CONFORMAL MICROSTRIP GPS ANTENNA FOR MISSILE APPLICATION

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ABSTRACT

Conformal Microstrip GPS Antenna for Missile Application

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Optimal missile guidance and flight performance require accurate and continuously updated in-flight coordinate data. The Global Positioning System (GPS) is used for this positional awareness. However, due to missile rotation and orientation variations during flight, GPS signal reception using traditional antennas may be intermittent. To remain cost competitive, Stellar Exploration Inc. is developing a low-cost omnidirectional GPS antenna for guided missile prototypes.

In this thesis, existing products and design techniques are examined, design constraints for supersonic missile applications are investigated, and corresponding performance goals are established. A conformal microstrip patch antenna is developed and simulated in Agilent's Advanced Design System (ADS). The resulting antenna is constructed and characterized. Prototype testing verifies that the antenna maintains GPS signal lock regardless of orientation. The final cost is significantly lower than existing conformal products.

A second revision investigates enhanced modeling, dimensional reductions (via increased dielectric constant), and radome construction. Performance is compared to first revision antenna results and differences are examined. Suggestions for further revisions are discussed.

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Chapter 1: Introduction

1.1 The Silver Sword Project

The main purpose of a missile defense system is to intercept and destroy incoming missiles as a line of defense against ballistic missile attack. The Missile Defense Agency, part of the U.S. Department of Defense, currently develops, tests, and deploys missile defense technologies to counter a variety of ballistic threats, collectively known as the Ballistic Missile Defense System (BMDS) [1].

To test, improve, and demonstrate these systems, reliable targets are developed. Target missiles allow for (1) improved system testing, (2) operational readiness and qualification, (3) maintained proficiency of deployed systems, and (4) threat deterrence via visible system demonstration. Stellar Exploration seeks to design, test, and manufacture affordable, dedicated short-range target missiles with its Silver Sword project for use in high-confidence missile defense system testing [2]. A diagram of the Silver Sword target missile is shown in Figure 1.1.

Figure 1.1 – Silver Sword Target Missile [2]

The current version Silver Sword missile offers the following features [2]:

- Solid rocket motor
- Launch mass: 73 kg, diameter: 6 inches, length: 10 feet
- Maximum range: 152 km, maximum altitude: 70 km
- Peak velocity: Mach 5

1.2 The Global Positioning System

In-flight missile coordinates are required for performance monitoring and guidance. The Global Positioning System (GPS) provides accurate position information (within 100 feet) via its 24-satellite constellation. The system utilizes triangulation, requiring a minimum of four satellites to calculate latitude, longitude, and elevation. The distance from the GPS satellites to the receiver is determined through propagation delay measurements (signal transmit time). These signals also contain ephemeris data (satellite position) and timing pulse information (generated by each satellite's atomic clock). Using this information, the GPS receiver calculates its coordinates [3].

Due to relatively large satellite to receiver distances, GPS signals are less than -130 dBm. The system operates at two frequencies: 1.57542 GHz for L1 (commercial and public use) and 1.22760 GHz for L2 (military use) [3].

The avionics system within the Silver Sword missile contains a GPS receiver to track in-flight coordinates by processing L1 GPS data. To receive incoming signals, a GPS antenna must either be purchased or designed.

1.3 Existing Technologies

Haigh-Farr Inc. designs and manufactures a variety of antenna products intended for defense and aerospace applications. Their wraparound antenna offers omnidirectional coverage, conformal mounting, and protection against harsh flight environments (high temperatures, G forces, vibrations) [4]. Customers select from a variety of design specifications including operating frequency, number of channels, bandwidth, polarization, weight, and dimensions [5].

Figure 1.2 shows the physical configuration of a typical Haigh-Farr wraparound antenna (dimensions are a design parameter). Figure 1.3 shows corresponding example radiation patterns.

Figure 1.2 – Conformal Antenna Manufactured by Haigh-Farr Inc. [5]

Figure 1.3 – Haigh-Farr Inc. Conformal Antenna Radiation Patterns (L1 GPS) [5]

Although Haigh-Farr’s wraparound product would serve well as the Silver Sword missile’s GPS antenna, it is expensive (estimated at \$50k) and outside the project’s budget. The target missile contracts are price-sensitive; to remain competitive, Stellar Exploration must minimize design and manufacturing costs while maintaining comparable performance [2].

1.4 Project Goals and Design Specifications

The primary project goals are to design, construct, and test a GPS antenna for use on a supersonic missile that is (1) less expensive than existing products, and (2) has comparable performance (i.e. provides uninterrupted missile coordinates tracking). Funding is provided by Stellar Exploration, Inc., San Luis Obispo, CA.

1.4.1 General Project Considerations

Before beginning the design process, system requirements were determined, outlined below.

The antenna must be flush with the missile surface. The missile casing is recessed at the antenna location to accommodate the dielectric thickness. Protrusions beyond the missile surface generate air drag (reducing missile velocity) and are susceptible to increased temperatures during supersonic flight. Thus, protrusions are not allowable. The antenna must also fit within the antenna section allotted by Stellar Exploration.

The antenna must also provide continuous signal transmission and reception as it rotates during flight. Additional protective measures must be considered, including structural damage during transportation (e.g. feed line scratching, PCB flexing and fracture, accidental removal of adhesive substrate) and high surface temperatures (up to 400°F) during flight.

A simulation tool such as Agilent's Advanced Design System (ADS) must be used to create, simulate, and optimize the antenna feed network and radiator. Construction materials must be selected to optimize antenna performance. Critical interface issues must be addressed including low-loss connections to the internal electronics and reliable connections to the missile surface.

Later in the design process, substrates with high dielectric constants ($\epsilon_r \approx 10$) are investigated to reduce antenna dimensions and minimize space consumption on the missile.

The overall antenna cost must not exceed \$10,000 (compare to \$50k Haigh-Farr estimate), including labor, flex PCB, dielectric substrate, heat shield, connectors, and cables. This estimated budget limit is subject to change based on missile project funding and available materials.

1.4.2 Initial Antenna Design Specifications

The antenna operates with the missile's GPS system. Operating specifications are summarized below:

Operating Frequency: The antenna must receive signals transmitted on the standard L1 GPS carrier frequency of 1.57542 GHz (± 7.5 MHz).

Operating Bandwidth: For proper operation, a minimum 15 MHz (1.57542 GHz ± 7.5 MHz) "VSWR < 2" bandwidth is desired ($\geq 1\%$ BW).

Polarization: Horizontal (z) polarization (see Figure 1.4 for polarization definition). Alternatively, an array of circularly-polarized patches would enable right-hand circular polarization (RHCP) for maximum GPS signal reception. The linearly-polarized design is pursued due to simpler implementation, accepting the 3 dB linear to circular polarization mismatch loss [6]. Due to time constraints, the circularly-polarized design was not pursued in later revisions.

Figure 1.4 – Polarization Definition for Conformal Patch Antenna on Cylindrical Surface

Gain/Beam Pattern: The beam pattern should be omnidirectional with nominal gain within the range -10 dBi to 0 dBi and a maximum gain variation of ± 5 dB. This will provide GPS reception as the missile rotates during flight. Passive antenna gain is insufficient; thus, additional gain can be provided via a commercial low-noise amplifier (LNA) within the missile's GPS receiver. Nulls located at the missile's fore and aft directions are acceptable ($< 20^\circ$ width); see Figure 1.5.

Figure 1.5 – Definition of Acceptable Fore and Aft Null Widths

The GPS antenna initial design requirements are summarized in Table 1.1. Requirements were slightly modified during the design process.

Table 1.1 – Initial GPS Antenna Design Requirements

Parameter	Value
Operating Frequency	1.57542 GHz
Bandwidth (VSWR < 2)	15 MHz
Polarization	Linear (see Figure 1.4)
Gain	0 dBi (< 5 dB ripple)
Beam Pattern	Omnidirectional (fore and aft null widths $\leq 20^\circ$)

1.4.3 Material and Mechanical Considerations

Antenna construction involves additional design considerations, including substrate selection, connector specification, electronics interfacing, and heat shield/radome design, as summarized below:

Substrate Selection: The dielectric substrate must be flexible in order to wrap around the missile surface without breaking. Antenna dimensions are adjusted based on the dielectric constant; dimension reductions require larger values ($\epsilon_r \approx 10$).

Connector Specification: The connector must exhibit less than 0.5 dB loss over the operating frequency range. Connector type must match internal circuit connectors.

Electronics Interfacing: The antenna feed point interfaces with internal circuitry by feed cables through an opening in the missile casing. The distance from antenna feed point to internal circuitry is minimized to reduce cable losses.

Heat Shield/Radome: During supersonic missile flight, maximum surface temperatures near the antenna are estimated at 400°F, averaging 240°F over flight duration. An aerodynamic heating analysis was performed by Stellar Exploration for the specific missile structure [7]. A high-temperature coating must be used to protect the antenna PCB. Heat shields with dielectric constants greater than 1.0 may shift the antenna operating frequency and affect input matching. Therefore, the dielectric constant should be chosen as close to 1.0 as possible. Conformal coatings offer controlled dielectric constant and ease of application to non-planar surfaces. The antenna design must compensate for operational changes due to the heat shield.

Chapter 2: Antenna Design and Simulation

2.1 Configuration

The design procedure for conformal missile antennas has been described in the literature [8-13]. A particular design method outlined in [8] includes radiator length, required number of feeds, and feed input impedance. Although numerous antenna types exist, microstrip antennas stand out as the clear choice for missile applications, based on the following discussion.

The geometry for a microstrip patch antenna, shown in Figure 2.1, consists of three layers: (1) conducting ground plane, (2) insulating substrate with specified height and relative dielectric constant, and (3) top conducting layer (feed network and patch). Microstrip antennas are resonant structures. Patch length (L) determines the operating frequency (approximately $\lambda/2$). Open-circuit discontinuities at the patch ends create radiation (identified as W in Figure 2.1) [8, 9, 15].

Figure 2.1 – Microstrip Patch Antenna Geometry

Microstrip patch antennas have several advantages and disadvantages, as follows [8,9,15]:

Advantages:

- Low profile (dependent on dielectric substrate thickness)
- Inexpensive to manufacture (via standard PCB etching techniques)
- Light weight
- Conformable (can etch on flexible substrates)

Disadvantages:

- Inherently narrow bandwidth (1-5% typical)
- Unrealistically large dimensions at lower frequencies (< 1 GHz)
- Low gain (passive antenna)

Figure 2.2 indicates the antenna section provided on the Silver Sword missile. Figure 2.3 depicts antenna components and corresponding interconnections, while Figure 2.4 presents a system cross-section for antenna interfacing to the missile.

Figure 2.2 – Antenna Section on Silver Sword Missile

Figure 2.3 – Antenna Components

Figure 2.4 – Antenna System Cross-Section

The functional blocks shown in Figure 2.3 are described below:

Radiator: Copper radiator “patch” used as radiation mechanism (receives/transmits incoming/outgoing signals). The radiator is essentially an elongated microstrip patch antenna supported by multiple feeds (designed and simulated via software). The resulting PCB design is manufactured by an outside company (Advanced Assembly; see Section 3.1.3).

The radiator length depends on operating frequency and substrate dielectric constant. The radiator width must wrap around the missile (to provide omnidirectional coverage) without exceeding the circumference (18.8 inches). The gap between radiator edges should be less than 2 cm (electrically small: $< \lambda/10$), to accommodate fabrication variations/overlap.

Feed Network: Microstrip transmission lines composed of power splitters and quarter-wave transformers to (1) direct the signal to and from the input and radiator, and (2) provide impedance matching between the $50\ \Omega$ input and radiator feed points. This component is designed and simulated via software. The resulting PCB design is manufactured by an outside company (Advanced Assembly; see Section 3.1.3).

The feed network length is minimized to reduce space consumption. At least one radiator feed is required for each guided wavelength λ_g along the radiator width [8]. Guided wavelength is dependent on the effective dielectric constant (see Section 5.2.1). For example, if the radiator width is $4\lambda_g$, four feeds must be provided. The feed network must extend around the missile circumference to provide appropriate feed spacing (equally spaced). The network is optimized via ADS to provide matching ($VSWR < 2$) at the operating frequency.

Dielectric Substrate: A non-conducting layer with specified dielectric constant and material thickness. A recession (100 mil) milled into the missile surface at the antenna section (see Figure 2.2) accommodates the substrate. The dielectric constant and thickness affects overall antenna design and performance (dimensions, operating frequency, bandwidth). Optimum dielectric constant and thickness are determined through ADS simulations on available materials.

Protective Heat Shield (not shown): A protective conformal coating that shields sensitive microstrip structures from flight conditions (400°F maximum, 240°F average). Conformal coatings painted onto PCB surfaces protect against environmental effects. The recess dimensions accommodate the thin coat, which is sanded to eliminate uneven surfaces and protrusions.

The coating's dielectric constant (ideally $\epsilon_r = 1.0$) and temperature resistance (up to 400°F) are selected based on material data sheets and ease of curing [14]. Temperature resistance is defined as the maximum temperature before the coating breaks down and no longer insulates the underlying layers from heat exposure.

Antenna performance variations due to heat shield presence is simulated in ADS and measured in the anechoic chamber. Heat shield durability may be tested via controlled heating applied to antenna prototypes and resulting physical effects observed or during test flight.

Missile Interface: Provides electrical connections between the feed network and supporting electronics. Consists of a low-loss connector (< 0.5 dB insertion loss) and low-loss cable (< 1 dB/ft loss) designed for high-frequency operation.

Missile Surface: The missile's aluminum cylindrical shell provides the microstrip antenna ground plane. The missile shell is designed, manufactured, and provided by Stellar Exploration. It is electrically conductive and recessed in the patch antenna area to accommodate the dielectric substrate and PCB thickness for flush mounting.

2.2 Design

The generalized GPS antenna structure (N feeds) is shown in Figure 2.5, based on the required patch antenna components outlined in Figure 2.3.

Figure 2.5 – Generalized GPS Antenna Structure (N Feeds) (line widths not to scale)

2.2.1 Substrate Selections and Structure

The feed network and patch copper traces must be etched onto a flexible substrate for wraparound applications. Advanced Assembly fabricates PCBs for Stellar Exploration, which uses Kapton substrate material to fabricate flexible PCBs. Kapton contains polyimide and withstands temperatures up to 752°F [16]. The Kapton substrate used by Advanced Assembly has a relative dielectric constant $\epsilon_r = 3.1$.

Advanced Assembly offers Kapton substrates with thicknesses ranging from 1 to 10 mil. Thicker patch antenna substrates yield higher bandwidths [8]. Substrate thickness effects on patch antenna bandwidth was briefly investigated in ADS for $\epsilon_r = 3.0$, shown in Figure 2.6.

