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Effects of RF Power Deviations on BCAS Link Reliability

7 June 1977

Prepared for the Federal Aviation Administration by

Lincoln Laboratory

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

LEXINGTON, MASSACHUSETTS

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16. Abstract

In the design of BCAS there is some freedom in the choice of specifications for BCAS transmitter power and receiver MTL (Minimum Triggering Level). Transmitter power should be high enough to provide adequate link reliability while being low enough to prevent interference problems. The question of providing adequate link reliability for the DABS mode of BCAS is addressed in this study. The study makes use of aircraft antenna gain data resulting from a model measurement program, and is otherwise analytical. It is concluded that appropriate nominal design values are transmitter power = 500 watts and receiver MTL = –77 dBm (referred to the BCAS unit). It is shown that these values provide sufficient power margin, at the air-to-air ranges appropriate for BCAS, so as to allow for adverse power deviations that might result from aircraft antenna gains, antenna cabling, and the expected transmitter and receiver deviations due to manufacturing nonuniformities and aging.

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1. INTRODUCTION

In the design of BCAS there is some freedom in the choice of specifications for BCAS transmitter power and receiver MTL (Minimum Triggering Level). Transmitter power should be high enough to provide adequate link reliability and low enough to prevent interference problems. The question of providing adequate link reliability is addressed in this study.

A natural or baseline specification worth considering is simply the assignment of the standard DABS transponder parameters to BCAS namely:

$$\text{BCAS transmitter power (1030 MHz)} = \begin{cases} 500 \text{ watts nominal} \\ \pm 3 \text{ dB tolerance} \end{cases}$$

$$\text{BCAS receiver MTL (1090 MHz)} = \begin{cases} -77 \text{ dBm nominal} \\ \pm 3 \text{ dB tolerance} \end{cases}$$

where the levels are referred to the RF port(s) of the BCAS unit. Based on this assignment, a link power calculation under nominal conditions and at an air-to-air range of 10 nmi would appear as in Table I. The "nominal margin" (two way) as defined in the table expresses the amount by which receiver power levels exceed receiver MTL levels in both links. Nominal margin varies as a function of range, and also would change if the nominal values in the transmitter/receiver specification were changed. Although the nominal margin shown here is 9.5 dB, the actual margin at this range in any particular air-to-air encounter may be greater or less due to deviations in any or all the items in

TABLE I
Air-to-Air Link Power Calculation Under Nominal Conditions and at a Range of 10 nmi.

ITEM	UNITS	INTERROGATION LINK (1030 MHz)	REPLY LINK (1090 MHz)
1. transmitter power	dBm	57	57
2. transmitter cabling loss	dB	3	3
3. transmitter mismatch loss	dB	0	0
4. transmitter antenna gain	dB	0	0
5. free space path loss	dB	118	118.5
6. receiving antenna gain	dB	0	0
7. receiving mismatch loss	dB	0	0
8. receiving cabling loss	dB	3	3
9. received power	dBm	-67	-67.5
10. MTL	dBm	-77	-77
11. nominal margin (one way)	dB	10	9.5
12. nominal margin (two way)	dB	9.5	

Notes:

Items 3 and 7, mismatch losses, refer to the differences, if any, that result when cables are attached to the antennas as compared with connections to perfectly matched loads. The nominal value is arbitrarily taken to be 0 dB.

Items 4 and 6 -- the nominal value of aircraft antenna gain is arbitrarily taken to be 0 dB.

Item 5, free space path loss = $20 \log(4\pi R/\lambda)$ where R = range and λ = wavelength.

Item 9, received power equals the sum of items 1, 4, and 6 minus the sum of items 2, 3, 5, 7, and 8.

Item 10, MTL, denotes Minimum Triggering Level.

Item 11, nominal margin (one way) equals item 9 minus item 10. The small difference originates in free space path loss which is slightly different at the two frequencies.

Item 12, nominal margin (two way) is the lesser of the two values in item 11.

the table -- except for free-space path loss which is entirely predictable. Thus, for reliable link operation at a given range, it is necessary that a sufficiently large value of nominal margin be provided by the system design. It seems reasonable to provide at least enough to offset the sum of the adverse tolerances for transmitter and receiver, which in this case are 3 dB for transmitter and 3 dB for receiver, totalling 6 dB. Yet a nominal margin of 6 dB may not be adequate in view of cabling effects, mismatch effects, and especially antenna gain effects. This study approaches the problem of choosing an adequate amount of nominal margin from a statistical point of view.

2. APPROACH

In BCAS, very high link reliability at long ranges is probably not necessary. Unlike DABS which requires very high link reliability for all targets under surveillance (for purposes of delivering IPC commands), BCAS probably can function properly even if the link is somewhat intermittant for some of the longer range targets in track. What is critical in BCAS is that for any approaching target, detection and threat evaluation be successfully carried out in time to display appropriate warnings and commands to the pilot. Thus, there is a strict requirement on a sort of cumulative link reliability and no direct requirement for instantaneous link reliability.

Straight flight situations and turning flight situations each present characteristic problems. In turning flight, aircraft banking tends to increase the liklihood of deep antenna fades; however, since geometries are continually changing, these fades are not long lived. In straight flight situations, fades

are more constant, and as a result fades can persist for longer times. Because BCAS link reliability is to be judged by a cumulative probability, straight flight may well constitute the more severe test on which the link design should be based.

When two constant velocity aircraft are on a collision course, the bearing angle at which each aircraft sees the other is constant. As a result, any antenna fades which by chance have occurred will persist for the duration of the encounter up until the point of an escape maneuver. Flight irregularities due to wind turbulence or any other source would improve the situation, but for link design purposes, the constant-bearing-angle encounter seems to be a worst case which can occur and should be allowed for.

An analysis has been carried out to indicate the relationship between nominal margin and BCAS link reliability in this constant bearing angle worst case and in an environment free of interference. The approach taken is to adopt statistical descriptions for each of the deviations in the link calculation and to combine these so as to calculate the probability of having adequate received power for each possible value of nominal margin.

3. SUMMARY OF RESULTS

The results of this analysis are summarized in Figs. 1 and 2. Figure 1 gives the computed relationship between nominal margin and link reliability, shown for various degrees of antenna diversity. To interpret "link reliability" plotted vertically in Fig. 1, imagine a population of diversity-equipped aircraft in which the following properties vary from aircraft to aircraft:

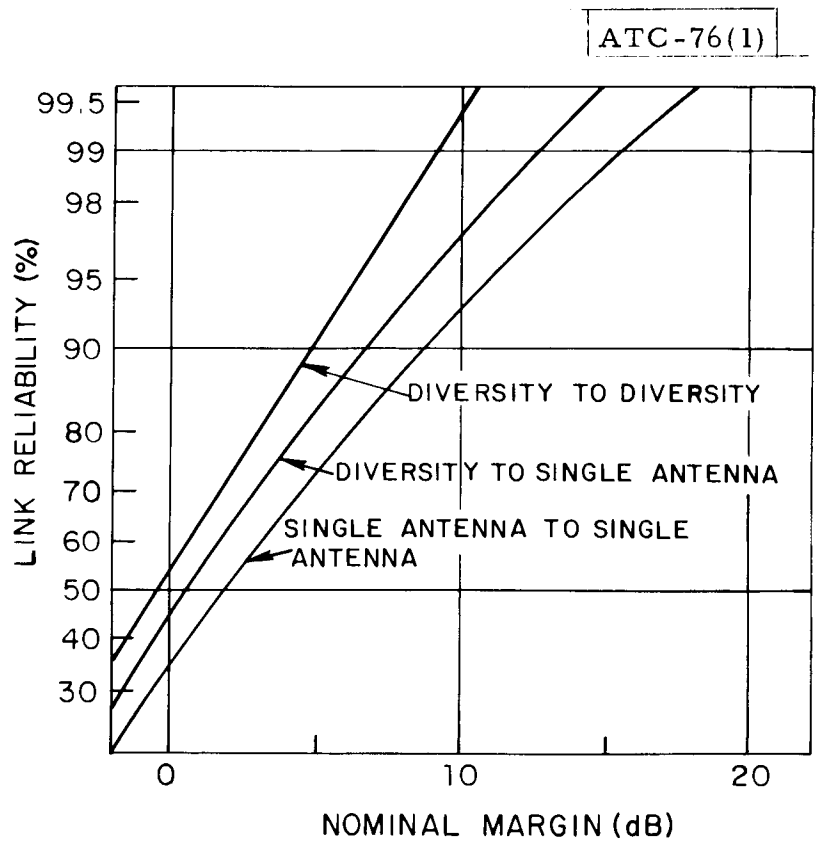

Fig. 1. Computed relationship between nominal margin and BCAS link reliability.

