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LOW PROFILE ANTENNA PERFORMANCE STUDY PART II: BROADBAND ANTENNA TECHNIQUES SURVEY

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Communications/ADP Laboratory

October 1977

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This report is Part II of a three part series of reports investigating small antennas, their bandwidth and efficiency capabilities. Reviews and brief outlines of techniques published in the literature over the past 10-20 years, for broadbanding antennas is provided in this report. Experimental results from measurements of the Goubau antenna, a low-profile antenna (>0.05λ at the lowest operating frequency) are presented to show that this antenna possesses an octave bandwidth, regarding both impedance and radiation characteristics. Numerical results for some top-loaded structures are presented and matching network elements

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variations are determined in order to estimate the bandwidth. It is shown that ~2:1 and ~4:1 increases in bandwidth are achieved when top-loading is applied to the stub and the loop antenna, respectively, and an L-network is used for tuning and matching. It is concluded that there may be several small but broadband antenna configurations possible from a clever (but as yet unknown) combination of the ideas and techniques presented in this report.

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LOW-PROFILE ANTENNA PERFORMANCE STUDY

PART II: BROADBAND ANTENNA TECHNIQUES SURVEY

1. INTRODUCTION

In Part 1 [1] of this study, we examined some fundamental aspects of the efficiency and bandwidth of small antennas, and gave a brief review of Army needs and applications for such antennas. In this report, we will examine techniques for increasing the bandwidth of small and/or low profile antennas [2].

There have been many theories, ideas, and techniques, published in the literature aimed at improving the bandwidth of antennas. Many of these ideas and techniques will be reviewed in this report; preliminary experimental and numerical results on a top-loaded, folded antenna will be presented; numerical results of a parasite-loaded dipole antenna modeled on the computer will be given; and a recent, novel design of a low-profile broadband antenna [3] will be discussed. Part III of this report series will contain a selected bibliography of published literature on the topic of small antennas.

2. DISCUSSION

A. Overview

There have been many antenna configurations published in the literature over the past twenty years, aimed at improving the impedance and radiation bandwidths. Some have been claimed to achieve bandwidths of the order of an octave while maintaining relatively small size. In other configurations, half-wave resonant structures with increased cross-sectional dimensions have been used to increase the bandwidth. The majority of the literature has been experimental in nature; a few authors have presented analyses based on circuit concepts; an even smaller number have presented theoretical results verified by experiments; and there have been one or two numerical analyses to examine broadbanding techniques on small antennas. This last approach, i.e., numerical modeling, is believed to be the most powerful approach available at the present time for analyzing small antennas of complex configuration.

B. Passive Loading Using Parasite Elements

Jasik [4] shows a "partial-sleeve" loaded antenna (see Fig. 1a) which has an octave bandwidt at a VSWR $\lesssim$ 1.8:1. This antenna consists of a monopole which is resonant at about the geometric mean frequency of the band. The two parasite elements are about half the length of the main element for best

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[1] Part I, Low Profile Antenna Performance Study, R&D Tech Report, ECOM-4502, June 1977.

[2] Small antenna is defined, in this study, to be an antenna with maximum dimension of 0.1λ or less at the lowest operating frequency.

[3] See G. Goubau, "Multi-element Monopole Antennas," Proc. ECOM-ARO Workshop on Electrically Small Antennas, Oct 1976, pp 63-67.

[4] Jasik Antenna Engineering Handbook, Chapter 27, pp 27-34 ff.

bandwidth performance. A version of this antenna has been modeled on the computer, and preliminary results are given in a later section of this report. The antenna of Fig. 1a operated in the 300-650 MHz band. Scaling the dimensions by a factor 10 to reach the VHF band produces a not-too-unreasonable antenna design which could be accomplished using the present AS-1729 or AS-2731 antenna as the driven element. This approach could be an effective intermediate solution to the broadband antenna requirements of a fast frequency hopping (FFH) system. However, in its present form, the parasite-loaded dipole is by no means a small antenna.

Other more recent applications of the parasite-loading or "partial-sleeve technique" have appeared in the literature [5], [6], [7]; one version, a sleeve-loaded monopole, is shown in Fig. 1B. While all of these elements are large compared to our 0.1λ, small antenna constraint, the parasite-loading technique should be kept in mind for possible application to the small or low-profile antenna problem.

C. Top-Loaded Antennas

In Part I of this report series, the technique of top-loading an antenna was mentioned primarily as a means of increasing a small antenna's efficiency. Top-loading also tends to increase the instantaneous bandwidth (from the matching standpoint) of the antenna by lowering the antenna reactance and by making the current distribution along the antenna more uniform with frequency. This tends to minimize the antenna's radiation resistance variation with frequency.

Some techniques which have been investigated in the literature [8], [9], [10], both analytically and experimentally, are shown in Figures 2a,b, and c. Other references to top-loading are contained in the selected bibliography

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[5] Wong, J.L., and King, Howard E., "A Cavity-Backed Dipole Antenna with Wide-Bandwidth Characteristics," IEEE Transactions on Antennas and Propagation, pp 725-727, September 1973.

[6] Poggio, A.J., and Mayes, P.E., "Pattern Bandwidth Optimization of the Sleeve Monopole Antenna," IEEE Transactions on Antennas and Propagation, pp 643-645, September 1966.

[7] King, H.E., and Wong, J.L., "An Experimental Study of Balun-Fed Open-Sleeve Dipole in Front of a Metallic Reflector," IEEE Transactions on Antennas and Propagation, pp 201-204, March 1972.

[8] Simpson, Ted L., "The Theory of Top-Loaded Antennas: Integral Equations for the Currents," IEEE Transactions on Antennas and Propagation, Vol. AP-1, No. 2, pp 186-190.

[9] Gangi, A.F., Sensiper, S., and Dunn, G.R., "The Characteristics of Electrically Short Umbrella Top-Loaded Antennas," IEEE Transactions on Antennas and Propagation, Vol. AP-13, No. 6, pp 864-871, Nov 75.

[10] Bhojwani, Hiro R., and Zelby, Leon W., "Spiral Top-Loaded Antenna: Characteristics and Design," IEEE Transactions on Antennas and Propagation, Vol. 21, No. 3, pp 293-298, May 1973.

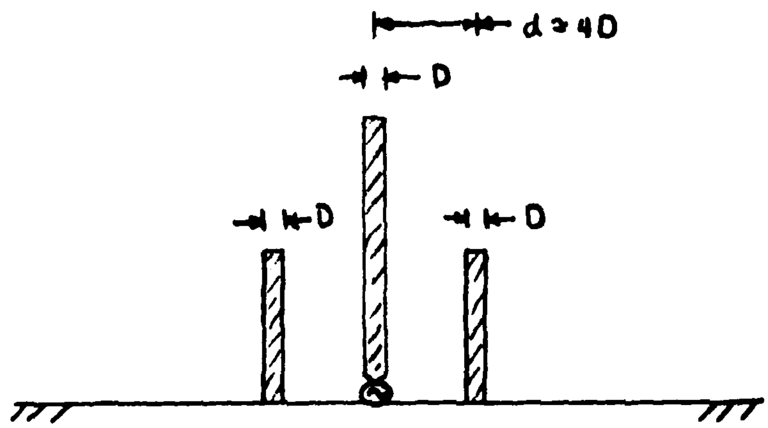

Fig. 1a
Partial-Sleeve or Parasite-Loaded Monopole

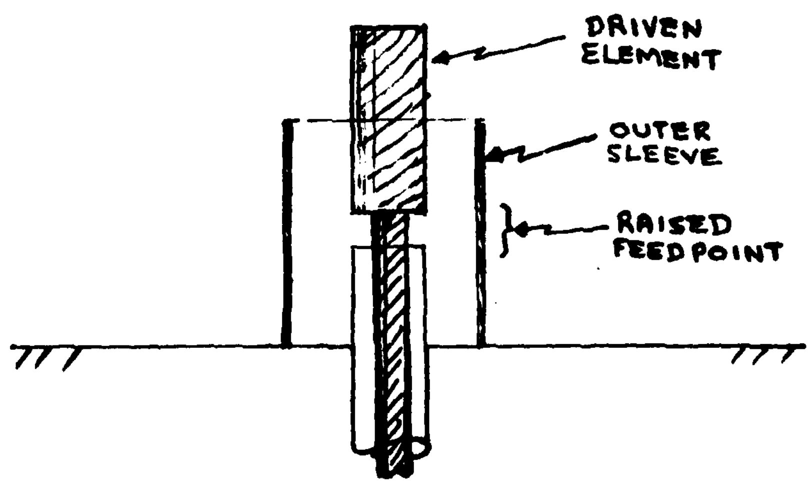

Fig. 1b
Sleeve-Loaded Monopole

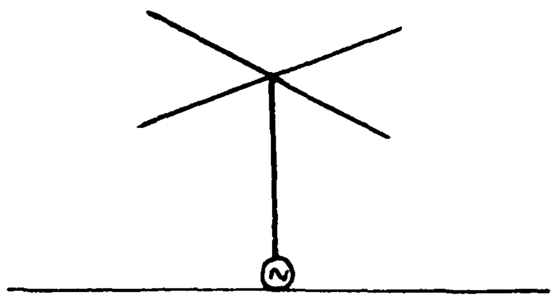

Fig. 2a
Four-Element, Top-Loaded Antenna

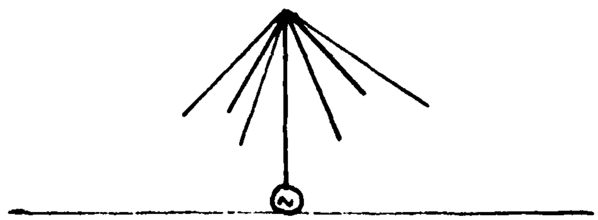

Fig. 2b
Umbrella, Top-Loaded antenna

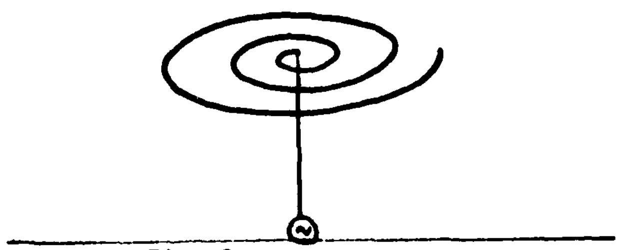

Fig. 2c
Spiral, Top-Loaded Antenna

given in Part 3 of this study. In the cited analytical studies, approximate numerical techniques are employed to solve the integral equations for the currents. The top-loading techniques of Figures 2b and c were originally investigated to improve LF and VLF antennas where, because of the large wavelengths involved, the $\leq 0.1\lambda$ size criterion is easily adhered to. However, these techniques have been applied at higher frequencies to make small or low-profile antennas and so, should be kept in mind as useful techniques for VHF applications. The technique of Fig. 2c, in particular, can be used to achieve resonance in a small structure, a desirable condition for good efficiency.

D. Electrically Thick Antennas

It is well known that increasing the thickness or diameter of a wire antenna tends to lower the Q which is an indication of an improvement in bandwidth. Quantitatively, thickening tends to lower the inductance of the antenna, thereby increasing the stored magnetic energy in the system. Thus, the difference between electric and magnetic energy is minimized. At the same time, the input resistance variation with frequency is minimized, which is an indication that the current distribution on the antenna tends to be more uniform.

The theory of the electrically thick monopole is available in the literature [11], [12]. Numerical methods have also been applied to the solution of the electrically thick antenna problem; in one case, in particular [13], the problem of the optimum shape for maximum bandwidth has been addressed. Fig. 3a shows a resulting broadband configuration which, however, tends to be

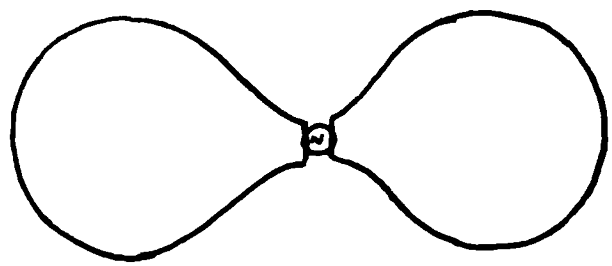

Fig. 3a
Bulb-Dipole Geometry for a Broadband Antenna

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[11] Chang, David C., "On the Electrically Thick Monopole Part I-Theoretical Solution," IEEE Transactions on Antennas and Propagation Vol. AP-16, No. 1, pp 58-64, January 1968.

[12] Chang, David C., "On the Electrically Thick Monopole," Part II, Experimental Study, IEEE Transactions on Antennas and Propagation, Vol. AP-16, No. 1, pp 64-71, January 1968.

[13] Kalafus, Rudolph M., "Broad-Band Dipole Design Using the Method of Moments," IEEE Transactions on Antennas and Propagation, pp 771-773, November 1971.

much larger than the 0.1λ criterion. This, and several other unusually shaped radiators, presented in the literature [14], [15], and depicted in Figs. 3b and c, resemble the biconical antenna and Alford's tapered-horn structure which was described in Part I of this study.

None of these antennas can be classified as small, but are presented here to show the wide variety of shapes possible and, to keep in mind, that increasing the cross-sectional dimensions of the antenna while maintaining a low profile, may be a very useful technique when applied to the problem of small VHF antennas. (Other literature on thick antennas is cited in the bibliography of Part III). The antennas depicted in Fig. 3 are claimed to have bandwidths in excess of 2:1.

