THE ANTENNA COMPARISON TECHNIQUE (ACT)

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1. Introduction

This paper presents a technique that can help antenna designers select the best antenna from several competing designs, based on the results of antenna computer simulations and on the relative importance (to the antenna user) of various antenna performance measures.

The Antenna Comparison Technique (ACT) [1] uses data generated by any antenna simulation program. In our applications of the ACT we have primarily used a PC version of the Numerical Electromagnetics Code (NEC) called GNEC [2]. GNEC uses the Method of Moments technique [3,4], but any computational electromagnetics code (finite element based, finite difference based, etc.) capable of creating a certain set of output data (discussed in subsequent sections) can be used with the ACT.

The topics presented in this paper include definitions of the antenna performance factor and the simulation confidence factor, followed by a formula for the Antenna Comparison Factor (ACF), a relative "figure of merit" used to compare antennas in a quantitative manner. Finally, a practical example of the ACT is presented.

2. The Antenna Comparison Technique (ACT)

The purpose of the ACT is to quantitatively rank antennas within a "comparison" set based on objective antenna performance measures and user-defined subjective weights for each performance measure. The result of the ACT is the Antenna Comparison Factor (ACF) for each of the antennas in the comparison set. The ACF is a relative "grade" (greater than 0 and less than or equal to 1) for a specific antenna within a specific antenna comparison set. The same antenna can have different values of ACF for different antenna comparison sets, or even for the same comparison set, but for a different selection of user-defined parameters (such as feed line impedance).

The ACF is a product of the antenna performance factor and the antenna confidence factor, as shown below.

ACF = (performance factor) x (confidence factor)

$$\text{performance factor} \begin{cases} \text{antenna performance measures} \\ \text{subjective weights} \end{cases}$$

Figure 1 – Antenna Comparison Factor (ACF)

The antenna performance factor is a function of objective antenna performance measures and the user-defined subjective weights applied to those performance measures. Subjective weights reflect the relative importance to the antenna user of each performance measure. The confidence factor quantifies the user's trust in the accuracy of the computer simulations and is based on the principle of power conservation. For a lossless antenna in free space, the following statements apply: (1) The power delivered to the antenna input equals the total power radiated by the antenna. (2) The average antenna gain computed over a spherical surface of a large (relative to the operating wavelength) radius will be equal to 1 [2]. (3) The difference between the value of the average gain obtained by computer simulation and 1 at any particular frequency can be used as a measure of the confidence in the results. Although the above is strictly true for lossless antennas only, in practice antennas are usually designed to have very low losses (on the order of a percent or so) and thus their average gains should be very close to 1. For an antenna simulation over a range of frequencies the root-mean square error $\mathrm{RMS}_{\mathrm{error}}$ of the simulated average gain can be used to form a measure of confidence in the simulation results that we refer to as the "confidence factor":

$$\textit{confidence factor} = \frac{1}{1 + \mathrm{RMS}_{\mathrm{error}}} \quad (1)$$

Since the confidence factor multiplies the performance factors, and the value of the confidence factor decreases as the accuracy of the simulation decreases, the ACF decreases for antennas with less accurate simulations.

3. Antenna Performance Measures

In order to identify a "minimum" set of the most important antenna performance measures of interest to an antenna user we have focused on:

- antenna overall efficiency
- antenna bandwidth
- transmitter VSWR restriction.

The antenna overall efficiency is defined as the ratio of the power radiated by the antenna into the "target" solid angle and the power delivered by the transmitter to the transmission line. For any practical antenna the overall efficiency is a function of operating frequency. The antenna overall efficiency incorporates the effects of antenna mismatch, thermal losses within the antenna, and the antenna beam efficiency (radiation into a desired solid angle) [1]. The antenna bandwidth can be determined from the antenna overall efficiency, as the difference of the upper and lower cutoff frequencies at which the antenna overall efficiency drops to ½ of its average value. The information on the variation of antenna overall efficiency with frequency can be "condensed" to four real numbers:

- the upper and lower cutoff frequencies (defining the antenna bandwidth),
- the mean value of the antenna overall efficiency within the bandwidth, and
- the standard deviation of the antenna overall efficiency within the bandwidth.

