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ANTENNA DETUNING ON PROJECTILES

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As more precision munitions are requiring in-flight radio services, such as Global Positioning System (GPS) or telemetry, it is important to get the antenna designs that are used right. This memorandum describes the effects of antenna detuning, a phenomena where unintended close proximity of an antenna's radiating elements to the metal projectile body and the dielectric loading caused by radome or a windscreen will shift the antenna out of its designed radio frequency band. This will reduce or eliminate its ability to provide radio coverage by shifting its center frequency, reducing its gain, and skewing its radiation pattern. Project managers should expect this to occur in every precision munition end-application and will result in decreased performance and even test failure if not mitigated. An explanation of the two phenomena are given for the case of GPS microstrip (patch) antennas, along with methods of correction.

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CONTENTS

FIGURES

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INTRODUCTION

Unlike other electronic components, an antenna is an open radiating device where its performance will depend not only on how it's made, but on how it is mounted and what materials are in close proximity. For a precision munition program, it should be expected and planned into a project schedule to either develop custom antennas for that airframe or to have to purchase off-the-shelf radiating elements and physically modify them (i.e., tune them) to achieve the desired resonate frequency. This should be expected to occur once the projectile's airframe and radome materials are nearly finalized as any design or material changes will require a new antenna design and further frequency tuning. In addition, radio frequency (RF) links follow a logarithmic scale—what appears to work in the laboratory at a range of a few meters will not be a guarantee of what will work in-flight at a range of several kilometers when fired at high quadrant elevations. Therefore, it is imperative that RF engineers with appropriate knowledge and experience in antenna design work in tandem with projectile mechanical engineers on programs as the projectile is being developed.

Because Global Positioning System (GPS) is widely used, there are many commercially available antenna options at different price points for product integrators to select from when developing a receiver. At higher price points, there are GPS antennas that come prepackaged with mounting and radome solutions so as to not degrade the antenna performance. However, these solutions typically cannot be used on a projectile airframe—either the mounting scheme or the radome need to be changed.

These bare antenna elements can be purchased. Recognize, however, that they are designed to function when mounted on a specific ground plane and under a specific radome. They should be expected to require physical modification in order to tune them when mounted in the end-application projectile. In the case of GPS patch elements, the geometry of the elements are designed to function when placed on a flat surface, typically flush with the ground plane of the patch element so as to act as an extension of it. If they are buried within a metallic pocket, which is usually done so that the patch element doesn't protrude from the projectile's outer profile, it will detune via a mechanism of equivalent-cavity perturbation. If they are covered with a plastic radome material, dielectric loading will detune them further. Both of these mechanisms are explained further on.

Detuning causes two issues:

- Mismatch loss, where the RF energy received by the antenna is not transferred to its feedline and receiver. This loss subtracts directly from the gain pattern of the antenna.

- Polarization loss, where in the case of GPS patch antennas, circular polarization is lost. In the case of receiving right-hand circularly polarized (RHCP) GPS signals, this reduces the gain further, up to a maximum of 3 dB where the antenna becomes fully linearly polarized.

Both losses act to reduce the overall gain of the antenna and skew the final resulting radiation pattern as the antenna element is mounted. From a system's point of view, this results in shrinking of the antenna beam-width (i.e., section of the sky) that a quality link can be established. In order words, it is easy to go from full-sky coverage to partial-sky coverage, or in the worst case, no coverage at all. In the case of GPS, a smaller coverage area also results in poorer dilution of precision (ref. 1).

Retuning may be possible through physical modification of the radiation element, such as trimming the antenna patch, but usually requires a tradeoff in bandwidth, loss of circular polarization, or may not be possible at all depending on the degree of detuning.

The best performance will be achieved with a custom antenna that is designed with the projectile airframe and radome from the start. In order to ensure a cost-effective solution is obtained, project managers include this as early in the design efforts as possible as opposed to later in the development and fabrication phase. It also requires the projectile airframe and radome material be selected early on and be relayed to the antenna designer. Effective communication between the projectile mechanical team and antenna design team is a must as any change to the airframe or radome will result in changes to the resonate properties of the antenna. Importantly, multiple iterations of the antenna design should be expected and built into the contract vehicle.

NEARLY SQUARE CERAMIC GLOBAL POSITIONING SYSTEM PATCH ANTENNAS

Ceramic patch antennas are a popular choice used for GPS systems. These electrically-small antennas are typically formed from a ceramic dielectric square with metallization on the top for a rectangular patch, metallization on the bottom for the ground plane, and a probe feed that couples the patch to a coaxial cable feed. While there are several techniques to achieve circular polarization, a popular choice is a "nearly-square patch" design. It achieves RHCP polarization by exciting two orthogonal transverse magnetic (TM) modes (TM10 and TM01) within the cavity of the patch (refs. 2 and 3). The resonant frequencies of the modes are designed to be slightly above and slightly below L1 (1575.42 GHz) and are driven 90 deg out of phase, achieving circular polarization. To excite each mode evenly, a probe feed is placed along the main diagonal and positioned so that the match to each mode is at its greatest. Figure 1 shows the GPS ceramic patch element (ref. 4). Figure 2 shows a diagram of a microstrip (patch) antenna.

