ESSCO

25 METER MILLIMETER WAVE TELESCOPE
MEMO No. 134

THE PERFORMANCE AND ECONOMICS OF RADOME-ENCLOSED ANTENNA SUBSYSTEMS

January 1980

Prepared By The Staffs Of

Electronic Space Systems Corporation

and

ESSCO Collins Ltd.

PROLOGUE

This paper sets forth the convictions of a group of highly competent engineers who have each spent an average of over 20 years in the design and analysis of all forms of radome enclosures for ground based antenna systems. In presenting their conclusions, great care has been exercised in the endeavor to set forth only arguments that are analytically supportable.

It is recognized that some hold views divergent from those of the authors. Differences of opinion may be validly based on the special circumstances of particular applications, which may not be truly typical and representative.

An open minded, careful reading of this document is solicited, and a dialogue on those divergent views that still prevail is sincerely invited.

SUMMARY

A radome is an electromagnetically transparent structural enclosure for antenna subsystems, analogous in many respects to a watch case and its timing mechanism. As such, radomes should be evaluated along with other system components and design methods to achieve a total system capability that must meet and maintain performance requirements at minimum life-cycle cost. Frequently, required system performance cannot be met without using a radome. In systems which do not possess such clear distinction, an in-depth analysis is illuminating. This discussion, therefore, addresses antenna subsystem design and the engineering and management decision process effecting overall system performance, and evaluates effectiveness based on the three main criteria:

I. Radome-Antenna Electromagnetic Performance;

II. System Availability and Reliability; and

III. Life-Cycle Costs.

Full consideration of these aspects leads to the following important conclusions:

1. THE OVERALL PERFORMANCE OF A RADOME-ENCLOSED SYSTEM, WITH THE ANTENNA DESIGNED FOR THE RADOME ENVIRONMENT, IS EQUAL TO OR BETTER THAN ENVIRONMENTALLY-EXPOSED SYSTEMS.

2. A RADOME-ENCLOSED SYSTEM INSURES THAT THE AVAILABILITY AND RELIABILITY REQUIREMENTS OF CONTEMPORARY AND FUTURE SYSTEMS WILL BE MET.

3. ON A LIFE-CYCLE COSTING BASIS, A RADOME ENCLOSED ANTENNA SYSTEM IS GENERALLY THE MOST COST-EFFECTIVE DESIGN.

INTRODUCTION

The complexities of contemporary antenna systems demand a sophisticated design approach if required performance, cost and operational needs are to be achieved. Our primary concern in this paper is directed at the antenna subsystem as a key element of partial or fully steerable reflector or multi-dimensional array systems.

The function of the antenna subsystem is to provide a directional or focused beam of electromagnetic energy exhibiting a specified distribution in three dimensional space with attendant pointing/tracking accuracies. In addition, reliability, operating availability and life-cycle cost requirements must be achieved--all within the environmental conditions imposed. The mechanical-structural configuration must preserve the electromagnetic characteristics, and provide the means of achieving the attendant pointing/tracking accuracies, reliability and availability.

In essence then, the "block" denoting the Antenna Subsystem in the overall system block diagram, need not concern itself with the design detail but only system requirements. The system's analysis should require that the gain, sidelobe level, noise temperature, pointing/tracking accuracy, reliability, availability and life-cycle cost of the antenna subsystem be achieved. Further, it is desirable that the degree of performance not be a function of time or environmental conditions.

How an antenna subsystem designer fulfills these requirements--whether by building up and otherwise reinforcing the mechanical-structural configuration or by eliminating the environmental forces with an electromagnetically transparent shelter--should be determined by equating performance among alternatives and comparing their relative costs.

Antenna designers are frequently faced with stringent specifications requiring full operating performance in high winds, rain, snow or ice precipitation, as well as strong solar loads. Further, the trend in microwave communications, radar, radio astronomy and other applications is toward utilization of the higher frequencies with corresponding demands for more precision in pointing and tracking and higher overall antenna efficiencies. It has become painfully and expensively evident that a standard "brute force" approach to these design requirements is inadequate. This inadequacy is demonstrated by the fact that radomes are frequently added to existing systems, originally designed to withstand their environments without the use of radomes, in order to truly attain the antenna subsystem's intended objectives. System performance and physical specifications are not adequately measured when exposed to actual prevailing environments, and continued assurance is even less likely.

Thus, the practical, cost-effective approach is to eliminate the detrimental effects of the environment by the full employment of radomes. In fact, as shown in this paper, it is possible to obtain a higher degree of performance at lower cost--especially with the trend to higher frequencies.

With the uncertainties and complexities of the environment eliminated, mechanical and structural analyses can be carried out with textbook precision. From the electromagnetic viewpoint, prediction of the key parameters of gain, sidelobe levels, noise temperature and pointing/tracking accuracies can be accomplished with reasonable certainty. From the mechanical-structural viewpoint, subreflector and feed support mechanisms may be optimized to produce higher efficiency; heavy and costly components may be reduced in size and optimized structurally; drive power requirements lowered significantly; deflection characteristics reduced and deterioration practically eliminated--all with dramatically increased reliability and operating availability.

Significantly, the price for such achievement is negligible; in fact, savings are evident in most cases. Initial capital costs and service-life maintenance expense, which often far exceed the original capital outlays, combine to produce attractively lower life-cycle costs.

To more fully appreciate and quantify this design approach, the following sections provide detailed comparisons between environmentally-exposed and radome-covered antenna subsystems.

I. RADOME-ANTENNA ELECTROMAGNETIC PERFORMANCE

This section addresses the effects of environment on the electromagnetic characteristics of exposed antenna subsystems compared to the effects of that same environment when the antenna subsystem includes a radome. The term "radome" as used in this paper includes all types (such as rigid-metal or plastic; flexible-air inflated) as best suited to performance requirements. For the sake of illustration, a basic paraboloidal reflector antenna subsystem will be examined. In order to limit but quantify the discussion, environmental or radome-induced effects on an antenna subsystem are each viewed as influencing the effective RMS error of the reflector. Evaluation of the effects of the environment on an exposed antenna subsystem can then be directly compared with those induced by a radome.

A. Exposed Antenna Electromagnetic Performance

In any optimum design outcome, performance should be time-invariant, precise, reliable and repeatable over the service life of the system. Unfortunately, environmental forces produced by wind, sun and precipitation in all forms are always at work. These forces are usually taken in their expected extremes; i.e., the highest winds, the heaviest ice or snow loads, etc. and imposed on an antenna structural configuration by the designer in order to assure survivability. However, without detracting from that important aspect, the more significant requirement is often that of continuous operating performance at the specified levels of all primary electromagnetic constraints under the influence of all variations of the environment, up to and including the extremes.

What does this imply? An examination of antenna efficiency factors[1] illustrates our concerns. We can compute the gain of an antenna subsystem as:

$$G = (K_1\ K_2\ K_3 \text{--},\ K_n)\ \frac{4\pi A}{\lambda^2}$$

Where K_1, K_2, K_3--K_n are factors contributing to the overall efficiency of the antenna,
A is the area of the physical aperture of the paraboloidal reflector, and
λ is the wavelength at any specified operating frequency.

K_1, K_2, etc. include such factors as feed illumination taper and spillover, reflector aperture blockage, RMS error contribution, radome efficiency and several others. The essential point is that practically all of these factors are affected by the prevailing environment in which the antenna system must perform.

