AMRAAM S-BAND TELEMETRY ANTENNA THEORY AND DEVELOPMENT

Rollin H. Koontz
Pacific Missile Test Center
Point Mugu, CA 93042-5000

INTRODUCTION

The Advanced Medium-Range Air-To-Air Missile (AMRAAM) is one of our newest additions to tactical weaponry. Recently the Pacific Missile Test Center (PMTC) was given the responsibility to develop a new telemetry (TM) package for the AMRAAM that is warhead compatible. The difficulty of this undertaking can best be appreciated if one examines a sketch of the missile as shown in figure 1. Note that the sketch reveals a harness cover opposite top dead center (TDC) for flight that extends over 2/3 the length of the missile. Within this cover is housed all interconnect electrical cabling for the missile. It was also within this harness cover that PMTC had to mount the entire TM package including the S-band antenna. Of necessity there had to be an increase in the height of the harness cover in order to accommodate the TM package. However, this increase was held to only 0.10 inches resulting in no significant change to the flight profile. This report deals only with the design and development of the harness cover mounted TM antenna.

RADIATION COVERAGE REQUIREMENTS

Early in the AMRAAM TM package development, representatives of the Navy, the Air Force, and PMTC met to establish the radiation coverage requirements for AMRAAM. Figure 2 presents the agreed upon requirements. I was not involved in these discussions, but I understand they were predicated on Range requirements together with what was considered feasible in the field of antenna design. These requirements were presented to me basically in the form of a specification. It will be noted that there is no coverage requirement over a 90 degree sector centered below the missile in the roll plane. I suspect that this was desired to cut down specular reflection from the sea. Since the antenna had to be mounted in the harness cover directly below TDC, and since it had to occupy a minimum volume, pattern synthesis was out of the question. Thus, this aspect of the coverage was summarily dismissed and the operating specification became that of figure 2 with the lower 90 degree sector filled in.

POLARIZATION REQUIREMENTS

Polarization of the antenna was not specified, although there were occasional preferences expressed for vertical polarization to reduce multipath. In the AMRAAM case the improvement in multipath is more perceived than real, since tracking will be done near the horizon at near grazing angles. For such angles, dielectric interface reflection coefficients for both vertical and horizontal polarization are essentially identical and equal to unity. Multipath rejection for this case then, of necessity, is related only to the tracking antenna directivity. The finalized antenna is essentially horizontally polarized.

ANTENNA SELECTION

Because of size and space restrictions, it was evident from the outset that the TM antenna would most likely have to be composed of a single element design. Some thought was given to the half-wave rectangular microstrip patch element, but previous radiation pattern measurements showed the patch to be deficient in coverage in the roll plane. The single-mode patch also suffers from bandwidth limitations as well as temperature sensitivity problems. In reviewing the radiation requirements of the antenna, the thought emerged that a good candidate would be the axial slotted cylinder. AMRAAM has a diameter of 7 inches, which is just right to support good roll plane coverage for an axial slot at TM frequencies. The problem at hand then was how to implement such a design. As it turned out, I had a model of a candidate design stuck away in my desk that I had fabricated a year or so earlier. This model consisted of a parasitically loaded microstrip patch type structure utilizing an air dielectric. It was an ideal implementation for simulation of the axial slot and had the added advantage of extended bandwidth as a result of the parasitic loading. It also was an inherently more stable structure since it was all metallic. A picture of the finalized antenna is shown in figure 3 and will be discused in detail below.

DESIGN THEORY

Design of the antenna was predicated on a paper by C. Wood[1]. However, unlike the Wood antennas, the AMRAAM antenna is a completely metallic structure with enclosed sides. Enclosing the antenna on the sides was done to stabilize its environment and is not necessary to the design. From an analysis viewpoint, the antenna can be considered as a quarter-wave driven patch element capacitively coupled to a similar quarter-wave parasitic element as shown in figure 4. As such, the AMRAAM antenna can be considered an air equivalent of the Wood design. In the analysis below I will in general follow the Wood development with some comments of my own.

Note that at the resonant frequency of a patch antenna, the input admittance may be approximated by that of a lossless parallel resonant circuit composed of elements G, L, and C. G represents the radiation conductance while L and C make up the equivalent susceptance. This analogy results from the fact that the patch antenna is in general a high Q narrow band device. A similar representation can be applied to the parasitically loaded patch as shown in figure 5 where G now represents the radiation conductance of the slot between the two patches and C_c is the effective coupling capacity. Note that V_1 and V_2 are referenced to the edge of the driven and parasitic patch respectively. Analysis proceeds by investigating the admittance of the antenna Y_e taken at the edge of the driven patch.

