Computer-Automated Evolution of an X-Band Antenna for NASA's Space Technology 5 Mission

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Abstract

Whereas the current practice of designing antennas by hand is severely limited because it is both time and labor intensive and requires a significant amount of domain knowledge, evolutionary algorithms can be used to search the design space and automatically find novel antenna designs that are more effective than would otherwise be developed. Here we present our work in using evolutionary algorithms to automatically design an X-band antenna for NASA's Space Technology 5 (ST5) spacecraft. Two evolutionary algorithms were used: the first uses a vector of real-valued parameters and the second uses a tree-structured generative representation for constructing the antenna. The highest-performance antennas from both algorithms were fabricated and tested and both outperformed a hand-designed antenna produced by the antenna contractor for the mission. Subsequent changes to the spacecraft orbit resulted in a change in requirements for the spacecraft antenna. By adjusting our fitness function we were able to rapidly evolve a new set of antennas for this mission in less than a month. One of these new antenna designs was built, tested and approved for deployment on the three ST5 spacecraft, which were successfully launched into space on March 22, 2006. This evolved antenna design is the first computer-evolved antenna to be deployed for any application and is the first computer-evolved hardware in space.

Keywords

antenna, automated design, computational design, evolutionary design, generative representation, spacecraft

1   Introduction

The current practice of designing and optimizing antennas by hand is limited in its ability to develop new and better antenna designs because it requires significant domain expertise and is both time and labor intensive. With this approach, an antenna engineer will select a particular class of antennas and then spend weeks or months testing and adjusting a design, mostly in simulation using electromagnetics modeling software. As an alternative, researchers have been investigating evolutionary antenna design and optimization since the early 1990s (e.g., (Altshuler and Linden, 1997b; Haupt, 1995; Michielssen et al., 1993; 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, evolutionary algorithms have been used to evolve antennas *in-situ* (Linden, 2000), that is, taking into account the effects of surrounding structures, which is very difficult for antenna designers to do by hand due to the complexities of electromagnetic interactions. Here we describe two evolutionary algorithm (EA) approaches to a challenging antenna design problem on NASA's Space Technology 5 (ST5) mission.[1]

ST5 is one of NASA's New Millennium Program missions to launch multiple miniature spacecraft to test, demonstrate and flight-qualify innovative concepts and technologies in the harsh environment of space for application on future space missions. The ST5 mission consists of three miniaturized satellites, called micro-sats, flying in the test track of Earth's magnetosphere. The micro-sats are approximately 53 cm across and 48 cm high and, when fully fueled, weigh approximately 25 kilograms. Each satellite has two antennas, centered on the top and bottom of each spacecraft. The advantages of flying clusters of multiple spacecraft is that it reduces the risk of an entire mission failing if one system or one instrument fails. Images of the ST5 spacecraft are shown in Figure 1. During flight validation of its technologies, the ST5 spacecraft measured the effects of solar activity on the Earth's magnetosphere over a period of three months.

To produce an antenna for the ST5 mission we used two EAs, each using different representations and different fitness functions, to evolve antenna designs. For the initial mission requirements we selected a suitable class of antennas to evolve, configured our evolutionary design systems for this class, and then evolved a set of antenna designs that met the requirements. However, while these antennas were undergoing flight-qualification testing, the mission's orbital vehicle was changed, putting it into a much lower earth orbit and changing the specifications for the mission. With minimal changes to our evolutionary system, mostly in the fitness function, we were able to evolve new antennas for the revised mission requirements and, within one month of this change, two new antennas were designed and prototyped. One of these newly evolved antennas was approved for deployment on the ST5 mission and a fabricated antenna was used on each of the three ST5 spacecraft that were successfully launched into space on March 22, 2006. The three antennas built from the evolved design are the first computer-evolved antennas to be deployed for any application and the first computer-evolved hardware in space.

The rest of this paper is organized into two parts as follows. In the first part of this paper the initial ST5 mission requirements are given (in Section 2), followed by descriptions of the two EAs that were used to evolve antennas for these requirements (in Section 3) and then a section on the two best evolved antennas produced by these EAs (in Section 4). In the second part of this paper the revised mission requirements are given along with a description of the revisions that were made to the two EAs (in Section 5), the results of evolving antennas for the revised mission requirements (in Section 6) and a discussion on the successful launch and operation of NASA's ST5 mission (in Section 7). Finally, the last section is a summary of this work.
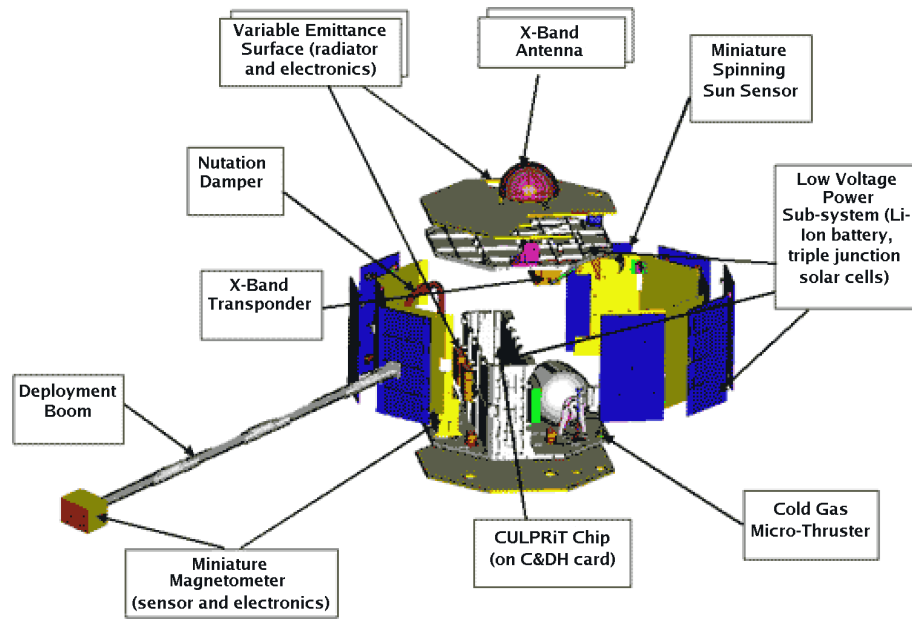
(a)
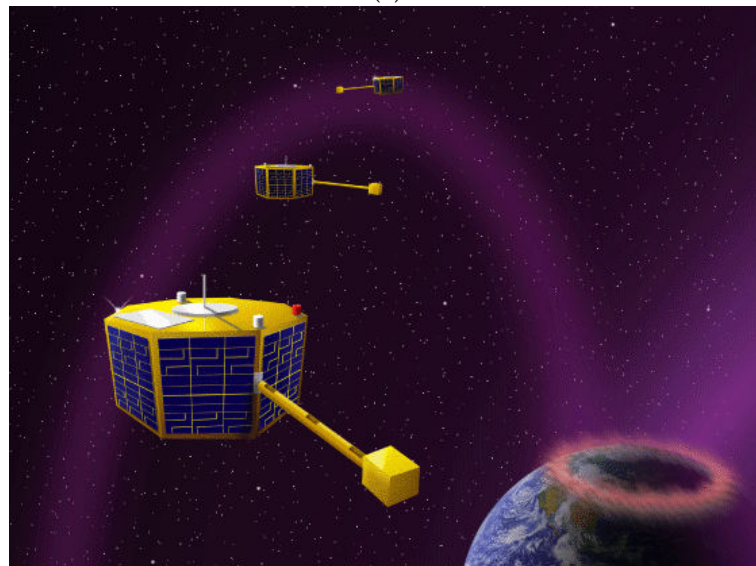
(b)

Figure 1: Artist's depiction of: (a) the spacecraft model showing the different spacecraft components, and (b) the ST5 mission with the three spacecraft in their string of pearls orbit.

