Evolutionary Design of a Phased Array Antenna Element

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Introduction

We present an evolved S-band phased array antenna element design that meets the requirements of NASA's TDRS-C communications satellite scheduled for launch early next decade. The original specification called for two types of elements, one for receive only and one for transmit/receive. We were able to evolve a single element design that meets both specifications thereby simplifying the antenna and reducing testing and integration costs. The highest performance antenna found using a genetic algorithm and *stochastic hill-climbing* has been fabricated and tested. Laboratory results are largely consistent with simulation.

Researchers have been investigating evolutionary antenna design and optimization since the early 1990s (e.g, [1]), and the field has grown in recent years as computer speed has increased and electromagnetic simulators have improved. Many antenna types have been investigated, including wire antennas [2], antenna arrays [3], and quadrifilar helical antennas [4]. In particular, our laboratory evolved a wire antenna design for NASA's Space Technology 5 (ST5) spacecraft. This antenna [5] has been fabricated, tested, and is scheduled for launch on the three spacecraft in 2006.

TDRS-C Mission Requirements

TDRS-C is designed to carry a number of antennas, including a 46 element phased array. Element spacing is triangular at approximately 2λ. Each element gain must be $>$ 15dBic on the boresight and $>$ 10dBic to $\theta = 20^o$ off boresight with both polarizations. For $\theta > 30^o$, gain must be $<$ 5dBic. Axial ratio must be $\leq$ 5dB over the field of view $(0 - 20^o)$. Receive-only element bandwidth covers 2200-2300 MHz. Transmit and receive element bandwidth covers 2030-2113.5 MHz. Input impedance is 50Ω. Element spacing determines maximum footprint and there is no maximum height in the specification, although minimizing height and mass is a design goal. The combination of fairly broad bandwidth, the efficiency required and circular polarization at high gain makes for a challenging design problem.

Evolved Antenna Design

We constrained our evolutionary design to a crossed-element yagi antenna. The element nearest the spacecraft is slightly separated and these two wires can be fed in such a way as to create circular polarization in either sense. All crossed-elements, including the first, are spaced and sized by evolution. While the evolutionary loop is fairly standard for a variety of problems, three elements must be defined to evolve a design: 1. representation - data that precisely defines the design space, 2. variation

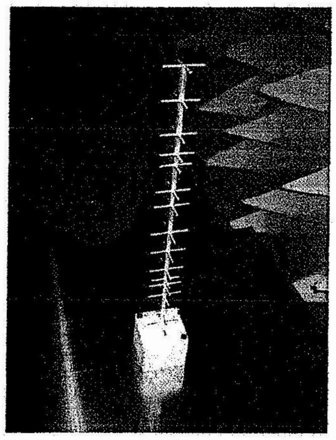

Figure 1: Computer graphics rendering of the best evolved antenna. It is 47 cm high, covers a 2.3 cm footprint, and uses 1.587 mm radius wire. There are 15 crossed-elements.

operators - code that takes one or more design representations as input and outputs a design derived from them, and 3. fitness function - a function that evaluates a design.

The representation is a fixed length list of floating point numbers (X_i). All X_i are in the interval $0-1$ to simplify the variation operators. Antenna parameters are determined from X_i by linear interpolation within an interval chosen to generate reasonable parameters. X_1 determines the height of the antenna within the interval $3\lambda - 4\lambda$ at the lowest frequency (2030 MHz). The remaining pairs $((X_{2n+1}, X_{2n+2}), n \geq 0)$ determine the size and spaceing of each crossed-element (including the first, separated one). X_{2n+1} determines the spacing between elements and X_{2n+2} determines the size of the cross. For the first element, this is the absolute size of the cross in the interval $0.001\lambda - 1.5\lambda$. For the remaining elements this is from the interval $0.8s - 1.2s$ where s is the size of the previous element. This representation is modified by a wide variety of standard and custom mutation and crossover operators.

Antennas fitness is a function of the standing wave ratio (VSWR) and gain values at 2030, 2075, 2120, 2210, 2255, and 2300 MHz. This fitness function to minimize is:

$$\sum_f rms(3, v_f)^5 + rms(1.5, v_f) + rms(1.0, v_f) + min(0, 15.25 - g_{f_0}) + min(0, 10.25 - g_{f_{20}}) \tag{1}$$

where $rms(t, v)$ is the root mean square of a value above a target value t, v_f is the VSWR at frequency f, g_{f_0} is the gain at the boresight, and $g_{f_{20}}$ is gain 20^o off boresight. Note that VSWR above three is severely punished and improvements are always rewarded. Gain at the boresight and 20^o off bore sight is encouraged until it clears with a safety factor since simulation is never completely accurate. Side lobe minimization is not explicitly encouraged but is achieved as a side effect of high gain

