COMPUTER-AIDED ANALYSIS OF COAXIAL CABLE ATTENUATION AS A FUNCTION OF FREQUENCY AND TEMPERATURE

Jacob Shekel and Eric Winston

Jerrold Electronics Corporation

ABSTRACT

A thorough understanding of cable attenuation as a function of frequency and temperature is of prime importance to the user, as well as the manufacturer, of the cable. This paper describes measurements of attenuation conducted in an automated, computer-controlled test facility, suggests different ways to present the data, and describes the analysis of the data by computer-aided mathematical techniques.

The analysis exposes the differences in the temperature behavior of different cables, and shows how to design an optimum equalization scheme (with fixed and thermal equalizers) for any particular type of cable. The results also indicate that the widely accepted analysis of approximating the frequency response by $\sqrt{f}$ and f terms, is not always the correct way to separate the dielectric losses from the conductor losses.

1.0 INTRODUCTION

Anyone who attempts to design a CATV system must have a thorough knowledge of the properties of coaxial cable. Most of the equipment that makes up the trunk and distribution lines is there only to compensate for the attenuation of the cable. It is therefore important to know, in full detail, how cable attenuation depends on various parameters, such as frequency and temperature.

Even if we restrict the analysis to variation with frequency and temperature, we are faced with a quite complex function of 2 variables. We have to consider 3 aspects of the problem:

1. How to get enough measured data to represent the function;

2. How to digest and present the data in a form that will lend itself to analysis and interpretation;

3. How to use the data in the design of a system.

In this paper we shall report on work done related to these aspects of studying the attenuation of coaxial cables.

2.0 DESCRIPTION OF MEASUREMENT PROCEDURE

The attenuation of the cables was measured by an automated sweep test facility, controlled by a NOVA 1200 minicomputer. A suitable sweep generator, modified for digital control of frequency, was used as the primary signal source. The local oscillator of the receiver was another sweep generator at a fixed frequency difference, which allowed using a very narrow band IF amplifier for noise reduction and increased dynamic range. The final measurement of signal level was done by means of a Pacific Measurements Model 1036 (a logarithmic RF power meter, $\pm$0.02 dB accuracy). The results of the measurements were tabulated, stored in the minicomputer for further processing, or punched out on paper tape. The tape was used to transfer the data to a teletype terminal for analysis by various programs on GE Time-Sharing Mark III service.

Cables were furnished on reels (with the exception of one inch O.D."Spirafil", received as a coil of 6 ft. diameter). After initial mechanical testing, and measurements of impedance, return loss, and attenuation at 70°F, each reel was placed in a large environmental-control van(which is normally used for system evaluation). The van temperature was successively stabilized at -40, -20, 0, 35, 70, 100, 120 and 140°F, and the attenuation of the cable measured at each of these temperatures. Before each measurement, the cable would dwell at the nominal temperature (within $\pm$5°F) for not less than 4 hours; total cycle for the measurements was 96 hours.

3.0 PRESENTATION OF DATA

Cable attenuation data are of particular reportorial interest, since there are so many methods of presentation, depending on the specific technical interest to be served. Cable manufacturers may concentrate on dielectric material control; equipment suppliers may want to know how closely their various thermatic equalizers compensate a given cable; the system operator or designer focusses on changes in attenuation along the cable plant, and the consequent effects on subscriber set signal levels, signal distortion etc.

The problem is, basically, how best to present a function of 2 variables on a two-dimensional sheet of paper. This is usually done by a set of curves, with one variable plotted along the horizontal axis, and the other variable as a parameter defining the different curves in the set. We therefore have the choice of presenting dB vs. frequency for different temperatures, or dB vs. temperature for different frequencies.

4.0 ATTENUATION VERSUS FREQUENCY

This method of presentation, which is directly related to the frequency response of the cable system and its components, is the traditional method. Fig. 1 shows the measurements on 3 different types of cable, plotted for 3 temperatures. The horizontal axis is conventionally drawn proportional to $\sqrt{f}$, resulting in less curvature of the plots (theoretically, a cable with no dielectric losses would be represented by a straight line in this presentation). For comparison, the measurements on each cable were normalized to a loss of 20 dB at 300 MHz and 70°F.

