Chapter 1

AN EVOLVED ANTENNA FOR DEPLOYMENT ON NASA'S SPACE TECHNOLOGY 5 MISSION

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Abstract We present an evolved X-band antenna design and flight prototype currently on schedule to be deployed on NASA's Space Technology 5 (ST5) spacecraft. Current methods of designing and optimizing antennas by hand are time and labor intensive, limit complexity, and require significant expertise and experience. Evolutionary design techniques can overcome these limitations by searching the design space and automatically finding effective solutions that would ordinarily not be found. The ST5 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. Two evolutionary algorithms were used: one used a genetic algorithm style representation that did not allow branching in the antenna arms; the second used a genetic programming style tree-structured representation that allowed branching in the antenna arms. The highest performance antennas from both algorithms were fabricated and tested, and both yielded very similar performance. Both antennas were comparable in performance to a hand-designed antenna produced by the antenna contractor for the mission, and so we consider them examples of human-competitive performance by evolutionary algorithms. As of this writing, one of our evolved antenna prototypes is undergoing flight qualification testing. If successful, the resulting antenna would represent the first evolved hardware in space, and the first deployed evolved antenna.

Keywords: Design, computational design, antenna, wire antenna, spacecraft, genetic programming, evolutionary computation.

Introduction

Researchers have been investigating evolutionary antenna design and optimization since the early 1990s (e.g., [Michielssen et al., 1993, Haupt, 1995, Altshuler and Linden, 1997a, Rahmat-Samii and Michielssen, 1999]), 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 [Linden and Altshuler, 1996], antenna arrays [Haupt, 1996], and quadrifilar helical antennas [Lohn et al., 2002]. In addition, the ability to evolve antennas *in-situ* [Linden, 2000], that is, taking into account the effects of surrounding structures, opens new design possibilities. Such an approach is very difficult for antenna designers due to the complexity of electromagnetic interactions, yet easy to integrate into evolutionary techniques.

Below we describe two evolutionary algorithm (EA) approaches to a challenging antenna design problem on NASA's Space Technology 5 (ST5) mission [ST5]. ST5's objective is to demonstrate and flight qualify innovative technologies and concepts for application to future space missions. Images showing the ST5 spacecraft are seen in Figure 1.1. The mission duration is planned for three months.

1. ST5 Mission Antenna Requirements

The three ST5 spacecraft will orbit at close separations in a highly elliptical geosynchronous transfer orbit approximately 35,000 km above Earth and will communicate with a 34 meter ground-based dish antenna. 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 typically used in modeling and design.

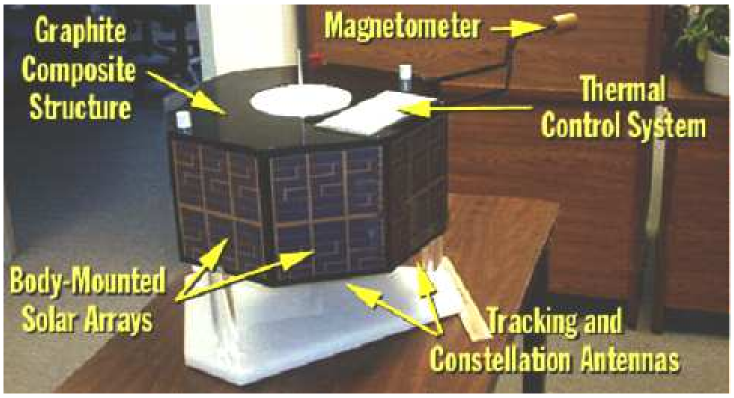


Figure 1.1. ST5 satellite mock-up. The satellite will have two antennas, centered on the top and bottom of each spacecraft.