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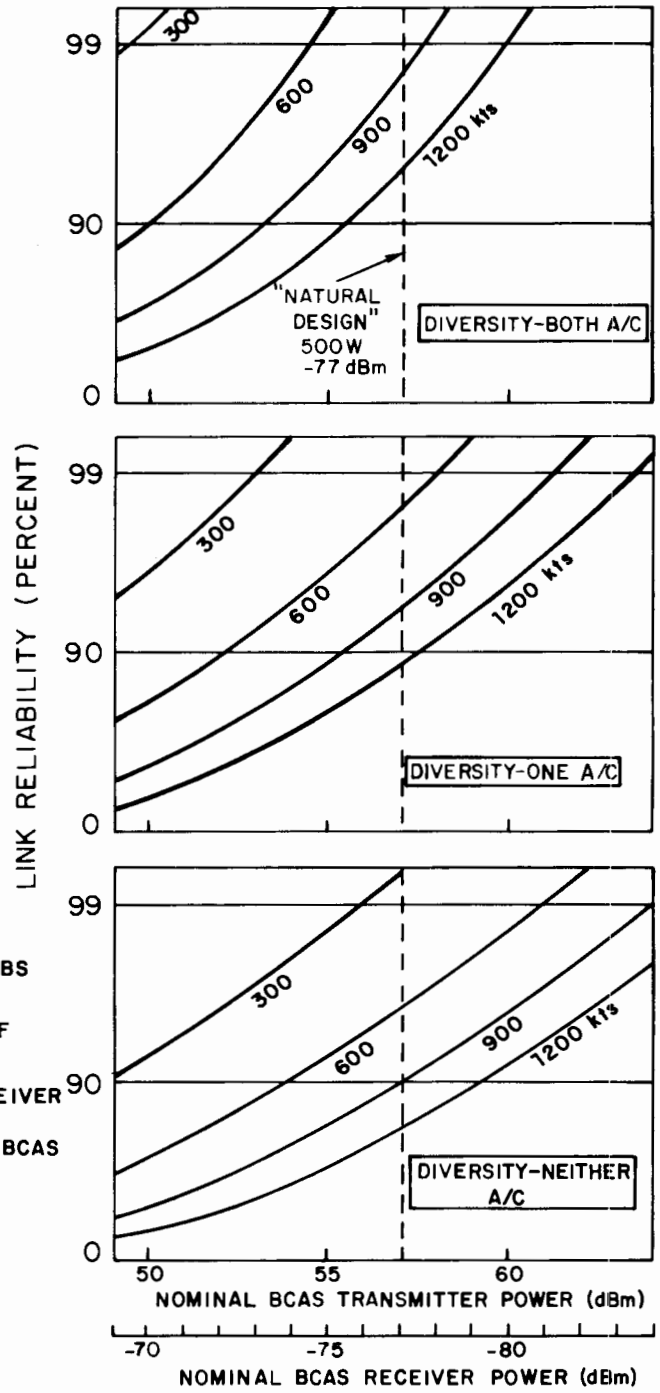

NOTES:

(a) REFERS TO THE DABS MODE OF BCAS

(b) IN THE ABSENCE OF INTERFERENCE

(c) TRANSMITTER/RECEIVER POWER LEVELS REFERRED TO THE BCAS UNIT

Fig. 2. BCAS link reliability vs transmitter/receiver specifications.

- type of aircraft
- antenna locations
- direction of flight
- BCAS transmitter power
- BCAS receiver MTL
- DABS transmitter power
- DABS receiver MTL
- antenna cabling losses
- antenna mismatch losses

where the transmitter/receiver deviations express the nonuniformities accounted for by the tolerance ranges in the equipment specifications. Then if two aircraft are picked at random from this population, "link reliability" expresses the probability that any given value of nominal margin will be sufficient to offset the combination of all of the deviations in the link calculation. This describes link reliability in a diversity-to-diversity encounter. In the other types of encounters, involving single-antenna installations, the description is the same except drawing from a second population of aircraft all having single bottom-mounted antennas.

Although, as mentioned above, nominal margin depends on range, the curves plotted in Fig. 1 are independent of range.

Antenna diversity is seen, in Fig. 1, to appreciably improve link reliability. For link reliability values on the order of 99%, the benefit of

adding diversity to one aircraft is about equivalent to a 3 dB change in the transmitter/receiver specifications, and the benefit of adding diversity to the other aircraft is another 3 dB. The mechanism causing this diversity benefit in straight flight is discussed in Section 5.1.

When the data of Fig. 1 are combined with the range requirements of the DABS mode of BCAS, the results are as shown in Fig. 2. Here, link reliability is plotted as a function of the BCAS transmitter/receiver nominal specification (varying transmitter and receiver by equal amounts so as to maintain balance in the two links). BCAS range requirements depend on closing speed, and for this reason results are given separately for different values of closing speed. The results show that, for example, in an encounter with 1200 knot closing speed, link reliability (in an interference-free environment) is 95% if both aircraft are diversity equipped, 89% if one aircraft is diversity equipped, and 82% if neither aircraft is diversity equipped.

4. DISCUSSION OF RESULTS

Before judging the adequacy of transmitter/receiver specifications from these results, a review of certain inputs to the calculation would be appropriate. Fig. 3 summarizes the distributions of transmitter powers, receiver MTL's, and antenna cabling and mismatch losses adopted for purposes of this calculation. These are seen to be idealized rectangular distributions. For example, BCAS transmitter power is characterized as being uniformly distributed over the ± 3 dB tolerance range. In reality it may be expected that the distribution would depart from the assumed rectangle possibly having a concentration near the center part of the tolerance range, and a more gradual

