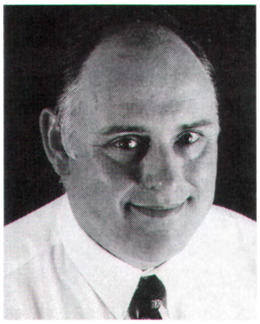

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Foreword by the Editor

Digital TV broadcasting has brought wire antennas back to the fore in terms of antenna engineering. Wire antennas were some of the first structures that were rigorously analyzed using numerical methods (using the Method of Moments in the 1960s). This issue's contribution describes a modern Web-based optimization tool built around *MiniNEC*, for long one of the workhorses of computational electromagnetics.

We thank the authors for their contribution. The software described can be accessed on the Web.

Analysis and Optimization of Wire Antennas over the Internet

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Abstract

With the recent deployment of wireless digital TV systems around the world [1-3], wire antennas are once again i widespread use. This article introduces the software *GRADMAX for Web*, a *Java* applet for analyzing and optimizing arrays (wire antennas. The analysis algorithm is based on the point-matching technique of the Method of Moments (*MININE* engine) [4-6], and the optimization layer employs the modified gradient method [7]. *GRADMAX for Web* is designed for th Internet, and runs directly from the Web browser on all common operating systems (*Windows*, Macintosh, *Linux*, *Solari* etc.).

Keywords: Wire antennas; numerical analysis; moment methods; optimization methods; Internet

1. Introduction

Wire antennas have always been linked to low-frequency broadcasting systems, such as radio and TV. Monopole, dipole, Yagi-Uda, log-periodic, helix, and loop antennas are among the popular choices. Although they have always been employed with other applications at frequencies usually lower than 2 GHz – such as GPS, mobile devices, and others – they were not as usual as in the past until the recent worldwide deployment of digital broadcasting TV systems [1-3].

The possibility of designing elaborate arrays of wire antenna elements, including shaped geometries [7], requires access to precise numerical codes. The Method of Moments is normally employed to determine the current distribution and input impedance with high accuracy, as it naturally accounts for mutual-coupling effects [4-6]. There are many computer codes available, ranging from standalone applications, to scripts for commercial mathematical packages, including a few with optimization capabilities [8-11]. The advantages of the code herein described (*GRADMAX for Web*) over others available are twofold: 1) Its verified accuracy over almost two decades of use in teaching and research (the *DOS* version was released in 1991, although not published internationally); and 2) its ease of use and access, as it runs directly from the Web browser on all common operating systems (*Windows*, Macintosh, *Linux*, *Solaris*, etc.).

The authors have previous experience with *Java*-applet technology [12]. They are very pleased to introduce another useful free code to the antenna community, given that the previous one has been successfully used by different people around the world over the past couple of years. Although there are examples of antenna codes that are accessible over the Internet, most require a server-client type of environment, or possess simplified algorithms that are not able to analyze more-complex geometries [13-14]. Based on the authors' previous experience, server-client environments may lead to problems, such as server congestion and server services not properly started after maintenance or updates. For a complete summary of the *Java* technology, including its limitations, the reader is referred to [12].

2. The Method of Moments

The analysis part of *GRADMAX for Web* is based on the point-matching technique of the Method of Moments (*MININEC* engine), an algorithm well described in the literature [4-6]. The algorithm employs the thin-wire approximation for straight elements in order to simplify the numerical implementation, although there are procedures available in the literature that treat the problem in a more-generalized way [15-16]. Here, we only present the main equation representing a system of integral-differential equations, as implemented in the code:

$$\sum \int_{s_{1p}}^{s_{2p}} \left[\hat{i}_p \bullet \hat{s}(p) I(s_p) + \frac{1}{k^2} \frac{dI_p(s_p)}{ds_p} \hat{i}_q \bullet \nabla \right] \left[\frac{1}{2\pi} \int_{-\pi}^{\pi} \frac{e^{-jkR}}{R} d\varphi \right] ds_p = \frac{4\pi}{jw\mu_0} \hat{i}_q \bullet \vec{E}_i , \qquad (1)$$

where k is the phase constant; $\hat{s}(p)$ indicates the direction of the pth straight wire element, with axial length s_p; $\hat{i}_q$ is the unitary vector denoting the direction of the qth wire; R is the distance between the pth and qth wires; and ϕ is the circumferential angle with reference to the qth wire.

