Evolution, Re-evolution, and Prototype of an X-Band Antenna for NASA's Space Technology 5 Mission

Jason D. Lohn[1], Gregory S. Hornby[2], and Derek S. Linden[3]

[1] Computational Sciences Division
NASA Ames Research Center
Moffett Field, CA 94035, USA
jlohn@arc.nasa.gov
http://ic.arc.nasa.gov/projects/esg/
[2] QSS Group Inc.
NASA Ames Research Center
Moffett Field, CA 94035, USA
hornby@email.arc.nasa.gov
[3] JEM Engineering
8683 Cherry Lane
Laurel, MD 20707
dlinden@jemengineering.com

Abstract. One of the challenges in engineering design is responding to a change of design requirements. Previously we presented a four-arm symmetric evolved antenna for NASA's Space Technology 5 mission. However, the mission's orbital vehicle was changed, putting it into a much lower earth orbit, changing the specifications for the mission. With minimal changes to our evolutionary system, mostly in the fitness function, we were able to evolve antennas for the new mission requirements and, within one month of this change, two new antennas were designed and prototyped. Both antennas were tested and both had acceptable performance compared with the new specifications. This rapid response shows that evolutionary design processes are able to accommodate new requirements quickly and with minimal human effort.

1 Introduction

One of the challenges in engineering design is responding to a change in design requirements. Previously we presented our work in using evolutionary algorithms to automatically design an X-band antenna for NASA's Space Technology 5 (ST5) spacecraft [4]. Since our original evolutionary runs and the fabrication and testing of antennas ST5-3-10 and ST5-4W-03, the launch vehicle for the ST5 spacecraft has changed resulting in a lower orbit and different antenna requirements. With traditional engineering design such a change in requirements would necessitate redoing much of the design work with a near doubling of design costs. In contrast, with an evolutionary design system for automatically creating antennas once the software has been developed, modifying it to produce antennas for a similar design problem requires only a minimal amount of human effort to implement the change a re-evolve new antennas with minimal additional cost.

The ST5 mission consists of three spacecraft which will orbit at close separations in a highly elliptical geosynchronous transfer orbit and will communicate with a 34 meter ground-based dish antenna. Each spacecraft will have two antennas attached, one on each side of the spacecraft, Figure 1. Initially the spacecraft were to fly approximately 35,000 km above Earth and the requirements for the communications antenna were for a gain pattern of $\geq$0 dBic from 40° - 80° from zenith. With the change in launch vehicle and the new, lower orbit this necessitated the addition of a new requirement on the gain pattern of $\geq$-5 dBic from 0° 40° from zenith. The complete set of requirements for the antennas on the ST5 Mission are summarized in table 1. VSWR is a way to quantify reflected-wave interference, a measure of the impedance mismatch. It is the ratio between the highest voltage and the lowest voltage in the signal envelope along a transmission line, with a ratio of 1 being perfect VSWR.

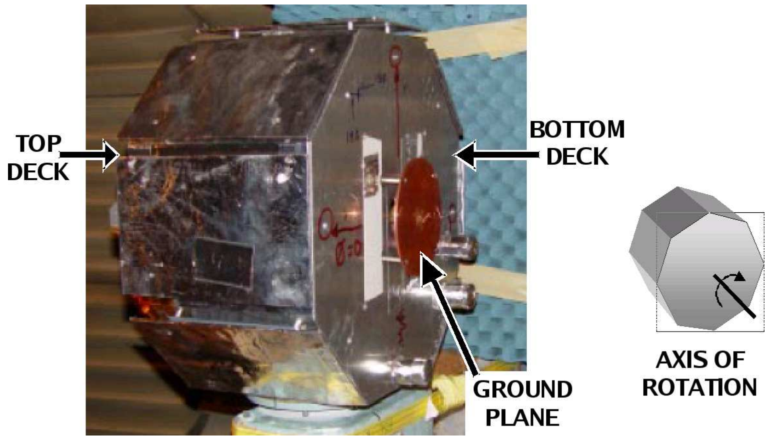


Fig. 1. Photograph of the ST5 mock-up with antennas mounted (only the antenna on the top deck is visible).