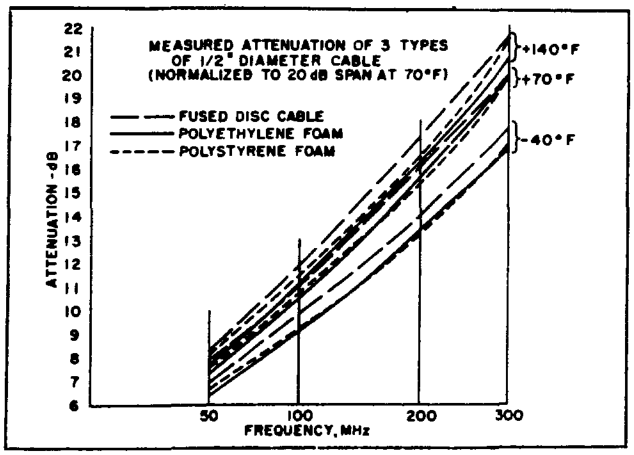

Fig. 1

Even from this simple presentation, it is obvious that the cables do not behave in a similar manner when temperature or frequency is changed. But the different curves are all jumbled together, and it is not easy to find the difference (similarity) between different cables.

A presentation as in Figs. 2-4, where the attenuation at any temperature is plotted relative to the attenuation at 70°F, makes it much easier to study the effects of temperature. The resulting curves indicate the thermal compensation needed such as thermal equalizers, ALC, ASC. Fig 2 shows the attenuation of three different 1/2"polystyrene dielectric cables, for which the attenuation of a span (20 dB) at 300 MHz will increase by 1.4 dB at +140°F, and decrease by 2.8 dB at -40°F. Fig.3 shows the same data for four cables with gas injected polyethylene foam dielectric; note the comparative similarity in low temperature performance, but the disparity at high temperatures. Still more striking are the data in Fig.4, showing fused-disc and "Spirafil" cables; the latter shows 3.5 dB increase at -40°F, compared with 2.5 dB for polyethylene foam. Clearly a thermal device optimized for one of these cables will be inadequate for the other.

This type of presentation could readily be utilized as a generic cable specification for system design, pre-assigning attenuation limits for given temperature extremes.

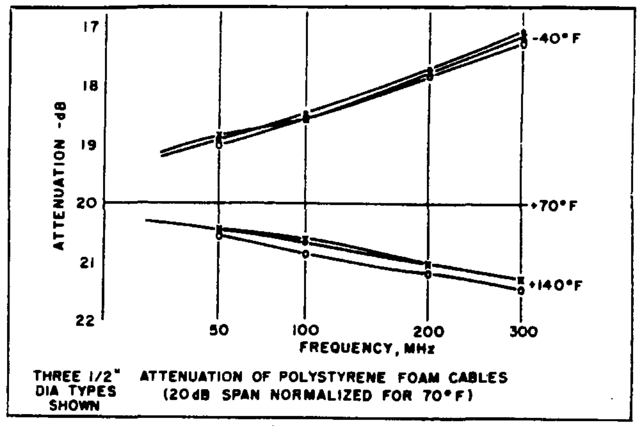

Fig. 2

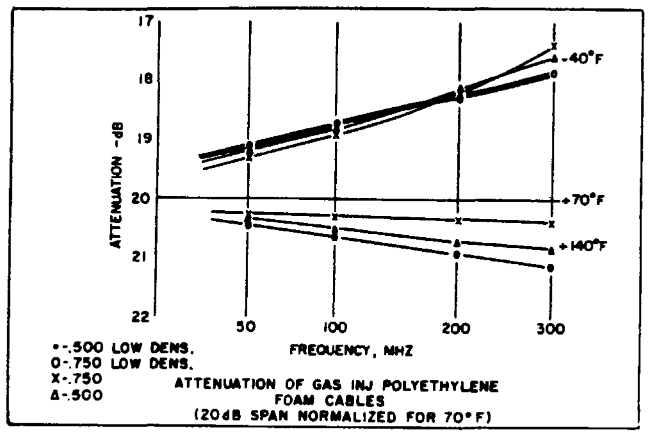

Fig. 3

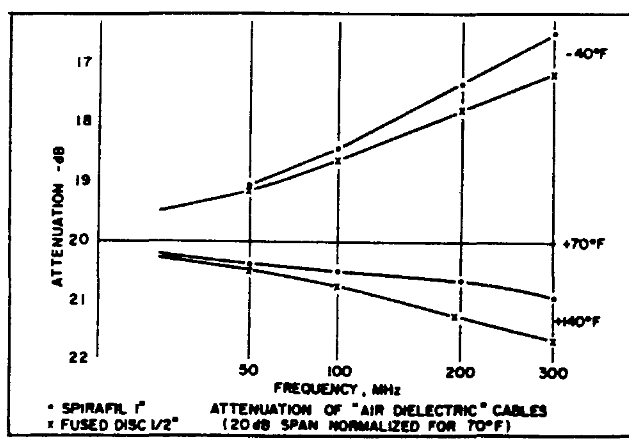

Fig. 4

5.0 ATTENUATION VERSUS TEMPERATURE

There is an accepted rule of thumb in CATV system design, that the attenuation of cable changes by 1% (more precisely, 1.1%) for every 10°F. This implies that the plot of attenuation vs. temperature, at any frequency, would be a straight line.

