Issues in Antenna Optimization - A Monopole Case Study

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Abstract **─** A typical antenna design optimization problem is presented, and various issues involved in the design process are discussed. Defining a suitable objective function is a central question, as is the type of optimization algorithm that should be used, stochastic versus deterministic. These questions are addressed by way of an example. A single-resistor loaded broadband HF monopole design is considered in detail, and the resulting antenna compared to published results for similar continuously loaded and discrete resistor loaded designs.

Index Terms **─** Algorithm, bandwidth, broadband, central force optimization, CFO, HF, impedance loading, monopole, numerical methods, optimization, and wire antenna.

I. INTRODUCTION

"*Good against remotes is one thing. Good against the living, that's something else*". Han Solo thus cautioned Luke Skywalker as he practiced lightsaber skills in the classic 1977 film **Star Wars**. This note echoes a similar sentiment when it comes to designing antennas with optimization algorithms, "*Good against benchmarks is one thing. Good against 'real world' antennas, that's something else*". This admonition is examined by way of an example, designing an optimized resistively-loaded broadband high-frequency (HF) base-fed monopole. The antenna and its ground plane are perfectly electrically conducting (PEC), so that decreased radiation efficiency results solely from i^2R losses in the resistor. This example highlights the importance of, and the difficulties in, choosing an appropriate objective function and the advantages of using a deterministic optimizer in doing so.

Optimization algorithms typically are evaluated against benchmarks with known extrema (fitnesses and locations). How well an algorithm works is measured by its accuracy and efficiency, referring respectively to how close it gets to the extrema and how much computational effort is expended in the process (usually the number of function evaluations). An algorithm's performance often depends on user-specified setup parameters, and it may change dramatically with different values. Additional complications are introduced by inherently stochastic optimizers, such as particle swarm or ant colony optimization, because this type of algorithm returns a different answer on successive runs, relying as they do on true random variables computed from a probability distribution. Even before an antenna problem has been precisely stated, the designer must choose suitable run parameters for a stochastic optimizer and somehow guess how well it will work on the antenna problem at hand, neither of which is a simple matter.

The picture is further complicated because real world antenna problems introduce yet another level of complexity, defining a suitable objective function. If an optimization algorithm's performance is sensitive to its setup parameters, and if its results vary from one run to the next, then the added problem of having to define a "good" objective function can be daunting. Of course, this question does not come up in benchmark testing because the benchmark itself is the objective function. But, as the results reported here show, this question is central in optimizing even a simple antenna.

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II. DESIGN GOALS

The first step in antenna optimization is defining a clear set of performance goals. There are many measures to consider, such as directivity, radiation pattern, bandwidth, efficiency, and physical size, among others. Goals for all parameters must be articulated in order to define an objective function that effectively measures how well they are met. There are two main objectives for the monopole example described here: (1) as flat as possible an impedance bandwidth from 5 MHz to 30 MHz and (2) maximum gain. The PEC metallic monopole element is 10.7 meters high with 0.005 meter radius (dimensions chosen for comparison to other designs) fed against a PEC ground plane.

III. THE OBJECTIVE FUNCTION

The next step is defining an objective function that measures how well a particular antenna design meets the performance goals. For purposes of illustration, the monopole's decision space, Π, is chosen to be two-dimensional (2-D) because the objective function's topology ("landscape") can be visualized. The decision variables are (1) the value of the loading resistor, R (Ω) and (2) its placement along the monopole, H (m), as shown in Fig. 1. The decision space is defined as $\Pi:\left\{(R,H)\,\middle|\,0\le R\le 1000\;\Omega\,,\,0.05\le H\le 10.65\text{ m}\right\}$. Real world antenna problems, of course, usually contain many more than two variables, often far more, which considerably complicates the definition of a good objective function because then the landscape cannot be visualized.

The antenna parameters considered for inclusion in the objective function in this example are: minimum radiation efficiency, $Min(\varepsilon)$; minimum value of the maximum gain, $Min(G_{max})$; the voltage standing wave ratio $VSWR//Z_0$ computed relative to a purely resistive feed system characteristic impedance Z_0; and monopole input impedance $Z_{in} = R_{in} + jX_n$. Each parameter is evaluated as a function of frequency, and G_{max} at a given frequency is the maximum gain over the polar angle θ in Fig. 1.

Needless to say, there are myriad ways these parameters can be combined, and the question is, which combination is best? Unfortunately, there is no answer to this query, other than trying different possibilities and evaluating each one's performance. A deterministic optimizer can make a big difference in this regard. Because stochastic algorithms return different results for every run, there is no (good) way of determining whether or not better designs are the result of a more suitable objective function or the inherent variability of the algorithm itself. By contrast, a deterministic optimizer always returns the same results for given setup parameters, so that any improvement in the antenna performance is attributable to changes in the objective function. These considerations are illustrated below using three different objective functions for the loaded monopole.

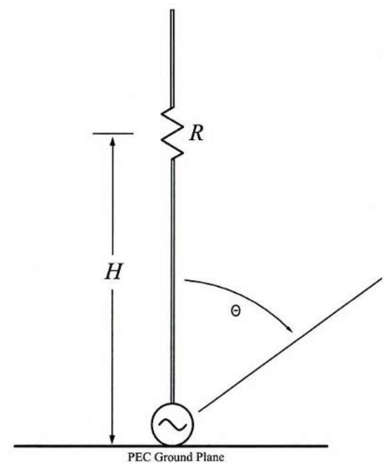


Fig. 1. Base-fed monopole geometry.