Figure 2.6 – Patch Antenna Bandwidth versus Substrate Thickness

Figure 2.6 demonstrates that bandwidth varies with substrate thickness. For a 20 MHz bandwidth (1.27% BW), a substrate thickness ≥ 60 mil is required. Since the maximum substrate thickness for a flex PCB is 10 mil, an alternative substrate must be used.

Reference [13] addresses this issue by using a two-layer structure. The first (top) layer consists of the thin flex PCB ($\epsilon_r = 3.1$) containing the copper-etched antenna and the second (bottom) layer consists of a thicker dielectric substrate ($\epsilon_r = 1.06$). Momentum can simulate multilayer substrates composed of multiple materials with different dielectric constants and thicknesses; thus, the thin PCB substrate is included in the design process.

Emerson & Cuming Microwave Products offers various dielectric substrates with ϵ_r ranging from 1.03 to 30 [17].

Preliminary designs and simulations were performed to identify an appropriate substrate material. Various dielectric constants were investigated during this process.

First, a thin layer with $\epsilon_r = 3.1$ was used to examine design feasibility, which mirrored the specified dielectric constant of the Kapton flex PCB. After the bandwidth investigation of Figure 2.6, a multilayer substrate with a spacer dielectric $\epsilon_r = 2.4$ layer was used. This dielectric is based on Emerson & Cuming's Eccostock CPE material, which was the optimum choice until further research revealed that the material is too rigid for conformal application.

Finally, a flexible, double-adhesive dielectric substrate known as Eccostock PP-4 with $\epsilon_r = 1.06$ was selected. The resulting substrate structure is shown in Figure 2.7.

Figure 2.7 – GPS Antenna Multilayer Substrate Structure (not to scale)

2.2.2 Initial Calculations

The initial design was created via calculations shown below [8, 9]. Refer to Figure 2.5 for dimension definitions.

Patch Length:

$$\lambda_0 = \frac{c}{f} = \frac{3 \times 10^8 \text{ m/s}}{1.57542 \times 10^9 \text{ Hz}} = 19.043 \text{ cm},$$

$$L = \frac{0.49 \lambda_0}{\sqrt{\epsilon_r}} = \frac{(0.49)(19.043 \text{ cm})}{\sqrt{1.06}} = 9.063 \text{ cm}.$$

NOTE: A value of $\epsilon_r = 1.06$ was used since it is the dominant substrate (2 mil Kapton layer only accounts for 3% of total thickness). Design adjustments accounting for both substrates are made in ADS by simulating multi-layer substrates.

Patch Width:

$$\text{Circumference} = \pi \cdot D = \pi(15.24\text{cm}) = 47.878\text{cm}$$

Select radiator width: 46.0 cm to allow 1.878 cm gap

NOTE: The total Kapton flex PCB is 47.5 cm wide (equal to missile circumference at antenna section). Small margins (0.75 cm) between the Kapton substrate edge and the copper patch edges are provided for fabrication considerations. Thus, the patch width must be $47.5\text{ cm} - 2(0.75\text{ cm}) = 46.0\text{ cm}$ (see Figure 2.8).

Figure 2.8 – Patch and PCB Width Dimensions

Number of Feeds:

$$W_{\lambda} = \frac{W\sqrt{\epsilon_r}}{\lambda_0} = \frac{(46.0cm)(\sqrt{1.06})}{19.043cm} = 2.49 \Rightarrow W_{\lambda} = 2.49\lambda_g.$$

Select number of feeds: $N_F \geq W_{\lambda} = 2.49\lambda_g \therefore N_F = 4$.

NOTE: The design of the wide radiator described in [8, 9] requires one feed per guided wavelength, evenly spaced. Each feed is placed at the center of each “patch” ($0.5\lambda_g$ from each edge). According to [9], if fewer feeds are provided, higher-order modes are created on the radiator, which result in roll-plane radiation pattern ripple and nulls.

Approximate Feed Input Resistance:

$$R_{in} = \frac{N_F \cdot 60 \cdot \lambda_0}{W} = \frac{(4)(60)(19.043cm)}{(46.0cm)} \approx 100\Omega.$$

NOTE: The above feed input impedance estimation is provided in [8, 9], but does not account for complex impedance (resistance only). The estimation was developed by analyzing the admittance of a slot radiator [9].

Ignoring the imaginary component (reactance) allows for simpler feed network designs, whereas matching complex impedances requires more complex designs (stubs). For design simplicity, only the real component of the input impedance is used. If performance requirements are not met, the feed network will be redesigned to account for the complex impedance (resistance and reactance).

2.2.3 Feed Network Design

Figure 2.9 shows the general structure of a 4-feed corporate network.

Figure 2.9 – General Structure for 4-Feed Corporate Network (impedances not shown)

The feed network matches four 100 Ω feed points (connected to the patch) to the 50 Ω input via quarter-wave transformers and T-junctions. The quarter-wave transformers provide impedance matching based on the transmission line's characteristic impedance, as follows [18]:

$$Z_{oT} = \sqrt{Z_1 \cdot Z_2} ,$$

where:

Z_{oT} = quarter-wave transformer characteristic impedance;

Z_1 = impedance seen at transformer input;

Z_2 = impedance seen at transformer output.

The resulting feed network design is shown in Figure 2.10.

Figure 2.10 – Feed Network Design

2.3 Simulation

Agilent's Advanced Design System (ADS) was used as the simulation tool for this project due to availability. The Schematic module within ADS provides design, simulation, and optimization of matching networks. The Momentum module provides electromagnetic simulations, including antenna radiation patterns.

One major drawback with using ADS for this project is its inability to model and simulate three-dimensional structures. Ideally, an alternative design software such as Ansoft's High-Frequency Structure Simulator (HFSS) would be used, but a license was not available at Stellar Exploration.

Thus, the antenna must be designed within ADS as a planar antenna and then constructed as a non-planar antenna (cylindrical). Potential performance variations between planar and non-planar designs are investigated later (see Section 4.2).

2.3.1 Feed Network Simulation

The design procedure listed in Appendix A was used to model and optimize the feed network in ADS.

In ADS Schematic, the feed labeled as “P1” (see Figure 2.10) was terminated with a 50 Ω *S*-parameter simulation termination (“Term” under “Simulation-S_Param” component palette). The remaining feeds (“P2” through “P5”) were terminated with *S*-parameter simulation terminations set to 100 Ω each. Properly terminating each feed with *S*-parameter terminations allows for *S*-parameter simulations in ADS Schematic. A schematic screenshot is shown in Figure 2.11 (1-to-4 port network, see Figure 2.10). The corresponding simulation results for the completed feed network are shown in Figure 2.12.

Figure 2.11 – ADS Schematic Screenshot for Feed Network

Figure 2.12 – Feed Network Simulated S -Parameters (ADS Schematic)

Input matching $|S_{11}|$ at the operating frequency (1.575 GHz) is approximately -28 dB. The transmission loss between the input port (port 1) and any output port (ports 2 through 5) is -6.03 dB, as expected, since the network contains two T-junctions with 3 dB transmission loss each.

2.3.2 Antenna S-Parameter Simulation (Feed Network with Patch)

The S -parameter simulation terminations were removed from the schematic. The feed labeled as “P1” (see Figure 2.10) was replaced with a Momentum simulation port set to 50 Ω ; properly terminated feed ports allow for S -parameter simulations in Momentum. The feeds labeled as “P2” through “P5” were replaced by the antenna radiator (rectangular copper patch). The final antenna layout in Momentum is shown in Figure 2.13.

Figure 2.13 – Feed Network with Patch (ADS Layout/Momentum)

The multilayer substrate was defined in Momentum (Figure 2.14). Initially, the $|S_{11}|$ minimum occurred at 1.548 GHz. The patch length was incrementally decreased until the simulated $|S_{11}|$ minimum (peak input matching) shifted to the operating frequency (1.575 GHz). Figure 2.15 shows the effect of patch length versus peak input matching. The final adjusted performance is shown in Figure 2.16.

Figure 2.14 – Multilayer Substrate Defined in ADS Momentum

Figure 2.15 – Patch Length vs. Peak Input Matching Frequency

Figure 2.16 – Simulated Input Matching $|S_{11}|$ for Trimmed Patch with Feed Network

The simulated $|S_{11}|$ response of Figure 2.16 indicates a peak input matching of approximately -20 dB at the GPS operating frequency of 1.575 GHz. The corresponding VSWR 2:1 bandwidth is 25 MHz (1.6% BW).

2.3.3 Antenna Radiation Pattern Simulation

The corresponding antenna radiation patterns for this design were generated in Momentum, as shown in Figures 2.18 through 2.21. Figure 2.17 and Table 2.1 define the antenna polarization relative to the layout.

Figure 2.17 – Polarization Definition for Layout

Table 2.1 – Polarization Definitions Corresponding to Figure 2.17

Plane	Co-Polarization	Cross-Polarization
E-plane (yz-plane)	θ	ϕ
H-plane (xz-plane)	ϕ	θ

Figure 2.18 – GPS Antenna 3D Radiation Pattern (co-polarization)

Figure 2.19 – GPS Antenna Gain Patterns
Left: H-plane ($\phi = 0^\circ$, θ scan); Right: E-plane: ($\phi = 90^\circ$, θ scan); co-polarization

Figure 2.20 – GPS Antenna Circular (LCP/RCP) (left) and Horizontal (right) Polarization 2D Radiation Patterns (H-plane ($\phi = 0^\circ$, θ scan); co-/cross-polarizations)

Figure 2.21 – GPS Antenna Circular (LCP/RCP) (left) and Horizontal (right) Polarization 2D Radiation Patterns (E-plane ($\phi = 90^\circ$, θ scan); co-/cross-polarizations)

Based on Figures 2.18 through 2.21, co-polarization patterns yield greater magnitude levels over cross-polarization patterns, as expected. According to [9], the radiation pattern for an unwrapped conformal antenna (Figure 2.13) should exhibit a “high gain fan beam antenna pattern.” Simulated radiation patterns (Figures 2.18 through 2.21) indicate fan beams, which corresponds with this prediction.

Chapter 3: Antenna Fabrication

After completing simulations and adjustments (Chapter 2), the various antenna materials and components were selected and ordered, as outlined in this chapter.

3.1 Materials and Component Selection

As discussed in Sections 2.1 and 2.2, the GPS antenna is composed of multiple interconnecting layers. Figure 3.1 shows a cross-section of this multilayer structure.

Figure 3.1 – Multilayer GPS Antenna Cross-Section

The selection of layer materials is discussed below.

3.1.1 Layer #1 – Aluminum Ground Plane

Since the antenna is mounted flush to the missile surface, the missile casing was selected as the antenna's ground plane. The missile casing is composed of a 0.375-inch thick aluminum cylinder with a 5.75-inch diameter. A smaller subsection (18 inches long) – referred to as the antenna section (see Figure 2.2) – is used to mount the antenna. Both components were fabricated by Stellar Exploration.

3.1.2 Layer #2 – Dielectric Substrate

As discussed in Section 2.1.1, a thicker (≥ 60 mils) supplemental dielectric substrate is used in addition to the flex PCB (Layer #3) to increase antenna bandwidth to the design goal (15-20 MHz). This “spacer” dielectric was supplied by Emerson & Cuming Microwave Products – Stellar Exploration’s vendor of choice for microwave materials. During the antenna’s design stage, only one flexible dielectric material was available from the vendor that allowed for conformal, adhesive application (Eccostock PP-4 with $\epsilon_r = 1.06$ composed of polypropylene). This material was selected and ordered to serve as the antenna’s second layer. Material specifications are shown in Figure 3.2.

Typical Properties		
	PP-2	PP-4
Service Temperature, °F (°C)	-112 to 185 (-80.0 to 85.0)	-112 to 185 (-80.0 to 85.0)
Compression Strength, psi @ 25%, (psi @ 50%)	5 (14)	9 (19)
Compression Set (% of original thickness)	28	16
Hardness, Shore A	7	15
Loss Tangent	0.0001	0.0001
Dielectric Constant	1.03	1.06
Density, lbs/ft ³	1.8 - 2.2	3.6 - 4.4
Tensile Strength, kg/cm ²	2.5	5.5
Elongation %	220	290
Thermal Conductivity, (cal)(cm)/(sec)(cm ²)(°C)	0.000096	0.00010
Water Absorption, lb/ft ² of cut surface	0.04	0.04
Available Thickness	1/8" & 1/4"	1/16" & 1/8" & 1/4"

Figure 3.2 – Eccostock PP-4 Material Properties [19]

3.1.3 Layer #3 – Strip Conductor (Antenna PCB)

Stellar Exploration's printed circuit board vendor Advanced Assembly offers flexible PCB fabrication. Kapton is used to manufacture flex PCBs with a relative dielectric constant of $\epsilon_r = 3.1$. A 2 mil thickness was selected to remain small as compared to the dielectric spacer of Layer #2 (62 mil thick). The antenna pattern is etched on the Kapton surface with 1 ounce copper (1.34 mil thick).

3.1.4 Layer #4 – Protective Radome

One method of protecting printed circuit boards (PCBs) from its environment is conformal coating, a non-conductive dielectric layer applied to a PCB surface [20]. For the conformal GPS antenna, one major concern is thermal protection from high temperatures during missile flight.

Several conformal coating types exist, including acrylics, polyurethanes, epoxies, and silicones. Silicone conformal coatings are best suited for protection in high-temperature environments [21]. Table 3.1 compares conformal coating properties (desirable characteristics highlighted in red).

Table 3.1 – Comparison of Various Conformal Coatings [21]

Characteristic	Acrylic	Polyurethane	Epoxy	Silicone
Humidity Resistance	Excellent	Excellent	Good	Excellent
Abrasion Resistance	Fair	Good	Excellent	Good
Mechanical Strength	Fair	Excellent	Excellent	Good
Stress on Coated Components Resulting from Temperature Variation	High	High	High	Low
Temperature Resistance	Good	Fair	Fair	Excellent
Dielectric Constant @ 23°C, 1 MHz	2.2-3.2	4.5-5.2	3.3-4.0	2.6-2.7

A prominent supplier of silicone conformal coating is Dow Corning, used in [21]. Dow Corning conformal coatings are supplied in three product families: RTV elastomeric coatings, solventless heat cure coatings, and RTV elastoplastic coatings. RTV elastoplastic coatings cure with abrasion resistant properties, while RTV elastomeric and solventless heat cure coatings cure with a rubbery surfaces for stress relief [22].

For missile applications, an abrasion resistant surface is desired to protect against scratches, thus implying the likely use of RTV elastoplastics. A quick comparison of the various properties of the Dow Corning product families is shown in Table 3.2.

