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Defeating Theater Missile Defense Radars with Active Decoys

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A study is made of how decoys of different levels of sophistication can defeat theater missile defense radars. In particular we describe an active decoy system consisting of transponders, located on both decoy and warhead, which are "deceptive jammers," producing returns to the radars that are identical for both decoy and warhead. The signals override the normal signals reflected from warhead or decoy. The method depends only on knowledge of electromagnetic theory and requires no knowledge of "classified" material. It capitalizes on special properties of readily available "frequency independent" antennas. Such decoys can defeat the presently planned THAAD ABM system.

INTRODUCTION

The deployment of well-designed decoys is a well-known path to take to defeat an ABM system.[1] Undoubtedly this path will be taken by any power in the future facing strong US defenses. The key question is whether one can make the decoys indistinguishable from the missile. Indistinguishable means that the electromagnetic returns at any wavelength employed by the radar are identical for both decoy and missile.[2]

Large sums are presently expended by the U.S. Government's Ballistic Missile Defense Organization for the study and deployment of anti-ballistic missiles designed to destroy attacking missiles in flight. In such ABM systems, radars locate the incoming missile and provide the information for launching an ABM designed to seek out and destroy it. The basic question, whose answer must determine whether such efforts are cost effective, is whether countermeasures exist which negate their effectiveness. In that event, one would want to emphasize other methods of protecting against ballistic missiles that might be demonstrated to be effective. Such methods include boost-phase intercepts and destruction of launching platforms.

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In this paper we study a general purpose decoy system but focus on how an enemy would defeat the Theater High Altitude Area Defense (THAAD) ABM system. This system is presently being designed and is expected to be deployed around 2004. It is designed to intercept warheads *above the atmosphere* where, in fact, decoy design is the simplest. Indeed the intercept decision must be made before the time of entry into the atmosphere since there is insufficient time after that event for the ABM interception to succeed.

One important difference for decoys used in theater warfare is the extremely short flight times compared with those that would have accompanied intercontinental ballistic missiles. Thus, decoys should be more effective, the shorter the range of the missile.

In our work we have studied three kinds of decoys: (1) the conventional passive decoy which is inert and only reflects radar signals, (2) the "active deception" *transponder-armed* system which returns signals at the received frequency, rebroadcasting a preprogrammed "jamming" and "masking" signal, and (3) the intelligent decoy/missile that can use a built-in computer to determine the proper transponder signal performance from information received in flight.

However, this report concentrates mainly on examination of the transponder-armed decoy and missile, which we have studied theoretically and experimentally. (We emphasize that there is no implication that properly designed passive decoys may not be effective. Passive decoys differ from the small decoys we describe in that they must be larger in size to simulate the radar time profile of the missile or warhead return. Very small active decoys can also differ from passive decoys in their reentry characteristics.)

The radars can be part of a defense system consisting of search and tracking radars operating in different wavelength bands. They can be of high-range resolution thereby being capable of measuring the length of the attacking missile or warhead. They may also have the capability to employ advanced polarization analysis, frequency hopping, autocorrelation, and pulse compression methods, etc. to recognize incoming missiles or warheads. Thus, the active decoy system must be capable of defeating the counter-counter measures that such capabilities might bring to bear.

The "active" decoys we have designed return detected signals from *both* decoy and missile at the received frequency, whatever it might be, over a huge range of frequencies. They are "deceptive jammers" which mask the normal response back to the defending radars in a variety of ways. Further, the time profile of the signals from the transponders on both decoy and warhead can be made identical. No access to classified material is needed for the design since it depends only on the known physics of electromagnetic radiation.

We also describe a cryptographically secure data storage tape, simulating the return signals from a radar with fractional nanosecond time resolution. It could be interrogated by the Ballistic Missile Defense Organization (BMDO) or any independent countermeasures study group to determine whether our goal has been achieved.

A basic premise of this work is that it is possible for engineers, in any third world country capable of launching ballistic missiles, to design systems at least as good as the ones we shall describe. The needed components are off-the-shelf so that they are easily purchased on the open market. There are no prohibitions in the sale of the antennas and amplifiers that would make up a transponder decoy system.

The study of active decoys is a nice intellectual engineering design problem suitable for training students. As part of their senior theses, two University of Pennsylvania electrical engineering students,[3] with the aid of two engineers,[4] studied the transponder system under the direction of the author. We performed measurements in an anechoic chamber[5] and employing antennas,[6] amplifiers, and spectrum analyzers[7] donated by companies and research workers.[8] The engineers acted as a "red team" for testing out some of the basic decoy ideas examined in this study.

ACTIVE DECOYS

The basic idea, circumventing the notion that there is classified information about the defense radars that must be known to design a decoy system, is that one will have a system that returns, to the radar, signals which are indistinguishable from those reflected from either missile or decoy.

For example, the defender has the possibility of changing the radar frequency, unknown to the attacker. However, it will not be necessary to know the radar frequency. This is made possible by the existence of frequency independent antennas which did not exist many decades ago and which can receive or transmit frequencies over a huge band. Together with similarly wide band amplifiers, they can send high amplitude confusing jamming signals back to the radars at the received frequency. Thus changes in radar frequency, even from pulse to pulse, will not be able to confuse the decoy system we shall describe.

It is desirable to use small, light decoys so that a large number of decoys can be deployed without much loss of warhead range. Since small decoys have different differential radar cross sections than the larger missile (meaning that the magnitude of the reflected signals at different angles of the radar