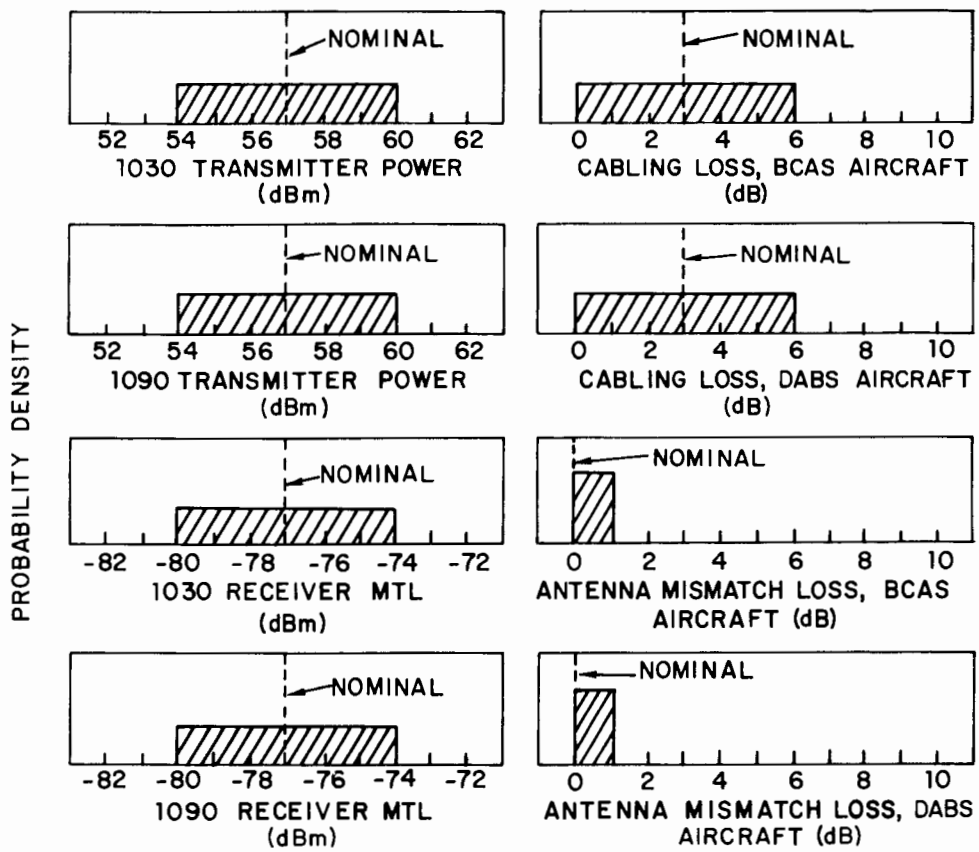

Fig. 3. Probability distributions adopted in this study.

fall-off at each end, with some fraction of the population being out of tolerance above and below. The precise shapes of these distributions would be difficult to predict. However, as will be discussed in Section 5.2, due to a central-limit-theorem phenomenon the results of this analysis depend primarily on means and variances, being otherwise quite insensitive to shapes of distributions. While these rectangular distributions are not altogether realistic, their means and variances appear to be reasonable characterizations (assuming most units are built within the tolerances), and on this basis the results given in Figs. 1 and 2 may be accepted as valid.

On the other hand, an assumption that most DABS transponders will comply with the power and MTL tolerances cannot be taken for granted (as was demonstrated in the Colby/Crocker ATCRBS transponder test program*). There are a number of reasons why close agreement is not assured between airborne transponders and the National Standard. Yet, recognizing the possibility for widespread out-of-tolerance performance brings up the question of whether or not BCAS should be designed to compensate for such performance. It is our present opinion that it would not be reasonable to oversize the BCAS transmitter and receiver to bear this burden.

Concerning the concept of link margin, it might be advisable to allocate a portion of the margin as a "safety factor" for offsetting possible unexpected conditions such as departures from the adopted statistical characterizations

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*Ref., G.V. Colby and E.A. Crocker, "Final Report, Transponder Test Program", M.I.T. Lincoln Laboratory, FAA-RD-72-30, 12 April 1972, p. 40-43. For example, among general aviation transponders, approximately 40% were out of tolerance in MTL.

in Fig. 3, and possible changes in the BCAS threat logic which would affect range requirements. In generating Fig. 2, no safety factor was included, where instead all of the margin was used to offset effects that are to be expected. Additional margin for the unexpected could be provided by simply adding the appropriate amount to the nominal transmitter power and receiver MTL values plotted in Fig. 2. Our present design does not include such an allowance, although this is a preliminary position which could change as new information becomes available.

With these points in mind, the performance shown in Fig. 2 may be judged. Assuming use of diversity by all BCAS units and by most of the intruders encountered above 10,000 ft. altitude (where high speed encounters are possible), the link performance with the "natural design" values of transmitter power and receiver MTL appears to be acceptable in the absence of interference. In a 1200 knot encounter, link reliability is moderately high, and improves greatly under slower speed conditions.

The conclusions from this work, and the relationships with other work yet to be factored-in, may be summarized as follows. An appropriate transmitter/receiver specification for the DABS mode of BCAS, providing adequate link reliability in the absence of interference, is the "natural design" (500 watts/-77 dBm). This design includes sufficient margin for a number of possible deviations in the air-to-air link, yet it does not include an additional safety factor for the unexpected. Considerations yet to be included are: (1) interference and multipath, (2) the ATCRBS mode of BCAS whose power requirements may affect the design of the DABS mode, and (3) link power measurements which data when available will either validate or indicate the need for changes in the analytical considerations given here.

5. DERIVATION OF RESULTS

5.1 Characterization of Aircraft Antenna Gain

One source of data for assessing the variability of aircraft antenna gain is the model measurement program that was carried out by Lincoln Laboratory and Boeing in 1973-4 (Ref., G.J. Schlieckert, "An Analysis of Aircraft L-Band Beacon Antenna Patterns", M.I.T. Lincoln Laboratory, FAA-RD-74-144, 15 January 1975). An example of these data is shown in Fig. 4. The plot includes three cuts from the aircraft antenna pattern of a Grumman Gulfstream, for one of two bottom antenna positions that were tested. In this example, an adverse gain variation occurs in the forward direction, in the amount of about -5 dB. To help in understanding the frequency of occurrence of such conditions, the data base from the model measurements has been processed in several ways, one of which leads to the plots in Fig. 5. In this format, the data give the cumulative probability distribution of antenna gain values for a population of aircraft orientations. Each curve gives the result for a single aircraft type and antenna mounting location. The fact that the different curves do not coincide reflects the differences between different aircraft types and antenna locations. Evidently these differences are large enough to show up as statistically significant. The four separate plots in Fig. 5 correspond to the four combinations of level vs turning flight and antenna diversity vs a single bottom antenna, where the diversity cases consist of one bottom antenna together with one top antenna. Level and turning flight are defined in terms of the following orientation statistics:

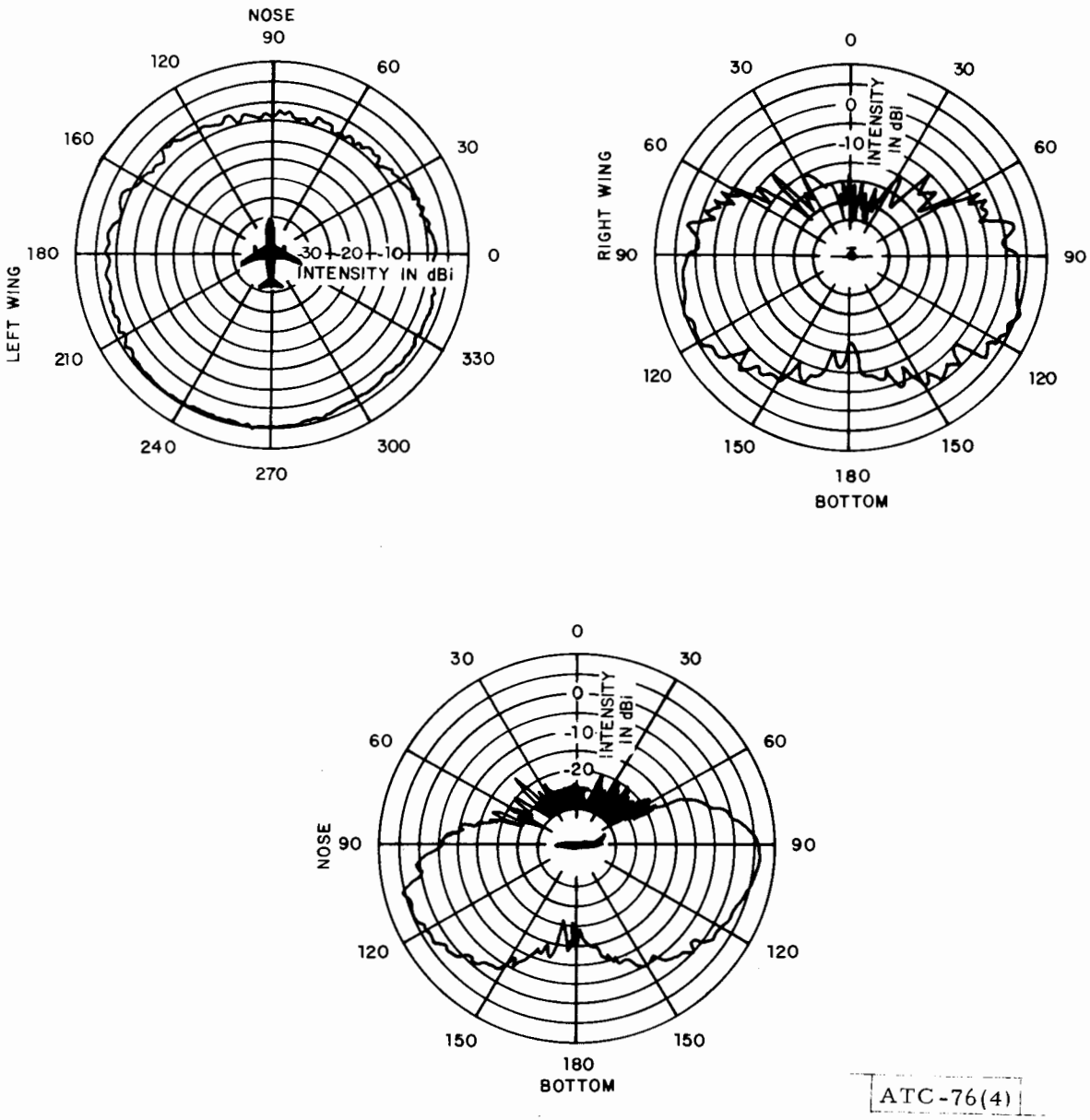

Fig. 4. Aircraft antenna antenna patterns, from model measurements (Grumman Gulfstream; bottom mounted, rear antenna, flaps up, wheels up).

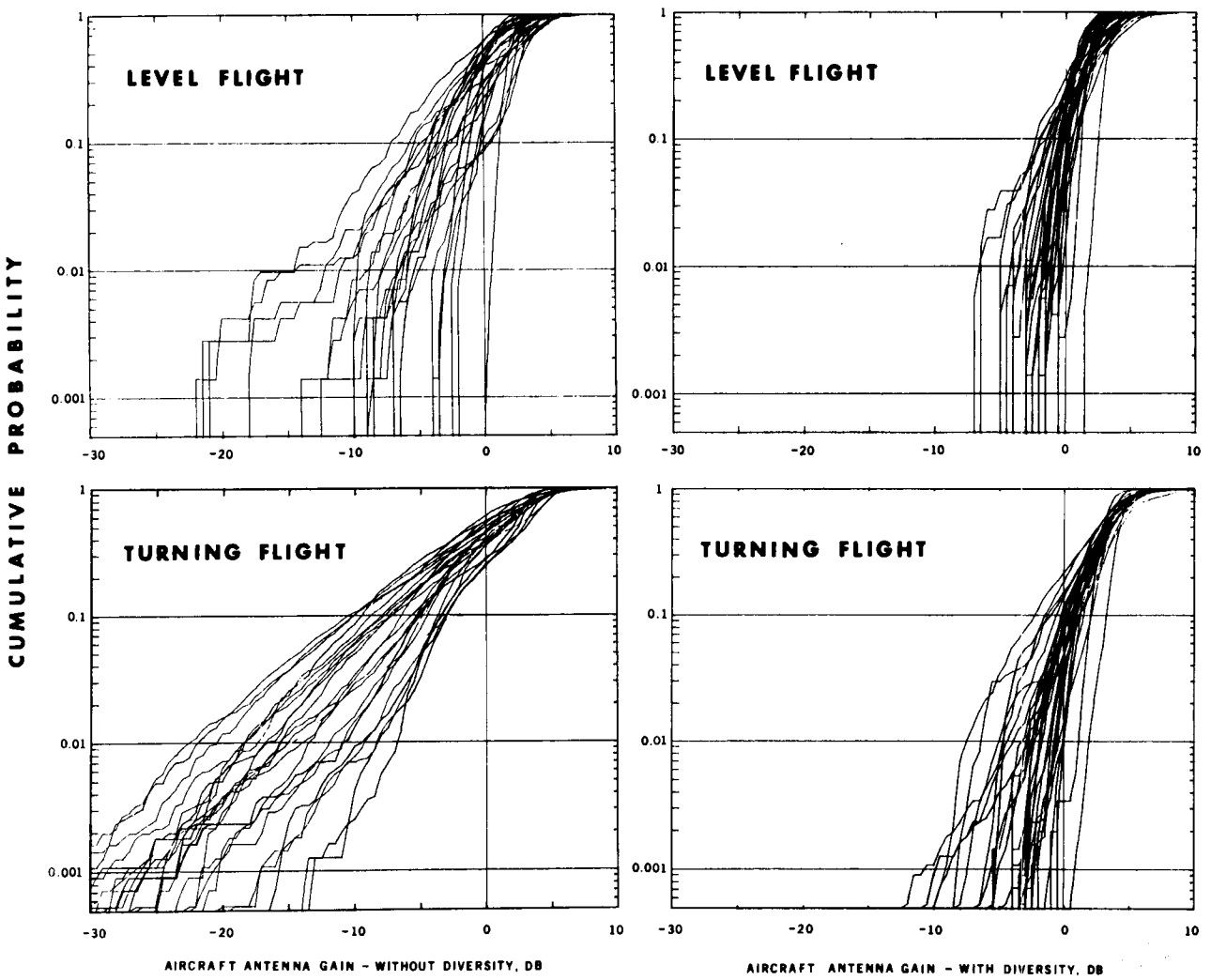

Fig. 5. Antenna gain distributions superimposed.

"level flight": azimuth = uniformly distributed over 360°

bank angle = uniformly distributed over -3° to $+3^{\circ}$

"turning flight": azimuth = uniformly distributed over 360°

bank angle = uniformly distributed over -30° to $+30^{\circ}$

Diversity is expected to offer its primary advantage in turning situations when aircraft banking will at times shield a single antenna from view, and this advantage is quite evident in Fig. 5. However, it may seem surprising at first to see in Fig. 5 that diversity offers an appreciable advantage in level flight situations as well. This advantage results largely from the horizon-cutoff variability of aircraft antenna patterns -- a phenomenon that is illustrated in Fig. 6. Here the elevation angle cuts of the Grumman Gulfstream patterns in Fig. 4 are plotted together and compared with the pattern of an ideal dipole on a perfect plane. The following properties are apparent in this plot: (1) Below the horizon and excluding the region within about 10° of the horizon, the measured antenna patterns are moderately well approximated by the ideal curve. Thus, for example, gains of about +4 dB are typical at about 20° below horizontal. (2) whereas the ideal curve makes a large and abrupt jump at the horizon, the measured curves have a gradual horizon cutoff which usually begins below the horizon. (3) The cutoff is more abrupt in the fore and aft cuts, in which directions the ground plane is more extensive. (4) This horizon cutoff may be moved up or down in elevation angle according to where the antenna is mounted. (5) As a result of this up-or-down variability and as a result of the steepness of the curves around the horizon, gain values at the horizon have a large spread.

