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Summary of Results of Antenna Design Cost Studies

J.-C. Sureau

19 February 1974

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY
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16. Abstract

Design/cost studies on antenna systems for DABS have been carried out by Texas Instruments and Westinghouse under Lincoln Laboratory sponsorship. For independent, mechanically-rotating systems aperture widths between 10' and 35' and heights between 4' and 16' were considered, with estimated corresponding production costs ranging from $10K to more than $200K. No generally-recommended implementation emerged although the trend was to choose planar arrays for stringent performance requirements and to accept less expensive reflectors when requirements were sufficiently relaxed. Although the aperture size was found to have a significant cost impact on the remainder of the system (pedestal, drive, tower), the antenna usually accounted for less than half of the total antenna installation cost.

With the use of off-boresight monopulse direction-finding, agile beam arrays require only slightly more than one beam position per beamwidth. Even with the resulting simplification in the beam-forming circuitry, their cost is about twice that of comparable rotators and starts at about $200K.

DABS systems which share the same pedestal as primary radars ("co-located") are inherently highly constrained and tend to lead to unique implementations. For an ASR installation, an integral monopulse beacon feed constitutes an economical (less than $5K) and expedient implementation with performance parameters which, though not optimum, are acceptable for DABS (4° beamwidth and 2 dB/degree elevation cut-off rate). A back-mounted antenna of the same (or smaller) aperture size as the ASR reflector can also be implemented as a retrofit for about $40K.

For ARSR installations, integral monopulse beacon feeds are also feasible at a very nominal cost but some performance compromises have to be accepted. Back-mounted DABS antennas can be accommodated in a large range of aperture sizes.

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INTRODUCTION

1.1 BACKGROUND

The Discrete Address Beacon System (DABS) will provide the primary Air Traffic Control (ATC) surveillance information for the 1980-1990 time period as it is introduced gradually as a replacement for the present Air Traffic Control Radar Beacon System (ATCRBS). The DABS Technical Development Plan (TDP) (October 1971), identifies related technical issues, discusses options, and presents a program leading to the definitions, design and evaluation of prototype DABS equipment. One of the technical issues identified in the DABS TDP was that of selecting, specifying and validating new beacon antenna systems which would differ significantly from the present ATCRBS antenna in two major areas:

a. Addition of monopulse direction finding capability to the system; this is to permit a large reduction in the interrogation rate from that required by present beam splitting technique, with no loss in accuracy.

b. Increase in the antenna vertical aperture to generate elevation patterns which provide low illumination of the ground (this trend is not unique to DABS; it has also been recommended as an interim improvement for ATCRBS).

This report discusses and summarizes the results of two DABS antenna system design-cost trade off studies performed by industrial concerns with substantial design, fabrication and field maintenance experience related to similar antenna systems now in the field. The data from these studies, was to be used to support other Lincoln Laboratory DABS studies leading to the definition and specification of a cost-effective system design.

1.2 STUDY FORMULATION

In its role as the Systems Engineering Contractor for the FAA, the Lincoln Laboratory sponsored two design/cost studies to be carried out by qualified potential vendors of antenna systems.

For purposes of the study, antenna systems were sub-divided into three categories to be investigated independently:

a. Independent Rotators: These are mechanically rotated antennas for DABS sensors whose look angle is not physically dependent upon that of any primary radar.

b. Independent Agile Beam Antennas: These are electronically-scanned arrays whose beam positioning sequence is completely flexible.

c. Co-located Antennas: For mechanically-rotating systems, co-location was defined as beacon and radar antennas sharing the same pedestal. For agile systems co-location meant sharing the same tower with the radar.

Antenna performance parameters of interest are summarized in Table 1.1.

Table 1.1. Specified range of interest of antenna systems parameters.

Antenna Requirements

Gain:	> 20 dB
Azimuth Beamwidth:	$> 2^{o}$
Power Handling:	2.5 kW peak, 1 kW average(1)
Mainbeam Ripple (elev.):	$\pm$ 1.5 dB(2)

Antenna System Parameters:

Direction-Finding Accuracy:	0.1^{o} to 1.0^{o} (3σ)
Elevation cut-off rate:	1 to 5 dB/deg.
Azimuth Sidelobes:	20 to 40 dB
Elevation sidelobes	13 to 23 dB
Up-date time (rotators)	1 to 15 sec(3)
Beam Reposition Time (agile):	1 to 5 μsec
Beam Hop-over:	none, 2^{o}, 4^{o}

(1) It now appears that the power requirements for DABS can considerably be relaxed (up to a factor of five)

(2) Rather than the sector-type elevation pattern implied by the specification shaped-beams of the cosecant-squared type are currently favored for the DABS application.

(3) The interest in the lower up-date times was notivated by potential applications to parallel approach monitoring, metering, and spacing.

The cost information on any one configuration was intended to reflect the procurement price for a production lot of 100 units designed to meet current pertinent FAA specifications.

Emphasis was to be given by the study contractors to the direction-finding portion of the performance analysis. The accuracy to be determined usually referred to as "inherent accuracy," was to include only the sensor-induced errors. Explicitly excluded were interference and multipath effects. The impact of various combinations of signal strengths, signal structure, and number of replies were to be examined.

1.3 STUDY EXECUTION

Texas Instruments (Dallas) and Westinghouse (Baltimore) were selected* to carry out studies on all three types of systems. The efforts lasted about five months, from August to December 1972, with progress being monitored at regular intervals. Study guidelines were modified as necessary during the study program to reflect the evolution of the DABS concepts and requirements. Each contractor's findings are presented in final reports, from which most of the information presented in this report is drawn.

1.4 AIMS OF REPORT

The basic aim of this report is to present in a single document the essential results of the two studies which are pertinent to the present status of the DABS program, and in such a manner as to be useful to those who might need to make decisions based on these results.

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*After the release of an RFP to more than a dozen interested companies, seven proposals were received and each was evaluated on the basis of technical content and cost independently.

While every attempt was made at directly extracting the appropriate information from the contractors' final reports, it was found necessary to occasionally modify some of the material so that the above stated goal could be best achieved. In general, we have preserved the anonymity of the source of any item; since our contractors were intentionally allowed to differ in their interpretation of the requirements details, some inappropriate comparisons might otherwise be made. In order to streamline the presentation, many of the design procedures and details included in the final reports have been omitted.

This report does not culminate in a recommended design, primarily because no single configuration emerged as unquestionably superior. What has been established as a result of these studies are the existence and associated cost of solutions to a range of performance parameters as well as parametric trends. As such, they will significantly contribute to the formulation of a rational set of system specifications.

1.5 ORGANIZATION OF REPORT

This report is organized into sections corresponding to the three different categories of antenna systems, i.e. rotating, agile beam, and co-located.

In rotators, the design cost issues associated with the major subsystems are first discussed individually. This is followed by a summary of the cost of complete systems which provide various levels of performance, and by some discussion of the trade-offs which exist at the total antenna system level. A discussion of the associated monopulse direction finding performance is also included.

In agile beam cylindrical arrays, the discussion follows the same general outline but is more restricted in scope since fewer design options were found to be worth considering.

Systems which are co-located with primary radar are discussed separately for the ASR and ARSR installations. Various configurations, varying from integral beacon feeds to back-to-back mounting, are discussed.

SECTION 2

INDEPENDENT ROTATORS

2.1 ANTENNA SYSTEM COMPONENTS

2.1.1 Planar Array

Planar arrays (see Fig. 2.1) which appear to be suitable for DABS are characterized by:

- Vertical dipoles on a rectangular element grid: 0.5 to 0.6 λ spacing in the vertical direction and about 0.8 to 0.9 λ in the horizontal direction.
- Column elements interconnected by identical power-dividing networks to permit elevation pattern control.
- Elevation networks connected by two horizontal networks to generate independent sum and difference azimuth monopulse patterns.

Independent vertical and horizontal control of the aperture illumination and the flexibility this allows in shaping the radiation pattern are the key features of planar arrays. Individually-optimized sum and difference patterns can be obtained, subject only to the aperture size constraints. By virtue of the pattern separability the apparent azimuth beamwidth and other related parameters such as monopulse slope, vary monotonically with the elevation angle.

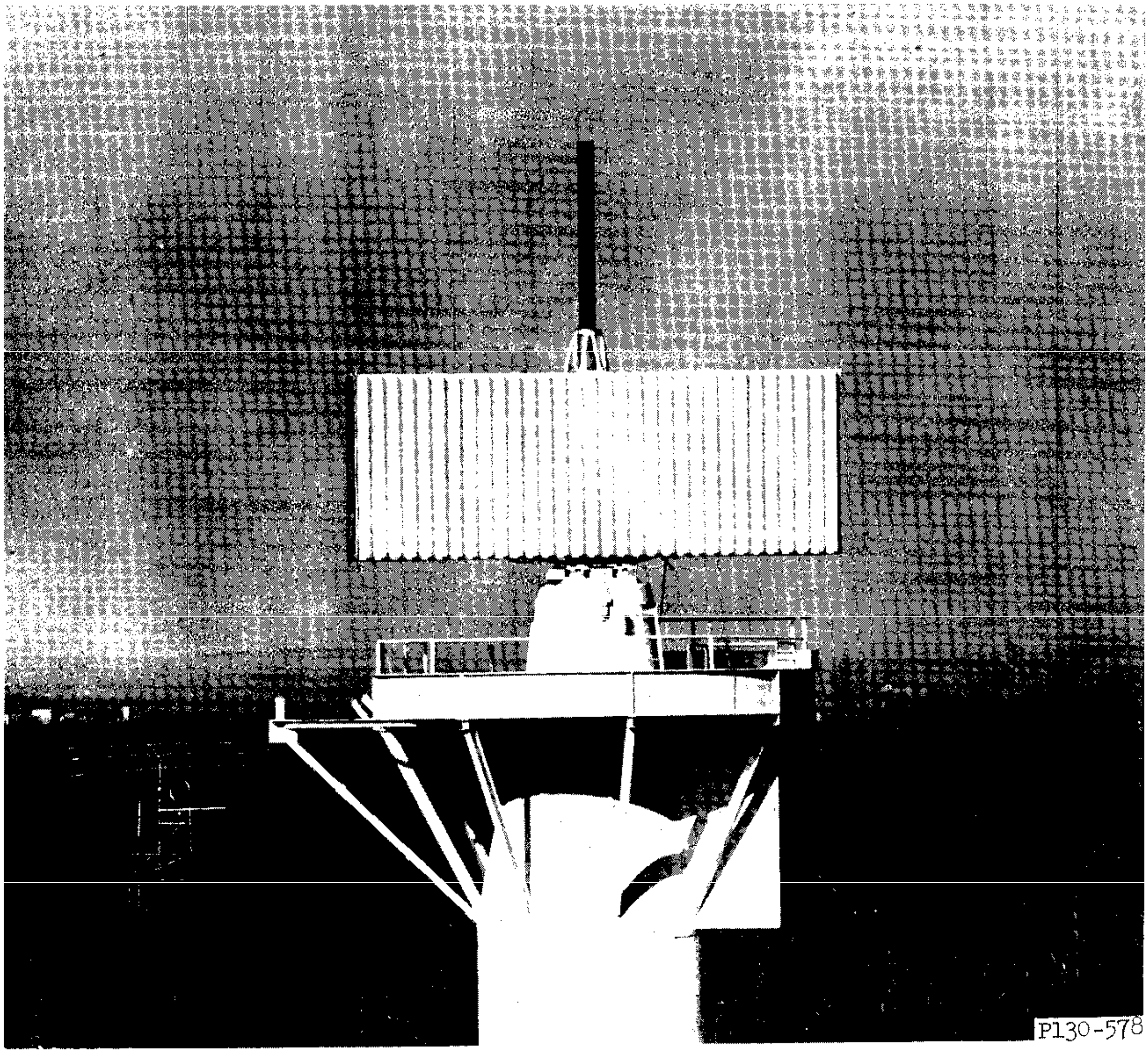


Fig. 2. 1. Planar Array Configuration (DABS Experimental Facility).

The horizon cut-off rate of the elevation pattern is to first order, determined by the aperture height, and, to second order, by the elevation sidelobes and mainbeam ripple. A nominal value of the horizon cut-off rate may be taken as the slope at the -6 dB point of the diffraction-limited beam generated by the same size aperture. The shape of the elevation pattern may be varied from the "sector" to the cosecant-squared type without significant effects upon the the cut-off properties. Hopover of the beam is a feature closely connected with the elevation pattern generation and, if required, must be included as an integral feature (as opposed to an add-on modification kit).

From the results of the two studies it may be concluded that the cost of the antenna structure including dipole elements, elevation networks and ground plane, is nearly proportional to the aperture area. The proportionality factor lies between $200 and $400 per square foot, depending on the aperture size and manufacturing technique. The azimuth monopulse feed network completes the antenna assembly; its cost is about $115 per linear foot of aperture width. Typically, the fabrication techniques consist of printed circuit etched dipoles, stripline distribution networks and coaxial cable interconnections similar to those used for the DABS Experimental Facility array. The fact that the results could be summarized, even though only approximately in terms of a linearized cost model, implies that no cost breakpoints were exhibited.

The range of aperture sizes considered and the usually associated performance parameters are given in Table 2.1. Two special features were also evaluated: limited agility and hopover. The type of limited agility considered during the study consisted of two possible beam positions symmetrically located about broadside and separated by about one beamwidth. The added

Table 2.1. Planar Array Aperture Sizes.

Beamwidth	Width
2°	29' - 32'
4°	14' - 16'

Cutoff Rate	Height
1 dB/deg	4' - 4.7'
3 dB/deg	9' - 10'
5 dB/deg	16' - 18'

cost was $400 per foot of aperture width. The cost of discrete step hop-over was evaluated at approximately $10 per square foot of aperture (two steps maximum).

2.1.2 Paraboloidal Reflectors

Unlike planar arrays, paraboloidal reflectors (see Fig. 2.2) are very much affected by the elevation patterns requirements which can result in two design approaches.

- Single feed, spoiled reflector designs are most suited for high gain patterns, such as cosecant-squared or low cut-off sector beams. They are exemplified by the ASR and ARSR designs. Beam hopover can be implemented, when desired, using an auxiliary feed similar to the passive horn in the ASR and ARSR.
- Vertically stacked feeds are employed to generate sector beams with sharp horizon cut-offs. For comparable performance, the height is essentially the same as for arrays. The multiple feeds provide a natural means of implementing hopover.

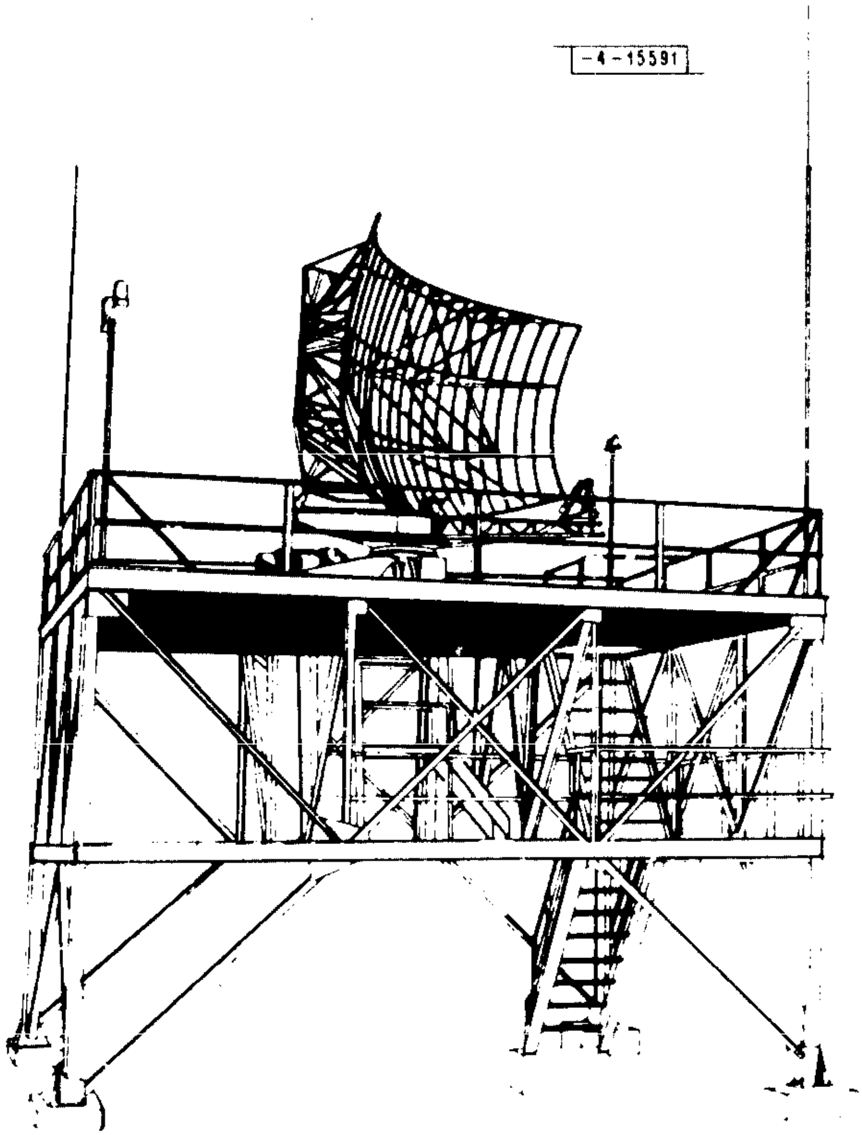


Fig. 2.2. Paraboloidal Reflector Antenna and Tower.