Through the application of straight forward circuit analysis to figure 5, Y_e is given by the expression:

$$Y_e = \frac{GB^2 + j\{B^3 + 3B_CB^2 + 2(G^2 + B_C^2)B\}}{G^2 + (B + B_C)^2} \qquad (1)$$

where

$$jB = j\omega C + \frac{1}{j\omega L} = -jY_0 \cot\left(\frac{2\pi\ell\sqrt{\epsilon_{eff}}}{\lambda}\right)$$

and

$$jB_C = j\omega C_C.$$

Y_0 and ϵ_{eff} , are respectively the characteristic admittance and effective dielectric constant of a transmission line of width W and length ℓ corresponding to the patch dimensions. λ corresponds to the free space wavelength. G, the radiation conductance of the slot is given by:

$$G = \frac{\pi}{\lambda\eta}\left\{1 - \frac{(ka)^2}{24}\right\} \qquad \frac{a}{\lambda} < 0.1 \qquad (2)$$

where

k = wave number in the medium
η = intrinsic impedance of the medium
a = the aperture height

This equation was taken from Harrington[(2)] and represents the conductance of a parallel plate guide radiating into half space for E field excitation transverse to the slot. For the AMRAAM case I felt it to be more representative than the equation used by Wood which was derived from an open circuited microstrip line. The slot also exhibits a radiation susceptance (B_a), again from Harrington, given by the following expression:

$$B_a \simeq \frac{1}{\lambda\eta}\{3.135 - 2\log(ka)\} \qquad \frac{a}{\lambda} < 0.1 \qquad (3)$$

This susceptance is capacitive in nature and gets lumped in with the coupling to form an overall effective capacity C_c. Another equation important to the development is that involving the ratio of the two voltages on the resonators. This ratio, which is readily derivable from circuit analysis, is given by:

$$\frac{V_2}{V_1} = \frac{G + jB_C}{G + j(B + B_C)} \tag{4}$$

Returning to (1), the expression for Y_e, we can define resonance based on $Im(Y_e) = 0$. The resulting cubic equattion defines the following three roots for B:

$$B_{r1} = 0, \quad B_{r2} = -B_C, \quad B_{r3} = -2B_C \tag{5}$$

It is instructive to examine the antenna characteristics for these three roots assuming the practical situation where $B_c^2 >> 8G^2$.

The first resonance occurs at the resonant frequency of the individual elements. However, the ratio of voltages for this case is unity. Therefore, there is no excitation of the slot and thus no slot radiation. Wood considered this a non-radiating mode and attributed any radiation present due to side wall fields. Our investigation demonstrated strong radiation present for this mode related to other mechanisms, as will be discussed later.

At the second resonance, the parasitic element will have a much higher voltage excitation than the driven element causing the circuit to appear as a single driven parasitic element. This results in no bandwidth improvement over a single driven element. Since $B_{r2} = -B_c$ for this case, the resonant frequency must occur below that of the individual elements in order for the resonators to look inductive. In our investigation we were not able to demonstrate the presence of this mode. After reviewing the circuit it was concluded that manifestation of this mode required a source generator of near zero impedance since the parasitic element is in series resonance with the coupling capacitance. This was not true for the real antenna and thus the mode was suppressed.

At the third resonance we have the interesting situation where the voltage ratio equals -1. This puts the two voltages in phase opposition and results in doubling the voltage across the slot when compared to a single patch with the same excitation. Doubling the voltage will increase the radiated power by a factor of four. However the stored energy is doubled, since there are now two active resonators. The net result is an increase in the ratio of stored to dissipated energy by a factor of two. Since this ratio, by definition, is proportional to Q; the bandwidth of the parasitically loaded element operating in this mode will be double that of the single element. This resonance also occurs below that of the individual element resonance and also below the second resonance case since $B_{r3} - 2B_{r2} = -2B_c$.

ANTENNA DEVELOPMENT

In principle, the above equations constitute all the information necessary to design the antenna. Unfortunately, the coupling capacity, and to a lesser extent the radiation admittance are both difficult to specify exactly. This is particularly true in the AMRAAM case since the antenna is covered with a dielectric having a dielectric constant of approximately 5.0. As a practical matter it becomes necessary to model the antenna and use its measured properties to close on the design. In figure 6 is shown a broad band sweep of the prototype AMRAAM antenna without dielectric loading. Note the presence of the two distinct modes referred to above. Verification of the higher frequency B = 0 mode was first done by shorting the slot. It was surmised that this mode would not change appreciably when shorted and indeed this was the case. Under a short circuit the anti-phase mode disappears. It was then decided to probe the fields to measure relative phase. In figure 7 is shown a phase plot of the antenna for probes located at the edge of both the driven and parasitic elements. Note that for all practical purposes the differential phase associated with the anti-phase mode is 180 degrees while there is no differential phase at the other mode. Our conclusion was that the higher frequency resonance definitely corresponded to the B = 0 mode.

Having established the presence of the anti-phase mode, the remaining effort centered around tailoring the antenna and getting it on frequency. Since the harness cover loads the antenna appreciably, and because there was some question as to the exact reproducibility of the cover, it was decided to incorporate tuning screws in the design. There was also a more theoretical reason to incorporate them for the analysis tacitly assumes that the driven and parasitic elements are synchronously tuned. In practice this would not be the case for physically identical elements when the feed line is present, since it would load or perturb the natural resonant frequency of the driven element. Thus tuning screws were added to assure us of exact anti-phase tuning.

Although the B = 0 mode was not the mode of interest for AMRAAM, it was of considerable academic interest. Through measurements and analysis it appears that as the parasitic element is brought into the coupled region of the driven element, there is a splitting of the quarter-wave resonance such that the two distinct modes are established. What is of particular interest is that our analysis suggests that the polarization of the radiation associated with this B = 0 mode changes from horizontal to vertical. The horizontal polarization is that of a quarter-wave patch while the vertical is that of a half-wave short circuited dipole. We have yet to verify this through pattern measurements, but plan to do so soon.