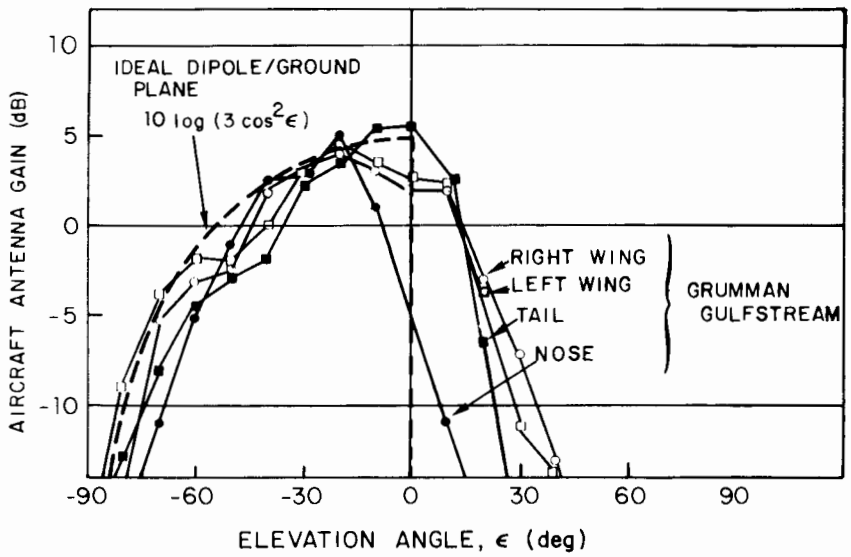

Fig. 6. Differences in horizon cutoff characteristics of aircraft antenna patterns.

These properties seem to be generally true among all of the aircraft antenna patterns in the data base. The advantage which diversity offers in level flight results simply from the availability of two patterns instead of one, which are somewhat unlikely to both have low-gain values in a given direction.

The data in Fig. 5 have been further reduced by computing probabilities of antenna gain values for a condition in which the aircraft type and antenna location are selected at random, with the separate curves in Fig. 5 being equally likely. The results are shown in Fig. 7 for level flight, with and without diversity*. It may be seen here that, for example, there is a 10% chance of having antenna gain be less than -3 dB for a single antenna installation, whereas for a diversity installation, the liklihood is about 1%.

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*If it is true that the diversity benefit in level flight results primarily from having two independent chances instead of one, then the two curves in Fig. 7 should be related, approximately, by a square law. That is, if $P_1(G)$ and $P_2(G)$ denote the cumulative probability distributions for single-antenna installations and diversity installations respectively, then it should be approximately true that

$$P_2(G) = [P_1(G)]^2, \text{ for all } G.$$

The data in Fig. 7 can be seen to agree with this simple relationship, which serves as a reasonableness check of the data reduction process and of the conceptual understanding of the diversity benefit.

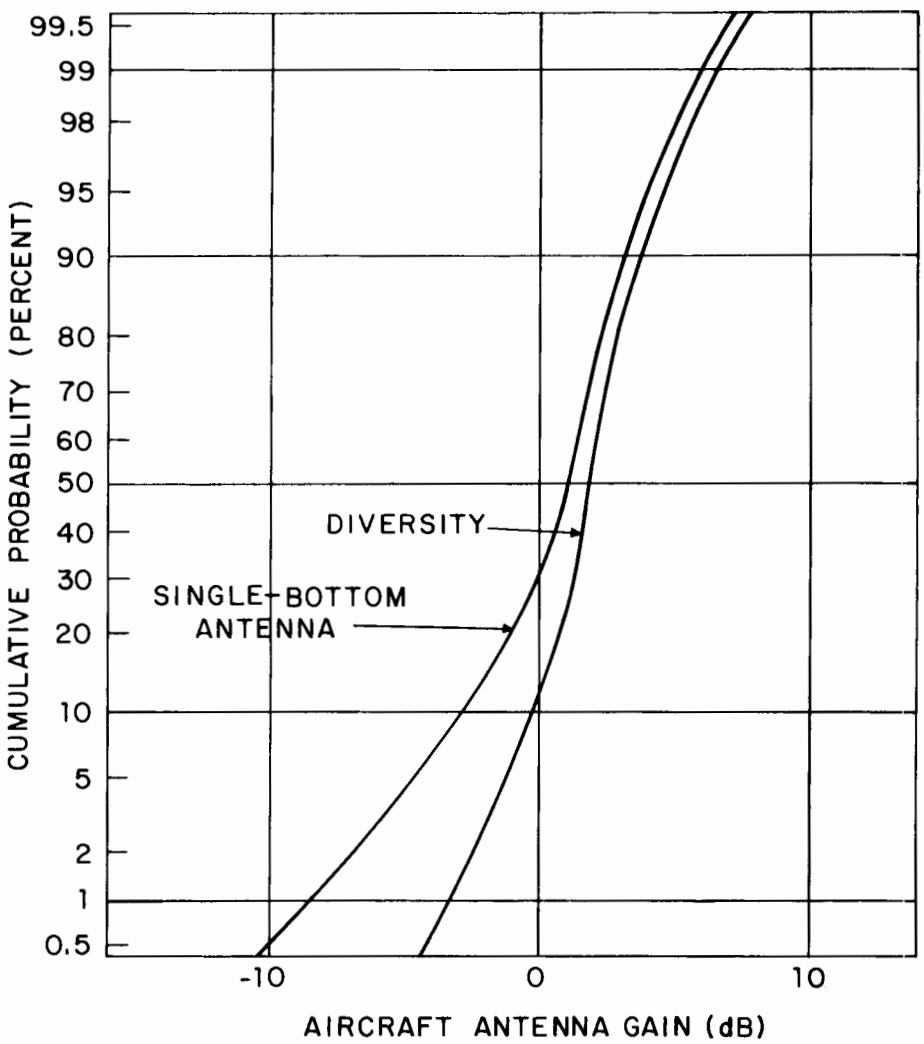

Fig. 7. Aircraft antenna summary statistics.

5.2 Statistical Analysis of Combined Effects

The aircraft antenna characterization in Fig. 7 has been combined with other effects in the air-to-air link as follows. Define PD (power deviation) to be

$$PD = \text{margin (dB)} - \text{nominal margin (dB)}$$

where nominal margin is computed as in Table I, item 12, and where margin is computed in the same way except under actual conditions rather than nominal conditions. We proceed to calculate the probability distribution of PD.