Table 3.2 – Comparison of Dow Corning Silicone Coating Product Families [22]

Property	RTV Elastomeric Coatings	Solventless Heat Cure Coatings	RTV Elastoplastic Coatings
Cure at Room Temperature?	Yes	No	Yes
Speed of cure	Good at 60°C	Very rapid above 100°C	Good at 60°C
Cured properties	Very soft for optimum stress relief	Very soft for optimum stress relief	Firm, dry surface for best handling properties

Based on Table 3.2, the RTV elastoplastic coating product family is the best choice for missile antenna applications. Dow Corning also provides a comprehensive data sheet for conformal silicon coatings. Specific descriptions for RTV elastoplastic conformal coatings are provided below (emphasis added):

Potential Uses: “Protective coating for rigid and *flexible* circuit boards ... ideally suited for electronic printed wiring board (PWB) applications, particularly those requiring toughness and *abrasion resistance* [23].”

Application Methods: “Applied by spray, brush, flow, dip, or automated pattern coating [23].”

Cure: “Time required ... can be reduced with heat. A typical cure schedule for 3 mil coatings is 10 minutes at room temperature, followed by 10 minutes at 80° C [23].”

Dow Corning offers a total of four different RTV elastoplastic conformal coatings, two of which are Low VOC versions; “Low Volatile Organic Compound,” which contains lower concentrations of volatile organic compounds (environmentally friendly) [21,23]. Various mechanical and electrical properties of these products are summarized and compared in Tables 3.3 and 3.4, respectively (emphasis added in red).

Datasheets for all products are provided in [24-27].

Table 3.3 – Dow Corning RTV Elastoplastic Conformal Coatings:
Mechanical Properties Comparison [23]; all translucent

Product	Viscosity [centipose or mPa·s]	RT Tack Free Time [minutes]	RT Cure Time [minutes]	Temperature Range [° C]
1-2577 RTV Coating	950	7	60	-65 to 200
1-2577 Low VOC RTV Coating	1050	6	60	-65 to 200
1-2620 RTV Coating	150	5	60	-65 to 200
1-2620 Low VOC RTV Coating	350	5	60	-65 to 200

Table 3.4 – Dow Corning RTV Elastoplastic Conformal Coatings:
Electrical Properties Comparison [23]

Product	Dielectric Constant (at 100 kHz)	Volume Resistivity [ohm·cm]	Dissipation Factor (at 1 kHz)	Dissipation Factor (at 1 MHz)
1-2577 RTV Coating	2.74	5.0E+13	<0.0002	-
1-2577 Low VOC RTV Coating	2.33	1.9E+14	0.0003	-
1-2620 RTV Coating	2.68	4.6E+13	0.0003	-
1-2620 Low VOC RTV Coating	2.48	1.05E+15	0.004	-

Based on Table 3.4, the dielectric constant for all products is near the ideal value of 1.0 (dielectric constant of air). A sensitivity analysis was performed via ADS simulations (see Figures 3.3 and 3.4), indicating the effects of protective coating thickness and dielectric constant.

Figure 3.3 – Effect of Radome Dielectric Constant on Antenna Performance

Figure 3.4 – Effect of Radome Thickness on Antenna Performance

These simulation results indicate that as the radome's dielectric constant or thickness is increased, the antenna's operating frequency (minimum insertion loss) decreases. Thus, minimized protective coating thickness with a relative dielectric constant of approximately 1.0 is required.

Due to lower viscosities, it is preferable to select either the 1-2620 RTV coating or 1-2620 Low VOC RTV coating for ease of application. The Dow Corning website allows the user to search for distributors by area. A brief summary of prices and distributors are summarized in Table 3.5.

Table 3.5 – Brief Price and Distributor Summary

Product	Distributor	CA Location	Amount	Quantity	Price
1-2620 RTV Coating	K. R. Anderson, Inc.	Morgan Hill	3.6 kg/8 lb	1	\$218.66
1-2620 Low VOC RTV Coating	K. R. Anderson, Inc.	Morgan Hill	18 kg/40 lb	1	\$886.38
1-2620 Low VOC RTV Coating	Ellsworth Adhesives	Carlsbad, Hayward, Walnut Creek, and more	3 kg	1	\$202.66
			15 kg	1	\$479.49

Based on the above analysis, Stellar Exploration selected the 1-2620 Low VOC RTV Coating to serve as the antenna's protective coating.

3.2 Cylindrical Antenna Assembly

All GPS antenna components arrived by September 30th, 2010. Each component is shown in Figures 3.5 and 3.6. The following is an inventory of antenna components and materials or parts used for each:

(1) Missile antenna section.

- a. Aluminum segment of missile body intended for mounting antennas.
- b. Serves as ground plane.
- c. Contains feed hole for mounting connector.
- d. Provided by Stellar Exploration, Inc.
- e. Dimensions: 18.125 inches tall, 5.75 inches wide, 0.375 inches thick.

(2) Dielectric substrate.

- a. PP-4 (polypropylene) with $\epsilon_r = 1.06$.
- b. 0.0625 inches thick.
- c. Contains adhesive on each side.
- d. Manufactured by Emerson & Cuming Microwave Products.

(3) Microstrip flex PCB.

- a. Consists of designed radiator and feed network etched with copper on thin (2 mil) flexible Kapton dielectric substrate ($\epsilon_r = 3.1$).
- b. Manufactured by Advanced Assembly.

(4) SMA female connector.

- a. Long pin (0.5 inches) to penetrate missile thickness (0.375 inches).
- b. Supplied by Pasternack Enterprises.

Figure 3.5 – Aluminum Missile Section (left) and Dielectric Substrate (right)

Figure 3.6 – Microstrip Flex PCB (left) and SMA Connector (right)

The GPS antenna was assembled on October 6th, 2010, using the procedure outlined in Appendix B. The assembled antenna is shown in Figure 3.7.

Figure 3.7 – Conformal GPS Antenna Applied to Missile Section

Applying the dielectric substrate and flex PCB to the missile surface proved more difficult than anticipated. The large missile circumference (17.5 inches) made it difficult to align the substrate and PCB edges with the recess edges. Additionally, the rigidity of the substrate's adhesive cover resulted in the formation of creases and ripples as it was wrapped. Images depicting the ripples and misalignment are shown in Figures 3.8 and 3.9.

Figure 3.8 – Ripples on Antenna Patch

Figure 3.9 –Misalignment of Layers

The ripples and misalignment cause the antenna to protrude from the missile surface (not flush). As described in Chapter 1, any protrusions above the missile surface can generate unwanted air drag and locally extreme temperatures during supersonic flight

(up to 600°F). To improve assembly methods in the future, a list of possible preventative measures was created, as follows:

- (1) Apply flex PCB to dielectric substrate adhesive *before* wrapping around missile section. This eliminates the presence of the semi-rigid adhesive cover and increases material flexibility, which furthermore decreases the ripples.
- (2) Cut a slightly smaller dielectric substrate rectangle (3 mm less on each edge) to ensure the antenna fits within the missile section recess (no overlap or protrusions).
- (3) Construct makeshift guides (wood or plastic) to place around the missile section. These guides maintain antenna alignment when wrapping (to prevent misalignment where edges meet).

NOTE: Compare above items to original procedure found in Appendix B.

3.3 Planar Antenna Assembly

When the GPS antenna design was finalized in ADS, three flex PCBs were ordered and fabricated. One flex PCB was used to construct the cylindrical antenna (Section 3.2), leaving two unused flex PCBs.

To observe the curvature effects of the wraparound antenna, a second unwrapped antenna was constructed. Using one of the remaining PCBs, the antenna was constructed on a flat aluminum ground plane.

Antenna components and materials used to construct the unwrapped antenna is identical for the cylindrical antenna (see Section 3.2), with the exception of the ground plane, as discussed below (see Figure 3.10).

(1) Ground plane.

- a. Aluminum sheet for mounting antenna.
- b. Contains feed hole for mounting connector.
- c. Provided by Stellar Exploration, Inc.
- d. Dimensions: 12.5 inches x 23 inches; 0.050 inches thick.

Figure 3.10 – Aluminum Ground Plane (left) and SMA Connector (right)

The unwrapped GPS antenna was assembled on December 1st, 2010, using the procedure outlined in Appendix B. The assembled unwrapped antenna is shown in Figure 3.11.

Figure 3.11 – Unwrapped GPS Antenna Applied to Planar Ground Plane

Chapter 4: Antenna Testing

4.1 Anechoic Chamber Characterization

Cal Poly's anechoic chamber provides an isolated, echo-free environment that is optimum for measuring antenna performance (input matching, radiation patterns).

4.1.1 Setup

To prepare for the anechoic chamber test, a preliminary test plan was written to specify the test setup and list the desired radiation patterns, as follows:

- (1) Horn antenna calibration.
- (2) VNA calibration.
- (3) $|S_{11}|$ characterization (1.40 GHz to 1.70 GHz).
- (4) Radiation pattern acquisition (5-degree increments, $f = 1.575$ GHz).
 - a. TX: horizontal-polarization.
 - i. E-plane, co-polarization:
 1. $\varphi = 0^\circ$, θ scan.
 2. $\varphi = 90^\circ$, θ scan.
 3. $\varphi = 180^\circ$, θ scan.
 4. $\varphi = -90^\circ$, θ scan.
 - ii. H-plane, co-polarization:
 1. $\theta = 90^\circ$, φ scan.
 - b. TX: vertical-polarization.
 - i. E-plane, cross-polarization:
 1. $\varphi = 0^\circ$, θ scan.
 2. $\varphi = 90^\circ$, θ scan.

3. $\varphi = 180^\circ$, θ scan.
 4. $\varphi = -90^\circ$, θ scan.
- ii. H-plane, cross-polarization:
1. $\theta = 90^\circ$, φ scan.

The coordinate system used to define the above radiation patterns is shown in Figure 4.1.

Figure 4.1 – Coordinate System Definition for Anechoic Chamber Characterization

The GPS antenna was tested in the anechoic chamber on October 14th, 2010.

Figures 4.2 and 4.3 show the antenna (with test fixture) inside the anechoic chamber.

Figure 4.2 – Attaching Test Fixture to Positioner Head

Figure 4.3 – GPS Antenna Mounted to Positioner in Anechoic Chamber

4.1.2 Results

The resulting data was formatted and plotted in Microsoft Excel; see Figures 4.4 through 4.9.

Figure 4.4 – $|S_{11}|$ Input Matching

Figure 4.5 – 1.575 GHz (L1 GPS) ϕ Scan (H-plane, $\theta = 90^\circ$) Radiation Patterns (co-pol: TX horizontal polarization, cross-pol: TX vertical polarization)

Figure 4.6 – 1.575 GHz (L1 GPS) θ Scan (E-plane, $\phi = 0^\circ$) Radiation Patterns (co-pol: TX horizontal polarization, cross-pol: TX vertical polarization)

Figure 4.7 – 1.575 GHz (L1 GPS) θ Scan (E-plane, $\phi = -90^\circ$) Radiation Patterns (co-pol: TX horizontal polarization, cross-pol: TX vertical polarization)

Figure 4.8 – 1.575 GHz (L1 GPS) θ Scan (E-plane, $\phi = 90^\circ$) Radiation Patterns (co-pol: TX horizontal polarization, cross-pol: TX vertical polarization)

Figure 4.9 – 1.575 GHz (L1 GPS) θ Scan (E-plane, $\phi = 180^\circ$) Radiation Patterns (co-pol: TX horizontal polarization, cross-pol: TX vertical polarization)

NOTE: Measured radiation patterns (Figures 4.5 through 4.9) are calibrated gain measurements based on standard gain horns. Initial $|S_{21}|$ measurements are adjusted via calibration factor before plotting.

4.1.3 Analysis

Peak input matching (Figure 4.4) occurred at 1.471 GHz (-16.58 dB), 104 MHz less than desired (1.575 GHz). Poor matching increases signal reflection and yields higher insertion loss. Improving the match at the operating frequency will increase antenna gain. The simulated $|S_{11}|$ response (Figure 2.16) exhibits peak matching at 1.577 GHz (-20.12 dB).

One potential source of error stems from input impedance estimations at the four radiator feed points. These impedances were estimated to be approximately 100Ω each

(see Section 2.2.2). The feed network was designed to match these approximated impedances to the 50 Ω input. If the actual impedances differ from 100 Ω , the designed matching network is not optimized for the actual impedances and should be adjusted accordingly.

Another potential source of error stems from the planar design (in ADS) of a non-planar antenna. Wrapping the planar antenna around the missile cylinder could result in performance variations. The effect of curvature on antenna performance is negligible when the missile cylinder radius is greater than one guided wavelength [11,12]. The guided wavelength in the GPS antenna is estimated [28] as follows:

$$\lambda_g = \frac{\lambda_0}{\sqrt{\epsilon_{eff}}},$$

where:

λ_g = guided wavelength,

λ_0 = free-space wavelength = c/f ,

ϵ_{eff} = effective dielectric constant.

For the microstrip radiator, the patch width is much greater than substrate height ($W \gg h$), and ϵ_{eff} can thus be approximated as $\epsilon_{eff} \approx \epsilon_r$ [28]. For the microstrip feed network, the W and h dimensions are closer in value, and the ADS tool LineCalc was used to estimate ϵ_{eff} . For a microstrip line 60 mil wide (average width), $\epsilon_{eff} = 1.039$. Thus, we can calculate the guided wavelength for each case.

$$\lambda_0 = \frac{c}{f} = \frac{3 \times 10^8 \text{ m/s}}{1.57542 \times 10^9 \text{ Hz}} = 19.04 \text{ cm}$$

Patch:

$$\lambda_g = \frac{0.1904 \text{ m}}{\sqrt{1.06}} = 18.49 \text{ cm}$$

Feed Lines:

$$\lambda_g = \frac{0.1904m}{\sqrt{1.039}} = 18.68cm$$

Thus, the approximate guided wavelength is 18.5 cm. The missile curvature radius is 7.30 cm, which is 11.2 cm less than the guided wavelength. Thus, missile curvature effects may not be considered negligible and could partially account for discrepancies between simulated and actual results.

To avoid missile curvature effects in the planar design, the guided wavelength is reduced by increasing the substrate dielectric constant, which is investigated in Chapter 5.

For each set of radiation patterns (Figures 4.5 through 4.9), cross-polarization measurements exhibited higher average gains and smaller gain variations compared to co-polarization measurements. Table 4.1 below lists maximum and minimum gain values for each radiation pattern.