The shaping of azimuth patterns is a problem common to both types of feed. There is a considerable inventory of experience available for use, however, in designing optimized monopulse feeds. While patterns obtainable using reflectors are not as accurately predictable and development involves more empirical work, past experience has shown that such antennas can be made to satisfy a large range of specifications. The behavior of the monopulse patterns versus elevation angle for the paraboloidal antenna is generally more complex than it is for arrays, especially at the higher elevation angles. Because this behavior could not be examined in detail, monopulse behavior similar to that of arrays was assumed in the direction finding analysis.

For cost accounting purposes, we can break down the antenna into the reflector structure, the feed and the feed supports. The current production techniques for reflectors result in costs of \$40 to \$50 per square foot of aperture. For most systems the cost for the feed and supports is small compared to the total cost and is independent of the reflector size.

The aperture sizes considered are shown in Table 2.2.

Table 2.2. Paraboloidal Reflector Sizes.

Beamwidth	Width
2^{o}	29' - 37'
4^{o}	14.5' - 18.5
6^{o}	9.5' - 12.5'

Cutoff Rate	Height
1 dB/deg	3.5' - 8'
3 dB/deg	9' - 11'
5 dB/deg	15' - 19'

2.1.3 Horizontal Parabolic Reflector

This implementation (see Fig. 2.3) is a hybrid between the array and the paraboloid; it derives its array-like azimuth properties from a linear array feed and its paraboloid-like elevation properties either from the reflector contour (cosecant-squared pattern) or the way in which linear feeds are vertically-stacked (sector beam). The reflector itself must be extended somewhat horizontally to properly image the extreme elements of the feed. The monopulse properties of such an antenna are identical to those of planar arrays.

For costing purposes, the antenna conveniently divides into two parts. The reflector and associated structure again costs approximately $40 to $50 per square foot. In one configuration, the feed is a simple linear array similar in external appearance to the present ATCRBS antenna but internally different to provide sum and difference outputs. Although these data were not provided explicitly, the cost is inferred to be approximately $350 to $400 per linear foot. When stacked line sources are used, the feed is actually a planar array with a few rows and the array cost guidelines previously given apply. The range of aperture sizes considered is shown in Table 2.3.

Table 2.3. Horizontal Parabolic Reflector Sizes

Beamwidth	Width
2°	30.5' - 35.4'
4°	17.5' - 20'
6°	10' - 11'

Cutoff Rate	Height
1 dB/ deg	3.5' - 8.2'
3 dB/ deg	9.5' - 12'
5 dB/ deg	16' - 20'

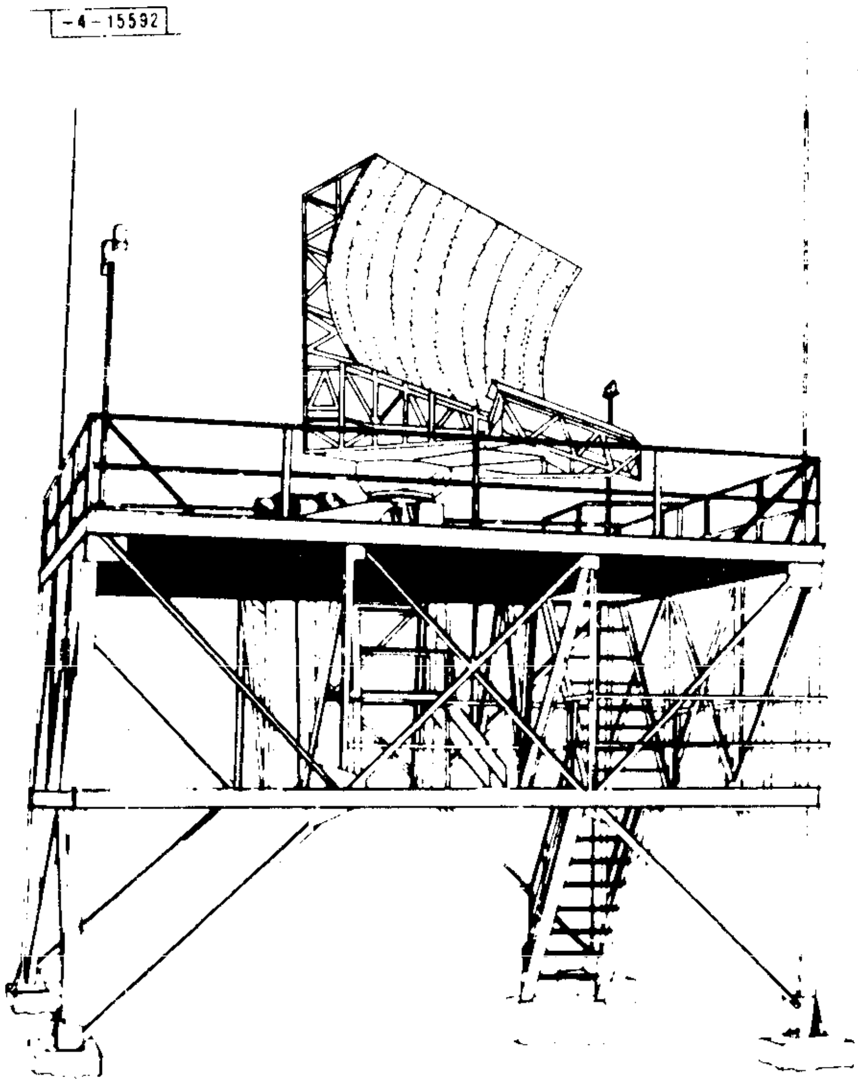


Fig. 2.3. Horizontal Parabolic Reflector and Tower.

2.1.4 Vertical Parabolic Reflector

This is also a hybrid between the array and the paraboloid but in the opposite sense to the horizontal parabolic cyclinder. It derives its array-like elevation properties from the vertical linear feed (see Fig. 2.4) and its reflector-like azimuth properties from the horizontal feed shaping. The main limitation of this arrangement is the large blocking of the feed which cannot be offset if adequate azimuth monopulse operation is to be achieved. There is also an aperture defocusing problem which occurs at higher elevation angles (similar to the circular array problem) which results in broadened beams and high sidelobes. It is an attractive configuration when large cut-offs and moderate beamwidths are required (aperture height larger than the width).

The cost features are very similar to those of the horizontal parabolic reflector.

2.1.5 Omni-directional Antenna

Separate omni antennas whose elevation patterns are the same as that of the directional antenna usually take the form of a vertical array of elements. These are inherently about as tall as the directional antenna. The elevation pattern is shaped by a power dividing network which feeds the elements. The omni-directional property is obtained by positioning elements around a vertical axis of symmetry. These antennas cost typically about $500 per linear foot.

2.1.6 Monopulse Processor

The purpose of the monopulse processor is to provide an estimate of the azimuth angle associated with an identified reply (or replies). In the

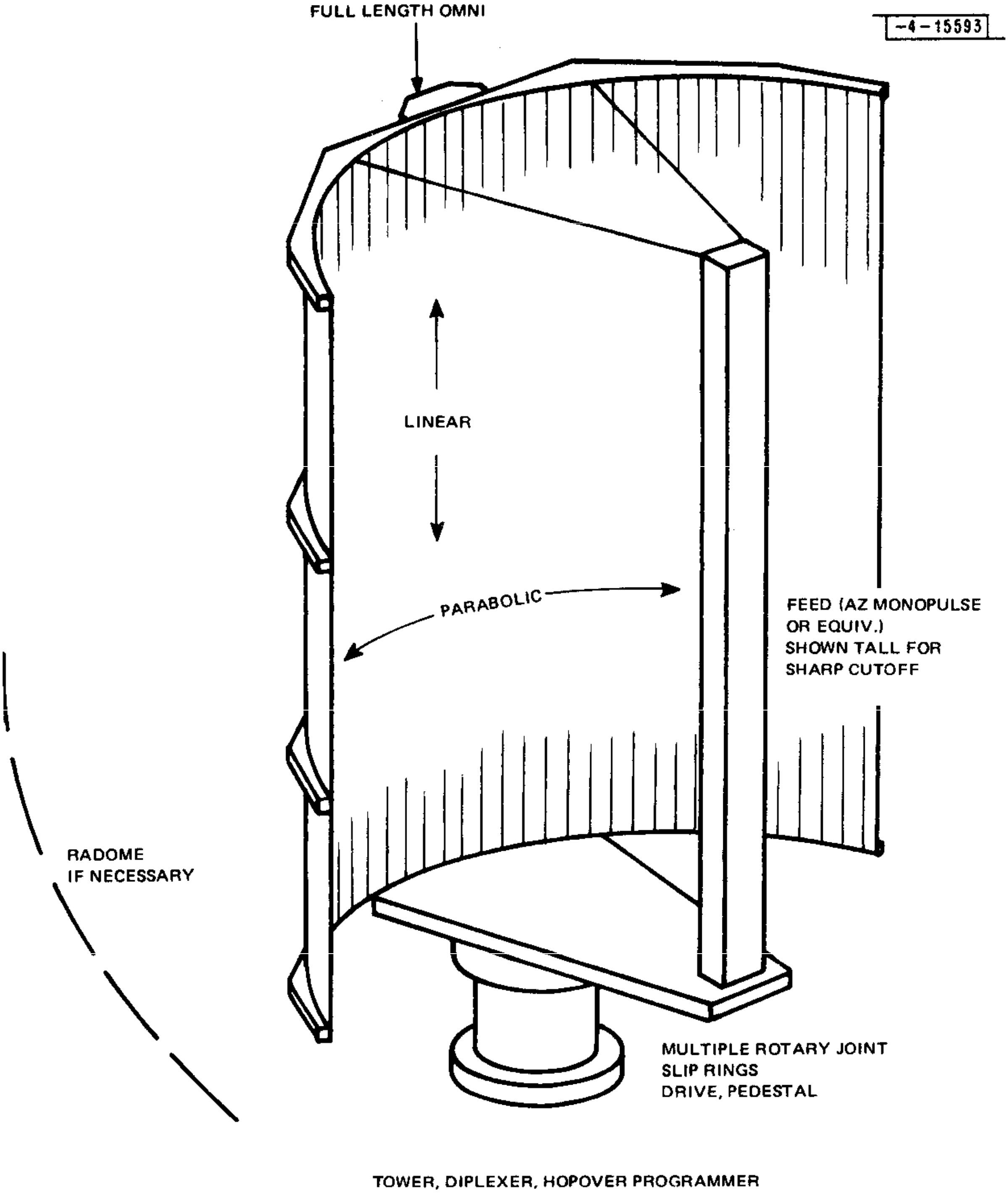


Fig. 2.4. Vertical Parabolic Reflector Antenna.

design cost study, detection and data editing were to be provided by other unspecified hardware. Thus, the significance of this simplified processor design cost effort was that of providing means of separately evaluating the impact of the monopulse processor and associated hardware on the inherent accuracy. It is now apparent that in an actual DABS sensor, the functions of detection, decoding, direction finding, and special purpose data editing will be more integrated in the hardware than was assumed to be the case for purposes of the studies.

Three types of monopulse receivers suitable for DABS were investigated. Each provides a normalized output independent of the signal strength, and unambiguously related to the off-boresight angle. Simplified block diagrams are shown in Fig. 2.5.

The scheme of Fig. 2.5a, referred to as a "logarithmic ratio processor," generates the difference of the logarithms of the sum and difference signals (equivalent to the logarithm of their ratio). This provides an unambiguous relationship between output signal and azimuth angle (the polarity is obtained by a phase detector) considerably beyond the 3 dB beamwidth. This output can be quantized as is or it can be passed through an exponentation circuit before quantization to get back to the ratio, and produce a more linear angular calibration, if desired. The basic drawback of this scheme is the 30 to 40 dB additional dynamic range required to handle the difference pattern variation. Using a 7-stage log amplifier with a 45 dB dynamic range (this implies the elimination of the effect of range variation by sensitivity control) the price of this receiver is $7K; the receiver imperfections contribute a maximum DF error which is 1.7% of the off-boresight angle. The angle

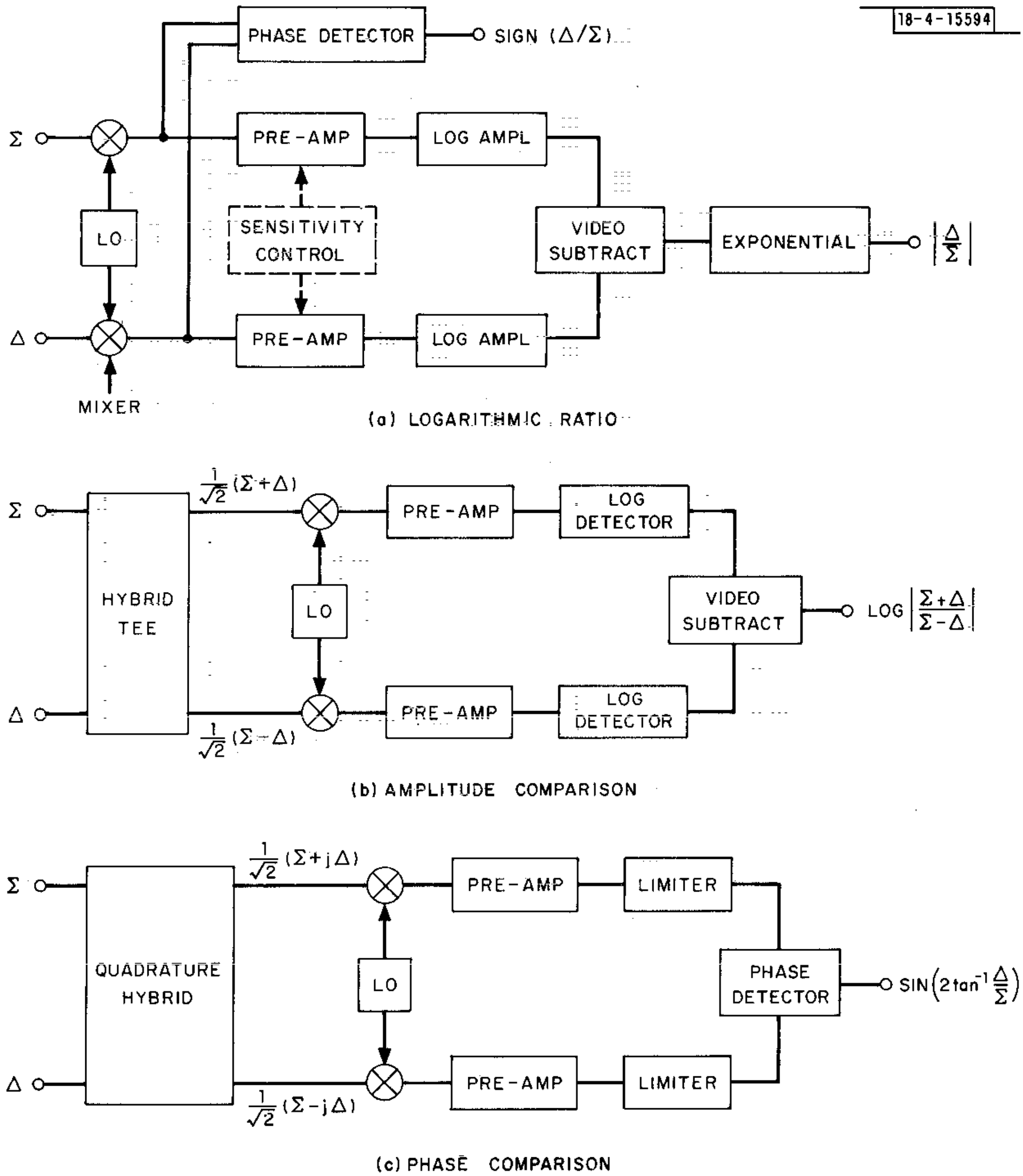


Fig. 2.5. Block Diagrams of Monopulse Processors.

estimate is also based, in this case, on a linear calibration curve. From other related data provided one can infer that the cost of a read-only memory used for compensation of non-linearities would constitute only a fractional increase in the basic receiver cost.