The total air-to-air power deviation, PD, is a combination of individual power deviations of separate effects. The relationships may be expressed mathematically as follows (based on the form of the link calculation in Table I)

$$PD = \text{lesser of } (\Delta I + 0.5) \text{ and } (\Delta R)$$

where ΔI and ΔR are respectively the interrogation link and reply link deviations, given by

$$\Delta I = \Delta 10 - \Delta 11 - \Delta 12 + \Delta 13 + \Delta 14 - \Delta 15 - \Delta 16 - \Delta 17$$

$$\Delta R = \Delta 20 - \Delta 21 - \Delta 22 + \Delta 23 + \Delta 24 - \Delta 25 - \Delta 26 - \Delta 27$$

and where $\Delta 10$, $\Delta 11$, etc., express the deviations of individual terms. These are defined as follows:

	INTERROGATION	REPLY
tr. power (dBm)	57 + Δ10	57 + Δ20
tr. cabling loss (dB)	3 + Δ11	3 + Δ21
tr. mismatch loss (dB)	Δ12	Δ22
tr. antenna gain (dB)	Δ13	Δ23
rec. ant. gain (dB)	Δ14	Δ24
rec. mismatch loss (dB)	Δ15	Δ25
rec. cabling loss (dB)	3 + Δ16	3 + Δ26
MTL (dBm)	-77 + Δ17	-77 + Δ27

Each of these is modeled as a random variable with a prespecified probability distribution, and the resulting probability distribution of PD is calculated. Certain pairs of these variables are related. For example, Δ13 and Δ24 both refer to the same antenna, only differing in frequency. To account for these conditions, the following relationships are adopted.

$$\Delta 13 = \Delta 24$$

$$\Delta 14 = \Delta 23$$

$$\Delta 11 = \Delta 26$$

$$\Delta 16 = \Delta 21$$

Otherwise the variables are taken to be statistically independent. The antenna gain terms are modeled by the data in Fig. 7 (applicable to level flight encounters). Deviations in transmitter power and receiver MTL values are modeled as uniformly distributed over the ± 3 dB tolerance ranges.

$$\left.\begin{matrix}\Delta 10\\ \Delta 17\\ \\ \Delta 20\\ \Delta 27\end{matrix}\right\} = \text{independent, uniformly distributed over } (-3,\ 3)$$

Cabling losses are modeled as being uniformly distributed over 0 to 6 dB. That is

$$\left.\begin{matrix}\Delta 11\\ \\ \Delta 16\end{matrix}\right\} = \text{independent, uniformly distributed over } (-3,\ 3)$$

Mismatch losses are modeled as being uniformly distributed over 0 to 1 dB.

$$\left.\begin{matrix}\Delta 12\\ \Delta 15\\ \\ \Delta 22\\ \Delta 25\end{matrix}\right\} = \text{independent, uniformly distributed over } (0,\ 1)$$

The results were obtained by a computerized Monte Carlo simulation, using 20,000 trials, which is sufficient for stable and accurate results with probabilities as small as 0.5%, and as large as 99.5%.

The results for the case in which one aircraft is diversity equipped and the other is not are shown in Fig. 8. This plot shows the original antenna data and some of the intermediate results as well.

It is interesting to observe how the combination of a number of effects causes PD in dB to be approximately a Gaussian random variable. Such "central-limit-theorem" behavior is generally expected whenever a number of statistically independent terms are added. This phenomenon is made evident in Fig. 8 which is

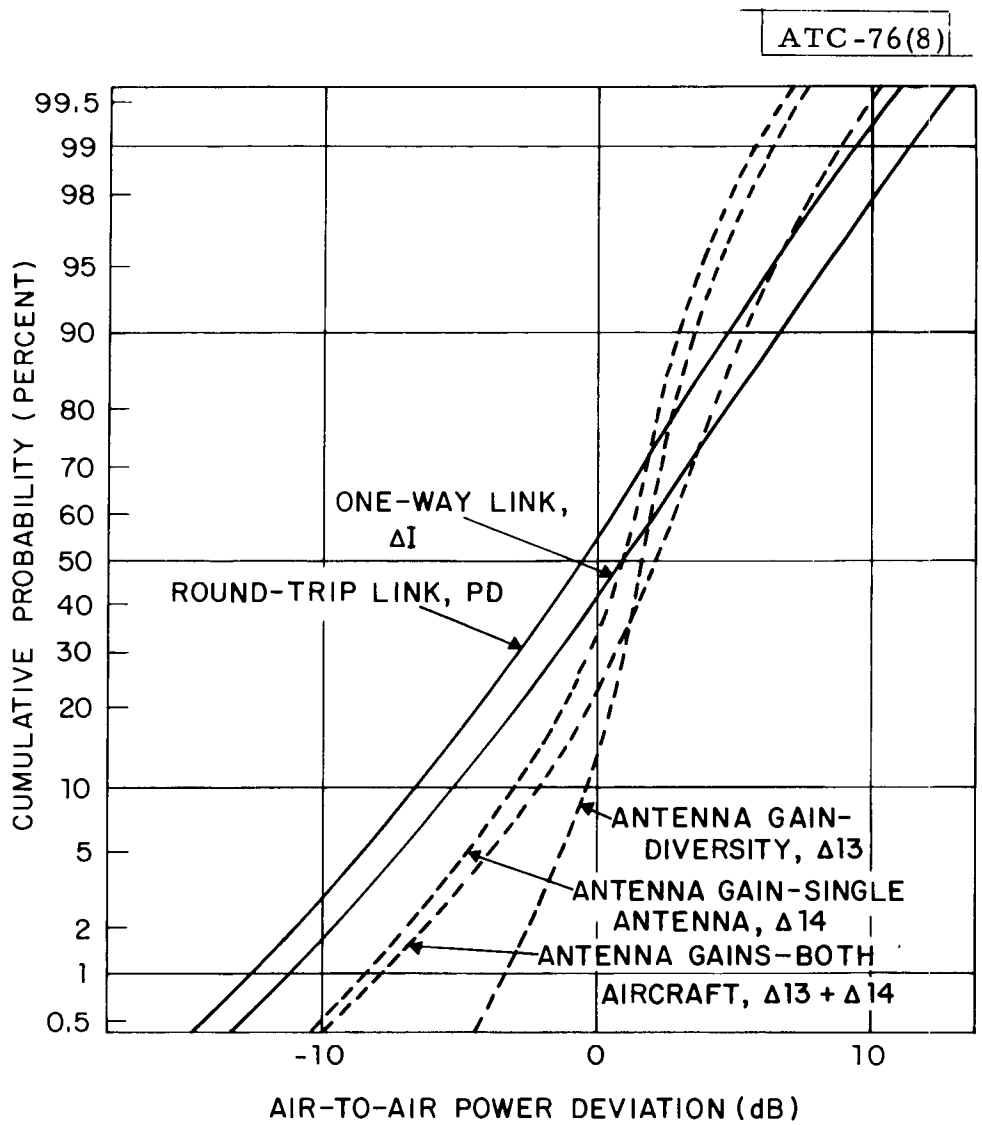

Fig. 8. Power deviation results - BCAS with diversity, intruder without.

plotted on Gaussian probability paper (on which any Gaussian distribution appears as a straight line). The individual antenna gain terms, $\Delta 13$ and $\Delta 14$, appear as curved functions and are clearly non-Gaussian. However, when added, the result ($\Delta 13$ and $\Delta 14$) is seen to be more nearly Gaussian, and when all of the terms in the interrogation link are combined, the result is accurately Gaussian over a broad range. It may be concluded from this observation that the results of this analysis have a considerable tolerance to possible inaccuracies in the original assumptions. The PD results depend almost entirely on the means and variances of the individual terms, being otherwise independent of the shapes of their probability distributions.

Results were also generated for the case in which both aircraft are diversity equipped and a case in which neither is diversity equipped. These results are given in Figs. 9 and 10. The three cases are summarized in Fig. 11. The results shown in Fig. 1 above are exactly the same as in Fig. 11 except with the axes inverted. That is, for each value of Nominal Margin (NM) in Fig. 1, Link Reliability (LR) is

$$LR = \text{prob. (margin} \geq 0)$$

which is equivalent to

$$LR = \text{prob. (PD} \geq -\text{NM)} = 1 - \text{prob. (PD} \leq -\text{NM)}$$

Thus LR is the complementary probability (1 minus the probability) that PD is less than - NM).