Fig. 5 presents the attenuation of four types of cable, at 50 and 300 MHz, plotted against temperature. Some of the lines are nearly straight, although the slope of the 50 MHz line is different from that of the 300 MHz line, and both are different from the .0011/°F coefficient.

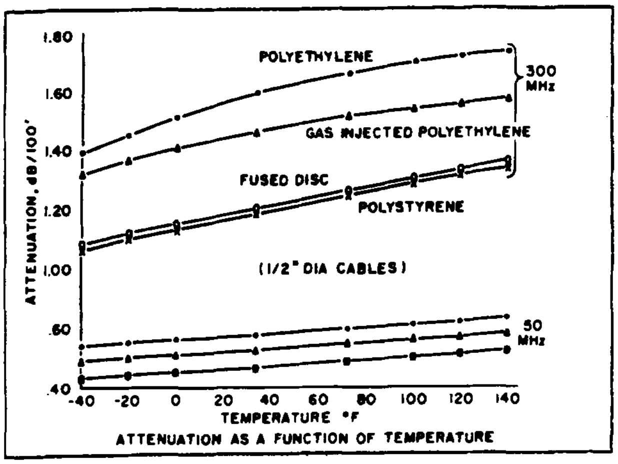

Fig. 5

Some lines, however, are noticeably curved. A careful examination of the "nearly straight" lines will show that they have different slopes at the two ends of the temperature scale.

For purposes of system design, the temperature range may conveniently be divided into two zones, arbitrarily defined as "high" (70 to 140°F) and "low" (-40 to 70°F). Two temperature coefficients assigned to these zones, may be defined as follows:

$$C_H = \frac{A_{140} - A_{70}}{70 \times A_{70}} \qquad C_L = \frac{A_{70} - A_{-40}}{110 \times A_{70}}$$

These represent attenuation change per degree F and are comparable to the theoretical value of .0011 derived for conductor loss (see Appendix A).

C_H and C_L values were calculated for all cables studied, and each cable was plotted as a point in C_H-C_L coordinates in Fig. 6, using the values computed for 300 MHz. A cable with no dielectric loss would appear as a point at the intersection of the two lines at .0011 on each axis. It is evident that departure from this value must be due to the effect of the cable dielectric.

Fig. 6 is separated into 4 quadrants relative to the .0011 point. Each quadrant defines the type of attenuation vs. temperature relationship to be expected. Note the preponderance of points in the lower right quadrant, as anticipated by the curves generally having greater slope in the low-temperature part of the A-T curves of Fig. 5. The points representing the polystyrene dielectric and the fused-disc cables are quite close to the theoretical value; the low-density gas-injected foam dielectric cable is in the quadrant showing the least A vs T slope.

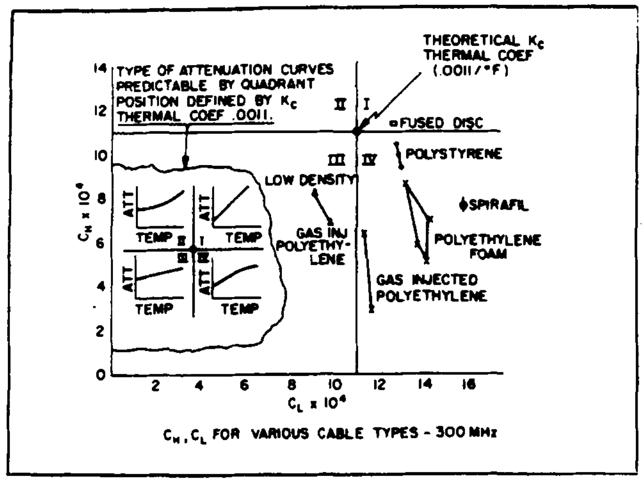

Fig. 6

Fig. 7 shows the same configurations for 50 MHz attenuation. The points are clustered much closer to the theoretical .0011 value, indicating the reduced effect of dielectric losses at the lower frequency.

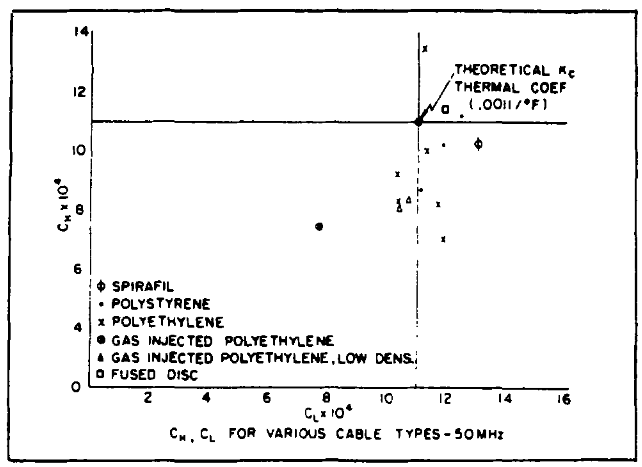

Fig. 7

The C_H-C_L groupings, indicated by the connecting lines in Fig. 6, provide a means to examine and compare a large number of cable attenuation characteristics and may help in defining specifications for A vs T limits for a given type of dielectric.