Figure 1 illustrates the aperture blockage efficiency factor, showing the difference between a typical feed-subreflector support configuration designed for full exposure to high winds, ice and/or snow loads, and the design for a benign environment.[2] The efficiency factors (K) are 0.83 and 0.94 respectively or an improvement of about ½ dB for the benign environmental design. Because of the importance of this factor in the design of exposed versus radome-enclosed antenna subsystems, it will be discussed further under Section I.B. of this report.

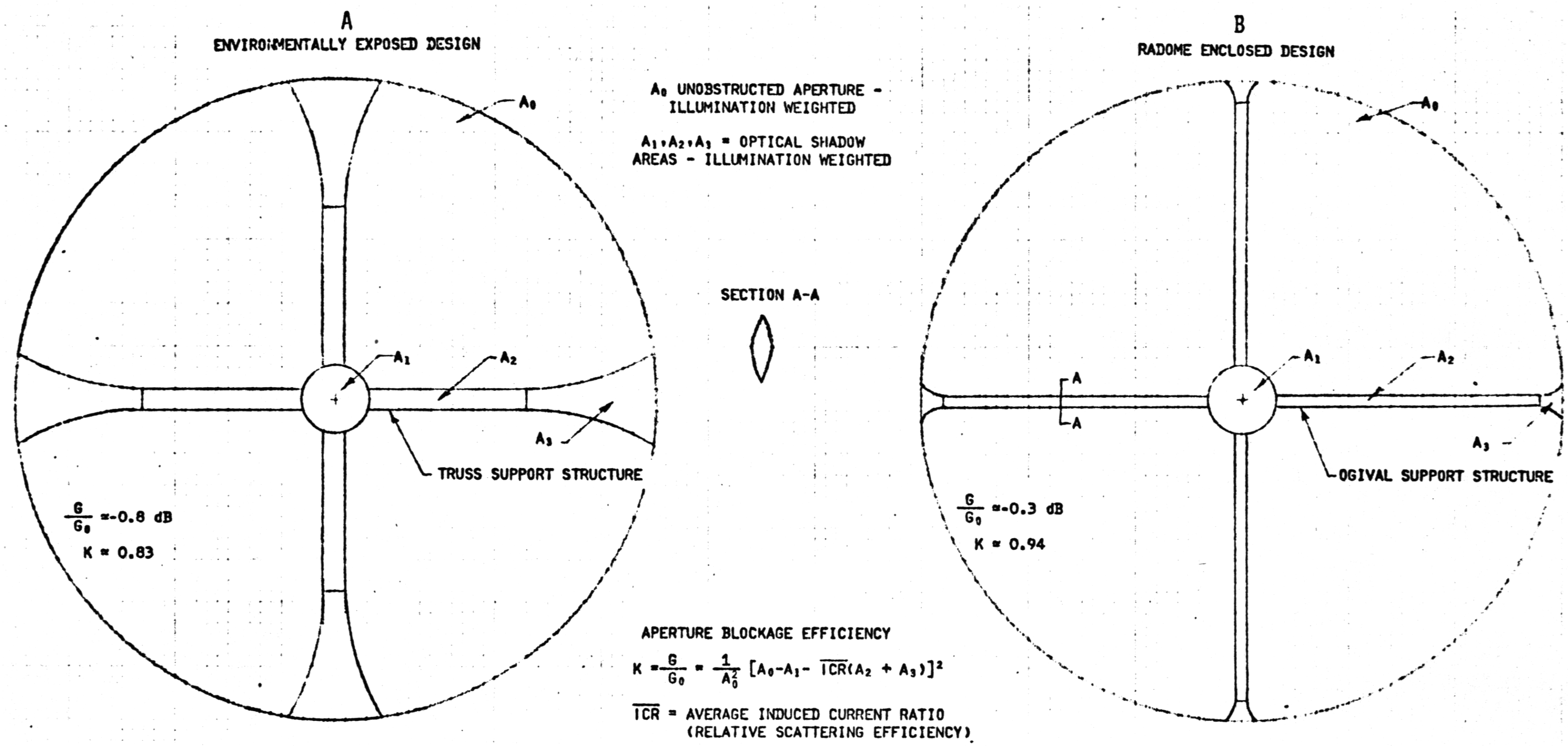

FIGURE 1

TYPICAL 13.7 METER PARABOLIC REFLECTOR ANTENNA APERTURE BLOCKAGES

A - EXPOSED DESIGN APERTURE BLOCKAGE, K ≈ 0.83

B - RADOME ENCLOSED DESIGN APERTURE BLOCKAGE, K ≈ 0.94

Another key design parameter, the RMS reflector error, has a strong influence on at least three of the primary electromagnetic performance requirements; namely, antenna subsystem gain, sidelobe levels and noise temperature. The RMS error (ε) is defined as the square root of the mean of the sum of the squared surface deviations from a perfect paraboloid[3]. For a Gaussian distribution of surface deviations, x_i, we can write the RMS error as:

$$\varepsilon = \sqrt{\frac{\sum_{i=1}^{i=n} x_i^2}{n}}$$

Figure 2 shows the independent influence of this factor on the efficiency of the antenna subsystem, as a function of frequency. Generally, the smaller the RMS error requirement compared to the expected operating wavelength(s), the more difficult and costly it is to achieve. For this reason, antenna designers choose an RMS error consistent with a performance versus cost trade-off.

Let us examine an operating frequency of 10 GHz and a designer's requirement of a fortieth of a wavelength ($\lambda/40$) or 0.75 mm in benign environmental conditions and no greater than a twentieth of a wavelength ($\lambda/20$) or 1.5 mm under any exposed condition; e.g., wind gusts up to 100 km/hr. We can observe from Figure 2 that as a result of these operating RMS errors, antenna gain can be decreased by about 1¼ dB. Further, it is necessary to add losses associated with pointing/tracking inaccuracies along with the detrimental effects produced by varying environmental conditions on other efficiency factors noted above. These added losses are subtly disclosed in antenna manufacturer's catalogue data and exposed system operating specifications. It is not uncommon to observe the acknowledgement of a 1-2 dB gain loss due to wind alone without a similar acknowledgement of any increase in pointing/tracking error, sidelobe level or noise temperature contribution. It is thus clear why antenna subsystems often become inoperable or are, at best, operable with severely degraded performance. Note that as the frequency increases, the RMS error constraints become much more stringent. For example, at 100 GHz, the difference between $\lambda/40$ and $\lambda/20$ RMS errors is equivalent to an allowance of only 0.075 mm for the effects of the environment.

The energy extracted from the main directivity of an exposed antenna, as measured by a gain reduction, is redistributed, adding to existing sidelobe levels and creating varying perturbations.[3] This effect results in much higher sidelobe levels than expected or allowed which, in turn, contributes to increases in the antenna subsystem noise temperature. For example at 10 GHz, assuming that the system operation experienced a total environmentally induced gain decrease of 2 dB and only 25% of this lost gain impinges on the "hot earth", an increase in system noise temperature of greater than 30°K can be expected. For low noise applications, where the antenna noise temperature under benign environmental conditions is also 30°K, the combination can result in a gain to noise temperature ratio (G/T figure of merit) decrease of 5 dB. In contrast, noise temperature contribution of a radome membrane is less than 2°K, and in the absence of an environmentally induced gain reduction results in negligible change in the G/T ratio.