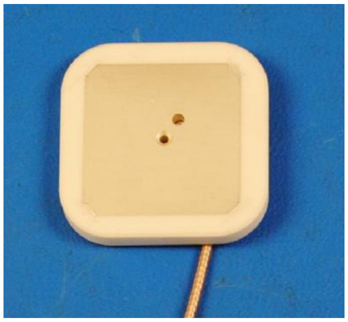
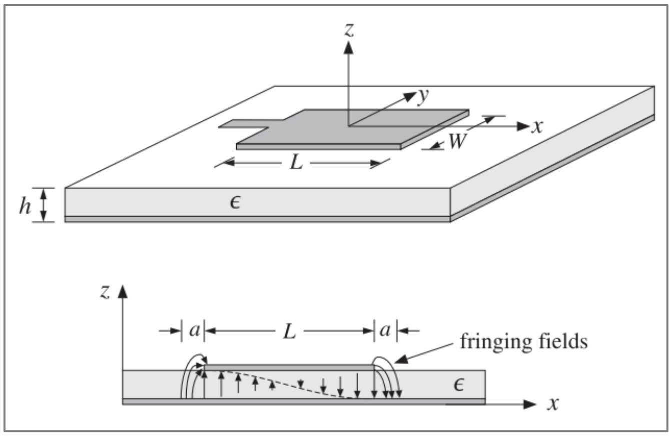


Figure 1
GPS ceramic patch element [the corners of the patch has been trimmed for tuning (ref. 5)]



Note: E-field magnitude and direction with fringing fields.

Figure 2
Diagram of microstrip (patch) antenna reproduced from reference 6

As seen in figure 3, TM10 mode is characterized by a single half-sinusoid variation in the E-field and H-field magnitudes in the X-axis. The E-field points along the Z-axis with a null in the middle of the patch and fringing fields on the sidewalls where the magnitude is maximum. The H-field points along the Y-axis with a maximum in the middle of the patch where there are fringing fields in this region as well. All of the fields are uniform in the Z-axis. The TM01 mode is characterized similarly, with only the roles of the X and Y axes having been reversed with fringing fields on the opposite sidewalls. All of the fields vary in time at the operating frequency.

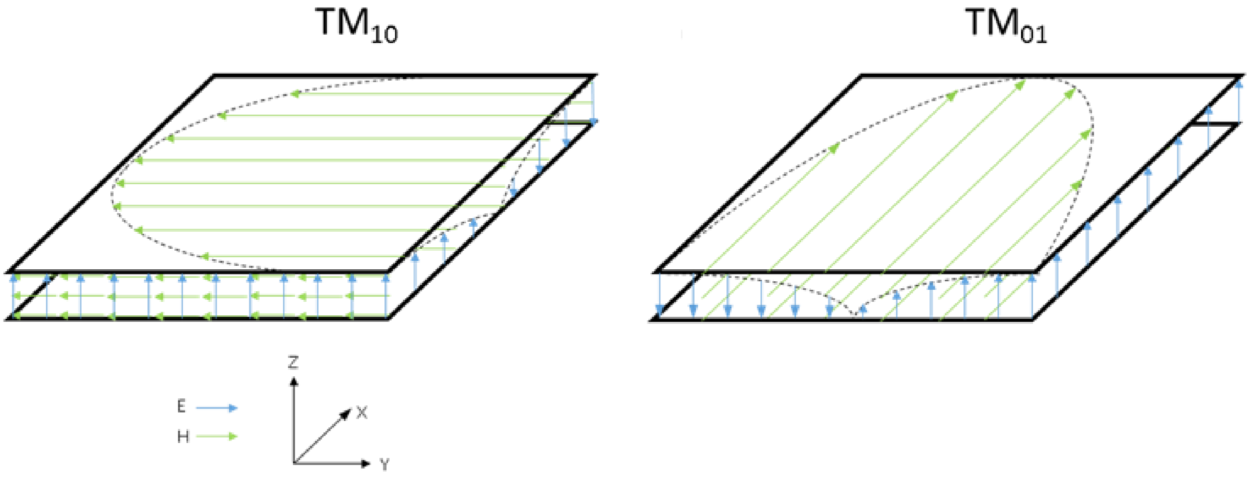


Figure 3
Diagram of E and H fields within patch cavity for both TM10 (left) and TM01 (right) modes

There are three important dimensions in a nearly square patch. First, the X-axis length of the patch, which controls the resonant frequency of the TM10 mode. Second, the Y-axis length of the patch, which controls the resonant frequency of the TM01 mode. The X and Y lengths correspond to a one-half wavelength of the frequency of mode in the substrate material with a small correction from the fringing fields (ref. 2). Substrate materials with higher dielectrics correspond to smaller patch dimensions at the cost of smaller bandwidth. Third, the (Xp,Yp) position P of the feed, which controls the matching between the mode and the feedline (ref. 2).

Return loss is a metric (measured in dB) that is used to determine how well an antenna will transfer RF power to its feed. It represents the energy an antenna does not accept from its source, which will also represent how much energy an antenna will not deliver to its source in receive mode, assuming the antenna material is lossless. A poorly matched antenna will exhibit a mismatch loss; a certain amount of carrier power will be lost, both in transmit and receive mode. A 3-dB return loss corresponds to a 3-dB mismatch loss. A 10-dB return loss is typically considered acceptable with only 0.5-db mismatch loss. Return loss can be measured using a properly calibrated vector network analyzer (VNA). Care must be taken so that feed-line radiation does not affect the measurement. Usually this is done by having the coaxial cable used to feed the antenna, run behind the ground plane. A nearly-square patch, properly operating, usually shows a characteristic doubly-tuned return loss pattern.