IV. FUNCTION $f_1(R,H,Z_0)$

The first monopole objective function (to be maximized) combines the minimum radiation efficiency and maximum gain with the maximum VSWR excursion in a simple formula,

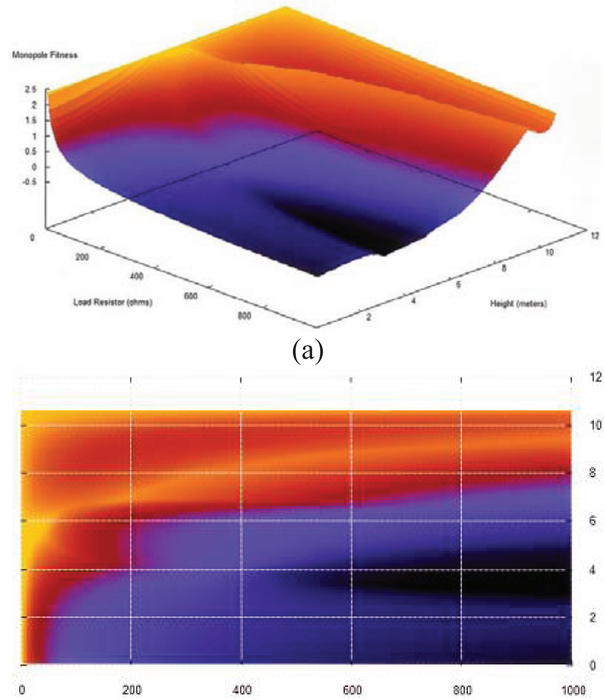
$$f_1(R,H,Z_0)=\frac{Min\,(\varepsilon)+Min\,(G_{\max})}{\Delta VSWR\,(Z_0)} \qquad (1)$$

where $\Delta VSWR(Z_0)$ is the difference between maximum and minimum standing wave ratios over the 5 MHz-30 MHz HF band relative to Z_0. The fitness increases with increasing efficiency and minimum gain and decreasing VSWR difference. f_1's landscape with Z_0 = 50 Ω appears in Fig. 2 (a)-(b), which show, respectively, perspective and plan views and projections onto the $R-Z$ and $H-Z$ planes. f_1 is smoothly varying and unimodal with a maximum fitness of 2.3764… at the point $(R,H)=\ (5.025126\;\Omega\,,1.621357\text{ m})$. The global maximum was located by computing $f_1(R,H,50)$ over the decision space Π using a grid of 200 × 200 points and searching for the maximum. This procedure is used for each of the 2-D landscapes discussed here.

The monopole was modeled using numerical electromagnetics code (NEC), version 2, double precision [1, 2]. The 10.7 meter tall element was divided into 107 segments with the resistor placed at the segment's midpoint using NEC's "LD" loading cards. Because the antenna is loaded by segment number, not by distance above the ground plane, the height coordinate H was converted to the loading segment number as $n = [0.5 + H/\Delta]$ where $\Delta = 0.1$ m is the segment length. A typical NEC input file appears in Fig. 3.

While f_1's functional form may seem quite reasonable for measuring the monopole's performance, an examination of its topology reveals two potential concerns: (1) maximum fitness occurs close to Π's lower resistance boundary and (2) it varies very little with height. The first characteristic may impede an optimization algorithm's ability to search Π while the second may impede convergence (exploration versus exploitation). In a higher dimensionality decision space these characteristics cannot be ascertained by inspection, which is a further complication in defining a useful 'real world' objective function.

Apart from the question of how "searchable" Π is for f_1's maxima, perhaps the more important question is how well f_1 actually reflects a good monopole design, that is, one that performs well against the stated performance objectives. In this example, because f_1's maximum can be visualized and located, the resulting "best" monopole design can be evaluated by computing its performance using the known maximum's coordinates. A feed system characteristic impedance of $Z_0 = 50\ \Omega$ is assumed because typical HF transmitters are designed for 50 Ω systems, and the results appear in Fig. 4. In the plots, calculated data points are shown as symbols (5 MHz-30 MHz every 1 MHz), and the solid curves are interpolated using a natural cubic spline. Total power gain was computed every 10° for $0^\circ \le \theta \le 90^\circ$ where θ is the polar angle in NEC's standard right-handed spherical polar coordinate system (see Fig. 1).



(a)

(b)

Fig. 2. Landscape for objective function $f_1(R,H,50)$.

The radiation efficiency and maximum gain numbers are quite good. Minimum efficiency is just below 80 %, and for most part the efficiency exceeds 95 % above 10 MHz. Of course, this result is not altogether unexpected in view of the very light loading, $R \approx 5\ \Omega$. The maximum power gain figures also are quite good, with minimum $G_{max} \approx 4$ dBi. This result also is expected in view of the light loading. But in stark contrast, the VSWR performance is very poor. The goal of flattening VSWR as much as possible was missed completely. VSWR varies from 1.61 to nearly 37 with pronounced fluctuations. The impedance bandwidth of this design, typically specified as VSWR ≤ 2:1 (return loss ≤ -10 dB), is extremely small. Perhaps somewhat surprisingly, even though $f_1(R,H,50)$'s functional form appeared to be a reasonable measure of how well the loaded monopole meets the design goals, the fact is, it is not. The best that a perfectly accurate optimization algorithm could do is to discover the design in Figs. 3 and 4, and that design happens to be quite poor. This example shows how important it is to choose an appropriate objective function.

```
CM File: DES1.NEC
CM NEC2D run using R,Z values
CM from DESIGN #1 DS plot
CM R=5.025126 ohms, Z=1.621357 m
CM seg # = INT(0.5+Z/SegLen) = 16
CM Z0=50 ohms
CE
GW1,107,0.,0.,0.,0.,0.,10.7,.005
GE1
LD0,1,16,16,5.025126,0.,0.
GN1
FR 0,26,0,0,5.,1.
EX 0,1,1,1,1.,0.
RP 0,10,1,1001,0.,0.,10.,0.,100000.
EN
```

Fig. 3. Typical monopole NEC input file.