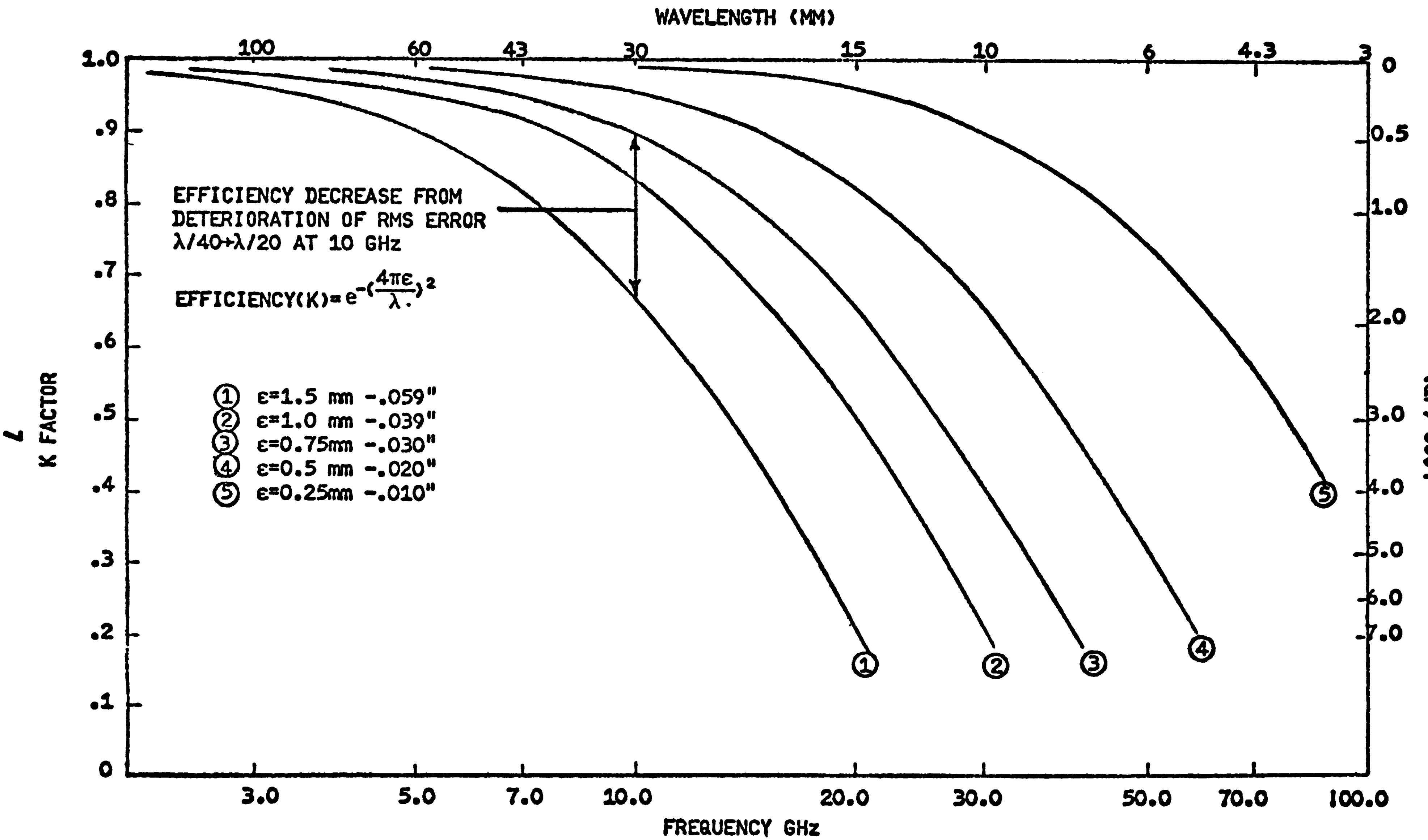

FIGURE 2

EFFICIENCY (K) FACTORS AND GAIN LOSS (dB) DUE TO REFLECTOR SURFACE RMS ERRORS

In addition, the designer must still cope with the degrading effects of all forms of precipitation. It can be argued that ice and snow can be eliminated by de-icing mechanisms, thereby reducing this threat to that of water or rain or, more generally, a "wet" condition. However, de-icing equipment does have a cost impact and can produce distortions in the structure similar to the effects of a differential temperature distribution as caused by various combinations of light wind and solar loads. These temperature differentials further degrade the effective RMS error of the paraboloidal reflector and can lead to serious pointing/tracking inaccuracies, especially at the higher frequencies. In fact, at the shorter millimeter wavelengths utilized for precision radar tracking and radio astronomy, temperature differentials make it all but impossible to meet the stringent pointing/tracking requirements, usually specified in arc seconds.[4]

When de-icing equipment is not utilized, snow and ice take their toll. Since accumulations are neither selective nor uniform, severe degradation of all electromagnetic characteristics is experienced. Even in limited cases where a primary paraboloidal reflector is clear, accumulations of ice and/or snow on the feed or subreflector support legs can cause significant degradation to aperture blockage, pointing/tracking and impedance efficiency factors. Again, non-operability or at best degraded performance is the result.

For the general "wet" case, similar reasoning applies. Water on a feed illumination element not only affects the illumination of a paraboloidal reflector, but also seriously impairs the impedance efficiency factor. Equally critical is the wetting process of a primary reflector, since wetting is generally not uniform but takes the form of streams, rivulets or droplets. At microwave frequencies, these water formations contribute to the further degradation of the RMS error, and thus the performance, of the antenna subsystem.

B. Radome-Enclosed Antenna Performance

Antenna subsystems designed to operate under the full combined effects of the prevailing environment can suffer large losses along with potentially hazardous limitations on operating availability. This degradation is in marked contrast to an alternate antenna subsystem design which introduces an electromagnetically transparent enclosure--a radome--as an integral element of the system. (Design-cost implications are discussed in a later section of this paper.)

It is apparent that the environmental loads previously applied directly to the radiating elements (the paraboloidal reflector antenna) are now applied to the radome. The radiating element itself, therefore, operates in an essentially benign environment. Under these conditions, maximum efficiency is directly attained and maintained without degradation.

Because of the elimination of all environmental forces, the design of feed-subreflector support legs, as noted above, can be optimized in the form of elongated supports extending to the perimeter of the paraboloidal reflector backstructure. Since the cross section of these support legs can be ogival[5], as shown in Figure 1, stiffness is placed where it is most desirable--in the plane perpendicular to the aperture. As a result of the ogival cross section, the back-scatter to the feed (for Cassegrain configurations), or back-scattered reflected energy from the support legs after parabolic collimation, is practically zero. In addition, overall aperture blockage is significantly decreased due to the reduction in required structural needs and effective elimination of practically all of the "shadow" area (See Figure 1, Area A_3) produced by support legs that would otherwise intersect the parabolic surface at intermediate points between the center and perimeter of the reflector. Typically, subreflector or feed supports for environmentally-exposed antennas are effectively twice the size of those required for radome-enclosed subsystems and can exhibit surprisingly high losses.[2,6] Thus, antenna subsystem gain can be directly increased by ½ dB or more. Other attempts at further reducing antenna aperture blockage such as cantilever type feeds and off-set parabolic reflector configurations, while possessing moderate design merit when protected by a radome, continue to suffer from size, cost and environmental limitations when exposed to the elements. It is important to recognize that like the RMS reflector error, aperture blockage is a significant contributor to the level of antenna sidelobes and noise temperature.