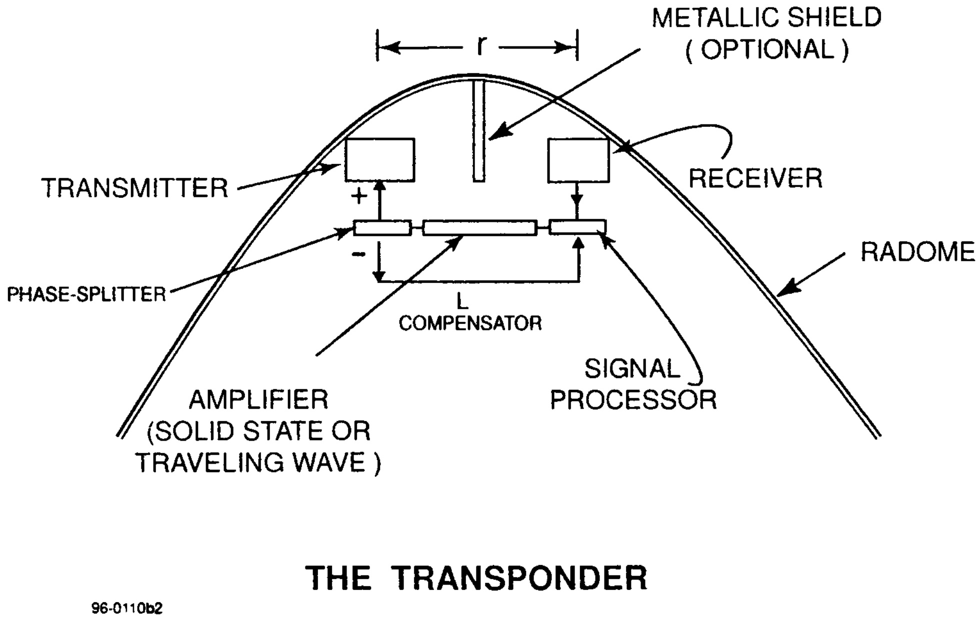

Figure 1: Schematic arrangement inside the radome. The transponder unit consists of the receive and transmit antennas, an amplifier, and a signal processor that modifies the retransmitted microwave signal to simulate real reflections. An optional feature includes a phase-splitter and feedback loop, the compensator, to increase the isolation of the receiving antenna from the transmitting antenna.

beam relative to its target may differ), and since radars of high range resolution can distinguish targets based on their length and shape, one will have to be able to compensate for these differences by proper masking techniques. Fortunately, the designer of the decoys can measure all the properties of both decoy and missile so the design information is available. Further, the designer has the opportunity not only to make the decoy look like the missile but to make the missile look like the decoy.[9]

The basic idea is to mount on the tip of both missile and decoy a transponder, as shown in the crude sketch in figure 1. (The exact shape of the warhead nose is unimportant for the following discussion.)

The transponder has the following properties: (a) the transponder receiver, placed near the tip of the warhead or decoy, receives signals from the radar somewhat earlier than the signals reflecting off the main missile/decoy body, and (b) it then retransmits a signal at the received frequency, which has been amplified and coded, back to the radar via a transponder transmitting antenna. The mean amplification is determined from the known ratio of the signal strengths reflected from missile and transponder. The return signal is made larger than the signals reflected from the decoy or missile bodies and arrives earlier at the radar. The transponder is not a very high gain "amplitude jammer," designed to paralyze the radar receivers, but is a "deceptive jammer." (While the figure shows a phase-splitter and return feedback path marked L compensation, assume they are not used for the discussion which follows, but that the amplifier is connected directly to the transmitter.)

The return signal from a missile may have spikes due to ridges on the missile and returns from sharp edges and the rear of the missile. Radar operators learn to recognize these features, and mathematical techniques, made practical with modern computers, can compare the return signals from successive radar pulses to get a good estimate of the time distribution of the radar return associated with a particular missile. Thus, in principle, they can tell missiles from decoys by examining the details of the rejected signals.

However, the return signal from both decoy and missile transponders is a fabricated signal which creates spikes and other returns characteristic of a true missile reflected signal. One way to accomplish this in a linear fashion is to pass the signals through very short delay lines, adding the signals to produce simulated reflections at different times, corresponding to different reflections along the missile length.

The pulses are, however, spread over a time period equivalent to the length of the true missile return. In this way, the pulses from both decoy and missile are identical in length and are made similar in their response characteristics. (Actually, the transponder responses need not be identical and could vary from decoy to decoy to warhead so that no *common* signal, characteristic of "the" warhead, could be accumulated and stored for pattern recognition. Further, to confuse autocorrelation circuits, additional pulses can be generated where the positions are randomized in time and are changed *from radar pulse to radar pulse*. These would interfere with autocorrelation analyses, producing a very effective noise signal to foil the attempt to pull out the direct missile reflections.)

Just as the decoys can be tailored, so can the missiles. For example, one can put randomized physical protrusions along the missiles so no two missiles have the same time profile, and so, therefore, there is no standard missile pattern, even for the reflected signals which, in any case, would be masked by the more powerful transponder signals. Further, to help prevent recognition, the missile designer can also make the problem easier by using coating techniques to reduce missile cross sections. The coatings could also be used to change each missile profile. Some of the modern methods are wide-band. Using thin layers of ferrite absorbers (five layers of 1.5 mm thickness), one can get attenuations of 10 db from 5–20 GHz.[10] Acetylene black rubber loaded with carbon also produce 10–12 db loss. There is a whole industry making such absorbers.

We now list several questions that we have had to answer whose solutions are treated in the following sections:

(i) What transponder antennas can be used to automatically return the frequencies received?

(ii) What antennas can be used that are off-the-shelf and which can be configured so that the transponder transmitter is sufficiently decoupled from the receiver?

(iii) What power gains are needed in the amplifiers?

(iv) How will the system handle changes of the polarization of the signals from the radar to ensure that the transponder signals overpower the reflected signals no matter what polarization is incident and how the polarization ellipse changes on reflection?

SUITABLE ANTENNAS

Because the exact radar frequency may not be known, one needs to use an antenna capable of receiving and transmitting over a wide frequency band. Such antennas are known as "frequency independent" antennas and there are many varieties to choose from: spiral, ambidextrous spiral, log periodic, helix and horn. One antenna we have studied experimentally for transponder use is the AEL[11] ASO 1563 spiral antenna. It is of Archemedean type and transmits circularly polarized radiation. It has a bandwidth of 2–18 Gigahertz (GHz), easily covering the whole expected radar spectrum. Such antennas have the property that their antenna patterns are in principle and in practice almost frequency independent. They are light and small in size. The antennas we experimented with were two inches in diameter and weigh about 5 oz. Antennas of half that diameter are easily fabricated if a 4–18 GHz spread is accepted and even smaller ones are possible. (The lower bandwidth antennas usually have narrower beams and higher gains and require lower power transponder amplifiers.)