MEASURED ANTENNA PARAMETERS

In figures 8, 9, and 10 respectively are shown the principal plane cuts of the antenna taken on an AMRAAM missile model including the fins. The antenna meets the radiation requirements in all respects. There is some skew to the pattern symmetry and there is one deep null in the pitch cut outside the defined area of interest. This is attributed to the very close proximity of the missile fins. In figure 11 is shown the return loss for the antenna. Note that the antenna has a VSWR of less than 2 over the entire TM band of 2.2 to 2.3 GHz. We have had some difficulty in the past achieving this bandwidth even for multi-mode microstrip elements of equal height. The antenna was tested in a vacuum chamber for high altitude operation and found to be free of corona discharge up to power levels of 30 watts cw. The AMRAAM TM transmitter has a power output of 2 watts. Temperature tests have not been completed on the antenna because harness covers were at a premium early in the program. However, preliminary measurements in the laboratory indicate a negative temperature coefficient of 0.03 MHz per degree Celsius.

CONCLUSIONS

Antennas for TM application are faced with many stringent requirements. They often must be conformable, light in weight, and small in size. They also must have reasonable electrical properties which all to often conflict with the physical properties. The AMRAAM antenna, although not in the conformable category, meets many of these requirements. It represents one of the many new techniques to extend bandwidth that have come forward in recent years. In applications similar to AMRAAM it should serve well.

ACKNOWLEDGMENT

I acknowledge with pleasure the useful discussions I have had with E. L. Law and T. P. Waddell of PMTC on the AMRAAM antenna development.

REFERENCES

1. Wood C., 1980, “Improved bandwidth of microstrip antennas using parasitic elements”, IEE PROC., Vol 127 Pt. H. No.4., pp 231-234.