DETUNING FROM A METAL POCKET

Placing a patch antenna in a metal pocket is generally not a good idea from a tuning standpoint. The projectile housing should be flush with the ground plane of the patch and no higher. The raised walls of the pocket over the ground plane will cause the center frequencies of the modes to shift. In the case of a nearly-square patch, one mode will be shifted lower and the other mode higher, creating a mismatch loss and losing circular polarization. One explanation for this is that the fields under the patch, with their respective fringing fields, can be treated together to form an equivalent-cavity.

As shown in figure 4, the left and right sides of the patch pictured are known as the radiating edges for the TM10 mode. They experience the strongest E-field magnitude with fringing. The sidewalls of the pocket will act to increase the E-field magnitude further in the fringing area, hence increasing the time-averaged electric energy W_e stored in the total equivalent-cavity as if its volume was increased in this region. From cavity perturbation theory (ref. 7), increasing W_e within the cavity (without change material properties) acts to decrease the resonant frequency.

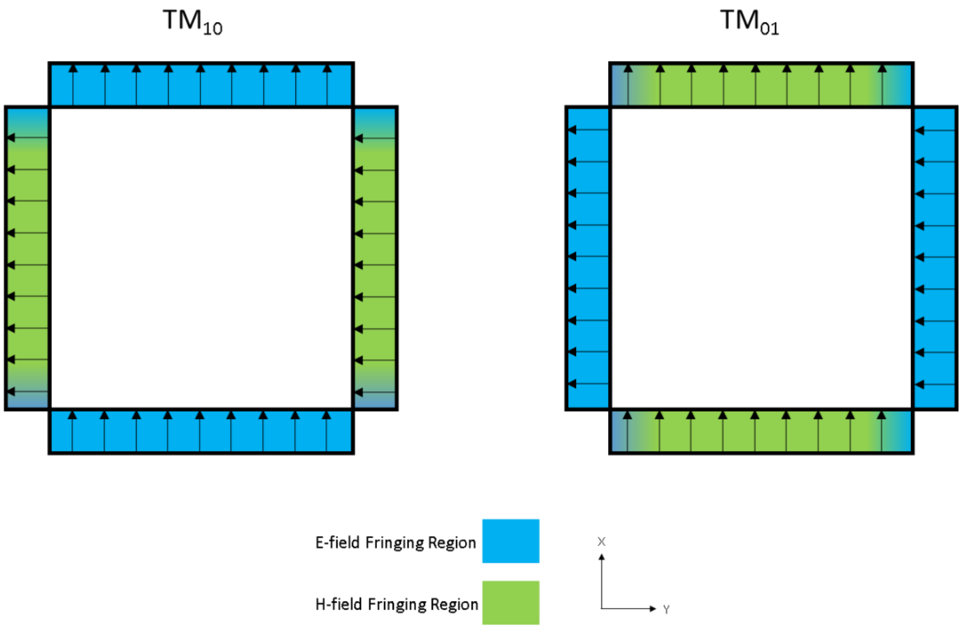


Figure 4
Diagram of patch element fringing field regions for both TM10 and TM01 modes

The top and bottom sides of the patch, also called the nonradiating edges for the TM10 mode, experience the strongest H-field magnitude with fringing. When placed in a metal pocket, currents will form on the sidewalls, acting as image currents for the current distribution on the patch, which then act to increase the fringing H-field magnitude in the fringing region. This will increase the time-averaged magnetic energy W_m stored in the equivalent-cavity for the TM10 mode as if its volume was increased in this region. From cavity perturbation theory once more, increasing W_m acts to increase the resonant frequency of the mode.

For the other mode (TM01), the roles of the radiating and nonradiating edges are reversed; hence, the effects written above for the left/right and top/bottom pocket sidewalls are also reversed.

Once this detuning occurs, it is possible to bring the antenna back in tune by removing patch material from each of the edges. This acts to change the resonant frequency of the modes again by cavity perturbation since now the cavity is being reshaped. The corners of the patch can be cut, transforming the patch into an irregular shape. A mathematical model of corner-cut patches is given in reference 8. In the case of trimming an edge back entirely, the X and Y dimensions of the patch are altered, keeping the patch shape rectangular but with the modes at new resonant frequencies.

However, this works only up to a point. Since the feed is still in the same position, the match for each mode becomes worse the more it is retuned. If observed on a VNA, the return loss for the mode will move upward as it is moved left or right. In addition, one can only remove so much material without altering the fields of the modes significantly, which will degrade the radiation pattern.

From a mechanical point of view, it is best not to bury patch antennas in a pocket. However, if this is unavoidable, it helps to realize that the degree of detuning depends on how close the sidewalls are to the patch element. By keeping a larger separation distance away from the patch, the sidewalls don't interact with the fields of the patch as much, and detuning is reduced. One rule of thumb is to keep the pocket walls away from the patch by twice the height of the patch substrate or more.

The space between the patch and the sidewalls should be filled with a material of a known dielectric constant, which can include the patch substrate. Thus, another mitigation option is to use the same patch element but with a wider substrate and ground plane. Experimentation and computer simulation can help to determine what degree of detuning will be experienced and options for correction.

Another option is to premetallize the edges of the substrate and have the antenna patch designed with this in place. This will act to desensitize the equivalent-cavity from the metal of the projectile beyond this metallization.