V. FUNCTION $f_2(R,H,Z_0)$

$f_1(R,H,Z_0)$'s disappointing results make it clear that another, hopefully better, objective function must be defined. f_1's major failing was its inability to flatten the VSWR curve, which suggests that a more aggressive approach is required. Dealing directly with $Z_{in} = R_{in} + j\,X_{in}$, for example, might work better than trying to minimize VSWR variability. To that end, a quite different objective function will be considered next,

$$f_2(R,H,Z_0) = \frac{Min(\varepsilon)}{|Z_0 - Max(R_{in})| \cdot |Max(X_{in})|} . \quad (2)$$

As before, this functional form is simple and ostensibly serves to achieve the design goals. As will be seen below, it does perform better than $f_1(R,H,Z_0)$ with respect to VSWR, but its topology is such that many optimization algorithms will have considerable difficulty locating maxima. $f_2(R,H,Z_0)$'s global maximum of 0.11117… at the point (R, H) = (819.095477, 2.953015). The loading resistance $R \approx 819\ \Omega$ is much heavier than before, which will reduce efficiency and maximum gain but hopefully will tame the VSWR. This reflects the inevitable trade-off in using impedance loading for improving antenna bandwidth, which increases with heavier loading at the expense of the radiation efficiency and gain.

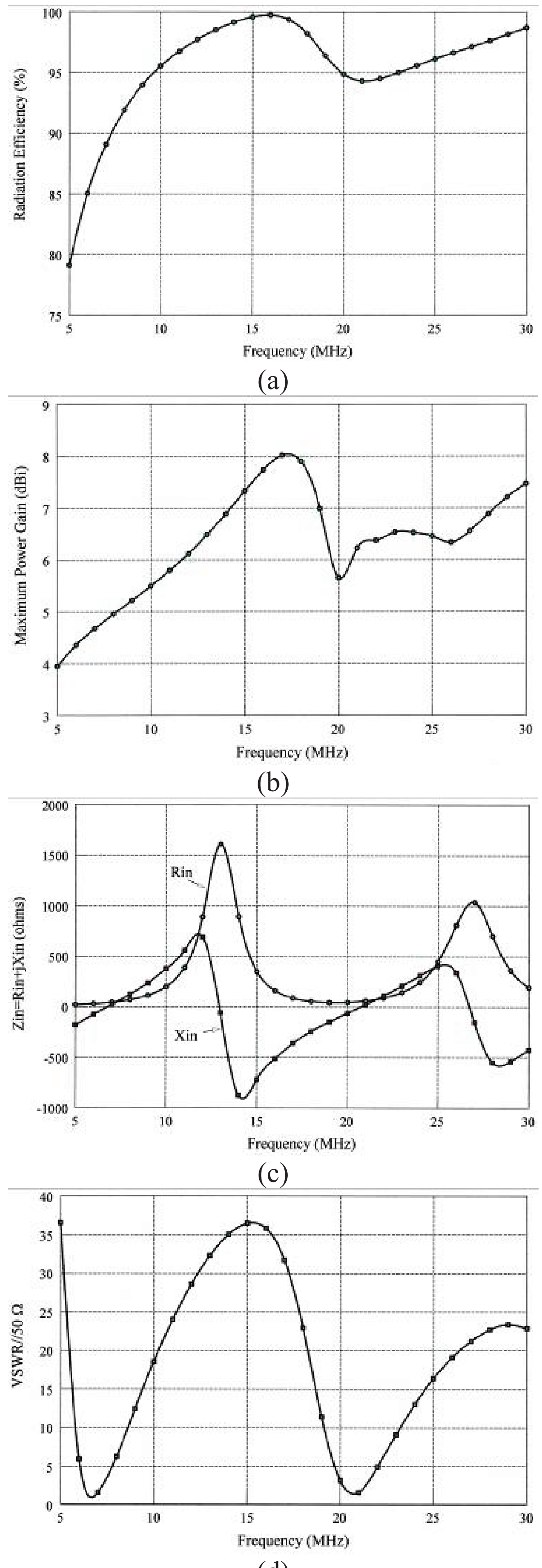
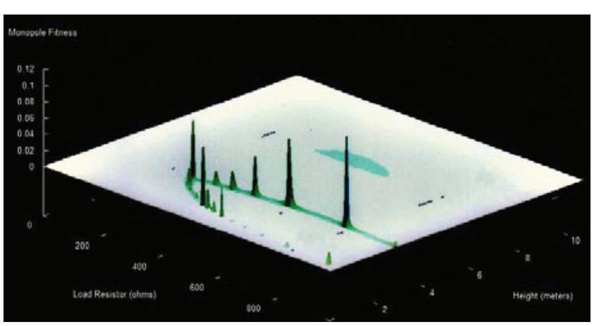


Fig. 4. Performance of monopole design #1, $f_1(5.025,1.62,50)$.

Figure 5 shows f_2's landscape. It comprises a series of spikes along a bullet-shaped curve in the (R, H)-plane, and the peaks are quite sharp. For example, changing H slightly from 2.8731… to 2.8198… with R = 819.0954… results in nearly three orders of magnitude decrease in fitness. Topologies like this usually are described as "pathological" because many optimization algorithms have difficulty dealing with them. Thus, even though objective function f_2 may be better than f_1 for achieving the design goals, its pathological landscape may impede an optimization algorithm to such a degree that better designs are not discovered.