In the rest of this paper we describe the two evolutionary design systems we used for evolving the initial antennas for this mission and the changes we made to them to address the change in mission requirements. We then present the performance of the new antenna designs, both from simulation and from fabricated units. One of our newly evolved antennas, ST5-33.142.7, meets the new mission requirements and has successfully passed environmental testing. Three of these antennas are scheduled to be launched in 2006 and will be the first evolved hardware in space and the first evolved antennas to be fielded.

Table 1. Key ST5 Antenna Requirements

Property	Specification
Transmit Frequency	8470 MHz
Receive Frequency	7209.125 MHz
VSWR	$< 1.2 : 1$ at Transmit Freq
	$< 1.5 : 1$ at Receive Freq
Original Gain Pattern	$\geq$ 0 dBic, $40° \leq \theta \leq 80°$, $0° \leq \phi \leq 360°$
Additional Gain Pattern Requirement	$\geq$ -5 dBic, $0° \leq \theta \leq 40°$, $0° \leq \phi \leq 360°$
Input Impedance	50 Ω
Diameter	< 15.24 cm
Height	< 15.24 cm
Antenna Mass	< 165 g

2 Evolutionary Antenna Design Systems

As a result of the new ST5 mission requirements we needed to change both the type of antenna we were evolving and the fitness function. The original antennas we evolved were constrained to a monopole wire antenna with four identical arms, with each arm rotated 90° from its neighbors. There the EA evolved genotypes that specified the design for one arm and the phenotype consisted of four copies of the evolved arm. Because of symmetry, the previous four-arm design has a null at zenith that is built into the design and is unacceptable for the revised mission. To achieve an antenna that meets the new mission requirements the new antenna designs were configured to produce a single arm. In addition, because of the difficulties we experienced in fabricating branching antennas to the required precision, here we constrained our antenna designs to non-branching antennas. In the remainder of this section we describe the two evolutionary algorithms we used to evolve antennas for the ST5 mission and how we changed them to address the new requirements.

2.1 Parameterized EA for Non-Branching Designs

The first EA was used in our previous work in evolutionary antenna design [3] and it is a standard genetic algorithm (GA) that evolves non-branching wire forms. With this EA the design space used a vector of real-valued triplets that specify the X, Y and Z locations of segment end-points. The fitness function for this EA used pattern quality scores at 7.2 GHz and 8.47 GHz. Unlike the second EA, VSWR was not explicitly used in this fitness calculation, rather it is included implicitly by how it affects the gain pattern. To quantify the pattern quality at a single frequency, PQ_f, the following formula was used:

$$\mathrm{PQ}_f = \sum_{\substack{0° \leq \phi < 360° \\ 0° \leq \theta \leq 80°}} (\mathrm{gain}_{\phi,\theta} - T)^2 \quad \text{if } \mathrm{gain}_{\phi,\theta} < T$$

where $\text{gain}_{\phi,\theta}$ is the gain of the antenna in dBic (right-hand polarization) at a particular angle, T is the target gain (3 dBic was used in this case), ϕ is the azimuth, and θ is the elevation. To compute the overall fitness of an antenna design, the pattern quality measures at the transmit and receive frequencies were summed, lower values corresponding to better antennas:

$$F = \text{PQ}_{7.2} + \text{PQ}_{8.47}$$

Modifying this evolutionary design system to produce antennas for the new orbit consisted of changing the fitness function to check angles $0° \leq \theta < 40°$ as well the original range of $40° \leq \theta \leq 80°$.