In the other amplitude comparison scheme, shown in Figure 2.5b, RF antenna outputs corresponding to two angle-squinted beams are fed through logarithmic detectors and then subtracted, yielding a bi-polar video from which the angle can be deduced. For reference, such a receiver with an 80 dB dynamic range and 2.5% maximum possible slope error was priced at $9K. The angular region over which this scheme generates an unambiguous output is more limited than desired. This is due to the fact that:

- When the squinted beams are generated directly by the antenna, the limit is determined by the first nulls of the individual patterns.
- When the squinted beams are generated from linear combinations of independent sum and difference beams ("$\Sigma + \Delta$" and "$\Sigma - \Delta$"), the limit corresponds to the sum to difference crossover or about 3 dB beamwidth.

Although this limitation was not of consequence according to the original study ground rules, it reduces the desired flexibility for DABS interrogation. Specifically, it may preclude direction finding in situations when there is sufficient signal strength to perform detection and communication, for example, for near-in targets outside the 3 dB beamwidth.

The phase comparison scheme shown in Fig. 2.5c has its origin in the simple DF scheme in which the bearing angle is obtained by measuring the relative phase between two displaced antennas. This scheme is refined in optimized monopulse systems by first generating independent sum and difference patterns, each having low sidelobes and making maximum use of the available aperture, then combining them through a hybrid to yield outputs given by "$\Sigma + j\Delta$" and "$\Sigma - j\Delta$". It can be verified that the aperture illuminations associated with these new patterns tend to look like overlapping antennas with displaced phase centers. The normalization of the two signals is accomplished by phase-matched limiters. The bipolar video output of the phase detector contains all the angle information. The detector characteristics assumed during the study were of the simple sinusoidal type and yield ambiguous outputs beyond $\pm 90^{\circ}$ phase difference. This results in the same restriction in the unambiguous monopulse "field of view" as the previous amplitude comparison system. Fortunately, unlike the amplitude system, the phase comparison system can be made to work over the full beam by providing a phase detector which is unambiguous over $\pm 180^{\circ}$; such a scheme is being considered.

Although there is no fundamental difference between the amplitude and phase comparison systems, the nature of the hardware favors the latter for improved accuracy. To further reduce receiver errors, induced by phase imbalance, it is suggested that the two channels be interchanged on a pulse to pulse basis or equivalent rate (the same scheme could have also been applied to the amplitude system); after A/D conversion, sampled data are averaged taking the sign reversal into account. A read-only memory performs the non-linear conversion of the data to an angle estimate. Such a receiver/processor was costed at $14K; this includes a separate logarithmic channel for the signal out of the "sum" beam.

2.1.7 Radome

The possible use of a radome is considered for two reasons. Firstly, past experience has shown that when a radome is included from the outset, significant relaxations in the design of the remainder of the antenna system can be tolerated, resulting, in some cases, in lower overall cost. Secondly, the radome may be added to accommodate more stringent operational or environmental conditions at some locations.

Foam-core radomes with fiberglass shells were considered well-suited for the frequency and sizes of interest. Costs provided are summarized in Table 2.4.

Table 2.4. Radome Costs.

Radome diameter	22 ft	26.5 ft	48 ft
Antenna size	10-14 ft	14-18 ft	18-38 ft
Costs	\$12K	\$19K	\$34K

2.1.8 Pedestal and Drive

In contrast with antennas which are generally custom-made for a particular system, pedestals and drives are traditionally selected from an inventory of FAA-qualified designs on which a considerable amount of field experience is available. Therefore, for purposes of this study, activity was reduced to selecting the right combination of pedestal and drive to meet the requirements imposed by a particular antenna. Both study contractors placed an upper bound on the selected drive rating (HP) which they felt could meet the reliability and maintainability requirements of the FAA 2100 specs. The ratings were, however, different. In one case, 10 hp was the selected limit and in the other it was 30 hp. Whenever these drive requirements were exceeded, a radome was used. Most costs are based on pedestals and drive similar to the ASR-7 types. No parametric cost information was available on the pedestals. Drive costs are about $7.5K for 5 hp with a local sensitivity of $250/hp. The total cost of pedestal and drive ranged from $30K to $60K.

2.1.9 Tower

Tower designs and costs are based on the ASR-7 type designed to meet FAA specifications. This configuration consists of a 16 ft high basic section to which can be added up to six 10 ft sections. The cost of the basic section, (parts only) ranges from $15K to $22K and the cost of 10 ft sections correspondingly varies from $3K to $4.4K.

2.2 ANTENNA SYSTEM COSTS

Initially, it was felt that DF accuracy was a natural independent parameter for the basic characterization of a DABS antenna system. This was reflected in a way in which the studies were carried out and results reported. After looking at the results this does not seem to be so. The reasons for this lie in the fact that the system DF accuracy is dependent on too many non-constant or unconstrained parameters. From the results of the study it is clear that azimuth beamwidth is a more useful characterization in terms of performance and cost. The systems which were costed in detail fell into either the 2, 4, or in a few cases, the 6° beamwidth category. These beamwidths provided DF accuracy in the range of interest.

The next major parameter that influences cost is the rate of vertical cut-off whose impact was evaluated for aperture heights corresponding to

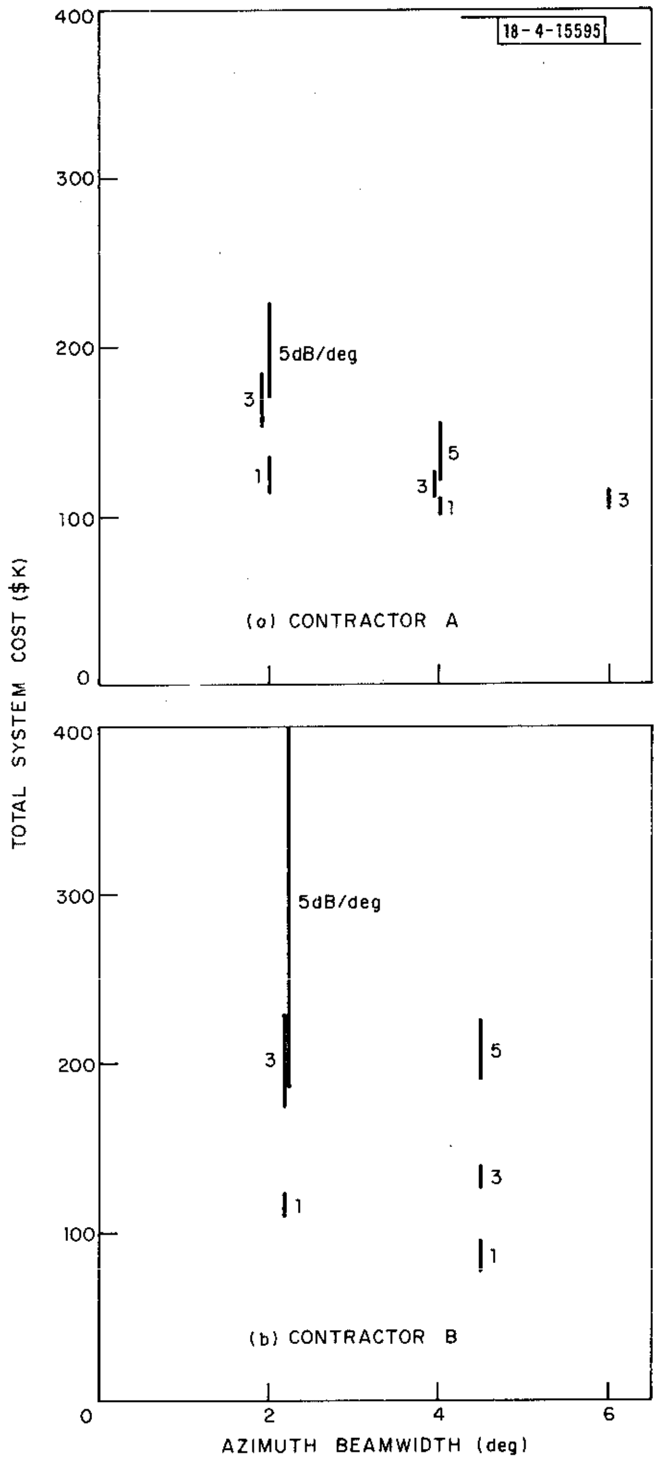


Fig. 2.6. Summary of Total System Costs.

the following nominal values: 1, 3, and 5 dB/degree (see Tables 2.1, 2.2, and 2.3.) The total system costs are summarized in Fig. 2.6. For any combination of beamwidth and cut-off rate, the spread in costs includes the effects of such factors as azimuth sidelobes (20 to 30 dB), elevation sidelobes (13 to 20 dB), and alternate viable implementations. The cost data for each contractor were kept separate and illustrate the sort of variation encountered in competitive bidding for new antenna systems. Further variations, not included in the data, result from the inclusion of hopover and from data rates other than 4 seconds; the impact of the latter is discussed further below.

The impact of sidelobes on cost was taken into account in a dual fashion. Firstly, to the extent that azimuth sidelobes are determined by the amplitude tapers, the apertures were typically sized according to the curves shown in Fig. 2.7. The same procedure was used for the elevation sidelobes by controlling those of the individual component beams. The results of Fig. 2.7, combined with the costs per unit area provided earlier make it possible to determine one of the direct contributors to the cost impact of sidelobe levels. Secondly, for one contractor at least, the type of antenna to be implemented was selected on the basis of the sidelobe performance required. This selection process was not always clear cut, and, in this case, the cost trade-off was not explicitly furnished.

Another interesting statistic is the cost of the antenna in relation to the total antenna system cost. The picture is unfortunately clouded by the fact that our two contractors did not have the same cost breakdown procedures and that they did not always select the same implementation. The figures

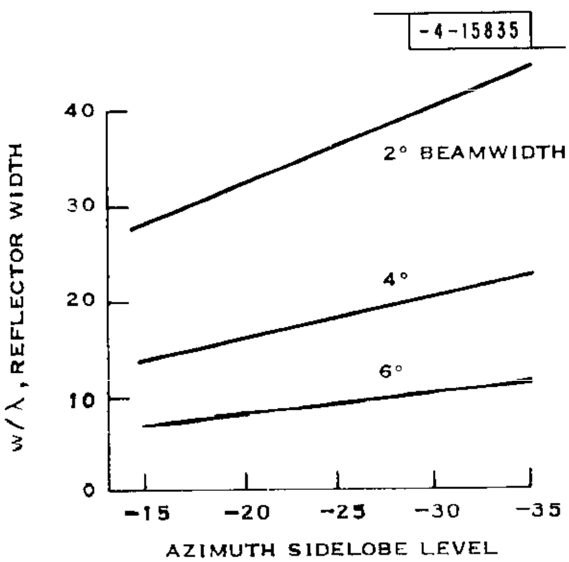


Fig. 2.7. Aperture Size vs Sidelobe Level.

quoted below are based in each case on what we believe from the combined results to be the lower available cost. The basic trend is for the antenna to represent a larger fraction of the total cost as its size increases. The largest and most expensive antenna considered (2^o beamwidths and 5 dB/deg cut-off rate) represents 60% of the total cost; this represents the top of the scale not only in terms of size but also in terms of antenna cost per square foot. The breakdown in Table 2.5 for the case of a 2^o beamwidth and 3 dB/deg cutoff shows that the antenna can represent a small fraction of the total system cost. In this case the radome, which is recommended for this antenna size, permits the use of the less expensive but also less aperture-efficient horizontal cylinder reflector. In the 4^o beamwidth and 3 dB/degree cut-off range, that same implementation results in an antenna cost which is 22% of the total cost (note that the radome is no longer needed). The least expensive antenna both in absolute and relative terms is a spoiled paraboloidal reflector antenna with a 4^o beamwidth and 1 dB/deg. cut-off (or about 2.5 dB/deg in a cosecant-squared mode) which represents only 14% of the total system cost. On the basis of the above results, the basic conclusion reached is that the antenna RF performance is generally not the largest cost determining factor; one of our contractors believes that this conclusion is a consequence of environmental and reliability requirements and the way they influence the remainder of the system.

From the discussion in Section 2.1, it can be concluded that there are no significant cost break points when the subsystems are looked at individually; costs are simply a progressively increasing smooth function of performance measures. The same is true for the system as a whole with one major exception.

Table 2.5. Cost Breakdown for Sample Systems.

(In Percent of Total Antenna System Cost)

Performance Item	2° BW, 3 dB/deg (Contractor A)	4° BW, 3 dB/deg (Combination A & B)	4° BW, 1 dB/deg (Contractor B)
Antenna	23.5	22.0	14.0
SLS Omni	2.0	7.5	3.5
Monopulse Receiver	5.5	9.5	11.5
Pedestal and Drive	21.0	44.0	51.0
Tower	20.5	17.0	20.0
Radome	27.5	0	0
Total	100%	100%	100%

As mentioned earlier in Section 2.1.8, when the combination of aperture dimensions and rotation rates are such that the required drive power exceeds some threshold value, 10 hp for one contractor and 30 hp for the other, a radome is used and the drive and pedestal are redesigned accordingly. Figure 2.8, provided by one contractor, shows the required drive powers as a function of the antenna dimensions and rotation rate, with and without a radome. Clearly, the impact of the radome is significant. For the 4° beamwidth systems rotated at 15 rpm, no radome is required. When the rotation is increased to 30 rpm, the required drive powers lie in the transition region. At 60 rmp the required drive definitely exceeds the imposed limit and, accordingly, a radome is warranted. Although the radome acquisition cost is in this case about $29K this is still considerably less than the cost which would be incurred if one were to try a brute force approach using drive powers of the order of 100 hp.

For the 2° beamwidth systems, even at 15 rpm the only apertures that do not require radomes are those corresponding to a 1 dB/deg cut-off. For apertures with a 3 dB/deg cut-off the situation is marginal. At the 5 dB/deg rate, the use of a radome was judged to be cost effective even though the net cost is between $40K and $50K. When the rotation rate is increased to 30 rpm then, all 2° beamwidth configurations require a radome. At 60 rpm, one contractor even recommended the use of a shroud ($30K) over the antenna to reduce the turbulence inside the radome.

2.3 SYSTEM DIRECTION FINDING ACCURACY

The accuracy with which the azimuth angle of a target can be estimated using the systems described above, in the absence of multipath and interference

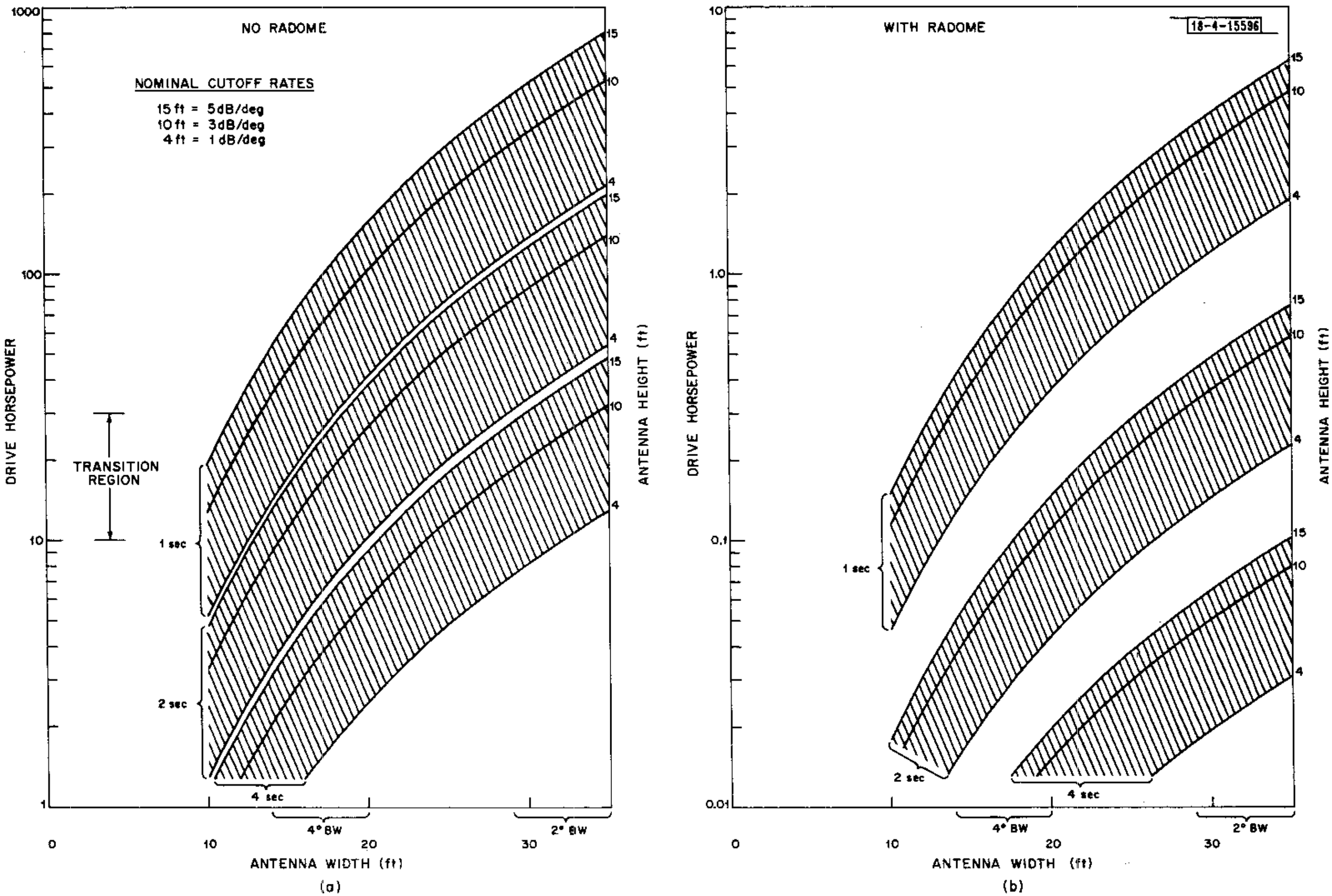


Fig. 2.8. Required Drive Power.

has been called "inherent" accuracy. The approach that has been used is to evaluate, for various sources, the error in reported azimuth when only a single reply is available. This will be taken as the "baseline performance." Subsequently, the utilization of several replies, when available, will be discussed and improvements evaluated. Rather than following the convention of resolving overall errors into contributions by subsystems, the errors will be ordered according to their statistical nature.