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
Gain Pattern	≥ 0 dBic, $40° \leq \theta \leq 80°$,
	$0° \leq \phi \leq 360°$
Input Impedance	$50\,\Omega$
Diameter	< 15.24 cm
Height	< 15.24 cm
Antenna Mass	< 165 g

2   Initial ST5 Mission Antenna Requirements

The ST5 mission consists of three spacecraft which are orbiting in a "string of pearls" constellation in a highly elliptical, geosynchronous transfer orbit that was originally set at approximately 35,000 km above Earth. A 34 meter, ground-based, dish antenna is used to communicate with these spacecraft, and the initial requirements for the spacecraft's communication antenna 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 $0° \leq \phi \leq 360°$ (ϕ is the azimuth and θ is the elevation) for right-hand circular polarization (RHCP). 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, and is the ratio between the highest voltage and the lowest voltage in the signal envelope along a transmission line. At both the transmit and receive frequencies the input impedance should be $50\,\Omega$. 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. These requirements are summarized in Table 1.

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 53 cm, the spacecraft is 13-15 wavelengths across which makes antenna simulation computationally intensive. Consequently, an infinite ground plane approximation, or smaller finite ground plane, is typically used in modeling and design.

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 $0° \leq \phi \leq 360°$, the desired gain was: 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 antenna (QHA) (see Figure 2) to meet these specifications.

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[1]The official ST5 website is at: http://nmp.jpl.nasa.gov/st5/.
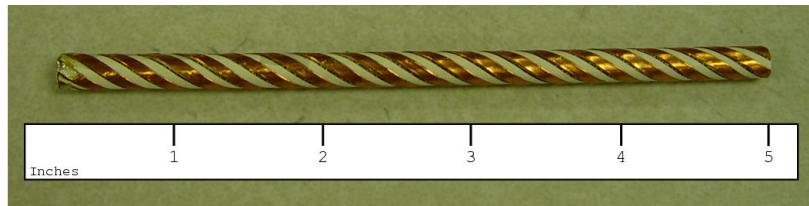
(a)
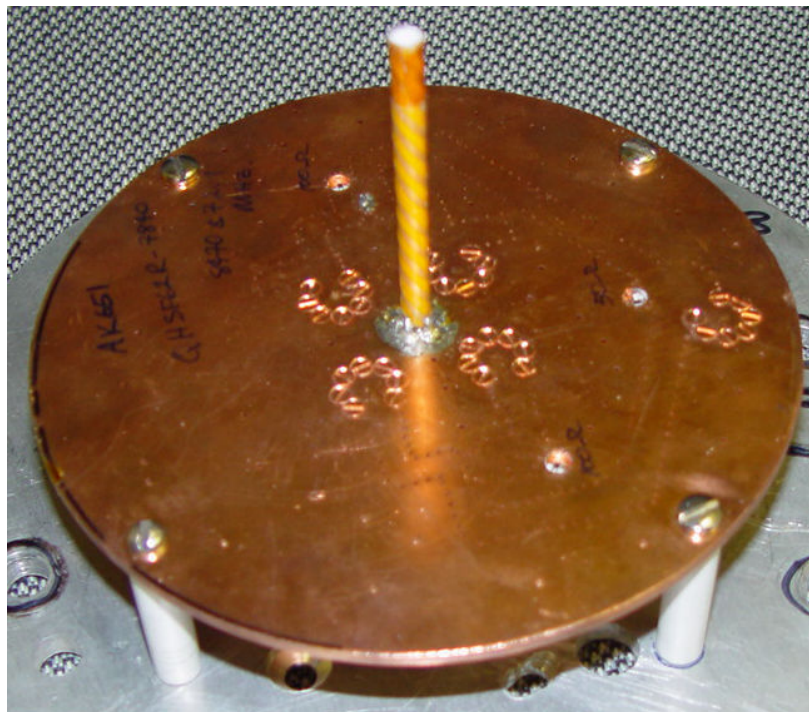
(b)

Figure 2: Conventionally-designed quadrifilar helical antenna: (a) radiator; and (b) radiator mounted on a ground plane.

3 Initial Evolutionary Antenna Design Systems

From past experience in designing wire antennas (Linden, 1997), it was decided to constrain our evolutionary design to a monopole wire antenna with four identical arms, with each arm rotated 90° from its neighbors. To produce this type of antennas, the EA evolves genotypes that specify the design for one arm and evaluates these individuals by building a complete antenna using four copies of the evolved arm.

Two different evolutionary algorithms were used (Lohn et al., 2004a,b), with the first EA being the one we have used in our previous work in evolutionary antenna design (Linden and Altshuler, 1996; Linden, 2000) and it is a standard GA that evolves non-branching wire forms using a parameterized representation of an antenna. The second algorithm is based on our previous work evolving rod-structured, robot morphologies (Hornby et al., 2003) and with it we varied both the representation and the fitness function to see if we could improve upon our original EA. This EA uses an open-ended, generative representation to construct an antenna from a genetic programming (GP) style, tree-structured encoding that allows branching in the wire forms. Our group had not had the ability to evolve antennas with branching in our previous work so we were interested to see if an EA with this capability would find better results.