2. Harrington R. F., 1961, “Time-Harmonic Electromagnetic Fields”, McGraw Hill, pp 180-183.

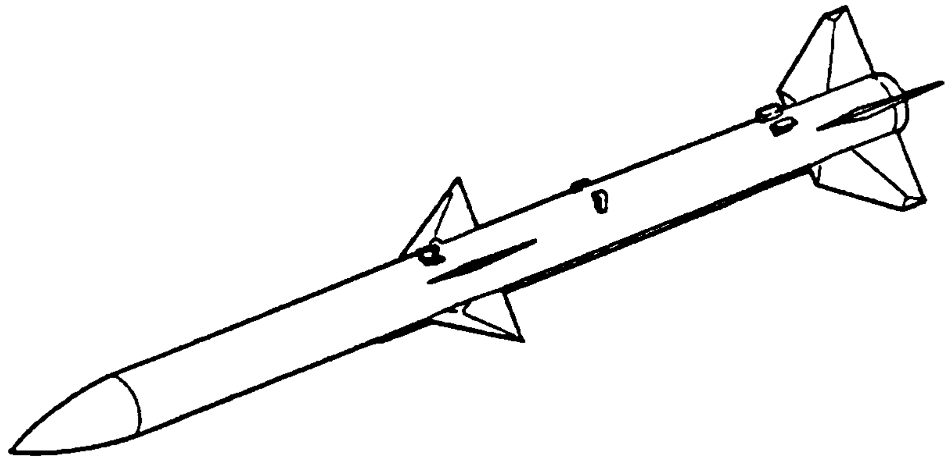

Figure 1. AMRAAM Missile

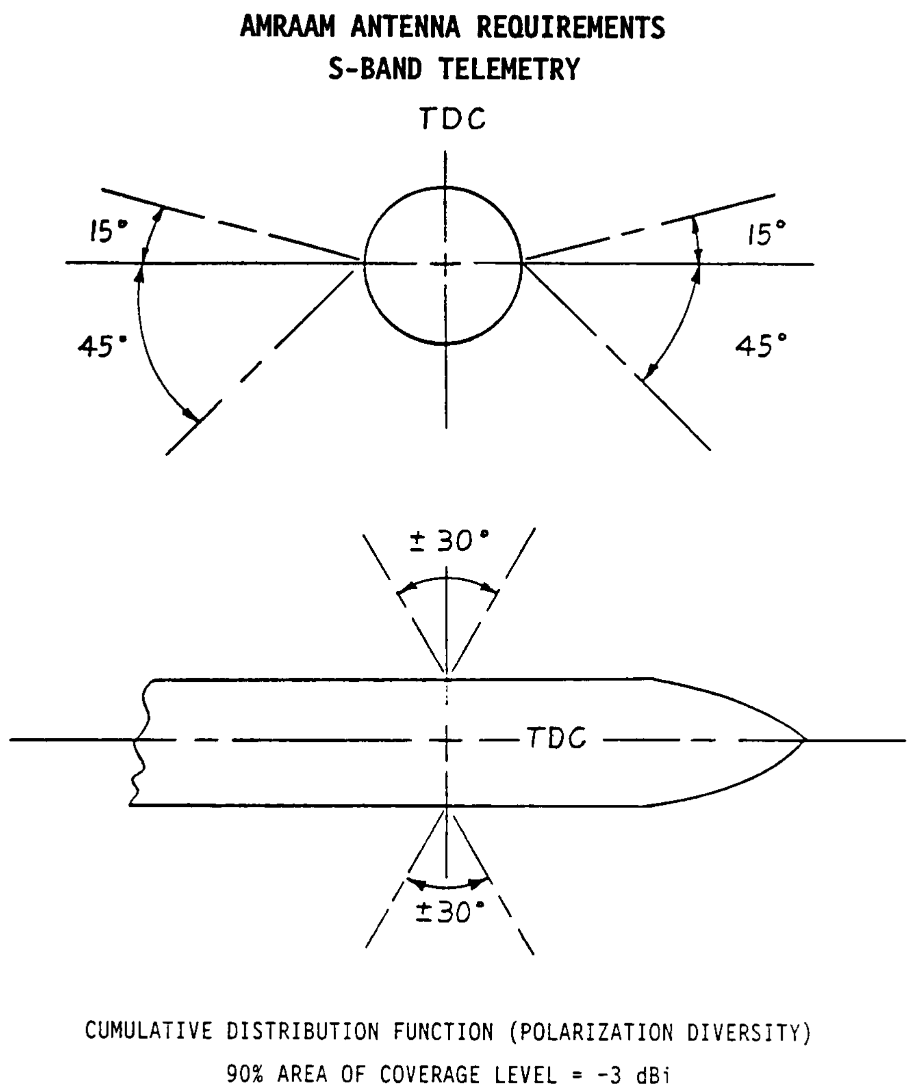

Figure 2. AMRAAM S-band Antenna Requirements.

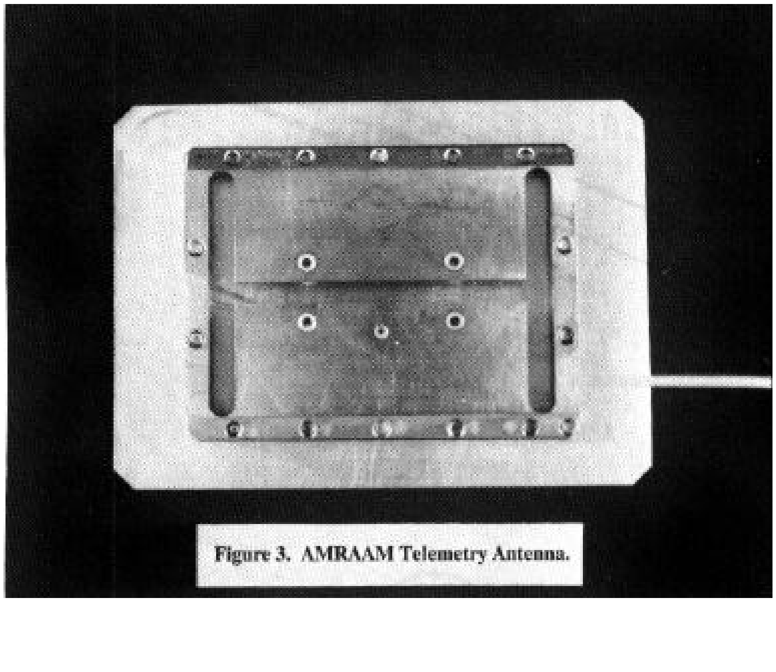

Figure 3. AMRAAM Telemetry Antenna.

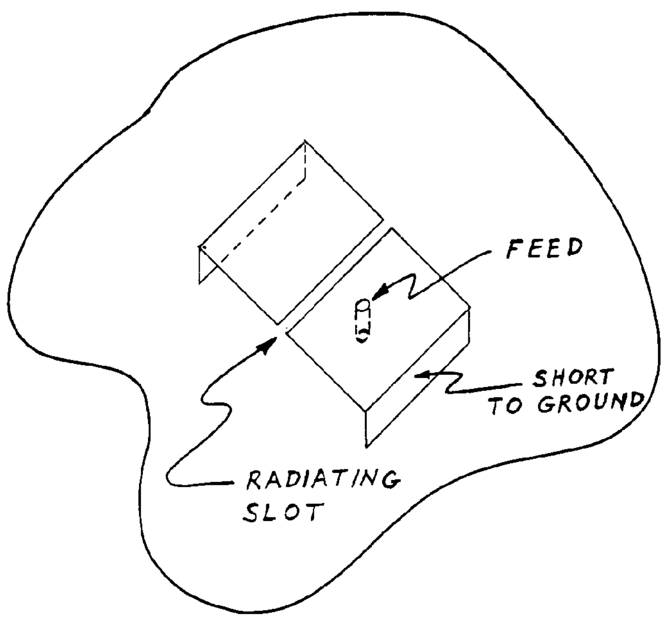

Figure 4. Telemetry Antenna Model

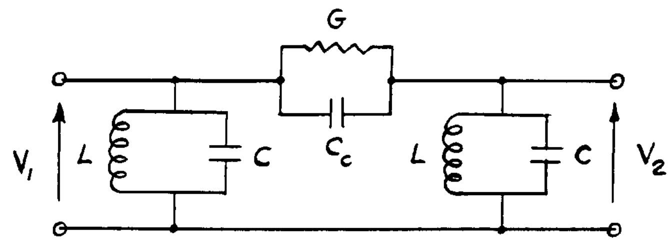

Figure 5. Antenna Circuit Model.