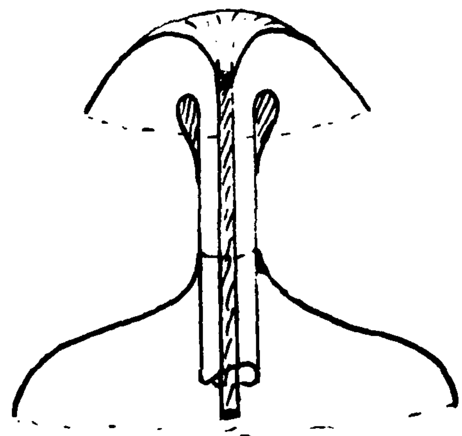

Fig. 3b
Wide-Band Antenna of Unusual Shape (in Cross-Section)

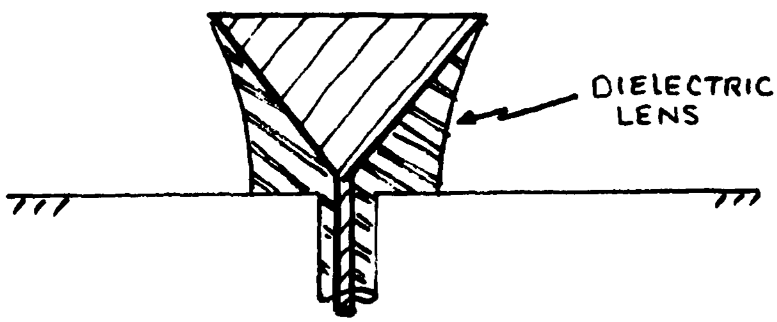

Fig. 3c
Tapered, Dielectric-Lens Antenna

[14] Foldes, P., "Mathematical and Experimental Studies of a Wide-Band Vertically-Polarized Antenna," IRE Transactions on Antennas and Propagation, pp 469-476, September 1960.

[15] Bates, R.H.T., and Burrell, G.A., "Towards Faithful Radio Transmission of Very Wide Bandwidth Signals," IEEE Transactions on Antennas and Propagation, Vol. AP-20, No. 6, pp 684-690, Nov 1972.

E. Folded Antennas

The technique of folding a wire antenna to form a thin wire loop, Fig. 4a, has been investigated extensively. If the antenna is near a resonant length in the desired operating band, the input impedance variation of the antenna is smoothed out, resulting in increased instantaneous bandwidth. In effect, the transmission line impedance arising from transmission line balanced currents which tend to flow in the closely-spaced, parallel wires of the antenna, in addition to the radiating currents, partially compensates the antenna impedance over a band of frequencies. There is also an impedance transformation such that the radiation resistance normally expected from an antenna of a given height, is increased by a factor equal to the square of the number of closely spaced parallel wires.

Based on the literature uncovered, the folding technique seems to be widely used when it is desired to increase the bandwidth of an antenna, even an antenna satisfying the 0.1λ size constraint. The key feature of such antennas seems to be the multiple radiating elements in close proximity to each other (recall section B of this report on parasitic elements). Qualitatively, these multiple, closely-spaced, radiating elements may be approaching a homogeneous antenna of equivalent thickness or cross-sectional dimension although such a relationship has not been clearly demonstrated.

A general theory of folded antennas, based on the separation of the currents existing on the wires into transmission line currents and radiating currents, was developed by Harrison and King [16]. They treated various forms of the folded antenna, including folded elements with loading coils within or at the ends of the antenna, and folded loop antennas. In an earlier paper [17], the same authors dealt witn tne theory of coupled, folded antennas.

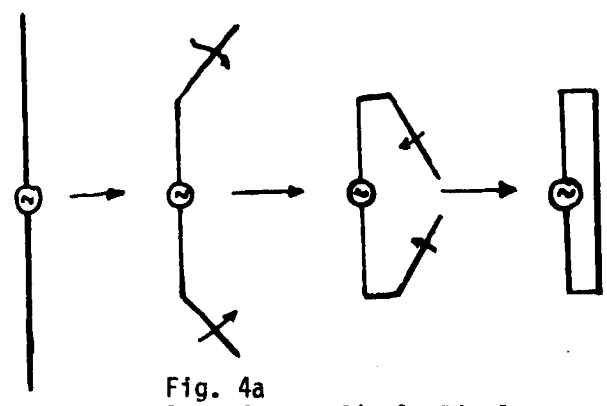

Fig. 4a
A Folded Dipole Evolved from a Simple Dipole

[16] Harrison, Jr., C.W., and King, R.W., "Folded Dipoles and Loops," IRE Transactions on Antennas and Propagation, pp 171-187, March 1961.

[17] Harrison, Jr., C.W., and King, Ronold, "Theory of Coupled Folded Antennas," IRE Transactions on Antennas and Propagation, pp 131-135, March 1960.

Two other papers [18], [19], deal with changes in the electrical characteristics caused by varying the physical parameters of the folded antenna, such as element length, diameter, and spacing. It is interesting to note that one of the articles [18] discusses the use of the folding principle for small antennas, notes the importance of designing some of the tuning and matching network elements into the radiating structure, and uses the shunt input L-network, discussed in Part I of this study, to achieve better bandwidth characteristics.

The other paper [19] discusses the bandwidth possibilities of the folded dipole and lists some general conclusions regarding parameter variations; i.e., increased spacing between the conductors and increased conductor size improve the bandwidth, in general. Note, however, that only λ/4 element lengths were considered in this paper.

Several techniques and principles of the type just discussed have been incorporated into actual antennas. Fig. 4b [20] shows the use of a folded adjustable-length antenna to maintain a constant input resistance and a simple compensating network to maintain resonance. While the bandwidth is secured through a mechanical tuning arrangement, the important point to note is that the antenna height needed to maintain a 50Ω input resistance is ∿0.1λ, our small or low profile antenna criterion. Thus, it may be possible to match this antenna over a broader instantaneous bandwidth if some means of electrically maintaining the electrical height with frequency can be found.

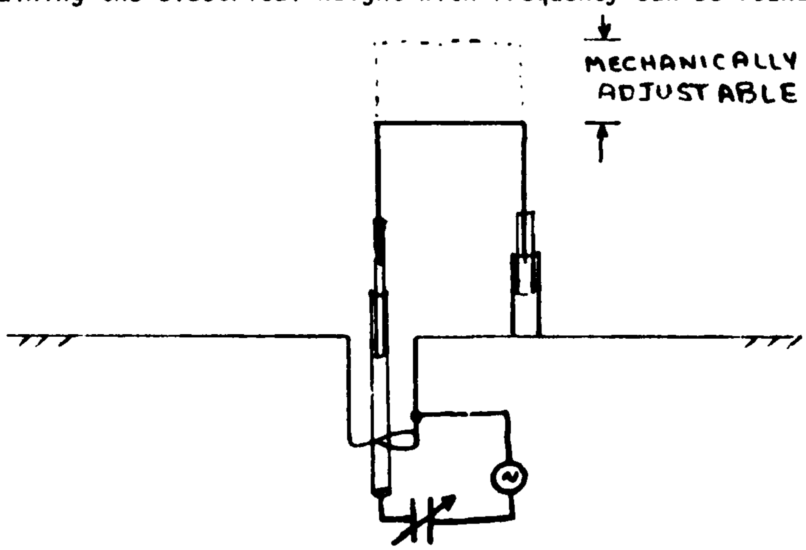

Fig. 4b
Adjustable Length Folded Monopole

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[18] Leonhard, J., Mattuck, R.D., and Pote, A.J., "Folded Unipole Antennas," IRE Transactions on Antennas & Propagation, pp 111-116, July 55.

[19] German, J.P., and Brooks, Jr., F.E., "The Effects of the Physical Parameters on the Bandwidth of a Folded Dipole," IRE Transactions on Antennas and Propagation, pp 186-190, April 1958.

[20] Giddis, A.R., "A Technique for Matching an Adjustable Folded Monopole Over a 15:1 Frequency Band," IEEE Transactions on Antennas and Propagation, pp 370-371, May 1964.

Seely [21] has investigated the top-loaded folded monopole, see Fig. 4c, of height ~0.1λ and has found that a broadband antenna ~1.24:1 band for VSWR ≤ 3:1) can be achieved. He also found that the spacing between elements affects the resonant frequency of the antenna while the diameter ratio affects the radiation resistance. Disc loading apparently provides some of the instantaneous length compensation mentioned in the previous paragraph. This disc-loading configuration is considered to be essential in achieving a small or low-profile antenna with broadband characteristics.

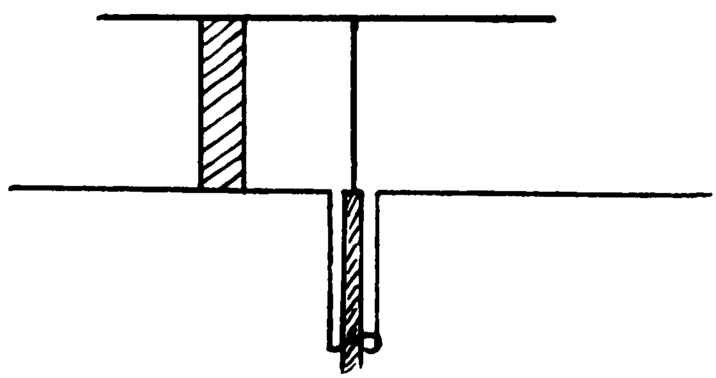

Fig. 4c
Top-Loaded, Folded Monopole

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[21] Seeley, E.W., "An Experimental Study of the Disc-Loaded Folded Monopole," IRE Transactions on Antennas and Propagation, pp 27-28, January 1956.

Fig. 4d [22] shows still another technique for broadbanding a small antenna (∿0.1λ dimensions). The effects of positive and negative mutual coupling (using transformers) is claimed to have beneficial effects on the bandwidth. Unfortunately, the cited article is not sufficiently detailed to draw quantitative conclusions, but there is experimental evidence (to be discussed in a later section) to support the statements about mutual coupling effects on bandwidth.

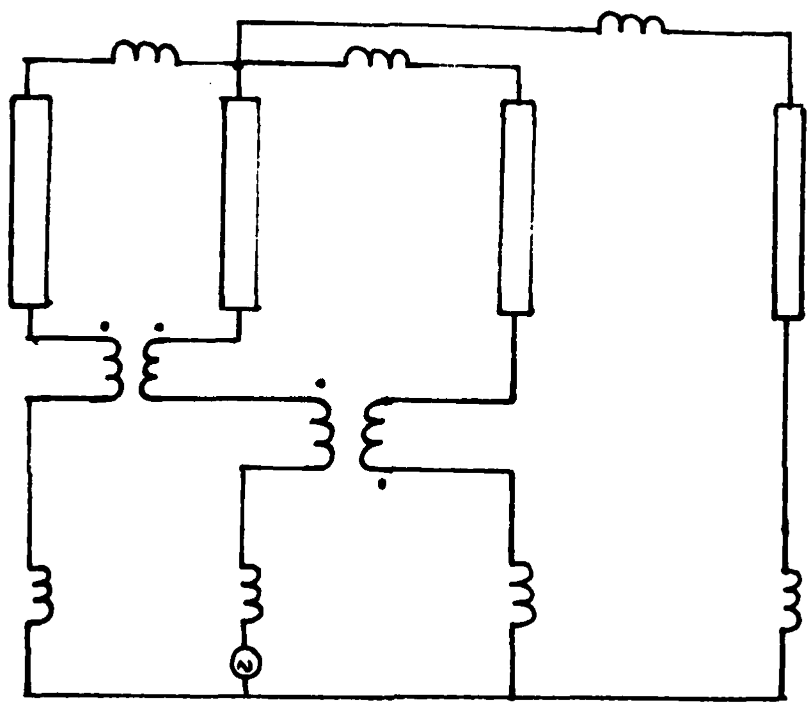

Fig. 4d
Multiple, Folded Antenna with Mutual Coupling

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[22] Vallese, L.M., "A Broad-Banded Folded Monopole Antenna," IEEE Transactions on Antennas and Propagation, pp 92-94, January 1972.

An antenna structure called the slotted-cone antenna [23], reported in the literature, is low profile $\gtrsim .125\lambda$ high) and, apparently, has extremely broad bandwidth (>3:1). The unusual structure is shown in Fig. 4e. The principles behind this structure should be more fully studied since they seem to hold a key to broadband, small antenna design.

The final folding technique to be considered in this section is shown in Fig. 4f and comes from a paper by R.C. Fenwick [24]. This approach exploits the low-profile concept, i.e., small height but large cross-section. This technique is characterized by a top-load structure which is more than a simple disc. In one form, a spiral top-load is used which improves the bandwidth of the antenna. This complex top-load configuration seems also to be useful broadbanding technique; apparently, it is a way to incorporate tuning and matching elements with distributed electrical properties into the antenna structure.