A pair of antennas placed side by side make up a right circular polarized transponder unit which receives and sends back right circularly polarized radiation. Losses of only about 3 db occur when receiving plane polarized radi-

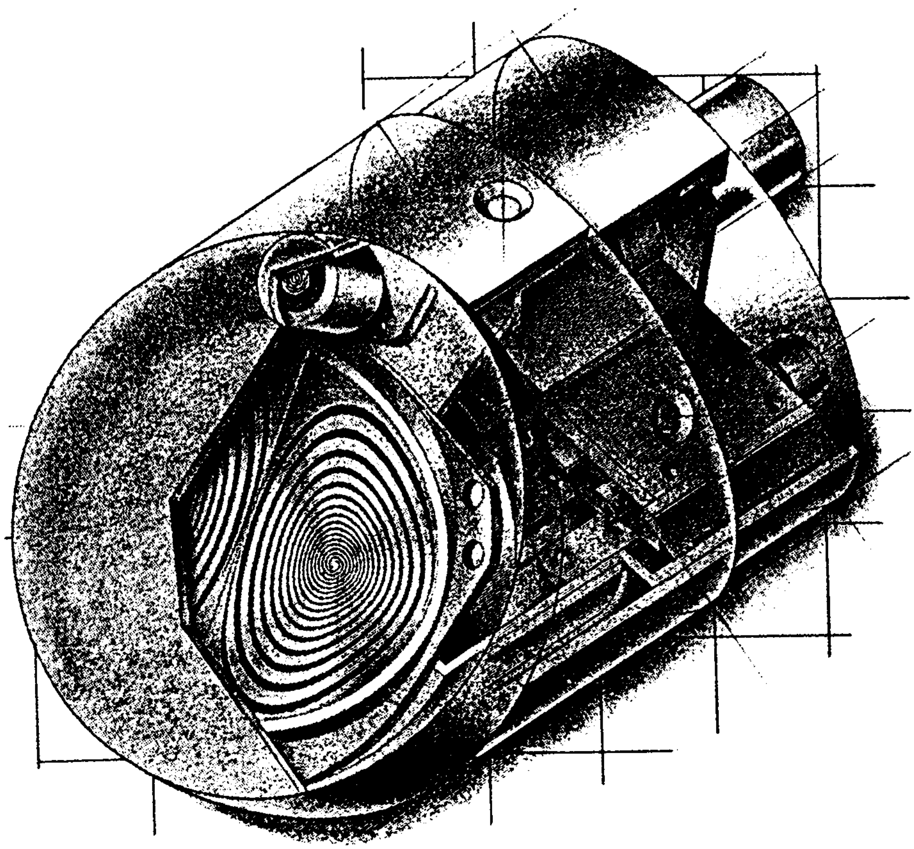

Figure 2: An AEL defense corporation ambidextrous antenna, which can receive left and right circular polarized signals. It will also receive plane polarized radiation.

ation. "Ambidextrous" Archemedean antennas that combine right and left circular polarization reception and transmission are also available. Figure 2 shows such a typical ambidextrous antenna, reproduced from the AEL antenna catalogue.

A quartet transponder with one right-handed and one left-handed pair will accept either sense of polarization as well as any linear polarized signals. Only one pair of ambidextrous antennas would suffice. Thus, such transponders will handle the polarization of any defensive radar.

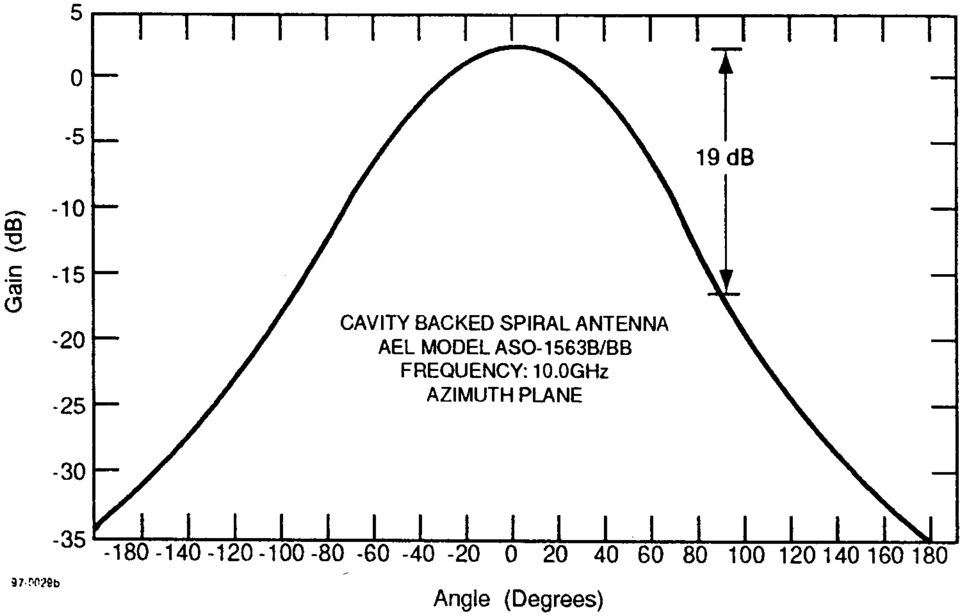

Figure 3: AEL antenna pattern at 10 GHz. for the spiral antenna studied in figure 4.

We wish to emphasize that the bandwidths of the present frequency independent antennas are much wider than that of any single radar antenna to be used in the foreseeable future. The THAAD antennas lie in the 8–12 GHz region.

It is important to know how much power gain can be used in the amplifier, shown in figure 1 connected between receiver and transmitter, so that the transponder will not oscillate. This requires knowledge of the "isolation" between the antennas, i.e., the fraction of the power from the transmitter that is unavoidably picked up by the receiver.