2.3.1 Totally Random Errors

In practice, the only source of error which is random on a pulse to pulse basis is noise, contributed mainly by the mixer and early stages of the receiver. Its effect on azimuth error is given by the following formula:

$$\sigma = \frac{\theta_B}{2\sqrt{2 \cdot \mathrm{SNR} \cdot N}} \cdot \sqrt{1 + (2\theta/\theta_B)^2} \qquad (1)$$

where

σ = Azimuth accuracy, standard deviation.

θ_B = Beamwidth (3 dB).

SNR = Operating single chip signal-to-noise ratio in sum channel

N = Number of independent samples.

θ = Off-boresight angle.

This approximate formula assumes a linear Δ/Σ ratio and cross-over at the 3 dB point. The quantity θ_B/σ is sometimes referred to as the "beam-split ratio," and is plotted in Fig. 2.9 as a function of the product SNR x N (effective SNR) because of the large range of values which this parameter can take on particularly in the absence of sensitivity time control.

In the ATCRBS mode, we can conservatively assume that in some cases only the two bracket pulses will be available; with a 14 dB SNR (nominal minimum detection threshold level), the beam splitting factor on a single reply is 15 and represents the "rock bottom" performance. A reasonable design for the DABS downlink power budget would more likely be adjusted to provide about 20 dB SNR at a 100 nmi maximum range except under extreme fading conditions. With 10 available samples declared free of multipath and interference by the reply processor, the beamsplitting ratio would be of the order of 70.

Another approach is to evaluate the dependence of this noise-limited accuracy measure on beamwidth for some constant incoming signal. This permits one to exhibit explicitly the important trade-off for DABS between the higher on-axis accuracy of a high gain antenna, and the wider field of view of a broader beam. We can express the operating SNR as a function of beamwidth and off-axis angle in terms of, for example, the on-axis SNR for a 2° beamwidth.

$$SNR = SNR_{ref} \left(\frac{2}{\theta_B}\right) \Sigma(\theta/\theta_B) \qquad (2)$$

where $\Sigma(\theta/\theta_B)$ is the normalized sum pattern. Substituting (2) in (1) this yields

$$\sigma = \frac{1}{\sqrt{SNR_{ref} \times N}} \cdot \frac{\theta_B^{3/2}}{4} \frac{\sqrt{1 + (2\theta/\theta_B)^2}}{\Sigma(\theta/\theta_B)} \, . \qquad (3)$$

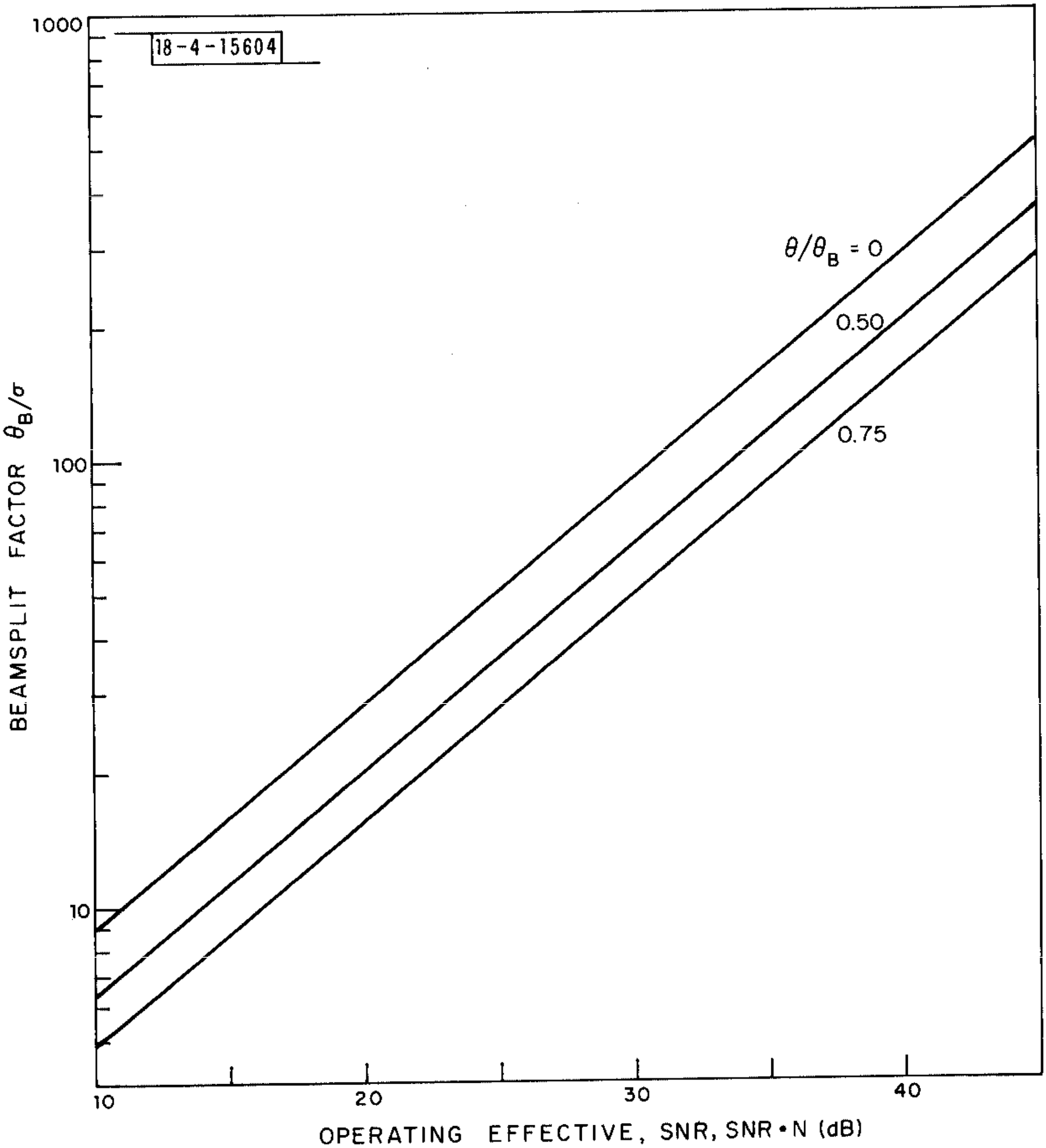


Fig. 2.9. Noise Limited Beamsplitting Ratio.

Figure 2.10 is useful when the monopulse window can be treated as the independent parameter characterizing the design requirements. It gives one input for the selection of the beamwidth which provides the best overall performance over the entire desired window. For example, if direction-finding were desired over $\pm 2^{\circ}$ there is a difficult trade-off to be made between the 2 and 4° beamwidths; a 3° beamwidth might, in this case, be a reasonable compromise. It is important to keep in mind that the results plotted in Fig. 2.10 were obtained by assuming a constant incident power density on the antenna thereby allowing the narrower beamwidths to realize the full benefits of increased gain; they would not apply if, for example, one attempted to take advantage of the increase in gain by lowering the transponder power.

2.3.2 "Reply-dependent" Errors

Certain errors are constant from pulse to pulse, within a reply, but their magnitude depends on some of the parameters which describe individual interrogations. For example, they depend on the off-boresight angle which, for a given sweep, can be thought of as partially random. Depending on the structure of the scheduler, it may not be truly random. When several replies are received on a single scan at different off-boresight angles one can, through some averaging process, smooth out the azimuth estimate in a manner analogous to the way that independent samples are averaged within a reply to reduce the effects of noise.

Calibration errors are the prime contributors to this kind of inaccuracy. On a single reply basis they are difficult to tie down because they depend on the extent to which nonlinearities are taken into account. Whereas, one contractor made his error computations based on the best linear fit, the other included

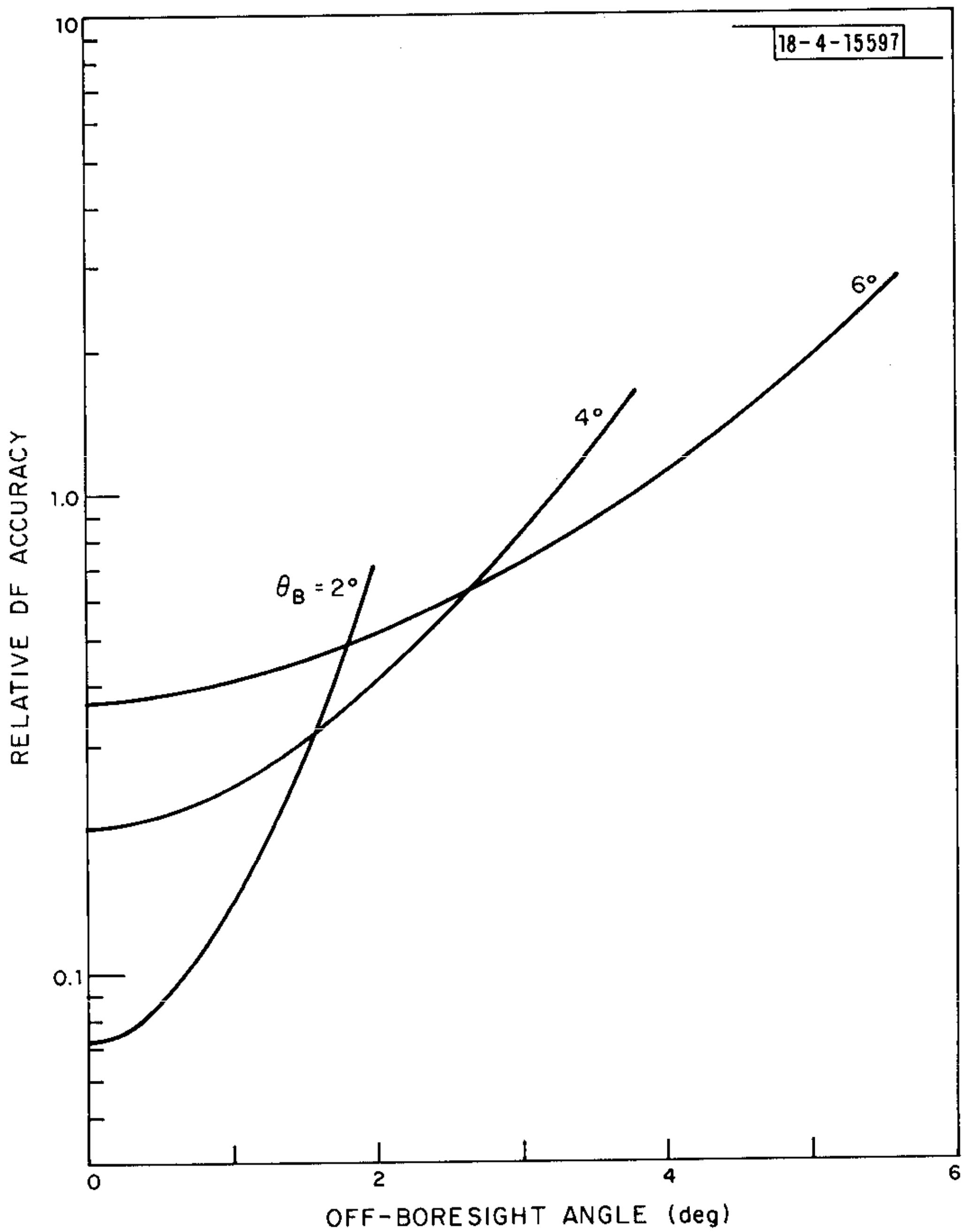


Fig. 2.10. Noise Induced DF Error vs Off Boresight Angle.

a "look-up" table, implemented as a read-only memory, in its design process (and cost) thereby virtually eliminating the problem. The present trend toward utilization of more than 3 dB beamwidth implies that significant non-linearities in the monopulse function are to be expected. The modest incremental cost of an adequate read-only-memory seems to heavily bias the trade-off in its favor. Because the monopulse function is monotonically increasing, any calibration error will also tend to increase with off-boresight angle. When the curve is linear, the error, $\delta\theta$, may be the approximately written in terms of the off-boresight angle, θ, the fractional receiver calibration error, δm, and the fractional antenna pattern slope error, δk, as

$$\delta\theta = \theta\ [\delta m + \delta k].$$

In the logarithmic amplitude processor, a typical upper bound on δm is about 2% over the full range of amplitude and reply frequency. No equivalent number was available for the phase processing system but our experience at the DABSEF indicates that smaller values can be achieved.

Although the effect of elevation angle (α) on the pattern slope can be explained using different viewpoints, the common element is the coordinate transformation associated with a ρ - θ system. That error is given by

$$\delta k(\alpha) = \frac{\cos \alpha_c - \cos \alpha}{\cos \alpha_c}$$

where α_c is the selected calibration angle and, as shown in Fig. 2.11, is small for low elevation angles. Since traffic densities are highest at low elevation angles, the error will correspondingly be small for a large fraction of the A/C population.

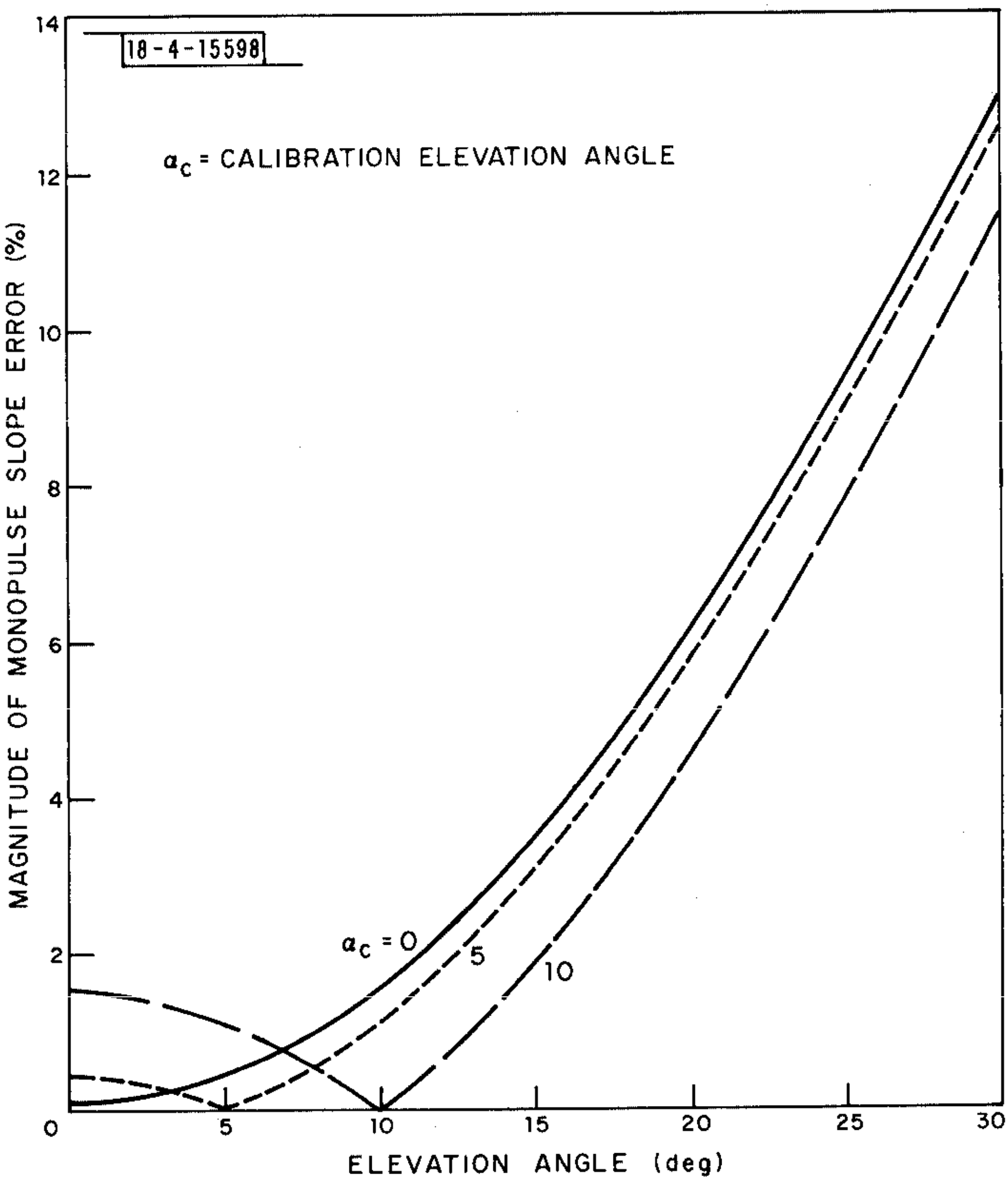


Fig. 2.11. Calibration Slope Error vs Elevation Angle.