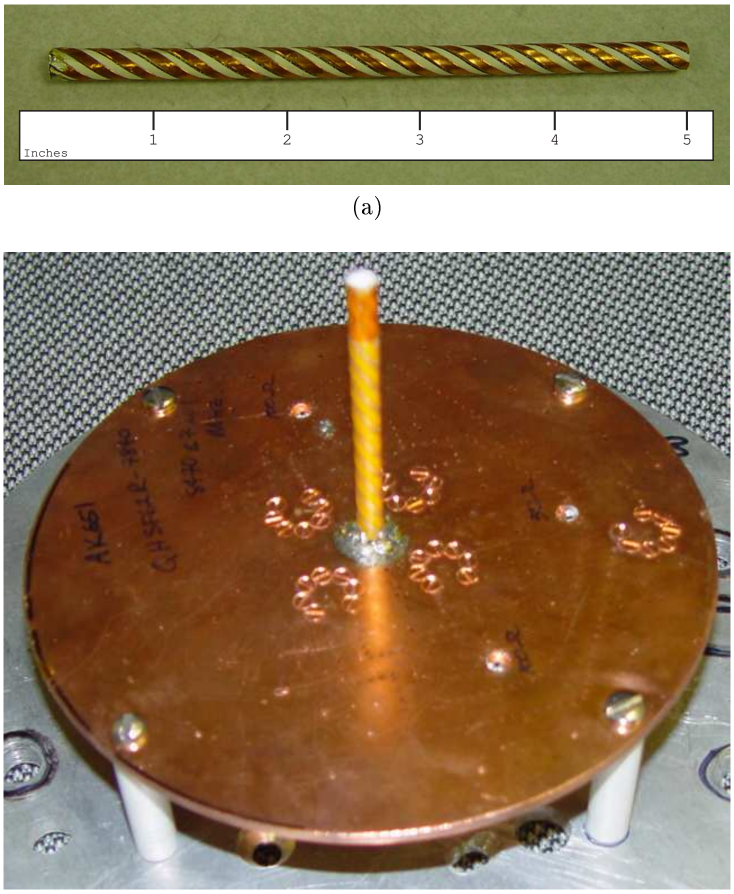
The antenna requirements are as follows. The gain pattern must be greater than or equal to 0 dBic (decibels as referenced to an isotropic radiator that is circularly polarized) at $40° \leq \theta \leq 80°$ and $0° \leq \phi \leq 360°$ for right-hand circular polarization. The antenna must have a voltage standing wave ratio (VSWR) of under 1.2 at the transmit frequency (8470 MHz) and under 1.5 at the receive frequency (7209.125 MHz) – VSWR is a way to quantify reflected-wave interference, and thus the amount of impedance mismatch at the junction. At both frequencies the input impedance should be 50 Ω. The antenna is restricted in shape to a mass of under 165 g, and must fit in a cylinder of height and diameter of 15.24 cm.

In addition to these requirements, 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: 2 dBic for $\theta = 80°$, and 4 dBic for $\theta = 90°$.

ST5 mission managers were willing to accept antenna performance that aligned closer to the "desired" field pattern specifications noted above, and the contractor, using conventional design practices, produced a quadrifilar helical (QFH) (see Figure 1.2) antenna to meet these specifications.

2. Evolved Antenna Design

From past experience in designing wire antennas [Linden, 1997], we decided to constrain our evolutionary design to a monopole wire antenna with four identical arms, each arm rotated 90° from its neighbors. The



(a)

(b)

Figure 1.2. Conventionally-designed quadrifilar helical (QHF) antenna: (a) Radiator; (b) Radiator mounted on ground plane.

EA thus evolves genotypes that specify the design for one arm, and builds the complete antenna using four copies of the evolved arm.

In the remainder of this section we describe the two evolutionary algorithms used. The first algorithm was used in our previous work in evolutionary antenna design [Linden and Altshuler, 1996] and it is a standard genetic algorithm (GA) that evolves non-branching wire forms. The second algorithm is based on our previous work evolving rod-structured, robot morphologies [Hornby and Pollack, 2002]. This EA has a genetic programming (GP) style tree-structured representation that allows branching in the wire forms. In addition, the two EAs use different fitness functions.