By letting q vary from 1 to N in Equation (1), where N is the total number of wires, a system of N equations is generated, each one representing the enforcement of the boundary condition $E_{tan} = E_s + E^i = 0$ on the conducting surface. The solution of this system leads to an approximation of the current distribution on the antenna, from which the electrical behavior can be assessed (input impedance, radiation patterns, gain, etc.). It is also possible to have a perfect ground plane, and to include lumped elements in the analysis.

3. The Optimization Layer

The modified gradient method [7] was implemented in *GRADMAX for Web* in order to search for geometries that maximized the gain. Both the shape of a wire (modeled as a set of straight wires) and the distance between different wires can be optimized, but restricted to an array of monopoles. The gradient method has the advantage of being very robust and applicable to a wide variety of problems, although it has limitations as discussed in the last paragraph of this section. Genetic algorithms [17-19] have been widely used with antennas within the last decade or so. They offer the advantage of normally yielding more than one solution, which gives an additional advantage of being able to select the solution most fit for the practical implementation.

The direction of the gradient points to the maximum variation of the parameter (or cost function) in the n-dimensional space, where n is the number of variables necessary to analyze and optimize the electrical behavior of the antenna. The derivations necessary to compute the gradient are approximated by small deviations, such that the sensibility of the parameter to be optimized with respect to each variable can be approximated accurately. Once the direction of the gradient is computed, the step to be taken in each iteration is determined by the Golden Section Method [7], hence the name "modified" gradient method. This method employs the golden number (i.e., 1.6180339885, where $\text{golden number} - 1 = 1/\text{golden number}$) to search for the best step to be taken.

In order to illustrate the gradient method, we consider the simple tri-dimensional function defined in Equation (2) and shown in Figure 1:

$$z = D[\text{not in dB}] = f(x,y) = \frac{\sin\left(\sqrt{x^2+y^2}\right)}{\sqrt{x^2+y^2}} . \qquad (2)$$

In this example, since the analytical form of the function to be optimized is known (which is not the case for the optimization of wire antennas), the gradient can be determined as follows:

$$\vec{\nabla} z(x,y) = a\vec{x}\frac{\partial z}{\partial x} + a\vec{y}\frac{\partial z}{\partial y} , \qquad (3)$$

leading to

$$\vec{\nabla} z = \frac{\left(\sqrt{x^2+y^2}\cos\sqrt{x^2+y^2} - \sin\sqrt{x^2+y^2}\right)}{\left(\sqrt{x^2+y^2}\right)^{3/2}}\left(x\,a\vec{x} + y\,a\vec{y}\right), \tag{4}$$

which can be normalized by

$$\vec{g} = \frac{\vec{\nabla} z}{\sqrt{\left(\vec{\nabla} z\right)_x^2 + \left(\vec{\nabla} z\right)_y^2}}. \tag{5}$$

In order to illustrate the method, consider that we started at the coordinates $(x_0, y_0) = (-2, 4)$, yielding $z = -0.2172$, $g_x = 0.4472$, and $g_y = -0.8944$. With a step of $t = 3$, we arrived at $x_1 = x_0 + t g_x = -0.6584$ and $y_1 = y_0 + t g_y = 1.3168$, yielding $z = 0.676$. This showed that in just one iteration, we improved the value of the function from -0.2172 to 0.676. After three iterations, we achieved $z = 0.99999999996$ at $(-0.00000729, 0.00001459)$, which was very close to the global maximum of one at $(0,0)$.

It is worth mentioning that the gradient method may not always converge to the global maximum, and may stop at a local maximum. One way to estimate the probability of having achieved the overall maximum is to run the code many times, with different starting geometries, and to compute the ratio between the number of times the point suspected to be the maximum was achieved by the total number of runs. In *GRADMAX for Web*, when optimizing both the angles of elements (i.e., shaping), as well as the distance between them, it alternating the iterations between them is recommended.

4. *GRADMAX for Web*

The code for *GRADMAX for Web* was implemented with the *Java*-applet technology. It is available freely at the following Internet address: http://www.ene.unb.br/~terada/antennas.