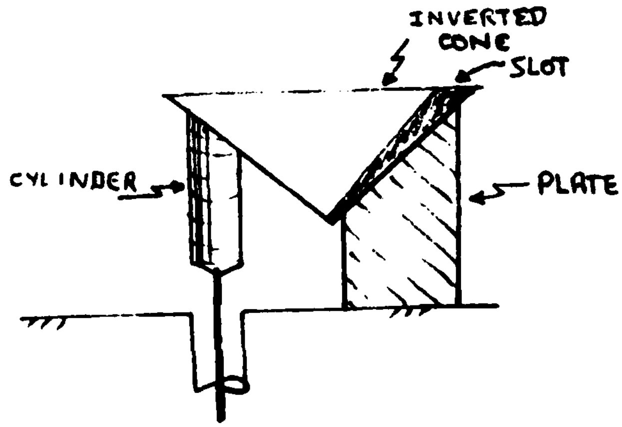

Fig. 4e
Broadband Slotted-Cone Antenna

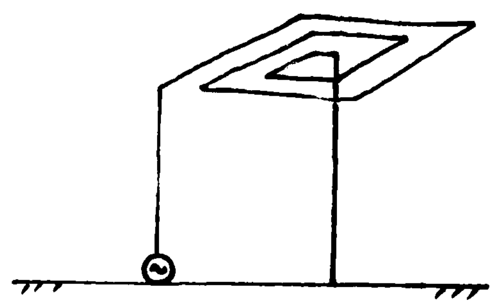

Fig. 4f
Spiral, Top-Loaded, Folded Antenna

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[23] Wanselow, R.D., and Milligan, D.W., "Broadband Slotted-Cone Antenna," IEEE Transactions on Antennas and Propagation, Vol. AP-14 No. 2, pp. 179-182, March 1966.

[24] Fenwick, R.C., "A New Class of Electrically Small Antennas," IEEE Transactions on Antennas and Propagation, pp 379-383, May 1965.

F. Conjugate Reactance Loading

If a reactance function could be realized which compensated the impedance of an antenna over a broadband, and did it without loss, then the shape and size of the antenna would be irrelevant. On the other hand, it may be possible to shape the antenna so that a realizable network can compensate for the antenna's impedance variation. Techniques for conjugate matching have appeared in the literature. Distributed-capacitive loading [25] (see Fig. 5a) and inductive (negative unrealizable in a passive element) loading [26] have been considered; in the former case, a $\lambda/2$ dipole (at lowest frequency of interest) was considered and experimental results yielded a 3:1 bandwidth in one model! Perhaps, this distributed loading technique can be extended to low-profile antennas whose cross-section is allowed to gradually increase, e.g., a distributed-capacity loaded, inverted-conical antenna. (A further discussion of the technique appears in Section 2G of this report.)

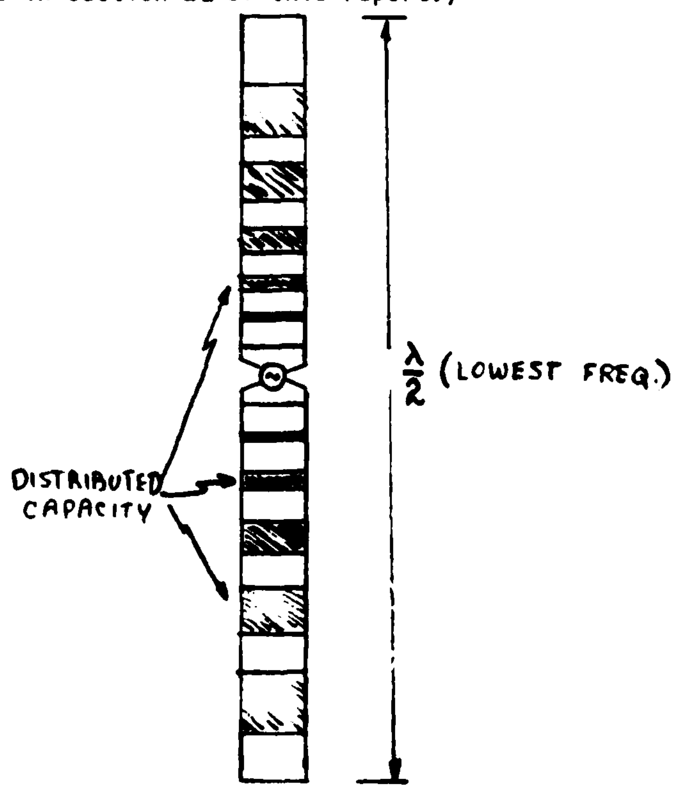

Fig. 5a
Hallen´ Antenna

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[25] Rao, B.L.J., Ferris, Joseph E., and Zimmerman, Wiley E., "Broadband Characteristics of Cylindrical Antennas with Exponentially Tapered Capacitive Loading," IEEE Transactions on Antennas and Propagation, pp 145-151, Vol. AP-17, No. 2, March 1969.

[26] Poggio, A.J., "Bandwidth Extension for Dipole Antennas by Conjugate Reactance Loading," IEEE Transactions on Antennas and Propagation, pp 544-547, July 1971.

A very recent article [27] investigates a form of conjugate matching by using two closely spaced antennas (see Fig. 5b) coupled by their mutual fields and hybrid networks. The antennas are designed so that one is above and the other below resonance in such a way that the impedances over the desired frequency band compensate each other through a hybrid coupler. The technique is interesting for small antennas since the individual elements can be made very small while maintaining resonance and the elements are closely spaced.

G. Unusual Designs

While many of the antenna designs and techniques already discussed could fit into the category of unusual, there are several techniques useful for small broadband antennas which are not easily classified under any one of the previous headings, i.e., the antenna design may be comprised of several of the previous techniques.

The first of these, called the monopole-slot antenna [28] shown in Fig.6a, combines a short monopole (electric dipole) with its dual or reciprocal radiator, the slot (magnetic dipole), on the same feedline. It is shown that a small broadband antenna results (>3:1). However, the efficiency is low and the size of the cavity (under the ground plane), in particular the depth, must be of the order of 0.25λ or greater at the geometric mean frequency of the desired

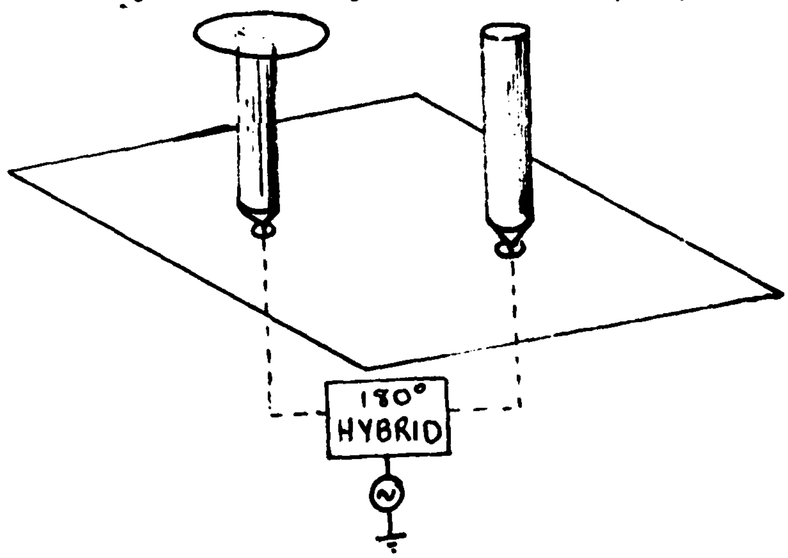

Fig. 5b
Complementary-Pair Monopole Antenna

[27] Schroader, Klaus G., and Soo Hoo, Keith M., "Electrically Small Complementary Pair (ESCP) with Interelement Coupling," IEEE Transactions on Antennas and Propagation, Vol. AP-24, No. 4, pp 411-418, July 1976.

[28] Mayes, Paul E., Warren, W.T., and Wiesenmeyer, F.M., "The Monopole Slot: A Small Broad-Band Unidirectional Antenna," IEEE Transactions on Antennas and Propagation, pp 489-493, July 1972.

band for best bandwidth. It is also shown that this depth can be decreased by varying some other parameter in the system in order to maintain the complementary impedance features. The monopole could be replaced, conceivably, by one of the antenna structures being examined in this report; in combination with a shallow-cavity-backed slot, an optimum bandwidth and efficiency might be achieved. Such combinations deserve further investigation.

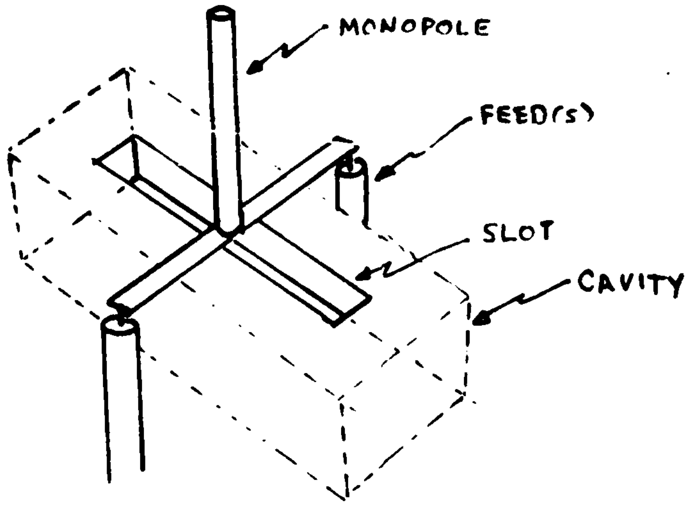

Fig. 6a
Monopole-Slot Antenna

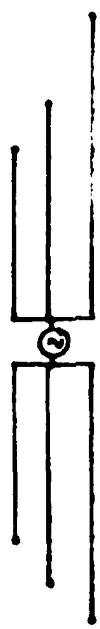

Fig. 6b
Multi-Element Dipole Antenna

The final technique to be considered is the multi-element dipole antenna [29] shown in Fig. 6b. Several closely spaced elements of different lengths driven by the same generator are shown to produce an antenna with a broadband input impedance characteristic. The multi-element feature has appeared in our previous reviews, but here all of the elements are driven. The lengths of the elements are such that they resonate somewhere in the desired band; using the coupling between these resonant antennas, a change in bandwidth can be affected. It is expected that the elements can be loaded to shorten their overall length, thus fitting into the 0.1λ criterion; and perhaps this combination of loaded, driven elements at different resonant frequencies, closely spaced to take advantage of mutual coupling effects could lead to a broadband antenna of small size. It should also be determined whether this multi-element technique is or is not equivalent to a thick antenna of comparable dimensions.

3. EXPERIMENTAL RESULTS

The folded-antenna configuration appears to have potentially broadband characteristics. We have seen in the previous sections of this report that theory and experiments support this observation. In the following sections, we will present some experimental data to further strengthen this support. While much of the information to be presented is not new, it will be informative to review it from the standpoint of antenna bandwidth.

A. Stubs and Loops

We will start with measurements of:

(1) A small stub;

(2) a small loop (folded antenna);

(3) a stub with a top-load; and,

(4) a folded, top-loaded antenna.

Measurements of the input impedance of these different types of antennas over the 200-400 MHz frequency range are shown in Fig. 7. These measurements were made with a swept frequency network analyser. The antennas were mounted on a four-foot square metal ground plane and the measured impedances were referenced to the base of the antenna just under the ground plane. Errors introduced by the measurement system were estimated by making a swept-frequency impedance measurement of a short circuit placed at the point where the antenna would ordinarily be connected. A perfect measurement would result in a single dot occurring at the 0 impedance point on the Smith Chart. The measured short circuit impedance over the 200-400 MHz range is shown in Fig. 7 as the curve marked (5). It can be seen that there were residual errors in the system, but the magnitude of these errors was considered small enough for our intended purpose, i.e., to predict bandwidth trends. Further compensation of the measurement system would be necessary to obtain more accurate impedance data.

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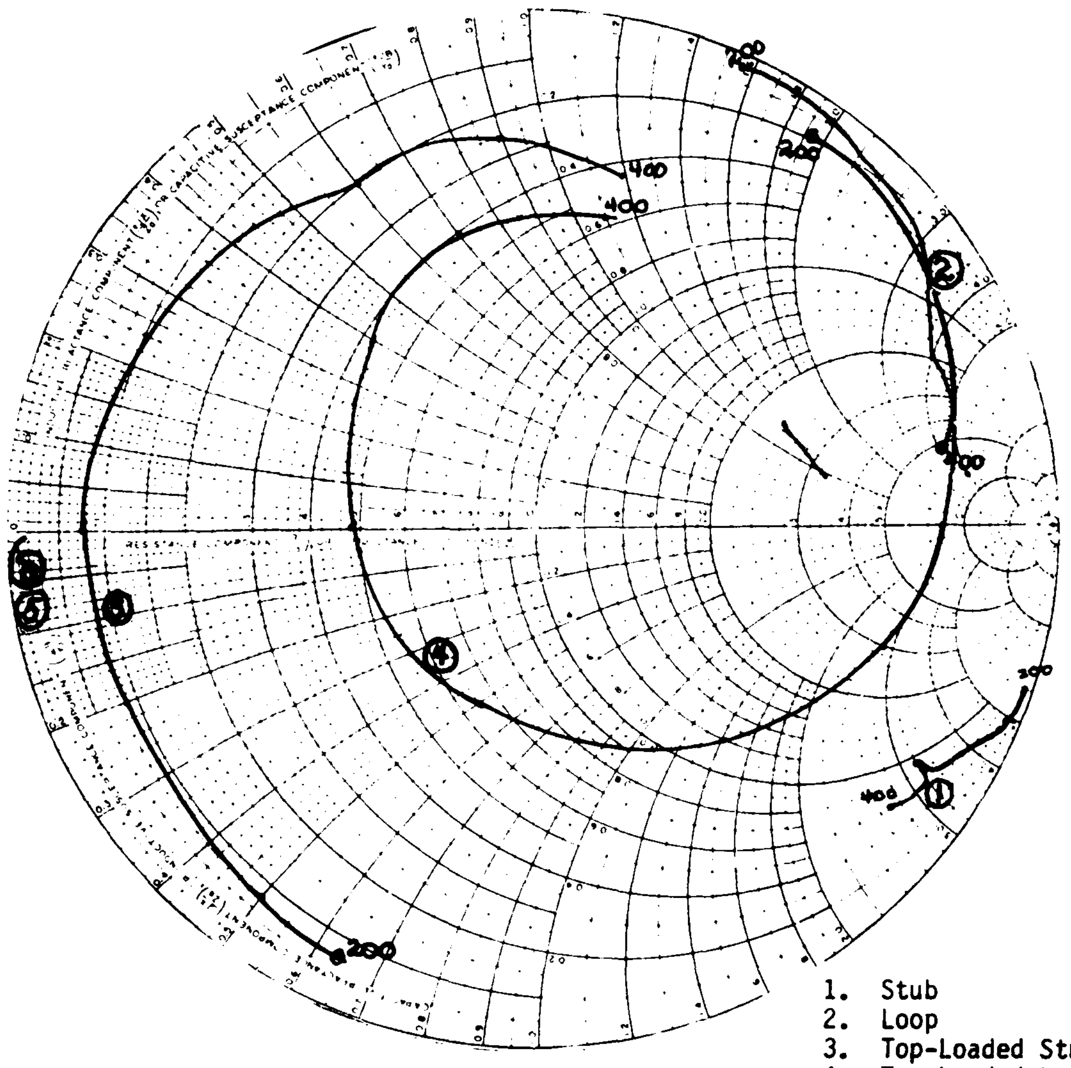
[29] Chowdhury, S.K., "Impedance of Multi-element Dipoles," IEEE Transactions on Antennas and Propagation, pp 682-684, September 1971.