Non-branching EA

In this EA, the design was constrained to non-branching arms and the encoding used real numbers. The feed wire for the antenna is not optimized, but is specified by the user. The size constraints used, an example of an evolved arm, and the resulting antenna are shown in Figure 1.3.

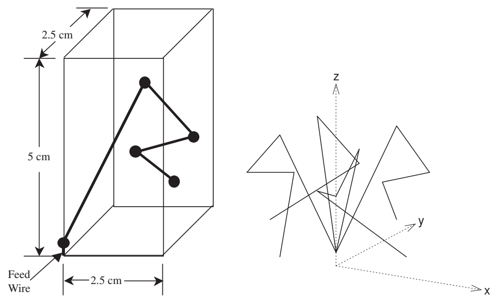


Figure 1.3. (a) size constraints and evolved arm; (b) resulting 4-wire antenna after rotations.

Representation

The design is specified by a set of real-valued scalars, one for each coordinate of each point. Thus, for a four-segment design (shown in Figure 1.3), 12 parameters are required.

Adewuya's method of mating [Adewuya, 1996] and Gaussian mutation are used to evolve effective designs from initial random populations. This EA has been shown to work extremely well on many different antenna problems [Altshuler and Linden, 1997b, Altshuler, 0002, Linden and MacMillan, 2000].

Fitness Function

This EA used pattern quality scores at 7.2 GHz and 8.47 GHz in the fitness function. Unlike the second EA, VSWR was not used in this fitness calculation. To quantify the pattern quality at a single frequency, PQ_f, the following was used:

$$\mathrm{PQ}_f = \sum_{\substack{0^\circ < \phi < 360^\circ \\ 40^\circ < \theta < 80^\circ}} (\mathrm{gain}_{\phi,\theta} - T)^2 \quad \text{if } \mathrm{gain}_{\phi,\theta} < T$$

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:

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

Branching EA

The EA in this section allows for branching in the antenna arms. Rather than using linear sequences of bits or real-values as is traditionally done, here we use a tree-structured representation which naturally represents branching in the antenna arms.

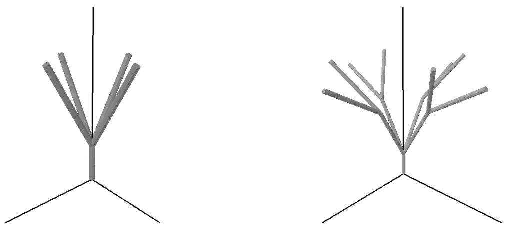
Representation

The representation for encoding branching antennas is an extension of our previous work in using a linear-representation for encoding rod-based robots [Hornby and Pollack, 2002]. Each node in the tree-structured representation is an antenna-construction command and an antenna is created by executing the commands at each node in the tree, starting with the root node. In constructing an antenna the current state (location and orientation) is maintained and commands add wires or change the current state. The commands 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.

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. That is, the design starts with the single feedwire from (0.0, 0.0, 0.0) to (0.0, 0.0, 0.4) and the current construction state (location and orientation) for the next wire will be started from location (0.0, 0.0, 0.4) with the orientation along the positive Z-axis.

To produce antennas that are four-way symmetric about the z-axis, the construction process is restricted to producing antenna wires that are fully contained in the positive XY quadrant and then after construction is complete, this arm is copied three times and these copies are placed in each of the other quadrants through rotations of 90°/180°/270°. For example, in executing the program `rotate-z(0.523598776) forward(1.0,0.032)`, the `rotate-z()` command causes the the current orientation to rotate 0.523598776 radians (30°) about the Z axis. The `forward()` command adds a wire of length 1.0 cm and radius 0.032 cm in the current forward direction. This wire is then copied into each of the other three XY quadrants. The resulting antenna is shown in Figure 1.4(a).



(a) (b)

Figure 1.4. Example antennas: (a) non-branching arms; (b) branching arms.

