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Evolutionary Design of an X-Band Antenna for NASA's Space Technology 5 Mission

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1 Introduction

We present an evolved X-band antenna design and flight prototype currently on schedule to be deployed on NASA's Space Technology 5 [10] spacecraft in late 2004. The antenna was evolved to meet a challenging set of mission requirements, most notably the combination of wide beamwidth for a circularly-polarized wave and wide bandwidth. The highest performance antenna found using a genetic algorithm was fabricated and tested.

Researchers have been investigating evolutionary antenna design and optimization since the early 1990s (e.g., [8, 3, 1]), and the field has grown in recent years as computer speed has increased and electromagnetics simulators have improved. Many antenna types have been investigated, including wire antennas [5], antenna arrays [4], and quadrifilar helical antennas [7]. In addition, the ability to evolve design antennas *in-situ* [6], that is, taking into account the effects of surrounding structures, opens new design possibilities. Such an approach is very difficult for designers due to the complexity of electromagnetic interactions, yet easy to integrate into evolutionary techniques.

2 ST5 Mission Antenna Requirements

The key ST5 mission antenna requirements are as follows: Transmit Frequency: 8470 MHz; Receive Frequency: 7209.125 MHz; VSWR: $< 1.2 : 1$ at Transmit Freq and $< 1.5 : 1$ at Receive Freq; Gain Pattern: ≥ 0 dBic, $40° \leq \theta \leq 80°$ and $0° \leq \phi \leq 360°$; Input Impedance: 50 Ω; Diameter < 15.24 cm; Height: < 15.24 cm; Mass: < 165 g.

The combination of wide beamwidth for a circularly-polarized wave and wide bandwidth make for a challenging design problem. In terms of simulation challenges, because the diameter of the spacecraft is 54.2 cm, the spacecraft is 13-15 wavelengths across which makes antenna simulation computationally intensive. For that reason, an infinite ground plane approximation or smaller finite ground plane is used.

In addition to the requirements above, an additional "desired" specification was issued for the field pattern. Because of the spacecraft's relative orientation to the Earth, high gain in the field pattern was desired at low elevation angles. Specifically, across $0° \leq \phi \leq 360°$, gain was desired to meet: 0 dBic for $\theta = 40°$, 2 dBic for $\theta = 80°$, and 4 dBic for $\theta = 90°$.

3 Evolved Antenna Design

We constrained our evolutionary design to a monopole wire antenna with four identical arms, each arm rotated 90° from its neighbors. A tree-based, LOGO-like antenna constructing programming language was devised. Each node in the tree-structured representation is an antenna-construction command that either specifies the length and radius of a wire or rotates the coordinate system a specified number of degrees. An antenna design is created by starting with an initial feedwire and adding wires. For the ST5 mission the initial feed wire starts at the origin and has a length of 0.4 cm along the Z-axis. To take into account imprecision in manufacturing an antenna, antenna designs are evaluated multiple times, each time with a small random perturbation applied to joint angles and wire radii. Also, designs evolved with this manufacturing noise tend to perform well across a broader range of frequencies than do antennas evolved without this noise.

The fitness function used to evaluate antennas is a function of the voltage standing wave ratio (VSWR) and gain values on the transmit and receive frequencies. The VSWR component of the fitness function is constructed to put strong pressure to evolving antennas with receive and transmit VSWR values below the required amounts of 1.2 and 1.5, reduced pressure at a value below these requirements (1.15 and 1.25) and then no pressure to go below 1.1. For example, for the VSWR at the transmit frequency (v_t):

$$v'_t = \begin{cases} v_t + 2.0(v_t - 1.15) & \text{if } v_t > 1.15 \\ v_t & \text{if } 1.15 > v_t > 1.1 \\ 1.1 & \text{if } v_t < 1.1 \end{cases}$$

The overall VSWR component is then: $vswr = v'_r v'_t$ with v'_r being calculated in an analogous manner. The gain component of the fitness function uses the gain (in decibels) in 5° increments about the angles of interest: from $40° \leq \theta \leq 90°$ and $0° \leq \phi \leq 360°$:

$$\begin{aligned} gain_{ij} &= \text{gain at } \theta = 5°i,\ \phi = 5°j \\ gain(i,j) &= \begin{cases} 0 & \text{if } gain_{ij} > 0.5 \\ 0.5 - gain_{ij} & \text{if } gain_{ij} < 0.5 \end{cases} \\ gain &= 1 + 0.1 \sum_{i=8}^{i<19} \sum_{j=0}^{j=72} gain(i,j) \end{aligned}$$

The third component of the fitness function rewards antenna designs for having samples with gains greater than zero. It is computed as: $outlier = 1 + \sum_{i=8}^{i<19} \sum_{j=0}^{j=72} outlier(i,j)$ where $outlier(i,j) = 0.1$ if $gain_{ij} < 0.01$ or 0 otherwise. These three components are multiplied together to produce the overall fitness score, F, which is a cost function: $F = vswr \times gain \times outlier$

4 GA Run Setup and Results

To keep the antenna evaluations fast, an infinite ground plane approximation was used in all runs. This was found to provide sufficient accuracy to achieve several good designs. Designs were then analyzed on a finite ground plane the same shape and size as the top of the ST5 body to determine their effectiveness at meeting requirements in a realistic environment. The Numerical Electromagnetics Code, Version 4 (NEC4) [2] was used to evaluate all antenna designs. A population of 200 and a mutation rate of 50% was used.