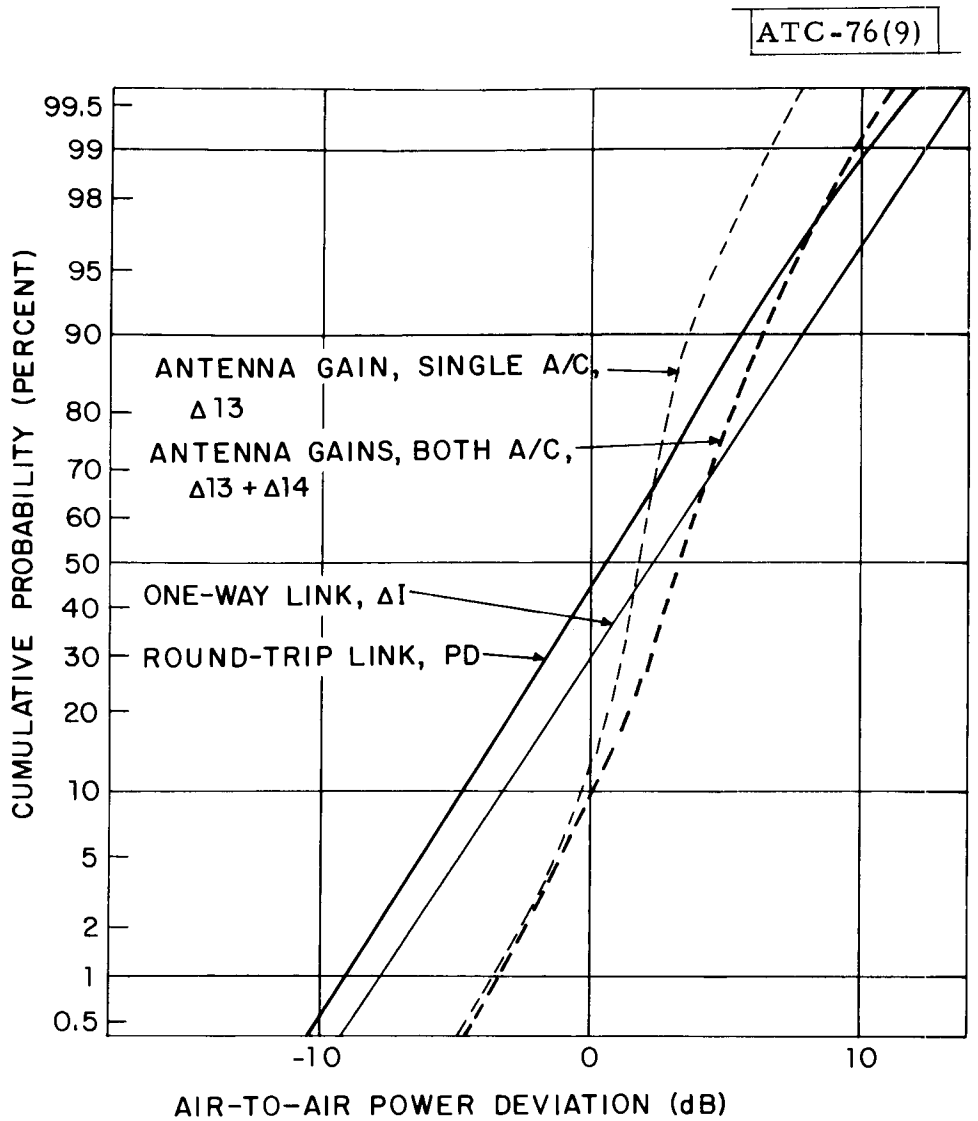

Fig. 9. Power deviation results - both aircraft diversity equipped.

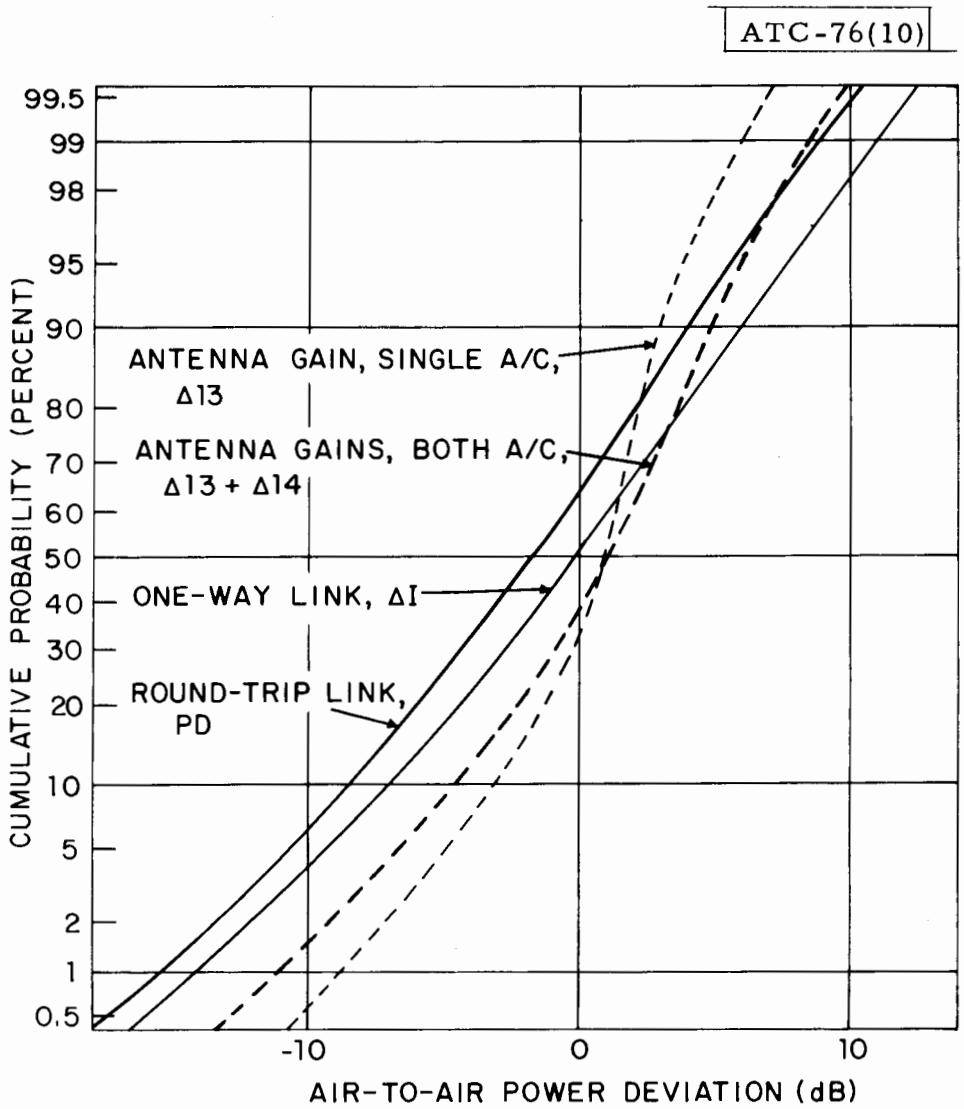

Fig. 10. Power deviation results - neither aircraft diversity equipped.