Antenna designs were evaluated with the Numerical Electromagnetics Code, Version 4 (NEC-4) (Burke and Poggio, 1981), an antenna simulation system written in FORTRAN. NEC-4 computes the impedance of the antenna for the frequencies of interest and, for a user-specified range of points, the total gain and axial ratio. Using standard electromagnetics equations these output values are converted to scores for VSWR and circularly polarized gain (Kraus and Marhefka, 2002; Ramo et al., 1994). Since we had the source code for NEC-4 we were able to link our EAs directly to it and each antenna simulation took a few seconds of wall-clock time to run. On our Beowulf cluster, of approximately 100 processors an entire evolutionary run took approximately 6-10 hours.
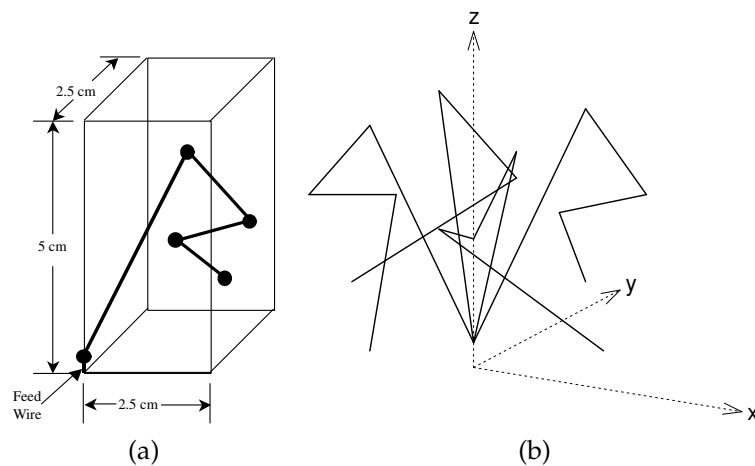
3.1 Parameterized EA

Figure 3: (a) Size constraints and evolved arm; (b) resulting 4-wire antenna after rotations.

With the parameterized EA the design space was constrained to non-branching arms using a real-valued representation. This real-valued, parameterized representation consists of a fixed-length vector of triplets that specify the X, Y and Z locations of segment end-points. Based on some trial runs, we settled on 6 segments (which works out to 18 parameters) and constrained the points to be in a 2cm×2cm×2cm box. Since a linear vector of X, Y, and Z coordinates is used, this limits antenna designs to non-branching antennas. The initial population of random antennas was created by generating random points with a uniform distribution within the allowable coordinate space.

Quadratic crossover (Adewuya, 1996) with Gaussian mutation is used to evolve effective designs from initial random populations and this EA has been shown to work extremely well on many different antenna problems (Altshuler, 2002; Altshuler and Linden, 1997a; Linden and MacMillan, 2000). An example of an evolved arm, along with the size constraints, is shown in Figure 3(a) and the resulting antenna with four arms is shown in Figure 3(b). The feed wire for the antenna is not optimized, but is specified by the user.

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

$$PQ_f = \sum_{\substack{0° < \phi < 360° \\ 40° < \theta < 80°}} (\text{gain}_{\phi,\theta} - T)^2 \quad \text{if gain}_{\phi,\theta} < T \tag{1}$$

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. This style of fitness function is a standard least-squares engineering approach of trying to minimize the sum of the squared errors and is what we have used in past work.

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:

$$F = \text{PQ}_{7.2} + \text{PQ}_{8.47} \tag{2}$$

3.2 Open-ended EA with a Generative Representation

While we had had success in using the EA in Section 3.1 for a number of years, we were also interested in seeing if we could improve upon it by varying in a couple of ways. The EA in this section allows for branching in the antenna arms by using an open-ended, generative representation. Rather than using a linear sequence of bits or real-values, as is traditionally done, this EA has a tree-structured, generative representation that specifies how to construct an antenna and which naturally represents branching in the antenna arms. The generative representation for encoding branching antennas is an extension of our previous work in using a linear-representation for encoding rod-based robots (Hornby et al., 2001, 2003; Hornby and Pollack, 2002). To build antennas instead of robots, we used the same construction language of building an object out of line segments but used a tree-structured genotype instead of a linear one. In addition to changing the representation, we also tried using a fitness function that more explicitly captured the mission specifications.

Each node in the tree-structured, generative 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.

An antenna design is created by starting with an initial feedwire and adding wires. The initial feed wire was set to start at the origin with 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. After an antenna is constructed, it is tested to see if there are any intersecting wires and, if so, it is not evaluated but is given the worst possible fitness score so that it will not reproduce. For evolving an ST5 communications antenna, the radius of the wire segments was fixed at the start of a run, with all wire segments in all antenna designs having the same radius.

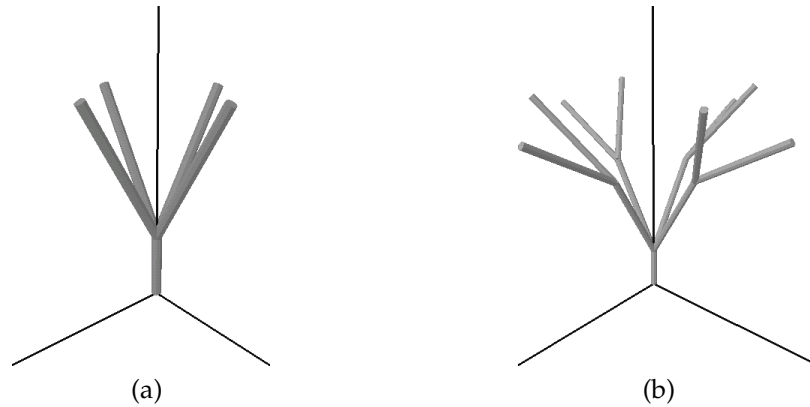(a)   (b)

Figure 4: Example antennas: (a) non-branching arms; (b) branching arms.

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(0.5236)` `forward(0.01,0.000406),` the `rotate-z()` operator causes the current orientation to rotate 0.5236 radians (30°) about the Z axis. The `forward()` operator adds a

wire of length 0.01 m and radius 0.000406 m (which corresponds to a 20 gauge wire) 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 4(a).