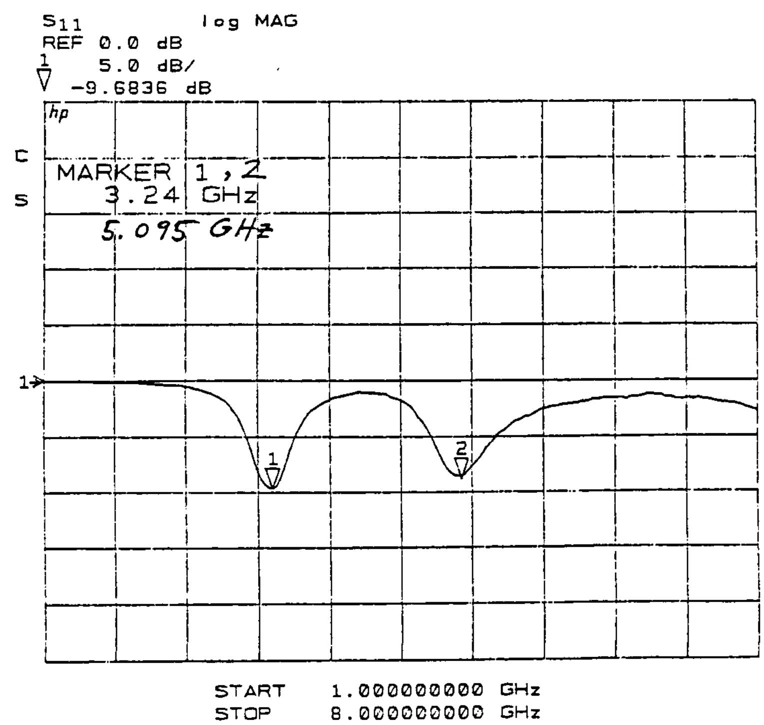

Figure 6. Broad Band Sweep of Return Loss.
(No Dielectric Loading)

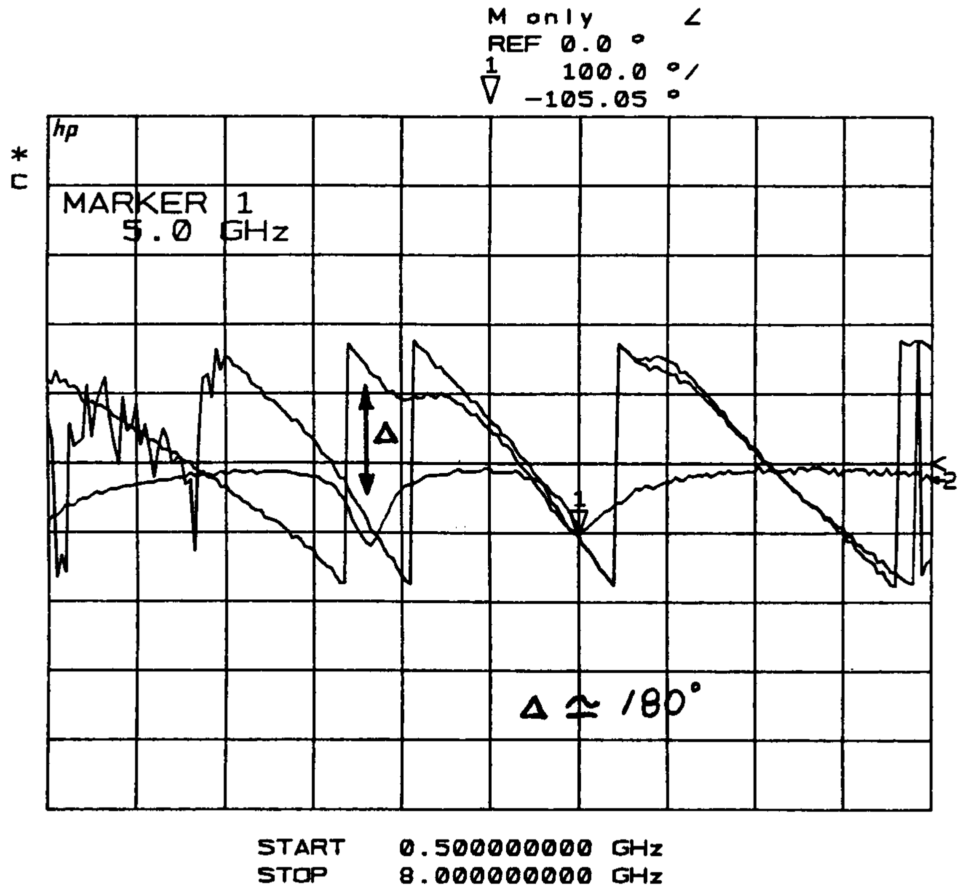

Figure 7. Broad Band Sweep of Phase for Both Elements.