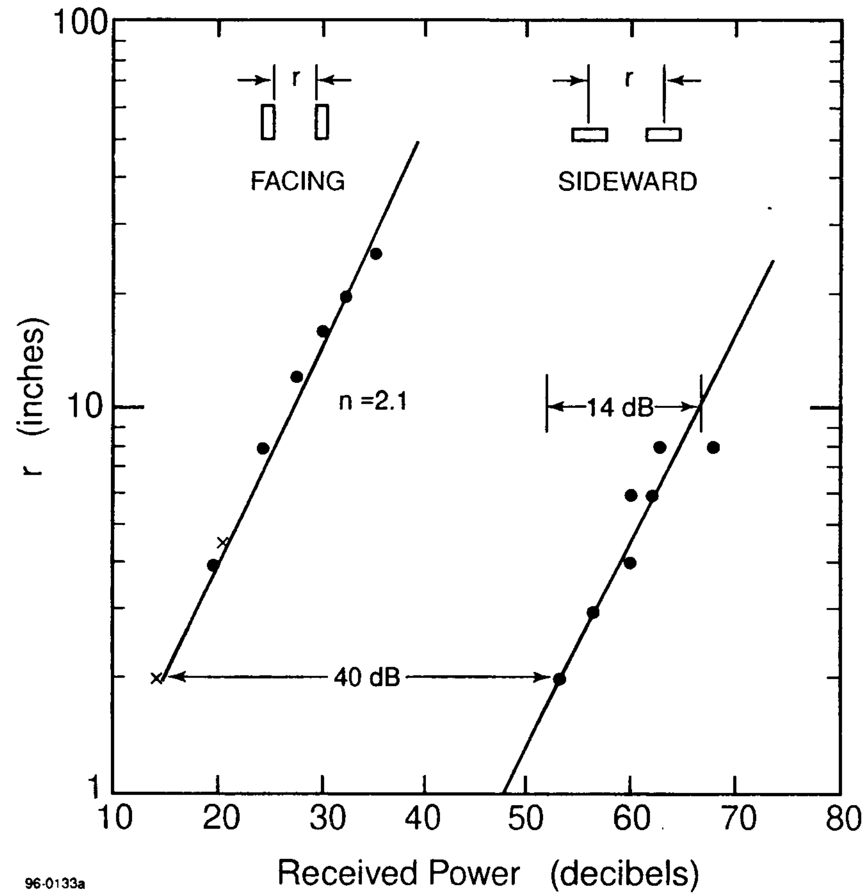

Figure 4: Received power vs. separation for antennas facing each other and in the transponder configuration where they are both facing outward, showing both the $1/r^2$ variation and the isolation factor.

The isolation of the pair can be measured in situ but we have also demonstrated for both spiral and horn antennas that the cross coupling can be calculated from the far field (Fraunhofer) antenna patterns published for the antennas. It is interesting to note that we have observed that the power received by an antenna, as a function of its distance from an identical transmitting antenna, falls off even in the near field (Fresnel) region, as $1/r^2$. That region is where their separation is of the order of a few wavelengths. Interestingly, we find that the same $1/r^2$ falloff takes place when the antennas are facing out in the same direction, as in a transponder. In this case (see figure 4), we have found this isolation to be 40 db for two spiral antennas placed side-by-

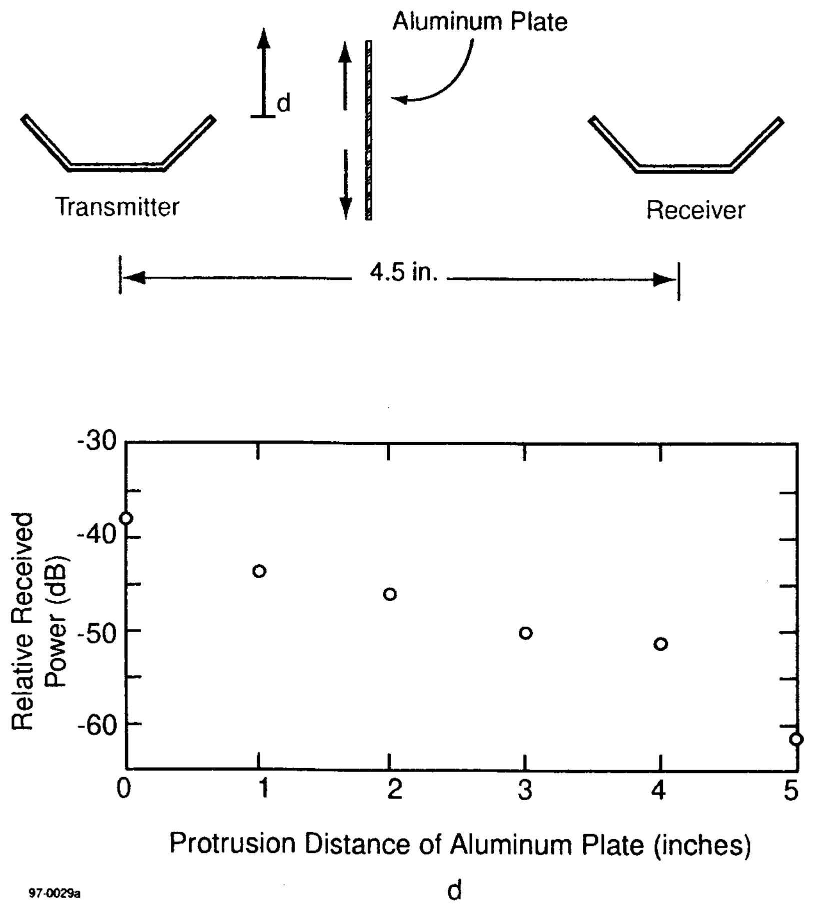

Figure 5: Effect of aluminum shielding on isolation.

side and two inches apart at 10 GHz. At ten inch separation an additional isolation of 14 db is attained. If $P(\theta)$ is the angular distribution of an antenna, the isolation in the transponder configuration should be $P^2(90°)$. The antenna pattern of the antenna we studied is shown in figure 3. The verification of these considerations is shown in figure 4. (Actually, as seen in figure 4, the isolation is somewhat larger since the power was measured relative to the receiver two inches from the transmitter where it only picked up part of the transmitted power. We estimate, by using figure 3 and the antenna dimension, that an additional 3 db of isolation should be added to the values shown in figure 4.)

We have also checked the relationship for the spiral antenna at 3 and 12 GHz. The calculated isolation for 3 GHz was 23 db and the measured isolation 23.8 db. The 3 GHz region is at the lowest end of the frequency independent region. At 12 GHz the calculated isolation was 40 db and the measured value was 32 db. These values are less reliable, however, since they were not based on a full curve as in figure 4 but on a single comparison of head-on and rotated antennas. The isolation should be larger for small horns with narrower angular distributions.