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(0.5236) [ forward(1.0,0.032) [ rotate-z(0.5236)
[ forward(1.0,0.032) ] rotate-x(0.5236) [
forward(1.0,0.032) ] ] ]
```

This antenna is shown in Figure 4(b).

One of the concerns in designing this generative representation for branched antennas was to prevent bloat, elements of the genotype that are not used in constructing the phenotype. If genotypic bloat is possible then, as the population nears a local optima, there is increased selective pressure to produce more and more bloat in individuals and then variation is less and less likely to change the genotype in a way that results in a change of phenotype. This increase of bloat to reduce the effects of variation happens because as the population approaches a local optima most changes in the phenotype tend to produce offspring that have worse fitness than their parent(s). To significantly reduce the amount of bloat in the genotypes, the genotypes were constrained so that only wire creation operators may be leaf nodes of the genotype. This property is enforced in the generation of random individuals and also with the variation operators. The advantage of this constraint is that it forces the phenotype to be a product of all nodes in the genotype since all leaf nodes contain operators which create a wire segment in the phenotype and all nodes above the leaf node contain operators which either affect the angle of the wire(s) created from nodes below them in the genotype or create wire segments. Bloat is still possible, such as through branches in which both child sub-trees immediately have a `forward()` operator so that the resulting wire segments overlap, or through rotations which rotate the last wire segment about its axis.

With this EA, the fitness function for evaluating antennas is a function of the VSWR and gain values on the transmit and receive frequencies. Unlike the fitness function of the previous EA, which only optimized for gain, here we decided to explicitly reward for efficiency (VSWR) as well as gain.

The VSWR component of the fitness function is constructed to put strong pressure toward 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 and then no pressure to go below 1.1:

$$v_r = \text{VSWR at receive frequency} \tag{3}$$

$$v_r' = \begin{cases} v_r + 2.0(v_r - 1.25) & \text{if } v_r > 1.25 \\ v_r & \text{if } 1.25 > v_r > 1.1 \\ 1.1 & \text{if } v_r < 1.1 \end{cases} \tag{4}$$

$$v_t = \text{VSWR at transmit frequency} \tag{5}$$

$$v_t' = \begin{cases} v_t + 2.0(v_t - 1.15) & \text{if } v_t > 1.15 \\ v_t & \text{if } 1.15 > v_t > 1.1 \\ 1.1 & \text{if } v_t < 1.1 \end{cases} \tag{6}$$

$$vswr = v_r' v_t' \tag{7}$$

In the above equations the constant values of 1.15 and 1.25 were used since they are

just below the target values.

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

$$gain_{ij} = \text{gain at } \theta = 5°i, \ \phi = 5°j \tag{8}$$

$$gain(i,j) = \begin{cases} 0 & \text{if } gain_{ij} > 0.5 \\ 0.5 - gain_{ij} & \text{if } gain_{ij} < 0.5 \end{cases} \tag{9}$$

$$gain = 1 + 0.1 \sum_{i=8}^{i<19} \sum_{j=0}^{j=72} gain(i,j) \tag{10}$$

While the actual minimum required gain value is 0 dBic for $40° \leq \theta \leq 80°$, and the desired gain values are at least 2 dBic for $80° \leq \theta < 90°$ and at least 4 dBic for $\theta = 90°$, only a single target gain of 0.5 dBic is used here. This target value provides some headroom to account for errors in simulation over the minimum of 0 dBic and does not attempt to meet the 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:

$$outlier(i,j) = \begin{cases} 0.1 & \text{if } gain_{ij} < 0.01 \\ 0 & \text{otherwise} \end{cases} \tag{11}$$

$$outlier = 1 + \sum_{i=8}^{i<19} \sum_{j=0}^{j=72} outlier(i,j) \tag{12}$$

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

$$F = vswr \times gain \times outlier \tag{13}$$

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

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 positions and wire radii. This error was in the range of $\pm0.05mm$ for each coordinate and $\pm0.03mm$ for the 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 manufacturing noise.

4 Evolved Antenna Results

To evolve antennas for the ST5 mission the two EAs described in the previous section used different configurations. With the parameterized EA, a population of fifty individuals was maintained, of which 50% were kept from generation to generation. The mutation rate was 1%, with a Gaussian mutation standard deviation of 10% of the value range. This EA was halted after one hundred generations had been completed, the EA's best score was stagnant for forty generations, or the EA's average score was stagnant for ten generations. This method for halting the EA was used because, based

on previous experience, there is a very low probability that anything significant will be produced and, even if something slightly more fit is evolved, this difference is not likely to be noticeable when it comes to comparing fabricated designs. With the open-ended EA, a population size of two hundred individuals was evolved with a generational EA. For this EA, new individuals were created with an equal probability of using mutation or recombination, with parents selected using remainder stochastic sampling and rank-based exponential scaling (Michalewicz, 1992).

As stated earlier, the ST5 spacecraft is 13-15 wavelengths wide, which makes simulation of the antenna on the full craft very computationally 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.