6.0 A 3-DIMENSIONAL APPROACH

The data obtained from the measurements would be best represented as a surface in 3 dimensions. Even though such a surface is not easy to represent on a 2-dimensional sheet of paper, the table in Fig. 8 can suggest a representation of such a surface. If the columns and rows are considered as the horizontal and vertical axis (representing temperature and frequency), each entry (dB attenuation) is the elevation of the corresponding point above the horizontal base plane. The attenuation $A(f_i,t_k)$ at the frequency f_i and temperature t_k is a function of 2 variables, defined over a discrete set of points.

TABLE I

TEMP / FREQ	-40	-20	0	35	70	100	120	140
50 MHZ	7.32	7.60	7.82	8.24	8.60	8.93	9.05	9.12
60 MHZ	7.99	8.31	8.56	9.03	9.51	9.70	9.93	9.90
70 MHZ	8.70	9.04	9.33	9.85	10.39	10.68	10.83	10.90
80 MHZ	9.29	9.69	9.99	10.55	11.14	11.47	11.61	11.67
90 MHZ	9.92	10.33	10.66	11.30	11.93	12.27	12.41	12.47
100 MHZ	10.43	10.88	11.22	11.90	12.58	12.94	13.10	13.16
110 MHZ	10.98	11.47	11.84	12.53	13.25	13.66	13.84	13.89
120 MHZ	11.52	12.04	12.44	13.19	13.96	14.39	14.55	14.58
130 MHZ	11.99	12.55	12.96	13.76	14.57	15.01	15.18	15.23
140 MHZ	12.49	13.06	13.52	14.37	15.21	15.67	15.85	15.87
150 MHZ	10.96	13.56	14.02	14.89	15.82	16.27	16.44	16.48
160 MHZ	13.44	14.07	14.54	15.45	16.39	16.88	17.09	17.14
170 MHZ	13.84	14.50	15.00	15.95	16.90	17.45	17.65	17.67
180 MHZ	14.25	14.94	15.48	16.51	17.48	18.04	18.21	18.22
190 MHZ	14.79	15.52	16.05	17.09	18.15	18.69	18.89	18.91
200 MHZ	15.11	15.85	16.43	17.52	18.58	19.18	19.35	19.35
210 MHZ	15.55	16.32	16.91	18.04	19.17	19.74	19.93	19.95
220 MHZ	15.98	16.77	17.36	18.49	19.66	20.26	20.49	20.51
230 MHZ	16.28	17.11	17.71	18.89	20.08	20.72	20.93	20.95
240 MHZ	16.78	17.62	18.26	19.50	20.70	21.37	21.58	21.57
250 MHZ	17.15	18.01	18.63	19.94	21.22	21.86	22.07	22.08
260 MHZ	17.57	18.47	19.14	20.43	21.71	22.44	22.63	22.62
270 MHZ	17.96	18.86	19.55	20.89	22.23	22.91	23.10	23.14
280 MHZ	18.26	19.20	19.90	21.29	22.63	23.33	23.52	23.53
290 MHZ	18.66	19.58	20.31	21.69	23.11	23.81	23.99	24.01
300 MHZ	19.04	20.03	20.79	22.20	23.66	24.38	24.59	24.57
310 MHZ	19.39	20.39	21.13	22.59	24.07	24.85	25.02	25.04
320 MHZ	19.80	20.84	21.62	23.13	24.62	25.38	25.59	25.54

Fig. 8

We may assume a continuous function $\bar{A}(f,t)$ tc represent this continuous surface, of which we know only a discrete set of points. The function $\bar{A}$ can be defined in an arbitrary manner, but it would be of any use only if it fits the measurements at the discrete set of frequency-temperature pairs. The error for each measured point is:

$$E(f_i, t_k) = A(f_i, t_k) - \bar{A}(f_i, t_k)$$

and the parameters of the function $\bar{A}$ are varied to minimize the expression

$$\Sigma_i \Sigma_k \left[E(f_i, t_k)\right]^2$$

resulting in a "least squares" fit. The function $\bar{A}$ may be defined with 5 or 6 variable parameters, and the summation may involve about 200 measured points; the surface fitting therefore will also help to smooth out the errors contributed by any one measurement.