NEC-2D again was used to model the monopole with $f_2(R,H,50)$'s best fitness, and the results appear in Fig. 6. As expected, the radiation efficiency is much lower, especially at low frequencies. Below 15 MHz it ranges from about 5 % to 25 %. The efficiency does increase substantially mid-band, reaching a peak near 80 % at 19 MHz and falling thereafter. The power gain more or less tracks the efficiency, but it is quite low at low frequencies. Above 15 MHz, however, the gain is moderate to good. The heavier loading in this case considerably reduced the input impedance variation resulting in a fairly smooth variation in R_{in} and to a lesser degree in X_{in} as well. As a result VSWR variability is less than in the previous design, but still quite substantial. The VSWR is well-behaved and moderate, ≤ 5:1, above 20 MHz, but it is very high at lower frequencies with a peak ≈ 21:1 at 18 MHz. Thus, while f_2 is an improvement over f_1 in terms of meeting the design goals, it still falls far short of yielding a good monopole design. In addition, its pathological landscape may defeat the effectiveness of many optimization algorithms. Further refinement of the objective function is required.



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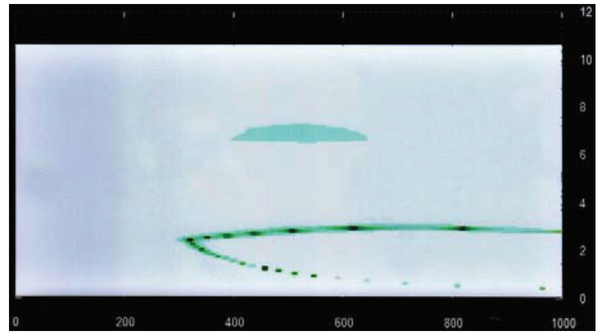

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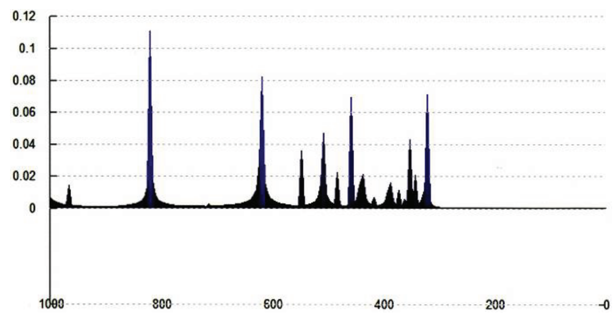

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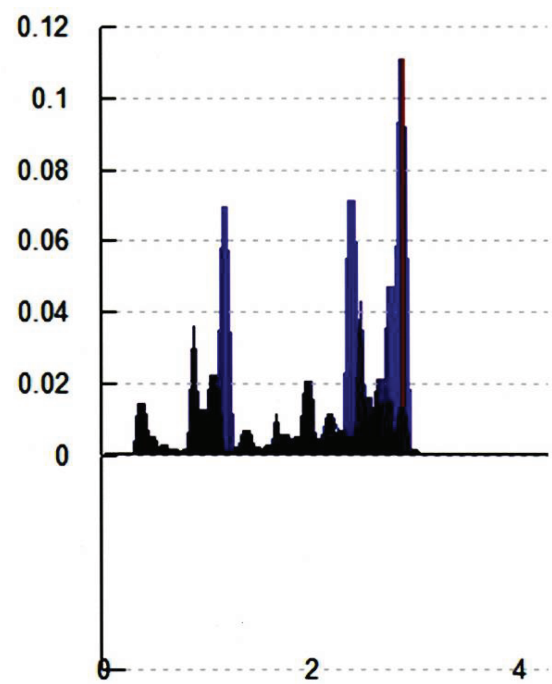

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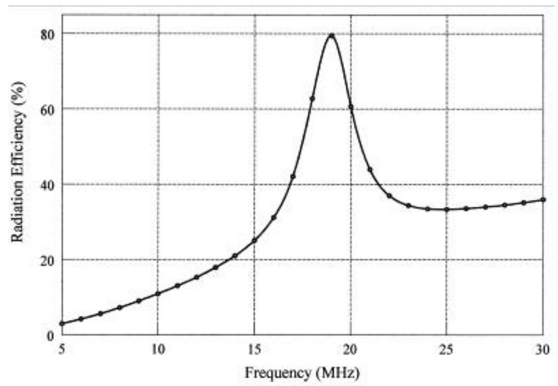
Fig. 5. Landscape for objective function $f_2(R,H,50)$.



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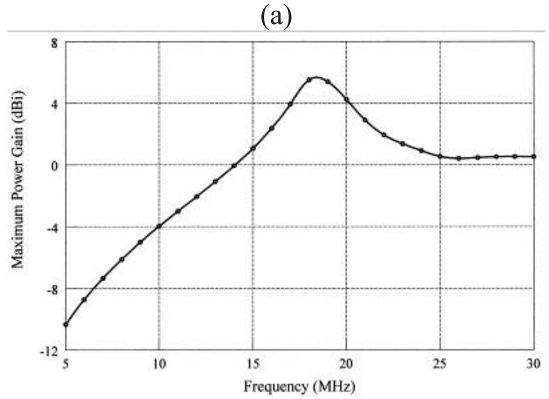

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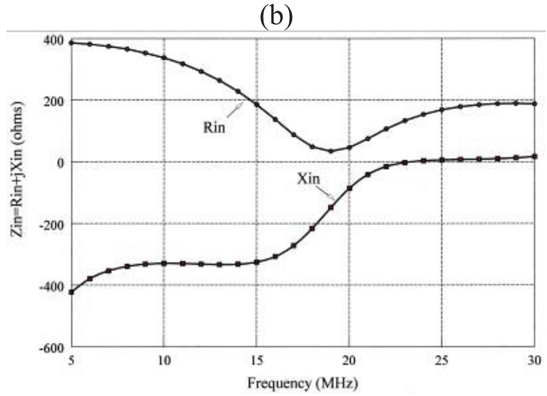

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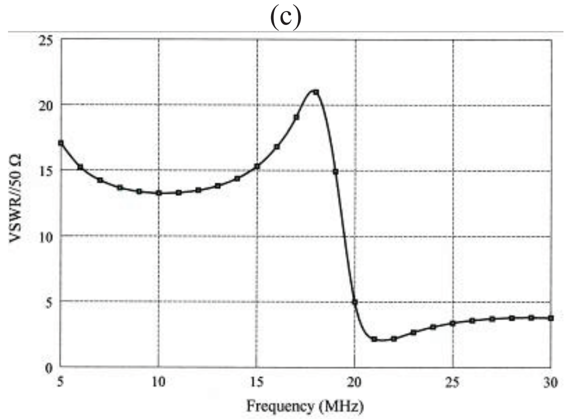


(d)

Fig. 6. Performance of monopole design # 2, $f_2(819.1,2.95,50)$.