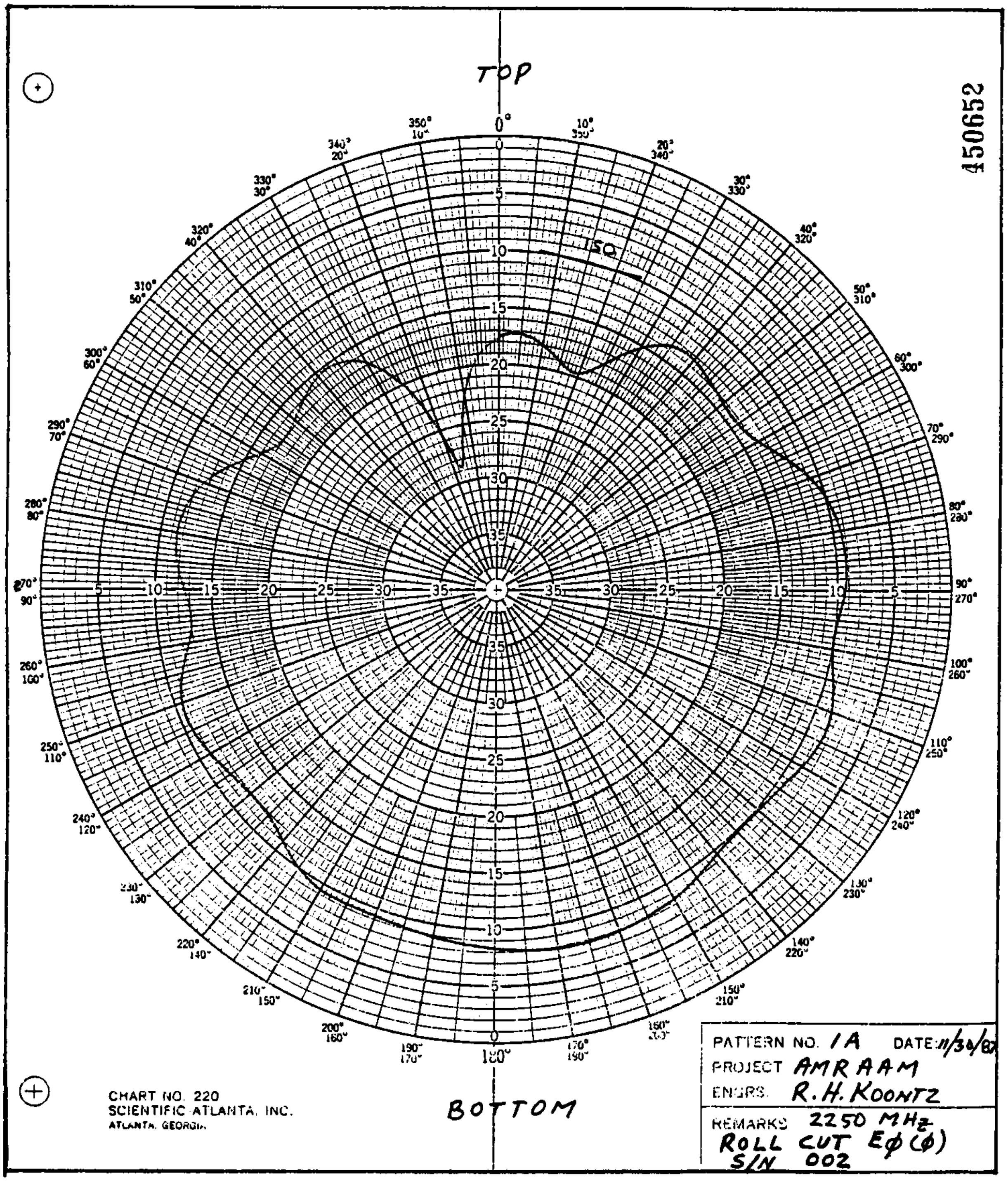

Figure 8. Roll Plane Cut.