The choice of $\bar{A}$ is, in principle, arbitrary. We shall see that different functions can be made to fit the same set of measured data equally well; the particular form of matching function A should therefore be selected according to the purpose for which the approximation will be used.

7.0 DESIGN OF OPTIMUM EQUALIZATION

To a system designer, the variation of attenuation with frequency and temperature is an effect to be compensated by equalization. From this point of view, the cable attenuation can be represented by a function of the form:

$$\bar{A}(f,t) = P_1(f) + P_2(f)\,Q(t-70)$$

This represents the attenuation as a combination of 3 functions:

- $P_1(f)$ the attenuation of the cable at 70°F, to be compensated by a fixed equalizer;
- $P_2(f)$ the frequency response of a temperature-dependent equalizer;
- $Q(t-70)$ the amount of thermal equalization necessary at t°F.

The formula assumes that the thermal equalizers, and the ASC network in the amplifiers, are "Bode" equalizers, whose frequency response is independent of temperature (except for a constant multiplier).

Assuming that, to a first approximation, attenuation varies linearly with temperature and with the square-root of frequency, we specify the functions as

$$P_1(f) = a_1\sqrt{f} + b_1 f$$

$$P_2(f) = a_2\sqrt{f} + b_2 f$$

$$Q(t) = (t-70)\left[1 + c\,(t-70)\right]$$

We have thus defined $\bar{A}(f,t)$ with 5 arbitrary parameters : a_1, b_1, a_2, b_2 and c.
Note that the values obtained for these parameters by curve fitting do not represent any intrinsic properties of the cable; they are only guides in the design of equalizers for the cable.

Table II (in Fig.9) shows the result of fitting the function to measured attenuation of 3 cables (all measurements normalized to an attenuation of 20 dB at 300 MHz and 70°F).

The first part of the table shows the values of the 5 parameters for each cable, and the largest deviation from the measured value (the point of worst fit). These parameters are then used to compute the optimum equalizers for each cable.

The fixed equalization is based on the function $P_1(f)$, and shows the value of equalizer attenuation at 3 frequencies (relative to 0 dB at 300 MHz). The numbers in parenthesis are the values of attenuation normalized to the attenuation at 50 MHz, and indicate the frequency response of the equalizer. The numbers show that the differ-

TABLE II

SURFACE-FITTING FOR OPTIMUM EQUALIZATION

	Cable A	Cable B	Cable C
Dielectric type:	Polyethylene foam	Styrene foam	Polyethylene discs
Fitting function:			
a_1	.976	1.09	1.05
b_1	.0108	.00399	.00576
a_2	.000707	.00104	.000891
b_2	.0000184	.0000135	.000036
c	-.00555	-.00137	-.0000721
Maximum deviation dB/20 dB span	.2	.2	.2
Fixed Equalization, dB/20 dB span			
50 MHz	12.6 (1.000)	12.2 (1.000)	12.3 (1.000)
100 MHz	9.2 (0.733)	8.7 (0.721)	8.9 (0.724)
200 MHz	4.2 (0.329)	3.8 (0.318)	3.9 (0.321)
ALC control at 67.25 MHz, dB/20 dB span			
-40^oF	-1.25	-1.20	-1.08
$+140^oF$	+0.30	+0.60	+0.68
Fig. 9 Thermal Equalization, dB/20 dB span/100^oF			
50 MHz	.53 (1.000)	1.21 (1.000)	1.80 (1.000)
100 MHz	.39 (0.748)	.89 (0.735)	1.36 (0.757)
200 MHz	.18 (0.345)	.40 (0.332)	.64 (0.355)

ent cables need equalizers with different frequency responses. The change of attenuation at 67.25 MHz (ALC pilot frequency) indicates that different cables place different requirements on the ALC system.

In particular, cable A varies much less in the high temperature region than in the temperatures below 70^oF (compare the C_L-C_H groupings described in an earlier section).

Thermal equalization (whether by thermal equalizers or by automatic slope control) is specified in the last part of the table. The equalization is given per span and 100^oF change, but it can be used as a guide to the frequency of placing equalizers of a similar frequency response. The normalized frequency response is shown by the numbers in parenthesis. The table indicates that the different cables need equalizers of different frequency responses; also that for each cable, the frequency response of the optimum thermal equalizer is different from the response of the optimum fixed equalizer for that cable. It also indicates that thermal equalizers, or ASC stations, should be placed more frequently in systems built with cable C than in those with cable A.

8.0 CONDUCTOR AND DIELECTRIC LOSSES

For cable manufacturers, it is very important to separate the losses into conductor and dielectric losses. How can this be done?

