Standard Linear Antennas, 30 to 1000 MHz

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Abstract—**It is demonstrated that the insertion loss between pairs of thin, linear antennas may be calculated using fairly simple equations that are generally considered to be good engineering approximations. Although the insertion loss calculation does not involve antenna gain directly (some measurements are actually made in the near-field where gain is not defined), the result is precisely the quantity obtained using the antenna gains in Friis's transmission formula, assuming the mismatch losses are zero. Therefore, the antenna gain product is implicit in the more general insertion loss equations. The particular measurement of insertion loss used here yields a quantity called site attenuation by electromagnetic compatibility engineers. A close agreement between measured and calculated data provides confidence in the site attenuation calculations when the site is essentially perfect, and provides confidence in the gain product of the antenna pair calculated using basically the same equations as those used for insertion loss. It is assumed that one-half of the mean value of the difference between the calculated and measured data is a good estimate of individual antenna performance. For the antennas described here, this measure of performance is typically ≤0.05 dB and on the outside, ≤0.42 dB.**

I. Introduction

THIS PAPER DESCRIBES the performance of real, thin, linear dipoles and monopoles used as standard antennas in the 30 to 1000 MHz frequency range. The term "standard" is used to indicate that the performance parameters are predictable, and agreement with measured parameters is good. The performance parameter specifically discussed here is insertion loss between the terminals of pairs of these antennas when they are located over plane, assumed perfect, ground. The results of the work described here imply that a thin dipole fabricated from a good conductor, rigid enough to maintain a linear geometry, and having an overall length between λ/10 and λ/2 has calculable performance characteristics (λ is the wavelength). To achieve calculated performance with real dipole antennas, the balanced-to-unbalanced transmission line transformer (balun) is a coaxial hybrid junction that is removed from the dipole for the initial measurement required to determine insertion loss. Calculated performance is based upon well documented input impedance and mutual impedance equations. Far-field conditions are not imposed for the calculations or measurements, but assumptions are made in the mutual impedance formulations that may reduce their accuracy for antenna-to-antenna spacings of λ/4 or less.

Antenna gain is an antenna performance parameter that is difficult to measure in the 30 to 1000 MHz frequency range. Effective length is the only quantity used for calculating gain that is not used explicitly for calculating insertion loss. However, insertion loss between pairs of antennas is precisely the quantity obtained using the antenna gains in Friis's transmission formula [1], assuming the mismatch losses [2] are zero. Therefore, antenna gains are implicit in the more general insertion loss equations. Comparing measured and calculated insertion loss data is a valid method of determining the uncertainty in the gain product of two linear antennas if the test range is considered perfect.

Substitution loss [2] is a relative measure of the transmission properties of two different waveguide junctions (two-ports or two-terminal pair networks). It is the ratio, expressed in dB, of the power P_I measured in a load with the initial two-port in place, to the power P_F measured in the same load with the final two-port replacing the initial one in the transmission path. It is assumed that the generator and load characteristics remain the same for the two measurements. Insertion loss, a special case of substitution loss, is measured when the initial two-port is perfect (a lossless, reflectionless waveguide junction), and the reflection coefficients of the generator and load Γ_G and Γ_L are not necessarily equal to zero. Attenuation, another special case of substitution loss, is measured when the initial two-port is perfect, and $\Gamma_G = \Gamma_L = 0$ as well.

In the typical antenna pattern or gain measurement, substitution loss data are most often obtained. The initial waveguide junction may be as simple as a transmission-line-to-transmission-line adapter, or as complicated as an antenna pair with an initial propagation path between them. The final waveguide junction is the antenna pair with the final propagation path included. Since many calculations actually require attenuation rather than insertion loss, the difference between the insertion loss and attenuation may be estimated and accounted for in the error budget.

Fig. 1 should help explain the measurement procedure. The initial waveguide junction is shown in Fig. 1(a) at the vertical dashed line labeled SMA/BARREL/SMA (two type SMA coaxial cable connectors joined by a female–female SMA adapter). That is, the "perfect" initial junction employed in the measurement of P_I is approximated by *two* SMA adapters, one in each side of the balanced, 100 ohm, shielded transmission line between the 50 ohm hybrid junctions. The generator consists of the signal generator, hybrid junction, equal length cables to the 3 dB pads (attenuators) and the attenuators themselves. The receiver consists of similar components with a spectrum analyzer used to measure the load power. As a result of this arrangement, the characteristic balanced impedances of both the generator and the receiver are assumed to be 100 ohms. The 3 dB attenuators are employed to force Γ_G and Γ_L toward zero and help justify this assumption.