As mentioned in [12], security issues are constantly being improved, which however limit the access of applets to the remote computer hardware. Printing and loading/saving files, for example, are not permitted. In order to partially get around those limitations, *GRADMAX for Web* generates a string of data with the "Import/Export" feature, which can be copied and pasted into a text editor, and saved for future use (the string contains all the necessary input data to define an antenna's geometry). A "print screen" of the code is shown in Figure 2. The overall properties and common errors when using the code are listed below.

4.1 Overall Properties

1. Analysis of wire antennas using the Method of Moments:

a. Input impedance at all feeding points

b. Computation of the maximum gain of the structure

c. Radiation patterns

2. The possibility of simulating lumped elements (loads, such as capacitors and inductors)

3. Optimization of monopole arrays (angle and spacing)

4. The possibility of simulating a perfect ground plane (*xy* plane).

4.2 Common Errors and a Few Tips

1. The radiation patterns are plotted only in the *xy* and *xz* planes. The user needs to place the antenna such that at least one of the principal planes is plotted.

2. The ground plane must be the *xy* plane.

3. All dimensions must be in meters.

4. The option "Segments" shows the geometrical coordinates associated with each segment. This feature is important when increasing the number of segments for assuring the convergence of the imaginary part of the input impedance. If the number of segments is changed, the pulse number of the feeding point(s) also needs to be changed.

5. An even number of segments results in an odd number of pulses, such that there is one pulse at the center of the wire.

6. The feeding point(s) must always be located within a wire or at a location with a connection different than zero.

7. A very small wire (e.g., 2.5 GHz) divided into a large number of segments will certainly cause numerical problems of overflow/underflow.

8. In order to assure good precision, using at least 10 to 20 segments per λ with a radius $\leq \lambda/100$ (thin-wire approximation) is recommended.

As with the original *MININEC* code, *GRADMAX for Web* requires the user to specify the connection types at the end of each wire. In order to simplify the explanation, the antenna geometry shown in Figure 3 was employed as an example. It is always highly recommended that the user draw the geometry with reference to a Cartesian rectangular system before entering the data into the code. A step-by-step procedure is outlined as follows.

1. The user can arbitrarily define the endpoints (E1/E2) of each wire. It is just necessary to be consistent when entering the data.

2. Connections of the *i*th wire:

2.1 A connection exists only to a previously specified wire.
2.2 Connection types for the *i*th wire:

- 0: No connection

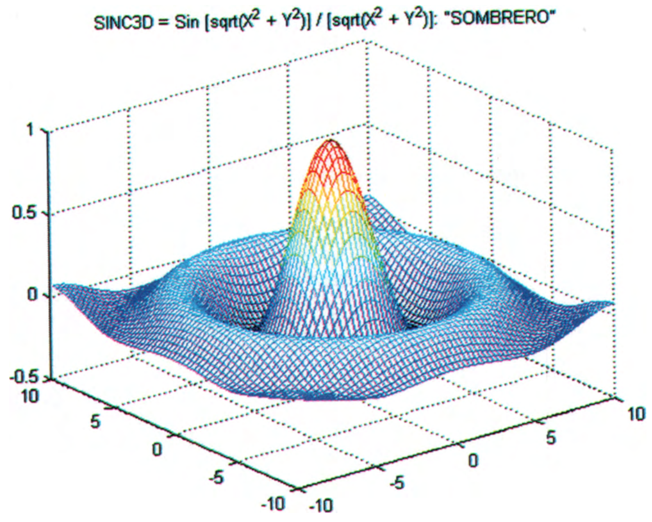

Figure 1. The "sombrero" function.

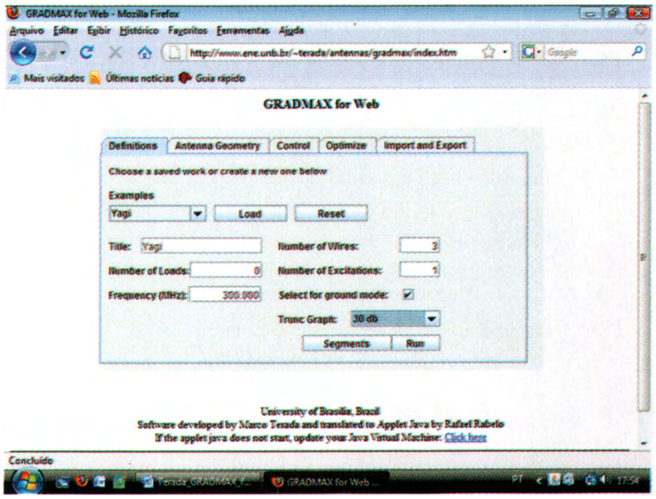

Figure 2. *GRADMAX for Web*.