Dozens of experimental runs were performed with each EA and the two best evolved antenna designs, one from each of the EAs described above, were fabricated and tested. The antenna named ST5-3-10 was produced by the open-ended EA that allowed branching, and the antenna named ST5-4W-03 was produced by the parameterized EA that did not allow for branching. Photographs of both prototyped antennas are shown in Figure 5.

The gain patterns for the two evolved antennas are shown in Figures 6 and 7 and the gain patterns for the traditionally designed QHA are shown in Figure 8. Data for these plots was taken from actual antennas that were tested in an anechoic chamber. Evolved antenna ST5-3-10 is 100% compliant with the original mission antenna performance requirements and this was confirmed by testing a prototype antenna in an anechoic test chamber at NASA Goddard Space Flight Center. The genotype of antenna ST5-3-10 is given in Appendix A.

In comparing the performance of ST5-3-10 with the QHA, note that with ST5-3-10 the minimum gain falls off steeply below $20°$. This is acceptable since those elevations were not required due to the orientation of the spacecraft with respect to Earth. In contrast, the QHA was optimized at the 8.47 GHz frequency to achieve high gain in the vicinity of $75° - 90°$. While the QHA does not strictly meet the field pattern requirements, it achieves high performance and was acceptable to the mission managers.

5 Revised Evolutionary Antenna Design Systems

While the original two antenna, ST5-3-10 and ST5-4W-03, were undergoing space-qualification testing, the launch vehicle for the ST5 spacecraft was changed, resulting in a new, lower orbit. This new orbit is a highly elliptical, Sun synchronous orbit ranging from 300 km to approximately 4,500 km above the Earth and it necessitated the addition of a new requirement on the gain pattern of $\geq$-5 dBic from $0°$ to $40°$ from zenith. The complete set of revised requirements for the antennas on the ST5 Mission are summarized in Table 2.

5.1 Revised Design Space

As a result of the new mission requirements, we needed to modify both the type of antenna being evolved and the fitness function (Lohn et al., 2005). The original antennas evolved for the ST5 mission were constrained to monopole wire antennas with four identical arms, with each arm rotated $90°$ from its neighbors. With these antennas the EA evolved genotypes that specified the design for one arm and the phenotype con-
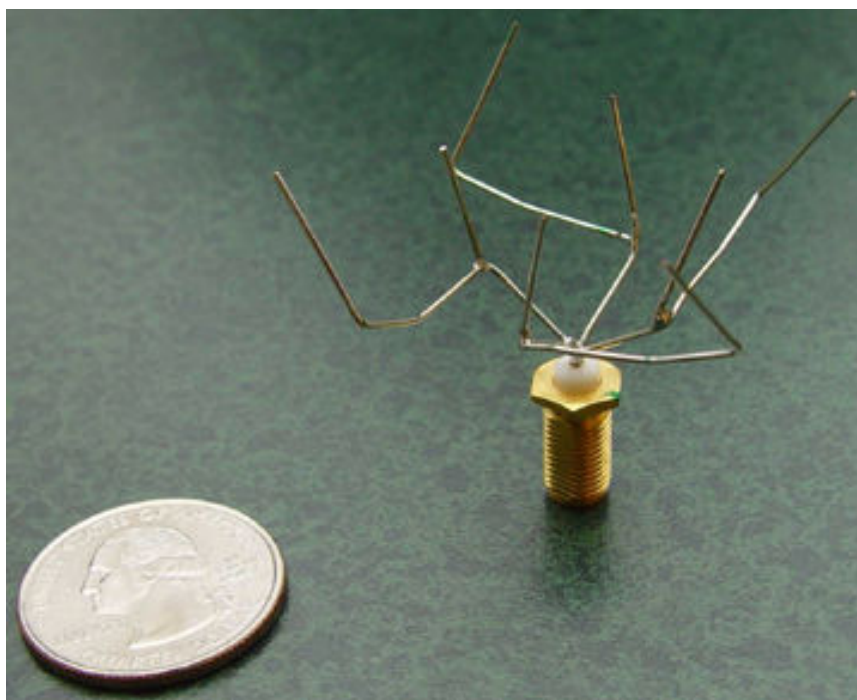
(a)
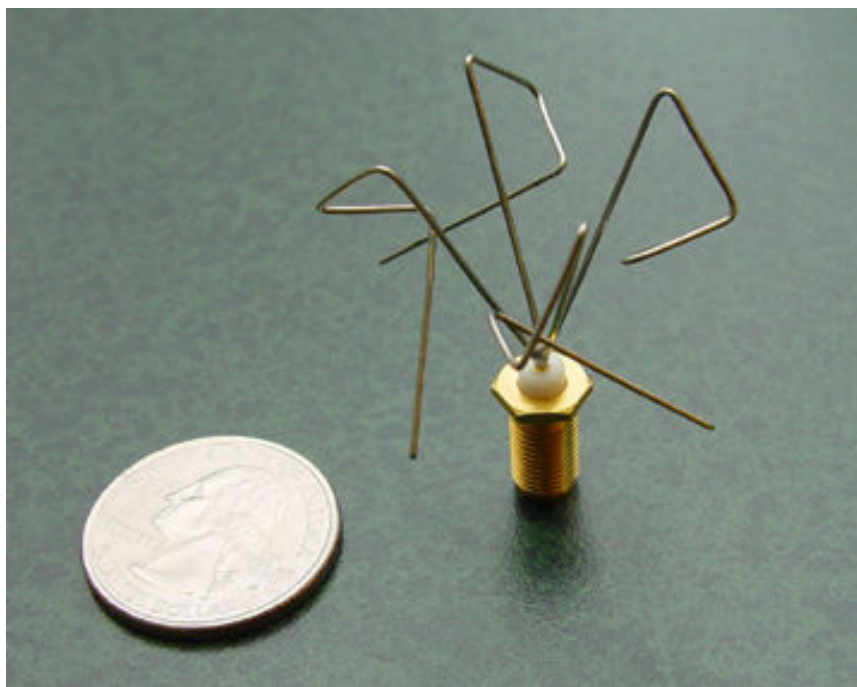
(b)

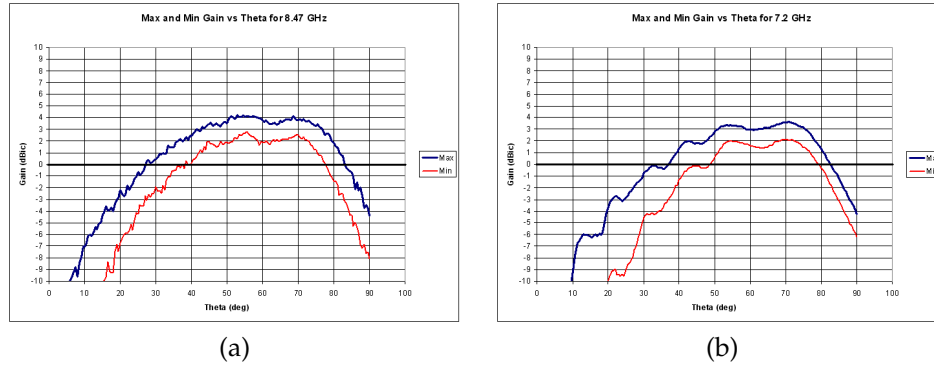Figure 5: Photographs of prototype evolved antennas: (a) ST5-3-10; (b) ST5-4W-03

Figure 6: Maximum and minimum gain for antenna ST5-4W-03, as measured in an anechoic test chamber at NASA Goddard Space Flight Center, at: (a) 8.47 GHz; and (b) 7.2GHz. This antenna was evolved with the parameterized EA.
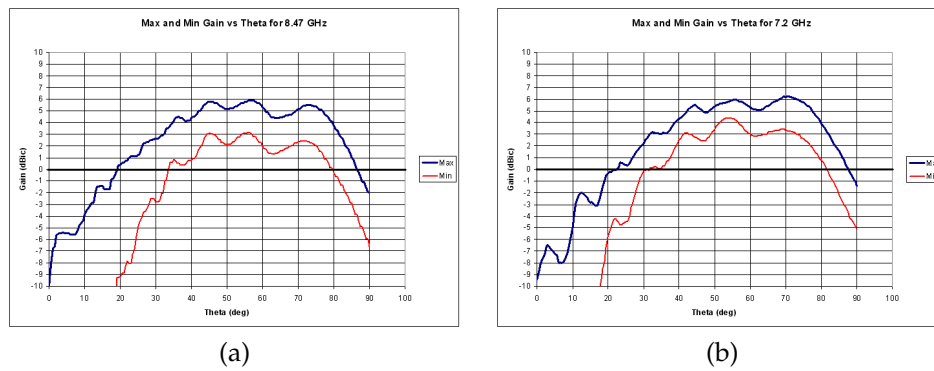

Figure 7: Maximum and minimum gain for antenna ST5-3-10, as measured in an anechoic test chamber at NASA Goddard Space Flight Center, at: (a) 8.47 GHz; and (b) 7.2GHz. This antenna was evolved with the open-ended EA which allowed branching.
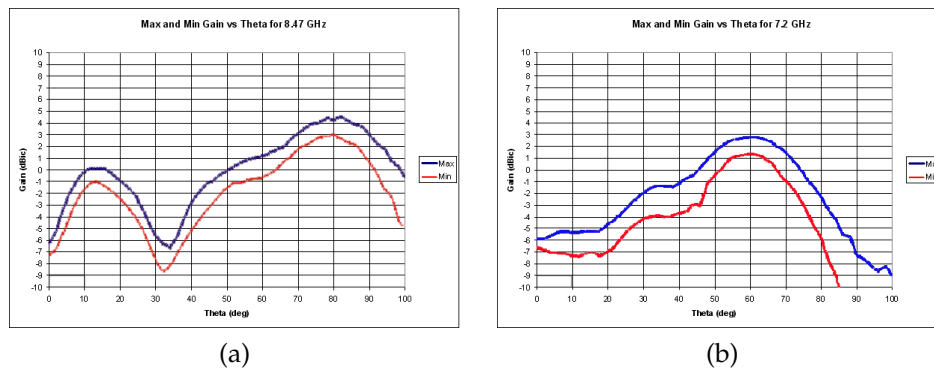

Figure 8: Maximum and minimum gain for the traditionally designed QHA at: (a) 8.47 GHz; and (b) 7.2GHz.

Table 2: 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	≥ 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	$50\,\Omega$
Diameter	< 15.24 cm
Height	< 15.24 cm
Antenna Mass	< 165 g

sisted of four copies of the evolved arm. Because of symmetry, this 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, we decided to search the space of single-arm antennas. In addition, because of our concerns in meeting space-qualification standards in the joints of a branching antenna, we constrained our antenna designs to non-branching ones. Producing a single-arm antenna to meet the mission requirements is a very challenging problem since the satellite is spinning at roughly 40 RPM and it is important that the antennas have uniform gain patterns in the azimuth. This criteria is difficult to meet with a single-arm antenna, because it is inherently asymmetric. In the remainder of this section we describe how we modified our two evolutionary algorithms to address these new requirements.

5.2 Revised Parameterized EA

With the parameterized EA, modifying it to produce antennas for the new mission requirements consisted of changing the fitness function to check angles $0° \leq \theta < 40°$ in addition to the original range of $40° \leq \theta \leq 80°$. Then, since the vector of parameters no longer specifies an arm that must be contained in one quadrant, the constraints on the coordinates in the genotype were modified to allow for points in all four of the XY quadrants.

5.3 Revised Open-Ended EA

Modifying the open-ended EA consisted of restricting the representation so as to only produce non-branching antennas and modifying the fitness function to address the new requirements. To restrict antennas to be non-branching the `forward()` operator was changed to only allow for a single child node. The original fitness function with the open-ended EA was a product of a VSWR component, a gain-error component and a gain-outlier component. For the revised fitness function the VSWR component was kept the same and the gain-error component was changed to include the elevation angles of $0° \leq \theta < 40°$ and made more flexible. In addition the outlier component was dropped, since it was somewhat redundant with the gain-error component but with less of a gradient. It was replaced with a smoothness component, since a smooth pattern is preferred.

Whereas the original gain component of the fitness function had the same weighting and target gain value for each elevation angle, the revised gain component allows

for a different target gain and weight for each elevation:

```
 1: procedure GAIN_PENALTY(i, j)
 2:     gain ← calculated gain at  θ = 5°i , φ = 5°j
 3:     if (gain ≥ target[i]) then
 4:         penalty ← 0.0                          ▷ Gain is better than target so no penalty.
 5:     else if (gain ≥ target[i] - 2.0) then
 6:         penalty ← target[i] - gain
 7:     else                                       ▷ Gain is worse than outlier range.
 8:         penalty ← 2.0 + 3.0 * (2.0 + target[i] - gain)
 9:     end if
10:     return penalty * weight[i]
11: end procedure
```

For the above function, the constants used are:

```
 1: target[] ← {2.0, 2.0, 2.0, 2.0, 2.0, 2.0, 2.0, 2.0, 2.0, 2.0, 2.0, 2.0, 2.0, 2.0, 2.0, 2.0, 2.0, -3.0,
    -3.0}
 2: weight[] ← {0.1, 0.1, 0.1, 0.1, 0.1, 0.1, 0.1, 0.1, 1.0, 1.0, 1.0, 1.0, 1.0, 1.0, 1.0, 1.0, 1.0,
    0.05, 0.05}                                    ▷ For scoring the low band.
 3: weight[] ← {0.4, 0.4, 0.4, 0.4, 0.4, 0.4, 0.4, 0.4, 3.0, 3.0, 3.0, 3.0, 3.0, 3.5, 4.0, 3.5, 3.0,
    0.2, 0.2}                                      ▷ For scoring the high band.
```

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. 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. For this component of the fitness function, numerical values were selected based on performing numerous evolutionary runs and tweaking the values to try to improve evolutionary results. 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 for a given elevation is the same as is used in calculating the gain penalty. As described in the following section, the addition of this component to the fitness function resulted in the evolution of antennas that had noticeably smoother patterns.

These three components are multiplied together to produce the overall fitness score of an antenna design, which is to be minimized:

$$F \quad = \quad vswr \times gain \times standard\ deviation \tag{14}$$

6 Re-evolved Antenna Results

In total, it took us approximately four weeks to both modify our two EAs and evolve new antennas for the revised mission requirements. The configuration of the two EAs (population size, selection/replacement, variation, etc.) remained the same as in the first set of evolutionary runs. Again, the best antennas evolved by the two EAs were then evaluated by hand 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
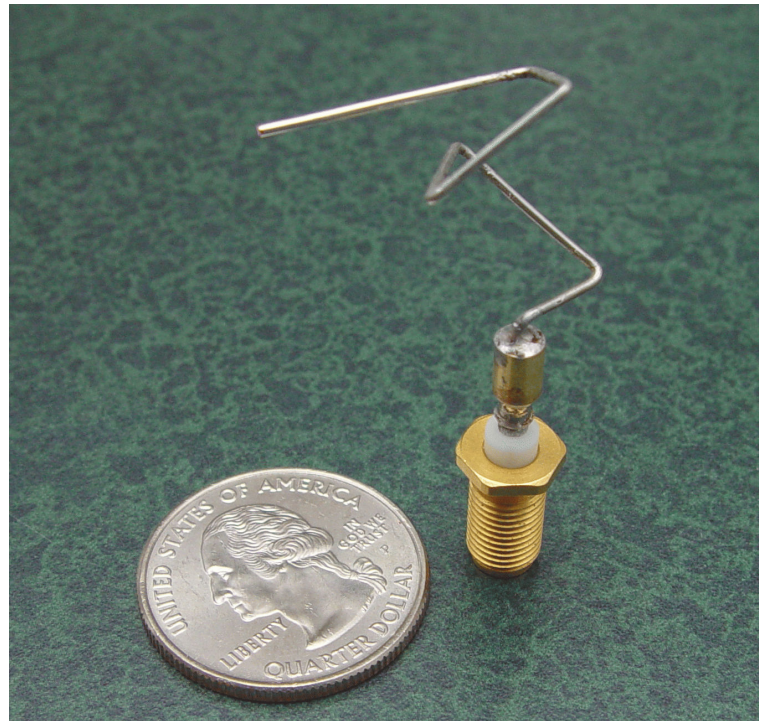
(a)
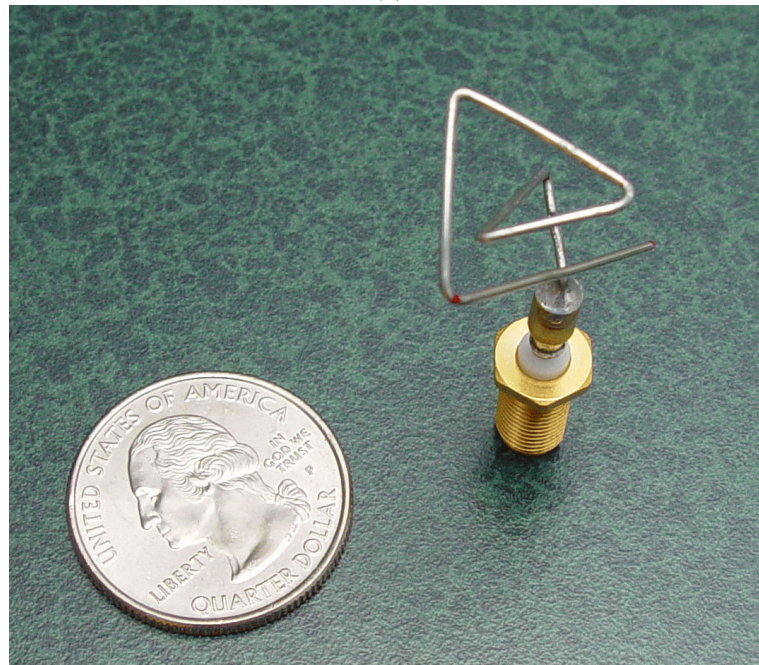
(b)

Figure 9: Evolved antenna designs: (a) evolved using a constructive process, named ST5-33.142.7; and (b) evolved using a vector of parameters, named ST5-104.33.
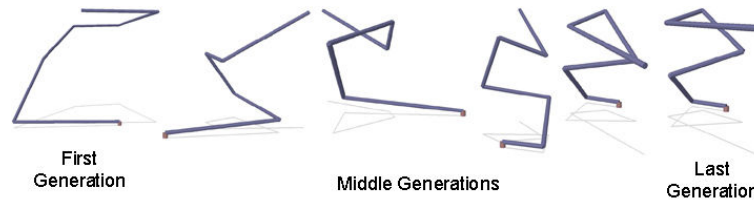
Figure 10: Sequence of evolved antennas leading up to antenna ST5-33.142.7.

mock-up. Based on these simulations the best antenna design from each EA was selected for fabrication, and these are shown in Figure 9: ST5-33.142.7 was evolved using the open-ended EA (Figure 9(a)) and ST5-104.33 was evolved using the parameterized EA (Figure 9(b)). A sequence of evolved antennas that produced antenna ST5-33.142.7 is shown in Figure 10.

Both ST5-33.142.7 and ST5-104.33 have excellent simulated RHCP patterns for the transmit frequency and they also have good circular polarization purity across a wide range of angles. To the best of our knowledge, this performance quality has never been seen before in this form of antenna.
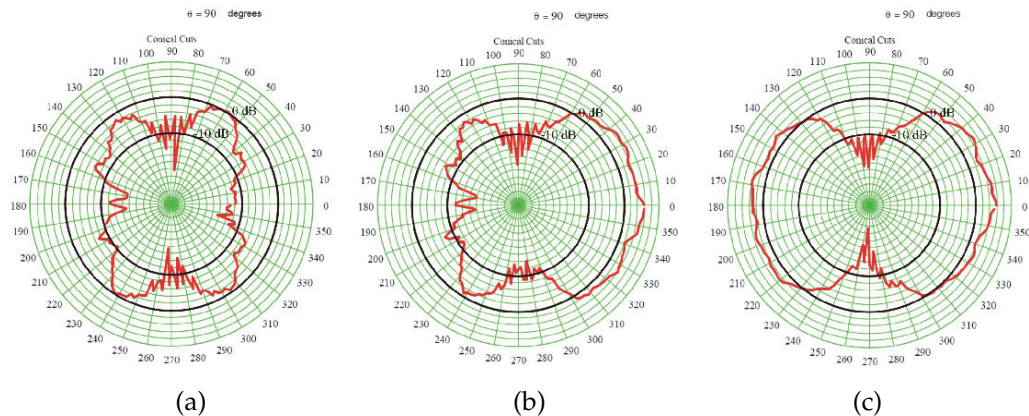

Figure 11: Measured patterns of the two antenna setup on the ST-5 mock-up of: (left) two QHA antennas; (middle) a QHA antenna on the left side of the ST-5 mock-up with the evolved antenna ST5-33.142.7 on the right side of the ST-5 mock-up; and (left) two evolved antennas ST5-33.142.7. All three graphs are conical cuts at $\theta = 90°$.

Since there are two antennas on each spacecraft, and not just one, it is important to measure the overall gain pattern with two antennas mounted on the spacecraft. For this, different combinations of the two evolved antennas and the QHA were tried on the the ST5 mock-up and measured in an anechoic chamber. With two QHAs 38% efficiency was achieved, using a QHA with an evolved antenna resulted in 80% efficiency, and using two evolved antennas resulted in 93% efficiency. Here "efficiency" means how much power is being radiated versus how much power is being eaten up in resistance, with greater efficiency resulting in a stronger signal and greater range. Figure 11