Table 4.1 – Maximum and Minimum Antenna Gains

Radiation Pattern	Co-Polarization			Cross-Polarization		
	Max. Gain	Min. Gain	Δ	Max. Gain [dB]	Min. Gain [dB]	Δ [dB]
φ Scan (θ = 90°)	-12.29 dB (φ = 115°)	-27.57 dB (φ = 155°)	15.28 dB	-1.51 dB (φ = 330°)	-11.76 dB (φ = 85°)	10.26 dB
θ Scan (φ = 0°)	-2.65 dB (θ = 355°)	-51.09 dB (θ = 50°)	48.44 dB	-1.32 dB (θ = 30°)	-25.64 dB (θ = 225°)	24.32 dB
θ Scan (φ = 90°)	-7.72 dB (θ = 355°)	-29.66 dB (θ = 155°)	21.94 dB	-3.67 dB (θ = 290°)	-20.75 dB (θ = 325°)	17.08 dB
θ Scan (φ = -90°)	-4.43 dB (θ = 330°)	-22.57 dB (θ = 55°)	18.14 dB	-2.32 dB (θ = 355°)	-20.90 dB (θ = 30°)	18.58 dB
θ Scan (φ = 180°)	-2.08 dB (θ = 355°)	-31.69 dB (θ = 220°)	29.61 dB	-0.77 dB (θ = 275°)	-19.57 dB (θ = 150°)	18.80 dB

Ideally, the beam pattern should be omnidirectional with 0 dBi gain and a maximum variation of ± 5 dB. The ϕ -scan ($\theta = 90^\circ$) roll pattern (Figure 4.5) best approximates this requirement. The beam shape approaches an ideal omnidirectional circle near -5 dBi.

The θ -scan ($\phi = 0^\circ, \pm 90^\circ, 180^\circ$) pitch patterns exhibit higher gains at the expense of larger gain variations. As a result, these patterns are less omnidirectional and have more gain variations in the azimuth plane.

The roll and pitch pattern shapes (Figures 4.5 through 4.9) are comparable to the Haigh-Farr patterns (Figure 1.3). However, gain variations for the constructed GPS antenna are more severe (± 18 dB average ripple).

4.2 Planar Antenna Characterization and Comparison

4.2.1 Setup

Wrapped (cylindrical) versus unwrapped (planar) Rev 1 GPS antenna performance is investigated. A spare Rev 1 flex PCB was used to construct an unwrapped test antenna (see Section 3.3). A modified wooden test fixture was constructed to allow for proper interfacing with the anechoic chamber's positioner head; see Figure 4.10.

Figure 4.10 – Modified Test Fixture for Unwrapped Rev 1 GPS Antenna

To prepare for the anechoic chamber test, a preliminary test plan was written to specify the test setup and list the desired radiation patterns, as follows:

- (1) VNA calibration.
- (2) $|S_{11}|$ characterization (1.40 GHz to 1.70 GHz).
- (3) Radiation pattern acquisition (5-degree increments).
 - a. Frequency: $f = 1.575$ GHz.
 - i. TX: vertical polarization.
 1. $\phi = 0^\circ$, θ scan (H-plane, co-polarization).
 2. $\phi = 90^\circ$, θ scan (E-plane, cross-polarization).
 - b. TX: horizontal polarization.
 1. $\phi = 0^\circ$, θ scan (H-plane, cross-polarization).
 2. $\phi = 90^\circ$, θ scan (E-plane, co-polarization).

The coordinate system used to define the above radiation patterns is shown in Figure 4.11.

Figure 4.11 – Planar Antenna Coordinate System Definition

The unwrapped GPS antenna was tested in the anechoic chamber on May 6 and May 13, 2011. Figure 4.12 shows the antenna (with test fixture) inside the anechoic chamber.

Figure 4.12 – Unwrapped GPS Antenna Mounted to Positioner in Chamber

4.2.2 Results

The resulting data was formatted and plotted in Microsoft Excel; see Figures 4.13 through 4.15.

Figure 4.13 – $|S_{11}|$ Input Matching

Figure 4.14 – 1.575 GHz (L1 GPS) θ Scan ($\phi = 0^\circ$, H-plane) Radiation Patterns (co-pol: TX vertical polarization, cross-pol: TX horizontal polarization)

Figure 4.15 – 1.575 GHz (L1 GPS) θ Scan ($\phi = 90^\circ$, E-plane) Radiation Patterns (co-pol: TX horizontal polarization, cross-pol: TX vertical polarization)

4.2.3 Tuning

After the radiation patterns were measured, a razor blade was used to incrementally trim the patch length. The resulting $|S_{11}|$ performance was observed on the VNA after each cut. The goal of this procedure is to increase the planar GPS antenna's operating frequency closer to the design goal (L1 GPS: 1.575 GHz).

The unwrapped structure was amenable to linear cuts along the patch, whereas the cylindrical structure was nearly impossible to trim accurately. The trimmed antenna's patch edge is shown in Figure 4.16. The corresponding $|S_{11}|$ performance is shown in Figure 4.17.

Figure 4.16 – Planar GPS Antenna Trimmed Patch Edge

Figure 4.17 – $|S_{11}|$ Input Matching (Trimmed Antenna)

Trimming 0.25 inches (250 mil or 6.35 mm) off the patch length shifted the peak input matching frequency up by 89.25 MHz to 1.575 GHz (L1 GPS). As a result of the shift, $|S_{11}| = -25.3$ dB.

After successfully tuning the antenna, two additional radiation patterns were taken at 1.575 GHz, shown in Figures 4.18 and 4.19. Refer to page 67 for a comparison of nominal versus tuned radiation pattern improvements.

Figure 4.18 – Tuned Planar GPS Antenna H-Plane Radiation Pattern
1.575 GHz (L1 GPS) θ Scan ($\phi = 0^\circ$), Co-Polarization (TX vertical polarization)

Figure 4.19 – Tuned Planar GPS Antenna E-Plane Radiation Pattern
1.575 GHz (L1 GPS) θ Scan ($\phi = 90^\circ$), Co-Polarization (TX horizontal polarization)

4.2.4 Analysis and Comparison

Peak input matching ($|S_{11}|$ minimum) occurred at $f = 1.48475$ GHz with a value of -19 dB. The input matching performance of the unwrapped and wrapped GPS antennas is superimposed in Figure 4.20.

Figure 4.20 – Unwrapped vs. Wrapped $|S_{11}|$ Input Matching Comparison

The unwrapped GPS antenna yielded an increased operating frequency (from 1.47125 GHz to 1.48475 GHz). Additionally, the minimum $|S_{11}|$ improved (from -16.4 dB to -19.1 dB).

These results indicate closer correspondence with simulations (simulated operating frequency: 1.575 GHz). This improvement is expected, since the antenna was designed using a planar simulation model in ADS. However, the planar antenna does not correspond exactly with the simulated design, indicating additional discrepancies, as follows:

(1) Input impedance variations:

- a. Values estimated in simulations.
- b. Manufacture and materials could affect actual impedances (solder connections, material variations).

(2) Ground plane dimensions:

- a. Simulation assumed infinite ground plane.
- b. Constructed ground plane is non-ideal (finite extent).

Trimming the planar antenna's patch length increased the operating frequency (peak input matching) to the L1 GPS frequency (1.575 GHz). A comparison of the nominal and tuned input matching measurements is shown in Figure 4.21.

Figure 4.21 – Planar Antenna Input Matching Comparison (Nominal vs. Tuned)

The measured radiation patterns (Figures 4.14 and 4.15) represent a fan beam, as expected from ADS simulations. Side-by-side comparisons of simulated versus measured radiation patterns are shown in Figures 4.22 and 4.23.

Figure 4.22 – Simulated (left) vs. Actual (right) H-Plane Radiation Pattern Gain (dBi)
(Planar GPS Antenna)

Figure 4.23 – Simulated (left) vs. Actual (right) E-Plane Radiation Pattern Gain (dBi)
(Planar GPS Antenna)

The backside radiation in the actual antenna's radiation patterns is due to the finite ground plane; simulations assumed an infinite ground plane.

Trimming the planar antenna improved the peak input matching performance, reducing the insertion loss by 6 dB. This improvement altered the corresponding radiation patterns, as can be seen in the superimposed comparisons of Figures 4.24 and 4.25.

Figure 4.24 – Nominal vs. Tuned Antenna Performance (H-Plane Radiation Pattern Gain, Co-Pol, θ Scan, $\phi = 0^\circ$, TX vertical polarization)

Figure 4.25 – Nominal vs. Tuned Antenna Performance (E-Plane Radiation Pattern Gain, Co-Pol, θ Scan, $\phi = 90^\circ$, TX horizontal polarization)

As a result of the improved input matching, the radiation patterns exhibit a gain increase. The maximum H-plane gain increased by 9 dB (from 4 dB to 13 dB) and the maximum E-plane gain increased by 7.5 dB (from 5.5 dB to 13 dB).

4.3 GPS Receiver Test

Although anechoic chamber testing completely characterizes radiation performance, testing the antenna within the operating system (i.e. missile electronics) provides further verification in actual environments.

4.3.1 Initial Test

The wraparound GPS antenna (on cylindrical missile section) was connected to the missile's GPS receiver board (located inside the missile), which is used during test flights to receive and process incoming GPS signals.

The receiver board's output was connected to a laptop to view received satellite signals. The GPS antenna was connected to the receiver board's antenna port. This test setup was placed on a table and moved to an open area outside, away from buildings.

When the receiver was activated, it locked onto one satellite. A second satellite passed in and out of reception. For comparison, a purchased active antenna (internal gain of 20-30 dB) was connected to the GPS receiver, which consistently locked onto seven satellites with moderate signal strength (indicated by reception bar height).

The low gain of the conformal GPS antenna (-10 to 0 dB) prevents the receiver from locking onto more than one satellite. Adding additional signal amplification via a low-noise amplifier (LNA) may result in acquiring additional satellites.

4.3.2 Setup

The initial GPS receiver test highlighted the need for additional amplification. Without an amplifier, one satellite was detected. This unacceptable performance can be attributed to polarization mismatch, power-splitter losses, and S_{11} mismatch. A low-noise, in-line amplifier was purchased (TW120 by Tallysman Wireless) to provide 25 dB gain at the L1 GPS operating frequency; see Figure 4.26. The missile's antenna section accommodates the additional component.

Figure 4.26 – Tallysman Wireless TW120 In-Line LNA (25 dB Gain) [29]

The wraparound antenna (applied to cylindrical missile section) was connected to the missile's GPS receiver board (located inside the missile), which receives and processes incoming GPS signals during flight.

The antenna is connected to the cascaded LNA and receiver board. The receiver board's output is connected to a laptop to view the received GPS signals. This test setup was placed on a plastic table (see Figure 4.27) and moved to an open area outside.

Figure 4.27 – GPS Receiver Test Setup

4.3.3 Results and Analysis

Following receiver activation, the laptop recorded GPS information packets. The antenna was placed in five different orientations (see Figure 4.28) to observe satellite lock versus antenna position. Since the receiver acquires packets at a rate of ten times per second, each test was executed for five seconds (≈ 500 data points per test). Additional orientations (i.e. different vertical angles) were not tested due to time constraints.

Figure 4.28 – GPS Receiver Test Antenna Orientation Definitions

Information packets were recorded and Matlab was used to extract, format, and place the data into an Excel spreadsheet (.xls). The *m*-file written to perform these functions is shown in Appendix C.

The number of received satellites over time was plotted in Excel for each orientation; see Figures 4.29 and 4.30. Data for the “down” orientation was plotted separately to distinguish variations. The orange and blue traces in Figure 4.29 are only partially visible for two reasons: (1) the number received satellites is the same (8 each), and (2) the test duration for the orange trace is about 10 seconds shorter.

Figure 4.29 – Number of Received Satellites versus Time
(Orientations: Up, Left, Right, Vertical)

Figure 4.30 – Number of Received Satellites versus Time (Orientation: Down)

At least four GPS satellites are required for altitude measurements. The antenna met this requirement at all orientations. Best reception occurred in the “up” and “right” positions, with eight satellites. The “left” and “vertical” positions also exhibited acceptable reception, with seven and six satellites, respectively. The “down” position

varied between four and nine satellites. One possible cause for this erratic behavior could be attributed to the patch feed facing the test table.

The GPS information packets also provided a signal-to-noise ratio (SNR) for each satellite. These values are summarized in Table 4.2 (values averaged over test duration).

Table 4.2 – GPS Receiver Test Data Averages

Position	Satellites [#]	SNR1 [dB·Hz]	SNR2 [dB·Hz]	SNR3 [dB·Hz]	SNR4 [dB·Hz]	SNR5 [dB·Hz]	SNR6 [dB·Hz]	SNR7 [dB·Hz]	SNR8 [dB·Hz]	SNR9 [dB·Hz]
Left	7	34	39	40	40	38	36	34	0	0
Up	8	37	35	35	42	36	38	38	38	0
Right	8	39	40	45	42	34	37	36	36	0
Down	7	33	34	35	34	32	32	32	32	31
Vertical	6	40	35	37	37	37	38	0	0	0

4.4 Missile Flight Test

4.4.1 Launch Preparation

In the week preceding the missile test launch, the protective conformal coating (1-2620 Low VOC RTV Coating by Dow Corning) was applied to the GPS antenna. This coating protects against structural damage during transportation (e.g. feed line scratching, PCB flexing and fracture, accidental removal of adhesive substrate) and high temperatures during flight (up to 200°C) [14].

After application, the coated antenna was connected to the GPS receiver and satellite reception was observed. The conformal coating slightly decreased satellite reception (average of 5-6 satellites as opposed to 7-8 satellites). The vertical orientation locked onto the fewest satellites (3-4). However, reception exceeded the minimum requirement of four satellites. Unfortunately, due to time constraints before the test launch, a formal GPS receiver test (to record data) was not performed.

Next, the antenna section was added to the assembled missile. The remaining components were also added to the missile (GPS receiver board, avionics, LNA), and the missile was loaded into the launcher; see Figures 4.31 and 4.32.

Figure 4.31 – Interior of Missile's Antenna Section

Figure 4.32 – Assembled Missile in Launcher

4.4.2 Launch Results

On January 22nd, 2011, the missile was tested in the Mojave desert at a test launch facility. Figure 4.33 shows the missile (without nose cone) in the deployed launcher. In the foreground, the avionics board and GPS antenna can be seen. Figure 4.34 shows the GPS antenna within the test launcher.

Figure 4.33 – Missile (Without Nose Cone) in Deployed Test Launcher

Figure 4.34 – GPS Antenna in Test Launcher

Figure 4.35 shows one of the two ground stations used to communicate with the missile's transmitter (located on avionics board inside nose cone). These ground stations receive signals transmitted by the GPS receiver board. The second ground station was established approximately 2.5 miles downrange near the expected point of impact.

Figure 4.35 – Ground Station at Launch Area

When the ground stations were set up and the missile was in the horizontal position (see Figure 4.33), between seven and nine satellites were consistently locked. However, when the missile was raised to the near-vertical position (see Figure 4.36), all GPS signals were lost (zero satellites). This is inconsistent with previous GPS antenna tests (anechoic chamber, GPS receiver tests). One possible cause is potential signal interference from the metal test launcher, which surrounds the antenna (see Figure 4.34). Another possible cause is component failure, disconnection, or short-circuit.