When a radome is included as part of the antenna subsystem, the blockage of its structural members must be combined with the blockage created by the feed-subreflector support. For an ESSCO Metal Space Frame Radome, blockage accounts for approximately ½ dB, essentially offsetting the increased efficiency gained from the ogival feed-subreflector support design. Accordingly, there is little or no net blockage attributable to a properly designed radome-enclosure for the subsystem. Furthermore, other benefits are apparent when separately evaluating the aperture blockage of a radome and that of feed-subreflector supports, primarily due to the differences in scattering energy before or after collimation. For example, when feed-subreflector supports are anchored mid-way between the center and the perimeter of a paraboloidal reflector, the direct intended illumination function is intercepted, leading to the "shadow areas". This effect is considered more detrimental than the broadly scattered energy of radome structural members after full collimation (plane wave formation) by a properly illuminated parabolic reflector. For the purpose of this paper, however, the net effect of adding a radome structure to the proper feed-subreflector support configuration may be taken as negligible. The important point is that even under benign environmental conditions, radome-enclosed antenna subsystems can exhibit equal or better gain, sidelobe and noise temperature performance than environmentally exposed systems.

The radome contains low dielectric, low loss, thin plastic membranes acting as "windows" attached to the structural framework. The membranes usually have a white exterior that rejects approximately 90% of the incident solar load, practically eliminating the effects of this environmental element. Typically, these membranes exhibit a dielectric

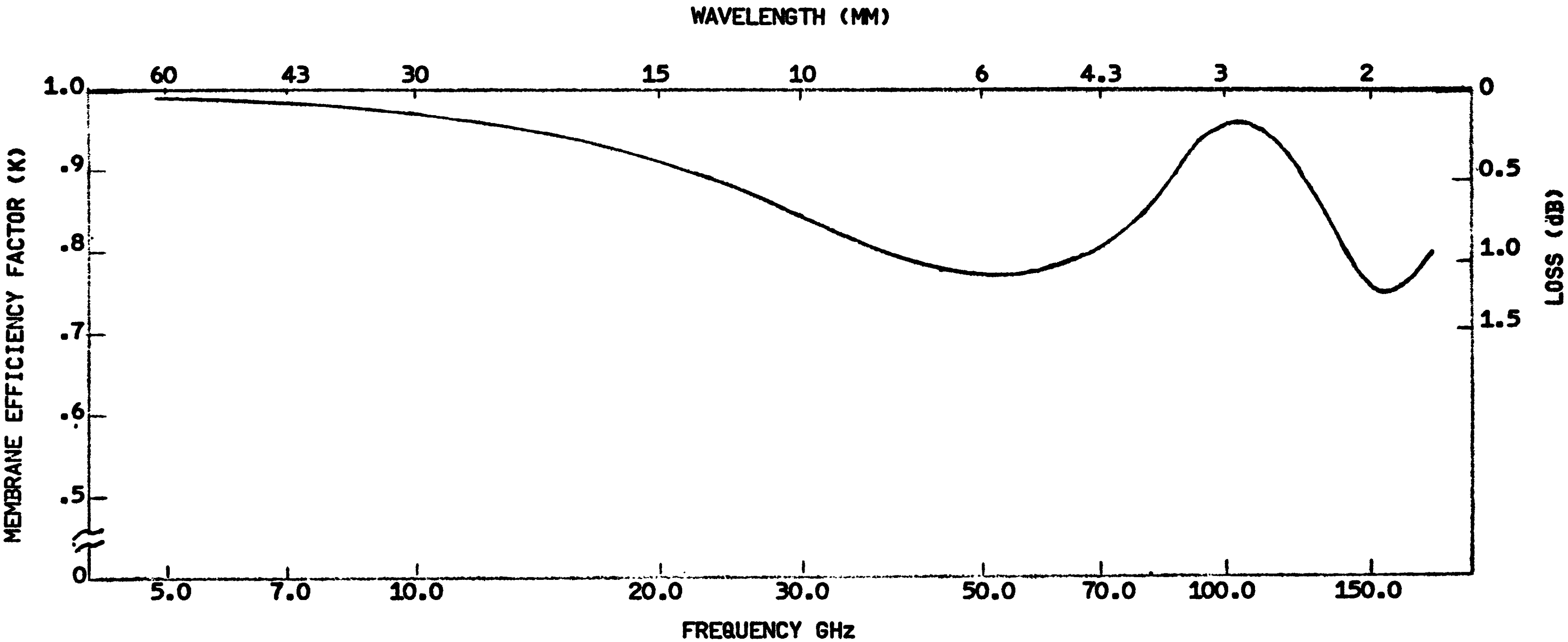

FIGURE 3

EFFICIENCY (K) FACTOR AND GAIN LOSS (dB) - TYPICAL ESSCOLAM™ RADOME MEMBRANE
DIELECTRIC CONSTANT = 2.8, TANα = 0.010, THICKNESS 0.85 MM

constant of between 2.5:1 and 3.0:1, and a loss tangent of between 0.003 and 0.015 depending on the materials employed for the specific application. The radome efficiency factor in the gain equation given in Section I.A. is essentially the membrane efficiency factor presented in Figure 3, since the small effect of radome structural members is offset by feed-subreflector support blockage reduction. It is necessary to recognize in comparing Figures 2 and 3 that the value of the radome efficiency factor as a function of frequency does not vary exponentially with frequency as does the RMS reflector error efficiency factor.

With respect to the effects of ice and snow, a radome-enclosed system has certain advantages as a result of the aerodynamic characteristics of spherical structures. It has been shown that the collection efficiency (i.e., the ability of frozen particles to impinge upon the structure while carried in a wind stream) is much lower for a spherical structure than for a paraboloidal reflector antenna.[7] Further, any collection or accumulation on a radome surface is generally "blown" away in the first wind due to the effective pressure distribution acting on the spherical structure.

In rain (or, more generally, the "wet" case), it is most desirable for moisture to run off the surface of a spherical radome in the form of rivulets and streams, and not to form a water film. For this reason, and for those applications sensitive to rain, radome membrane surfaces are fabricated with an integral water-repelling material which inhibits the creation of water films.[8]

Detailed experimental tests performed by ESSCO and others have verified that water films are not formed on such surfaces and that the effects of streams, rivulets and droplets on a radome with water repelling membranes have an effect on antenna gain similar to that exhibited by rain on the surface of an exposed reflector.[9,10] Accordingly, the effects of rain and its associated losses may be considered comparable for both antenna subsystem designs. There is, however, a significant net advantage since in a radome-covered case, the entire radiating element is protected so that rain does not effect the primary illumination process, and other effects such as corrosion do not impair overall equipment reliability.

In the absence of environmental loads on a radiating antenna structure, the effect of a radome can be isolated and quantified. Figure 4 shows a typical gain versus frequency curve for a radome-covered antenna subsystem, compared to that of a theoretically "perfect" antenna at all frequencies. In the "perfect" antenna, all gain efficiency factors are unity or fixed at specific values, but not variable with frequency or the environment. The only variable efficiency factor in Figure 4 is that of a radome.