Of course the antennas can be further decoupled with the use of either lateral metallic shielding or absorbers. The student data on the effect of shielding with a thin (1 mm) aluminum plate is shown in figure 5. The inclusion of the aluminum shield made some reduction in gain at very large angles, but 25 db of additional isolation was obtained. We did not study non-metallic absorbers. Fancier shielding methods are described in the literature.[12] As we shall see later, the amplifier gains needed to override missile reflections are much smaller than the achievable isolation.

A reduction in sensitivity that occurs when right-handed polarization enters a left-handed antenna, the cross polarization factor, is usually of the order of 40–50 db. We have shown only one amplifier in figure 1. However, if the ambidextrous antennas are used, each section might need its own amplifier. One can, however, build in a switching circuit that senses which spiral had the large output and switching the amplifier output to the appropriate-handed transmitter spiral. If this were not done, there would be large signals passed to both sections of the output transponder and the interference would produce a plane polarized return signal.

We now return to a more detailed description of figure 1. Again, for the moment, disregard the phase-splitter and L compensator shown in the diagram. In a configuration that does not have this "Compensator," the question that we answered by our measurements was the fraction of the transmitted power that was picked up by the receiver, which is called the "isolation." In order for such a transponder to be stable and free from oscillation, one requires that the gain of the receiver G_0, times the feedback fraction K be less than unity, i.e., $G_0 K < 1$. From the expression for the gain with feedback G, $G = G_0/(1 - G_0 K)$, so that one can see that if $G_0 K = 1$, the gain becomes infinite—another way of saying that the amplifier becomes unstable.

The possibility of oscillation only occurs when the phase of the feedback signal is the same as the phase of the input signal, i.e., that the signals add and not subtract. This is called positive feedback. If the radar were of a single frequency, one could insure that the feedback was negative by the length of cable used from receiving antenna to amplifier. However, this would not necessarily be valid for a wide frequency range.

Very large reduction in the feedback fraction can be guaranteed in principal by adding the "Compensator" shown in the figure. A phase-splitter which breaks the amplifier output into signals of equal magnitude is added to the circuit and a signal, opposite in sign to the amplifier signal directed to the transmitter, is returned to the amplifier input via a cable, after attenuation by a factor L (see figure 1). In this case, the gain becomes $G = G_0/(1 - [K - L]G_0)$. If one can trim the phase-splitter so that $(K - L)$ is one percent of K, one would obtain an additional power isolation of 40 db.

With this addition, one not only further eliminates the oscillation problem, but one can now solve several problems that limit the transponder's universality. First, one can use smaller physical receiver-transmitter separations, to further reduce the physical size of the decoy. Second, one can go to antennas that have an even wider angular antenna pattern than the antennas we have described. Even though the antennas we have examined have a signal reduced by a factor of 4 at 45° as seen in figure 3, one could now use wider angle antennas with a smaller reduction factor without fear of oscillation. This would give coverage of radars not along the target direction. Also, it could eliminate one effect that might allow the radar to distinguish decoy from warhead: Space objects often precess in their motion about their directional axis. This "wobble" may have a characteristic frequency different for warhead and decoy. However, if the antenna angular distribution $P(\theta)$ is essentially independent of θ, this wobble will not be detectable. Thus, while the compensator further reduces the isolation which we have shown is extremely large, its virtue lies in allowing the use of wider angle antennas, possibly near-isotropic antennas closer together.

TRANSPONDER AMPLIFIER CONSIDERATIONS

What amplification and what power level is needed to drive the transponder transmitting antennas? Amplification poses no problem since very small amplifiers with wide bandwidth are easily procured. An example is the MITEQ Corporation AFS4 with a bandwidth from 6–18 GHz and a power gain of 14 db. For larger gains, these amplifiers could be cascaded. But there are a whole variety of such amplifiers with different gains, bandwidths and noise figures. However, the power output requirements might require the use of traveling wave tubes (TWTs) that are designed for high power and wide bandwidth. These come in a wide variety of bandwidths and more than sufficient power output. For example, one Litton mini-TWT, the L-5936, covers 4.5–18 GHz, has a gain of 40 db and an output power of 20 watts. The Varian Company makes a wide variety of amplifiers, some designated as "electronic warfare" components. For example, one can obtain a 6–18 GHz traveling wave tube with a minimum of 80 watts output, a 12.3 × .8 × 1.8 cubic inch unit weighing 1.5 lbs. Because the units will be used with a small duty cycle and a low repetition rate, special light-weight power supplies, meant only to last a typical flight time, could easily be designed. Thomson sells such traveling wave units, powered to last for three minutes and designed as a 100 watt CW jammer. It covers 6–19 GHz and could be the basis of a light design meant for a small duty cycle. The knowhow exists to tailor the design of TWTs to any decoy application.

The power requirement is determined by the minimum range from missile to radar at which the decoy system need no longer function. The closer the missile is to the radar the larger the power received at the radar and we plan to have the transponders produce masking signals at least 10–100 times larger.

To determine the power from the transponder amplifier we need to know the gain and peak power of the radar antenna, the missile-to-radar range, the missile radar cross section (RCS), the transponder receiver effective area determined from its gain, and the transponder transmitting antenna gain. (The gain of an antenna tells how much the antenna focuses radiation in the forward direction; the cross section tells how much of the energy coming from the radar is intercepted by the missile or the decoy and received back at the radar.)

The closest distance that the missile gets to the target, at which distance the response time is too long to intercept the missile, determines the power level that is needed in the transponder. Our detailed calculations appear in Appendix A.

We have used a cutoff distance of 100 kilometers for a missile with a 1,000 kilometer range. We assume a radar with one megawatt peak power during the pulse and antenna dimensions of 9.2 square meters. These would be the dimensions of the planned THAAD Ground Based radar. We calculate for X band radar, a wavelength of three centimeters. The missile is assumed to have a cross section of 0.1 meters-squared while the transponder receiver has a cross section of 0.00014 meters-squared and a gain of two when all losses are included. ($G = 4\pi A / \lambda^2$. The directed gain is higher). To send back a signal ten times larger than the missile signal would require a transponder amplifier with a power gain of 34 db and a peak output power of roughly 0.4 watts. It is likely that units with solid state amplifiers and units with traveling wave amplifiers of higher output power and weight could both be used depending on the circumstances.