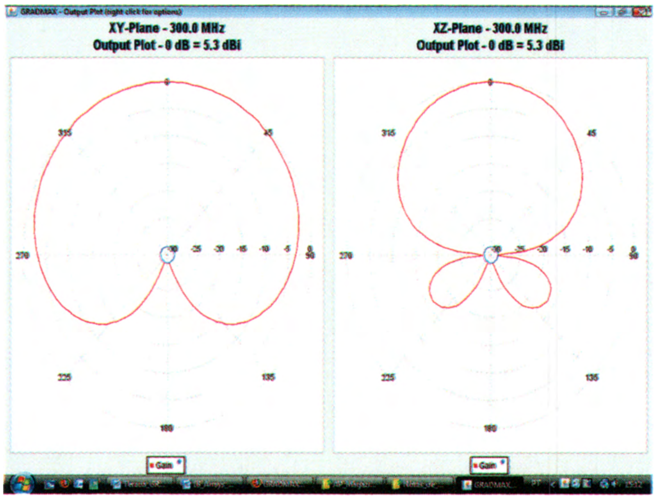

Figure 4. The cardioid pattern computed by *GRADMAX for Web* at 300 MHz.

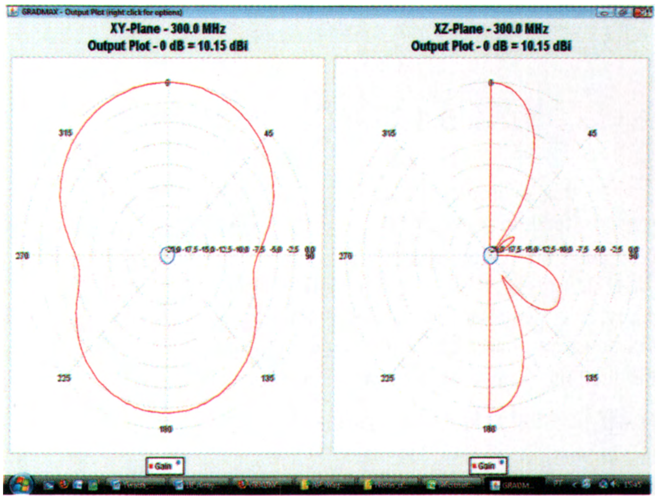

Figure 6. The radiation patterns of the shaped monopole shown in Figure 5.

- $-i$: Connection to the ground plane

- k: If the endpoint of the ith wire is connected to the kth wire (E1 to E2 or E2 to E1), where $k < i$.

- $-k$: If the endpoint of the ith wire is connected to the kth wire (E1 to E1 or E2 to E2), where $k < i$. Negative connections yield problems with the optimization option.

3. Wire 1: C1 (connection of point E1) $= -1$
   C2 = 0 (wires 2 and 3 have not yet been specified, thus the connection is zero).

4. Wire 2: C1 = 1 and C2 = 0

5. Wire 3: C1 = 1 (or -2) and C2 = 0

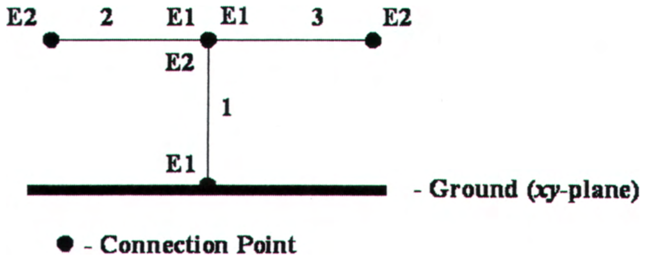

Figure 3. A monopole in "T."

5. Numerical Results

In this section, two numerical examples are presented and discussed in certain detail. The examples are simple geometries, but illustrate well the potential and precision of the code. Comparisons to the values encountered in the literature are made whenever possible.