The differences between the two curves in Figure 4 represent the expected loss attributable to the radome in a radome-covered antenna subsystem over a broad frequency spectrum. Up to approximately 10 GHz, this loss is practically negligible, 0.13 dB, gradually increasing to a maximum of approximately 1.15 dB at 53 GHz and 1.3 dB at 159 GHz.

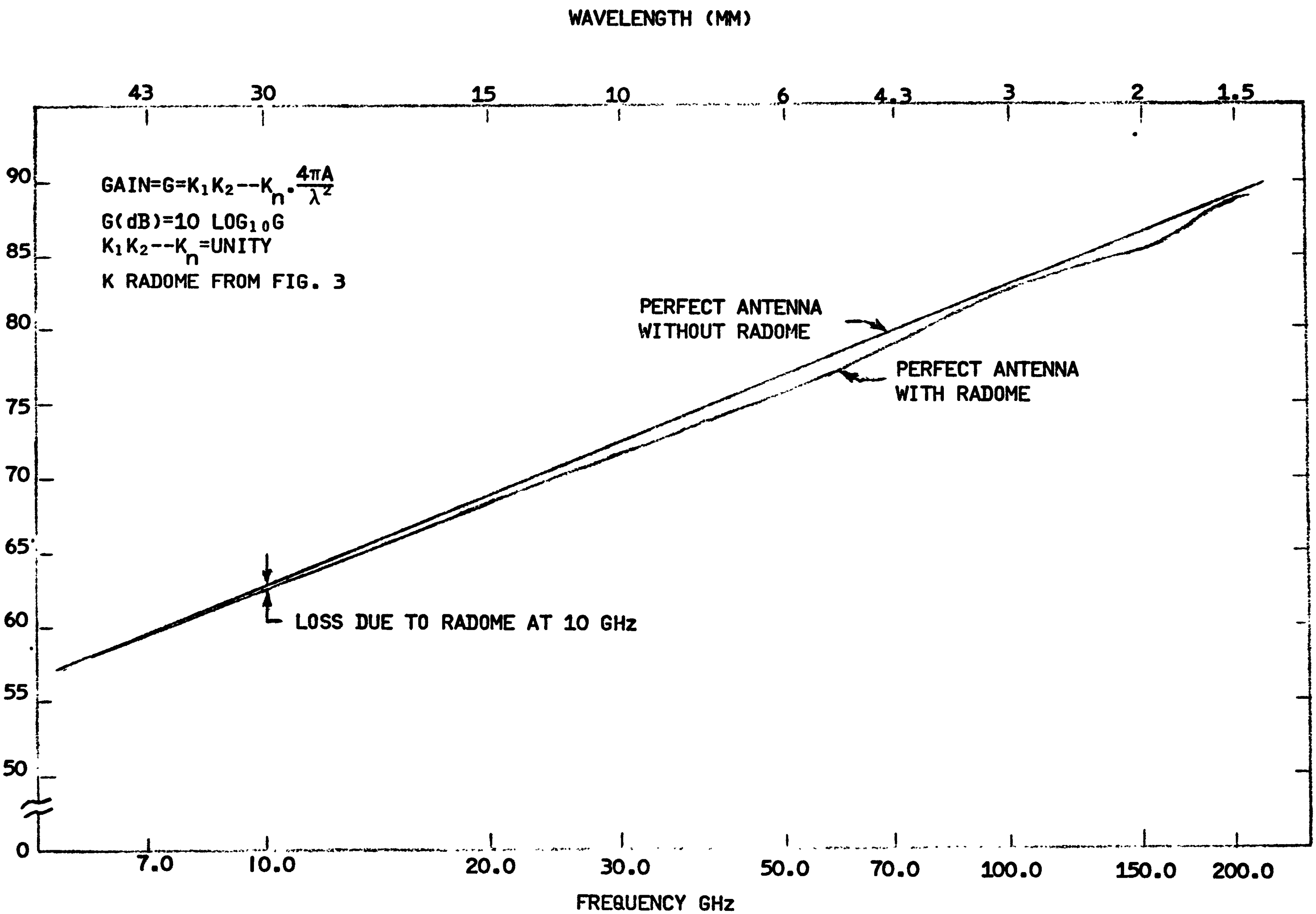

FIGURE 4

GAIN OF THEORETICALLY "PERFECT" ANTENNA WITH AND WITHOUT RADOME VS FREQUENCY
TYPICAL 13.7 METER DIAMETER REFLECTOR

With higher performance membranes, i.e., lower dielectric constants and loss tangents, the loss is correspondingly lower. (For those existing antenna subsystems where it may be impractical to optimize feed-subreflector supports, approximately 6% blockage should be added, increasing the loss attributable to the radome by about ½ dB.) For exposed antenna subsystems, it is not possible to confidently predict such performance. Designing for normal environments of widely varying wind, precipitation and thermal loads precludes reliable analyses, and results in continuous, often severe, performance degradation. On the other hand, the predicted performance of radome-enclosed subsystems, over a broad frequency spectrum, is time-invariant, reliable and repeatable.

Once the gain or efficiency factors can be considered stable, all other electromagnetic performance characteristics can be predicted. Certainly the pointing/tracking accuracies are unimpaired by the environment and, since well-designed metal space frame radomes exhibit an RMS boresight error normally between one-two hundredth and one-four hundredth of a half power beamwidth (0.005 HPBW to 0.0025 HPBW), this characteristic is well enhanced. In addition, any systematic errors may be calibrated out to produce maximum antenna efficiency and optimum pointing/tracking accuracy. Noise temperature contribution and sidelobe level perturbations are readily predictable on average, and exhaustive measurements on deviations in pointing, gain variations, polarization effects and noise granularity of a radome show that these effects are not discernible.[11]

Figure 5 shows curves which include an RMS reflector error efficiency factor as a variable parameter with frequency. A typical 13.7m antenna subsystem's performance with an RMS error tolerance of $\lambda/40$ at 10 GHz, enclosed in a radome, is compared with environmentally degraded performance due to an increased RMS error of $\lambda/20$ at 10 GHz. All other efficiency factors are taken as unity with the exception of the radome efficiency factor, utilized to optimize the performance of the antenna. Although other efficiency factors will be effected by the environment and will vary with frequency for an exposed antenna subsystem, they can be viewed for comparison purposes as a change or degradation of the overall effective RMS error. Examination of the graphs shown in Figure 5 indicates that the effect of a radome on system electromagnetic performance is clearly insignificant when compared with the major influence of an exposed antenna subsystem's RMS error efficiency factor. Even this insignificant effect can be eliminated, if desirable, by marginally increasing the diameter of radome-enclosed antennas, as discussed in Section III of this paper.