1. Stub
2. Loop
3. Top-Loaded Stub
4. Top-Loaded Loop
5. Short-Ckt Trace

Fig. 7
Impedance Variations of Several Types of Small Antennas

Curve (1) of Fig. 7 shows the impedance variation of a 5.2 cm high, 0.635 cm diameter stub antenna over the 200-400 MHz range. As was expected, the real part or resistance of this antenna was small (<5 ohms), while the reactive part was large and capacitive. Historically, such an impedance has proven to be impossible to match on a broadband basis.

Curve (2) of Fig. 7 is the impedance variation of a loop antenna 5.2 cm high; the vertical elements of the loop were 0.635 cm in diameter and were spaced apart by 3.2 cm. The connection at the top of these elements was made with a 1.2 cm wide, 10 mil. thick strip of copper. One of the elements was driven; the other was grounded to the ground plane. Again,as expected, the real part of the impedance was very small; smaller, in fact, than the stub of the same height; the reactance of this loop remained inductive but varied over a wider range than the reactance variation of the stub. In general, this impedance variation would be impossible to compensate over a broadband using non-varying circuit elements.

Curve (3) of Fig. 7 shows the 5 cm high stub with a 14 x 14 cm copperplate as a capacitive top load. Several features of this curve are notable: 1) a resonance occurs in the structure at mid-band; 2) the resistance of the top-loaded stub has not changed very much from that of the simple stub; and 3) the reactance value and variation has been reduced from that of the plain stub. Although curve (3) appears to have a greater variation, it occurs on the section of the Smith chart where the reactance varies more slowly.

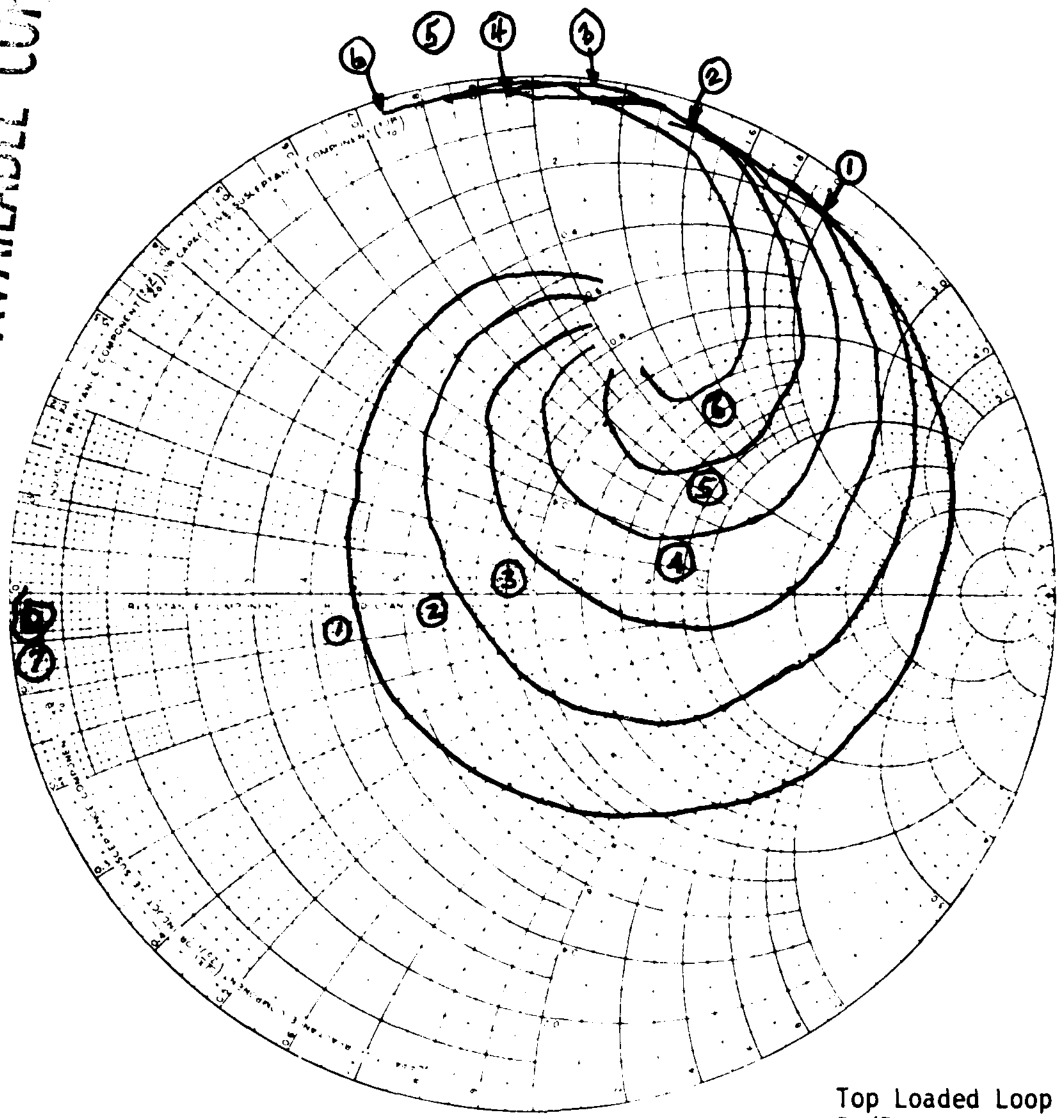
If we use the reactance variation as an indication of the potential bandwidth, i.e., large reactance variation → small bandwidth, small reactance variation → large bandwidth, then the top-loaded stub has a greater instantaneous bandwidth than the plain stub. The bandwidth criterion just established is justified on the basis that matching with fixed value circuit elements can be accomplished over a band of frequencies when the reactive component of the impedance is a slowly varying function.

Curve (4) shows the impedance variation of a top-loaded, folded-monopole antenna. It is a combination of the loop discussed previously and the 14 cm square copperplate. There are several interesting features in this curve: 1) two resonant points occurred; 2) at the higher frequencies, above 300 MHz, the real part increased substantially; and 3) the reactance variation in the 300-400 MHz was markedly reduced. Based on the bandwidth criterion discussed above, the top-loaded loop has a higher instantaneous bandwidth than the simple loop.

A comparison of the bandwidth capabilities of the top-loaded stub and the top-loaded loop indicates that the top-loaded loop has a higher instantaneous bandwidth than the top-loaded stub at frequencies above 300 MHz. Below this frequency, the stub may have a slight advantage. The height of these small antennas at 300 MHz is $1/20\lambda$, half of our small antenna criterion. Thus, an increase in height of either antenna would improve the bandwidth. However, it appears that the configuration of a loop with a top-load is a basic step in the direction of a small antenna with a wide instantaneous bandwidth.

B. Top-Loaded Loop Antenna

One other interesting feature of curve (4) in Fig. 7 is the transformation of the real part of the impedance to higher values than those of the simple loop. In order to investigate this effect, a series of impedance measurements were made using the top-loaded loop where the diameter of the grounded vertical element could be changed. The results are shown in Fig. 8. The ratio of grounded to ungrounded element diameter was changed from 1:1 to 6:1 in six integral steps. The resulting curves are numbered (1) to (6) in Fig. 8; curve (1) corresponds to the 1:1 ratio. The short-circuit measurement, curve (7), was also plotted as an indication of the measurement error. The low frequency end of each curve is marked with an arrow for clarity. It is apparent from



Top Loaded Loop
D_1/D_2 =

1. 1:1
2. 2:1
3. 3:1
4. 4:1
5. 5:1
6. 6:1
7. Short Ckt. Trace

Fig. 8
Effect of Varying Diameter Ratio of Vertical Elements
in a Folded, Top-Loaded Antenna

the variations that an impedance transformation occurs, but it does not seem to be the N^2:1 transformation which occurs in the half-wave, folded-dipole antenna configuration (see Ref. 30). In fact, at the band edges, 200 and 400 MHz, the transformation is less than a 1:1 transformation.

At 200 MHz, the resistance varies inversely with diameter ratio. It appears, therefore, that the variation of the diameter in such a small structure has a small transformation effect on the antenna input impedance and the major effect of increasing the diameter is a reduction in the inductance of the antenna.

However, it can be seen that a substantial transformation has occurred when a comparison between the simple loop impedance, curve (2) of Fig. 7, and the top-loaded loop, curve (4) of Fig. 7 is made. At the low frequency end, the transformation is about 2:1. At 400 MHz, there is ∿10:1 transformation for the real part of the impedance. The changes in the imaginary part of the impedance follow different transformation ratios.

C. The Goubau Antenna[31]

The Goubau antenna is a low-profile antenna (height <0.1λ at the highest operating frequency) which possesses both broad bandwidth and high efficiency. A 450-900 MHz version of the antenna is shown in Fig. 9, a side view. A schematic view is shown in Fig. 10. All measurements were made with the antenna mounted on a 4' x 4' ground plane. Radiation pattern measurements at 500 MHz and 900 MHz presented in Figs. 11 and 12 are essentially omnidirectional in the azimuthal plane. Measurements at intermediate frequencies were similar. These patterns indicate the "small antenna" character of this broadband antenna. Elevation plane patterns were not made, but are expected to be those of a monopole above a ground plane. Preliminary efficiency measurements of the Goubau antenna were made in the 400-900 MHz range by comparing the field strength produced by the antenna to that produced by a resonant λ/4 monopole transmitting the same power. These measurements were made in an anechoic chamber, and λ/4 monopoles were made for each frequency measured. The results, shown in Fig. 13, indicate that the Goubau antenna has high efficiency over its entire operating frequency range. These results, should only be viewed as preliminary since there was a 1 to 2 dB ambiguity in the input power measurements. However, even with an additive correction of this magnitude to the input power of the Goubau antenna, the efficiency results are impressive. A measurement of the input impedance of the Goubau antenna was made using the swept frequency network analyzer and these results are shown in Fig. 14. The frequency range was ∿400-1000 MHz. As can be seen, the bandwidth determined using a 3:1 VSWR limit extends from about 470 MHz to slightly over 940 MHz. All of these results are very impressive for an antenna whose overall dimensions are 3.5 cm high by 12.5 cm in diameter!

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[30] Mushiake, Uasuto, "An Exact Step-Up Impedance Ration Chart of a Folded Antenna," IRE Trans. AP, p 163, Oct 1953.