VI. FUNCTION $f_3(R,H,Z_0)$

Because VSWR variability is the biggest problem with the first two objective functions, an even more aggressive approach will be taken with the third function defined as,

$$f_3(R,H,Z_0)=\frac{Min(\varepsilon)}{\left|Z_0-Max(R_{in})\right|\cdot\Delta VSWR(Z_0)\cdot[Max(Xin)-Min(Xin)]}\,. \quad (3)$$

The gain does not appear in the numerator because it tracks fairly well with efficiency. The denominator comprises three factors that minimize VSWR in different ways. The first drives the real part of the input impedance toward the feed system characteristic impedance. The second minimizes the VSWR variability across the band, while the third attempts to flatten the input reactance.

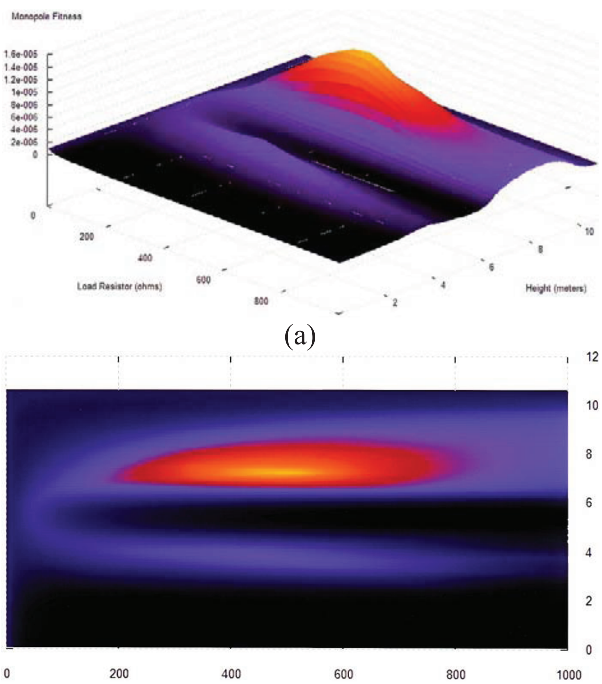
Because this functional form is determined empirically, other forms probably merit consideration as well. For example, the objective function $f_3(R,H,Z_0)$ could be written as

$$f_3(R,H,Z_0)=\frac{Min(\varepsilon)^{\eta_1}}{\left|Z_0-Max(R_{in})\right|^{\eta_2}\cdot\Delta VSWR(Z_0)^{\eta_3}\cdot[Max(Xin)-Min(Xin)]^{\eta_4}}\,, \quad (4)$$

where the exponents η_i are constants or functions of frequency. The terms in f_3 could be combined differently, say, by addition with weighting coefficients. Other functions, such as logarithms or trigonometric functions, might be useful in combining the antenna's performance measures. And, of course, other performance measures might be included as well. All of these considerations are involved in defining suitable objective functions. As the results for f_1 and f_2 show, presumably good ones can turn out to be quite poor. It consequently is imperative to investigate how the objective function's form influences the resulting antenna design.

$f_3(R,H,50)$ is unimodal with a smoothly varying topology and a maximum fitness of $1.4624...\text{x}10^{-5}$ at $(R,H)=(502.512563,7.2143215)$. Its landscape is plotted in Fig. 7. This objective function results in the design whose performance is shown in Fig. 8. The radiation efficiency increases more or less monotonically from just over 15 % at 5 MHz to nearly 40 % at 27 MHz and about 38 % at 30 MHz. Maximum power gain ranges from a low near -3.1 dBi to a maximum of

2 dBi. The input impedance is well behaved across the HF band, and the resulting VSWR is much flatter than in the previous cases. Maximum VSWR is just below 13:1 at 5 MHz, and it falls very quickly to just above 3:1 at 7.5 MHz. The VSWR increases to ~8:1 at 13 MHz and remains fairly flat thereafter. A comparison of these data to the curves in Figs. 4 (d) and 6 (d) clearly shows that f_3 $(R,H,50)$ is the best objective function of the three. Its monopole design is superior to the others, and its topology lends itself well to being searched by an optimization algorithm.



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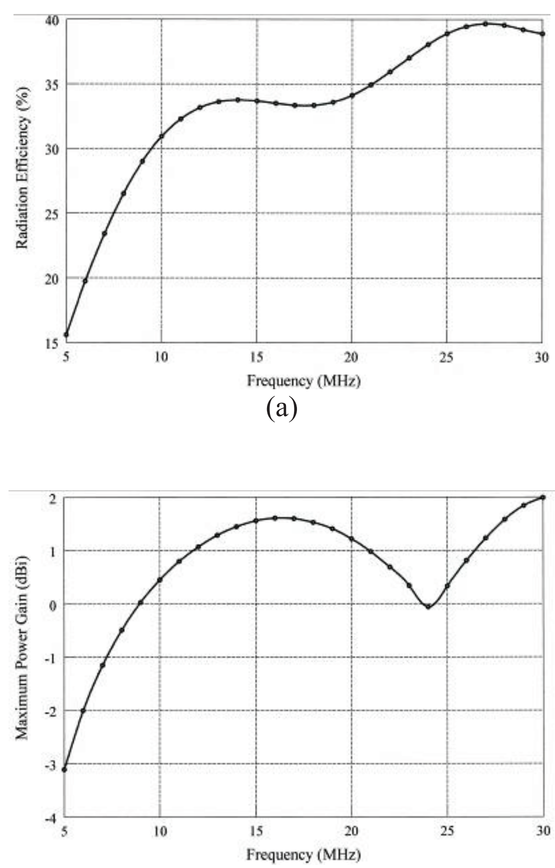
(b)

Fig. 7. Landscape for objective function $f_3(R,H,50)$.