Branches in the representation cause a branch in the flow of execution and create different branches in the constructed antenna. The following is an encoding of an antenna with branching in the arms, here brackets are used to separate the subtrees:

```
rotate-z(0.5235) [ forward(1.0,0.032) [ rotate-z(0.5235)
[ forward(1.0,0.032) ] rotate-x(0.5235) [ forward(1.0,0.032)
] ] ]
```

This antenna is shown in Figure 1.4(b).

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. The overall fitness of an antenna is the worst score of these evaluations. In this way, the fitness score assigned to an antenna design is a conservative estimate of how well it will perform if it were to be constructed. An additional side-effect of this is that antennas evolved with this manufacturing noise tend to perform well across a broader range of frequencies than do antennas evolved without this noise.

Fitness Function

The fitness function used to evaluate antennas is a function of the 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:

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

The gain component of the fitness function uses the gain (in decibels) in 5° increments about the angles of interest: from $40^\circ \leq \theta \leq 90^\circ$ and $0^\circ \leq \phi \leq 360^\circ$:

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

While the actual minimum required gain value is 0 dBic for $40^\circ \leq \theta \leq 80^\circ$, and desired gain values are 2 dBic for $\theta \geq 80^\circ$ and 4dBic for $\theta = 90^\circ$ only a single target gain of 0.5 dBic is used here. This provides some headroom to account for errors in simulation over the minimum of 0 dBic and does not attempt to meet desired gain values. Since achieving gain values greater than 0 dBic is the main part of the required specifications, the third component of the fitness function rewards antenna designs for having sample points with gains greater than zero:

$$outlier(i,j) = \begin{cases} 0.1 & \text{if } gain_{ij} < 0.01 \\ 0 & \text{otherwise} \end{cases}$$

$$outlier = 1 + \sum_{i=8}^{i<19} \sum_{j=0}^{j=72} outlier(i,j)$$

These three components are multiplied together to produce the overall fitness score of an antenna design:

$$F = vswr \times gain \times outlier$$

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

3. EA Run Setup

As mentioned earlier, the ST5 spacecraft is 13-15 wavelengths wide, which makes simulation of the antenna on the full craft very compute intensive. 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 of 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) [Burke and Poggio, 1981] was used to evaluate all antenna designs.

For the non-branching EA, a population of 50 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 100 generations had been completed, the EA's best score was stagnant for 40 generations, or EA's average score was stagnant for 10 generations. For the branching EA, a population of 200 individuals were created through either mutation or recombination, with an equal probability. For both algorithms, each antenna simulation took a few seconds of wall-clock time to run and an entire run took approximately 6-10 hours.

4. Evolved Antenna Results

The two best evolved antennas, one from each of the EAs described above, were fabricated and tested. The antenna named ST5-3-10 was produced by the EA that allowed branching, and the antenna named ST5-4W-03 was produced by the other EA. Photographs of the prototyped antennas are shown in Figure 1.5. Due to space limitations, only performance data from antenna ST5-3-10 is presented below.

Since the goal of our work was to produce requirements-compliant antennas for ST5, no attempt was made to compare the algorithms, either to each other, nor to other search techniques. Thus statistical sampling across multiple runs was not performed.

Evolved antenna ST5-3-10 is 100% compliant with the mission antenna performance requirements. This was confirmed by testing the prototype antenna in an anechoic test chamber at NASA Goddard Space Flight Center. The data measured in the test chamber is shown in the plots below.

The genotype of antenna ST5-3-10 is shown in Figure 1.6. The complexity of this large antenna-constructing program, as compared to the antenna arm design having one branch, suggests that it is not a minimal description of the design. For example, instead of using the minimal number of rotations to specify relative angles between wires (two) there are sequences of up to a dozen rotation commands.