DETUNING FROM A RADOME

Dielectric materials near an antenna will also act to detune it. Invoking the equivalent-cavity explanation once more, dielectric materials within proximity of the fringing fields represent a change in the permittivity of a small volume of the equivalent-cavity. This again alters the stored electrical energy W_e within the cavity. Using a version of cavity perturbation theory that deals with permittivity changes (ref. 7), increasing the dielectric constant of a small volume acts to reduce the resonant frequency of the mode. Since the dielectric materials generally have the same permeability as air, they have no effect on the stored magnetic energy W_m of the cavity. They will always act to reduce the center frequency of the antenna. In fact, dielectric loading is a popular method of creating electrical-small antennas. The substrate material itself can be viewed as dielectric loading.

For a nearly-square patch, if the antenna is evenly covered with the radome material, both modes should experience the same amount of shifting and maintain circular polarization, although at a lower center frequency. However, some radomes generally are thicker in one dimension than in the other, which leads to uneven shifting.

From a mechanical point of view, it is also best not to dielectrically load the patch by placing it in close proximity to the radome material. However, this is generally unavoidable as you typically need a radome to protect the antenna from propellant gas blow-by and outside elements, provide gun hardening by retaining the antenna element to the projectile body, and maintain the outer airframe profile of the projectile for aerodynamics. Since space is at a premium on the projectile, placing a gap between the antenna and its radome is usually not feasible but would help to reduce the effects of dielectric loading.

Thus, the antenna geometry should be designed to be mounted under the radome with the exact material that will be used. It is important to use material whose relative dielectric constant (εr) is known, is generally constant from piece to piece, and remains stable over temperature and is unaffected by moisture. Changing the radome material will result in the antenna needing to be retuned or redesigned.

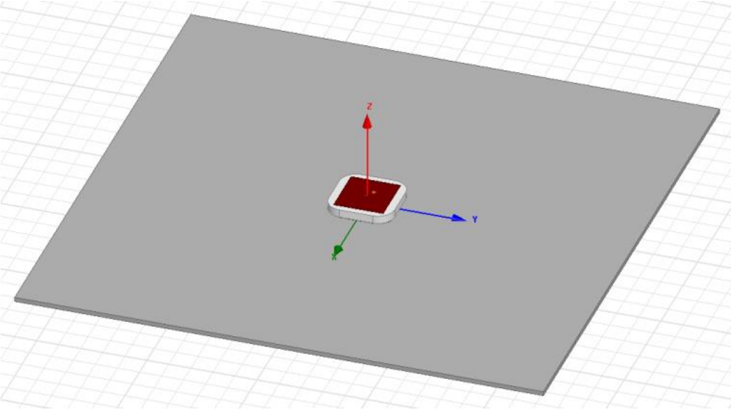
If an off-the-shelf antenna is to be used, then it should be expected that the same tuning procedure as described previously for detuning from a metal pocket will need to be performed. By trimming the patch antenna down, it is possible to raise the resonant frequencies of its modes to counter the dielectric loading. Again, however, without moving the feed point, this will only work up to a point as RF match to the feed is lost.

DETUNING EXAMPLES

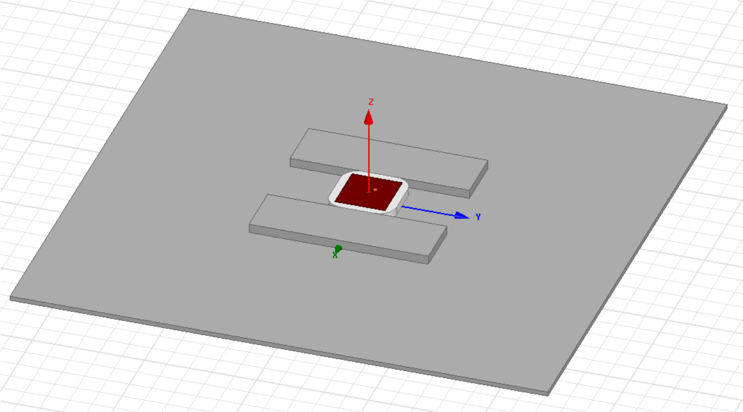
A ceramic, nearly-square GPS patch antenna was modeled in Ansys high-frequency structure simulator (HFSS) in three configurations:

- Resting on a 12-in. by 12-in. ground plane
- Resting on the same ground plane and placed in a 0.2-in. deep pocket with top and bottom side walls
- Resting on the same ground plane and placed in the same pocket but then embedded in a radome made of Ultem 2300.

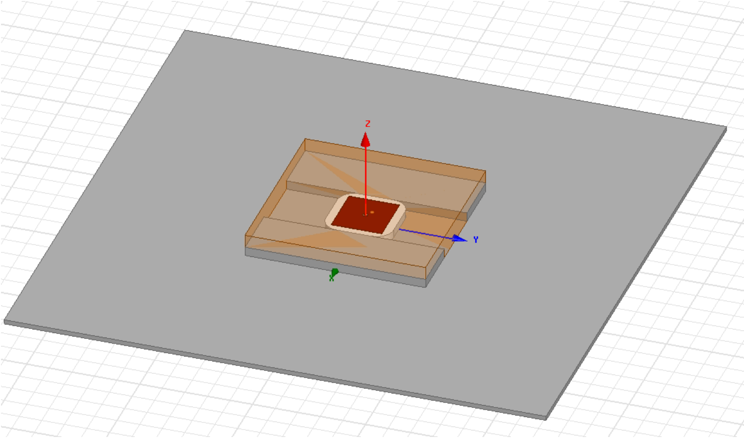
The antenna was designed to operate with RHCP at L1 (1575.42 MHz). Rendering of the simulations are shown in figure 5, along with the resulting return loss and radiation pattern simulations (fig. 6).