VII. OPTIMIZATION ALGORITHMS

The previous sections discussed some of the issues in defining suitable objective functions for the broadband HF monopole design problem. Three functions were considered, and the results varied considerably from one to the next, with the last one being the best. Each of these objective functions has a known global maximum that can be visualized because the monopole decision space is 2-D. Unfortunately, this cannot be done in higher dimensionality spaces, so that their topologies are unknown. The problem faced by the antenna designer therefore is defining an effective objective function that can be searched accurately and efficiently in the n-D decision space. The type of optimization algorithm can be an important factor in aiding or inhibiting the process of defining a suitable objective function.

Because stochastic optimization algorithms return different results on successive runs, it is difficult to assess the effects of changing the objective function on their accuracy and efficiency. For example, if particle swarm optimization is applied to the monopole problem, the antenna designer cannot know why successive runs using, say, $f_2(R,H,Z_0)$ and $f_3(R,H,Z_0)$, yield different results. It may be a consequence of the different objective functions (for example, pathological versus well-behaved), or it may be the algorithm's inherent randomness. Which of these it is can be ascertained only by doing a statistical analysis that probably requires tens or hundreds, possibly thousands, of runs. This dilemma is avoided by using a deterministic optimizer, one that yields the same answer for every run with the same setup.



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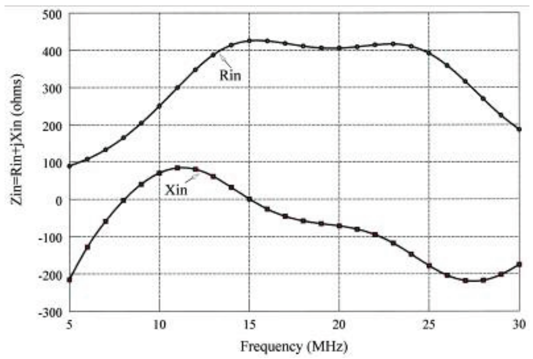

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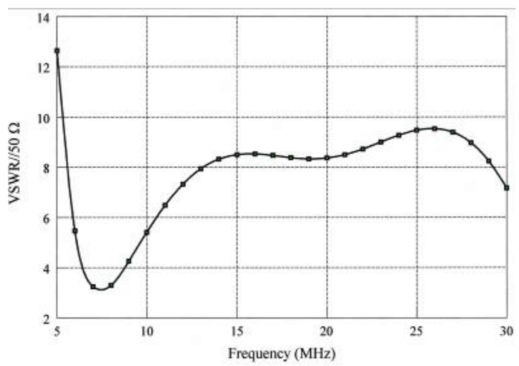

(d)

Fig. 8. Performance of monopole design # 3, $f_3(502.5,7.214,50)$.

Central force optimization (CFO) is a deterministic nature-inspired search and optimization metaheuristic for an evolutionary algorithm (EA) based on gravitational kinematics [4-6]. Proofs of convergence for CFO and an extended version have been developed [7, 8], and the algorithm has been implemented on a GPU using various topologies [9-11]. The algorithm has been successfully applied to a variety of problems, among them: training neural networks [12]; drinking water distribution networks [13]; solving nonlinear circuits [14]; array synthesis [15, 16]; microstrip patch antenna design [17]; multiband slotted bowtie design [18]; rectangular microstrip patch design [19]; microwave broadband absorber design [20]; antenna optimization generally [21]; notched ultra wideband E-shape antenna design [22]; and increasing impedance bandwidth [23, 24].

CFO therefore was used to search the decision spaces for each of the three monopole objective functions. A "parameter free" implementation was employed as described in [5, 6] without directional information in errant probe repositioning. CFO pseudocode appears in Fig. 9. Hardwired parameter values were $N_d = 2$, $F_{rep}^{init} = 0.5$, $\Delta F_{rep} = 0.1$, $F_{rep}^{\min} = 0.05$, $\gamma_{start} = 0$, $\gamma_{stop} = 1$, $\Delta\gamma = 0.3333$, $(N_p / N_d)_{\max} = 6$, $N_t = 200$ with an early termination criterion of fitness variation $\leq 10^{-6}$ for 25 consecutive steps starting at step #35.

Table 1 summarizes the CFO results. It shows that the algorithm performed well against objective functions f_1 and f_3 by discovering maxima close to the known values. The results for f_1 are consistent with its topology in which the global maximum is near Π's lower boundary in R and not particularly sensitive to variations in H. CFO essentially recovered f_3's global maximum, but clearly it had a problem with f_2's pathological landscape. As expected, NEC-2D's computed performance for the antenna design using CFO's (R,H) coordinates for the best objective function, f_3, is essentially the same as that shown in Fig. 8.

Table 1. CFO optimization results.

Objective Function	Known Max Fitness / Coords	CFO Max Fitness / Coords
$f_1(R,H,50)$	2.376 / (5.025,1.621)	2.371 / (8.179,5.361)
$f_2(R,H,50)$	0.1112 / (819.1,2.953)	0.0684 / (322.2,2.366)
$f_3(R,H,50)$	$1.462\text{x}10^{-5}$ / (502.5,7.241)	$1.401\text{x}10^{-5}$ / (499.6,7.302)

CFO's performance probably would be better still if a more stringent early termination criterion were employed, or if none were used in a much longer run. The purpose of this note, however, is to discuss real-world design issues, and one of those is having to make the engineering decision of when the design is "good enough" relative to the resources expended. In this case, CFO achieved an acceptable design very close to the known best design using f_3 and a total of 4,636 function evaluations. This meets the "good enough" test.