2.2 Open-Ended EA

The second EA uses an open-ended, variable-length representation in which elements of the genotype specify how to construct the antenna. Each node in the tree-structured representation is an antenna-construction operator and an antenna is created by executing the operators at each node in the tree, starting with the root node. In constructing an antenna the current state (location and orientation) is maintained and operators add wires or change the current state. The operators are as follows:

– `forward(length, radius)` - add a wire with the given length and radius extending from the current location and then change the current state location to the end of the new wire.
– `rotate-x(angle)` - change the orientation by rotating it by the specified amount (in radians) about the x-axis.
– `rotate-y(angle)` - change the orientation by rotating it by the specified amount (in radians) about the y-axis.
– `rotate-z(angle)` - change the orientation by rotating it by the specified amount (in radians) about the z-axis.

Since we constrained antennas to a single, bent wire with no branching each node in the genotype has at most one child. This constructive representation for encoding antennas is an extension of our previous work in using a linear-representation for encoding rod-based robots [2]. Aside from restricting antennas to not having branches, the only changes made to this evolutionary design system to address the new mission requirements were to change the fitness function.

The fitness function used to evaluate antennas is a function of the VSWR and gain values on the transmit and receive frequencies. These three components are multiplied together to produce the overall fitness score of an antenna design:

$$F = vswr \times gain \times standard\ deviation$$

The objective of the EA is to produce antenna designs that minimize F.

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:

$$
\begin{aligned}
v_r &= \text{VSWR at receive frequency} \\
v_r' &= \begin{cases} v_r + 2.0(v_r - 1.25) & \text{if } v_r > 1.25 \\ v_r & \text{if } 1.25 > v_r > 1.1 \\ 1.1 & \text{if } v_r < 1.1 \end{cases} \\
v_t &= \text{VSWR at transmit frequency} \\
v_t' &= \begin{cases} v_t + 2.0(v_t - 1.15) & \text{if } v_t > 1.15 \\ v_t & \text{if } 1.15 > v_t > 1.1 \\ 1.1 & \text{if } v_t < 1.1 \end{cases} \\
vswr &= v_r' v_t'
\end{aligned}
$$

The gain-penalty component of the fitness function uses the gain (in decibels) in 5° increments about the angles of interest: from $0° \leq \theta \leq 90°$ and $0° \leq \phi \leq 360°$. For each angle, the calculated gain score from simulation is compared against the target gain for that elevation and the outlier gain, which is the minimum gain value beyond which lower gain values receive a greater penalty. Gain penalty values are further adjusted based on the importance of the elevation:

```
gain_penalty (i, j):
        gain = calculated gain at θ = 5°i , φ = 5°j;
        if (gain ≥ target[i]) {
                penalty := 0.0;
        } else if ((target[i] > gain) and (gain ≥ outlier[i])) {
                penalty := (target[i] - gain);
        } else { /* outlier[i] > gain */
                penalty := (target[i]-outlier[i]) + 3.0 * (outlier[i] - gain));
        }
        return penalty * weight[i];
```

Target gain values at a given elevation are stored in the array `target[]` and are 2.0 dBic for i equal from 0 to 16 and are -3.0 dBic for i equal to 17 and 18. Outlier gain values for each elevation are stored in the array `outlier[]` and are 0.0 dBic for i equal from 0 to 16 and are -5.0 dBic for i equal to 17 and 18. Each gain penalty is scaled by values scored in the array `weight[]`. For the low band the values of `weight[]` are 0.1 for i equal to 0 through 7; values 1.0 for i equal to 8 through 16; and 0.05 for i equal to 17 and 18. For the high band the values of `weight[]` are 0.4 for i equal to 0 through 7; values 3.0 for i equal to 8 through 12; 3.5 for i equal to 13; 4.0 for i equal to 14; 3.5 for i equal to 15; 3.0 for i equal to 16; and 0.2 for i equal to 17 and 18. The final gain component of the fitness score of an antenna is the sum of gain penalties for all angles.

To put evolutionary pressure on producing antennas with smooth gain patterns around each elevation, the third component in scoring an antenna is based on the standard deviation of gain values. This score is a weighted sum of the standard deviation of the gain values for each elevation θ. The weight value used for a given elevation is the same as is used in calculating the gain penalty.