(a)
GPS patch on 12-in. by 12-in. ground plane



(b)
GPS patch on ground plane in metal pocket



(c)
GPS patch on ground plane, in metal pocket, and with radome covering

Figure 5
Three configurations of GPS patch

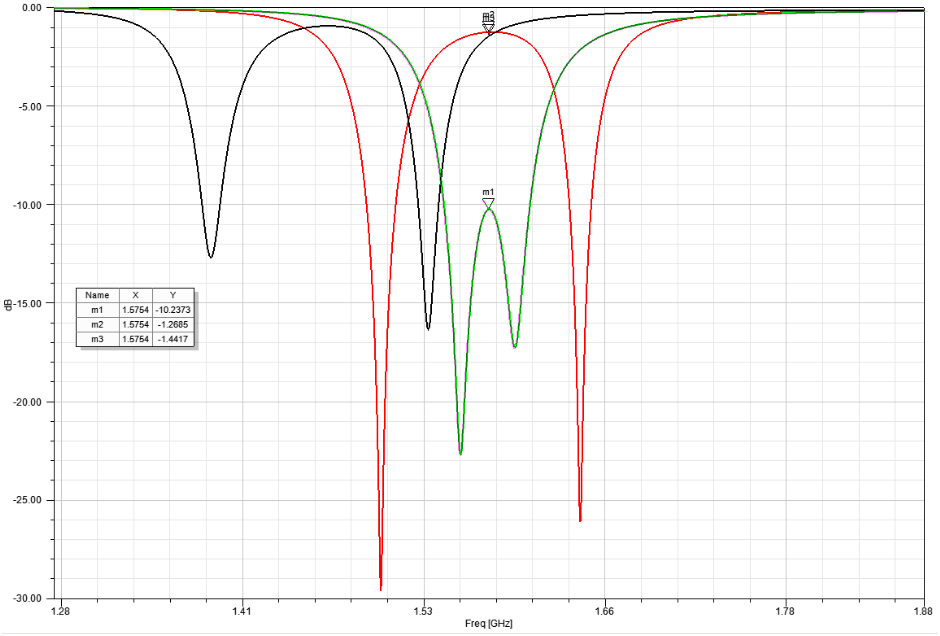


Figure 6
Return loss patterns for GPS patch

Figure 7 shows the successive loss in gain for the patch element in all three situations. This loss can be explained by the simulated return loss plots shown in figure 6. The results when the patch element is resting on the ground plane only are shown in green. The return loss shows a characteristic double-tuned response with L1 at an acceptable -10.24-dB level between the two resonances, which yields only 0.43 dB of mismatch loss. The resulting realized RHCP gain plot is shown in green in figure 7, which is a cut of the XZ plane. Realized RHCP gain takes into account the resulting mismatch loss from the return loss. Peak gain is 4.65 dBiC with a -3 dBiC beam width of 120 deg.