The best antenna design found was fabricated and tested. The antenna named ST5-3-10 is shown in Figure 1. It is 100% compliant with the mission antenna performance requirements, confirmed by testing the prototype antenna at NASA Goddard Space Flight Center. The VSWR plot and the 8.47 GHz max/min gain pattern are shown in Figure 2. The VSWR values are slightly higher than the requirements specify because of mismatch issues on the test equipment.

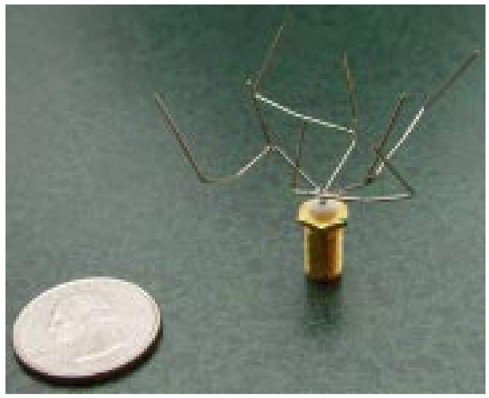

Figure 1: Photograph of prototype evolved antennas ST5-3-10

5 Conclusion

Evolved antenna ST5-3-10 was shown to be compliant with respect to the ST5 antenna performance requirements. It has an unusual organic-looking structure, one that expert antenna designers would likely not produce. Some of its potential benefits are as follows. The antenna achieves high gain (2-4dB) across a wider range of elevation angles. This would result in less power consumption. The evolved antenna does not require a matching network nor phasing circuit, removing two steps in design and fabrication of the antenna. The evolved antenna had a shorter design cycle: it was estimated that antenna ST5-3-10 took 3 person-months to design and fabricate the first prototype as compared to 5 person-months for the quadrifilar helical antenna.

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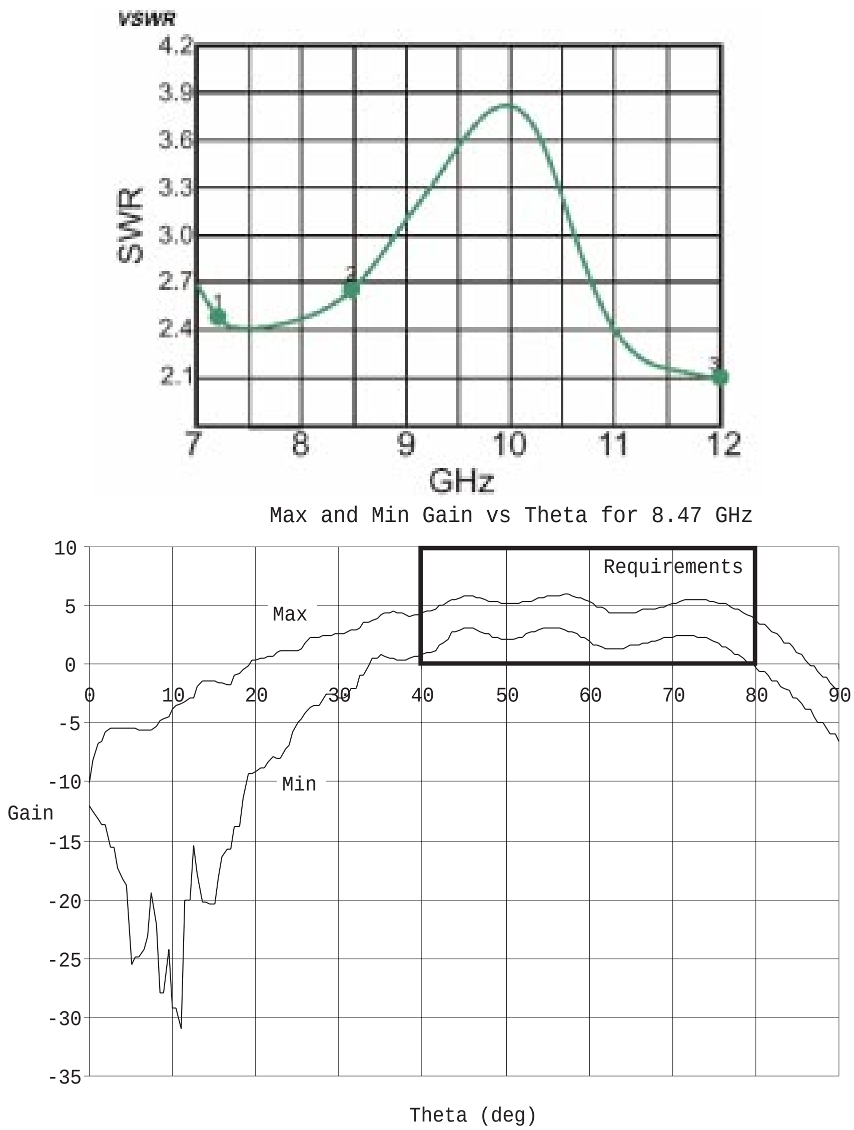

Figure 2: Measured VSWR (top); Min/max gain at 8.47 GHz (bottom).