Since the approximating formula used above has $\sqrt{f}$ and f terms, it is very tempting to assume that they represent the conductor and dielectric contributions to the total attenuation. If we follow this assumption, then the ratio a_2/a_1 would be the temperature coefficient of the conductor losses. For the 3 cables in Table II, the ratio is .000731 and .000954 and .000825 respectively. The values for cables A and C are too far from the theoretical value of .00109 (see Appendix A); and why should this value change so much between the 3 cables that differ in their dielectric only, but have the same conductor structure?

There is a subtle point involved in the fitting of a continuous function to a discrete set of measured points. It is true that the attenuation contributed by the conductors would follow a $\sqrt{f}$ function; but the converse is not true -- the $\sqrt{f}$ portion of an approximating function does not necessarily represent the conductor losses. Appendix B shows an example where the attenuation of a cable at one temperature is approximated by different functions, all of the form of a $\sqrt{f}$ term paired with another function. The coefficient of the $\sqrt{f}$ term in the approximation depends on the "other function" used, and the "goodness of fit" cannot be any guide in selecting the "correct" value of k_c.

One way to separate conductor from dielectric losses would be to compute the former from the cable dimensions and from the properties of the conducting materials (Appendix A). It is likely that the properties of drawn aluminum tubes and copper-clad aluminum wire are known in more detail and are easier controlled than those of the various dielectrics used in cables. On the other hand, we must realize that low-loss cables, as used in CATV, are designed for minimal dielectric losses (in addition to the inevitable conductor loss). If, for example, the dielectric loss is 5% of the total, an error of 1% in computing the conductor loss will result in a 20% error in the loss ascribed to the dielectric.

In a cable with a homogenous, low-loss dielectric, the dielectric losses are proportional to the frequency. We can try to fit the measured attenuation to the function

$$\bar{A}(f,t) = k_c\left[1+\alpha_c(t-70)\right]\sqrt{f} + k_d\left[1+\alpha_d(t-70)\right]f$$

which assumes linear temperature dependence of both components. Indeed, when this approximation is applied to cable B of Fig. 9, the deviation of any measured point is less than 0.2 dB, and the coefficients for best match are

$$k_c = 1.09 \qquad \alpha_c = 0.00102$$

$$k_d = 0.00395 \qquad \alpha_d = 0.00363$$

and the temperature coefficient of k_c is very close to the theoretical value. The same function applied to cable C, with a fit just as good, yields

$$k_c = 1.06 \qquad \alpha_c = 0.000847$$

$$k_d = 0.00576 \qquad \alpha_d = 0.00627$$

which seems very curious when the two cables are examined; cable C has much less dielectric than cable B, but its k_d contribution is much higher. The low value of α_c is another indication that the $\sqrt{f}$ term, in this approximation, does not represent conductor losses.

Could it be that we used an improper "other function" for cable C? Indeed, the derivation in Appendix C shows that if we assume the attenuation as a result of reflections from the supporting discs, rather than from dissipated energy within the dielectric, the loss ascribed to the dielectric should be proportional to f^2 (with added f^4, f^6... terms if needed for extra refinement). When the f term in $\bar{A}(f,t)$ above is replaced by an f^2 term, the fit (which is just as close as in the other examples) gives the following parameters:

$$k_c = 1.10 \qquad \alpha_c = 0.00110$$

$$k_d = 0.0000101 \qquad \alpha_d = 0.00610$$

The value of α_c is further assurance that we have selected the correct "other function" for the dielectric loss, and the k_c and k_d have a physical meaning.

In summary, the fact that an assumed function provides a good fit to the measurements is not sufficient proof, by itself, that the various components of the function correspond to particular physical parameters in the cable. If the form of the function can be justified by a theoretical analysis then the values of the parameters can be derived by curve fitting. If there is no a-priori justification for the selected functional form, one can use the derived value of known parameters as an indication that the function has physical meaning (or, at least, to reject a function as incorrect). We suggest that the temperature coefficient of the f term can be used as a guide to the possible correctness of the assumed function.

As an example, the measured attenuation of a spiral dielectric 1" cable was analyzed, with the following results:

sum of $\sqrt{f}$ and f terms	sum of $\sqrt{f}$ and f^2 terms
$k_c = 0.972$ $\alpha_c = 0.000703$	$k_c = 1.06$ $\alpha_c = 0.00101$
$k_d = 0.0105$ $\alpha_d = 0.00433$	$k_d = 0.000018$ $\alpha_d = 0.00433$

The value of α_c indicates that the second decomposition is likely to be the correct one, so that dielectric losses in this cable are proportional to f^2 (indicating that the loss mechanism is reflective rather than absorbtive).

CONCLUSION

A meticulous study of cable attenuation is of extreme importance to the designers of CATV equipment and systems. We have described a measurement procedure that provides detailed attenuation vs frequency and temperature data, and presents it in a form that is easily transferred to a computer for analysis. The analysis results in logical definition and computation of various parameters useful in the design of cable systems. It shows that some cables can be clustered in closely related groups with similar properties; and that a system properly designed for a cable in one group may not operate properly if a cable of a different group is used in the same design.