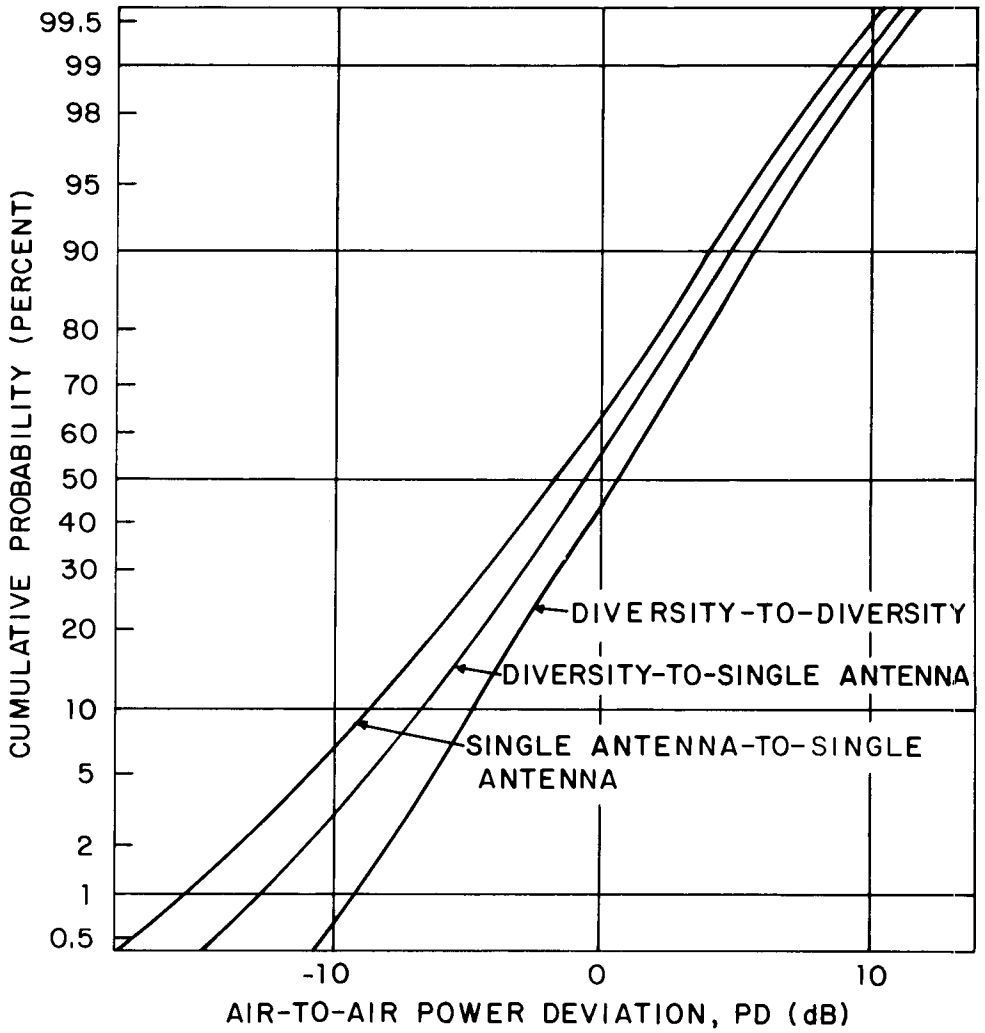

Fig. 11. Summary of air-to-air power deviations.

5.3 BCAS Range Requirements

In using these results, it is necessary to specify the maximum range at which the air-to-air link will be required to operate. The range requirements depend on closing speed as illustrated in Fig. 12. This plot shows the horizontal threat boundary according to the current BCAS design (described by a slope of 30 sec. and an offset of 1 nmi). In such a plot, a constant velocity encounter would proceed to the left on a horizontal line, as in the example plotted. Assuming that, in the DABS mode, up to an additional 10 sec. will be required between the time that the link power becomes adequate and the time that the threat boundary is penetrated (at which point a command is to be issued), it follows that the range requirement is 14.3 nmi for a 1200 knot encounter. For other closing speeds

$$\text{Range requirement} = 1 \text{ nmi} + 13.3 \text{ nmi} \left(\frac{\text{closing speed}}{1200 \text{ kt.}} \right)$$

This result is applicable only in the DABS mode, in which case 10 sec. should be sufficient to accomplish track acquisition. In the ATCRBS mode, the amount of time required for acquisition strongly depends on surveillance processing design. In the present baseline design, a time period of about 35 sec. is required. A large performance penalty may result from this long acquisition time.

The DABS mode range requirements may readily be combined with the power variation data in Fig. 1. For example, in the 1200 knot encounter for which the range requirement is 14.3 nmi, the nominal margin at the point of maximum range is 6.4 dB. According to Fig. 1, the probability of adequate power at

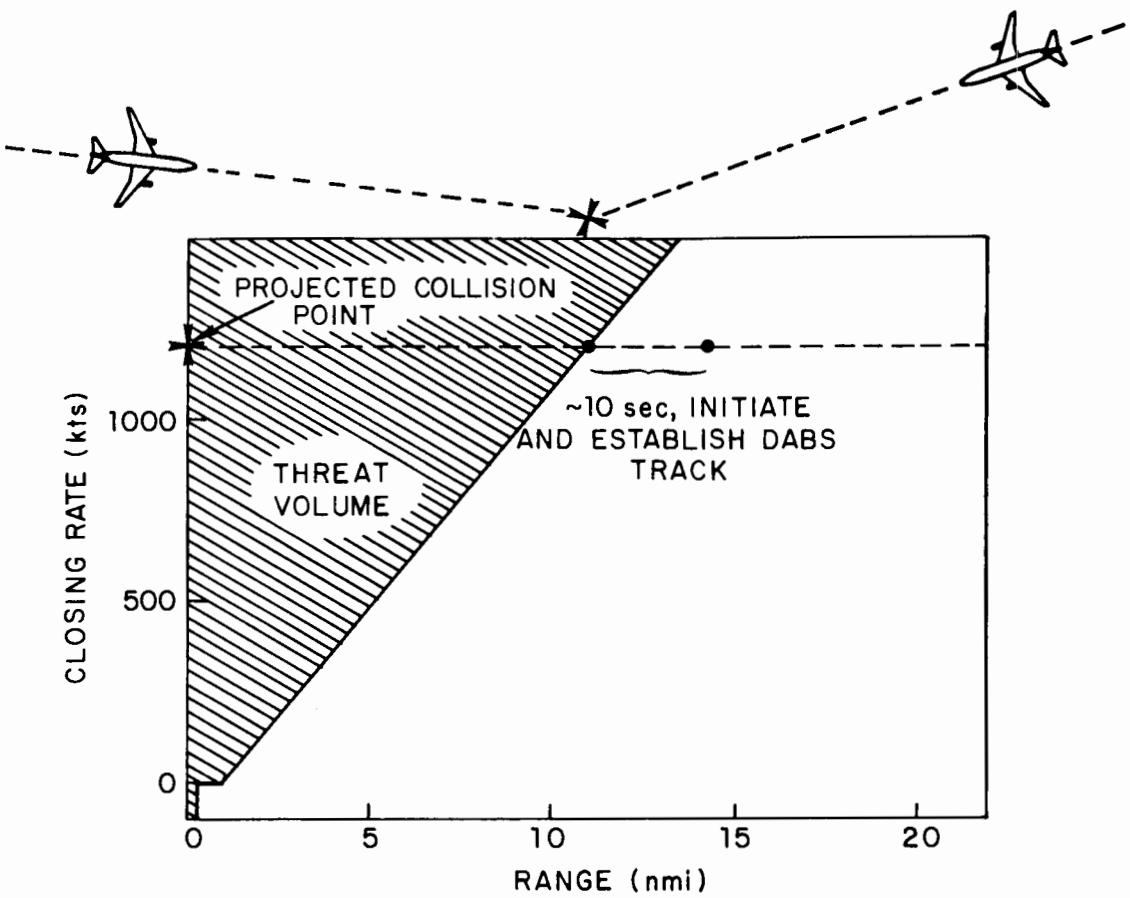

Fig. 12. Illustration of BCAS range requirements.

that point is 95% for a diversity-to-diversity encounter. Calculations of this sort have been carried out for various closing speeds, for various levels of diversity, and also for changes in the transmitter and receiver specifications, producing the results plotted in Fig. 2.