_1 (length of the outer loop) for different frequencies is depicted. The substrate has a dielectric constant of $\epsilon_r = 2.33$, loss tangent of $\tan\delta = 0.0004$, and thickness of $h = 3.175\,\mathrm{mm}$. It is seen that the phase curves versus L_1 are close to being parallel at the different frequencies. Due to these properties, the square loop/patch combination element will be used in the multi-faceted reflectarray. In the optimization, only L_1 is included as optimization variable and the width of the outer loop (w_1) and length of the inner square (L_2) are fixed with respect to L_1 as $w_1 = 0.075L_1$ and $L_2 = 0.75L_1$, respectively.

C. *Initial Starting Point*

The direct optimization technique is based on a gradient minimax algorithm. Since it is gradient based, a good initial point is required to ensure rapid convergence and to avoid non-optimum local minima. In many practical cases, identical array elements can be used as the starting point and yields good results [5]. However, for a multi-faceted contoured beam

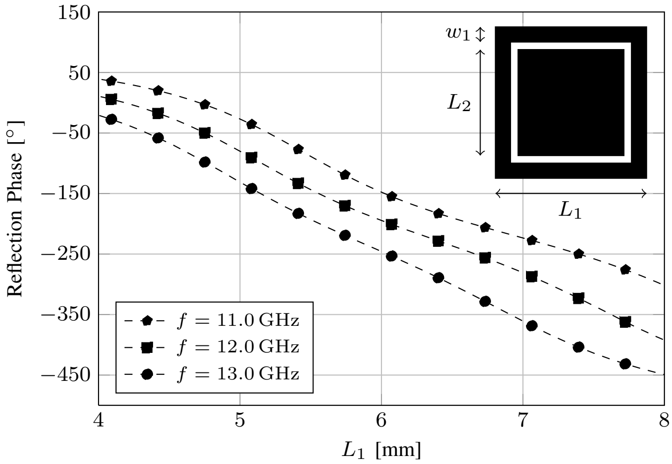


Fig. 2. The phase of the scattering coefficient of a square loop/patch combination element in a periodic environment as function of the outer loop length L_1 for different frequencies. The inner loop length is $L_2 = 0.75L_1$ and the width of the outer loop is $w_1 = 0.075L_1$.

design, this is not the case since the scattering from the different panels causes destructive interference, resulting in an initial pattern that does not resemble the required contoured beam. Consequently, the optimization results in a sub-optimal solution. The same issue exists if a pencil beam reflectarray is used as the starting point. To circumvent this, a more sophisticated starting point needs to be employed and is elaborated below.

Depending on the complexity and the requirements of the specified contour, a reflectarray that radiates an initial defocused elliptical beam can be a good initial starting point. Such a reflectarray can be obtained by adjusting the dimensions of the elements to match a properly selected phase variation over the reflectarray surface. However, work done in [15] suggests that using a reflectarray designed by a phase-only optimization technique as starting point usually provides the most optimal solution. Thus, for the optimization of the multi-faceted reflectarray, a phase-only optimized design will be used as the starting point.

To determine the phase distribution needed to radiate a given contoured beam, numerous phase-only synthesis techniques exist in the literature and several have been applied to the design of reflectarrays, e.g., [4]. In the present case, the required phase distribution is obtained from the radiation of a shaped reflector. Using the POS software, a shaped reflector that fulfils the coverage requirements can be easily designed. From the shaped reflector, the required phase distribution at the surface of the reflectarray panels at 12 GHz is extracted. This is done by using the GRASP software [16] by applying a plane wave expansion of the radiation from the shaped reflector. From the plane wave expansion, the required phase distribution can be calculated at any position on the reflectarray surface. The array elements are subsequently optimized, element by element, to comply with the phase distribution. This initial design is then used as the starting point for the optimization of the multi-faceted contoured beam design in the entire frequency range.

The mask layout of the optimized reflectarray is shown in Fig. 1a. The overall optimization time, including the design of the shaped reflector, on a 2.6 GHz Intel-core i7 laptop computer was less than 24 hours.