In many antenna applications the designer's objective for the antenna overall efficiency is to maximize its bandwidth and mean value and to minimize its standard deviation.

Antenna users are also concerned about the transmitter maximum VSWR restriction that may limit transmitter operation to a range of frequencies different than the antenna bandwidth defined by the antenna overall efficiency. Therefore, in addition to upper and lower cutoff frequencies for the antenna overall efficiency, we also have upper and lower cutoff frequencies for the maximum allowable VSWR. The minimum of six real numbers per antenna is thus needed to quantify antenna performance. These six numbers can be used to form six normalized performance measures, defined in the table below, that are needed when comparing a collection of antennas that have been placed in a "comparison set".

	Definition
Normalized mean overall efficiency (F_h)	$F_h = \dfrac{\text{antenna overall efficiency average}}{\text{maximum overall efficiency average of the comparison set}}$
Normalized standard deviation of overall efficiency (F_s)	$F_s = \dfrac{\text{minimum standard deviation of the overall efficiency in the comparison set}}{\text{antenna overall efficiency standard deviation}}$
Normalized lower cutoff frequency of the overall efficiency (F_f)	$F_f = \dfrac{\text{minimum lower cutoff frequency of the overall efficiency in the comparison set}}{\text{antenna lower cutoff frequency of the overall efficiency}}$
Normalized upper cutoff frequency of the overall efficiency (F_F)	$F_F = \dfrac{\text{antenna upper cutoff frequency of the overall efficiency}}{\text{maximum upper cutoff frequency of the overall efficiency in the comaprison set}}$
Normalized lower cutoff frequency for the maximum VSWR (F_v)	$F_v = \dfrac{\text{minimum lower cutoff frequency of the VSWR in the comparison set}}{\text{antenna lower cutoff frequency of the VSWR}}$
Normalized upper cutoff frequency for the maximum VSWR (F_V)	$F_V = \dfrac{\text{antenna upper cutoff frequency of the VSWR}}{\text{maximum upper cutoff frequency of the VSWR of the comaprison set}}$

Table 1 – Normalized Antenna Performance Measures

4. Subjective Antenna Performance Weights

The subjective antenna performance weights reflect the importance of different antenna performance features to the antenna user. Since we have "condensed" the antenna performance measures to six real numbers (mean and standard deviation of overall efficiency, and upper and lower cutoff frequencies for overall efficiency and maximum allowable VSWR) there are six weights as well, one per antenna performance measure. Each subjective weight is denoted as K with a subscript for the normalized performance measure it applies to. Four weights have been selected, corresponding to four importance levels, as shown in Table 2 below.

Importance Level	*Low*	*Medium*	*High*	*Very high*
Weight	*1*	*2*	*3*	*4*

Table 2 – Importance Levels and the Corresponding Weights

Shown in Table 3 is a sample assignment of subjective weights to the antenna performance measures.

Performance Measure	Standard deviation of overall efficiency	Lower and upper cutoff frequency for max VSWR	Average overall efficiency	Lower and upper cutoff frequency for overall efficiency
Weight	$K_\sigma = 1$	$K_v = 2$ $K_V = 2$	$K_\eta = 3$	$K_f = 4$ $K_F = 4$

Table 3 – Example of Subjective Weights

All the components needed to define the Antenna Comparison Factor (ACF) are now available.

5. The Antenna Comparison Factor

For antenna data obtained by computer simulation, the antenna comparison factor can be defined as the product of the antenna performance factor and the simulation confidence factor:

$$\mathrm{ACF} = \underbrace{\left(\frac{K_\eta F_\eta + K_\sigma F_\sigma + K_f F_f + K_F F_F + K_v F_v + K_V F_V}{K_\eta + K_\sigma + K_f + K_F + K_v + K_V} \right)}_{performance\ \ factor} \underbrace{\left(\frac{1}{1 + \mathrm{RMS}_{\mathrm{error}}} \right)}_{confidence\ \ factor} \tag{2}$$

Where the normalized performance measures (F's), the subjective weights (K's), and the RMS error of the simulated antenna average gain have been defined in the preceding sections. Note that the ACF can also be used to compare antennas whose performance data have been obtained by measurements, with the confidence factor either replaced by 1, or redefined based on the accuracy of the measurements (especially if the measurements of different antennas were not performed using the same equipment). When comparing a number of antennas, the ACF is calculated for each of the antennas in the comparison set. The values of the ACF for any of the antennas in the comparison set are between 0 and 1. The antenna with the highest ACF is considered as the best antenna. Again, changing user-defined parameters (such as reference or subjective weights) alters the values of the ACF for each antenna and may result in a different antenna ranking.