This simple monopole example demonstrates that how well an "optimized" antenna performs can be highly dependent upon both the objective function against, which it is optimized and how accurately and efficiently the optimization program performs against that function's landscape. Because CFO is deterministic, it allows the antenna designer to investigate the effects of changing the objective function's form and parameters that determine its landscape. It is evident that defining an effective function is much easier when the optimizer returns the same results every time instead of different ones. In the author's opinion this is an important consideration in addressing real-world antenna problems, or, for that matter, any problem in which definition of the objective function is an issue.

VIII. OTHER MONOPOLE DESIGNS

The monopole example was inspired by the HF monopole designed and tested by Rama Rao and Debroux [25, 26]. Theirs employed analytically computed continuous resistive loading and achieved VSWR $\le 2:1$ from 5 MHz-30 MHz with the use of a matching network. Radiation efficiency, gain, and pattern were reasonable and well-behaved for typical HF links. A CFO-designed discrete-resistance loading profile for the same antenna provided even better performance [23], and it is instructive to compare that CFO design, which utilized fourteen discrete resistors, to the $f_3(499.6,7.302,50)$ design utilizing only one resistor.

Figure 10 shows the NEC input file for the 14-segment, CFO-optimized monopole. Note that $Z_0 = 300\ \Omega$ instead of $Z_0 = 50\ \Omega$ because the 300 Ω reference was used in [25, 26]. Each segment is loaded at its center with a discrete resistor whose value ranges from about 7.2 Ω to 82.7 Ω ("LD" cards). The NEC-computed radiation efficiency ranges from about 8 % to 45 %, with maximum gain increasing from ~-5.5 dBi at 5 MHz to ~3 dBi at 28 MHz with a pronounced mid-band dip. VSWR//300Ω is quite good, $\le 2.25:1$ at all frequencies and $\le 2:1$ above about 5.5 MHz. The VSWR $\le 2:1$ goal is met essentially across the entire HF band with no matching network. The only additional element needed to feed this antenna from a 50 Ω system is a low-loss, broadband 6:1 unun, which is readily available.

The VSWR results for the 14-segment monopole suggest that a better feed system impedance for the $f_3(499.6,7.302,50)$ design might be $\approx 300\,\Omega$, a conjecture that was investigated by recalculating this design's VSWR parametrically in Z_0 from $225\,\Omega$ to $350\,\Omega$. Figure 11 plots the results. The best overall performance indeed does occur with $Z_0 \approx 300\,\Omega$ ($\le 2:1$ from ~7.5 MHz through ~28 MHz). Above 28 MHz VSWR remains fairly low, below 2.5:1, but at the low end of the band it increases quickly with decreasing frequency. The maximum is ~5.5:1 at 5 MHz, but even this value is quite acceptable because it is high only in a fairly narrow band (values $\le 10:1$ are readily matched).

At this point it is apparent that the PEC metallic monopole loaded by a single correctly placed resistor may perform nearly as well as one employing fourteen resistors, and probably better than the designs in [25, 26] employing continuous loading. Because the objective function's landscape changes with Z_0, even if only slightly, and because the $Z_0 = 50\,\Omega$ CFO-optimized antenna exhibits better VSWR when Z_0 is increased to 300 Ω, it is instructive to tweak the previous design by making another CFO run against f_3's landscape with $Z_0 = 300\ \Omega$, that is, with $f_3(R,H,300)$ as the objective function. CFO's best fitness in this case is 9.66379×10^{-5} at the point $(R,H) = (501.78982,7.107012)$ using 5,016 function evaluations.

This single-resistor monopole outperforms the 14-segment antenna by every measure except VSWR. Radiation efficiency increases nearly monotonically from a minimum of 15%, compared to the 14-segment's that starts off near 8% and exhibits considerable fluctuation with increasing frequency. The tweaked design's gain increases from ≈ -3.25 dBi at 5 MHz to ≈ 2.25 dBi at 30 MHz with a dip to 0 dBi at 24 MHz. The 14-segment design has a similar behavior, but a lower gain at 5 MHz (~ -5.6 dBi) and a very slightly higher gain at 28 MHz (~3.1 dBi).

VSWR for the tweaked antenna is somewhat worse, but nonetheless quite good, $\le 2:1$ from 7.5 MHz-26 MHz and only slightly above that through 30 MHz where it reaches $2.5:1$. Below 7.5 MHz VSWR increases quickly with decreasing frequency, reaching just over $5:1$ at 5 MHz, a degree of variability easily handled by a simple matching network. It therefore is reasonable to expect a VSWR below 2:1 across the entire 5 MHz-30 MHz band, possibly well below 2:1.

Another important measure of the tweaked monopole's effectiveness is its radiation pattern compared to the 14-segment's. The tweaked design generally exhibits higher power gain at all polar angles, especially in the range of interest for moderate to long HF links, $60^o \le \theta \le 80^o$. The single-resistor $f_3(R,H,300)$ loaded design actually provides better overall performance than the 14-segment monopole. Moreover, it is simpler to fabricate and maintain, and arguably substantially better than the continuously loaded designs in [25, 26].

Procedure $CFO[f(\vec{x}), N_d, \Pi]$

Internals: N_t, F_{rep}^{init}, ΔF_{rep}, $F_{rep}^{\min}$, $\left(\frac{N_p}{N_d}\right)_{MAX}$, γ_{start}, γ_{stop}, $\Delta\gamma$.