TRANSPONDER SIGNALS AND THEIR SIMULATION

The signal to be sent back from the transponders is determined by a pre-determined algorithm. The initial reflection is sent back at $t = 0$ and is the signal reflected from the receiving antenna. This is the small direct reflected signal from the transponder receiver occurring because the receiver cannot be perfectly matched to the load. At a time determined by the receiver-transmitter physical separation and the delay in the transponder amplifier of the order of a nanosecond, the signal from the transponder transmitter arrives, which is larger by the transponder gain. This is the signal which our algorithm generates. It is constructed by using a distributed delay line to produce a series of artificial reflections over a time period equal to the missile length. Thus, all returned pulses look identical and resemble the expected radar return signals from the missile. Some systems could also choose the delays with a random number generator that changed all returns *from radar pulse to radar pulse*, thereby producing a high powered "random" noiselike background. In this way, an autocorrelation study will fail on the random reflections. Groups of decoys might also have different fixed patterns.

Figure 6 shows a series of returns that the radar would see for both missile and decoy. A large difference in missile and decoy length is shown at the top. The illustration uses a one nanosecond resolution.

The first line shows the initial reflection from the receiver. Its size will be small both because of the receiver's physical size and its matching to the load.

The second line shows the delay between receiving and retransmitting.

The third line shows the reflection from the decoy body or the missile relative to the initial transponder reflection time.

The fourth line shows the signals from the missile transponder. White boxes represent random signals; black boxes are fixed timing signals. The varying smooth line is added to represent continuous reflections from a continuous missile body.

It is not difficult to prepare a tape consisting of a series of returns, such as shown in figure 6, spread in time over the path of the incoming missile/warhead. The pulse returns would be computed from the known characteristics of

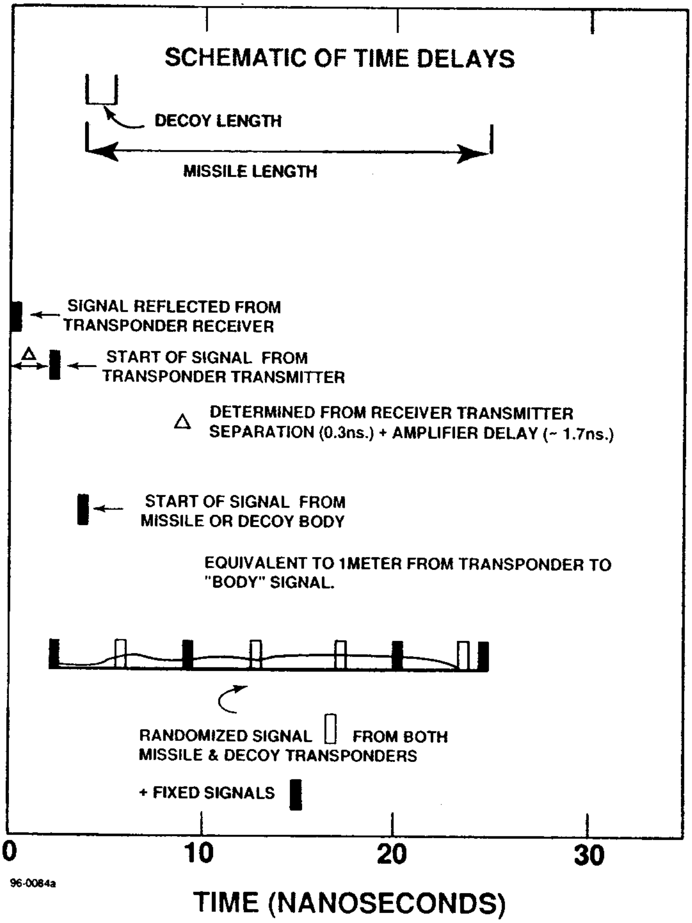

Figure 6: Schematic of time sequences and time delays of pulses emitted from the "deceptive jammer."

the missile and decoy differential radar cross sections as they approach the radar. Such a tape could be employed to see if the warhead could still be recognized by a clever defense team.

SUMMARY

We have studied the problem of defense against missiles above the atmosphere, as planned, for example, in the THAAD system. With the use of "transponders" mounted on the nose of both missile warhead and small decoys, we have shown that it is technically possible to return to the radar high power jamming signals which overwhelm the normal radar return, arrive early, and contain a variety of deceptive signals.

We have demonstrated from experiments with spirals and horns in an anechoic chamber that one can calculate from the transponder antenna patterns the isolation between the transponder transmitter and receiver. That isolation, plus the use, if desired, of metallic or lossy absorbers between the antennas, guarantees that the system will operate at very high power. Modifying the missile and decoy radar returns, using both mechanical modifications and emissivity control, again varied for each missile or decoy, can also reduce the ability to distinguish decoy from missile.

Further, we have found that there are off-the-shelf amplifiers and antennas of small size and weight that allow the system to work automatically over a huge band of radar frequencies, returning to the radar the frequency it employs in a linear system of amplification between transponder receiver and transmitter. These devices, in fact, are so wide-band that they would be effective in any foreseeable future system.

One cannot counter the validity of the proposed decoy system on grounds that there is classified information that would preclude the decoy's effectiveness since the method is only based on the known laws of electromagnetic theory.

Finally we remark that there is no implication here that "smart decoys" should replace all inert decoys as countermeasures. But they, and the "intelligent" decoys that can contain "built-in" computer chips, have the ability to provide another countermeasure dimension.

The reader should not interpret this work as decrying ballistic missile defense. Nonworking defenses are politically dangerous and threaten international ABM agreements. Since missile intercept above the atmosphere will fail, one should study other defensive measures such as boost phase intercept, air-born lasers, or launch site destruction, while ensuring that they will not waste valuable military resources.

While decoys are certain to be effective in the exoatmosphere, their behavior on entry into the atmosphere presents another problem, which we have begun to study.[13] Because our decoy bodies do not need to match the radar cross section of the warhead, it seems likely that small decoys of appropriate length, weight and nose angle can be made to match the warhead deceleration.