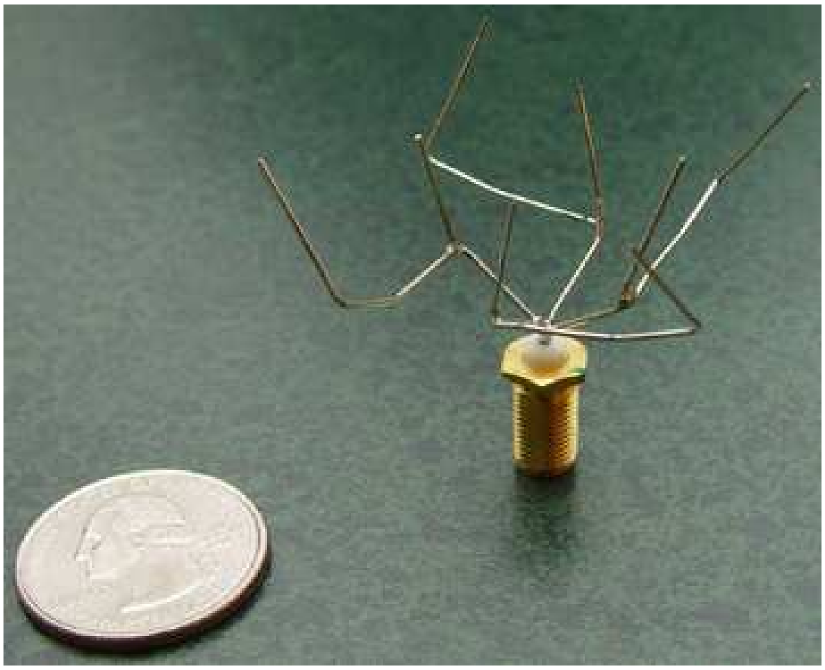
The 7.2 GHz max/min gain patterns for both evolved antenna ST5-3-10 and the QFH are shown in Figure 1.7. The 8.47 GHz max/min gain patterns for both antennas are shown in Figure 1.8. On the plots for antenna ST5-3-10, a box denoting the acceptable performance according to the requirements is shown. Note that the minimum gain falls off steeply below $20°$. This is acceptable as those elevations were not required due to the orientation of the spacecraft with respect to Earth. As noted above, the QFH antenna was optimized at the 8.47 GHz frequency to achieve high gain in the vicinity of $75° - 90°$.

5. Results Analysis

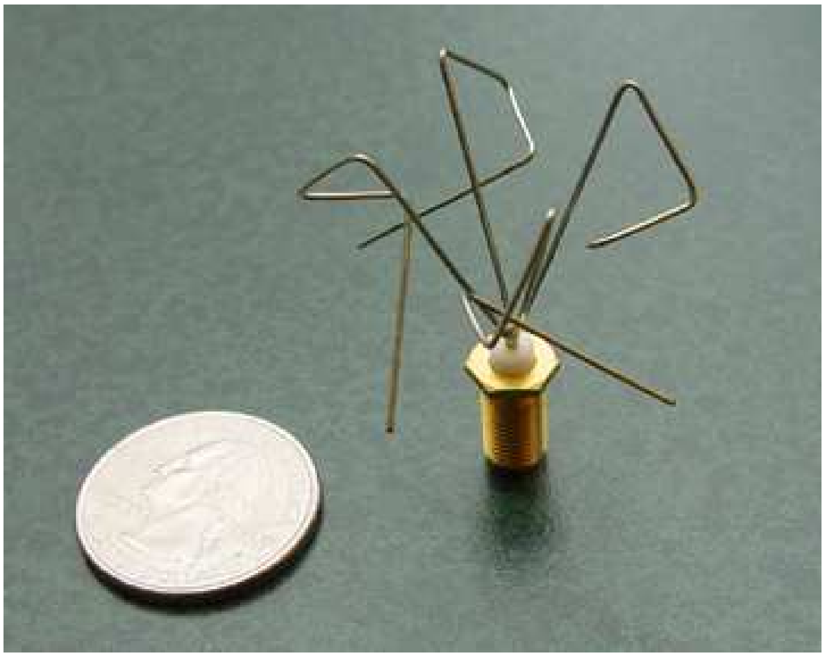
Antenna ST5-3-10 is a requirements-compliant antenna that was built and tested on an antenna test range. While it is slightly difficult to manufacture without the aid of automated wire-forming and soldering machines, it has a number of benefits as compared to the conventionally-designed antenna.