For the example given earlier in this section (10 GHz operating frequency with an allowable $\lambda/40$ RMS error under benign conditions and $\lambda/20$ RMS error under the force of the environment), there is negligible relative loss for the radome-enclosed case as compared to the expected 1¼ dB loss of the environmentally exposed antenna

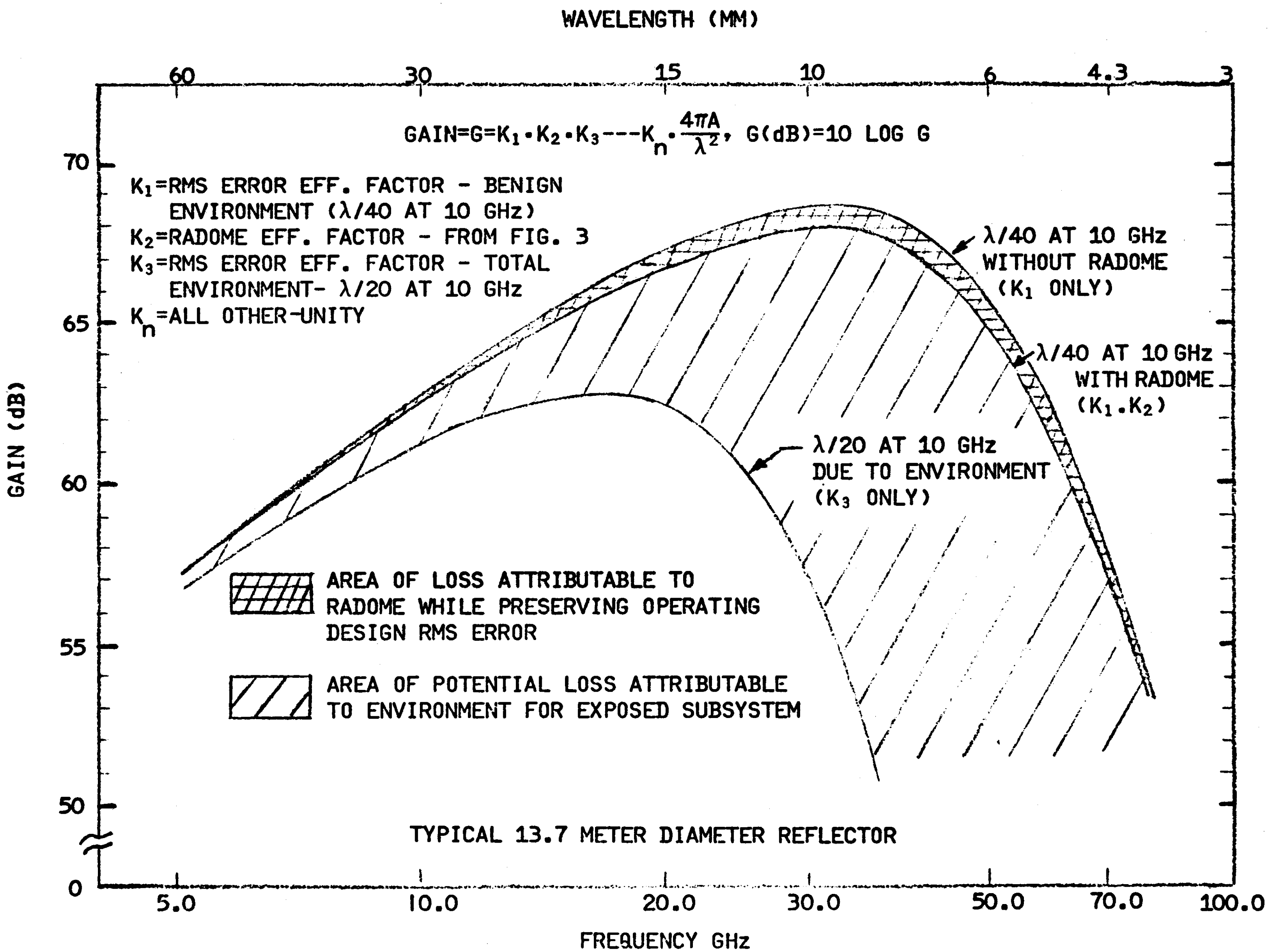

FIGURE 5

COMPARISON OF GAIN AS A FUNCTION OF FREQUENCY
FOR RADOME ENCLOSED VERSUS ENVIRONMENTALLY EXPOSED ANTENNA SUBSYSTEMS

subsystem. Examination of the operating capabilities of this antenna at higher frequencies, e.g. 20 or 30 GHz, dramatically indicates the performance benefits derived from radome-enclosed systems. Similar conclusions can be drawn from an evaluation of other designer selected parameters and operating frequencies. It is notable that opportunities present themselves to upgrade the performance and range of applications of existing antenna subsystem as operating frequency requirements are increased.

This discussion of the performance of antenna subsystems operating under the influence of prevailing environmental loads, up to and including their extremes, leads to the following definitive conclusion:

> The overall electromagnetic performance of a radome-enclosed antenna subsystem is equal to, and in practically all cases better than, that exhibited by environmentally-exposed systems.

II. SYSTEMS AVAILABILITY AND RELIABILITY

A radome protects the antenna and associated electronics from environmentally induced degradation. Numerous advantages accrue that simplify initial design (for new systems), improve operation and reduce maintenance. Since some of these benefits are often overlooked by system designers and facility operations managers, a summary of the principal mechanical advantages is presented in this section. The consequences in terms of Availability and Reliability are both illuminating and highly significant.

Degradation of the performance of exposed antenna systems due to environmental conditions and forces must invariably be followed by cumulative deterioration of the equipment resisting these loads. Elimination of all environmental loads, therefore, results in:

1. Reduced wear and tear on all rotating mechanisms, leading to increased life and accuracy of bearings;

2. Decreased power required to rotate or position an antenna subsystem at various velocities and accelerations, enhancing the life and accuracy expectation of the drive system;

3. Liberalized design safety factors and component de-rating;

4. Removal of expensive excess capacity to compensate for gradual performance deterioration;

5. Minimized need of protective coatings against corrosion;

6. Elimination of the necessity to apply diffusive paint to reflector surfaces to prevent solar energy concentrations at the feed or subreflector;

7. Ease of system calibration and alignment, accomplished in minimum time and under benign environmental conditions;

8. The ability to calibrate out systematic errors inherent in any mechanical-structural design, usually masked by non-repeatable environmental variations;

9. More protection provided by covers, seals and gaskets, since they need only withstand the benign radome environment;

10. The highest system availability with respect to the environment--the antenna subsystem is never inoperable due to an inability to perform in the prevailing environment; and

11. The highest antenna subsystem reliability, through removal or minimization of deterioration from other environmental factors such as:

    a) Salt atmospheres,

    b) Sand penetration and erosion,

    c) Dust infiltration,

    d) Direct actinic radiation,

    e) Atmospheric pollution such as "acid rain",

    f) Sleet and hail, and

    g) Relative humidity corrosion.

The above listing is not exhaustive, but representative of advantages of radome-enclosed antenna subsystems when examined from Maintainability, Availability, Reliability and Operational viewpoints. One can attempt to "design-away" some of the environmental effects, but it is not possible to totally escape from the relentless destructive forces of atmospheric conditions. Yielding to eventual performance degradation for exposed antenna subsystems ignores the fact that Availability and Reliability are paramount considerations. The equipment must be ready to operate precisely when required, and over the time interval required. Reliability also demands maintaining performance specifications during the required operational interval.

Exposed antennas are subject to a reduction in performance as local environmental conditions change. At some point they cannot meet requirements, and must eventually shut down to preserve their structural integrity, thus becoming unavailable. Attempts to design exposed antennas to operate with degraded performance in progressively severe environments very rapidly become non-cost effective and eventually not practical.