Two significant observations may be made. Firstly, the "reply bias" errors tend to be of opposite polarity on either side of boresight; this provides a rapid reduction of the net error when two or more replies, sufficiently separated, are available. Secondly, the errors are essentially independent of beamwidth; the driving parameter is off-boresight angle.

Unlike the present ATCRBS beam splitting technique which is highly constrained in performance, monopulse direction-finding in DABS is closely related to the interrogation management in general and scheduling in particular. It, therefore, seems appropriate to touch upon the impact of some of the proposed schedulers on this error. According to present plans, there may be four ATCRBS and DABS all-call interrogations uniformly distributed as the beam scans through the target. Even a simple estimate averaging algorithm will drastically reduce the net error: if one thinks of this error as random over the ensemble of possible interrogation timing, its average will be zero and its rms value is about 1/7 of the maximum single hit error. For DABS roll-call one or two interrogations might be prescheduled. In the one hit case, the reply-bias error is strongly affected by which portion of the sweep is allotted to prescheduling. When two hits are scheduled on either side of boresight, the sweep bias can be substantially lowered by direct averaging.

Other contributors to the reply-dependent errors are:

- A/D quantization of the monopulse signal: for an 8 bit (7 plus sign) converter, the rms error is about 1/4 % of the maximum off-boresight angle.
- Azimuth shaft encoder: for a 14 bit encoder, the rms error is less than 0.006° and is negligible.

2.3.3 Sweep-dependent Errors

These are errors which vary only from sweep-to-sweep (or scan-to-scan) and therefore cannot be eliminated by any kind of processing.

Wind-induced deflections of the antenna aperture causing a boresight shift is an example. One contractor indicates that from past experience the maximum shift for a 40 ft aperture can be kept to less than 0.05° for the usual FAA environmental requirements. The extent to which this depends on the antenna width is strongly influenced by the mechanical design criterion. For a constant maximum deflection, the error increases as the antenna gets smaller; this trend does not follow the intuitive notion that one should be able to better control a smaller antenna than a larger one. Such an issue can be resolved either by a more detailed consideration of the trade-off between manufacturing cost and structural rigidity or by explicitly specifying the tolerable angular deviation. Another such error can be caused by drive gear backlash in the presence of wind. For the drive mechanism quoted earlier, the error has been estimated at 0.02° maximum.

Whereas the above errors are related to time-varying factors, there are sweep dependent errors which are also azimuth-dependent. For example, a radome can, in principle, be a source of such an error; however, the use of a foam radome has been found to virtually eliminate this problem. The rotary joint can also introduce an error if the Σ and Δ channels do not track in amplitude. A 0.05 dB error appears to be a reasonable design specification and leads to an error which is 1/2% of the off-boresight angle.

2.3.4 Scan-independent Errors

The errors considered here are system biases. Sources of such errors include errors in the initial system boresight alignment during calibration. None of these appear sufficiently large to be taken into account in the total error budget. Also, since there are variations in the antenna boresight as a function of elevation which can not be taken into account in the calibration or alignment, this causes an additional bias error for a target which does not change altitude rapidly from scan-to-scan. This error is primarily attributed to aperture errors and is proportional to the azimuth beamwidth. The nominal figure is about $\pm 0.01^{o}$ per degree beamwidth maximum.

2.3.5 Direction Finding Summary

The overall picture of the DF accuracy is summarized on Table 2.6 for the two principal beamwidths of interest that is, 4^{o} and 2^{o}. The numbers tabulated are to be interpreted as a mixture of achievable performance and specified performance. Contributions which are negligible have been omitted. The 4^{o} beamwidth system can be expected to provide the DABS baseline accuracy of 0.15^{o} "one sigma."

Table 2.6. Direction Finding Accuracy Summary For Rotators.

Type	Origin	Bias	Error, 4° BW	Error, 2° BW
SYSTEM BIAS	Boresight vs elevation	0.01° per deg BW	0.04°	0.02°
SWEEP BIAS	Wind-induced bore-sight shift	0.07°	0.07°*	0.07°*
	Off-Boresight Calibration**	5% of off-boresight angle (a) DABS, 1 hit @ 3 dB pt (b) ATCRBS, 4 hits	 0.1° 0.025°	 0.05° 0.012°
SWEEP Random Error	Receiver Noise	20 dB SNR/chip (a) DABS, 10 samples (b) ATCRBS, 8 samples	 0.06° rms 0.07° rms	 0.03° rms 0.035° rms
	"Total" error: Bias + 3σ			
		(a) DABS (b) ATCRBS	0.40° 0.35°	0.23° 0.20°

*Zero when radome is used.

**Elevation angle is less than 20°.

SECTION 3

AGILE BEAM SYSTEMS

Early in the study, both contractors confirmed that of several possible configurations, cylindrical arrays best met the requirements of the DABS agile beam systems.

3.1 REVIEW OF DESIGN PROBLEM

3.1.1 Aperture

For the arrays that were considered, the elements are located on a rectangular grid wrapped around the cylinder. Elements along a common vertical line are interconnected by power distribution networks. In contrast to the unscanned planar arrays previously described, which can tolerate horizontal element spacings of about 0.9λ, 0.5λ element spacing was chosen for cylindrical arrays. The primary reason for this decrease is to control sidelobes; the nature of this problem is unique to circular arrays. This has a very significant cost impact because the number of columns (total or excited) per unit length is almost double that of rotating planar arrays. For equal beamwidths, the number of elements in the circular array is about 10 times that of a planar array. More detailed numerical information is presented in Fig. 3.1.

Another question is whether or not the array should be focused at more than one elevation angle. This too has a significant impact on the

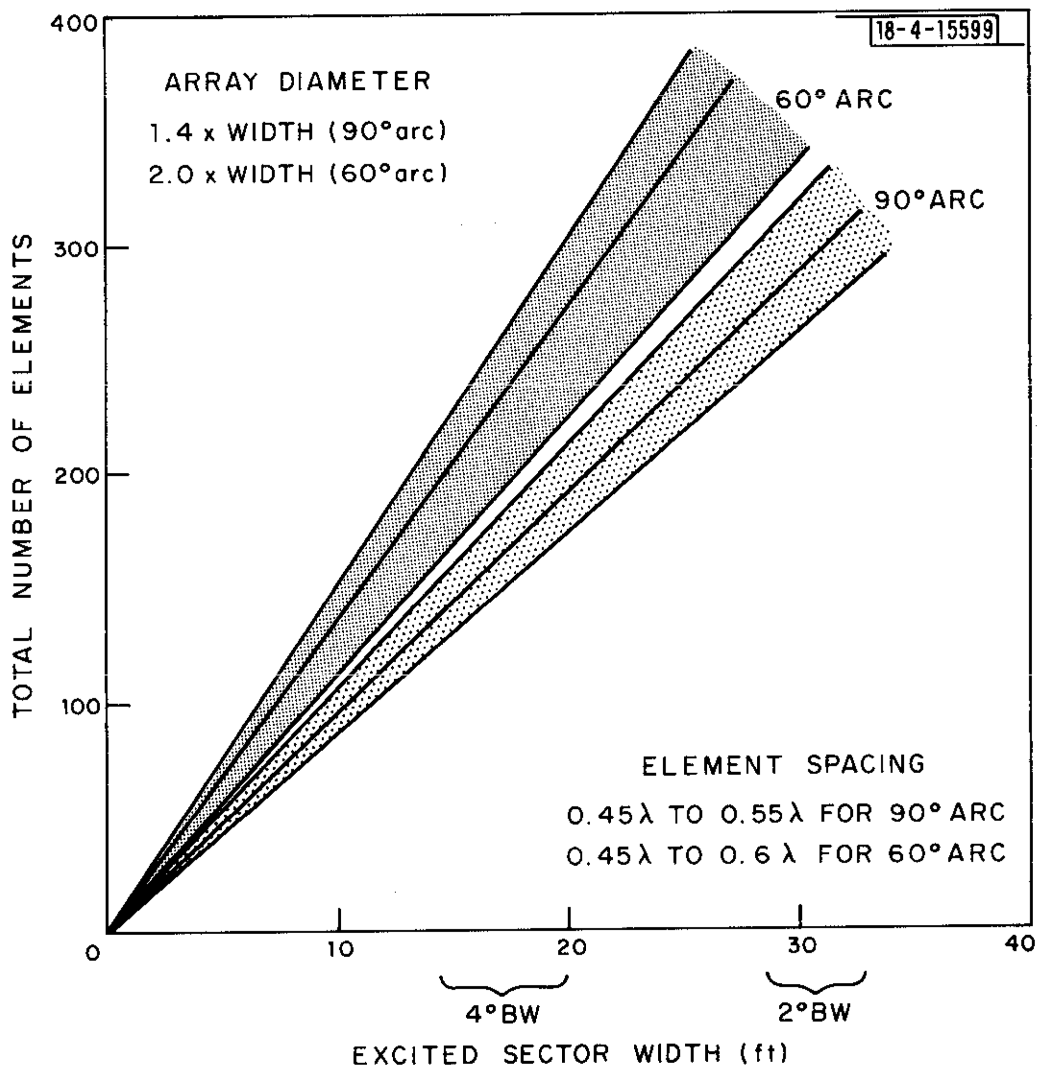


Fig. 3.1. Number of Elements vs Circular Array Size.

cost of the elevation networks. The selection is made by examining the "run off" or the maximum element phase error for elevation angles other than the focusing angle. In the cases that were examined, the choice was between one or two levels and is primarily determined by the radius. Therefore, the radius most seriously impacts the total cost of the aperture: doubling the radius doubles the number of elements and columns and, because of dual focusing, can require elevation networks of the double-ladder type as was found to be the case in going from 4^{o} BW to a 2^{o} BW.

3.1.2 Beam Forming and Steering

Cost/benefit trade-offs performed on several feed types resulted in the selection of the fully-commutating switch network (see Fig. 3.2) by both contractors. This feed is characterized by a number of beam positions equal to the total number of elements, and independent control of the amplitude of each excited element. There are no phase shifters. The number of beams thus generated is adequate only because off-boresight monopulse is used for direction finding. This arrangement represents a major departure from the E-scan antenna which was designed to be compatible with the ATCRBS beam-splitting technique.

The fact that smaller element spacings are required also has an impact on the feed complexity. The beam forming networks must have about twice as many elements as comparable planar arrays. Note that doubling the number of elements doubles the number of arc-selecting switches and more than doubles the number of components in the transfer switch.

The beam steering design is straightforward. The beam steering unit accepts a digitized beam position command of approximately 8 bits a

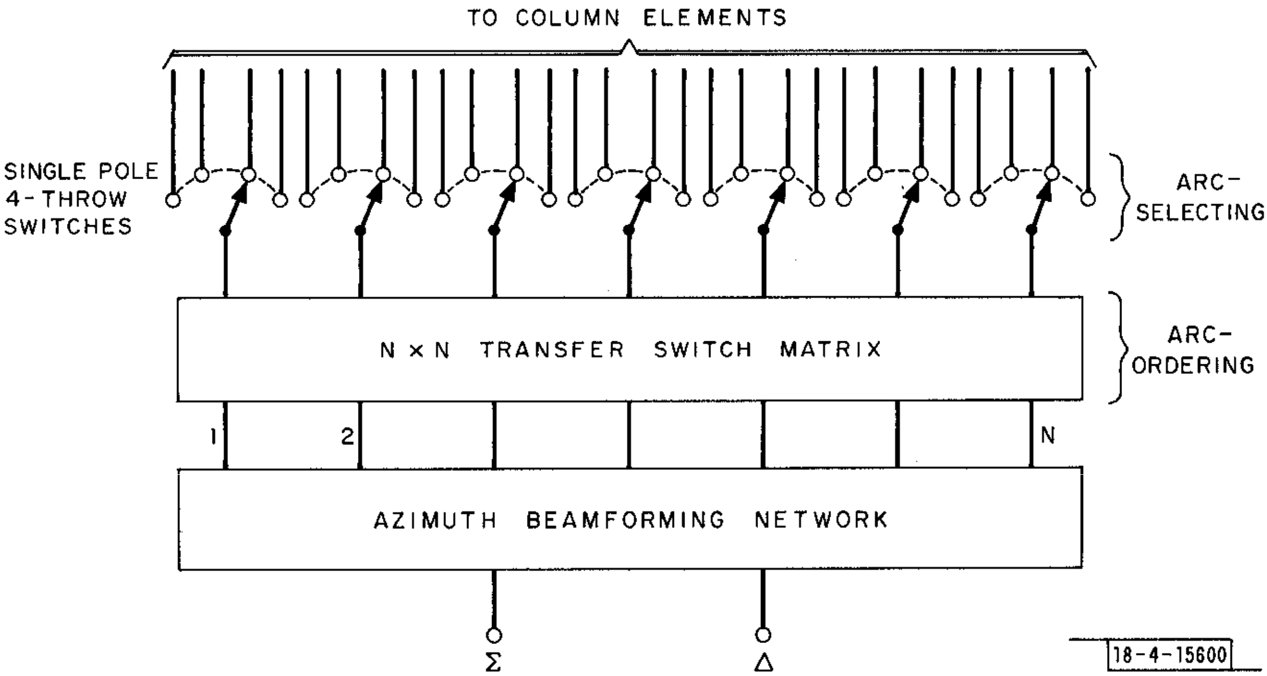


Fig. 3.2. Schematic of Fully Commutating Switch Network.

word from an external source and converts it to individual command signals to the various switching circuits. Read-only memories for the transfer switch and multiple-throw switches are used as look-up tables.

3.1.3 Monopulse Processor

The monopulse processors which are applicable to step-scanned circular arrays are in principle the same as those described for Rotators (see Section 2.1.6). However, the most significant difference is the fact that, because only discrete beam positions are available, the monopulse system must provide an unambiguous error signal up to several tenths of a degree (the uncertainty of azimuth) beyond the cross-over point between adjacent beams. One has to examine where that point lies relative to the sum-difference cross-over to evaluate the desirability of the processors previously described. This is a design detail having only a small effect on system cost.

3.2 ANTENNA SYSTEM COST

The physical characteristics pertinent to the azimuth performance of the system configurations evaluated are summarized in Table 3.1. From a cost viewpoint, these are the significant parameters. For each azimuth configuration, the impact of elevation cutoff rates of 1, 3 and 5 dB/deg was evaluated. The physical parameters associated with the above are given in Table 3.2.

Total systems costs are presented in Fig. 3.3 as a function of the total number of elements, a significant driving parameter. Note that the growth rate increases with the number of elements. This reflects the fact that the feed and aperture increase in complexity at a rate higher than proportional to the number of elements.

Table 3.1. Agile Beam Array Circumferential Parameters.