This fitness function differs from the one we used previously [4] in the fidelity to which the desired gain pattern can be specified and in explicitly rewarding for a smooth pattern. Our previous fitness function with the constructive EA had one target gain value for all elevations and weighted all elevations equal. With the new fitness function different target gain values can be set for different elevation angles and also the importance of achieving the desired gain at a given angle is specified through setting the weight value for a given elevation. The other difference with this fitness function is that previously there was a separate penalty for "outlier" gain values whereas in the new fitness function this is included in the gain component of the fitness score and a new component that measures pattern smoothness is included.

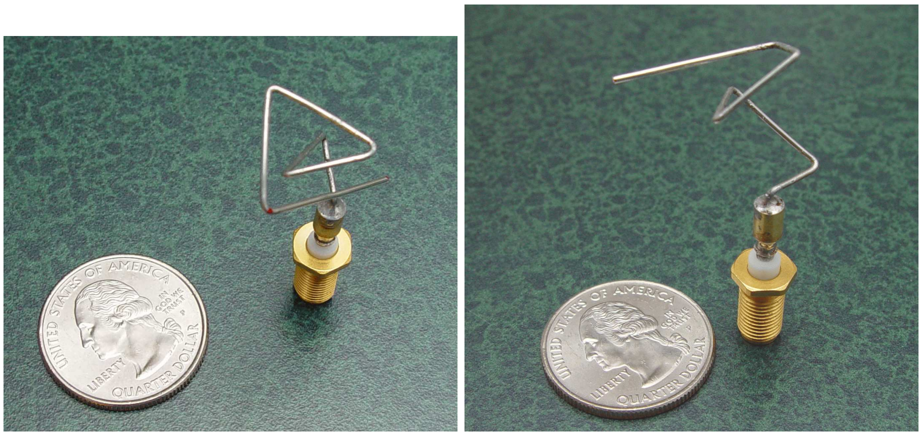
3 Evolved Antennas

To re-evolve antennas for the new ST5 mission requirements we used the same EA setup as in our initial set of evolutionary runs, however, we did not seed the first generation with previously evolved antenna designs. For the non-branching EA, a population of fifty individuals was used, 50% of which is kept from generation to generation. The mutation rate was 1%, with the Gaussian mutation standard deviation of 10% of the value range. The non-branching EA was halted after one hundred generations had been completed, the EA's best score was stagnant for forty generations, or EA's average score was stagnant for ten generations. For the branching EA, a population size of two hundred individuals was evolved with a generational EA. Parents were selected with remainder stochastic sampling based on rank, using exponential scaling [5]. New individuals were created with an equal probability of using mutation or recombination. The Numerical Electromagnetics Code, Version 4 (NEC4) [1] was used to evaluate all antenna designs.

The best antennas evolved by the two EAs were then evaluated on a second antenna simulation package, WIPL-D, with the addition of a 6" ground plane to determine which designs to fabricate and test on the ST5 mock-up. The best antenna design from each EA was selected for fabrication and these are shown in Figure 2. For these runs a single antenna evaluation took a few seconds of wall-clock time to simulate and an entire run took approximately six to ten hours.

3.1 Simulated Results

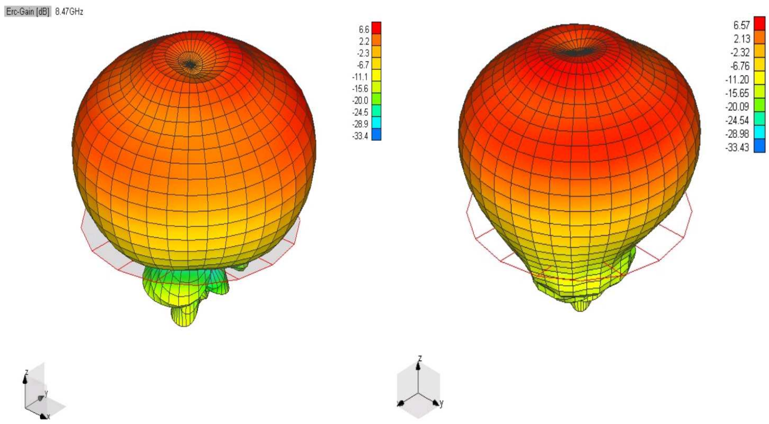
Both antenna designs have excellent simulated RHCP patterns, as shown in Figure 3 for the transmit frequency. The antennas also have good circular polarization purity across a wide range of angles, as shown in Figure 4 for ST5-104.33.