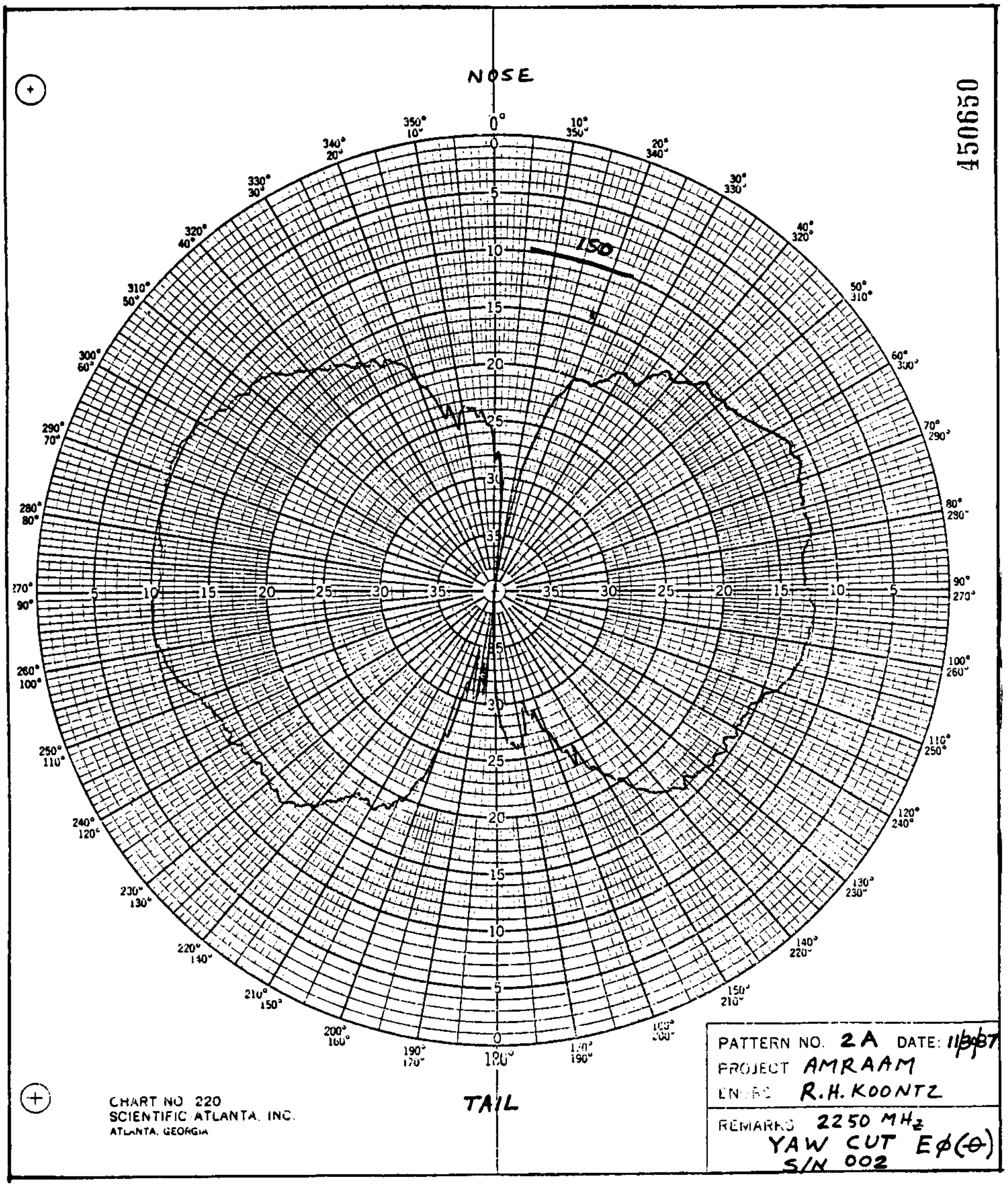

Figure 9. Yaw Plane Cut.