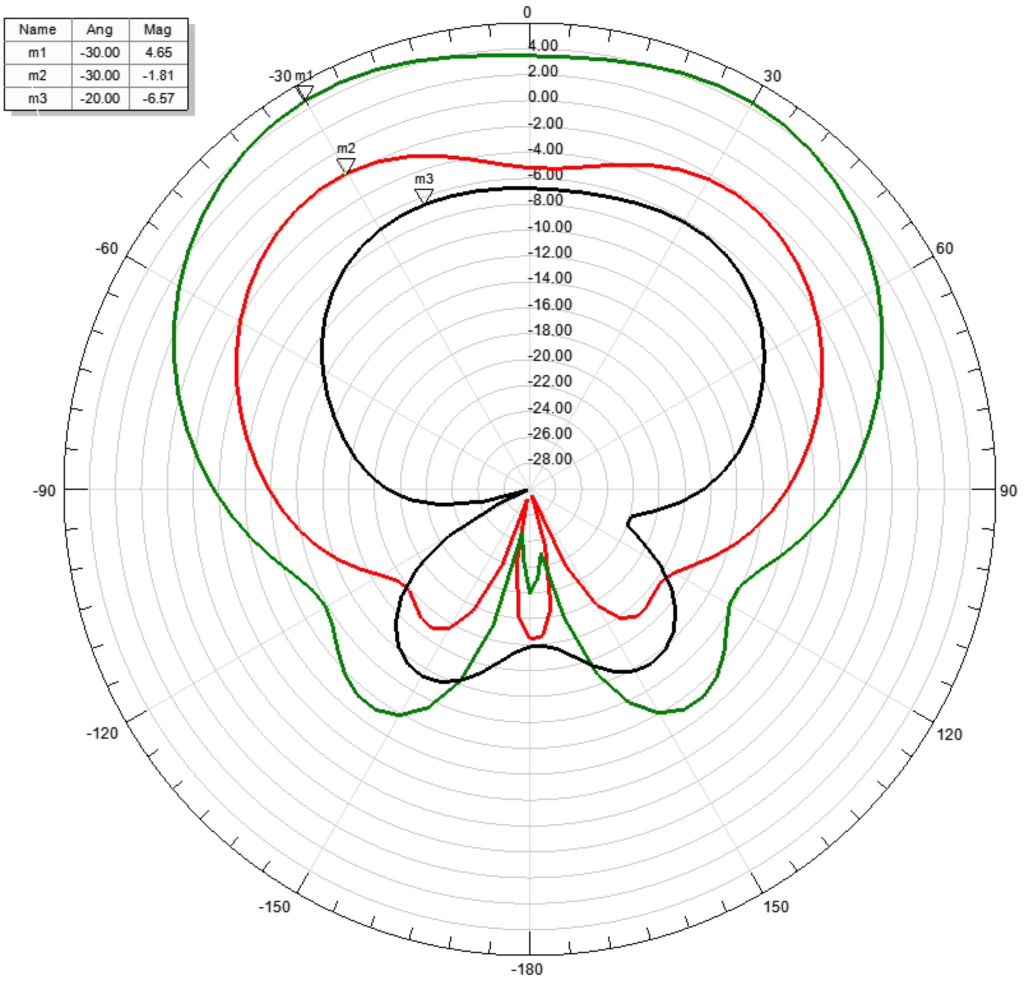


Figure 7
RHCP realized gain for GPS patch in the XZ plane

The results when the patch element is placed in the pocket are shown in red. The resonances have both shifted to higher and lower frequencies as expected, and the resulting return loss at L1 is an abysmal -1.27 dB. This corresponds to 5.96-dB mismatch loss. The resulting radiation pattern has been reduced in all directions with peak gain diminished to -1.81 dBiC, which is 5.92 dB less than the original.

Finally, the results when the patch element is mounted within the pocket and then covered in an Ultem 2300 radome[1] are shown above in black. Both resonances have shifted to lower frequencies, and the return loss at L1 is now -1.44 dB. The resulting radiation pattern has been reduced further with a peak gain now of -6.57 dBiC. While the return loss was nearly the same as before, the loss in gain can be attributed to a loss of circular polarization as now L1 is no longer between the two resonances.

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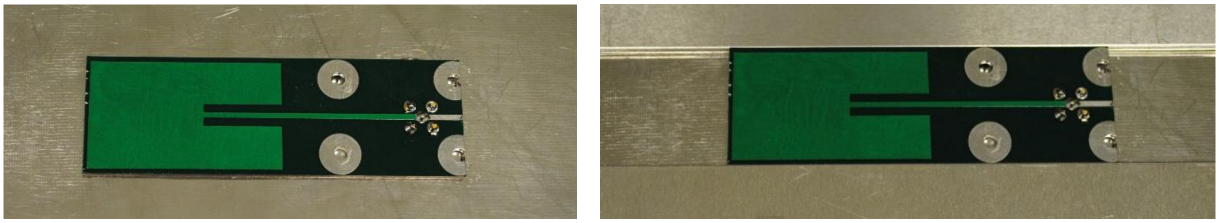
[1] Material properties: dk: 3.7; df: 0.0015 (ref. 9).

For a second example, an inset fed, linearly polarized patch was built and tested in the following four configurations:

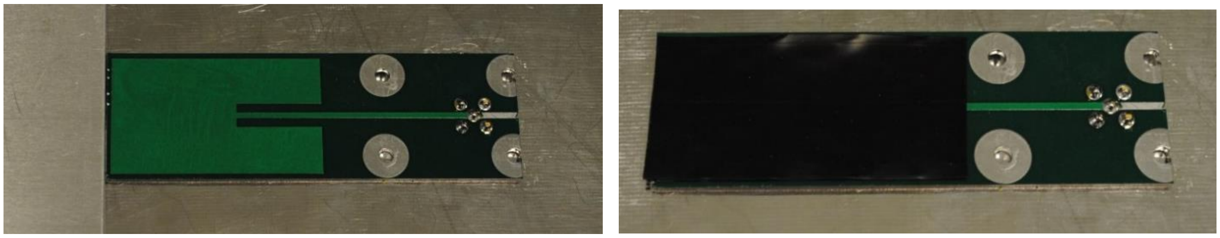
- On a 12-in. by 12-in. copper clad FR4 ground plane
- With two aluminum plates on the top and bottom, totaling 0.080 in. in height
- With two aluminum plates pushed on the left side of the patch
- With a piece of self-adhesive, 1-in. width, 0.030-in. thick silicon tape covering the patch, acting as a radome.

The antenna was removed from a larger array, designed to operate at 2.24 GHz, and is made of Rogers RT/Duroid 5870, 0.062-in. thick material. The antenna is linearly polarized, which means only one mode (TM10) is present in the patch cavity. Images of the four configurations are shown in figure 8.



(a)
Patch antenna on 12-in. by 12-in. ground plane

(b)
Patch antenna on ground plane with aluminum plates on upper and lower sides



(c)
Patch antenna on ground plane with aluminum plates on left-hand side

(d)
Patch antenna on ground plane with silicon tape covering only

Figure 8
Four configurations of an inset fed patch antenna

Return loss measurements were taken with a calibrated VNA and are plotted in figure 9. As expected, only a single resonance is observed from the single mode. In all cases, the operating band of the antenna is shifted away from 2.24 GHz. When the antenna is surrounded by the aluminum plates on the top and bottom, the operating band is shifted higher with a new center frequency of 2.27 Ghz. When the antenna is surrounded by the aluminum plates from the left side, the operating band is shifted lower with a new center frequency of 2.22 GHz. Finally, when the plates are removed, and the silicon tape is placed over the patch, the new operating band is shifted lower again with a new center frequency of 2.22 GHz.