5.1 The Cardioid

In this example, we derived the necessary input voltages to properly feed an array of two elements spaced by $\lambda/4$, in order to generate the well-known cardioid pattern [6]. Although *GRADMAX for Web* computes the mutual-coupling effects precisely, it is necessary to input the correct values of the voltages to yield current phasors with the same amplitude and 90° off phase at the feeding points of the two elements, such that $I_1 = |I_1|\angle 0°$, $I_2 = |I_1|\angle -90°$, $V_1 = 1\angle 0°$ (set as reference), and V_2 is to be determined. Assuming that both elements have the exact same geometry, we can write

$$\begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{12} & Z_{11} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \end{bmatrix}, \tag{6}$$

where Z_{11} is the self-impedance in free space (a single element alone), Z_{12} is the mutual impedance due to mutual coupling, and

$$Z_{12} = \frac{V_1}{I_2}\Big|_{I_1 = 0(open)}, \tag{7}$$

which can be interpreted as the "voltage in element one produced by element two." A way to determine Z_{12} with computer simulations, analytical models, or in a measurement setup is to short element two, and measure the input impedance of element one, Z_{sc}. This leads to [6]

$$Z_{12} = \sqrt{Z_{11}\left(Z_{11} - Z_{sc}\right)}. \tag{8}$$

For our cardioid example:

$$V_1 = |I_1| Z_{11} + |I_1| Z_{12}\angle -90°,$$
$$V_2 = |I_1| Z_{11}\angle -90° + |I_1| Z_{12}. \tag{9}$$

Then, given that $V_1 = 1\angle 0°$,

$$\frac{V_2}{V_1} = V_2 = \frac{-jZ_{11} + Z_{12}}{Z_{11} - jZ_{12}}. \tag{10}$$

Using the thin-wire approximation (theoretical), two dipoles of length $\lambda/2$ in parallel and spaced by $\lambda/4$ give

$$Z_{11} = 72 + j45.5,$$
$$Z_{12} = 40 - j30, \tag{11}$$
$$V_2 = \frac{82.5 - j103}{4.3 + j2.5} = \frac{131.97\angle -51.3°}{43.1\angle 3.33°} = 3.06\angle -54.66°.$$

Thus, in order to generate the cardioid pattern with two dipoles, we need to feed voltage into the second element about three times the amplitude of the first and lagging by about 55°, not a result that can easily be obtained by trial and error. Employing *GRADMAX for Web* to analyze two parallel dipoles of length 0.4781λ and spaced by 1.2 m at 300 MHz (each wire of radius 0.001 m), we obtained the following results:

$$Z_{oc} = Z_{11} = Z_{22} = 70.1391 - j1.3677$$
(supposedly 0 at resonance),
$$Z_{sc} = 67.1047 - j1.6497,$$
$$Z_{12} = \sqrt{Z_{oc}\left(Z_{oc} - Z_{sc}\right)}, \tag{12}$$
$$Z_{12} = 14.6 + j0.5 \text{ at } 1.2 \text{ m},$$

which agrees well with the curve provided in [6]. The radiation patterns shown in Figure 4 were obtained at 300 MHz with *GRADMAX for Web* when analyzing an array of two dipoles of length $\lambda/2$ spaced by $\lambda/4$ and fed according to Equation (11). The input impedances to each element were computed as $45.32 - j1.85\,\Omega$ and $134.68 + j76.99\,\Omega$.

5.2 The Shaped Monopole

In order to illustrate the use of the optimization feature in *GRADMAX for Web*, we considered the shaping of a single mono-