III. Numerical Results

The radiation pattern of the optimized multi-faceted reflectarray at 12 GHz is shown in Fig. 3. It is seen that the reflectarray radiates a contoured beam within the European coverage with a minimum directivity of $D_{\min} = 29.2\,\mathrm{dBi}$. The performance of the multi-faceted reflectarray is summarized in Table I and compared to that of an equivalent sized shaped reflector (see Fig. 1b) optimized using POS with the same coverage specifications. Furthermore, the table also contains the performance of a planar reflectarray (see Fig. 1c), designed using the same procedure as for the multi-faceted design.

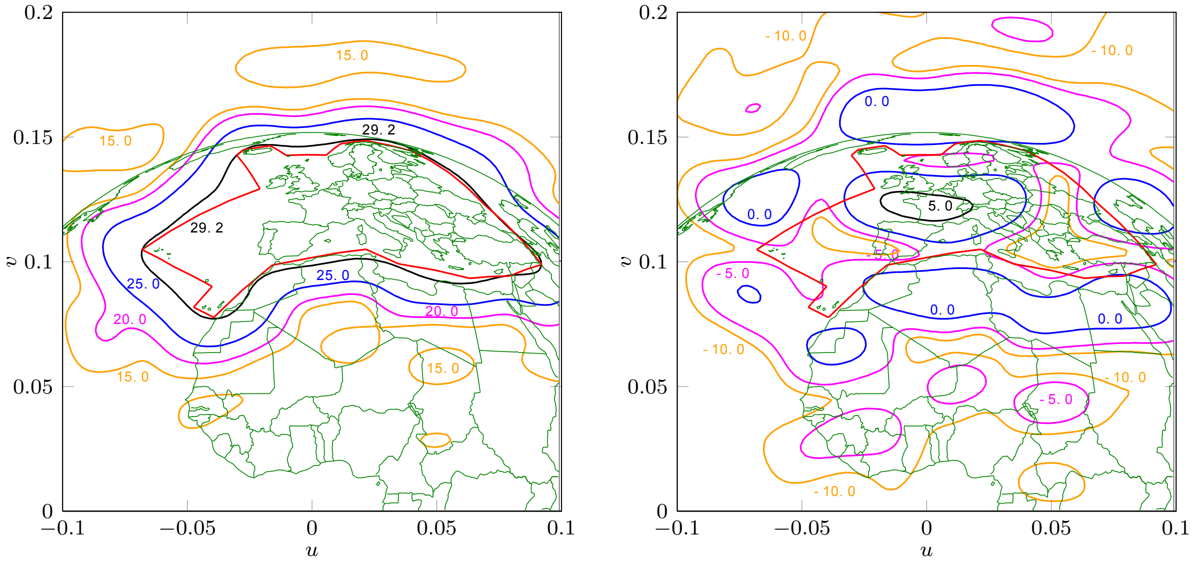
It is noted that outside the frequency range $11 - 13\,\mathrm{GHz}$ the minimum directivity drops for all three designs, indicating that the antennas are successfully optimized to operate in the specified frequency range. Within $11 - 13\,\mathrm{GHz}$, the minimum directivities for the planar reflectarray, the multi-faceted reflectarray, and the shaped reflector are $27.7\,\mathrm{dBi}$, $29.1\,\mathrm{dBi}$, and $29.4\,\mathrm{dBi}$, respectively.

The minimum directivity of the multi-faceted reflectarray exceeds that of the planar reflectarray with more than $1\,\mathrm{dB}$. For comparison purposes, a multi-faceted reflectarray consisting of square patches was also designed and compared to a similar planar design with square patches. The minimum directivity for the multi-faceted and the planar square patch designs were $28.2\,\mathrm{dBi}$ and $27.7\,\mathrm{dBi}$, respectively. This indicates that the performance of the planar designs, the square patch design and the square loop/patch combination element design, is restricted by the bandwidth limitations due to the spatial differential phase delay from the feed. For the multi-faceted square patch design, the performance is limited by the choice of the element. It can thus be concluded that with a proper array element, the performance improvements that can be achieved by using a multi-faceted reflectarray rather than its planar counterpart can be rather significant.