The computer-aided analysis method can also be used to probe into the mechanism responsible for the dielectric loss, and indicate some of the causes behind the grouping of cable types.

Since the study was conducted on a limited number of samples, we strongly caution against interpreting the results as inherently representative of any type of cable or dielectric. In fact, cable manufacturers agree that incoming dielectric materials, particularly polyethylene, may be subject to certain variations -- not yet fully understood -- which influence the dielectric constant and power factor, with a resulting variation in attenuation. Furthermore, there is no certainty that the results, as presented here, are valid for an extended life period of a cable.

ACKNOWLEDGEMENT

The study of cable attenuation was made possible, in part, by the contribution of sample reels from various cable manufacturers. This report is not intended to imply relative merit of one type of cable over another. The inclusion of any particular type was guided only by the desire to present the widest possible variety of data, and should not be interpreted in any other way.

APPENDIX A [1]

CONDUCTOR LOSSES IN COAXIAL CABLE

The RF resistance of a cylindrical copper conductor of diameter $\underline{d}$ mils at a frequency of $\underline{f}$ MHz and a temperature of 20°C (68°F) is [2]

$$R = 0.996\sqrt{f}/d \quad \text{ohms/100'}$$

Let $\underline{d}$ mils denote the diameter of the center conductor of a coaxial cable, and $\underline{D}$ mils the inner diameter of the outer conductor. It may be assumed that the RF current in the copper-clad inner conductor is confined to the copper skin. The conductivity of the aluminum outer conductor is 61% of that of copper [3], and the total RF resistance of the coaxial cable at $\underline{f}$ MHz is then

$$R=(0.996/d+1.276/D)\sqrt{f} \quad \text{ohms/100'}$$

The contribution of the conductor resistance to the cable attenuation at $\underline{f}$ MHz is [4]

$$A_c = 4.343\, R/Z_o$$

which for 75-ohm cable, reduces to

$$A_c=(5.771/d+7.389/D)\sqrt{f} \quad \text{dB/100'} = k_c\sqrt{f}$$

$$k_c = 5.771/d+7.389/D \quad \text{dB/100'}/\sqrt{\text{MHz}} \; .$$

The temperature coefficient of the resistivity of copper and aluminum is the same [5], 0.00393/°C, or .00218/°F. The resistivity of the coaxial cable conductors at any temperature t°F is therefore

$$\rho_t = \rho_{68}\left[1+0.00218\,(t-68)\right]$$

Because of skin-effect, the RF resistance is proportional to the square root of the resistivity [6], therefore

$$R_t=R_{68}\sqrt{1+0.00218\,(t-68)}$$

$$\approx R_{68}\left[1+0.00109\,(t-68)\right]$$

The k_c coefficient, which is proportional to the RF resistance, will have the same temperature coefficient, namely 0.00109/°F.

---

(1) The material in this Appendix is abstracted from "Calculations relating to aluminum shielded cables", by K.A. Simons, Jerrold Electronics Corporation Memorandum, Oct. 22, 1975.

(2) Reference Data for Radio Engineers, 5th Edition, ITT, 1972 printing; page 6-7.

(3) Texas Instruments Bulletin 516-WP26-1070.

(4) Reference 2, page 22-13.

(5) Reference 2, page 4-21.

(6) Reference 2, page 6-5.

APPENDIX B

CAN k_c BE DETERMINED BY CURVE FITTING ?

The first two columns in TABLE A show the measured attenuation vs frequency of a reel of cable at 70°F, the other columns indicate the result of trying to match the measurements to a curve of the form

$$k_c\sqrt{f} + k_d\, G(f)$$

The various columns pertain to different functions assumed for the dielectric loss G(f). Each column shows the assumed function, the resultant values for k_c and k_d that gave the best least-squares match, and how close each measured point is to the approximating smooth curve.

It is evident that very different values of k_c can be obtained, depending on the "other function" G(f) used in the approximation. The "goodness of fit" cannot be any guide in selecting the "right" approximation. The fit shown by the column from the right, with a k_c =0.398, is just as good as the second column which assumes dielectric loss proportional to $\underline{f}$ and giving k_c=0.893. In fact, even the value k_c=2.464 could not be rejected just on the basis of "poor fit".

This shows that the coefficient of a $\sqrt{f}$ term in an approximation that fits the measurements can not be interpreted, on the basis of good fit alone, as representing the conductor losses (or for that matter, any intrinsic property) of the coaxial cable.