Radius	Columns	Active Columns (Sector°)
7.2'	96	24 (90°)
10.7'	128	32 (90°)
12.5'	144	24 (60°)
12.6'	160	40 (90°)
18.8'	192	32 (60°)
23.1'	256	64 (90°)
25.0'	288	48 (60°)

Table 3.2. Agile Beam Array Axial Parameters.

Drop Off dB/Degree	Number of Dipoles Per Column	Height
1	7 - 8	3.6' - 4.5'
3	16 - 18	8.7' - 9.7'
5	28 - 32	16.0' - 18.2'

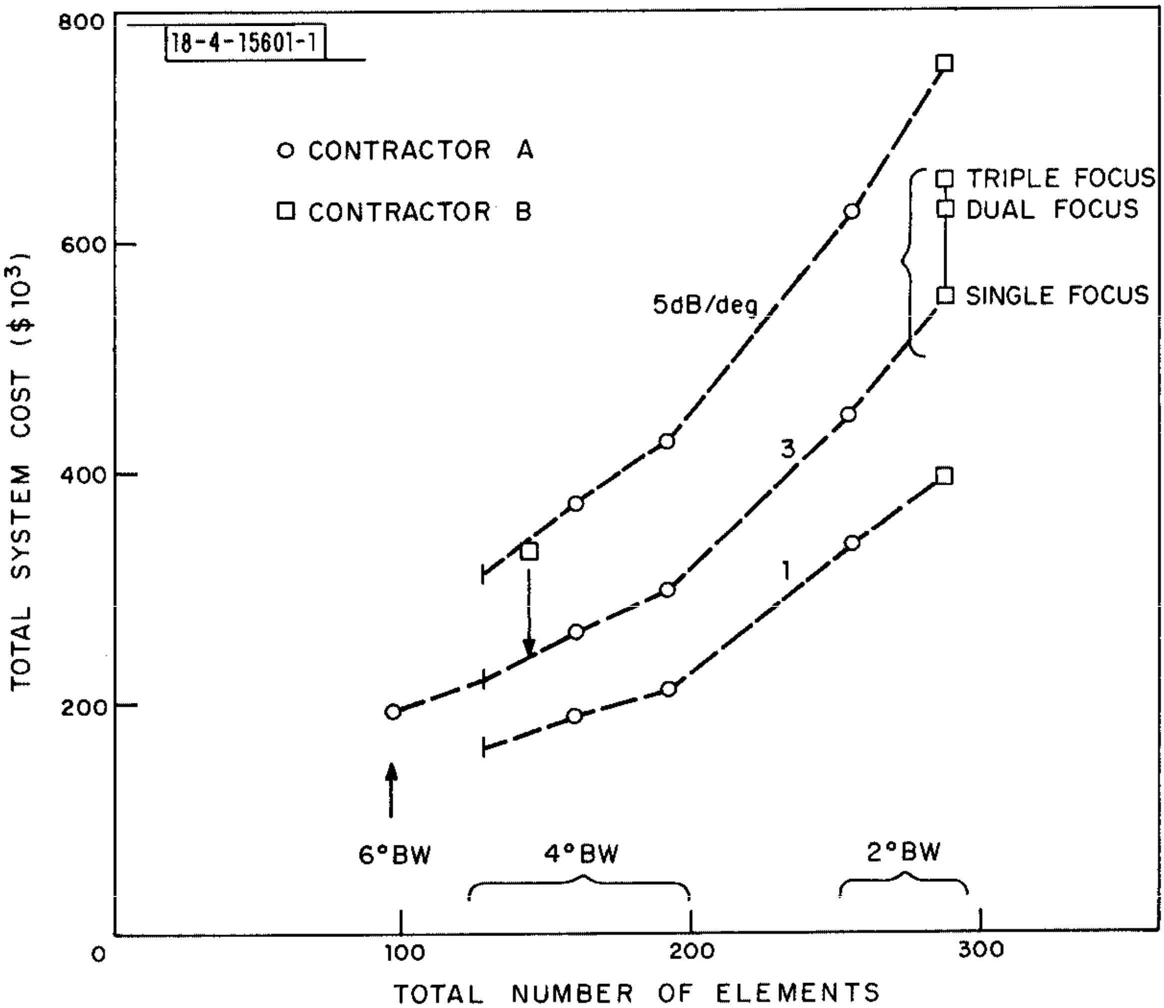


Fig. 3.3. Total Costs of Agile Beam Systems.

The items which were considered in the system costs are as follows:

- Array and associated beam steering control
- SLS omni antenna, integrated or separate
- Monopulse processor
- Tower construction, erection and foundation
- Electronics housing
- Field installation

Costs associated with sustaining engineering, tooling and development have been absorbed in the total costs.

One breakdown of the total cost of a system with 288 elements is shown in Table 3.3. The basic array aperture is seen to be the dominant contributor to the total cost. The data derived by our other contractor, and presented on Table 3.4, provides a slightly different breakdown in terms of the costs of the aperture and the beam forming and steering, relative to the total system price for various values of the performance parameter. In this case, these are net production costs which do not include tooling or development costs. Over the range of interest, the beam forming and steering cost is significantly smaller than that of the basic aperture.

Unlike rotators, some cost breakpoints can be identified for the cylindrical array. The single most important one corresponds to the point beyond which dual focusing must be used. All of the 4^{o} systems considered employ single level focusing only, whereas most 2^{o} systems required double level focusing. Actually, the break point seems to be quite close to 4^{o}.

Table 3.3. System Cost Breakdown for a 2° BW and 3 dB/degree cut-off rate (Contractor B).

Array structure	19%
Elevation network and dipoles	44%
Beam forming and steering	21%
Tower mounting	16%
Total	100%

Table 3.4. Percentage Cost Breakdown vs Performance (Contractor A).

BW/Drop off	1 dB/deg	3 dB/deg	5 dB/deg
6°		31%	
4°	23-24%	37-40%	48-50%
2°	22%	36%	47%

a - Aperture

BW/Drop off	1 dB/deg	3 dB/deg	5 dB/deg
6°		17%	
4°	17-21%	13-16%	9-11%
2°	32%	24%	18%

b - Beam Forming and Steering

Note: Remainder of system costs consists of structural support, electronics housing, installation, subtaining engineering and pro rata tooling and development costs.

One contractor's data indicates a $75K cost increment attributable to dual-focusing in a 2° beamwidth system. Beyond that break point, system costs tend to increase at a higher rate.

Other potential break points were thought to correspond to the use of a binary number of excited elements. They are less significant than originally anticipated and correspond more to local minima in the feed cost per element rather than true break points. For the systems that were considered there is no evidence of a significant savings which can be singularly attributed to binary operation. Given the overall trends it appears that to minimize costs, one should simply minimize the total number of elements.

The use of an integral, rather than separate, omni-directional antenna was found to increase the system cost by only about 1%. (Its impact on gain, discussed later, may be more significant.)

The addition of a hopover feature to the elevation pattern (one-step for a 3 dB/deg cut-off and two-step for a 5 dB/deg cut off) represents a 5 to 6% increase in total system cost.

In circular arrays the overall insertion loss, which is not significant for rotating antennas, can be a crucial trade-off parameter. Much of the loss occurs in the dielectric material used for the various RF components. One contractor noted that the selected material represents 7 to 16% of the total cost and, for their baseline system (4° BW, 3 dB/deg), yields an 8.6 dB insertion loss (16.5 dB net gain). This represents a point beyond which dielectric material costs escalate very rapidly. The data provided by our other contractor corroborates this result; its baseline system (2.2° beam-width, 3 dB/degree has a gain of only 19.2 dB.* The microwave diodes and

*All above quoted gains apply only to sector type elevation patterns.

RF cables selected represent at most 18% of the total price and their loss contribution is small enough to have reached the point of diminishing returns. The use of less expensive materials results in a rapid deterioration of overall performance.

3.3 SYSTEM PERFORMANCE

3.3.1 Gain

The gain of agile beam systems is considerably lower than the gain of conventional systems, and is therefore an important performance measure. Results for the systems considered are presented in Table 3.5. The most significant aspect of these results is the fact that the gains are about 6 to 7 dB lower than those for similar rotating antennas. The results also show that as the cut-off rate increases, the elevation network losses also increase at a higher rate than elevation pattern directivity yielding a net reduction in gain. (Also true in planar arrays.) This applies uniquely to sector type beams and the opposite trend can be expected of more directional elevation patterns such as those of the cosecant-squared type. The 1 dB or so reduction in gain attributed to the incorporation of an integral omni is probably not significant enough to negate the inherent benefits of such a feature, but is large enough to be explicitly taken into account in any power budget.

3.3.2 Sidelobes

In addition to amplitude taper and random errors, the sidelobes of circular arrays are influenced by the number and locations of the elevation angles at which collimation is achieved and by the element spacing. Since

Table 3.5. Gain of Agile Beam Array for 3 dB/Degree Cutoff - Sector beam only.

Radius	Columns	Active Columns (Sector)	BW	Gain (dB)
7.2	96	24 (90°)	6°	13.5
10.7	128	32 (90°)	4°	16.4
12.6	160	40 (90°)	4	15.0
18.8	192	32 (60°)	4	16.1
23.1	256	64 (90°)	2	17.4
25.0	288	48 (60°)	2.2	19.2

Notes:

1. For 1 dB/deg, gain is increased by 0.8 dB.
2. For 5 dB/deg, gain is reduced by 1.0 dB.
3. SLS omni reduces gain by 0.9 to 1.4 dB Integral.

the number of focusing angles has a strong cost impact it is particularly important in any design specification to take the pertinent system requirements into account rather than follow precedents.

For example, any evaluation of the impact of sidelobes on interference would have to take into account the volumetric distribution of aircraft in the type of environment likely to require an agile beam system. Although the contractors provided a substantial amount of information on the behavior of sidelobes a need remains to evaluate their effect on various aspects of the system performance.

3.3.3 Monopulse Patterns

In addition to the broadening of the azimuth beamwidth vs elevation angle, which, as in the planar array case, can be attributed to a coordinate transformation ("projection" effect), the mainbeam patterns of cylindrical arrays exhibit unique properties. The true and apparent beamwidths are further broadened by defocusing effects for elevation angles other than the collimation angle(s). Figure 3.4 shows a typical variation of the monopulse difference-to-sum ratio pattern for a single focus case. As can be seen from these results, the variation in monopulse slope accelerates rapidly at the higher elevation angles. This is due to the joint action of defocusing and projection effects. As with the sidelobes, one has to give a serious look at systems requirements for high elevation angles to evaluate the acceptability of this behavior in the light of the significant cost impact of reducing this by dual level focusing.

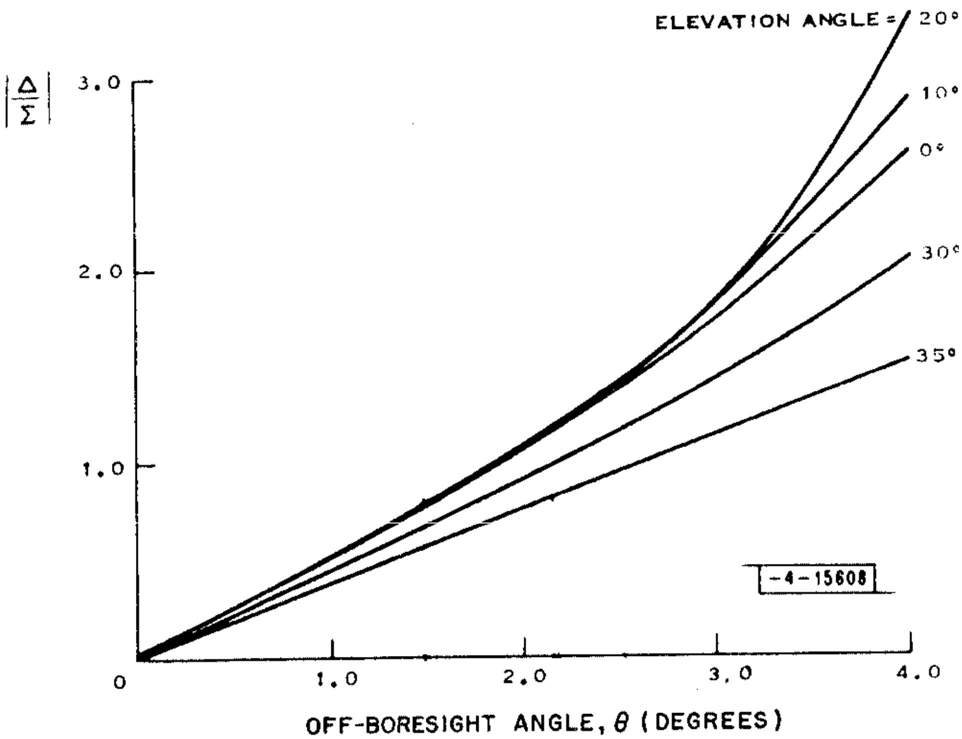


Fig. 3.4. Antenna Monopulse Ratio Function for 4° System Focused at 18° Elevation.

Because of the difference in the way in which the sum and difference illuminations interact with a defocused wavefront, the relative phase of their radiation will change with elevation angle. One contractor has considered exploiting this phenomenon as a form of elevation determinant which can be used to neutralize the monopulse pattern variation versus elevation angle.

A possiblity which was suggested, but could not be examined in detail, is to generate even and odd beams that are optimized for, and take advantage of, the step scanning property of the circular array. This is motivated by the following observation: if one could simultaneously excite two of the step-scanned beams, each being a true vertical fan beam, these could be used to generate sum and difference patterns which do not exhibit first order coning effects (individual beam broadening versus elevation will still leave a slope variation).

3.3.4 Direction-finding Accuracy

As in the case of rotators, the various kinds of direction finding errors are sub-divided according to their statistical properties. It is important to remember that the kinds of arrays that were examined generate a fixed set of discrete beam positions separated by less than one beamwidth. This implies some consistency in the dependence of DF performance on target azimuth, and suggests a somewhat different statistical behavior of the errors than in the case of rotators.

a. Random errors

Of interest here are the errors which are random from chip to chip and are due to thermal noise generated primarily in the receiver front end. The formulas, and graphs presented in Section 2.3.1 are still applicable.

There are, however, two observations which should be made in applying these results to circular arrays. Firstly, the antenna gain tends to be lower than that of a comparable rotator (by 6 to 7 dB for the feeds considered here). Secondly, because of the discrete boresight directions of the array, azimuth directions corresponding to the beam crossovers will consistently receive less power than others; the error will be twice as large at the -3 dB points as it is at the beam peak (see Eq. 1). In all likelihood this will lead to a reduction in the maximum slant range that the sensor will be expected to cover while maintaining a given accuracy. We will therefore assume that the nominal SNR for a target in the coverage volume of the agile beam sensor is again that which is sufficient to support the other signal processing functions; the numerical value previously used in the case of rotators was 20 dB. When 10 independent samples are available this yields an effective beam split factor of 70 for the noise-contributed error. It is important that the above assumption be kept in mind when any performance comparisons are made between rotators (independent or co-located) and agile beam systems.

b. Azimuth-dependent errors

Because the pattern of beams in space is fixed, there will be a strong dependence of the direction finding performance on the target locations with respect to this pattern. In particular, as long as a target is interrogated on the same beam, some errors will be constant. Because these errors are of a recurring nature, it is reasonable to focus our attention on the worst case. Although one would initially schedule interrogations of a target on a predicted closest beam, it is possible, because of tracking uncertainties, for the target to be interrogated beyond the crossover point with the adjacent beam. Unlike the rotator for which one can intentionally restrict the scheduling window, there is no way to directly avoid the problem in the step-scan array. One can get around it by rescheduling another interrogation over the adjacent beam after the target has been declared outside of the first beam. Therefore, when deriving a figure of merit for the direction finding accuracy of the array it seems appropriate, because of the above possibility, to consider only those azimuths between the crossover points. Numerical values for these crossover points for the specific arrays that were considered are given in Table 3.6.

As in the rotator case, the principal sources of the azimuth dependent errors are calibration errors associated with either the monopulse receiver or, with the variation of the array's monopulse patterns vs elevation angle.

Table 3.6. Beam Crossover Angle.

Beamwidth	Total Number of Elements (also beams)	Cross-Over Angle ($\pm$)
6^{o}	96	1.9^{o}
4^{o}	128	1.4^{o}
4^{o}	160	1.1^{o}
2.2^{o}	288	0.6^{o}
2^{o}	256	0.7^{o}

Previous comments on the monopulse receiver characteristics are again applicable. A 2 percent error in declared angle is a reasonable figure of merit.