Unfavorable weather resulting in reduced performance carries a very high price. For example, low frequency (and thus low data rate) international satellite systems indicate that being off the air represents a loss of revenue approximating as much as U.S. $30,000/hr for a heavy duty station. Typhoons, hurricanes, and other environmental extremes have caused losses in revenue as high as $3-4 million/year for such stations.[12]

All commercial and military activities are moving toward higher frequencies for a variety of reasons, particularly bandwidth availability and security. Antenna performance becomes increasingly sensitive to environmental factors, e.g., wind and solar loads, as the frequency increases. Use of a radome effectively overcomes system sensitivity to such forces.

To depend upon the simultaneous occurrence of acceptable weather at widely separated points for military, commercial and scientific operations is restrictive in planning and logistics, and has significant penalties. Utilizing a radome virtually eliminates the antenna subsystem from this dependence.

From Maintainability and Reliability aspects, recovery time due to equipment malfunction is substantially reduced for an antenna subsystem when a radome is employed. The more unfavorable the ambient environment, the more effective is the radome. If the antenna becomes unavailable at a critical time due to equipment failure, lost time in repairs can be dramatic, resulting in mission delay, mission abort and lost data. It is difficult to overestimate the gradual destructive power of nature, and the importance of personnel and operational problems. In this regard, rigid radomes, in addition to providing continuous equipment and personnel protection, are utilized as permanent overhead cranes or support structures available on sites for heavy maintenance and installation needs.

Without reservation, therefore, all the advantages and comments above lead to only one possible conclusion:

> The inclusion of a radome component in both contemporary and future antenna subsystems, not only insures that Availability and Reliability requirements will be met, but affords the system designer with important advantages that cannot be obtained in any other way.

III. LIFE-CYCLE COSTS

A. Capital Costs

The discussion in Section II of this paper makes it clear that there can be a significant difference in the design and manufacturing costs of antenna subsystems specifically developed for the protected radome environment and those designed to withstand all atmospheric conditions. This difference tends to be less for small antennas, becomes substantial for larger sizes and rapidly increases for all antenna subsystems at the high operating frequencies. All of the advantages listed in Section II strongly impact the initial capital cost of an antenna subsystem.

Designers can minimize obsolescence and updating modifications by designing key components, such as the pedestal and its drive system, to meet anticipated future requirements (possibly beyond the capability of any exposed system). Further, in the absence of environmentally induced loads and effects, the antenna subsystem's weight, moments, torques, frictions, etc., are minimized. Even radome transportation and installation costs are partially offset by the reduced weight of other components. As implied in Section II, installation of a radome covered antenna subsystem can and should proceed with the simultaneous emplacement of both the pedestal and radome. The remainder of the system such as reflector, electronic equipment, feed and supports, along with servo controls, subsystem alignment and calibration can then safely follow within the benign environment created by the radome enclosure. It is unnecessary and costly to design an antenna subsystem to endure the loads that would normally be encountered without a radome in place.

Therefore, drive power requirements are usually decreased to a small fraction of that required to drive exposed systems, even in moderately windy climates. As a result of drastically reduced power requirements to drive radome-enclosed antenna systems, the design of servo control subsystems is greatly simplified and thus much less expensive. Low horsepower (H.P.) motor requirements with correspondingly low reflected motor inertia combine with the absence of wind gusts to permit "text book" precision designs. Circuits, components and control techniques can be employed that are not practical with systems demanding high power drives.

All of the above comments focus on potential cost reductions of the pedestal, servo control system and radiating element of the antenna subsystem as compared to the original cost of the enclosing radome. A number of trade-off studies have been conducted which indicate that savings in the original capital cost can equal or exceed the cost of the radome component.[4,13,14,15]

Typically, the capital cost reduction associated with the pedestal, servo control subsystem and radiating element is between 10% - 30% of an environmentally exposed design, depending upon the reflector size, frequency (GHz), performance requirements and operating environmental conditions. The 13.7m antenna subsystem used for illustrative purposes in this paper, (See Figures 6 and 7), would utilize a nominal 20m diameter radome at a basic capital cost of approximately U.S. $150,000. The cost of a 13.7m antenna subsystem, to operate in the full environment and designed to equal the performance of the same antenna when enclosed in a radome is extremely high and probably not realizable. However, allowing for reduced performance and operating availability for environmentally exposed conditions, as delineated in some system specifications and antenna manufacturers' data (e.g., moderate gain reduction in 50 km/hr winds, degraded performance in 100 km/hr winds and driving to stow for survival in winds above 120 km/hr), the basic capital costs may lie between U.S. $500,000 and $1,000,000. Accessory, transportation and site costs are not included in the basic capital costs for ease of comparison. Thus, if the mid-range of savings (20%) is achieved by employing a radome, capital costs of new radome-enclosed antenna subsystems are at least comparable to those of exposed subsystems. It is clear, however, that we must ignore the differences in performance to make this comparison. Fully equal performance, under all prevailing atmospheric conditions, clearly favors a radome-enclosed antenna subsystem.

New radome-enclosed antenna subsystems can be designed to have marginally increased antenna diameters, compared to exposed designs, since the incremental cost for approximately a 12% diameter increase is small when all environmental loads are eliminated.[15,16,17] As noted in Section I.B., the resultant 1 dB increase in the aperture gain practically offsets the radome membrane loss (See Figure 4 of Section I), and provides performance superior to an exposed antenna subsystem even under the most benign environmental conditions.

B. Maintenance and Operating Costs

Placing the antenna within the protective environment of a radome capitalizes upon the various mechanical advantages cited in Section II of this paper. Each advantage listed has a positive impact on system maintenance and operating costs. Increased service life, reduced wear and tear, liberalized safety factors, and minimization of need for protection against corrosion, erosion and general deterioration directly correspond to increased mean time between failure (MTBF), decreased mean time to repair (MTTR) and lower overall maintainability costs. Seals, covers, gaskets, etc., need only withstand the benign radome environment and thus need far less frequent replacement, with resultant decreases in spare parts provisioning.

The differences between radome-enclosed and environmentally exposed antenna subsystems with regard to maintenance and operating costs should also take into account System Availability, Personnel Needs and Performance Loss Costs. System Availability includes both time to perform emergency and preventative maintenance as well as non-operational "downtime" due to inclement atmospheric conditions. Personnel Needs are dictated by both maintenance and operational activities of site technicians. Performance Loss costs may be translated into a decrease of revenue or increased operational costs to maintain the required performance.

Several studies have been made regarding maintenance costs on environmentally exposed and radome-enclosed antenna subsystems.[18,19,20,21] Even though system availability, personnel, performance loss, and other operating costs have not been considered, the data nevertheless permit reasonable estimates of the time required to amortize radome cost based only on potential reductions of antenna maintenance. The results of the four typical studies referenced are summarized here:

> The calculated amortization time is seldom longer than five years for normal environments, and can be as short as one or two years in harsh environments.
>
> Savings result from reduction in the rate of replacement of electronic components and power sources, as well as a reduction in the cost of protecting metal surfaces against corrosion, sand erosion, bearing failure, etc. The relative importance of each savings area depends on the application and maintenance philosophies employed.

System Availability, Personnel and Performance Loss costs are more difficult to quantify. As noted in Section II of this paper, when international satellite systems become non-operable, large costs which far surpass a radome cost are to be expected. Similarly in Air Traffic Control, Military and Scientific applications, unexpected "outages" can extract severe penalties.