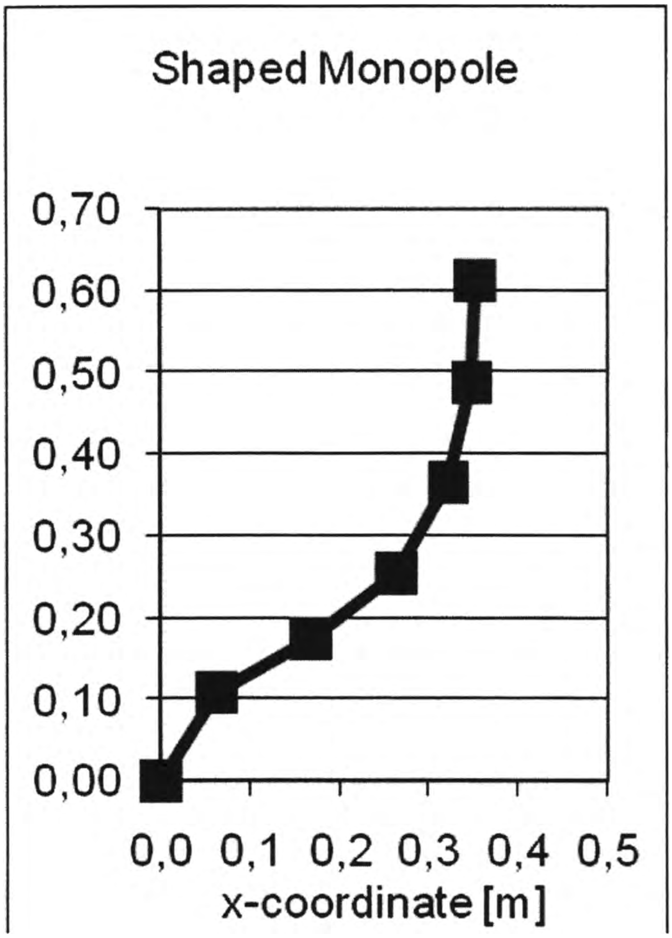

Figure 5. The shaped geometry for a 0.75λ monopole as obtained with *GRADMAX for Web* after five iterations (the monopole was modeled with six pieces of straight wire).

pole modeled as six straight and connected wires. The code also offers the possibility of optimizing the spacing between the elements of an array of monopoles. The goal is always to maximize the gain in the x direction.

A monopole of 0.75λ (in order to have phase inversions in the current distribution) was analyzed with *GRADMAX for Web*, yielding an input impedance of $70.42 + j20.35\,\Omega$ at 300 MHz, and a gain of 6.67 dBi (about 50° off the x direction). After five iterations, all in about 30 seconds with an Intel 2.4 GHz Core 2 quad CPU, the optimization process arrived at the geometry shown in Figure 5. The final computed input impedance was $57.86 + j6.47\,\Omega$, and a gain of 10.15 dBi (about 2 dB F/B ratio). The patterns are shown in Figure 6. Note that 20 segments per wire were employed during the optimization, which does not correspond to the default values for the monopole example available in the code.

The results of the optimization compared well with results previously published in the literature [7], considering that they are all based on numerical optimizations with different analysis kernels. The maximum discrepancy between the angles with reference to the vertical axis as computed by *GRADMAX for Web* and the angles published in [7] was about 16° for the fourth wire from the origin, but others were much closer. The gain for the corresponding dipole, as computed and measured by [7], was 7.2 dBi, corresponding to 10.2 dBi for a monopole, which agreed fairly well with the value of 10.15 dBi obtained with *GRADMAX for Web*. In addition, other authors, such as [20], reported gains for the corresponding monopole in the range of 10 to 10.13 dBi, also very close to the value herein obtained. Finally, the input resistance reported in [7] was 86 Ω, which differed somewhat from the value of 57.86 Ω computed by *GRADMAX for Web*. However, that may be explained by the number of segments used, as well as the modeling employed in the implementation of the Method of Moments.

6. Conclusions

The code *GRADMAX for Web* was introduced in this article. *GRADMAX* is a *Java* applet designed for analyzing and optimizing arrays of wire antennas, and runs directly from the Web browser on all common operating systems (*Windows*, Macintosh, *Linux*, *Solaris*, etc.). The analysis algorithm, based on the point-matching technique of the Method of Moments (*MININEC* engine), was briefly discussed. The optimization layer, which employs the modified gradient method, was explained in more detail. Finally, two examples to illustrate the use of the analysis and optimization capabilities of the code were presented. The numerical results were compared with the values available in the literature, indicating good precision for the code. *GRADMAX for Web* can be considered to be a valuable tool for teaching and research, due to its ease of use and access, combined with high accuracy and speed.

7. Acknowledgment

This work was partially supported by CNPq (Brazilian National Research Council).

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