Figure 4.36 – Missile in Near-Vertical Position

The decision was made to continue the launch without satellite lock, with the hope that lock would be regained once the missile cleared the metal test launcher. Figures 4.37 and 4.38 show the missile after ignition.

Figure 4.37 – Missile During Launch (≈ 0.25 seconds after ignition, high-speed camera)

Figure 4.38 – Missile During Launch (≈ 0.5 seconds after ignition, high-speed camera)

The projected flight timeline is shown in Table 4.3.

Table 4.3 – Projected Flight Timeline

Event	Time [seconds]	Altitude [feet]	Velocity [mach]
Ignition	0.0	0	0.000
Launcher Cleared	0.2	13	0.061
Max. Acceleration	2.4	1135	0.936
Sound Barrier	2.5	3420	1.0
Max. Dynamic Pressure	5.0	5127	1.827
SRM Burnout	6.2	7367	1.720
Apogee	37.4	26253	0.287
Max. Reentry Deceleration	37.5	26241	0.270
Max. Reentry Velocity	80.5	2244	0.837
Ground Impact	82.0	0	0.834
All Clear	164.0	0	0.000

After all clear, the nearest ground station was checked, and GPS satellite lock was never achieved (zero satellites, zero packets sent). The initial conclusion was that the GPS antenna failed electrically. However, upon missile recovery, it was discovered that several components did not survive the missile's supersonic flight environment.

The missile was found near the second ground station downrange, missing its nose cone, fins, and the entire antenna; see Figures 4.39 through 4.41.

Figure 4.39 – Missile at Crash Site

Figure 4.40 – GPS Antenna Missing from Housing

Figure 4.41 – Map Showing Launch Point and Landing Site Locations

4.4.3 Analysis

The inability to achieve satellite lock before launch (in the vertical position) may be due to the launcher, which envelopes the antenna (and missile) in a metal cage. This can potentially interfere with GPS reception (scattering, signal multipath, interference). The GPS receiver test (see Figure 4.29) indicated worst-case lock for vertical orientation. Already compromised reception in the vertical position could be further reduced (and potentially eliminated) when placed inside the test launcher.

The inability to achieve satellite lock after launch can most likely be attributed to the mechanical failure of the antenna. Within 2.5 seconds, the missile breaks the sound barrier and experiences up to 15 G-forces, which destroyed the nose cone, fins, and the flexible antenna. In a later revision, radome integration will be pursued to prevent mechanical antenna failure (see Chapter 5).

Chapter 5: Antenna Revision

For the remainder of the project, a second revision was pursued in an attempt to improve upon the original.

5.1 Second Revision Design Goals

The Rev 2 GPS antenna design goals are:

- (1) To reduce the total axial length (see Figure 2.5).
 - a. Rev 1 total axial length: 17.36 cm.
 - b. Rev 2 goal: ≤ 10.0 cm.
- (2) To fulfill the same design requirements defined in Table 1.1.

The primary feature of Rev 2 is reduced space consumption. Space is limited on the missile's antenna section (1.5 feet in length; see Figure 2.2). Reducing antenna dimensions allows additional antennas in the future.

5.2 Modifications

5.2.1 Dielectric Substrate

Increasing the substrate's dielectric constant to $\epsilon_r = 10$ reduces the guided wavelength and antenna dimensions by approximately 67% ($\lambda_{g(1.06)} = 18.50$ cm, $\lambda_{g(10)} = 6.02$ cm).

As discussed in Chapter 2, ADS does not allow for non-planar simulations (only flat mounting surfaces). Furthermore, wrapping a planar design around a cylindrical surface introduces variations in design performance. In order to use a planar design tool to approximate a non-planar antenna, the mounting cylinder radius must be greater than one guided wavelength [11]. This was demonstrated via the design and simulation of an omnidirectional conformal microstrip array.

For a dielectric constant of 10, the guided wavelength can be estimated by [28]:

$$\lambda_g = \frac{\lambda_0}{\sqrt{\epsilon_{eff}}},$$

where:

λ_g = guided wavelength,

λ_0 = free-space wavelength = c/f ,

ϵ_{eff} = effective dielectric constant.

For the microstrip radiator, the patch width is much greater ($W \approx 362h$) than substrate height ($W \gg h$), and ϵ_{eff} can be approximated as $\epsilon_{eff} \approx \epsilon_r = 10$ [28]. For the microstrip feed network, the W and h dimensions are closer ($W \approx h$) in value, and the ADS tool LineCalc was used to estimate ϵ_{eff} . For a microstrip line width of $W = 50$ mil and a substrate thickness of $h = 50$ mil, $\epsilon_{eff} \approx 6.7$.

$$\lambda_0 = \frac{c}{f} = \frac{3 \times 10^8 \text{ m/s}}{1.57542 \times 10^9 \text{ Hz}} = 19.04 \text{ cm}$$

Patch:

$$\lambda_g = \frac{0.1904 \text{ m}}{\sqrt{10}} = 6.02 \text{ cm}$$

Microstrip Line ($W = 50$ mil):

$$\lambda_g = \frac{0.1904 \text{ m}}{\sqrt{6.7}} = 7.36 \text{ cm}$$

The guided wavelength ranges from 6.02 cm to 7.36 cm, while the missile radius is 7.30 cm, $1.21\lambda_g$ for the patch and $0.99\lambda_g$ for the microstrip line.

For Rev 1, $\epsilon_r = 1.06$, which yields a guided wavelength of approximately 18.5 cm in both the patch and average microstrip line. The missile radius is $0.39\lambda_g$.

For $\epsilon_r = 10$, the missile radius is approximately equal to guided wavelength in a 50 mil microstrip line and larger than the guided wavelength in the patch. This is an improvement when compared to Rev 1. Thus, using a higher relative dielectric ($\epsilon_r = 10$) substrate yields a guided wavelength that is on the same order as the missile radius ($\pm 0.15\lambda_g$). This is summarized in Table 5.1.

Table 5.1 – Dielectric Substrate Dimensional Comparison

Relative Dielectric Constant ϵ_r	Free-Space Wavelength λ_0	Guided Wavelength Range* λ_g	Relative Missile Radius
1.06	19.04 cm	$\lambda_{g1} = 18.5$ cm $\lambda_{g2} = 18.7$ cm	$0.39\lambda_{g1}$ $0.39\lambda_{g2}$
10	19.04 cm	$\lambda_{g1} = 6.02$ cm $\lambda_{g2} = 7.36$ cm	$1.21\lambda_{g1}$ $0.99\lambda_{g2}$

*Range depends on ϵ_{eff} , which varies based on microstrip structure (W, h); λ_{g1} represents the minimum guided wavelength, while λ_{g2} represents the maximum.

5.2.2 Radome

For the Rev 1 design, a thin conformal coating was used instead of a radome. Due to the mechanical failure of the antenna during flight (see Section 4.4), a more robust radome with increased mechanical stability and protection from environmental factors was designed for the Rev 2 antenna.

The aerospace and mechanical engineers at Stellar Exploration provided a radome diagram; see Figure 5.1. NOTE: The figure shows the radome attached to the nose cone. Only the lower section (covering the antenna) is constructed for Rev 2 antenna testing.

Figure 5.1 – Radome Diagram (radome plus nose cone)

The antenna radome is an extension of the missile nose cone. As a result, the material selection and fabrication method are determined and controlled by Stellar Exploration, with input regarding dielectric constant and thickness selection.

The fiberglass composite used to fabricate the nose cone has a specified dielectric constant (ϵ_r) ranging from 4.2 to 4.9. Since the nose cone is a composite, introduction of supplementary materials may affect this value. Thus, the dielectric constant of the radome is not controlled, which may affect antenna performance when compared to simulations (where an estimated value of $\epsilon_r = 4.4$ is used). Momentum simulations are performed at the extremes to ensure proper operation.

Additionally, the nose cone thickness and surface quality (roughness) is not controlled due to the fabrication process used (molding); variations in radome thickness (± 50 mil) may also affect antenna performance and introduce undesired pattern variations.

Ideally, a high-quality radome material with precisely-controlled thickness and dielectric constant would be purchased from a radome manufacturer. At the current Silver Sword missile revision, Stellar Exploration manufactures its own nose cones. Since the radome is an extension of the nose cone, the radome provided by Stellar Exploration must be used.

5.3 Design

5.3.1 Substrate Selection and Structure

Rev 1 utilized the flexible, adhesive dielectric substrate known as Eccostock PP-4 with $\epsilon_r = 1.06$. For Rev 2, a flexible, adhesive dielectric substrate known as DES/DSS6M with $\epsilon_r = 10$ was selected (once again supplied by Emerson & Cuming Microwave Products). The resulting Rev 2 substrate structure is shown in Figure 5.2.

Figure 5.2 – Rev 2 GPS Antenna Substrate Structure (not to scale)

5.3.2 Initial Design (Real Impedance)

The initial design was created via calculations shown below [8, 9]. Refer to Figure 2.5 for dimension definitions.

Patch Length:

$$\lambda_0 = \frac{c}{f} = \frac{3 \times 10^8 \text{ m/s}}{1.575 \times 10^9 \text{ Hz}} = 19.048 \text{ cm} \rightarrow L = \frac{0.49 \lambda_0}{\sqrt{\epsilon_r}} = \frac{(0.49)(19.048 \text{ cm})}{\sqrt{10}} = 2.952 \text{ cm}$$

Patch Width: (same as Rev 1; see Section 2.2.2 and Figure 2.8)

Patch width: 46.0 cm (1.878 cm gap)

Number of Feeds:

$$W_\lambda = \frac{W \sqrt{\epsilon_r}}{\lambda_0} = \frac{(46.0 \text{ cm})(\sqrt{10})}{19.048 \text{ cm}} = 7.64 \Rightarrow W_\lambda = 7.64 \lambda_g.$$

Select number of feeds: $N_F \geq W_\lambda = 7.64 \lambda_g \therefore N_F = 8$.

NOTE: As with the Rev 1 design, one feed must be provided for each guided wavelength, spaced evenly apart [8, 9].

Approximate Feed Input Resistance:

The same feed input impedance estimation (real component only) from Section 2.2.2 was used for the initial design in order to best compare differing performances between the two designs. This yields an estimated R_{in} of 199 Ω . ADS simulations show that designs using this estimate do not meet performance requirements; corresponding design and simulation results are briefly discussed in the remainder of this section. Several design variations are also explored (e.g. reduced dielectric, complex impedance); see Sections 5.3.3 through 5.3.5.

Figure 5.3 shows the general structure of an 8-feed corporate network.

Figure 5.3 – General Structure for 8-Feed Corporate Network (impedances not shown)

The feed network for the real impedance design is shown in Figure 5.4. Only half of the network is shown; since the network is symmetric, the other half is simply the mirror image.

Figure 5.4 – Feed Network Design (Real Impedance Variation)

The design procedure listed in Appendix A was used to model and optimize the feed network in ADS. S -parameter simulations indicate sufficient input matching ($|S_{11}| = -48.8$ dB at 1.575 GHz).

When the feed network was imported into layout and simulated in Momentum, the $|S_{11}|$ minimum consistently occurred at 1.80 GHz. Due to multiple design variables (seven different transmission line lengths and widths), a new incremental tuning method was developed, in which each stage was adjusted and optimized. This procedure can be found in Appendix D. Optimization involved manual adjustments, since optimization routines do not exist in Momentum for complex structures (e.g. multiple interconnecting elements). This tuning procedure was applied to the feed network in Momentum; simulation results for the optimized indicate sufficient input matching ($|S_{11}| = -46$ dB at 1.575 GHz).

Next, simulation ports were removed from layout and replaced by the antenna patch; see Figure 5.5.

Figure 5.5 – Feed Network with Patch (Real Impedance Design)
(ADS Layout/Momentum)

The patch length was adjusted until the simulated $|S_{11}|$ minimum (peak input matching) occurred at the operating frequency (1.575 GHz). The resulting performance is shown in Figure 5.6.

Figure 5.6 – Simulated Input Matching $|S_{11}|$
(Trimmed Patch, Real Impedance Feed Network Design)

Despite excellent input matching for the feed network (-46 dB), adding the patch significantly reduced the input matching (-10 dB). Figure 5.6 indicates matching that marginally achieves the VSWR 2:1 minimum requirement. If the matching is improved, the overall antenna gain increases.

Neglecting the port reactance resulted in an improperly-designed feed network. A more accurate input impedance estimate is obtained (see Sections 5.3.4 and 5.3.5) and used to redesign the feed network.

5.3.3 Decreased Dielectric Design

The next design variation considers the initial design structure and reduces the substrate's relative dielectric constant from 10 to 5 to observe effects on performance.

The same feed structure was used, and the line impedances and dimensions were adjusted to account for the decrease in dielectric constant (via LineCalc). S -parameter simulation results indicate sufficient feed network input matching without the patch ($|S_{11}| = -80$ dB at 1.575 GHz). The patch was then added to the feed network (see

Figure 5.7) and simulated in Momentum. The patch length was trimmed for operation at 1.575 GHz. The resulting $|S_{11}|$ response is shown in Figure 5.8.

Figure 5.7 – Decreased Dielectric Design ($\epsilon_r = 5$) with Patch in ADS Layout/Momentum

Figure 5.8 – Input Matching $|S_{11}|$ for Decreased Dielectric Design ($\epsilon_r = 5$) with Patch

Adding the patch to the feed network once again resulted in a significant decrease in performance, this time yielding an $|S_{11}|$ of -6 dB. Thus, no improvement occurred as a result of decreasing the substrate dielectric constant.

5.3.4 Complex Impedance Design

As discussed in Section 5.3.2, a potential cause for inadequate input matching is the feed point input impedance estimation. Incorrect input impedance estimations (reactance incorrectly ignored) result in degraded input matching when the patch is added to the feed network.

Since the initial design's input matching network (IMN) properly matches a $199\ \Omega$ load to a $50\ \Omega$ input impedance, the IMN can be viewed as a system block that performs the following operation on the load impedance:

$$Z_{in} = f(Z_L) = (50\Omega/199\Omega) \cdot Z_L = 0.251 \cdot Z_L.$$

Adding the patch to the IMN (instead of using $199\ \Omega$ simulation terminations in ADS) introduces a new load impedance, Z'_L , which is transformed by the same IMN function as follows (Figure 5.9 contains a diagram for this situation):

$$Z'_{in} = 0.251 \cdot Z'_L \Rightarrow Z'_L = 3.98 \cdot Z'_{in}.$$

Figure 5.9 – Diagram Depicting Impedance Estimation

Furthermore, Z'_{in} is related to the measured S'_{11} by the following:

$$\bar{z}'_{in} = \frac{1 + S'_{11}}{1 - S'_{11}}, \text{ where: } \bar{z}'_{in} = Z'_{in} / Z_0 \text{ (normalized).}$$

Extracting the measured S'_{11} from simulation results yields Z'_{in} and Z'_L :

$$S'_{11} = 0.31 \angle 44.72^\circ \text{ (from Smith Chart),}$$

$$\bar{z}'_{in} = \frac{1 + 0.31 \angle 44.72^\circ}{1 - 0.31 \angle 44.72^\circ} = 1.379 + j0.666,$$

$$Z'_{in} = \bar{z}'_{in} \cdot Z_0 = (1.379 + j0.666) \cdot (50 \Omega) = 68.94 + j33.27 \Omega,$$

$$Z'_L = (3.98) \cdot (68.94 + j33.27 \Omega) = 274.4 + j132.4 \Omega.$$

Thus, the improved input impedance estimation is approximately $274.4 + j132.4 \Omega$. Note the large imaginary component, included in the following redesign.