Initialize $f_{\max}^{global}(\vec{x})$ = very large negative number, say, -10^{+4200}.

For $N_p/N_d = 2$ to $\left(\frac{N_p}{N_d}\right)_{MAX}$ by 2:

(a.0) Total number of probes: $N_p = N_d \cdot \left(\frac{N_p}{N_d}\right)$

For $\gamma = \gamma_{start}$ to γ_{stop} by $\Delta\gamma$:

(a.1) Re-initialize data structures for position/ acceleration vectors & fitness matrix.

(a.2) Compute IPD (see [4]).

(a.3) Compute initial fitness matrix, $M_0^p, 1 \le p \le N_p$.

(a.4) Initialize $F_{rep} = F_{rep}^{init}$.

For $j = 0$ to N_t (or earlier termination - see [4]):

(b) Compute position vectors, $\vec{R}_j^p, 1 \le p \le N_p$ (eq. (2) in [4])

(c) Retrieve errant probes ($1 \le p \le N_p$):

If $\vec{R}_j^p \cdot \hat{e}_i < x_i^{\min} \therefore \vec{R}_j^p \cdot \hat{e}_i = \max\{x_i^{\min} + F_{rep}(\vec{R}_{j-1}^p \cdot \hat{e}_i - x_i^{\min}), x_i^{\min}\}$.

If $\vec{R}_j^p \cdot \hat{e}_i > x_i^{\max} \therefore \vec{R}_j^p \cdot \hat{e}_i = \min\{x_i^{\max} - F_{rep}(x_i^{\max} - \vec{R}_{j-1}^p \cdot \hat{e}_i), x_i^{\max}\}$.

(d) Compute fitness matrix for current probe distribution, M_j^p, $1 \le p \le N_p$.

(e) Compute accelerations using current probe distribution and fitnesses (eq. (1) in [4]).

(f) Increment F_{rep}: $F_{rep} = F_{rep} + \Delta F_{rep}$; If $F_{rep} > 1 \therefore F_{rep} = F_{rep}^{\min}$..

(g) If $j \ge 20$ and j $MOD\, 10 = 0$ $\therefore$

(i) Shrink Ω around $\vec{R}_{best}$ (see [4].

(ii) Retrieve errant probes [procedure Step (c)].

Next j

(h) Reset Ω boundaries [values before shrinking].

(i) If $f_{\max}(\vec{x}) \ge f_{\max}^{global}(\vec{x}) \therefore f_{\max}^{global}(\vec{x}) = f_{\max}(\vec{x})$.

Next γ

Next N_p/N_d

Fig. 9. CFO pseudocode.

IX. CONCLUSION

This paper discussed an example antenna optimization problem using a single-resistor loaded HF monopole. It addressed issues in defining an objective function that effectively measures antenna performance, and the suitability of stochastic and deterministic optimization algorithms. Assessing how well a particular objective function will achieve design goals is a difficult question because the landscape of functions beyond 2-D cannot be visualized (note that CFO's tendency to distribute probes may be useful in this regard; see §9 in [4]). Three different objective functions and their landscapes were considered.

Deterministic central force optimization was applied to each objective function's topology and the results compared. The best objective function then was used to develop a final tweaked design that was compared to a similar, previously CFO-optimized design utilizing fourteen discrete loading resistors. The single-resistor monopole performs as well or better than the fourteen resistor version and better than other continuously loaded antennas reported in the literature.

```
CM File: LD_MONO.NEC
CM Run ID 02-16-2011 10:43:46
CM Nd= 14, p= 2, j= 120
CM Zo=300 ohms
CE
GW1,14,0.,0.,0.,0.,0.,10.668,.0254
GE1
LD0,1,1,1,82.7045,0.,0.
LD0,1,2,2,29.31145,0.,0.
LD0,1,3,3,9.2825,0.,0.
LD0,1,4,4,7.154042,0.,0.
LD0,1,5,5,7.397769,0.,0.
LD0,1,6,6,7.310225,0.,0.
LD0,1,7,7,27.58697,0.,0.
LD0,1,8,8,26.55749,0.,0.
LD0,1,9,9,24.70102,0.,0.
LD0,1,10,10,22.80148,0.,0.
LD0,1,11,11,20.82445,0.,0.
LD0,1,12,12,16.44918,0.,0.
LD0,1,13,13,11.4537,0.,0.
LD0,1,14,14,9.471994,0.,0.
GN1
FR 0,26,0,0,5.,1.
EX 0,1,1,1,1.,0.
RP 0,10,1,1001,0.,0.,10.,0.,100000.
EN
```

Fig. 10. NEC file for CFO-optimized 14-segment loaded monopole.

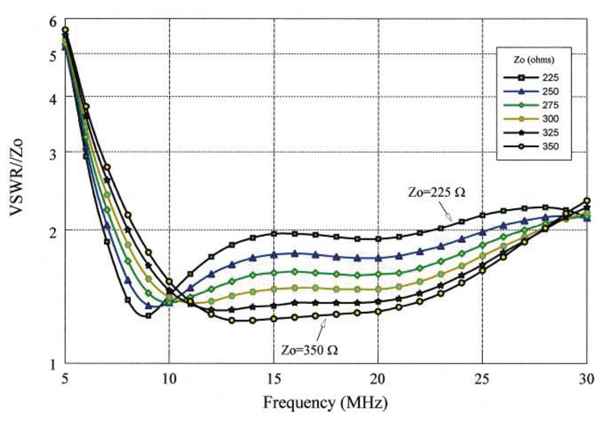

Fig. 11. VSWR for CFO design f_3 (499.6,7.302,Z_0) parametric in Z_0.

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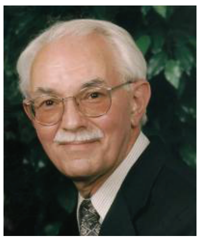

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