[31] G. Goubau, "Multi-Element Monopole Antennas," Proc. ECOM-ARO Workshop on Electrically Small Antennas, Oct 1976, pp 63-67

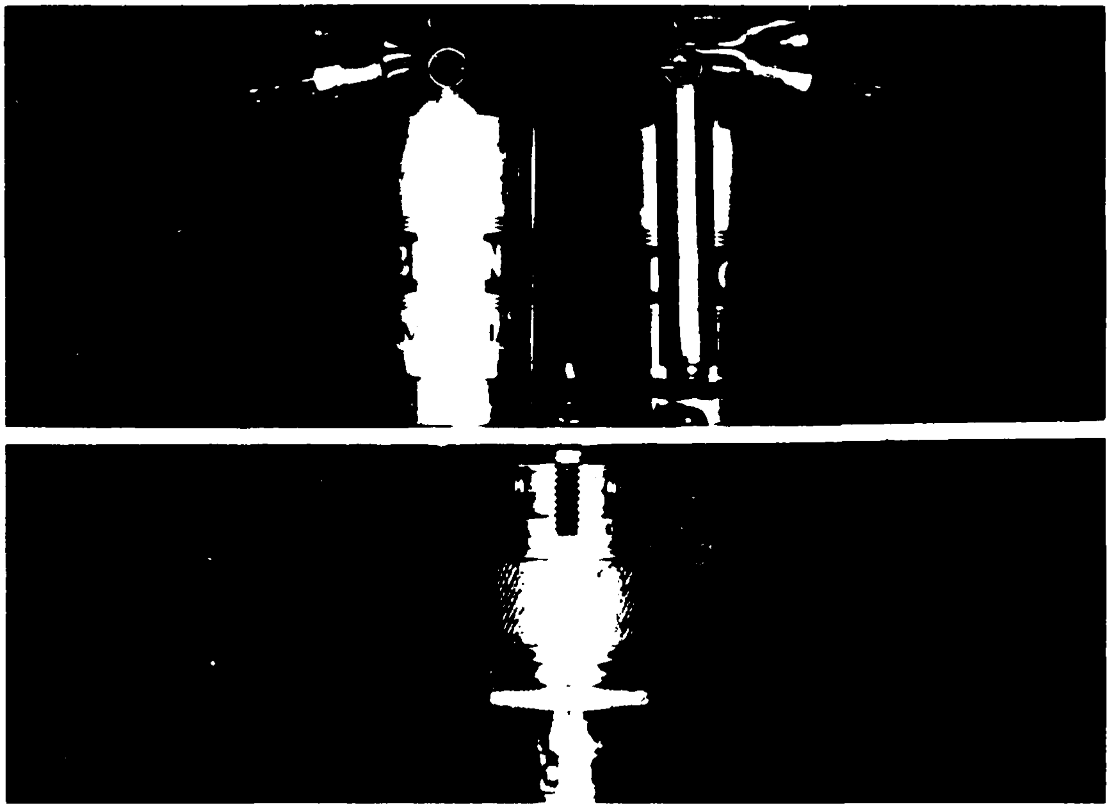

Fig. 9
Goubau Antenna - Side View

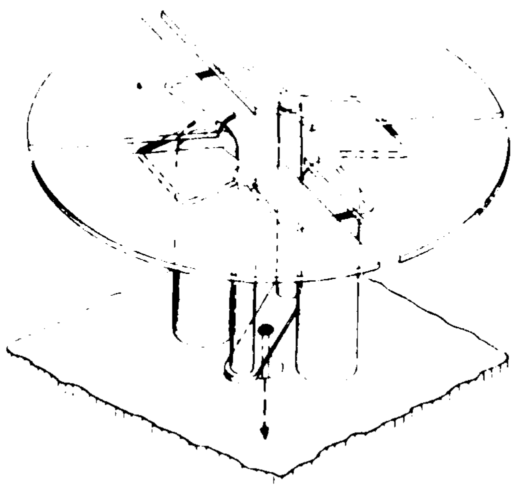

Fig. 10
Goubau Antenna - Schematic

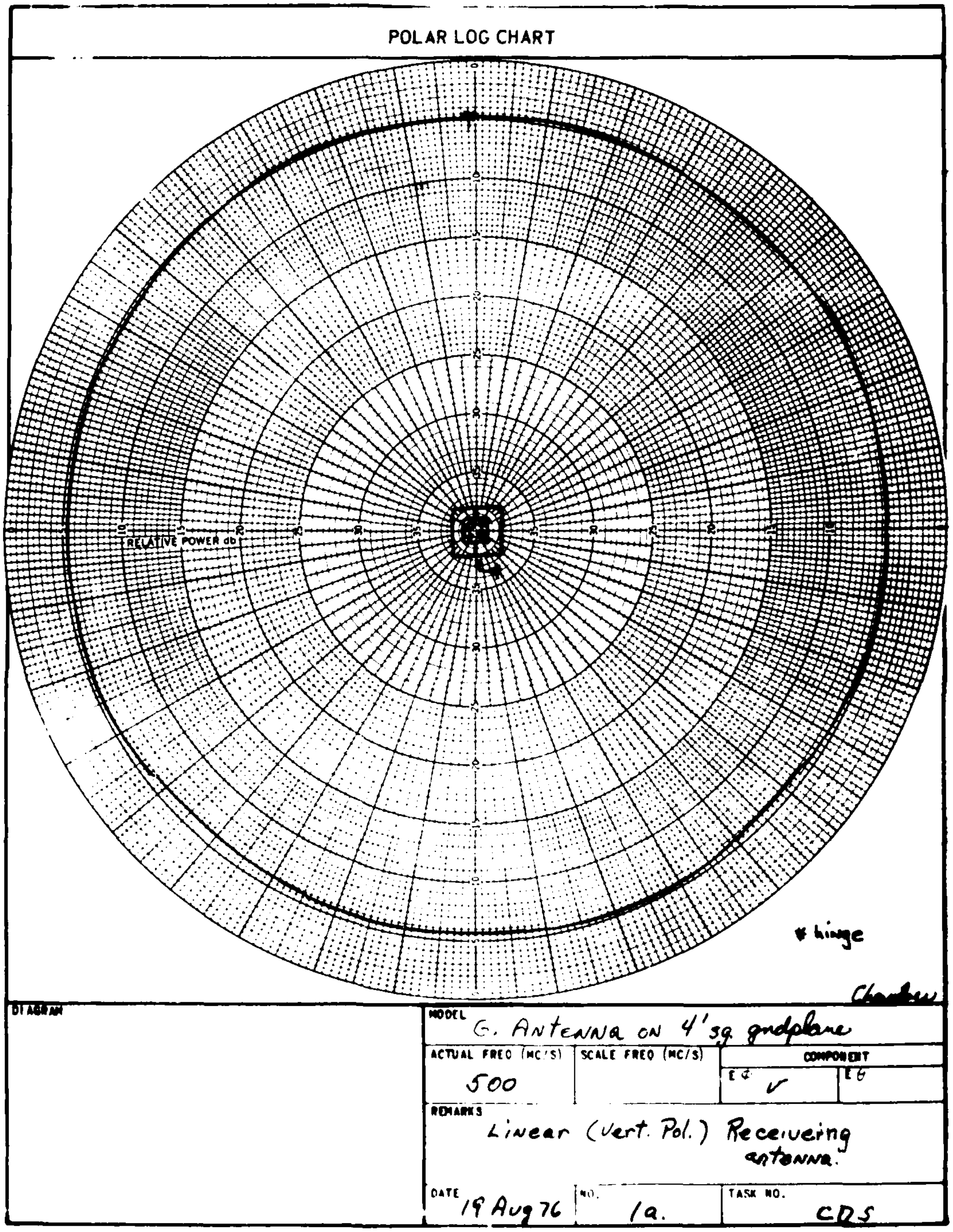

Fig. 11
Radiation Pattern - Azimuth Plane - 500 MHz

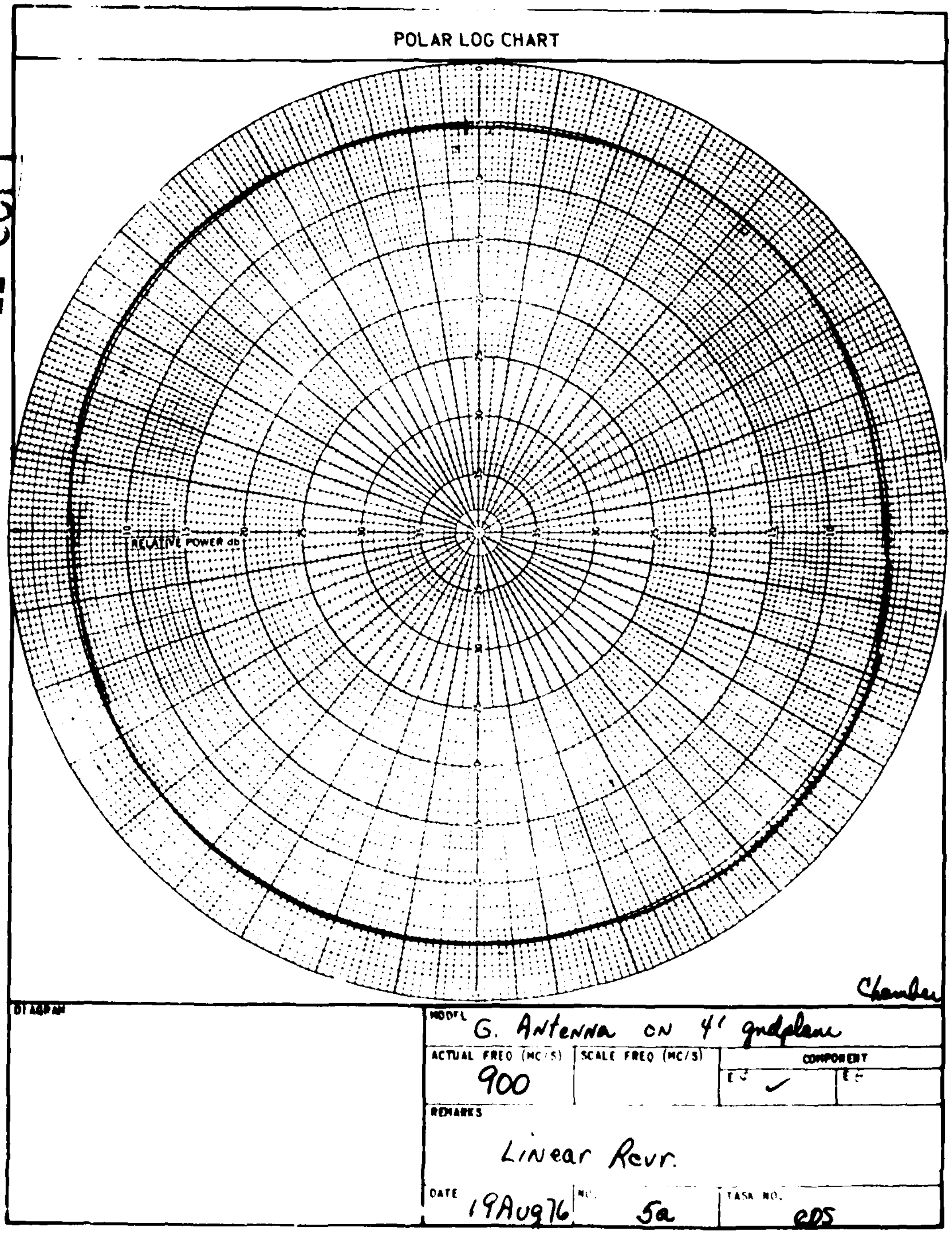

Fig. 12
Radiation Pattern - Azimuth Plane - 900 MHz

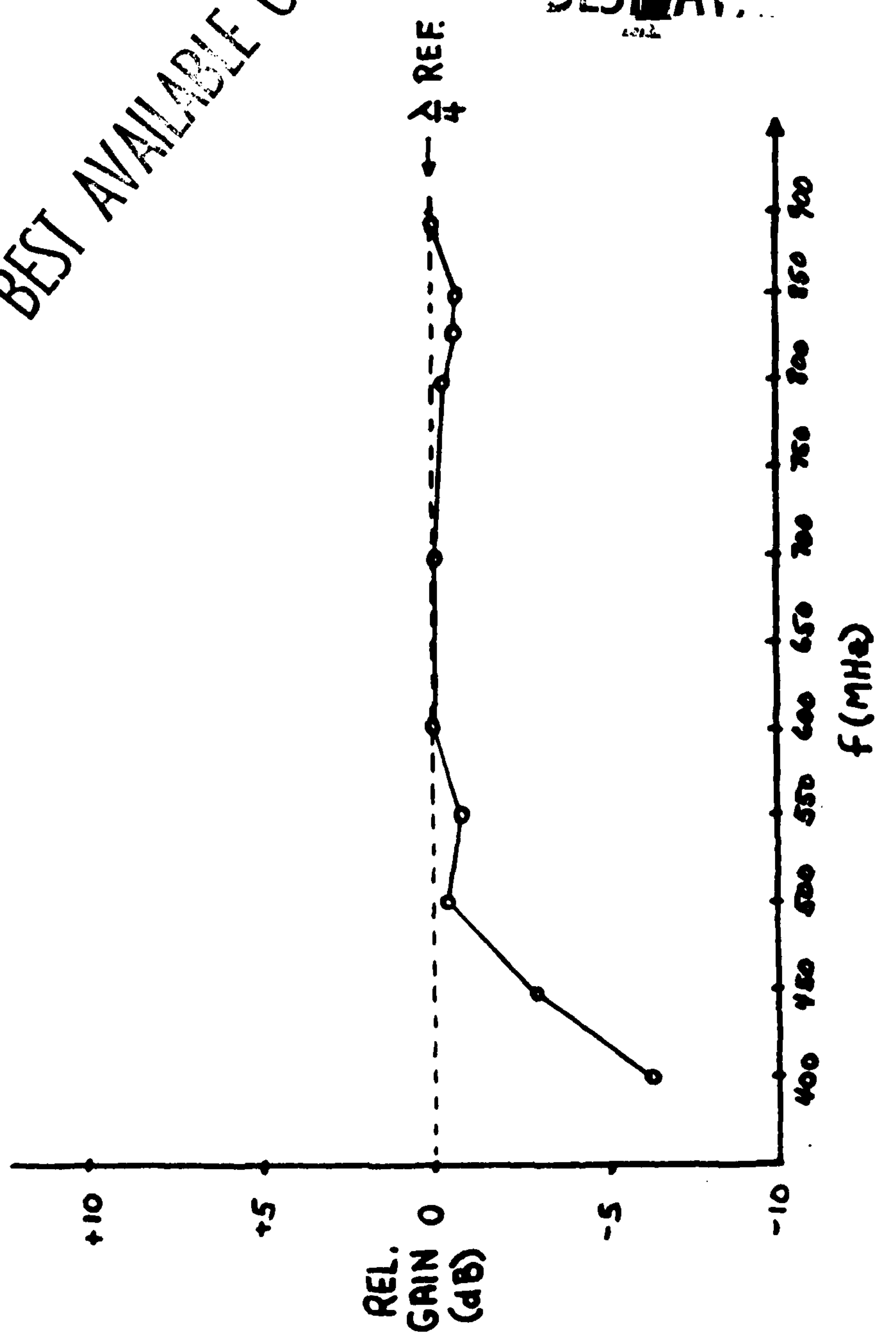

Fig. 13
Relative Gain - Goubau Antenna vs. λ/4 Monopole

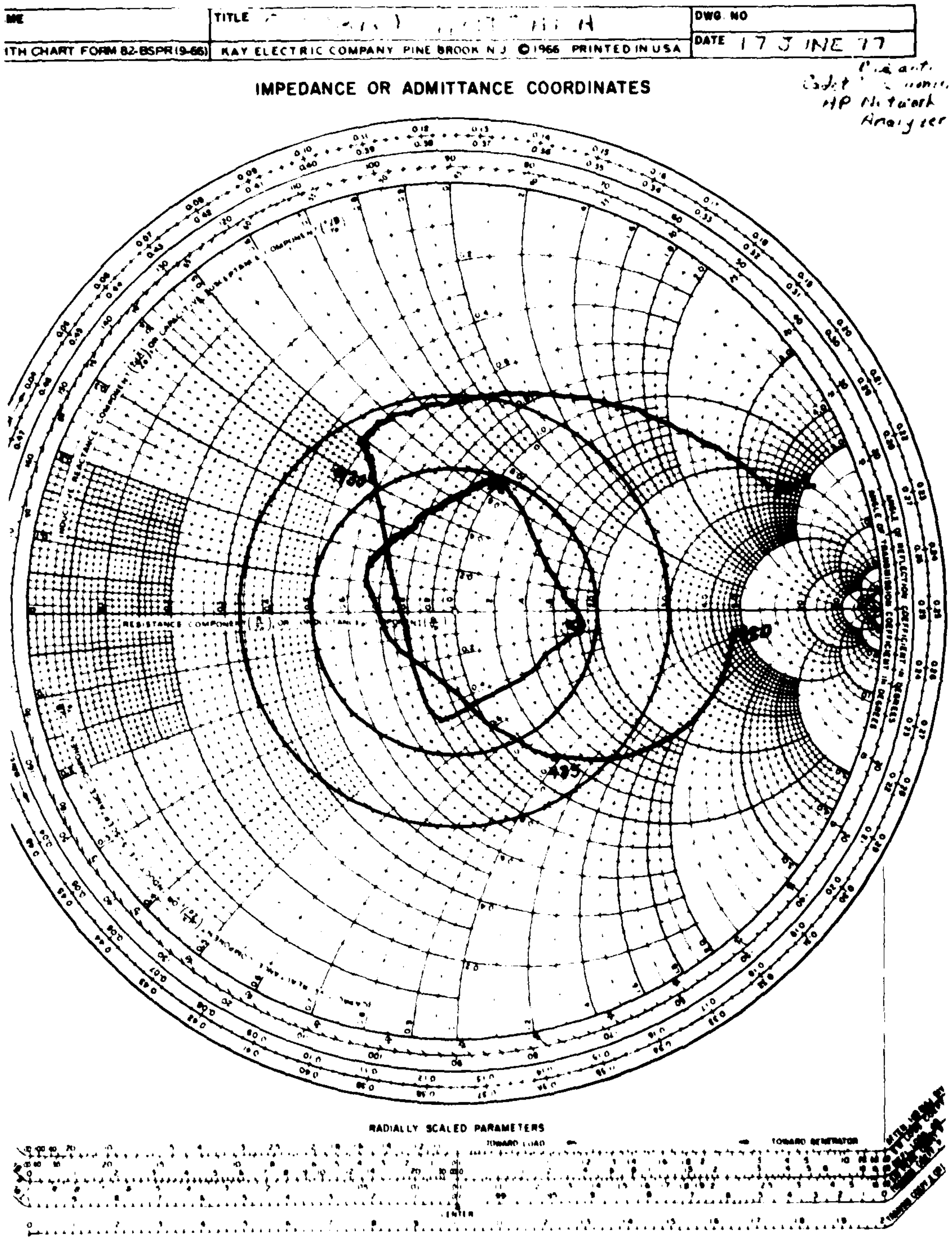

Fig. 14
Input Impedance of Goubau Antenna

Several observations were made as a result of experiments with the Goubau antenna, in which the input impedance with frequency was monitored:

(1) For the configuration of Figs. 9 and 10, the diameter of the top plate determined the lower frequency limit;

(2) The configuration of the driven elements in the antenna of Fig. 9 seemed to have a greater affect on the impedance at the lower frequencies, while the grounded element configuration affected the higher frequencies[32].

(3) Because the effective length of the conductors, i.e., vertical elements plus top load, is near $\lambda/4$ at the mid-frequencies, there is an impedance transformation occurring in accordance with an N^2:1 rule, where N is the number of vertical elements.

Experimental and theoretical investigation of the Goubau antenna is continuing. The primary aims are to understand the operation of the antenna, and to find means of reducing the top-load size without sacrificing the bandwidth and efficiency characteristics. One approach is to replace the vertical elements with coils to increase the inductance and thereby reduce the capacitance needed for the lower frequencies. Early experiments showed that this approach was feasible but that the input impedance at the higher frequencies was degraded. Experiments using this approach are continuing.

D. <u>Hallen´ Antenna</u>

Figure 5a showed a linear cylindrical monopole loaded with series capacitive elements at selected intervals along the length of the antenna. This idea was mentioned in Section 2f of this report. A brief internal memo by J. Rao (University of Michigan), 1967, described an experimental version of the antenna in which the element spacing was fixed and the capacitance varied according to an exponential taper. The antenna exhibited broadband characteristics (>8:1), stable dipole patterns and, apparently, good efficiency. The antenna operated over a 1-8 GHz range, but was electrically large ($\ell \gtrsim \lambda/2$ at the lowest frequency).

Popovic, et. al.,[33] describes a resistive-and capacitive-loaded antenna of the Hallen´type which exhibited an octave bandwidth and a claimed efficiency $\gtrsim$80%. The antenna length was $\simeq\lambda/2$ at the lowest frequency, 1 GHz.

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[32] Note, however, that the effective inductance of these vertical elements and the distribution of that inductance is also very important. In one experiment where the drive element consisted of an air core inductor, the grounded elements had very little effect on the impedance at any frequency.

[33] B.D. Popovic, M.B. Dragovic, & D.J. S. Paunovic, "Broadband Cylindrical Antenna with Continuous Resistive and Concentrated Capacitive Loadings," Electronics Letters, Vol. II, No. 25/26, 11 Dec 75, pp 611-613.