(a) (b)

Fig. 2. Evolved antenna designs: (a) evolved using a vector of parameters, named ST5-104.33; and (b) evolved using a constructive process, named ST5-33.142.7.

To the best of our knowledge, this quality has never been seen before in this form of antenna.



(a) (b)

Fig. 3. Simulated 3D patterns for ST5-104.33 and ST5-33.142.7 on 6” ground plane at 8470 MHz for RHCP polarization. Simulation performed by WIPL-D. Patterns are similar for 7209 MHz.

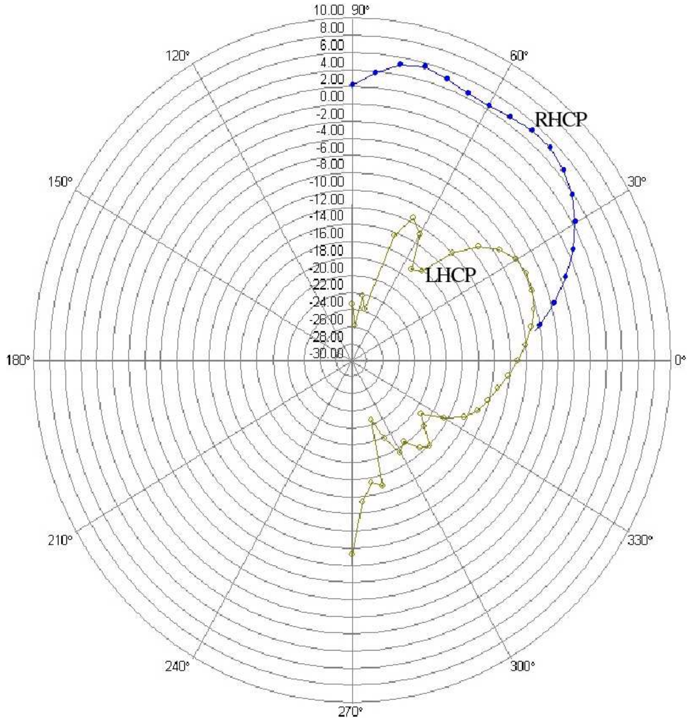


Fig. 4. RHCP vs LHCP performance of ST5-104.33. Plot has 2 dB/division.

3.2 Measured Results

The antennas were measured on the ST5 mock-up (Figure 1), and the results are shown in Figure 5. Because each spacecraft has two antennas, one on each side of the spacecraft, of interest is the performance of pairs of antennas on the spacecraft. The evolved antennas were arrayed with a Quadrafilar Helix Antenna (QHA) developed by New Mexico State University's Physical Science Laboratory that was the original antenna for this mission. This figure shows plots of two QHA antennas together, and a QHA and an ST5-104.33 antenna. Results are similar for ST5-33.142.7, which is the design that has been selected for use on the ST5 mission. Compared to using two QHAs together, the evolved antennas have much greater gain across the angles of interest.