Figure 5.10 shows Stages 1 and 2 of the redesigned feed network. Stage 3, which is added later, links the feed network of Figure 5.10 to its duplicate, resulting in a total of eight feed locations.

Figure 5.10 – Complex Impedance Feed Network Design (Stages 1 and 2)

Stage 1 design required transmission line analysis to account for the reactive component of the port impedance. This was accomplished by utilizing open-circuit shunt

stubs near each feed point, along with extra transmission lines for spacing and quarter-wave transformers). Refer to Appendix E for complete matching network design and corresponding calculations. The resulting design yields the following values:

$$\begin{aligned} Z_L &= 274.4 + j132.4 \, \Omega, \\ Z_{\text{ADJ}} &= 50 \, \Omega, \\ \beta l_{\text{ADJ}} &= 98.867^\circ \, (l_{\text{ADJ}} = 0.275\lambda), \\ Z_{\text{STUB}} &= 50 \, \Omega, \\ \beta l_{\text{STUB}} &= 70.56^\circ \, (l_{\text{STUB}} = 0.196\lambda), \\ Z_{T1} &= 50 \, \Omega, \\ \beta l_{T1} &= 90^\circ \, (l_{T1} = 0.25\lambda), \\ Z_{T2} &= 70 \, \Omega, \\ \beta l_{T2} &= 90^\circ \, (l_{T2} = 0.25\lambda). \end{aligned}$$

The line widths and lengths for each stage were optimized in ADS to obtain optimum input matching characteristics. Without the patch, S -parameter simulations indicate acceptable input matching ($|S_{11}| = -34.3$ dB at 1.575 GHz) between the input port ($50 \, \Omega$) and the complex feed impedance ($274.4 + j132.4 \, \Omega$). The patch was added to the feed network (Figure 5.11) and simulated in Momentum.

Figure 5.11 – Complex Impedance Shunt-Stub Design with Patch in ADS Layout/Momentum

The patch length was trimmed to adjust for appropriate operating frequency, and the resulting S_{11} performance is shown in Figure 5.12. The shunt stubs in each feed line eliminate the impedance's reactive component before the quarter-wave transformers that follow.

Figure 5.12 – Input Matching $|S_{11}|$ for Complex Impedance Shunt-Stub Design (w/Patch)

Adding the patch to the feed network resulted in a significant decrease in performance: $|S_{11}|$ of -2.2 dB. Thus, the new complex feed port impedance estimation caused a decrease in input matching performance, which is undesired. Further design variations are investigated.

5.3.5 Four-Stage Port-Tuning Design

The next design investigated the effects of varying the port impedance used for S -parameter simulations. The input port complex impedance was adjusted in Momentum, and the corresponding S_{11} was observed. This was done with the initial design (from Section 5.3.2).

Each time the port impedance was adjusted, the corresponding S_{11} was simulated in Momentum and recorded in Excel. The results are plotted in Figures 5.13 and 5.14.

Figure 5.13 – Input Matching $|S_{11}|$ versus Input Port Resistance (for Reactance = $j0$)

A port resistance of $75\ \Omega$ was selected to minimize $|S_{11}|$ without increasing the line impedance beyond minimum realizable trace width (~ 20 mil). With this value, the port reactance was varied; see Figure 5.14.

Figure 5.14 – Input Matching $|S_{11}|$ versus Input Port Reactance (for Resistance = $75\ \Omega$)

Peak matching (minimum $|S_{11}|$) occurred for a reactance of $-j35$. The corresponding $|S_{11}|$ is -52 dB, which shows a significant improvement over previous designs (with patch).

Using the new optimum port impedance of $75 - j35 \Omega$, a fourth stage was added to the feed network. This new stage consists of a shunt stub followed by a quarter wave transformer, transforming the impedance seen at the original port to a 50- Ω port impedance. The structure for the Stage 4 matching network is shown in Figure 5.15.

Figure 5.15 – Matching Configuration for Stage 4
(Open-Circuit Shunt Stub, Quarter-Wave Transformer)

Using $Z_0 = Z_{STUB} = 50 \Omega$, the open-circuit shunt stub was designed to eliminate the reactive component of the port impedance. The input impedance including the open-circuit stub is:

$$y_2 = y_1 + y_{IN_stub}.$$

To calculate y_1 :

$$y_1 = \frac{1}{z_1} = \frac{1}{1.5 - j0.7} = 0.547 + j0.255,$$

$$\therefore y_{IN_stub} = -j0.255,$$

$$\beta l = 165.7^\circ.$$

An open-circuit stub electrical length of $\beta l = 165.7^\circ$ (physical length: 1340 mil) results in a real input impedance at y_2 . To match g_2 to input impedance Z_{IN} , a quarter-wave transformer is used:

$$Z_T = \sqrt{Z_2 \cdot Z_{IN}} ,$$

where:

$$Z_2 = \frac{Z_0}{y_2} = \frac{50\Omega}{0.547} = 91.41\Omega .$$

$$\therefore Z_T = \sqrt{91.41 \cdot 50} = 67.6\Omega .$$

In summary,

$$Z_1 = 75 - j35 \Omega ,$$

$$Z_{STUB} = 50 \Omega ,$$

$$\beta l_{STUB} = 165.7^\circ (l_{STUB} = 0.46\lambda) ,$$

$$Z_T = 67.6 \Omega ,$$

$$\beta l_T = 90^\circ (l_T = 0.25\lambda) .$$

Adding Stage 4 to the feed network resulted in the four-stage design, shown in Figure 5.16.

Figure 5.16 – Four-Stage Design with Patch in ADS Layout

The shunt stub length and quarter-wave transformer width were manually varied in Momentum to obtain optimum matching performance (see Appendix D). A plot depicting antenna $|S_{11}|$ response with varying shunt stub length is shown in Figure 5.17. The final simulation results for optimum stub length is shown in Figure 5.18.

Figure 5.17 – Input Matching $|S_{11}|$ versus Shunt Stub Length for Four-Stage Design with Patch ($W_T = 28$ mil)

Figure 5.18 – Input Matching $|S_{11}|$ for Four-Stage Design with Patch

The shunt stub allows feed network tuning to the patch impedance. The simulated $|S_{11}|$ is -35 dB, which is 25 dB less than the initial design.

A new layer was created in Momentum to simulate the radome; see Figure 5.19.

Figure 5.19 – Multilayer Substrate (with Radome) Defined in ADS Momentum

The antenna was simulated in Momentum and the patch length and Stage 4 (shunt stub, transformer) were adjusted to achieve the desired operating frequency and input matching (see Appendix D). The resulting performance is shown in Figures 5.20.

Figure 5.20 – Input Matching $|S_{11}|$ for Four-Stage Design with Radome

Once again, adjusting the Stage 4 matching circuit (shunt stub length, transformer width) accounted for the presence of the radome layer, while still maintaining sufficient input matching performance ($|S_{11}| = -28$ dB). The corresponding bandwidth is 17 MHz ($VSWR < 2:1$).

The corresponding antenna radiation patterns for this design were generated in Momentum, as shown in Figure 5.21 through 5.24 (refer to Figure 2.17 and Table 2.1 for polarization definitions).

Figure 5.21 – 3D Radiation Pattern for Four-Stage Design (co-polarization)

Figure 5.22 – Rev 2 GPS Antenna, Gain Patterns
(left: H-plane ($\phi = 0^\circ$, θ scan); right: E-plane ($\phi = 90^\circ$, θ scan); co-polarization)

Figure 5.23 – Rev 2 GPS Antenna, Circular (LCP/RCP) and Horizontal Polarization 2D Radiation Patterns (H-plane ($\phi = 0^\circ$, θ scan); co-/cross-polarizations)

Figure 5.24 – Rev 2 GPS Antenna, Circular (LCP/RCP) and Horizontal Polarization 2D Radiation Patterns (E-plane ($\phi = 90^\circ$, θ scan); co-/cross-polarizations)

NOTE: The red and blue labels “E_left” and “E_right” in the above figures correspond to LHCP and RHCP, respectively.

As expected, the unwrapped antenna exhibits a fan beam radiation pattern. Design variations and corresponding simulation results are summarized in Table 5.2.

Table 5.2 – Summary of Rev 2 Design Variations and Simulated Performance

Design Number	Design Name	Operating Frequency f_0	Input Matching $ S_{11} $ at f_0	Design Requirements Met?
1	Initial	1.572 GHz	-10.9 dB	NO
2	Decreased Dielectric ($\epsilon_r = 5$)	1.571 GHz	-5.7 dB	NO
3	Complex Impedance (shunt stubs)	1.575 GHz	-2.2 dB	NO
4	Four-Stage Design without Radome (port tuning)	1.573 GHz	-35.2 dB	Yes
5	Four-Stage Design with Radome (port tuning)	1.579 GHz	-28.1 dB	Yes

For the four-stage design, iterative feed network port impedance adjustments enabled accurate input impedance estimation. Once determined, the input impedance is matched to the feed port. Using this method, the Rev 2 simulated performance meets operating frequency, input matching, and bandwidth requirements.

Axial Length Reduction:

One design consideration is minimization of the antenna's overall axial length (defined in Figure 2.5). Increasing the substrate's relative dielectric constant reduces this dimension. Further reductions are realized by utilizing curved transmission lines (see Figure 5.16).

To avoid undesired cross-coupling between parallel feed lines, maximum separation between lines was used while maintaining reduced overall axial length (separation $\geq 0.2\lambda_g$).

For the final optimized design (Figure 5.16), the antenna's overall axial length is 10.6 cm (or $1.76\lambda_g$), which is 6.76 cm less than Rev 1 (17.36 cm, or $2.88\lambda_g$), a 39% reduction in overall axial length.

5.3.6 Design Finalization

Design #5 (see Table 5.2) was finalized as per the following procedure and corresponding parts were purchased:

- (1) Double-check simulated performance.
- (2) Increase tuning stub length (by 800 mil) to allow for tuning after fabrication.
- (3) Generate Gerber files.
- (4) Verify antenna dimensions in Gerber files (compare with Layout dimensions).
- (5) Order flex PCB from Advanced Assembly (submit Gerber files, obtain quote).
- (6) Order substrate ($\epsilon_r = 10$, $t = 50$ mil) from Emerson & Cuming Microwave Products.

Chapter 6: Second Revision Fabrication

After completing simulations and adjustments (Chapter 5), the various antenna materials and components were ordered and assembled, as outlined in this chapter.

6.1 Assembly

A side-by-side comparison of the Rev 1 and Rev 2 antenna PCBs is shown in Figure 6.1.

Figure 6.1 - GPS Antenna PCB Size Comparison (Rev 1 vs. Rev 2)

The following is an inventory of the materials and parts used to construct the Rev 2 GPS antenna. New components are shown in Figures 6.2 and 6.3.

- (1) Missile antenna section (same as Rev 1, except reduced dimensions; see Section 3.2).
- (2) Dielectric substrate.
 - a. DES/DSS6M substrate with $\epsilon_r = 10$.
 - b. 0.050 inches thick.
 - c. Contains adhesive on each side.
 - d. Manufactured by Emerson & Cuming Microwave Products.

(3) Microstrip flex PCB (same manufacturer and materials as Rev 1; see Section 3.2).

(4) SMA female connector (same as Rev 1; see Section 3.2).

Figure 6.2 – Dielectric Substrate (with backing) and Rev 2 Flex PCB

Figure 6.3 – Rev 2 Aluminum Antenna Section

The Rev 2 GPS antenna was assembled on April 8th, 2011. The Rev 1 antenna assembly procedure (see Appendix A) was revised to improve assembly quality and reduce air pockets, ripples, and misalignments. This revised procedure is outlined in Appendix F. The assembled antenna is shown in Figure 6.4.

Figure 6.4 – Assembled Rev 2 GPS Antenna (radome not attached)

The Rev 1 GPS antenna contained many assembly defects (see Section 3.2). The surface exhibited ripples and air pockets. Additionally, the location where the PCB ends met were misaligned. However, due to careful construction, the assembled Rev 2 GPS antenna does not contain any of these defects. A side-by-side comparison between Rev 1 and Rev 2 is shown in Figures 6.5 and 6.6.

Figure 6.5 – Assembled Antennas Ripple Comparison (Rev 1 vs. Rev 2)

Figure 6.6 – Assembled Antennas Alignment Comparison (Rev 1 vs. Rev 2)

The radome must be flush with the antenna's surface, and the protruding solder connection could prevent this from occurring (see Figure 6.7).

Figure 6.7 – Protrusion at Solder Connection

To address this, the solder connection is trimmed as low as possible without compromising connectivity to the input. Additionally, a small recess will be sanded on the radome's interior surface (where it touches the solder connection).

Figure 6.8 shows a side-by-side comparison of the Rev 1 and Rev 2 GPS antennas on the cylindrical test fixtures.

Figure 6.8 – Antenna Size Comparison (Rev 2 left, Rev 1 right)

The size of the antenna and corresponding aluminum test fixture have been reduced in the Rev 2 GPS antenna. Additionally, the Rev 2 antenna (with test fixture) weighs 3.8 lbs, whereas the Rev 1 antenna (with test fixture) weighs 12.0 lbs. NOTE: antenna weight is a valid comparison, since the Rev 2 antenna requires a smaller antenna section due to radome/nose cone integration.

Radome fabrication was completed by April 18th, 2011. The radome fitted on the constructed Rev 2 GPS antenna is shown in Figure 6.9.

Figure 6.9 – Rev 2 GPS Antenna with Fitted Radome Section

Chapter 7: Second Revision Testing

7.1 Anechoic Chamber Characterization

Cal Poly's anechoic chamber was once again used to characterize the Rev 2 GPS antenna (obtain input matching and radiation patterns).