First, there are potential power savings. Antenna ST5-3-10 achieves high gain (2-4dB) across a wider range of elevation angles. This allows a broader range of angles over which maximum data throughput can be achieved and would result in less power being required from the solar array and batteries.

Second, unlike the QFH antenna, the evolved antenna does not require a matching network nor phasing circuit, removing two steps in design and fabrication of the antenna. A trivial transmission line may be used



(a)



(b)

Figure 1.5. Photographs of prototype evolved antennas: (a) ST5-3-10; (b) ST5-4W-03

for the match on the flight antenna, but simulation results suggest that one is not required if small changes to the feedpoint are made.

Third, the evolved antenna has more uniform coverage in that it has a uniform pattern with small ripples in the elevations of greatest interest ($40° - 80°$). This allows for reliable performance as elevation angle relative to the ground changes.

Fourth, 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.

From an algorithmic perspective, both evolutionary algorithms produced antennas that were satisfactory to the mission planners. The branching antenna, evolved using a GP-style representation, slightly outperformed the non-branching antenna in terms of field pattern and VSWR. A likely reason as to why the GP-style representation performed better is that it is more flexible and allows for the evolution of new topologies.

6. Conclusion

We have evolved and built two X-band antennas for potential use on NASA's upcoming ST5 mission to study the magnetosphere. ST5 antenna requirements, our evolutionary algorithms, and the resulting antennas and performance plots were presented.

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.

If flight qualification testing is successful, antenna ST5-3-10 would represent the first evolved hardware in space, and the first evolved antenna to be deployed. As the mission's primary goal is to test and validate new technologies for future NASA missions, flying an evolved antenna would fulfill this goal.

7. 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 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.