This writer has constructed a version of the antenna with fixed intervals and a capacitive variation which followed an exponential distribution. Only the impedance of this antenna was measured. The measured bandwidth, with a VSWR $\lesssim$3:1 extended from 1 to 2 GHz. The impedance at frequencies above 2 GHz was not measured but the antenna appeared to have much broader bandwidth characteristics. The radiation efficiency was not measured but seemed to be high, based on the antenna's sensitivity to objects placed near it. One version of the antenna was $\sim$15 cm in height. A second version was 5 cm in height with a 12 cm square metal top-load. The latter antenna was only $\lambda/6$ high and still exhibited broadband characteristics.

This data is only preliminary and the findings are offered here only as an independent verification that an antenna with this distributed capacitive loading does have broadband electrical characteristics. A separate report of this work will be prepared at a later date. However, this technique of loading may be useful even in an electrically small antenna and should be seriously considered.

4. NUMERICAL MODELING OF TOP-LOADED ANTENNAS

A. Top-Loaded Stub and Loop Antennas

Several small antenna configurations were modeled on the computer. The impedance variations with frequency for the top-loaded stub and top-loaded loop were calculated by modeling the structures with thin wire segments and using a moment method solution[34]. The wire models used for the problem are shown in Fig. 15a and b. The top load consisted of a pair of crossed wires. The impedance results are given in Table I. Using these impedances, an analysis of the bandwidth of these antennas when tuned and matched with a two-element L-network was made. These results are shown in Figs. 16 and 17 for the top-loaded stub, and Figs. 18 and 19 for the top-loaded loop. The curves give the required variations for the network elements in order to tune and match the antenna to within a 3:1 VSWR at all frequencies. In each figure, the immittance of a realizable element is also shown in order to estimate the instantaneous bandwidth of the system. This analysis follows closely the procedure described in detail in Part I of this report series.[35] Only the parallel-input, L-network is shown for the stub and the loop antennas since it yields the greater bandwidth as was shown previously[35]. Recall that the element nearest the antenna determines the achievable bandwidth.

An estimate of the bandwidth can be made by assuming that the first matching element is lossless and possesses a nearly constant immitance with frequency. In this case, the bandwidth for the stub-plus-L-network is approximately $\gtrsim$20% of any chosen mid-band frequency over the entire range from 30 to 80 MHz. For the loop, the bandwidth is $\sim$10% for any center frequency in the 30 to 80 MHz band. The bandwidths for the top-loaded elements are substantially greater than those of the simple stub and loop, i.e., an increase

[34] The antenna modeling program, AMP, was developed for the joint military services under contract number N0014-72-C-0187. MB Associates, Menlo Park, California, developed the program.

[35] C.M. DeSantis, "Low Profile Antenna Performance Study," ECOM-4502, June 1977.