The impact of the change in the array monopulse slope depends on what are determined to be the calibration and focusing conditions. Figure 3.5 shows the resulting bias error when the monopulse curves for a 4^{o} system, singly-focused at 18^{o} (see Fig. 3.4) are approximated for calibration purposes by a single judiciously-chosen straight line. Between 0 and 20^{o} elevation angle, the error up to 1.4^{o} off-boresight is less than 0.05^{o}; at 35^{o} the maximum error has increased to 0.35^{o}. A similar error for the doubly-focused 2^{o} beamwidth system is shown on Fig. 3.6 which was optimized for a larger window than would probably be used and is therefore somewhat pessimistic. Even up to 20^{o}, the bias is less than 0.05^{o} and reaches 0.20^{o} at 35^{o} elevation.

In evaluating the significance of the deterioration in the DF performance as a function of elevation angle one should keep in mind that the induced increase in the cross range errors are lessened by the associated reduction in the maximum target slant range.

In the event that the above bias errors are not acceptable, our contractors have suggested and provided data on means of reducing the error. This can be done by generating more beam positions (twice as many for example) and permitting a target to be interrogated at 2 or 3 different off-boresight angles, thereby benefiting from linear interpolation or averaging of several estimates. The details of these analyses go beyond the intended scope of this report and will not be reproduced here. It is sufficient at this point to note the existence

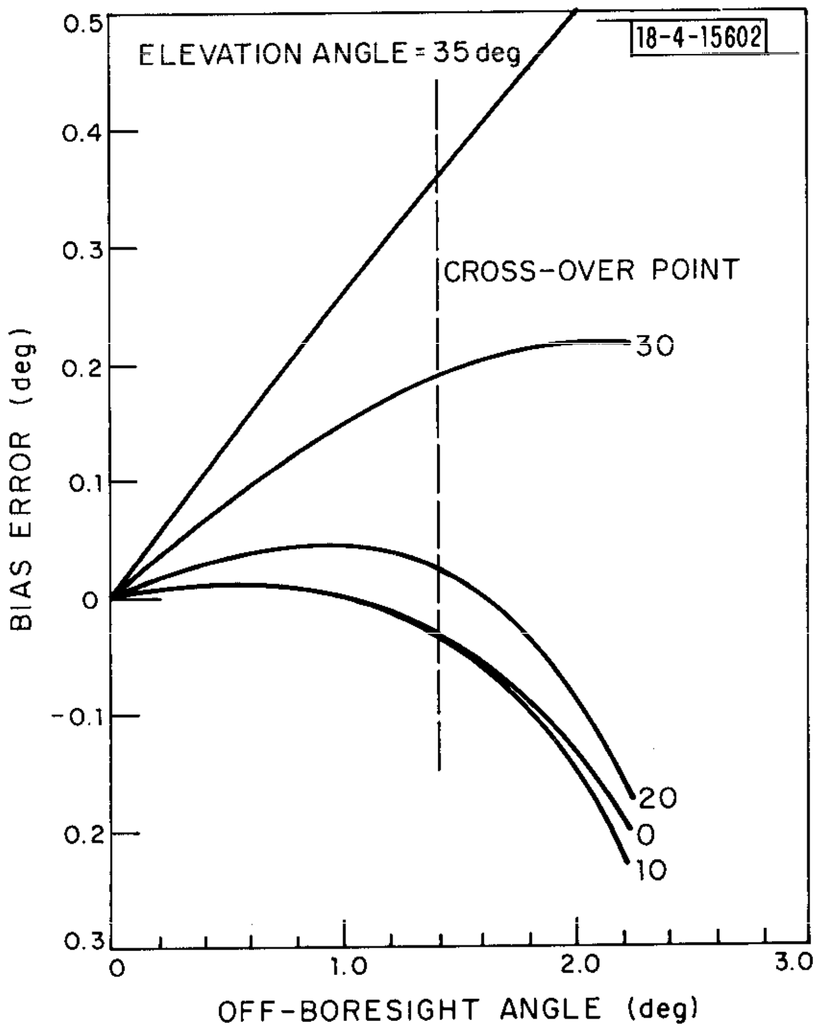


Fig. 3.5. Antenna Contribution to Single Reply Error and 4° Beamwidth.

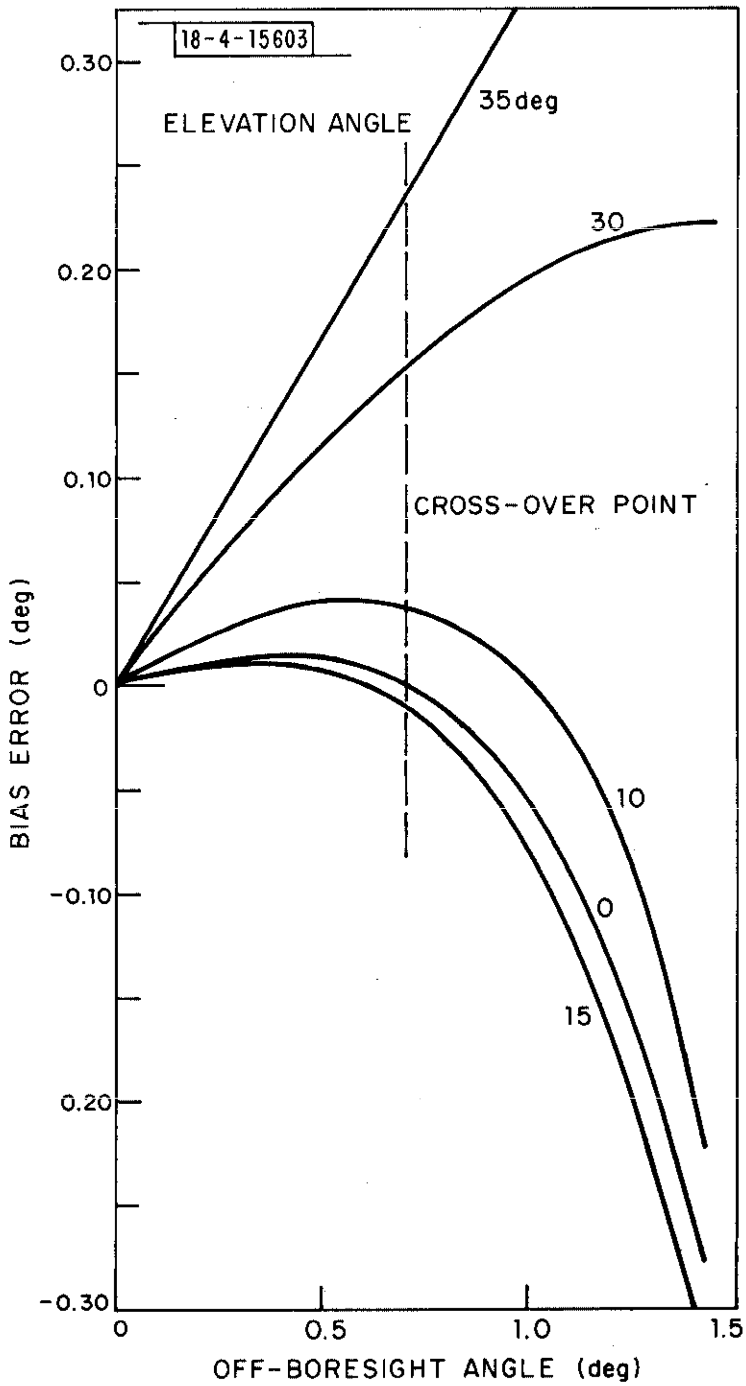


Fig. 3.6. Antenna Contribution to Single Reply Error, 2° Beamwidth.

of the possibility of reducing the bias error by a factor of two to ten, depending on which combination of interrogation scheduling and DF algorithm is used.

c. Miscellaneous Errors

Another source of DF error is the boresight shift versus elevation angle caused by aperture errors and, as in the planar array case, has been evaluated at $\pm 0.01^{\circ}$ per degree beamwidth. This is a bias type error over the time span during which a target does not change its elevation angle by more than a few degrees.

The rms value of the quantization error introduced by an 8 bit A/D conversion of the monopulse signal is about 1/4 percent of the maximum off-boresight angle and, for all practical purposes, is negligible.

d. Summary

A summary of the various contributions to the system DF error is presented in Table 3.7. The results are not significantly different from those for independent rotators.

Table 3.7. Summary of DF errors for cylindrical array systems.

Type	Origin	Criterion	Error 4° BW	Error 2° BW
Reply Random Error	Receiver Noise	20 dB SNR/chip		
		(a) DABS, 10 samples	0.06° rms	0.03° rms
		(b) ATCRBS, 8 samples	0.07° rms	0.035° rms
Reply bias	Boresight variation vs elevation	0.01°/deg BW	0.04°	0.02°
Reply bias	Antenna Monopulse	"best" linear fit between beam cross-over points	0.05° (< 20° elev) 0.35° (< 35° elev)	0.04°(<20° elev) 0.23°(<35° elev)
Reply bias	Receiver Calibration	2% off boresight angle	0.03°	0.015°
	Total error bias + 3σ		0.30°	0.11°

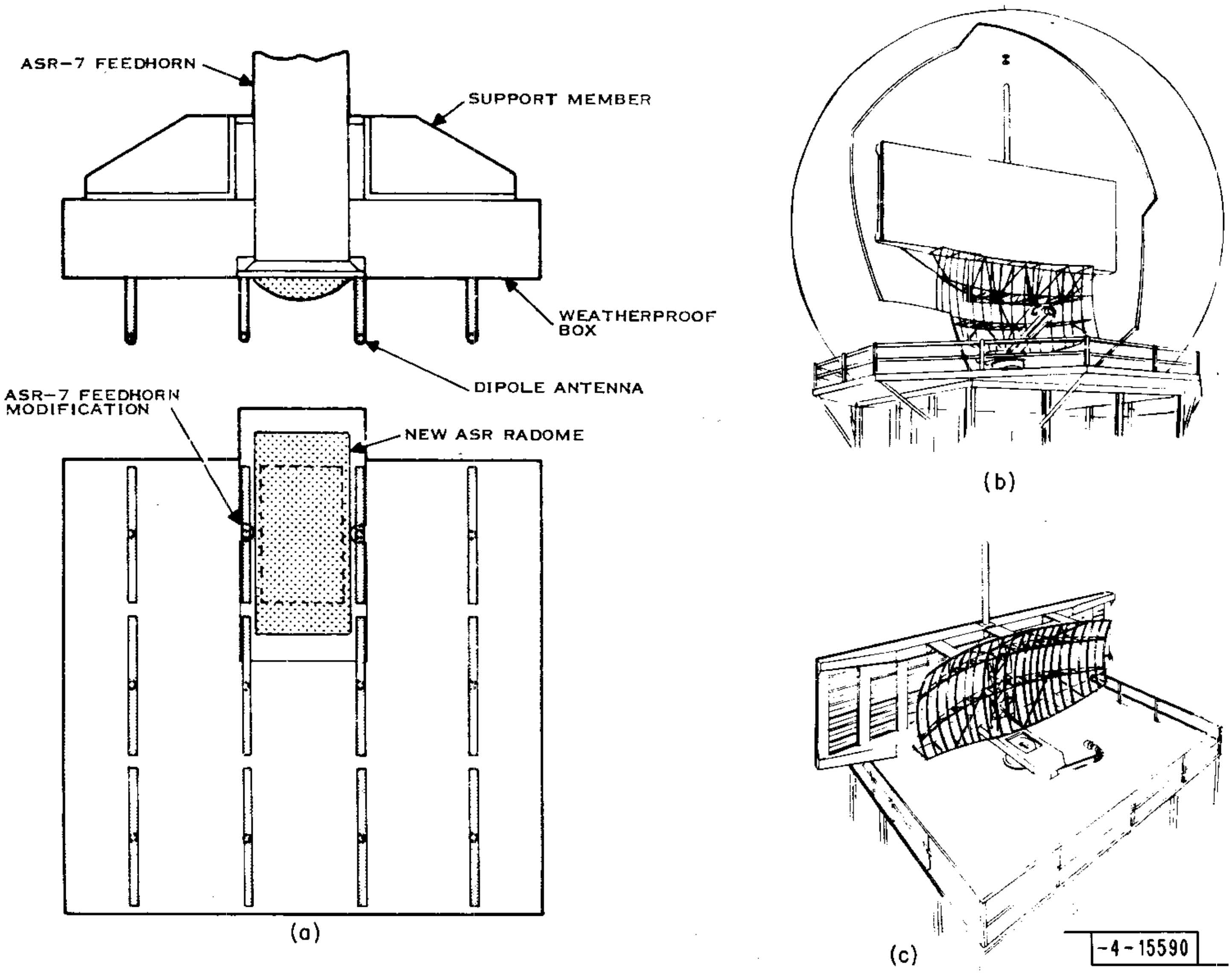
SECTION 4
CO-LOCATED ANTENNAS

Because of the unique physical constraints which prevail when the beacon and radar are co-located, design requirements were relaxed so as to permit a large range of configurations to be investigated. In particular, no requirements on coincidence between the radar and beacon pointing angles were imposed. The related requirement was that the two antennas share the same pedestal, thereby rotating in synchronism. Emphasis was placed on specific designs. The antenna designs that were considered, except for the feed modification kits, are identical to those used for rotators. Therefore, only the installation factors were examined. Also, since it was determined that co-location does not significantly affect the direction finding performance of the beacon antenna systems, the previous discussions on azimuth accuracy for rotators (Section 2.3) are applicable here.

4.1 ASR CO-LOCATION

4.1.1 Shared Reflector

This configuration uses the radar reflector for the beacon by providing a beacon feed (L-band) integrated with the radar feed (S-band) (see Fig. 4.1(a)). The studies were carried out from the point of view of performing such a modification on existing ASR antennas, as opposed to a total redesign of a combined radar/beacon antenna. The design investigated by both contractors


ASR–7 FEEDHORN
SUPPORT MEMBER
WEATHERPROOF BOX
DIPOLE ANTENNA
ASR–7 FEEDHORN MODIFICATION
NEW ASR RADOME
(a)
(b)
(c)
-4-15590

consisted of several interconnected dipoles located on both sides of the present radar horn. The azimuth beamwidth thus generated is at least 3.5°. If a single row of dipoles is used, the elevation pattern will tend to follow a cosecant-squared drop-off at high elevation angles, as does the radar. With several rows of dipoles, the pattern can be flattened over the coverage sector. An illustrative example of beacon azimuth and elevation patterns for the case of three rows of 4 dipoles is shown on Fig. 4.2. The cost of the complete conversion was estimated at between $13K and $20K, depending on the number of dipoles and selection of the monopulse receiver. This price includes installation of the feed modification kit, an additional channel on the rotary joint and a separate matched omni-antenna. If the omni and the monopulse receiver were excluded, the remainder of the conversion process would cost less than $10K.

4.1.2 Top-mounted Antenna

This top-mounted arrangement would be similar in concept to (Fig. 4.1(b) the existing ATCRBS/ASR configuration. It was calculated that the largest solid aperture which can be accommodated without exceeding the wind loading tolerances of the present installations (as determined by the FAA 2100 specs), is nominally 14 ft wide (4° beamwidth) and 4 ft tall (1.0 to 1.5 dB/deg cut-off). Planar array implementations are generally preferred because they require the minimum aperture area for a given performance. The conversion for such a configuration is around $40K. To accommodate larger top-mounted antennas, the preferable solution seems to be the use of a radome (for radome costs, see Section 2.1.7). Although costs for such larger top-mounted configurations were not explicitly provided, the cost of back-to-back systems discussed below should be fairly representative.