APPENDIX A: AMPLIFIER POWER AND GAIN CONSIDERATIONS

Radar Equation for Transponders

Since we are considering a decoy system that can handle essentially any wavelength emitted by the parent radar, we examine how our decoy response varies with wavelength. This is a useful exercise since the transponder antenna returns are somewhat different than simple reflection from an inert device with a usual radar cross section. The fact that the antennas have gains that are frequency independent results in valuable design simplifications.

The expression for the power received at the receiving antenna from the transponder can be shown to be:

$$P = P_0\,(1/4\pi r^2)^2\, g A_T^2 G_t^2 \qquad (1)$$

Where P_0 is the peak power (watts), r is the separation of transmitter and transponder, g is the amplification of the transponder amplifier, A_T is the area of the radar antenna and G_t is the frequency-independent gain of the spiral-type transponder antenna.

Thus, we demonstrate a useful result that *the power received is independent of* λ, if one employs frequency-independent transponder antennas. It depends only on the physical size of the radar transmitter A_t, and the (λ-independent) gain of these antennas G_t.

This will still be true for radar antennas positioned away from the transponder antenna axis since the antenna angular distributions are λ independent as well.

In the case of the spirals we have studied, the gain drops 5.5 db at 50° and the variation in the antenna patterns from 3–18 GHz is at most 1 db.

If the radar antenna makes an angle θ with the frequency-independent antenna axis, there will be an additional factor of $G(\theta^2)$in the above equation. The normalization here is $G(\theta^2 = 0) = 1$.

Power Output Required of the Transponder

The power output needed for the transponder is given by:

$$\text{P(transp)} = P_0 G_T (1/4\pi r^2) \times A_t \times g = P_0 (1/4\pi r^2) \times A_T G_t g \qquad (2)$$

Where:

P_0 = peak radar power = 10^6 watts

r is the smallest range to the radar = 100 km = 10^5 meters

$1/4\pi r^2 = 1/12.56\,(10)^{10} = 7.96 \times 10^{-12}$

A_T is the radar area = 9.2 square meters
G_t = transponder antenna gain = 2
G_T = radar antenna gain
and g = the gain of the transponder amplifier
P(transp) = 0.014 watts for g = 100 = 20 db gain or 1.4 watts for g = 10,000 = 40 db gain.

Note that this power output is also frequency independent so no knowledge of the frequency is needed to determine the power output.

Amplifier Gain Considerations

Let us now compute the gain g needed to make the return signal f times greater than the reflected signal from the missile.

The signal reflected by the missile back to the radar illuminating it is σ. Note that this depends on the orientation of the missile or transponder relative to the direction of the radar. Thus, the signal back at the radar from the missile or decoy is obtained by replacing $A_t G_t\, g$ by $f\sigma$, where f is the power ratio of the jamming to reflected signal. That is,

$$g = \sigma f / A_t G_t = 4\pi\sigma f / \lambda^2 G_t^2$$

If we require that the transponder power signal be 100 times the reentry vehicle reflected power, we find: For a small reentry vehicle, like the US Mk-21 with a radar cross section of 0.004 square meters, the required power would be 0.36 watts (g = 32 db), while for a large CSS-4 with a cross section of 0.09 square meters it would be 8 watts, (g = 45 db).

We now mention how σ depends on λ. For this purpose, we shall use a model which is a cylinder with a rounded nose cone. The transponder "effective cross section" $A_t G_t$, increases smoothly with λ^2. The radar cross sections are more complicated, showing oscillatory behavior with λ. However, for a typical cone sphere with a 15° half angle, the cross section also varies roughly as λ^2. Superimposed on this variation is an oscillation over about +/– 5 db as the wavelength changes relative to the sphere diameter. The average λ^2 dependence is typical for missile-like geometries.

APPENDIX B: KINEMATIC CONSIDERATIONS IN DEPLOYING DECOYS

In this appendix we give the kinematics of decoy deployment in and out of the plane of the missile trajectory. Figure 7 shows the geometry.

In-Plane Decoys

The relevant equation for the distance at which the decoy lands is given by

$$d = v_m^2/g \times [1 \pm (v_d/v_m)\cos 2\theta \mp \left(v_d^2/v_m^2 \right) \sin 2\theta] \qquad (1)$$

where d is the vector distance between launch and target, v_m is the initial vector velocity of the missile, and v_d is the vector velocity of the decoy in the plane of the trajectory relative to the missile. It is at right angles to the missile velocity v_m, while v_p is the velocity perpendicular to the earth and $v_{||}$ is the velocity parallel to the earth's surface. We assume the earth is flat and g is a constant. The angle θ is the launch angle relative to the surface of the earth, and d is the ground range. For simplicity, we assume deployment of the decoy at $d = 0$, but the proper ejection velocity comparable with the effect at $d = 0$ is easily computed for any decoy ejection point. (The perpendicular and horizontal components of the decoy velocity are then $v_\perp = v_m \sin\theta \pm v_d \cos\theta$ and $v_{||} = v_m \cos\theta \mp v_d \sin\theta$.) Note that the ratio v_d/v_m is a small number since the decoys travel near the missile and each other.

This is a very interesting equation because the term linear in v_d/v_m vanishes if $\theta = 45°$ so that the correction to d is quite small and the upward and downward decoys arrive close to the landing point of the missile. Actually one can find a value of θ, close to 45° where the focus is exact, since the last two terms can be made to vanish when $\tan\theta = v_m/v_d$.

Thus, deploying the decoys in the missile plane results in the decoys aiming for the same target even though they may reach different altitudes. Therefore, the defense cannot use the target point to distinguish decoy from warhead.