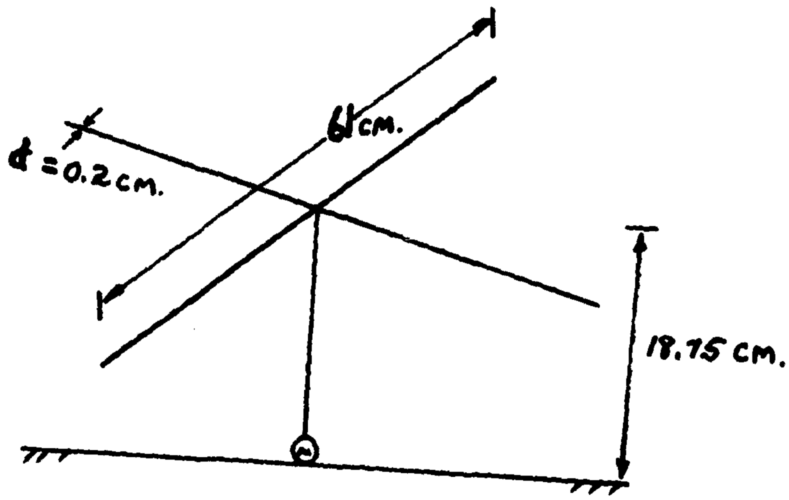

Fig. 15a
Model of Top-Loaded Monopole for Numerical Analysis

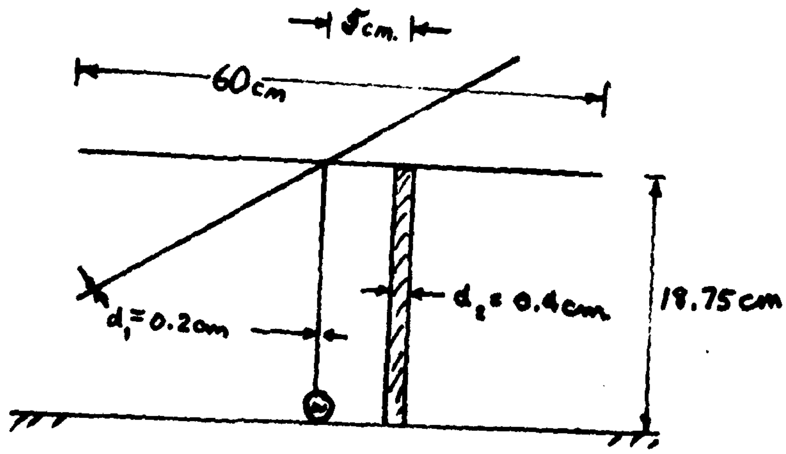

Fig. 15b
Model of Top-Loaded, Folded, Monopole for Numerical Analysis

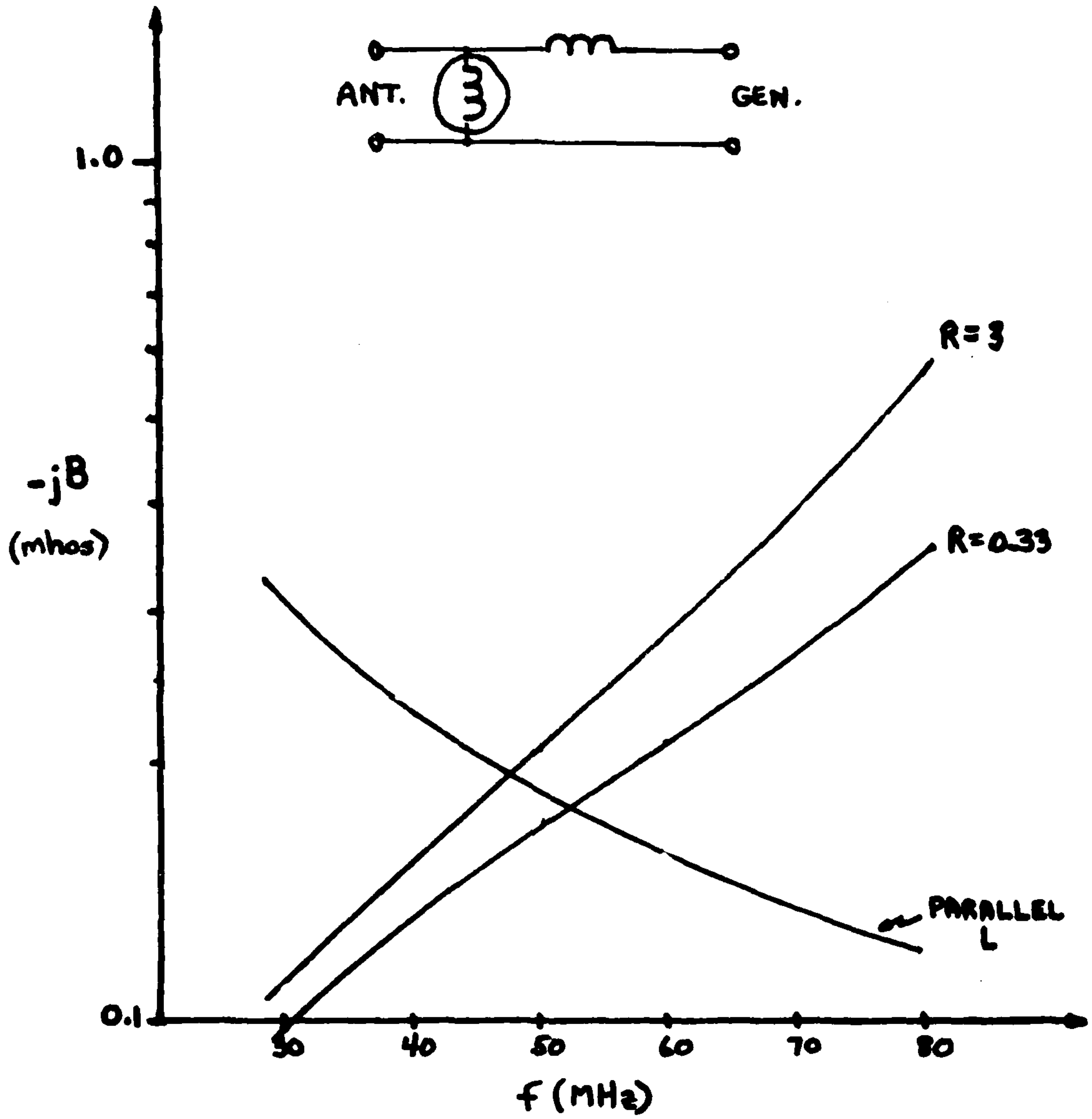

Fig. 16
Required Admittance Range of Shunt Inductor in an L-network
to Achieve Broadband Match

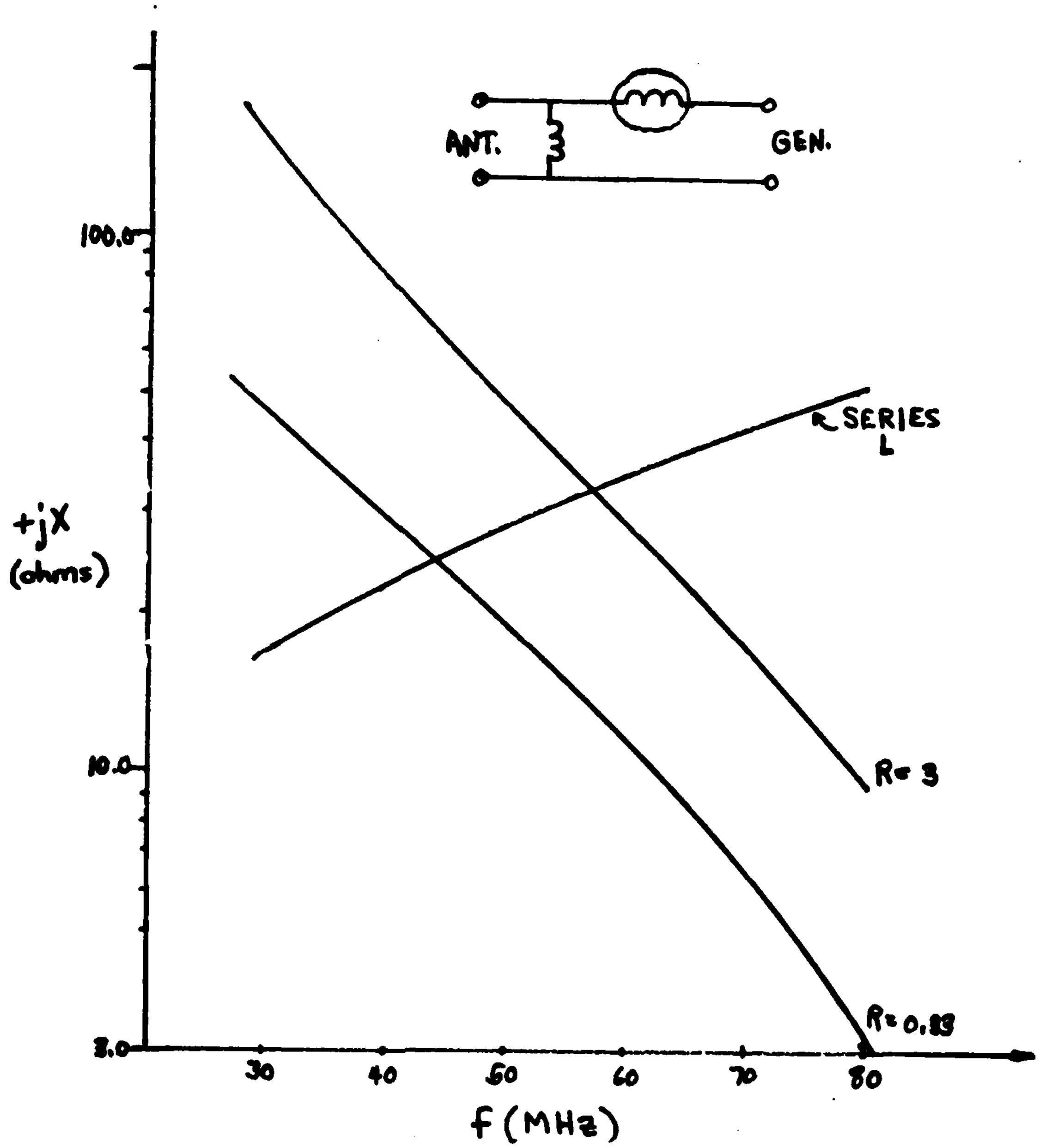

Fig. 17
Required Impedance Range of Series Inductor
to Achieve Broadband Match

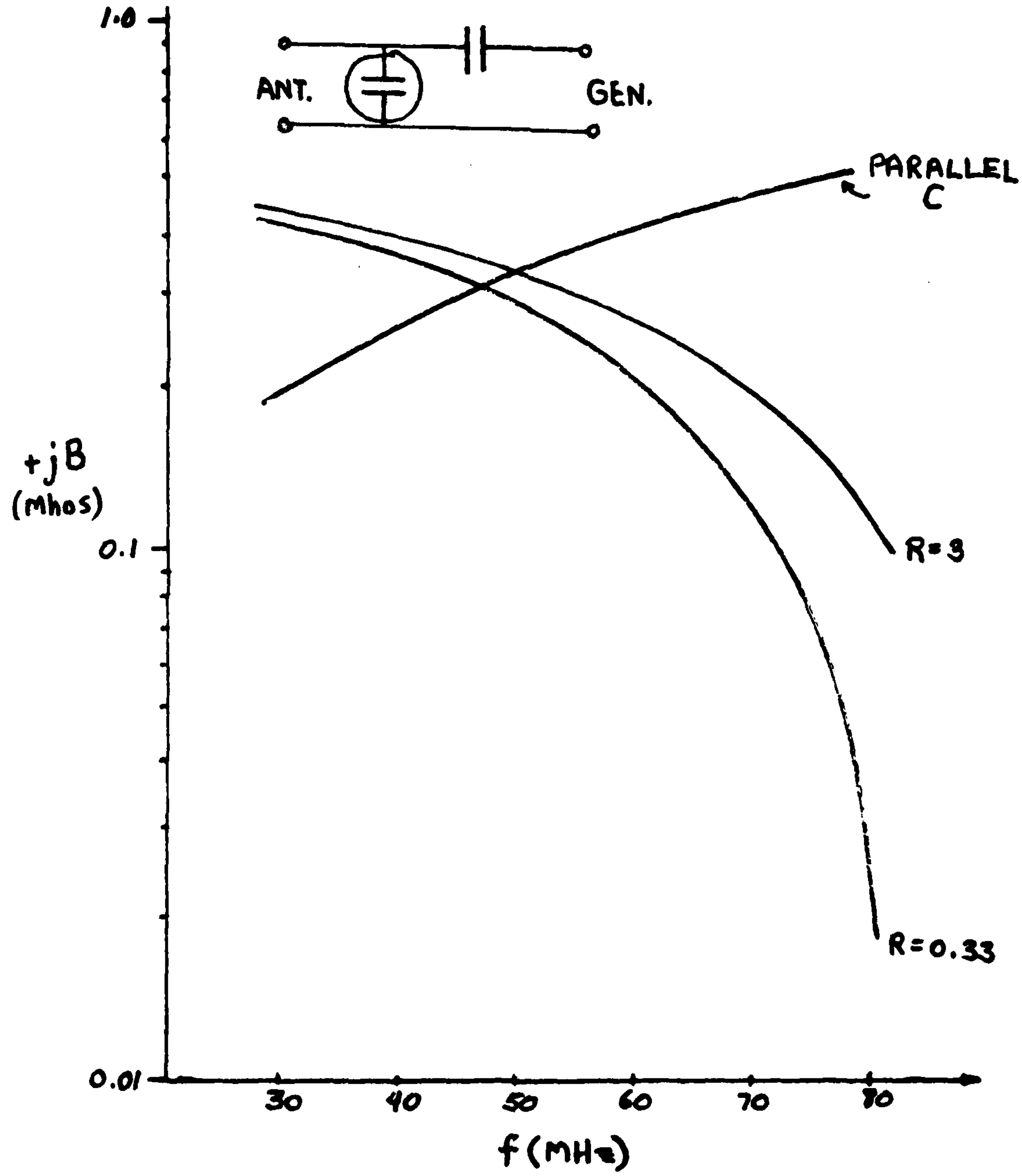

Fig. 18
Required Admittance Range of Shunt Capacitor for Broadband Match

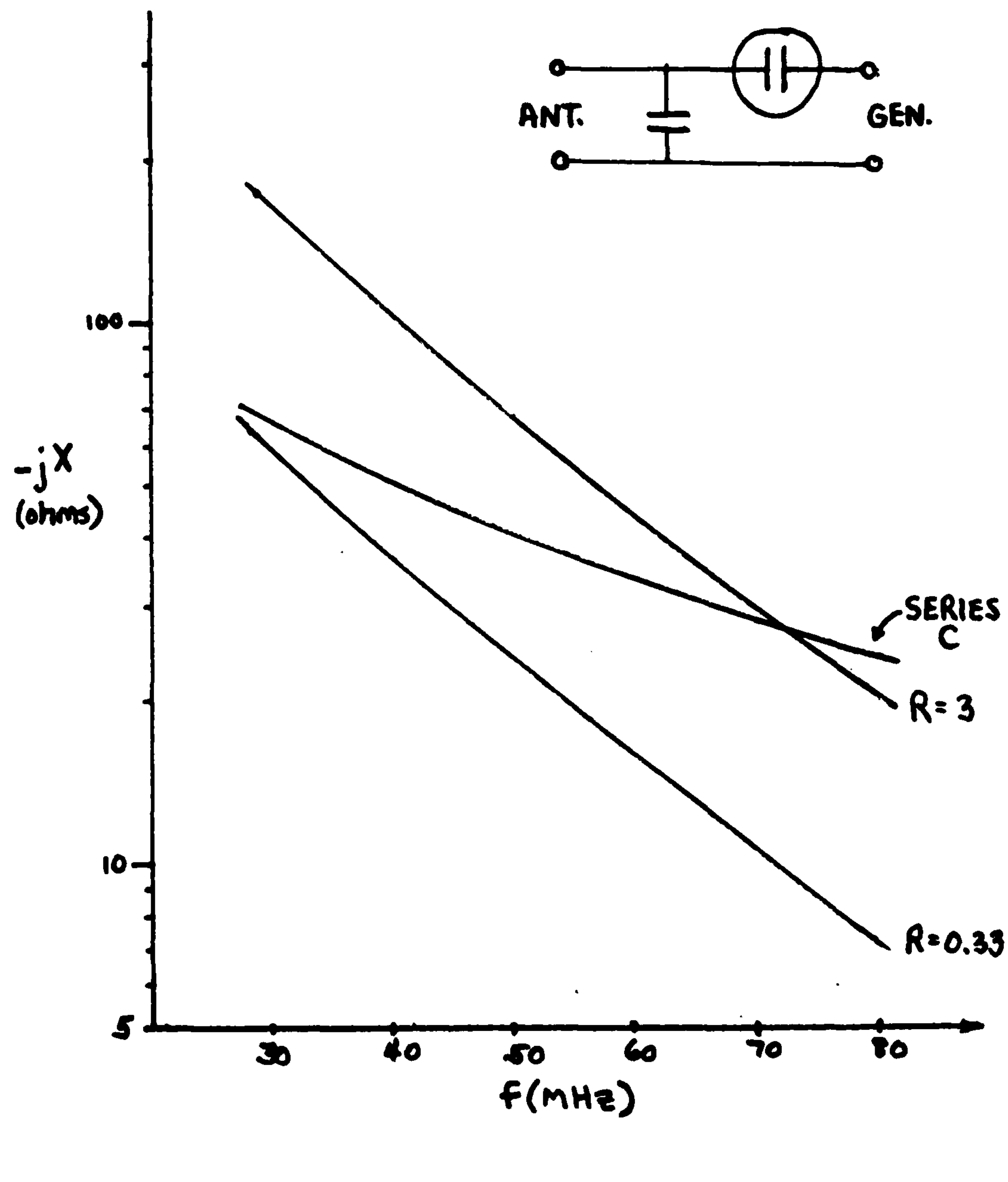

Fig. 19
Required Impedance Range of Series Capacitor
for Broadband Match

of $\sim$2:1% for top-loaded stub, and an increase $\stackrel{\sim}{>}$4:1% for the top-loaded loop! Recall that these bandwidth figures represent what is achievable with ideal, lossless networks with realizable immittances. Any losses in the system will cause an increase in the bandwidth.