shows these measured results for the combination of two QHAs together (left graph), a QHA on the left and an ST5-33.142.7 on the right (middle graph), and for two ST5-33.142.7 antennas (right graph). These three graphs show that the evolved antenna ST5-33.142.7 achieves considerably better gain than the QHA for angles 30° above the horizon and higher.

In comparing the two EAs, they achieved similar results to each other for both the original specifications and the revised specifications. Generally, if the design can be parameterized into a vector of parameters – such as for a non-branching antenna – we would expect that a standard GA-style EA would outperform an EA using a more open-ended representation. More recently we have performed evolutionary runs using the same EA and fitness function but different representations on a similar antenna design problem and have found that evolution with the parameterized representation (Hornby, 2009a) achieved better performance than with the constructive representation (Hornby, 2009b). Potentially this gap could be closed by using better variation operators with the constructive representation. Conversely, a constructive, generative representation allows for the topology to be evolved, and in our problem it also allowed for the evolution of the number of wire segments. Thus, while a parameterization may be better on parameterizable problems, a generative representation is necessary for topological optimization.

7   First Computer-Evolved Hardware in Space

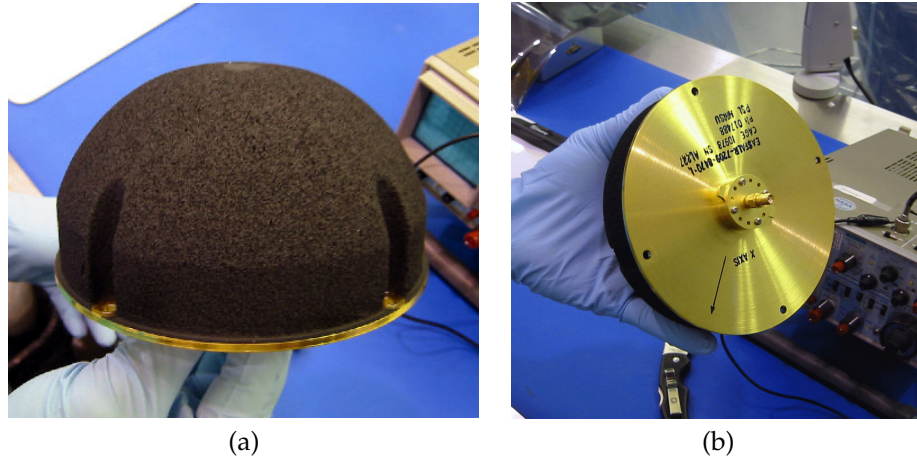(a)   (b)

Figure 12: Images of a completed, flight antenna: (a) a flight unit after it has been coated; and (c), the underside of a flight unit.

Of the two evolved antennas that were evolved to meet the revised ST5 mission specifications, antenna ST5-33.142.7 was approved for deployment and the first set of ST5-33.142.7 flight units were delivered to Goddard Space Flight Center (GSFC) on February 25, 2005 (Figure 12) to undergo environmental tests. The evolved wire configuration is the radiating element of the antenna and it sits on top of a 6" diameter ground plane and is encased inside a radome. The image in Figure 12(a) shows a flight antenna after the radome has been coated with a black paint to differentiate it from the QHAs and the image in Figure 12(b) shows the underside of a flight antenna with the connector, gold-plated ground plane and the tuning assembly. On April 8, 2005 the last

test was completed and passed, a thermal-vacuum testing in which the antenna performed above requirements during one survival cycle (-80°C to +80°C) and through each of eight qualification cycles (-70°C to +50°C).
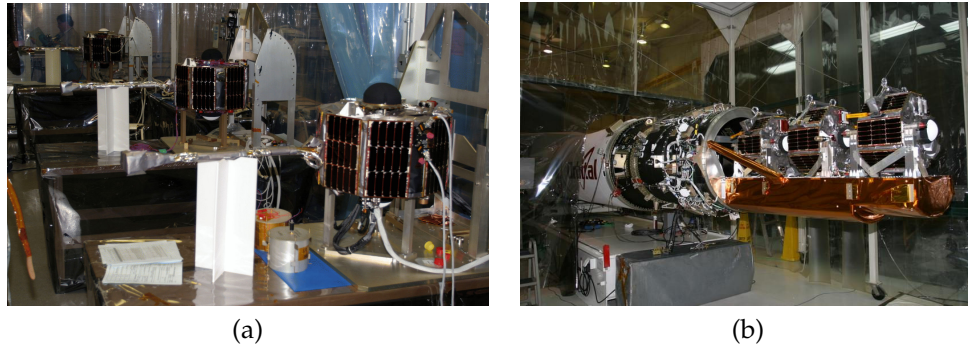

Figure 13: Images of the ST5 spacecraft: (a) the three ST5 spacecraft with the black radomes on top containing an evolved antenna, ST5-33.142.7; and (b) the three ST5 Spacecraft mounted for launch on a Pegasus XL rocket.

Having passed all tests, antenna ST5-33.142.7 was used as one of the communication antennas on each of the ST5 spacecraft. The image in Figure 13(a) shows the three ST5 Spacecraft in the NASA Goddard Spaceflight Center clean room, with the black radome on top of each spacecraft containing an evolved antenna, ST5-33.142.7 and the white radome on the bottom of the spacecraft containing a quadrifilar helical antenna. This image also shows the boom holding the magnetometer, the instrument for measuring the magnetosphere. In preparation for launch, the three ST5 spacecraft are now stacked on top of each on a Pegasus support structure, and then placed inside a Pegasus XL rocket, Figure 13(b), for which the mag-boom is folded alongside the spacecraft.

On March 22, 2006 at 9:04 a.m. E.S.T., NASA's Space Technology 5 mission successfully launched from Vandenberg Air Force Base, California on a Pegasus XL rocket. At 9:27 a.m. E.S.T. initial contact with the spacecraft was made using the evolved antennas as they passed over the McMurdo Ground Station in Antarctica. This mission lasted for three months, over which time the evolved antennas performed successfully and to the mission manager's satisfaction. This evolved antenna design has become the first computer-evolved antenna to be deployed for any application and is the first computer-evolved hardware in space.