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rotate-z(1.984442) 1 [rotate-x(2.251165) 1 [rotate-x(0.062240) 1
[rotate-x(0.083665) 1 [rotate-y(-2.449035) 1 [ rotate-z(-0.894357)
1 [rotate-y(-2.057702) 1 [rotate-y(0.661755) 1 [rotate-x(0.740703)
1 [rotate-y(2.057436) 1 [ forward(0.013292,0.000283) 2
[rotate-z(-1.796822) 1 [ rotate-x(-1.651348) 1 [rotate-y(-2.940880) 1
[rotate-x(0.095209) 1 [rotate-z(1.248723) 1 [forward(0.003815,0.000363)
1 [ forward(0.008289,0.000355) 1 [forward(0.008413,0.000369) 1 [
rotate-x(-0.006494) 1 [rotate-x(-0.592854) 1 [rotate-z(-2.085023) 1
[rotate-z(1.735374) 1 [rotate-z(-2.045125) 1 [ rotate-z(0.203076) 1
[rotate-z(1.750799) 1 [rotate-z(-2.038688) 1 [rotate-z(1.725007) 1
[rotate-y(1.478109) 1 [rotate-x(2.477117) 1 [rotate-x(-2.441858) 1
[forward(0.015082,0.000223) ] ] ] ] ] ] ] ] ] ] ] ] ] ] ] ] ] ] ] ] ]
rotate-y(2.335438) 1 [ rotate-y(-1.042201) 1 [rotate-y(-1.761594) 1
[rotate-x(2.518405) 1 [rotate-z(-0.739608) 1 [rotate-x(0.426553) 1 [
rotate-z(-0.291483) 1 [rotate-x(2.152738) 1 [ forward(0.013190,0.000414)
] ] ] ] ] ] ] ] ] ] ] ] ] ] ] ] ] ] ]
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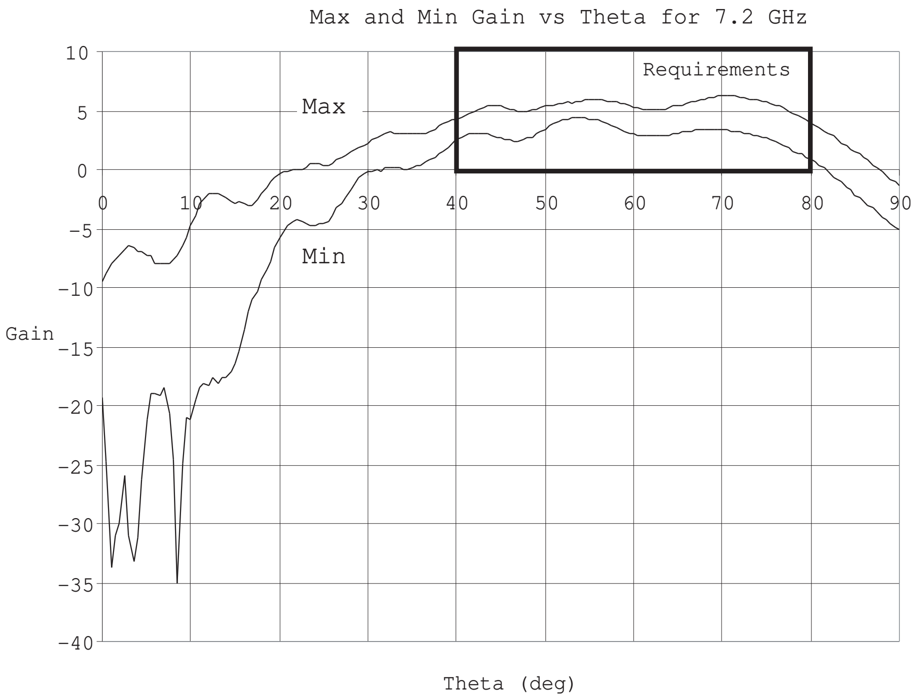
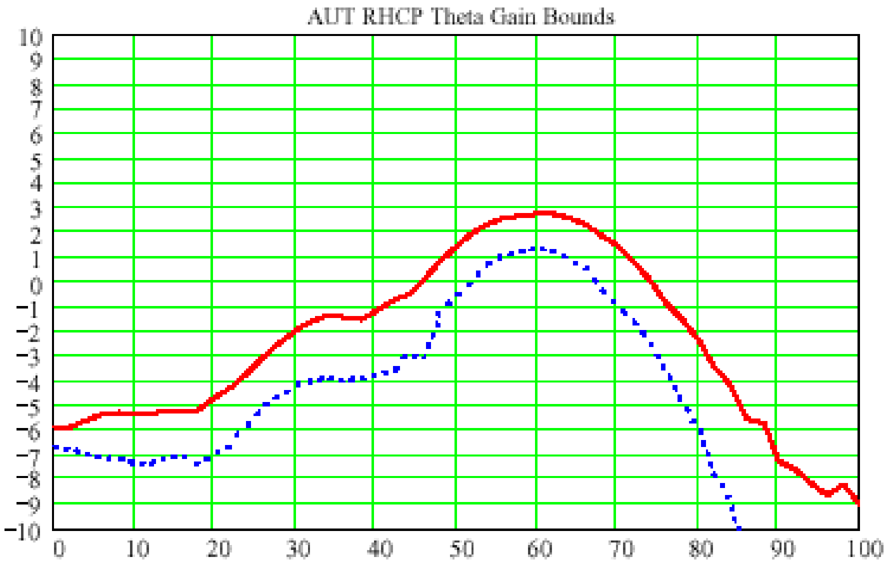
Figure 1.6. Genotype for evolved antenna ST5-3-10.