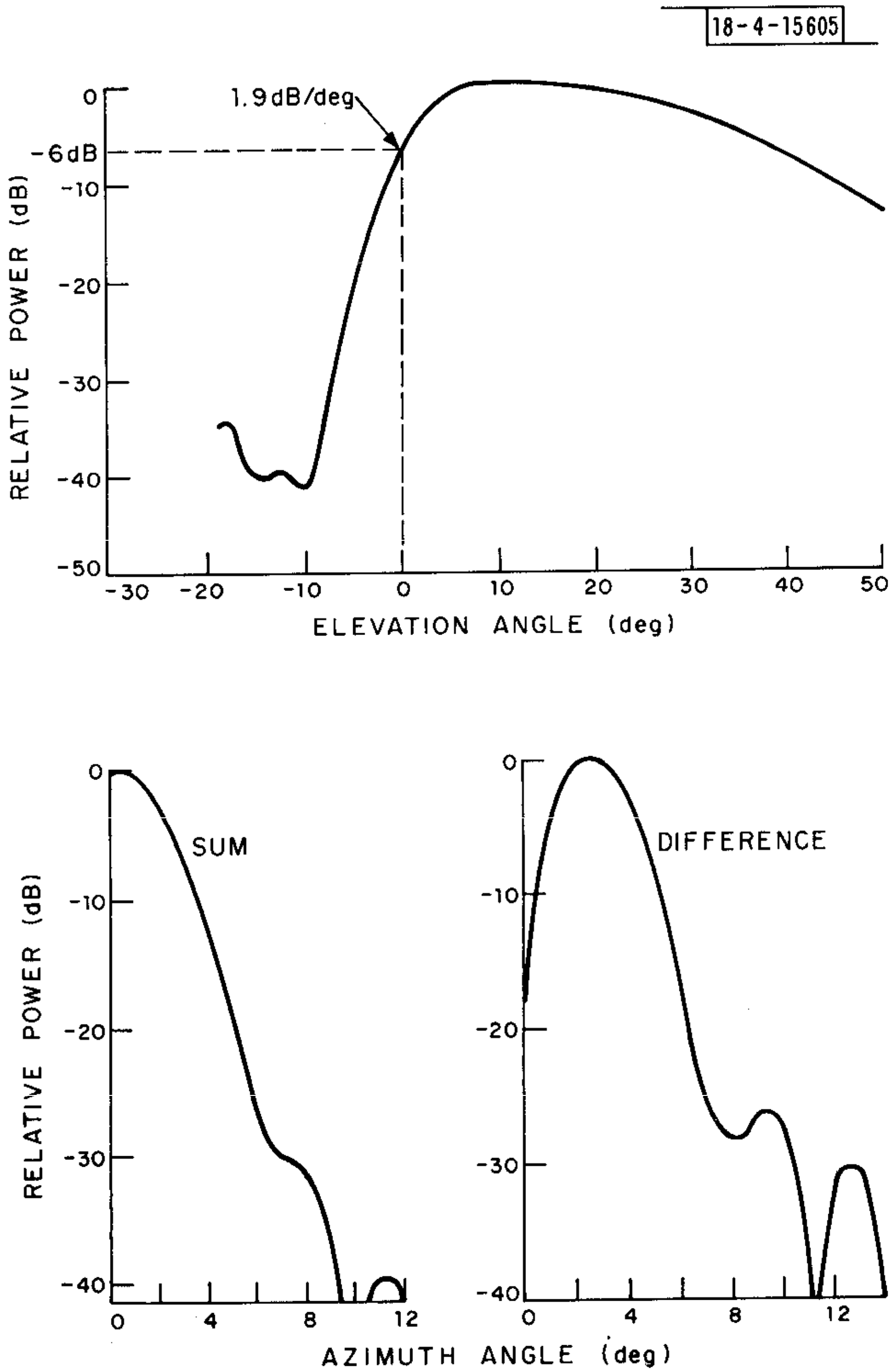


Fig. 4.2. Patterns for ASR Shared Reflector Configuration.

4.1.3 Back-to-back Configurations

It has been determined that a 16 ft wide by 10 ft high aperture can be accommodated on the back of the ASR antenna (Fig. 4.1(c)) with almost no modification to the present structure. This would permit installation, for example, of a planar array with a 4° beamwidth, 30 dB sidelobes and 3 dB/deg cut-off performance. The cost of the complete modification kit has been evaluated at $56K.

For larger apertures, the cost escalates rapidly because of the extent of the required modifications to the existing installation. Examples of these are included in the ASR colocation cost summary provided on Table 4.1.

4.2 ARSR CO-LOCATION

4.2.1 Shared Reflector

The basic difficulty in providing an integral beacon/radar feed for the ARSR reflector stems from the proximity of their operating frequencies. Because the original study guidelines called for a sector-type elevation pattern, only one of the alternatives that were considered could qualify as conditionally-acceptable. This beacon feed consists of dipoles located to the side of the radar feed (Fig. 4.3). Its main advantage is that it can be designed independently from any constraints imposed by the radar feed; this is important because of the monopulse requirements. Its main disadvantages are the separation between the radar and beacon beams (about 5°) and the beam skew vs elevation (about 0.7° at 30° elevation). A typical realizable elevation pattern is shown on Fig. 4.4. The total cost of the conversion process is about $25K. The feed modification kit is only about $8K. Interestingly, almost half of the

Table 4. 1. Cost Summary for ASR Co-location.

Configuration	Size	BW (degrees)	Cut-off Rate (dB/degree)	Cost ($ x 10^3)
Integral Feed	----	3. 5	1. 9	13-20
Top-Mounted Array	14' x 4'	4	1. 5	40
Back-Mounted Array	16' x 10'	4	3	56
Back-Mounted Array	30' x 10'	2	3	190 (1)
Back-Mounted Array	30' x 16'	2	5	312 (1)
Back-Mounted Reflector	31' x 10'	2	3	164 (1)

(1) Radome included.

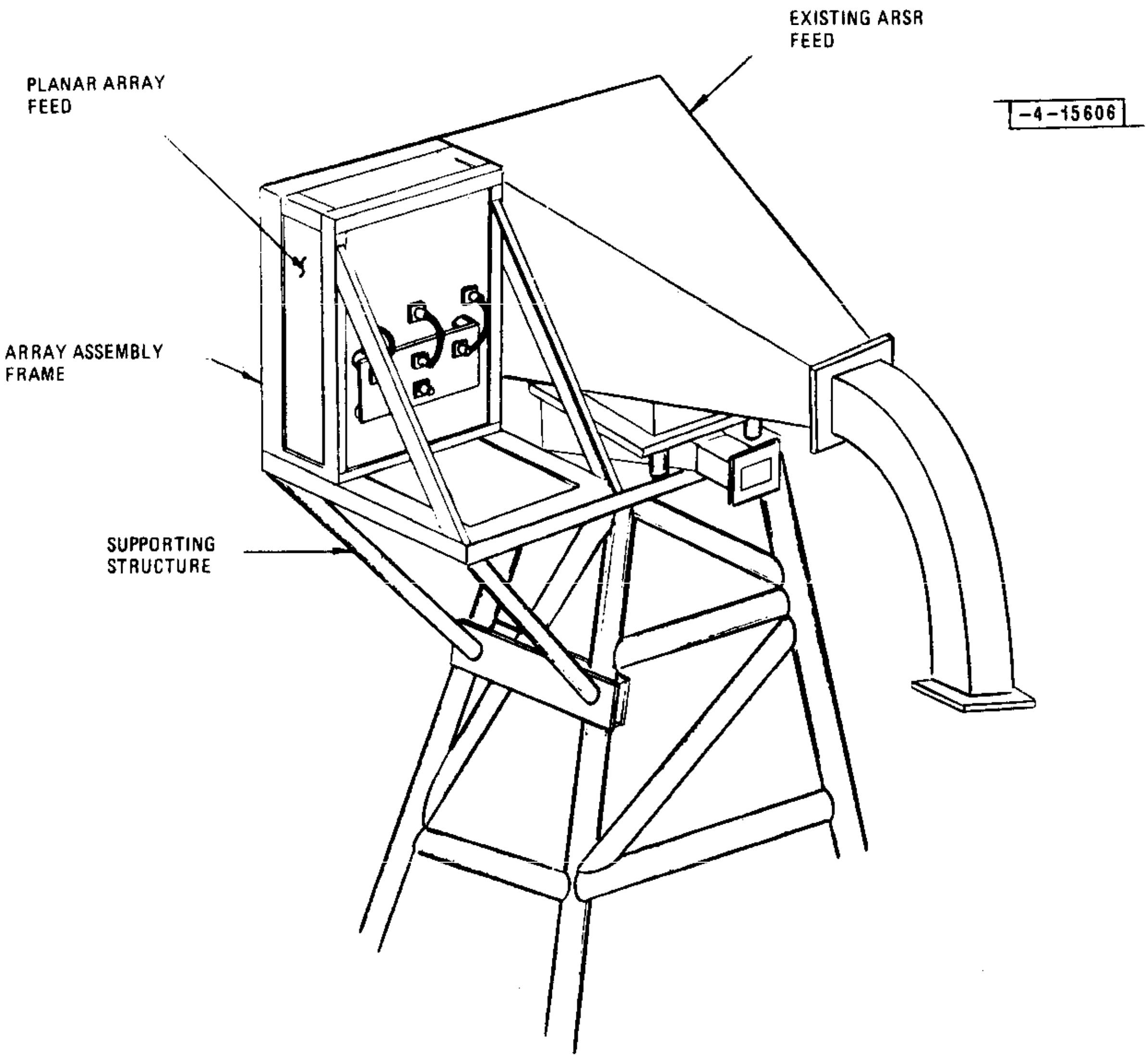


Fig. 4. 3. ARSR Integral Feed Configuration.

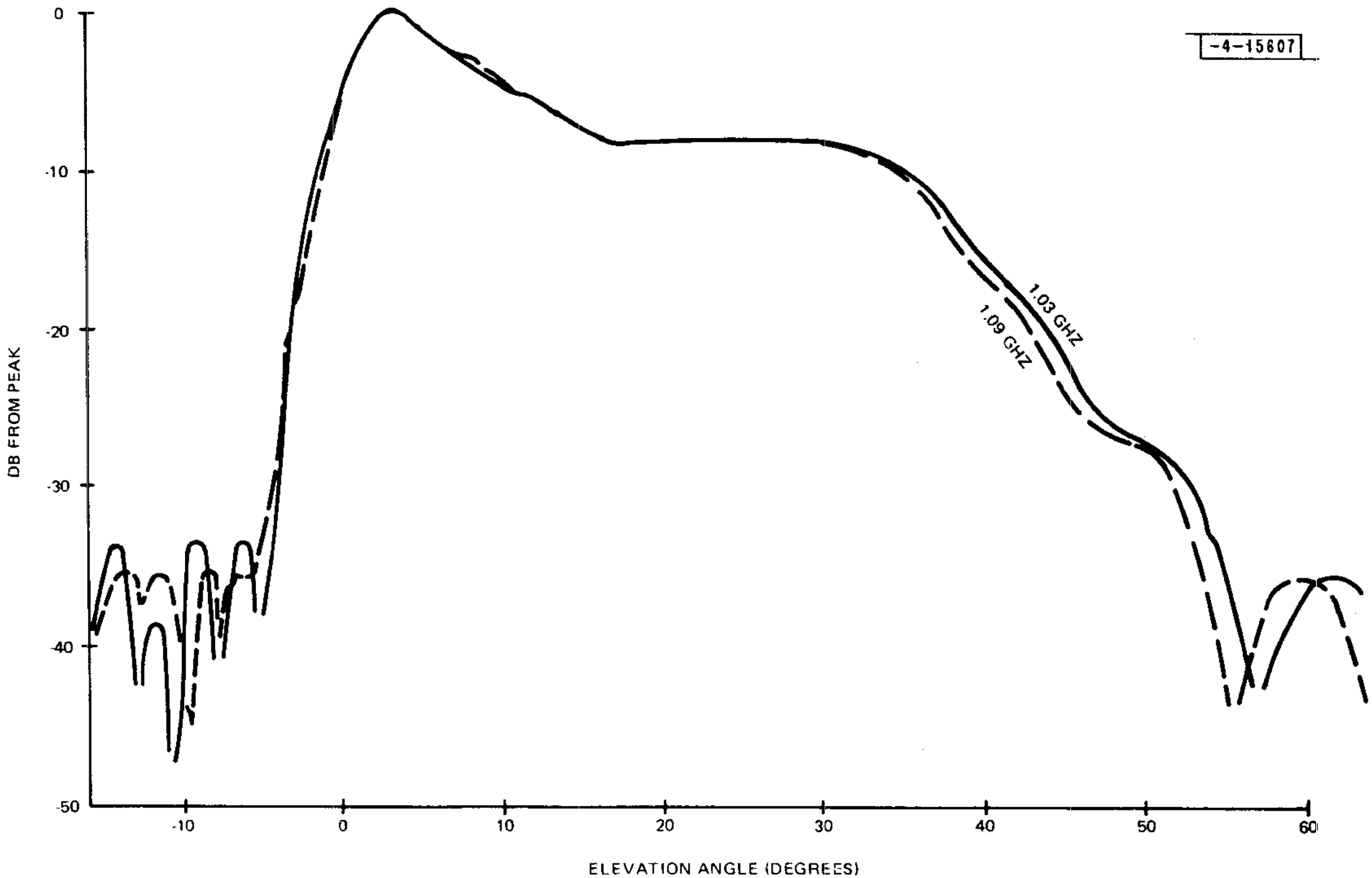


Fig. 4.4. Elevation Pattern for ARSR Integral Feed Configuration.

total cost is in the omni, matched to the high cut-off rate of the reflector (4 dB/deg). The installation of the omni was not considered in detail during the study but it is recognized to be potentially troublesome. On the basis of the results of the studies it must be concluded that there are still significant uncertainties about the overall performance of this kind of implementation. It is still very much worth pursuing in more depth because of the significant savings which may be realized.

4.2.2 Top-Mounted

Within the constraints imposed by the present radome, the tallest aperture which can be accommodated is about 4 ft. With an array implementation this can produce a cut-off rate of at least 1 dB/deg; however, because of radome effects near the top, one should not expect peak sidelobes lower than 20 dB. The total implementation cost has been estimated at $14K for a 4^{o} beamwidth and $62K for a 2^{o} beamwidth.

4.2.3 "Chin"-Mounted

The possibility of locating the antenna just in front of the radar horn was also briefly considered. Because of the uncertain plans for modifying the present ARSR pedestals, this was not pursued at the time.

4.2.4 Back-Mounted

With back-mounting, many of the cost and performance uncertainties associated with the previous configurations are eliminated. Even the largest aperture size considered (33' x 16') can be accommodated with the limited modifications. A problem is the 5 sec delay between the radar and beacon, an issue beyond the scope of this study. Typical costs are provided on the ARSR co-location cost summary shown in Table 4.2.

Table 4.2. Cost Summary for ARSR Co-location.

Configuration	Size	BW (Degrees)	Cut off Rate (dB/degree)	Cost ($ x 10^3)
Integral Feed		1.5 - 3.0	4.0	25
Top Mounted Array	30' x 4'	2.0	1.5	62
Top-Mounted Array	14' x 4'	4.0	1.5	40
Back-Mounted Array	30' x 10'	2.0	3.0	135
Back Mounted Array	30' x 16'	2.0	5.0	260

SECTION 5

CONCLUSIONS

For independent rotators, no single antenna implementation has emerged as clearly most cost-effective. There are, however, a number of trends which have been established:

- For the same aperture size, reflector antennas cost less than planar arrays.
- Reflectors require more aperture area than arrays to achieve the same gross performance; reflectors are still less expensive, although, there is some disagreement on precisely how much less.
- As peak sidelobes requirements get more stringent there is an increasing tendency for contractors to perfer arrays.
- The most cost-significant design issue is the trade-off between use of a radome or use of an appropriate pedestal/drive for the large antennas or high scan rates. In a 2° BW, 3 dB/deg cut-off, the critical point occurs around 15 rpm, whereas it occurs at 30 rpm in a 4° BW 3 dB/deg cut-off system. These happen to be sets of parameters which are on the border of the range of interest.

The most significant design conclusion for cylindrical arrays is that the use of off-boresight monopulse results in a considerable reduction in required number of discrete beam positions when compared, for example, to the number generated by the E-SCAN antenna. Typically, it is sufficient to have a number of beams equal to the number of columns around the array. Even though there are obvious advantages to beam agility and potential advantages to the lack of moving parts, there are two significant factors which seriously detract from the appeal of such arrays:

- Even with the design simplification mentioned above, cylindrical arrays were found to be about twice as costly as comparable mechanically-scanned systems.
- The antenna gain is at least 6 to 7 dB lower than that of conventional antennas. Although this can be compensated for in the uplink by increasing the transmitter power, it represents an irreversable loss of signal on the downlink.

In evaluating the economic advantages of co-location one can point to at least the direct savings of the tower and pedestal cost which is of the order of $50K minimum. Furthermore, the antenna realization can, by sharing the reflector with primary radar, be very attractive from a cost viewpoint; the performance constraints and uncertainties warrant that these configurations be pursued in greater depth than they have so far. In order to enjoy the benefit of the potential cost savings, the specifications imposed on any co-located design must accommodate whatever constraints are encountered while still implying a tolerable level of performance.

The last essential point to be made is common to all three types of antenna systems and deals with the characterization of the inherent direction-finding accuracy. Unlike the accuracy of the present ATCRBS system which in principle is a relatively constant parameter (primarily because of beam-splitting and STC), the accuracy of a DABS sensor is strongly dependent on target parameters such as range and altitude, off-boresight angle, number of replies in scan, and reply pulse content. Therefore, any characterization of a DABS sensor direction-finding accuracy must first include a convention by which at least all of the above parameters are also specified. It was determined during the study that, under a reasonable set of conditions described in the text, a beamwidth as wide as 4° was adequate to meet the 0.15° "one σ" nominal DABS accuracy requirements.