8 Conclusion

We have evolved and built four different X-band antennas, two for the initial ST5 mission requirements and two for the revised ST5 mission requirements. From an algorithmic perspective, both evolutionary algorithms produced antennas that were satisfactory to the mission planners. It took approximately 3 months to set up our evolutionary algorithms and produce the evolved antenna ST5-3-10 which was shown to be compliant with respect to the original ST5 antenna performance requirements. In response to the change in orbit, it took roughly 4 weeks to evolve antenna ST5-33.142.7, which was acceptable to mission managers for the revised set of mission requirements. One ST5-33.142.7 antenna is in use on each of the three ST5 spacecraft and, with their successful launch on March 22, 2006, they have become the first computer-evolved an-

tenna to be deployed and the first computer-evolved hardware in space.

In addition to being the first evolved hardware in space, the evolved antennas demonstrate several advantages over the conventionally designed antenna and over manual design in general. The evolutionary algorithms used were not limited to variations of previously developed antenna shapes but generated and tested thousands of completely new types of designs, many of which have unusual structures that expert antenna designers would not be likely to produce. By exploring such a wide range of designs EAs may be able to produce designs of previously unachievable performance. For example, the best antennas that were evolved achieve high gain across a wider range of elevation angles, which allows a broader range of angles over which maximum data throughput can be achieved and may require less power from the solar array and batteries. In addition, antenna ST5-33.142.7 has a very uniform pattern with small ripples in the elevations of greatest interest ($40°$ to $80°$) which allows for reliable performance as elevation angle relative to the ground changes. With the evolutionary design approach it took approximately 3 person-months of work to generate the initial evolved antennas versus 5 person-months for the conventionally designed antenna and, when the mission orbit changed, with the evolutionary approach we were able to modify our algorithms and re-evolve new antennas specifically designed for the new orbit and prototype hardware in 4 weeks. The faster design cycles of an evolutionary approach results in less development costs and allows for an iterative "what-if" design and test approach for different scenarios. This ability to rapidly respond to changing requirements is of great use to NASA since NASA mission requirements frequently change. As computer hardware becomes increasingly more powerful and as computer modeling packages become better at simulating different design domains we expect evolutionary design systems to become more useful in a wider range of design problems and gain wider acceptance and industrial usage.

9   Acknowledgments

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Appendix A: Genotype for Antenna ST5-3-10

Listed below is the evolved genotype of antenna ST5-3-10. 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 ]`. The different operators in the antenna-constructing language are given in section 3.2.

```
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) ] ] ]
] ] ] ] ] ] ] ] ] ] ] ] ]
```

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 operators.

Appendix B: Genotype for Antenna 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 ]`. For the ST5 mission antennas were constrained to be non-branching so each node in this genotype has at most one child, the only exception is the leaf node. The different operators in the antenna-constructing language are given in section 3.2.

```
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) ] ] ] ] ] ] ] ] ] ] ] ] ] ] ] ] ] ] ]
] ] ] ] ] ] ] ] ] ]
```