There is one final note about the top-loaded loop. For a fixed height and top-load area, the ratio of the diameters of the vertical elements can be changed to effect the shape of the curve shown in Fig. 18 at the lower frequencies. It appears that the curves R=3, R=.33 can be made to approach a zero slope at the low end of the band. As an example, consider the parallel element variation shown in Fig. 20 for a folded, top-loaded structure with a 4:1 diameter ratio of its vertical elements. A comparison with Fig. 18 shows a definite flattening of the required element variations for matching, thereby increasing the achievable bandwidth. It is not clear how far this effect can be carried, but a more thorough examination will be made as part of the general study of small antennas.

B. Parasite-Loaded Dipole

As a final numerical example, consider the parasite-loaded dipole antenna (see Ref. 2), shown in Fig. 21. A pair of parasite elements is placed next to the antenna; this configuration with the dimensions given was modeled on the computer and the calculated input impedance is plotted in Fig. 22. As can be seen, the antenna has a $\sim$2:1 impedance bandwidth without external matching in the frequency range from $\sim$275 MHz to $\sim$575 MHz, and from the variation of the impedance, it should be possible to extend the range with a simple external matching circuit. This antenna is not small by any measure. A VHF version would require a 15' long, 5" diameter driven element with parasites spaced 18" away. However, parasite-loading does produce broadband operation and, perhaps, in combination with one or several of the techniques described in this report, will lead ultimately to a small, broadband antenna. In this regard, the reader will recall the Goubau antenna which is a combination of driven and undriven elements in a "small" package.

5. CONCLUSION

We have discussed six general types of broadband antennas which have appeared in the literature. Several experimental antennas have been reported which possess large bandwidths. However, these may be classed into two broad categories: (a) antennas with bandwidths >50% of an octave; and (b) antennas with bandwidths <50% but >10% of an octave. The truly small or low-profile antennas have fallen, in general, into the second category while the octave and multi-octave bandwidth achievements have occurred in $\lambda/4^{-}$ and $\lambda/2^{-}$ dimension antennas. There were several octave-band antenna designs, such as the Goubau antenna and a top-loaded version of the Hallen´ antenna, which were low-profile, but large in cross-section. However, there does not seem to be a truly small antenna design which possesses large bandwidth. The Goubau antenna comes closest; it is an unusual design which has not appeared before; and yet, in reviewing the literature, the basic ideas for such an antenna seem to have been disclosed. If one had been clever enough, perhaps an antenna of the Goubau type could have been deduced from a combination of several techniques which have been reviewed in this report. One wonders how many other novel designs can be assembled out of that body of literature by "clever" deduction.

It seems clear that a broadband design must involve multi-element, folded, loaded, radiating structures if the antenna is going to be small, at least in one dimension. Perhaps a combination of the Hallen´ technique with one or several of the other techniques will produce the reflection-free guiding-to-radiating structure discussed by Alford. It is hoped that the collection of ideas gathered into this report series will lead to new knowledge. Part III of the series provides a bibliography of published articles on small antennas and broadband antenna techniques.

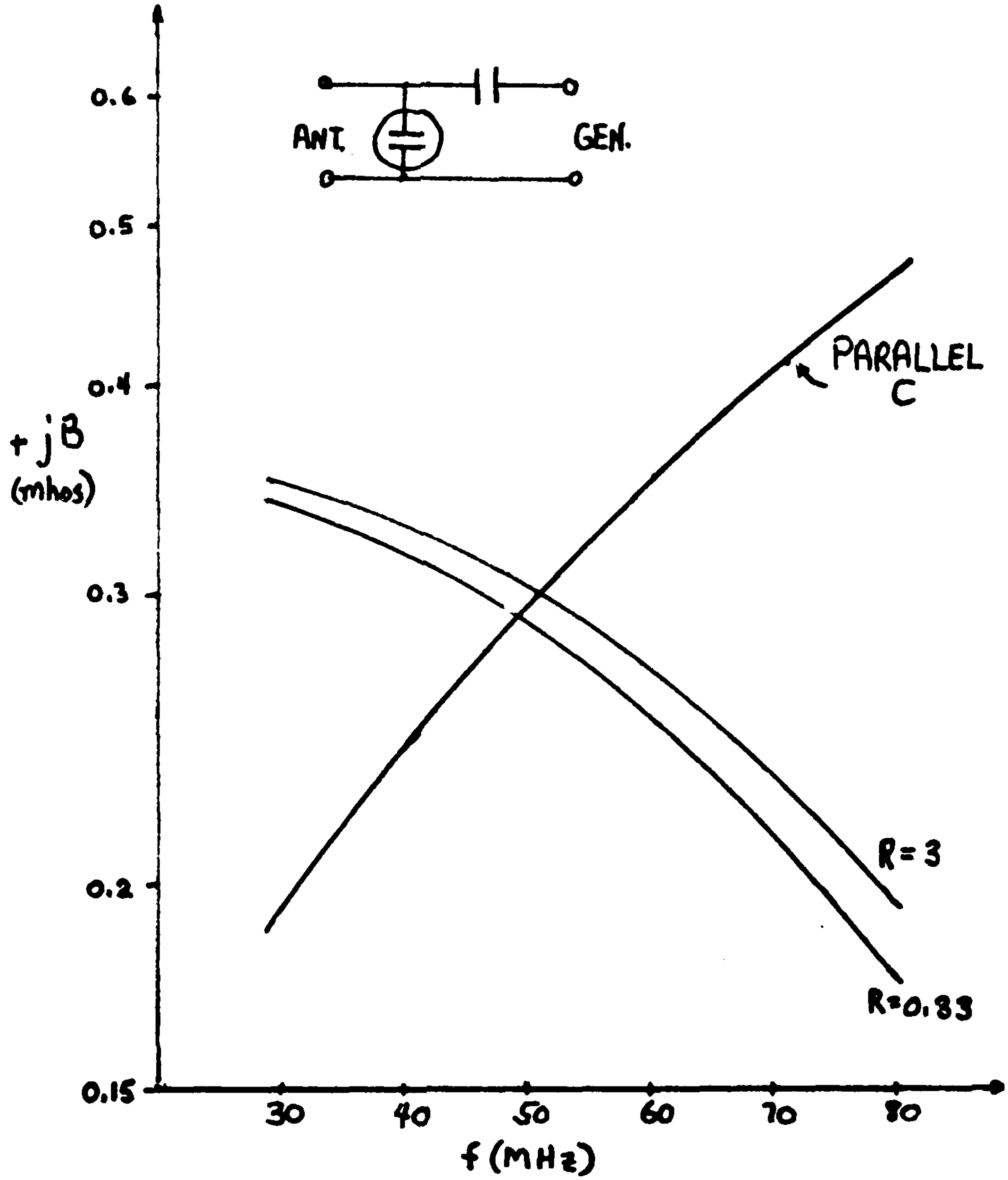

Fig. 20
Admittance Variation of Capacitor Required to Match a Folded Antenna Having a 4:1 Diameter Ratio in its Vertical Element

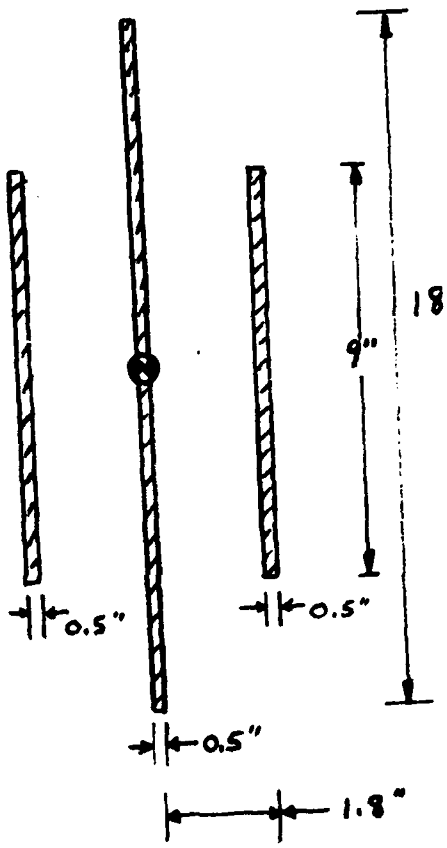

Fig. 21
Numerical Model Used for Parasite-Loaded Dipole

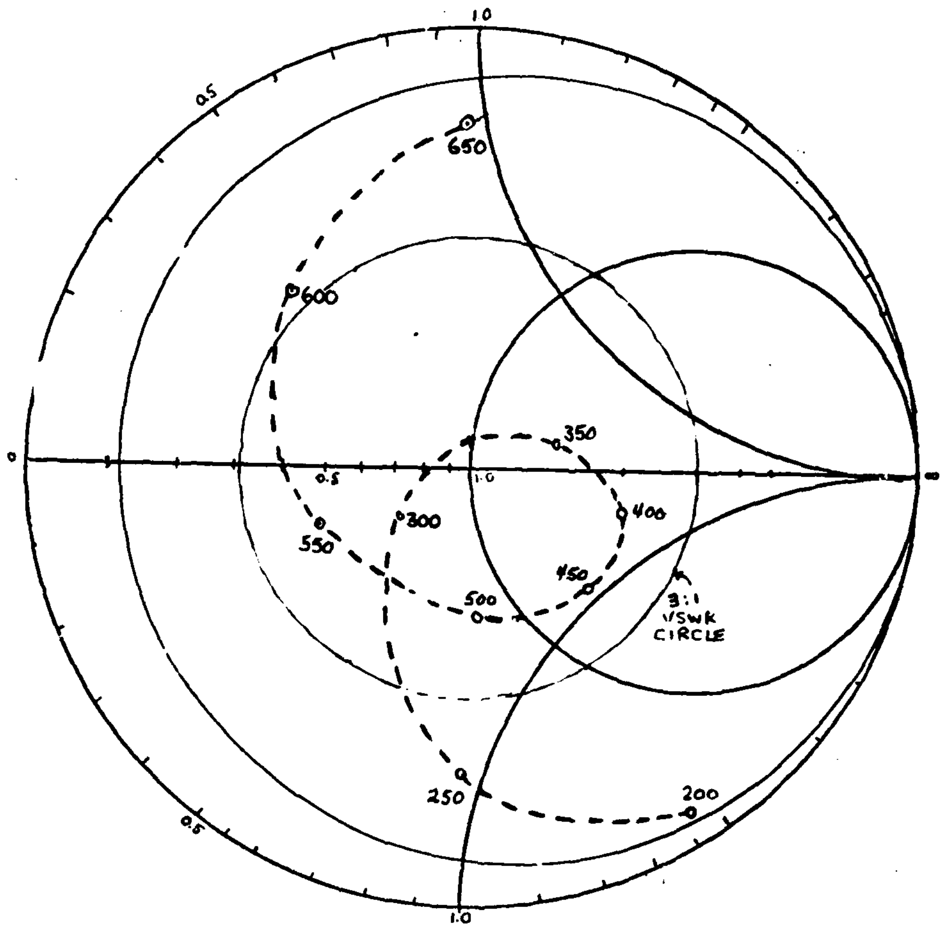

Fig. 22
Calculated Impedance Variation of Parasite-Loaded Dipole

TABLE 1 - CALCULATED INPUT IMPEDANCE

FREQ. MHZ	- - UNNORMALIZED IMPEDANCE - - RESISTANCE OHMS	REACTANCE OHMS	MAGNITUDE OHMS	PHASE DEGREES
TOP-LOADED MONOPOLE				
30.000	.47040	-429.07	429.07	-89.94
40.000	.84217	-300.49	300.49	-89.84
50.000	1.3280	-218.29	218.29	-89.65
60.000	1.9339	-159.16	159.18	-89.30
70.000	2.6679	-113.10	113.13	-88.65
80.000	3.5397	-75.064	75.147	-87.30
TOP-LOADED, FOLDED MONOPOLE				
30.000	2.849122E-02	112.52	112.52	89.99
40.000	9.72264E-02	125.41	125.41	89.96
50.000	.28485	147.70	147.70	89.89
60.000	.88949	180.89	180.90	89.72
70.000	3.0246	233.48	233.50	89.26
80.000	13.016	336.06	336.31	87.78

TABLE I