Comparing the performance of the multi-faceted reflectarray with the shaped reflector, the difference in minimum directivity is $0.3\,\mathrm{dB}$. This is rather small and can be considered as a very good result for the reflectarray. We believe the good

TABLE I
Performance Comparison of Reflectarray Designs with Shaped Reflector

Frequency [GHz]	Planar Reflectarray $D_{\min}$ [dBi]	Multi-faceted Reflectarray $D_{\min}$ [dBi]	Shaped Reflector $D_{\min}$ [dBi]
10.5	25.1	28.2	28.8
11.0	27.8	29.1	29.4
12.0	27.8	29.2	29.5
13.0	27.7	29.1	29.4
13.5	26.5	28.0	29.2



(a) Co-polar

(b) Cross-polar

Fig. 3. The radiation pattern of the multi-faceted reflectarray at 12 GHz, (a) co-polar pattern and (b) cross-polar pattern. The European coverage is shown as the red polygon.

performance is attributed to the combination of three factors: the multi-faceted structure, a suitable reflectarray element, and the direct optimization tool used to design the reflectarray. Although some measures were taken during the design process to ensure a good antenna performance, e.g., by selecting appropriate array elements, only one geometrical parameter was included in the optimization. It is expected that further improvements can be achieved if additional degrees of freedom are added to the optimization process. This could for instance be adding w_1 and L_2 as optimization variables, or by using other advanced element types with geometrical variations that can adjust the frequency response.

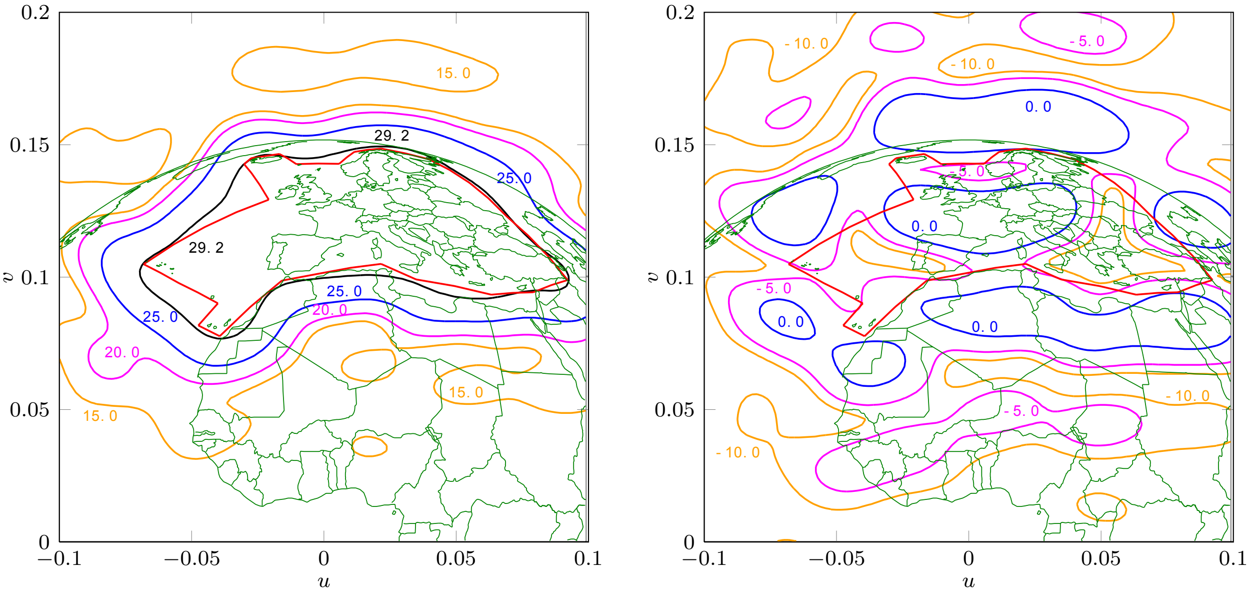
It is seen in Fig. 3b that the multi-faceted reflectarray has a relatively high cross-polar radiation. Within the specified frequency range, the minimum cross-polarization (XPD) for the multi-faceted reflectarray is $23.1\,\mathrm{dB}$ whereas it is $23.4\,\mathrm{dB}$ for the shaped reflector. To demonstrate another important feature of the direct optimization technique, the multi-faceted reflectarray is reoptimized with cross-polar suppression included in the optimization. The goal is to maintain the minimum directivity of $29.1\,\mathrm{dBi}$ within the frequency range, but to suppress the cross-polar radiation as much as possible. The radiation pattern of this optimized reflectarray at $12\,\mathrm{GHz}$ is shown in Fig. 4. It is seen that the radiation pattern is similar to that in Fig. 3, but the cross-polar radiation has been suppressed without any degradation of the co-polar radiation. The minimum XPD within the frequency range has been improved with $2.3\,\mathrm{dB}$ to $25.4\,\mathrm{dB}$. If the requirements for the co-polar radiation is slightly relaxed, further improvements in the minimum XPD can be achieved.