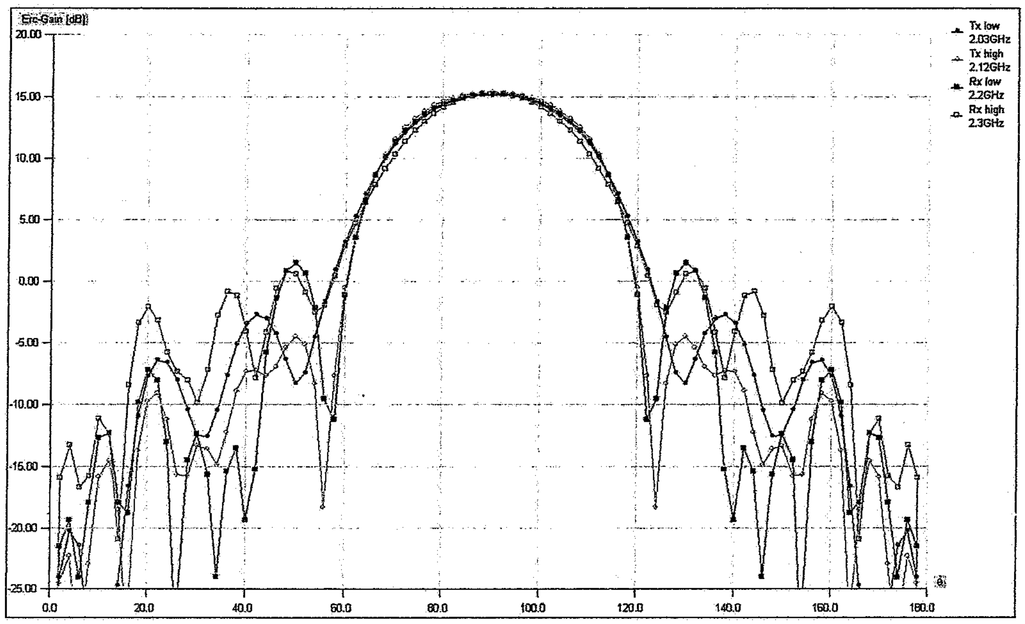

Figure 2: Best antenna gain pattern. 90^o is on boresight.

near the boresight.

GA and Hill Climbing Run Setup and Results

To speed antenna evaluations, an infinite ground plane was used in all runs. This was found to provide sufficient accuracy. The Numerical Electromagnetics Code, Version 4 (NEC4) was used to evaluate all antenna designs.

A three stage procedure evolved the best antenna. All stages were executed using the JavaGenes [6] general purpose, open source stochastic search code written in Java and developed at NASA Ames. The stages were: 1. Approximately 150 steady state genetic algorithm processes were run for up to 50,000 evaluations each with many parameters randomized (e.g., population size, number of crossed-elements, variation operators); 2. The best antenna from each of these runs was used as a start point for a stochastic hill climbing process with randomized mutation variation operators. These processes ran for up to 100,000 evaluations each; 3. The 23 best antennas from the first hill climbing procedure were subjected to another hill climbing procedure of up to 100,000 evaluations.

Most of the final 23 designs nearly met the specification, and one exceeded it. This design was subjected to further analysis by more accurate and complex simulation using WIPL-D version 5.2, and some minor tuning through another evolutionary algorithm process developed at JEM Engineering. The final antenna was fabricated and chamber tested. The results are largely consistent with the simulation. Gain and S1,1 plots are shown in figures 2 and 3.

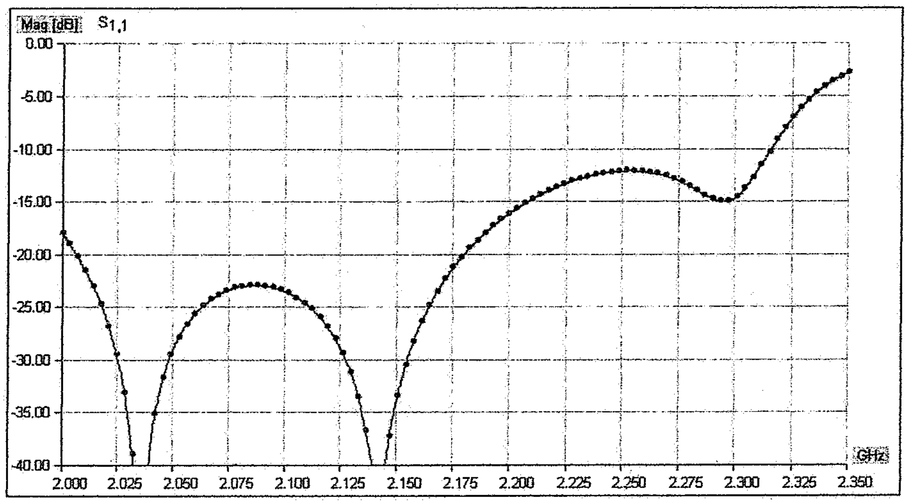

Figure 3: S1,1 for the best evolved antenna.

Acknowledgments

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References

[1] E. Michielssen, J.-M. Sajer, S. Ranjithan, and R. Mittra, "Design of lightweight, broad-band microwave absorbers using genetic algorithms", *IEEE Transactions on Microwave Theory and Techniques*, vol. 41, pp. 1024–1031, June/July 1993.

[2] Derek S. Linden and Edward E. Altshuler, "Automating wire antenna design using genetic algorithms", *Microwave Journal*, vol. 39, no. 3, pp. 1–4, March 1996.

[3] R. L. Haupt, "Genetic algorithm design of antenna arrays", in *IEEE Aerospace Applications Conference*, February 1996, vol. 1, pp. 103–109.

[4] Jason D. Lohn, William F. Draus, and Derek S. Linden, "Evolutionary optimization of a qadrifilar helical antenna", in *IEEE Antenna and Propagation Society Meeting*, June 2002, vol. 3, pp. 814–817.

[5] Jason D. Lohn, Derek S. Linden, Greg S. Hornby, William F. Kraus, A. Rodriguez, and S. Seufert, "Evolutionary design of an x-band antenna for nasa's space technology 5 mission", in *Proceedings of the 2004 IEEE Antenna and Propagation Society International Symposium and USNC/URSI National Radio Science Meeting*, 2004, vol. 3, pp. 2313–2316.

[6] Al Globus, James Crawford, Jason Lohn, and Anna Pryor, "Scheduling earth observing satellites with evolutionary algorithms", in *Conference on Space Mission Challenges for Information Technology (SMC-IT)*, 2003.