For performance loss costs, it has been suggested that an antenna system can be rated in accordance with its cost/gain ratio. For example, a U.S. $1,000,000 antenna subsystem with a 60 dB required gain, would indicate greater than a U.S. $16,000+ per dB performance cost. If environmental conditions created a performance loss averaging 1 dB, an inherent penalty cost of more than U.S. $16,000 should be assessed.

System designers and end-users strive to reduce the number of station personnel and in some applications, eliminate all operators. A radome-enclosed subsystem facilitates this effort and makes it a practical objective for sophisticated applications. As an approximation, elimination of one site operator might save U.S. $30,000--$50,000 per year, depending on site location, personnel grade, and facility costs.

As a typical example of "other" costs, it was noted in Section A above that a radome-enclosed system requires substantially less power to drive the antenna. This reduction can produce savings of 50% or more in power consumption, especially in windy environments for continuously rotating antennas. In typical surveillance applications (e.g., Air Traffic Control) with rotating speeds of between 2-10 RPM and in moderate winds of 40 Km/hr, a nominal 13 meter exposed antenna will require an incremental power cost, relative to a radome-enclosed alternative, of between U.S. $5,000 and $8,000 per year. The calculations are based on a conservative cost estimate of U.S. $0.05/KW hr.

ESSCO's contemporary radomes are essentially maintenance free, since they are designed and manufactured from materials that are corrosion and erosion resistant, usually requiring only annual inspection.

C. Life-Cycle Cost Evaluation

Life-Cycle Costs are equal to the sum of original Capital Costs plus Maintenance and Operating Costs, including Availability, Performance Loss and Personnel Costs over the expected life of the system, typically taken as 10-15 years. When a radome is included as a component of a new antenna subsystem, savings achieved in initial design and manufacture can offset the cost of the radome, as noted in Section III.A. above. Thus, the original capital cost can be essentially the same for radome-enclosed and environmentally exposed antenna subsystems. Because all other maintenance and operating cost factors are significantly higher for exposed systems, Life-Cycle Costs are substantially lower for radome-enclosed systems.

Although radomes may be added to exposed antenna subsystems for performance improvement without concern for life-cycle costs, it is also desirable that any cost reductions resulting from the elimination of all atmospheric conditions offset the radome capital cost. End-Users and System Designers should aggregate and evaluate the costs and potential savings for:

1. Non-availability or "Outages",
2. Environmental Performance Losses,
3. Personnel Reductions,
4. Power Consumption Savings, and
5. General Maintenance Reductions.

For the 13.7m antenna system being considered in this paper, estimates of the maintenance, power and performance loss cost savings are:

		U.S. $/YR.
1.	General Maintenance Reductions, assuming a normal environment as defined in the NASA Corrosion Report[18] based on 1979 prices. In harsh environments these costs are substantially higher.	$17,000 - 30,000
2.	Power Consumption Savings	5,000 - 8,000
3.	Performance Loss Costs	0 - 16,000

or a total of U.S. $22,000 to $54,000 per year are possible in normal environments.

Further, if radome emplacement allows a smaller site personnel complement, U.S. $30,000 to $50,000 per year per person should be added.

It can be seen, for example, that if general maintenance cost reductions amortize the radome capital cost over approximately a 5-6 year period, then power consumption savings, and reductions in personnel, performance loss and "outages" must shorten the amortization period, resulting in a life-cycle cost decrease.

In addition, availability reductions can exhibit moderate to very large costs and penalties depending on the specific application. We must leave to the end-user the estimation of the cost of a non-operable antenna subsystem.

Taking all of the above cost considerations into account, leads to the conclusion that:

> On a life-cycle costing basis, a radome-enclosed antenna system is generally the most cost-effective design.

REFERENCES

1. J. V. Evans and T. Hagfors, "Radar Astronomy". McGraw Hill, 1968, pp 409-429.

2. J. Ruze, "Antenna Gain Loss due to Feed Support Blockage", CAMROC Technical Memorandum No. 19, MIT Lincoln Laboratory, 10 February, 1967.

3. J. Ruze, "Antenna Tolerance Theory--A Review", Proceedings of the IEEE, Volume 54, No. 4, April, 1966.

4. "A Large Radio Radar Telescope", Vol. I. Proposal For A Research Facility; Vol. II, Final Engineering Report; Vol. III, Design Criteria, by North East Radio Observatory Committee, 30 June, 1970.

5. A. Cohen et al, Patent #3,419,871, "Antenna Feedhorn Support Structure", Filed October 23, 1965.

6. Paul A. Lantz, "The Blockage Gain Loss of a STADAN Reflector Antenna", Goddard Space Flight Center, December 1969.

7. James T. Greene, Jr. and Philip Davis, "A Mathematical Investigation of Rime Formation on a 31- and a 55-Foot Radome", Internal Report No. VII-3, MIT Lincoln Laboratory, April 20, 1965.

8. C. A. Siller, Jr., "Preliminary Testing of Teflon as a Hydrophobic Coating for Microwave Radomes", IEEE Transactions on Antenna and Propagation, Vol. AP-27, No. 4, July 1979.

9. C. Louis Cuccia, "Japan Bids for Leadership in Space Communications", Microwave Systems News, pages 57-74, March 1978.

10. Report on "The Effect of Rain on Esscolam 7 and 8 Membranes at X Band", ESSCO Engineering Document, D80-2, January 1980.

11. M. L. Meeks, J. Ruze, "Evaluation of the Haystack Antenna and Radome", IEEE Transactions on Antenna and Propagation, Vol. AP-19, No. 6, November 1971.

12. Private Communication, Cable & Wireless, Hong Kong Intelsat Station, June 1979.

13. Herbert J. Gall, "Corrosion Control For Manned Space Flight Network Facility", NASA Contractor Report, NASA, CR-1492, Chapter VI, Part B, Studies on the Use of Radomes, page 6-7: Reference to USAF Study by H.G. Weiss of MIT Lincoln Laboratory on a 40' Antenna, February 1970.

14. Ibid, Pages 6-8: Reference to Rohr Corporation Study of Wide-Range of Antenna Sizes.

15. D. L. Pope, "Parametric Representation of Ground Antennas for Communication System Studies", The Bell System Technical Journal, pages 2145-2168, December 1968.

16. John Ruze, "Antenna Cost, Efficiency and Antenna Noise", CAMROC Technical Memorandum No. 9, MIT Lincoln Laboratory, September 1, 1965.

17. John Ruze, "Antenna Cost and Surface Tolerance", CAMROC Technical Memorandum No. 16, MIT Lincoln Laboratory, October 14, 1966.

18. Herbert J. Gall, "Corrosion Control for Manned Space Flight Network Facility", NASA Contractor Report, NASA, CR-1492, Chapter IV, February 1970.

19. Private Communication, Harris Corp., Maintenance Contractor (for U.S. Navy) for U.S. Sat. Com. (DSCS)-TSC-54, "Antenna Terminals", March 1975.

20. Air Traffic Control Radar Systems Definition Report, FAA EM-72-1, March 1972.

21. Dr. Robert O'Donnell, et al, "Advanced Signal Processing for Airport Surveillance Radar", Lincoln Laboratory No. MS-3818, June 11, 1974.