TABLE A

MATCH MEASURED CABLE LOSS TO

$$K_C \cdot F^{.5} + K_D \cdot G(F)$$

G(F)=	1	F	$F^{1.5}$	F^2	LN(F)	F*LN(F)	$[LN(F)]^2$	$F^{.5}$ *LN(F)
K_C =	1.498	0.893	1.045	1.096	1.686	2.464	0.398	0.976
K_D =	-4.15	0.215E-01	0.739E-03	0.331E-04	-1.29	-0.639	0.151	0.293E-02

MHZ	MEASURED	ERROR IN APPROXIMATION BY MATCH							
100	10.99	0.16	-0.08	-0.20	-0.30	0.08	-0.11	0.04	-0.12
110	11.70	0.14	-0.02	-0.11	-0.20	0.09	-0.03	0.06	-0.05
120	12.37	0.11	0.01	-0.05	-0.11	0.09	0.02	0.07	-0.00
130	12.95	0.02	-0.02	-0.06	-0.11	0.01	-0.01	0.01	-0.03
140	13.56	-0.02	-0.01	-0.03	-0.06	-0.01	0.00	-0.00	-0.01
150	14.16	-0.04	0.01	0.00	-0.01	-0.02	0.02	-0.01	0.01
160	14.73	-0.07	0.00	0.02	0.02	-0.04	0.01	-0.03	0.01
170	15.30	-0.08	0.01	0.04	0.05	-0.05	0.02	-0.03	0.02
180	15.84	-0.11	-0.00	0.04	0.06	-0.07	0.00	-0.05	0.01
190	16.46	-0.04	0.00	0.12	0.16	-0.00	0.08	0.02	0.09
200	16.91	-0.13	-0.01	0.04	0.08	-0.09	-0.01	-0.07	0.01
210	17.48	-0.08	0.04	0.09	0.14	-0.05	0.03	-0.02	0.05
220	17.96	-0.11	-0.00	0.05	0.10	-0.08	-0.01	-0.06	0.01
230	18.44	-0.13	-0.04	0.02	0.07	-0.10	-0.04	-0.09	-0.02
240	19.06	0.00	0.08	0.12	0.17	0.02	0.07	0.04	0.09
250	19.51	-0.03	0.03	0.07	0.11	-0.02	0.02	-0.00	0.04
260	20.01	0.00	0.03	0.06	0.10	0.01	0.03	0.01	0.04
270	20.46	-0.01	-0.00	0.01	0.04	-0.01	-0.01	-0.01	-0.00
280	20.94	0.02	-0.01	-0.01	0.00	0.01	-0.01	0.00	-0.01
290	21.42	0.06	-0.01	-0.02	-0.03	0.03	-0.01	0.02	-0.01
300	21.93	0.13	0.03	-0.01	-0.03	0.10	0.03	0.08	0.02
310	22.31	0.08	-0.06	-0.12	-0.17	0.04	-0.06	0.01	-0.08
320	22.78	0.13	-0.06	-0.14	-0.22	0.07	-0.05	0.03	-0.08

APPENDIX C

DIELECTRIC LOSS IN FUSED DISC CABLE

In the following analysis, it is assumed that:

1. The thickness of the discs is very small compared to a wavelength, so the effect of a disc on the cable is that of a lumped capacitive loading.
2. The spacing between discs is small compared to half a wavelength, so that the periodic discontinuity will not result in a spike in the structural return loss.

At 300 MHz, the free-space wavelength is one meter, so that both assumptions are valid for a cable that has discs spaced about 1" apart.

Let each disc be represented by a capacity C, loading the cable by an admittance $j\omega C$. The reflection from a single discontinuity is

$$r = \frac{-j\omega C}{2Y_0 + j\omega C}$$

and if the loading is small compared to the characteristic admittance Y_0,

$$r = -j\omega C/2Y_0 = -jkf$$

where f is the frequency, and $k = \pi C/Y_0$

The ratio of the power transmitted beyond the discontinuity to the incident power is

$$1 - r^2 = 1 - k^2f^2$$

If the span of cable (100', or 20 dB, or whichever length is analyzed) contains n discs, the reflections from the discs will result in an output power of

$$(1-k^2f^2)^n = 1 - nk^2f^2 + \frac{n(n-1)}{2}k^4f^4 - \ldots$$

We can take the f^2 term for a first approximation, and higher terms (all in even powers of the frequency f) if further refinement is necessary.

The loss, expressed in dB, due to reflections from the discs, is

$$A_d = -10 \log(1-nk^2f^2) = -43.43 \ln(1-nk^2f^2)$$

$$\cong 43.43\, nk^2f^2$$

The last approximation is valid because $nk^2f^2 \ll 1$. (In the example in the body of the paper, the coefficient of f^2 for the fused-disc cable is about 10^{-5}).