4 Conclusion

Previously we reported our work on evolving two X-band antennas for potential use on NASA's upcoming ST5 mission to study the magnetosphere. While those antennas were mission compliant, a change in launch vehicle resulted in a change in orbit for the ST5 spacecraft and a change in requirements for their communication antennas. In response to this change in requirements we reconfigured our

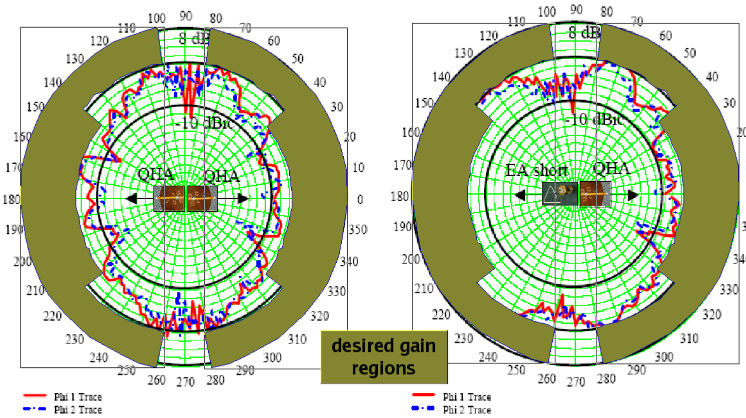


Fig. 5. Measured patterns on ST-5 mock-up of QHA antenna and ST5-104.33 plus QHA antenna. Phi 1 = 0 deg., Phi 2 = 90 deg.

evolutionary design systems and in under four weeks we were able to evolve new antenna designs that were acceptable to ST5 mission planners.

The first set of new ST5 evolved antenna flight units were delivered to Goddard Space Flight Center (GSFC) on February 25, 2005 (Figure 6). These flight units have passed all environmental testing and the current baseline plan is to fly at least three evolved antennas when the mission launches in 2006. Our ability to rapidly re-evolve new antenna designs shows that the evolutionary design process lends itself to rapid response to changing requirements, not only for automated antenna design but for automated design in general.

Fig. 6. Three images of a flight antenna; the evolved wire configuration for the radiator sits on top of a 6” diameter ground plane and is encased inside a radome

5 Acknowledgments

The work described in this paper was supported by Mission and Science Measurement Technology, NASA Headquarters, under its Computing, Information, and

Communications Technology Program. The work was performed at the Computational Sciences Division, NASA Ames Research Center, Linden Innovation Research and JEM Engineering, and NASA Goddard Space Flight Center. The support of Ken Perko of Microwave Systems Branch at NASA Goddard and Bruce Blevins of the Physical Science Laboratory at New Mexico State University is gratefully acknowledged.

Appendix: Genotype of ST5-33.142.7

Listed below is the evolved genotype of antenna ST5-33.142.7. The format for this tree-structured genotype consists of the operator followed by a number stating how many children this operator has, followed by square brackets which start '[' and end ']' the list of the node's children. For example the format for a node which is operator 1 and has two subtrees is written: `operator1 2 [ subtree-1 subtree-2 ]`. Since antennas were constrained to be non-branching each non-leaf node in has at most one child. The different operators in the antenna-constructing language are given in section 2.2.

```
rotate-z(0.723536) 1 [ rotate-x(2.628787) 1 [ rotate-z(1.145415) 1
[ rotate-x(1.930810) 1 [ rotate-z(2.069497) 1 [ rotate-x(1.822537)
1 [ forward(0.007343,0.000406) 1 [ rotate-z(1.901507) 1 [
forward(0.013581,0.000406) 1 [ rotate-x(1.909851) 1 [
rotate-y(2.345316) 1 [ rotate-y(0.308043) 1 [ rotate-y(2.890265) 1
[ rotate-x(0.409742) 1 [ rotate-y(2.397507) 1 [
forward(0.011671,0.000406) 1 [ rotate-x(2.187298) 1 [
rotate-y(2.497974) 1 [ rotate-y(0.235619) 1 [ rotate-x(0.611508) 1
[ rotate-y(2.713447) 1 [ rotate-y(2.631141) 1 [
forward(0.011597,0.000406) 1 [ rotate-y(1.573367) 1 [
forward(0.007000,0.000406) 1 [ rotate-x(-0.974118) 1 [
rotate-y(2.890265) 1 [ rotate-z(1.482916) 1 [
forward(0.019955,0.000406) ] ] ] ] ] ] ] ] ] ] ] ] ] ] ] ] ] ] ] ]
] ] ] ] ] ] ] ]
```

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