Out-of-Plane Decoys

If v_d is tangent to the plane, the time of arrival is independent of the transverse momentum for any decoy momentum since $\vec{v}_d \cdot \vec{v}_m = 0$. Now, the landing position is on a line at right angles to the path of the missile and the

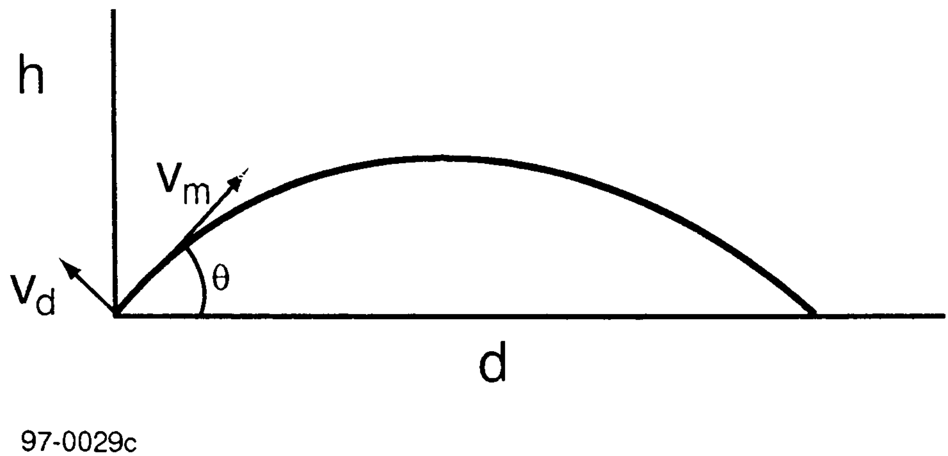

Figure 7: Geometry of missile trajectory.

fractional spread is $v_d/v_m \times d$ at any angle θ. Thus, away from 45°, where cos 2θ vanishes, the range spread for in-plane decoys and the lateral spread for out-of-plane decoys is quite similar and proportional to v_d/v_m.

APPENDIX C: DEFEATING CHIRP

Pulse Compression

If the radar uses the CHIRP frequency-modulated method to use a long, low peak power pulse to get good time resolution, the CHIRP system is easily defeated by a small addition to the transponder circuitry. CHIRP uses a very long frequency-modulated pulse and, on receiving the reflected signal, passes it through a frequency-dependent delay line that compensates for the frequency modulation. In essence, low frequency signals at the start of the pulse are delayed to catch up with the higher frequency signal at the end of the pulse. If the radar pulse is one microsecond long, a large delay time is needed. However, to smear a one meter decoy to look like a five meter missile only requires the use of a small frequency dependent delay line in the transponder, with only a small 25 ns delay capability. Essentially the small frequency dependent delay, unknowable at the radar site, smears the time resolution so the small decoy cannot be distinguished from the missile. This is technically easy to do, but not all the decoy transponders need be so equipped. Of course, the transponders overpower the return signals in any case, so this is just a refinement.

APPENDIX D: COMMENTS ON PASSIVE AND INTELLIGENT DECOYS

The American Physical Society study of the Strategic Defense Initiative, published almost a decade ago,[14] concentrated on directed energy weapons and made only small mention of decoys, referring only to the existence of classified briefings that were made to the APS panel. However, the use of decoys is an obvious countermeasure that has been often discussed. One method would require a balloon decoy with a balloon to be deployed around the missile as well.[15] Another classic method is the use of "chaff," small reflecting pieces of aluminum, sometimes in the shape of corner reflectors, that are deployed along with the missile to mask the radar returns. But good range resolution, for example the use of the "CHIRP" frequency delay system, might distinguish them from the missile target.

It is necessary to deploy passive decoys with a cross section that matches that of the missile. This could be done by making short decoys that are made with telescoping sections that expand out after deployment to have the shape of the missile or warhead. In this way, they not only have the same differential radar cross section, but range resolution cannot distinguish them from the true missile. The missile could also have protuberences on its skin to match any reflections from the seams of the various telescoping sections, an illustration once again of making the missile look like the decoy.

Uzi Rubin, of the Israeli Ministry of Defense, and Azriel Lorbert, of the Israeli Ministry of Science and Technology, in their recent review of missile defenses at the Eighth Multinational Conference on Theater Missile Defense, held in London in June, 1995, state: "...the most likely missile defense countermeasure that may appear in future Middle Eastern battlefield within the next 15 years are simple single purpose decoys." They then remark that "there is some likelihood for...low-power electronic countermeasures to make an appearance towards the end of this survey's time frame." [16]

With every announcement of a new INTEL chip and a new gadget for citizens in the street, such as cellular phones, pagers, global positioning satellite detectors that give their position to ten feet, etc., we are aware that tremendous computing power resides in sturdy inexpensive microchips. Specially designed computers-on-a-chip could make the decoy into an intelligent electronic countermeasure device.

Information on the position of the defender's radars and their frequencies could be introduced into the computer on the field, or the transponder receivers themselves could detect the radars early in flight and accumulate this information. This information would allow prediction of the signal that the radar would be receiving from the missile at any time in the flight path and could allow the gain of the transponder amplifier to be electronically controlled to improve the jamming performance. One might even make the transponder match the exact angular distribution of the missile. Such computer power opens up an interesting possibility of communication between warhead and decoys related to reentry problems.

NOTES AND REFERENCES

1. Under the SDI program of a decade ago, it was widely understood that decoys could play an important role. The American Physical Society study of SDI of April 1987 did not present any detailed study of decoys, partly because such countermeasures were considered to be highly classified. However, it did mention that very light decoys were practicable.

2. We use the word missile to describe either the missile carrying the warhead or the warhead deployed by the missile.

3. Michael Kasdan and Joshua Raha. These students' feasibility measurements carried out at the University of Pennsylvania appear in their theses.

4. Abraham Friedman and Philip Farnum.

5. We wish to thank Professor Nabil Farhat for use of his anechoic chamber facility for our studies.

6. The spiral antennas were donated by AEL Defense Corporation of Lansdale, PA.

7. We wish to thank Lockheed Martin for loan of their Hewlett-Packard 8620 spectrum analyzer which was crucial for our measurements.

8. Donald Carlson of the Moore School of Engineering was of great help in providing equipment useful in our laboratory measurements.

9. This approach has been known as "antisimulation," a concept that was treated earlier by R. L. Garwin.

10. Amin, M. B. and J. R. James, *The Radio and Electronic Engineer,* Vol. 51, p. 208, (1981).

11. We wish to thank Dr. George Sun of AEL Defense Corporation for arranging for the donation of the spiral antennas used in our study.

12. Corner obstacles are discussed in the *Antenna Engineering Handbook* by Richard C. Johnson and Henry Jasik, McGraw-Hill, (1984), p. 40–19.

13. Frankel, S., "Endoatmospheric Decoys," I/P Report 9610.

14. Reviews of Modern Physics Vol. 59, p. 3, (July 1987).

15. Garwin, R. L., *op. cit.*

16. AIAA-Collection of papers ISBN-1-56357-187-6.