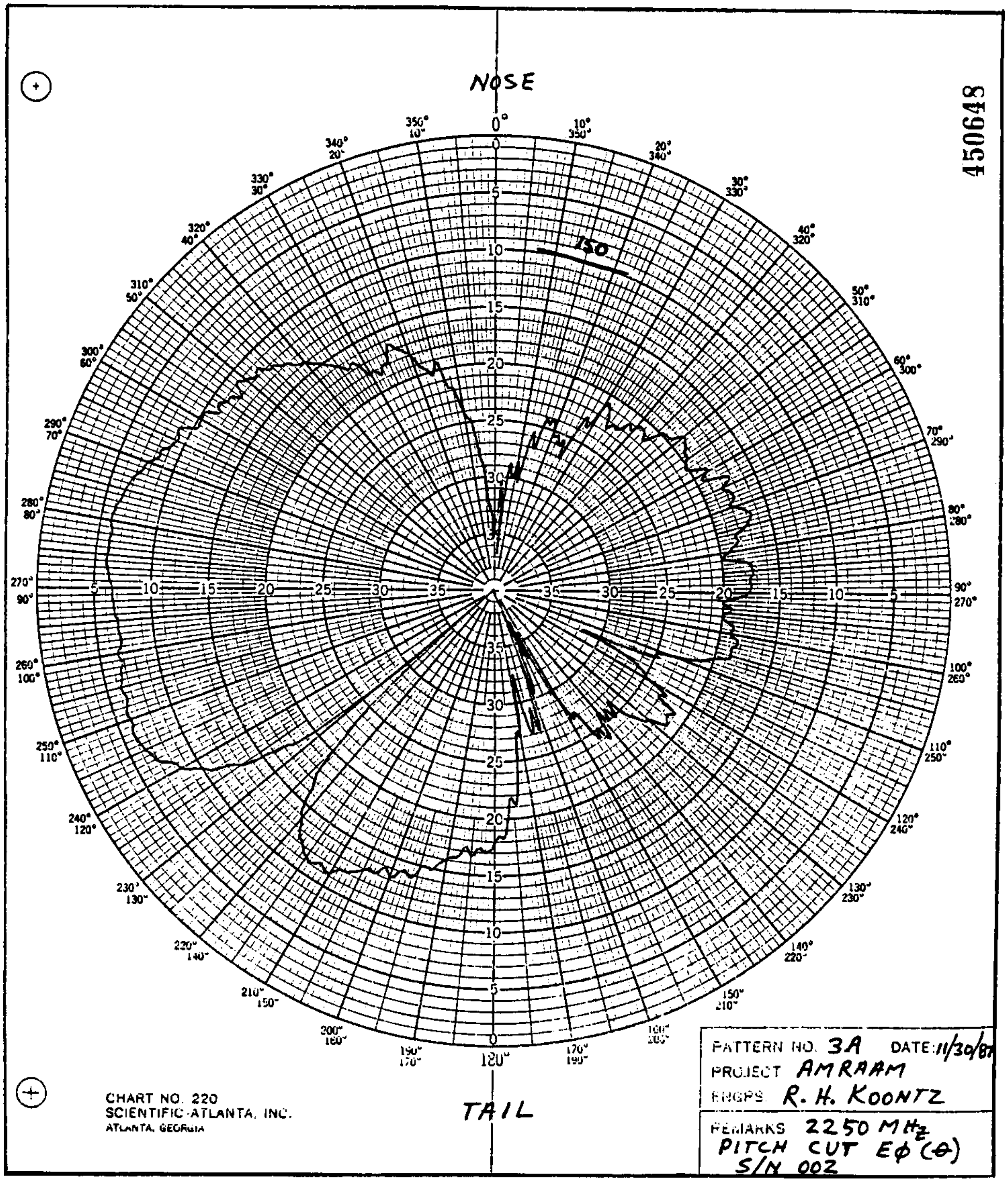

Figure 10. Pitch Plane Cut.

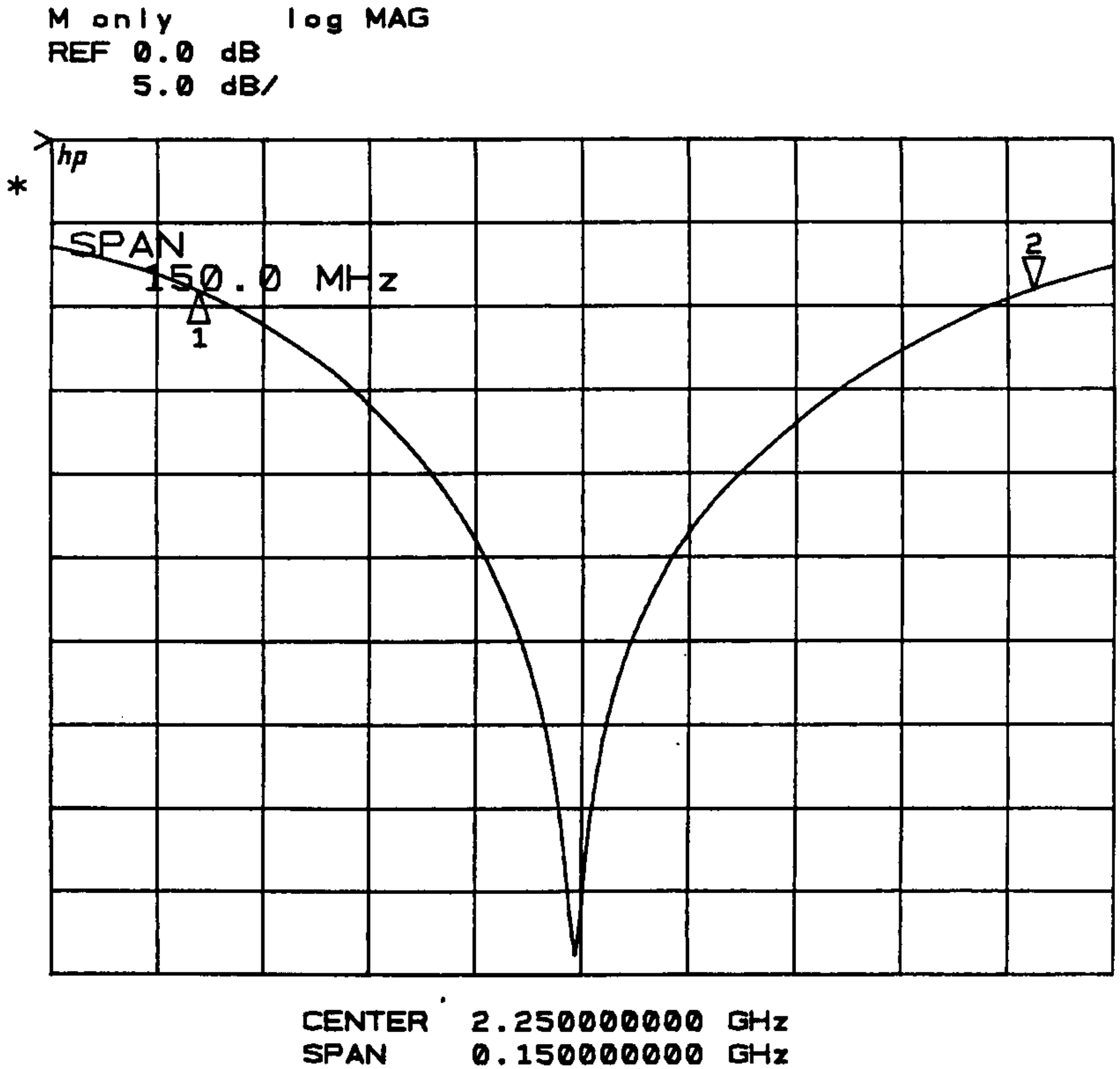

Figure 11. Return Loss for Mounted Antenna.