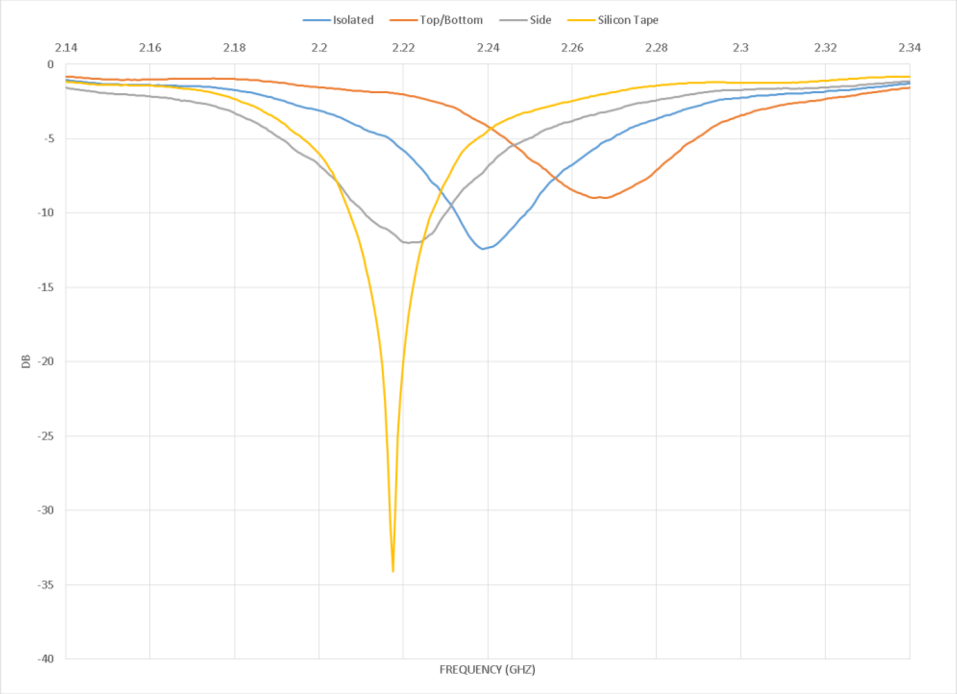


Figure 9
Return loss measurements for linearly polarized patch antenna

FREE-SPACE PATH LOSS (FSPL)

Confirmation of an RF system in a laboratory setting should be part of every program. It is deceptive to believe, however, that the radio services that work at a range of a few meters within the confines of a small room will work when that same projectile is downrange several kilometers since FSPL increases with distance. The FSPL is the amount of signal lost in an RF link from the distance between the transmitter and receiver. It varies logarithmically with distance by 20 dB per decade of increase. It is a part of the Friis transmission equation, which is part of a basic link budget calculation (ref. 2).

Figure 10 plots the theoretical FSPL for an example telemetry system operating at 2.25 GHz. At a range of a 1 m, it is 39.5 dB. At a range of 10 m, it is -59.5 dB. At a range of 1 km, it is -99.5 dB. A proper link budget will determine the amount of link margin needed for a given modulation scheme, bitrate, and acceptable bit rate error. The FPSL cuts right into that link margin and, for a projectile travelling at several hundred m/s, could easily deplete it in a matter of seconds.

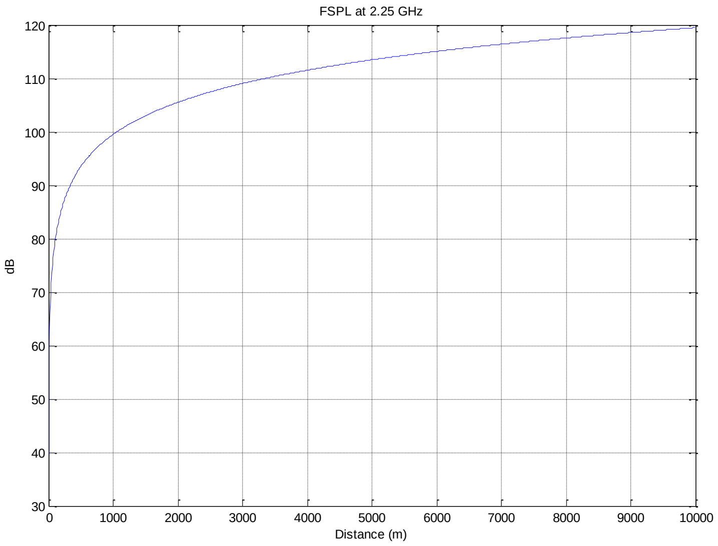


Figure 10
FSPL versus distance at 2.25 GHz

While this example centered on a projectile mounted S-Band transmitting antenna to a telemetry receiving ground station, the same theories and concepts are applicable to a GPS antenna receiving signals from a satellite. An RF system with a poorly detuned antenna will appear to work in the laboratory because there is plenty of margin available at such a short range to close the link but will fail to close once it is downrange. Hence, "working in the lab" should not be used as a surrogate for "working downrange." Proper return loss measurements, RF gain patterns of the antennas only when assembled on a fully built projectile, and an accurate link budget are the appropriate substitutes.