6. Practical Example of the ACT

As an example of the ACT application, we compare three antennas that each fit in a 40 cm by 40 cm square. The three antennas are:

- a wire-frame "bow tie" monopole (Figure 2a),
- a top-loaded wire monopole (Figure 2b), and
- a wire monopole (Figure 2c).

All antennas were "constructed" using 5mm solid wire, assumed as an ideal conductor and were assumed to operate over an infinite ideal (perfectly conducting) ground plane. The antennas were simulated using GNEC in the 30 – 300 MHz (VHF) frequency range. The maximum allowable VSWR was 3 for a transmission line of 50 ohms, and the directivity/gain was calculated in the upper half space.

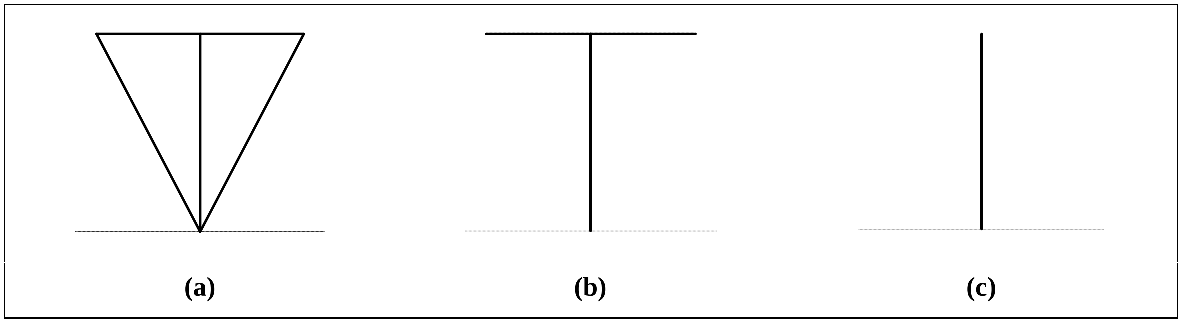

Figure 2 – Antenna Comparison Set used in the ACT Application Example

In this ACT example, each of the antenna performance measures (obtained from the GNEC simulations) was weighted by the same subjective weights as in Table 3. The analysis of GNEC simulation results for each antenna and their respective ACF results are presented in Table 4.

Type of Antenna (Figure 2)	**(a)**	**(b)**	**(c)**
spherical gain error (RMS_{error})	8.36 %	6.62 %	5.69 %
average of the overall efficiency	52.09 %	28.75 %	41.83 %
standard deviation of the overall efficiency	25.71 %	23.4 %	33.9 %
lower cutoff frequency of the overall efficiency	85 MHz	80 MHz	130 MHz
upper cutoff frequency of the overall efficiency	300 MHz	300 MHz	300 MHz
lower cutoff frequency for the maximum VSWR	110 MHz	100 MHz	160 MHz
upper cutoff frequency for the maximum VSWR	145 MHz	120 MHz	210 MHz
ACF performance factor	**0.930**	**0.862**	**0.801**
ACF confidence factor	**0.923**	**0.938**	**0.946**
ACF	***0.858***	***0.809***	***0.757***

Table 4 – Practical Example of the ACT Application

The ACT identifies that antenna (a) is the best within this antenna comparison set, because it has the highest ACF value, despite lower effective bandwidth, higher standard deviation and spherical gain error than type (b). As this example illustrates, using customer-defined weights to rank the relative importance of various antenna performance features, an antenna designer can determine which antenna will best meet the customer performance specifications.

7. References

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