7.1.1 Setup

To prepare for the anechoic chamber test, a preliminary test plan was written to specify the test setup and list the desired radiation patterns, as follows:

- (1) VNA calibration.
- (2) $|S_{11}|$ characterization (1.40 GHz to 1.70 GHz).
 - a. Without radome.
 - b. With radome (several orientations).
 - c. With radome (tuned).
- (3) Radiation pattern acquisition (5-degree increments).
 - a. Frequency #1: $f = 1.476$ GHz.
 - i. TX: horizontal polarization (co-polarization).
 1. $\varphi = 0^\circ$, θ scan (E-plane).
 2. $\theta = 90^\circ$, φ scan (H-plane).
 - ii. TX: vertical polarization (cross-polarization).
 1. $\varphi = 0^\circ$, θ scan (E-plane).
 2. $\theta = 90^\circ$, φ scan (H-plane).
 - b. Frequency #2: $f = 1.575$ GHz.
 - i. TX: horizontal polarization.
 1. E-plane, co-polarization:

- a. $\varphi = 0^\circ$, θ scan.
 - i. With radome.
 - ii. Without radome.
- b. $\varphi = 90^\circ$, θ scan.
- c. $\varphi = 180^\circ$, θ scan.
- d. $\varphi = -90^\circ$, θ scan.
- 2. H-plane, co-polarization:
 - a. $\theta = 90^\circ$, φ scan.
 - i. With radome.
 - ii. Without radome.
- ii. TX: vertical polarization.
 - 1. E-plane, cross-polarization:
 - a. $\varphi = 0^\circ$, θ scan.
 - b. $\varphi = 90^\circ$, θ scan.
 - c. $\varphi = 180^\circ$, θ scan.
 - d. $\varphi = -90^\circ$, θ scan.
 - 2. H-plane, cross polarization:
 - a. $\theta = 90^\circ$, φ scan.

The coordinate system used to define the above radiation patterns is shown in Figure 7.1.

Figure 7.1 – Coordinate System Definition for Anechoic Chamber Characterization

The Rev 2 GPS antenna was tested in the anechoic chamber on April 22 and April 25, 2011. Figure 7.2 shows the antenna (with test fixture) inside the anechoic chamber.

Figure 7.2 – Rev 2 GPS Antenna Mounted to Positioner in Anechoic Chamber

7.1.2 Results

The resulting data was formatted and plotted; see Figures 7.3 through 7.10.

Figure 7.3 – $|S_{11}|$ Input Matching for Various Radome Configurations

Figure 7.4 – 1.476 GHz (Peak Matching) ϕ Scan (H-plane, $\theta = 90^\circ$) Radiation Patterns (co-pol: TX horizontal polarization, cross-pol: TX vertical polarization)

Figure 7.5 – 1.476 GHz (Peak Matching) θ Scan (E-plane, $\phi = 0^\circ$) Radiation Patterns (co-pol: TX horizontal polarization, cross-pol: TX vertical polarization)

Figure 7.6 – 1.575 GHz (L1 GPS) ϕ Scan (H-plane, $\theta = 90^\circ$) Radiation Patterns (co-pol: TX horizontal polarization, cross-pol: TX vertical polarization)

Figure 7.7 – 1.575 GHz (L1 GPS) θ Scan (E-plane, $\phi = 0^\circ$) Radiation Patterns (co-pol: TX horizontal polarization, cross-pol: TX vertical polarization)

Figure 7.8 – 1.575 GHz (L1 GPS) θ Scan (E-plane, $\phi = -90^\circ$) Radiation Patterns (co-pol: TX horizontal polarization, cross-pol: TX vertical polarization)

Figure 7.9 – 1.575 GHz (L1 GPS) θ Scan (E-plane, $\phi = 90^\circ$) Radiation Patterns (co-pol: TX horizontal polarization, cross-pol: TX vertical polarization)

Figure 7.10 – 1.575 GHz (L1 GPS) θ Scan (E-plane, $\phi = 180^\circ$) Radiation Patterns (co-pol: TX horizontal polarization, cross-pol: TX vertical polarization)

7.1.3 Analysis

Input Matching:

The measured input matching (S_{11}) varied drastically depending on radome orientation. Poorly-controlled fabrication qualities (i.e. thickness and dielectric constant variations) are the most likely cause of the $|S_{11}|$ variations.

The traces labeled “Radome 1” through “Radome 3” in Figure 7.3 show the sensitivity of input matching to radome orientation. These traces were obtained by rotating the radome to three different random positions when mounted on the positioner in the anechoic chamber.

The input matching performance of the Rev 1 and Rev 2 GPS antennas are plotted on the same graph in Figure 7.11.

Figure 7.11 – Rev 1 vs. Rev 2 $|S_{11}|$ Input Matching Comparison

The input matching is improved for the un-tuned Rev 2 GPS antenna (31 dB lower at a value of -41.8 dB). However, the peak matching frequency is still less than desired (approximately 0.10 GHz less than 1.575 GHz).

Trimming the antenna's tuning stub shifted the peak input matching closer to the L1 GPS frequency (0.035 GHz less), but failed to reach this value.

Radiation Pattern Quality:

The measured radiation patterns exhibit more nulls and have less uniform shapes than the Rev 1 radiation patterns; see the comparisons in Figures 7.12 and 7.13.

Figure 7.12 – Rev 1 vs. Rev 2 Roll Plane Comparison (ϕ Scan, H-plane, $\theta = 90^\circ$)
(co-pol: TX horizontal polarization)

Figure 7.13 – Rev 1 vs. Rev 2 Pitch Plane Comparison (θ Scan, E-plane, $\phi = -90^\circ$)
(co-pol: TX horizontal polarization)

The Rev 2 patterns also exhibit lower gain, which is partly due to the radome – reduced radiated power. The following list outlines Rev 1 vs. Rev 2 GPS antenna differences:

- (1) Substrate high-dielectric constant ($\epsilon_r = 1.06$ Rev1, $\epsilon_r = 10$ Rev 2)
- (2) Radome (Rev 1: thin conformal coating, Rev 2: thick fiberglass shield)
- (3) Smaller ground plane (aluminum cylinder test fixture, Rev 2: 9 inches shorter)

These differences may affect antenna performance.

Although the Rev 2 radiation patterns exhibit more variations than the Rev 1 antenna (nulls, ripple, lobes), the patterns still represent a somewhat “omnidirectional” antenna. The GPS receiver test (Section 7.2) will attempt to confirm this.

Although degraded radiation patterns are a drawback, the Rev 2 GPS antenna still offers many improvements over the Rev 1 counterpart. The integration of a radome offers improved mechanical attachment to the missile surface and improved protection against the harsh environment experienced during launch.

The drastic reduction in size and weight is another advantage. Space and weight on a missile are limited. Reducing the space and weight consumption of the antenna presents significant savings in terms of missile design and cost.

In summary, the new antenna's radiation patterns compare well with the original antenna (relatively omnidirectional) while taking up less space and weight and having an improved mechanical attachment.

Tuning:

The shunt stub located near the antenna feed port allowed for antenna tuning. The stub was cut in small increments with a razor blade (about 0.25 cm per cut) while observing the resulting $|S_{11}|$ on the VNA. Since the guided wavelength is reduced due to the high-dielectric substrate, the antenna is much more sensitive to dimensional variations.

Each cut shifted the peak matching frequency upwards in an attempt to approach the L1 GPS operating frequency (1.57542 GHz). When half of the stub had been trimmed, maximum improved performance was obtained (-38 dB at 1.54 GHz). When the stub was trimmed beyond this point, the input matching worsened until the antenna became non-operational. The radome orientation was also varied to ensure maximum input matching was achieved.

7.2 GPS Receiver Test

The same GPS receiver test performed on the Rev 1 GPS antenna (see Section 4.3) was attempted for the Rev 2 antenna on May 13th, 2011. The test setup is shown in Figure 7.14.

Figure 7.14 – Rev 2 GPS Antenna Receiver Test Setup

The Rev 2 GPS antenna was connected to the receiver board and the received GPS signals were observed via laptop. After attempting multiple orientations, only 1 to 2 satellites were received. A minimum of 4 satellites are required to determine receiver coordinates and altitude.

Even though the measured radiation patterns (see Section 7.1) demonstrate somewhat omnidirectional coverage, decreased gain prevents the antenna from locking onto an adequate number of satellites. Further design revisions are required to reduce loss and improve performance (see Chapter 8 and Future Project Recommendations).

Chapter 8: Conclusion

Over the course of this project, a Rev 1 GPS antenna was successfully designed, simulated, constructed, and tested. ADS simulations demonstrated proper operation (design requirements fulfilled). After construction, anechoic chamber testing highlighted differences between expected and actual results (decrease in peak input matching frequency). A planar Rev 1 antenna was also characterized and resulting radiation patterns were compared to cylindrical counterpart. Trimming patch length shifted the operating point to target frequency (L1 GPS). GPS receiver testing further verified proper operation (7-9 satellites received regardless of antenna orientation).

As a result of the above accomplishments, a fully-functioning antenna was produced (Rev 1) that provided omnidirectional GPS signal coverage within budget (< \$6000). The antenna failed mechanically (ripped from surface) when used in a missile test launch, highlighting the need for improved attachments and aerodynamic considerations.

The Rev 2 GPS antenna improved upon the Rev 1 design, minimizing dimensions, introducing improved impedance matching, and incorporating a radome. ADS simulations demonstrated proper operation (design requirements fulfilled); however, tuning in the anechoic chamber failed to shift the operating point to the desired frequency (L1 GPS). Variations in radome fabrication also introduced uncontrolled variables and degraded antenna performance.

Increasing dielectric constant effectively reduced antenna dimensions; however, with a decreased guided wavelength, the performance changes more drastically with dimensional variations in antenna structure, making tuning more difficult. This discrepancy highlighted the important distinction between simulated performance and implementation; both aspects must be considered in proper antenna design.

Future Project Recommendations

The following is a list of recommended design modifications and investigations for future projects:

- (1) Revisit and improve Rev 1 GPS antenna design:
 - a. Modify based on tuning results (Section 4.2) for improved matching.
 - b. Incorporate robust radome and improved mechanical attachment.
- (2) Use alternative intermediate dielectric constant ($\epsilon_r \approx 5$) to maintain tuning feasibility while maintaining dimensional reductions.
- (3) Design patch antenna array (instead of single patch) for improved feed impedance estimation and tuning capabilities.
- (4) Design high-quality radome (controlled dielectric constant, thickness variations) to interface with Silver Sword missile.
- (5) Further investigate mechanical and aerodynamic effects at antenna section during supersonic missile flight.
- (6) Use three-dimensional structure simulation software (such as HFSS) to redesign antennas in cylindrical form.

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Appendix A: Feed Network Design Procedure in ADS

The following design procedure is used to create, simulate, and optimize the GPS antenna feed networks (Rev 1 and Rev 2) in ADS:

- (1) Create new ADS schematic and enter substrate parameters.
- (2) Place components corresponding to Stage 1 into schematic and use LineCalc to calculate microstrip lengths and width for each line specified in design (based on electrical length and impedance).
- (3) Simulate S -parameters. Adjust line lengths until $|S_{11}|$ minimum occurs at 1.575 GHz operating frequency.
- (4) Add Stage 2 components corresponding to schematic; Stage 1 and Stage 2 are interconnected. Use LineCalc to determine microstrip lengths and widths for each line specified in design (based on electrical length and impedance).
- (5) Repeat (3).
- (6) Add Stage 3 components to schematic; Stage 1, Stage 2, and Stage 3 are interconnected (complete network). Use LineCalc to determine microstrip lengths and widths for each line specified in design (based on electrical length and impedance).
- (7) Repeat (3).

Appendix B: Antenna Assembly Procedure

The following construction procedure is used to assemble the Rev 1 GPS antennas on cylindrical or planar ground planes:

- (1) Trim dielectric pin coating (white) on SMA connector to match ground plane thickness. Place SMA connector in ground plane hole (connector facing inside cylinder or protruding from bottom of planar ground plane; pin protruding from outer surface).
- (2) Trace outline of flex PCB and feed hole location onto dielectric substrate.
- (3) Cut (with razor blade) outlined dimensions of dielectric substrate.
- (4) Punch hole (with screwdriver) through feed hole marking on substrate.
- (5) Expose adhesive on one side of dielectric substrate and feed SMA connector pin through punched feed hole.
- (6) For cylindrical ground planes: line up dielectric edges with recess edges and wrap completely around missile section. For planar ground planes: center dielectric substrate and apply to surface. NOTE: Be careful to minimize ripples and air pockets. The substrate should adhere to the aluminum surface.
- (7) Expose adhesive on outside of dielectric substrate.
- (8) Place PCB feed hole through connector pin and wrap completely around missile section. The PCB should adhere to the dielectric substrate adhesive. Be sure to align the PCB with the substrate.
- (9) Epoxy SMA connector to inside of missile section. Use conductive epoxy.
- (10) Solder SMA connector pin to PCB feed point (copper pad). Trim excess.

Appendix C: Matlab Code

The following is the Matlab *m*-file written to extract data from the Rev 1 GPS

receiver test:

```
clear
load mod.csv

% (r,c)
r = 1;
t = 1;
sizeof = size(mod);
rows = sizeof(1);

while (r<=rows)

if or((and((mod(r,1)==2),(mod(r,2)==1))),(mod(r,1)==1))
count(t,1) = mod(r,3);
satID1(t,1) = mod(r,4);
elev1(t,1) = mod(r,5);
azim1(t,1) = mod(r,6);
SNR1(t,1) = mod(r,7);
satID2(t,1) = mod(r,8);
elev2(t,1) = mod(r,9);
azim2(t,1) = mod(r,10);
SNR2(t,1) = mod(r,11);
satID3(t,1) = mod(r,12);
elev3(t,1) = mod(r,13);
azim3(t,1) = mod(r,14);
SNR3(t,1) = mod(r,15);
satID4(t,1) = mod(r,16);
elev4(t,1) = mod(r,17);
azim4(t,1) = mod(r,18);
SNR4(t,1) = mod(r,19);

if mod(r,1)==1
    satID5(t,1) = 0;
    satID6(t,1) = 0;
    satID7(t,1) = 0;
    satID8(t,1) = 0;
    satID9(t,1) = 0;
    elev5(t,1) = 0;
    elev6(t,1) = 0;
    elev7(t,1) = 0;
    elev8(t,1) = 0;
    elev9(t,1) = 0;
    azim5(t,1) = 0;
    azim6(t,1) = 0;
    azim7(t,1) = 0;
    azim8(t,1) = 0;
    azim9(t,1) = 0;
    SNR5(t,1) = 0;
    SNR6(t,1) = 0;
    SNR7(t,1) = 0;
    SNR8(t,1) = 0;
    SNR9(t,1) = 0;
end

if mod(r,1)==2
    r = r + 1;
    if r > rows
        break
    end
elseif mod(r,1)==1
    r = r + 1;
    t = t + 1;
    if r > rows
```

```

        break
    end
end
end

if and((mod(r,1)==3),(mod(r,2)==1))
count(t,1) = mod(r,3);
satID1(t,1) = mod(r,4);
elev1(t,1) = mod(r,5);
azim1(t,1) = mod(r,6);
SNR1(t,1) = mod(r,7);
satID2(t,1) = mod(r,8);
elev2(t,1) = mod(r,9);
azim2(t,1) = mod(r,10);
SNR2(t,1) = mod(r,11);
satID3(t,1) = mod(r,12);
elev3(t,1) = mod(r,13);
azim3(t,1) = mod(r,14);
SNR3(t,1) = mod(r,15);
satID4(t,1) = mod(r,16);
elev4(t,1) = mod(r,17);
azim4(t,1) = mod(r,18);
SNR4(t,1) = mod(r,19);

r = r + 1;
if r > rows
    break
end
end

if or((and((mod(r,1)==2),(mod(r,2)==2))),(and((mod(r,1)==3),(mod(r,2)==2))))
satID5(t,1) = mod(r,4);
elev5(t,1) = mod(r,5);
azim5(t,1) = mod(r,6);
SNR5(t,1) = mod(r,7);
satID6(t,1) = mod(r,8);
elev6(t,1) = mod(r,9);
azim6(t,1) = mod(r,10);
SNR6(t,1) = mod(r,11);
satID7(t,1) = mod(r,12);
elev7(t,1) = mod(r,13);
azim7(t,1) = mod(r,14);
SNR7(t,1) = mod(r,15);
satID8(t,1) = mod(r,16);
elev8(t,1) = mod(r,17);
azim8(t,1) = mod(r,18);
SNR8(t,1) = mod(r,19);

if mod(r,1)==2
    satID9(t,1) = 0;
    elev9(t,1) = 0;
    azim9(t,1) = 0;
    SNR9(t,1) = 0;
end

if mod(r,1)==2
    r = r + 1;
    t = t + 1;
    if r > rows
        break
    end
elseif mod(r,1)==3
    r = r + 1;
    if r > rows
        break
    end
end
end
end

if and((mod(r,1)==3),(mod(r,2)==3))
satID9(t,1) = mod(r,4);