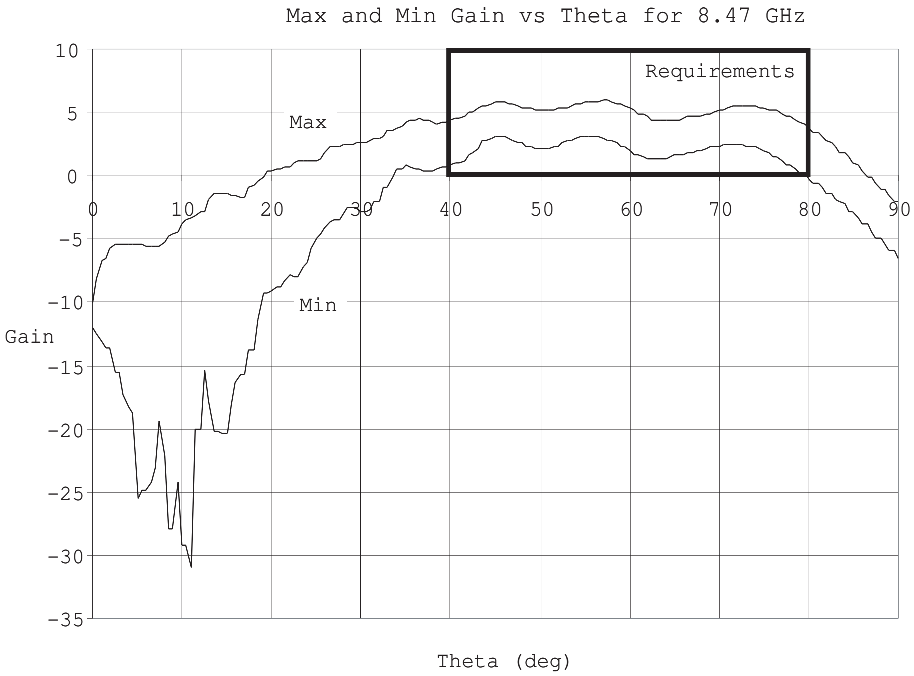


(a)

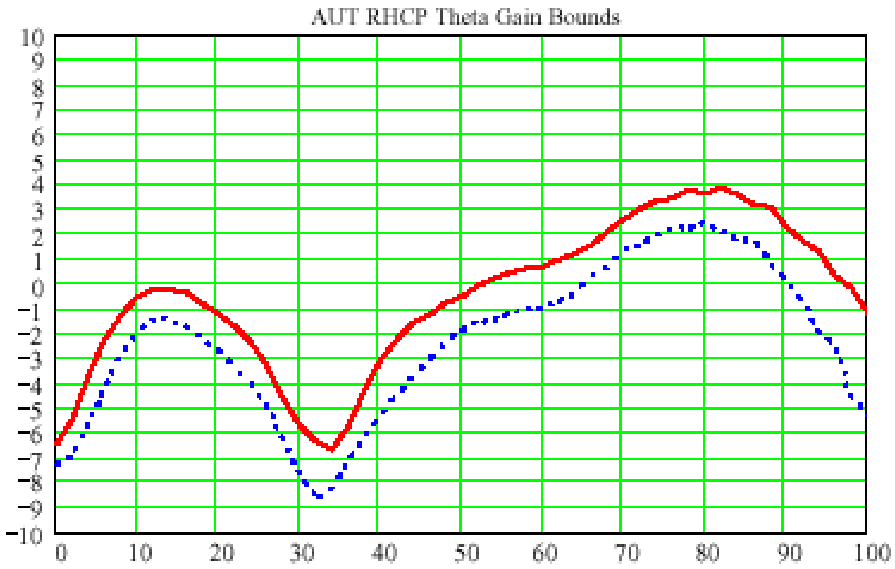


(b)

Figure 1.7. Maximum and minimum gain at 7.2 GHz for antennas (a) ST5-3-10; (b) QFH.



(a)



(b)

Figure 1.8. Maximum and minimum gain at 8.47 GHz for antennas (a) ST5-3-10; (b) QFH.