CONCLUSIONS

It is best to think of the entire antenna system as including the projectile metal airframe, the antenna element, and its radome. Stock patch antenna elements should not be expected to function when placed on a projectile, especially in a metal pocket and covered in a radome, as this is basically a different antenna system than what they were designed for. Metal pockets and radomes both act to shift the center frequency of the antenna, creating a mismatch loss, reducing gain, skewing the radiation pattern, and ultimately causing a loss of coverage. This can be explained qualitatively by viewing the fields within the patch and its fringing fields as an equivalent-cavity and applying cavity perturbation theory to it.

Tuning the antennas is therefore required, where a good match can be obtained and the majority of gain recovered in certain cases. Finally, a custom antenna, designed with the metal pocket and radome from the start, can achieve the best performance in terms of bandwidth, beam width, and gain, thus the greatest radio coverage over the sky. This requires the greatest cost in development time, the most antenna design knowledge, and must be integrated with the projectile mechanical design.

Antennas have been used on projectiles since the 1960s with little changes to their designs. With an understanding of what makes them work, what throws them off-tune when integrated, and a proper link budget, success is always within reach.

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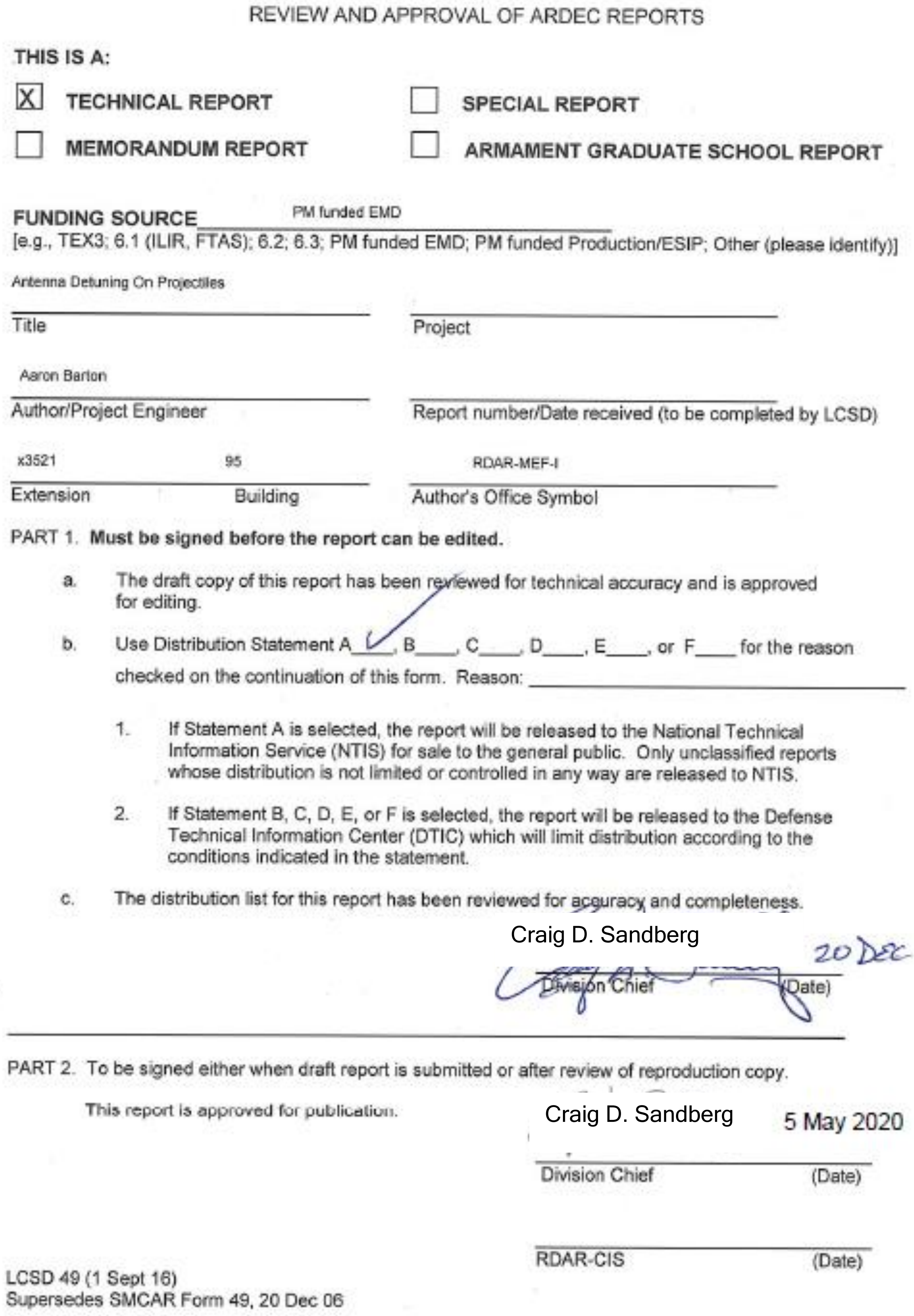

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Project:

Author/Project Engineer: Aaron Barton

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Craig D. Sandberg 20 Dec 2018

Division Chief (Date)

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Craig D. Sandberg 5 May 2020

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