```

```

elev9(t,1) = mod(r,5);
azim9(t,1) = mod(r,6);
SNR9(t,1) = mod(r,7);
r = r + 1;
t = t + 1;
if r > rows
    break
end
end
end

time = t - 1;
t = 1;

while (t<=time)
    final(t,1) = count(t);
    final(t,2) = SNR1(t);
    final(t,3) = SNR2(t);
    final(t,4) = SNR3(t);
    final(t,5) = SNR4(t);
    final(t,6) = SNR5(t);
    final(t,7) = SNR6(t);
    final(t,8) = SNR7(t);
    final(t,9) = SNR8(t);
    final(t,10) = SNR9(t);

    t = t + 1;
end

xlswrite('data.xls',final)

```

Appendix D: Incremental Tuning Method for Feed Network Optimization in ADS Momentum

The following procedure is used to adjust and optimize the GPS antenna feed network (Rev 2) in ADS Momentum:

- (1) Open existing Stage 1 schematic and import network into layout.
- (2) Define Momentum substrate.
- (3) Simulate S -parameters in Momentum. Adjust line widths and quarter-wave transformer lengths in layout until $|S_{11}|$ minimum occurs at desired frequency (1.575 GHz).
- (4) Add existing Stage 2 schematic to adjusted Stage 1 schematic. Import network into layout.
- (5) Repeat (3).
- (6) Add existing Stage 3 schematic to adjusted Stage 1/Stage 2 schematic. Import network into layout.
- (7) Repeat (3).

Appendix E: Complex Impedance Shunt-Stub Design Calculations

The matching configuration for the complex impedance shunt stub design of Section 5.3.4 is shown in Figure E.1.

Figure E.1 – Matching Configuration for Stage 1

(Spacer Transmission Line, Open-Circuit Stub, Quarter-Wave Transformer)

Since it is impractical to place a shunt stub directly against the radiating patch, a transmission line was inserted between the feed port and the remainder of the matching network. A spacing of 800 mil (2.032 cm) was chosen. The corresponding electrical length βl was found via LineCalc:

$$\beta l_{ADJ} = 98.867^\circ.$$

Using $Z_0 = Z_{ADJ} = 50 \, \Omega$, $Z_L = 274.4 + j132.4 \, \Omega$, and solving for the input impedance Z_1 :

$$Z_1 = (50\Omega) \cdot \frac{(274.4 + j132.4\Omega) + j(50\Omega) \tan(98.867^\circ)}{(50\Omega) + j(274.4 + j132.4\Omega) \tan(98.867^\circ)},$$

$$Z_1 = 7.4006 + j4.0191\Omega.$$

The input impedance including the open-circuit stub is:

$$Y_2 = Y_1 + Y_{IN_stub}.$$

To calculate y_1 :

$$y_1 = \frac{1}{z_1} = \frac{1}{0.14801 + j0.08038} = 5.2174 - j2.8335.$$

$$\therefore y_{IN_stub} = j2.8335,$$

$$\therefore \beta l = 70.56^\circ.$$

An open-circuit stub length of $\beta l = 70.56^\circ$ (571 mil) results in a purely real input impedance at y_2 . To match g_2 to input impedance Z_{IN2} , a pair of quarter-wave transformers are used. Two transformers are used to maintain line impedances low enough to avoid the minimum realizable trace width (20 mil).

$$Z_{T1} = \sqrt{Z_2 \cdot Z_{IN1}},$$

$$Z_{T2} = \sqrt{Z_{IN1} \cdot Z_{IN2}},$$

where:

$$Z_2 = z_2 \cdot Z_0 = \frac{Z_0}{y_2} = \frac{50\Omega}{5.2174} = 9.583\Omega.$$

Choosing $Z_{T1} = 50 \Omega$ yields:

$$Z_{IN1} = \frac{Z_{T1}^2}{Z_2} = \frac{50^2}{9.583} = 260.88\Omega.$$

Choosing $Z_{T2} = 70 \Omega$ (maximum realizable line impedance) yields:

$$Z_{IN2} = \frac{Z_{T2}^2}{Z_{IN1}} = \frac{70^2}{260.88} = 18.78\Omega.$$

Appendix F: Revised Antenna Assembly Procedure

The following construction is used to assemble the Rev 2 GPS antennas on the cylindrical ground planes. It is similar to the procedure outlined in Appendix B, except for modifications made to improve assembly quality (e.g. reduction of air pockets, ripples, and misalignment).

- (1) Trim dielectric coating (white) on SMA connector to match missile thickness.

Place SMA connector in casing hole (connector facing inside cylinder, pin protruding outwards).

- (2) Remove backing on one side of dielectric substrate to expose adhesive.

- (3) Place flex PCB onto exposed adhesive. Flatten surface so no ripples remain.

- (4) Trim excess dielectric substrate with razor blade. Dielectric substrate should now be same size as flex PCB.

- (5) Remove backing on other side of dielectric substrate to expose adhesive.

- (6) Carefully place the exposed dielectric through the protruding SMA pin and roll the PCB onto the aluminum cylinder. Flatten surface so no ripples remain.

- (7) Trim any overlap where the PCB ends meet.

- (8) Solder SMA connector pin to PCB feed point (copper trace). Trim excess.

- (9) Use conductive epoxy between SMA connector outer conductor and inside of aluminum missile section to ensure electrical connectivity and mechanical stability.

- (10) Verify connectivity with multimeter (conductivity test).

Appendix G: Analysis of Senior Project Design

G.1 Summary of Functional Requirements

The Stellar Exploration Silver Sword target missile Rev 1 antenna receives GPS signals at the L1 carrier frequency (1.575 GHz). The conformal design allows for signal lock regardless of orientation. The antenna interfaces with the target missile to provide flight coordinates. System performance is assessed in simulations, anechoic chamber measurements, and GPS receiver testing. The antenna failed mechanically (ripped from surface) during a missile test launch, highlighting the need for improved attachments and aerodynamic considerations.

The Rev 2 GPS antenna improves upon the Rev 1 design, minimizing dimensions, introducing improved impedance matching, and incorporating a radome. Design requirements are met in simulations. Anechoic chamber testing demonstrated inadequate input matching. GPS receiver testing resulted in failure to lock onto more than two satellites, highlighting the need for further revision.

G.2 Primary Constraints

Physical Limitations

The antenna must be flush with the missile surface. The missile casing is recessed at the antenna location to accommodate dielectric thickness. Protrusions beyond the missile surface generate air drag and are susceptible to increased temperature during supersonic flight. Thus, protrusions are not allowable and the antenna must conform to the provided antenna section.

The radome provided by Stellar Exploration is a fiberglass composite with a dielectric constant between 4.2 and 4.9. Since the material is a composite, introduction of supplementary materials affects this value. Thus, the dielectric constant of the radome is not well controlled, which affects antenna performance when compared to design and simulations. Additionally, radome thickness and surface quality (roughness) is not controlled due to the fabrication process used (molding); variations in radome thickness (± 50 mil) also affect antenna performance and introduce undesired radiation pattern variations.

Design Limitations

Agilent's Advanced Design System (ADS) was used as the simulation tool for this project due to availability. One major drawback with ADS is its inability to model and simulate three-dimensional structures. Ideally, an alternate design software such as Ansoft's High-Frequency Structure Simulator (HFSS) is used, but a license was not available at Stellar Exploration. Thus, the antenna was designed within ADS as a planar antenna and then constructed as a non-planar antenna (cylindrical).

Microstrip antenna bandwidth increases with substrate thickness. However, the maximum thickness for a flexible printed circuit board (PCB) is 10 mil. To achieve the desired bandwidth, a thicker dielectric substrate (62.5 mil, Eccostock PP-4) was selected to construct a multilayer substrate.

Testing and Tuning Limitations

Characterizing antenna performance (input matching, radiation patterns) required Cal Poly's anechoic chamber.

Tuning the antenna required patch length trimming; however, it was difficult to make consistent cuts around the conformal antenna's circumference. Furthermore, the increased dielectric constant of the Rev 2 antenna effectively decreased the guided wavelength. Thus, the performance changes more drastically with antenna structure dimensional variations, making tuning more difficult. Proper tuning required trimming 0.2 mm from the patch length. This precision is not physically possible.

G.3 Economic

Original Estimated Cost of Component Parts

A component parts estimate was not established at the start of the project; however, the project proposal indicated a desired total budget of less than \$10,000.

Actual Final Cost of Component Parts

The final cost of all component parts for both antennas is \$5,657.55. Total component cost for constructing *one* antenna is approximately \$1,000.00. The final cost of all antenna testing for both antennas is \$2,638.00. Design, simulation, construction, testing, and documentation required approximately 460 labor hours at a rate of \$16.00/hour, for a total of \$7,360.00.

Final Bill of Materials for All Components

Table G-1 – Final Bill of Materials

Item No.	Item Name	Cost/Unit	Qty	Total
1	Rev 1 Flex PCB (Advanced Assembly)	\$727.30	3	\$2,182.00
2	Rev 2 Flex PCB (Advanced Assembly)	\$727.30	3	\$2,182.00
3	Eccostock PP-4DSS9 Dielectric Substrate with $\epsilon_r = 1.06$ (Emerson & Cuming Microwave Products)	\$51.20	7	\$358.40
4	DSS6M Dielectric Substrate with $\epsilon_r = 10$ (Emerson & Cuming Microwave Products)	\$90.85	5	\$454.25
5	Long-sleeve SMA connectors	\$10.00/bag	1	\$10.00
6	Loctite 3888 Conductive Silver Epoxy	\$20.00	3	\$60.00
7	Tallysman Wireless 25 dB L1 GPS Amplifier	\$181.00	1	\$181.00
8	Coaxial cables	\$10.0/bag	1	\$10.00
9	1-2620 Low VOC Conformal Coating (Dow Corning)	\$219.90/tub	1	\$219.90

Additional Equipment Costs

In addition to antenna components, anechoic chamber testing introduced additional costs. The Rev 1 antenna testing cost \$753.00 and the Rev 2 antenna testing cost \$1,885.00, for a total of \$2,638.00.

Original Estimated Development Time

A Gantt chart work schedule was created at the start of each quarter to determine estimated completion time for project milestones. Exact time estimates were not developed; only milestone deadlines were set.

Actual Development Time

From start to finish, the total project required approximately 460 hours of labor to complete. This is equivalent to 57.5 eight-hour work days, or 11.5 work weeks.

G.4 Commercial Manufacturing

Individual GPS antennas will not be sold. Instead, they will be part of completed Silver Sword target missiles. Estimated number of devices sold per year, manufacturing costs, purchase prices, profit, and user cost is currently unknown.

G.5 Environmental Considerations

Antenna use does not impact the environment in any way. Manufacturing environmental impact depends on processes used by Advanced Assembly and Emerson & Cuming Microwave Products to fabricate flex PCBs and dielectric substrates.

G.6 Manufacturability

Antenna assembly requires careful application of adhesive dielectric substrate to both the flex PCB and cylindrical test fixture. Improper application results in undesired layer misalignment, air pockets, or ripples. Refer to Sections 3.2 and 6.1 for more details.

G.7 Sustainability

Issues or Challenges with Maintaining Completed Device

Once an antenna is assembled, tuned, and tested, it will remain in working order. Thus, no additional effort is required to maintain a completed device.

Impact on Sustainable Use of Resources

The Silver Sword target missile is intended for one-time use. When used to test a missile defense system, the target missile will be destroyed, along with all components, including the GPS antenna. In its intended application, the GPS antenna is also one-time use and is not recoverable. As a result, a new antenna must be constructed for each target missile.

Upgrades for Design Improvement

The GPS antenna design could be improved by implementing the following recommendations:

- (1) Modify Rev 1 GPS antenna design by incorporating tuning results (Section 4.2) for improved matching.
- (2) Modify Rev 1 GPS antenna design by incorporating robust radome and improved mechanical attachment.
- (3) Use alternative intermediate dielectric constant ($\epsilon_r \approx 5$) to maintain tuning feasibility while maintaining dimensional reductions.
- (4) Design patch array (instead of single patch) for improved feed impedance estimation and tuning capabilities.
- (5) Design high-quality radome (controlled dielectric constant, thickness variations) to interface with missile.

Issues or Challenges with Upgrading Design

For the given application, design upgrades should be implemented in a new antenna revision. Altering an already manufactured antenna would prove difficult.

G.8 Ethical Considerations

The ethical considerations for weapons systems design vary based on intended application. The Silver Sword target missile is intended to help the United States and its allies test and maintain defense systems to protect against ballistic missile attack.

G.9 Health and Safety

The GPS antenna poses no threat to health or safety.

G.10 Social and Political

Missile defense systems not only provide defense against ballistic missile attack, but can also serve as deterrents against hostile nations.

G.11 Development

New Tools/Techniques Learned Independently During Course of Project:

- Antenna design and simulations using ADS Momentum.
- Estimation of multi-stage feed network input impedance via iterative simulation procedure.
- Input matching and radiation pattern measurements in anechoic chamber.