IV. Suggested Future Works

Overall, the multi-faceted reflectarray exhibits great potential and should be considered as a serious contender to the shaped reflectors for space applications. The work presented in this paper can be extended and should be explored further.

First, more advanced element types should be explored in conjunction with the multi-faceted structure. As mentioned in Section III, the minimum directivity of the multi-faceted reflectarray was increased with almost $1\,\mathrm{dB}$ by using the square loop/patch combination element instead of square patches. In addition, only one geometrical parameter was included as optimization variable. The potential enhancement gained by adding additional degrees of freedom in the optimization should be exploited and investigated. Furthermore, the presented multi-faceted reflectarray was optimized for a single linear polarization. The use of e.g. a rectangular loop/rectangular patch combination element for dual-polarization should be examined.

Second, the dimension of the presented multi-faceted reflectarray at the center frequency is approximately $40 \times 40\,\lambda_0^2$ and the use of 9 panels provided good results. To obtain the optimal performance using larger reflectarrays, additional panels are required and this may complicate the manufacturing and stiffness of the multi-faceted structure. A reflectarray with elements printed on a curved parabolic surface circumvent this problem and has a number of additional distinct advantages, and thereby worth to investigate. The spatial phase delay from the feed is fully eliminated and the bandwidth of the reflectarray is mainly determined by the individual array elements. Additionally, a large doubly curved surface is inherently stiffer can thus be made more lightweight than its multi-faceted counterpart.



(a) Co-polar

(b) Cross-polar

Fig. 4. The radiation pattern at 12 GHz of the multi-faceted reflectarray with cross-polar suppression included in the optimization, (a) co-polar pattern and (b) cross-polar pattern.

V. Conclusions

The design and optimization of a single-layer multi-faceted contoured beam reflectarray are presented. The multi-faceted reflectarray is optimized using a direct optimization technique to radiate a contoured beam for a European coverage in a bandwidth of 17%. The multi-faceted reflectarray consists of 9801 array elements, where a square loop/patch combination element is used as element to ensure broadband performance. At the center frequency, the dimension of the reflectarray is approximately 40×40 square wavelengths. As the starting point for the optimization, a design obtained using a phase-only optimization technique is used. The performance of the optimized multi-faced reflectarray is compared to that of a planar reflectarray and a shaped reflector. In the specified frequency range, the minimum directivity ($D_{\min}$) within the coverage of the multi-faceted reflectarray surpasses that of its planar counterpart with more than 1 dB. Furthermore, the performance difference between the multi-faceted reflectarray and the shaped reflector is small where $D_{\min}$ differs with only 0.3 dB. The good performance of the multi-faceted reflectarray is attributed to the combination of the multi-faceted structure, the selected element type, and the direct optimization tool used to design the antenna. To improve the cross-polar radiation of the multi-faceted reflectarray, cross-polar suppression is included in the optimization and the minimum cross polar discrimination of the multi-faceted reflectarray is improved with 2.3 dB without any degradation of the co-polar radiation.

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