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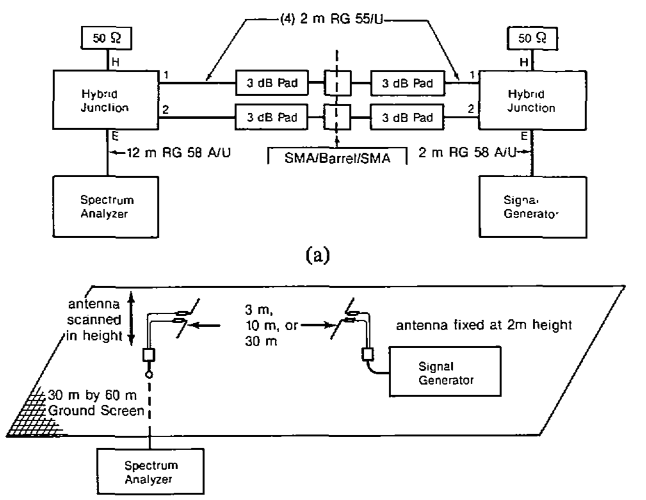


Fig. 1. Schematic diagram of the measurement procedure. (a) Measure initial received signal level P_I. (b) Measure final received signal level P_F.

The "different" junction that is substituted in place of the SMA adapters is a pair of co-polarized, vertical or horizontal, dipoles and the propagation path between them. This is shown in Fig. 1(b) for the particular test site geometry used to evaluate horizontally polarized site attenuation—a measure of test site performance employed by electromagnetic compatibility engineers and specified by the Federal Communications Commission (FCC). Site attenuation [3] is the minimum insertion loss measured between the terminals of two co-polarized antennas located on the test site when one antenna is moved vertically over a specified height range.

When measured as described in Fig. 1, site attenuation includes mismatch losses occurring at the two antenna feedpoints, but not balun or cable losses. Since the measured and calculated data agree so well, the test site may be assumed to be perfect, and as a result, the difference between measured and calculated data demonstrate the performance of the antenna pair rather than performance of the site. Measurements of site attenuation performed on the 30 by 60 m National Bureau of Standards (NBS) ground plane are used to determine dipole antenna performance in this paper. A single set of site attenuation data measured using a monopole and dipole antenna are included to determine monopole performance.

II. Antennas

A detailed description of the antennas is provided in [4], and a computer code is included for calculating gain versus elevation angle for vertical and horizontal dipoles over ground and monopoles on perfect ground.

The 50 ohm coaxial hybrid junctions, shown schematically in Fig. 1(a), are four-port devices serving as the dipole baluns and having the following minimum performance specifications:

1) isolation: 30 dB;
2) phase balance, E (diff) port feed: 180° ± 1°;
3) amplitude balance: 0.2 dB;
4) voltage standing-wave ratio (VSWR): 1.3;
5) insertion loss, E (diff) port feed: 0.75 dB.

Equal length cables, 2 m long, separate the hybrid junction from the dipole feedpoint assembly. Insertion loss versus frequency of the two hybrid junction, cable, attenuator assemblies is measured between the E-ports using the same test set-up as shown in Fig. 1(a), to verify their performance. Satisfactory performance is observed when the measured insertion loss is a smooth function of frequency, and is approximately equal to the sum of the expected losses of the hybrid junctions, cables, and attenuators.

III. Calculations

Insertion loss between two thin dipoles in echelon located in free space may be calculated using the mutual impedance between the dipoles [5] and the self-impedance of the dipoles. The mutual impedance is simply

$$Z_{21} = -V_{21}/I_{1b}. \tag{1}$$

The self-impedances of the dipoles, Z_t and Z_r, the subscripts denoting their transmitting and receiving functions, are calculated [1, ch. 13, p. 108] assuming a linear taper for the extensible elements. An initial received signal level (load power), P_I = 1 W, is used with Z_t and the generator impedance to calculate the base current, I_{1b}. The mutual impedance Z_{21} is calculated based upon the antenna geometry, and V_{21}, the receiving dipole open circuit voltage, is obtained using (1). The final received signal level (load power) P_F is calculated using V_{21}, Z_r, and the receiver impedance. It is assumed that the receiving dipole current has no effect on the mutual impedance. That is, any additional mutual impedance effects caused by the fact that the receiving dipole impedance is not an open circuit are ignored. The ratio P_I/P_F is the insertion loss between the free-space dipoles.

Insertion loss between two thin dipoles in echelon over perfectly conducting plane ground may be calculated if they are vertically or horizontally polarized (a restriction only for the mutual impedance formulations used here), and their positions are specified. The test range geometry and multiple mutual impedances required for the calculation are shown in Fig. 2 for horizontal polarization. The value of I_{1b} is calculated using P_I = 1 W and the transmitting dipole impedance Z_{int}, which is equal to Z_t properly combined with the mutual impedance between it and its image in the perfectly conducting ground. A total mutual impedance consisting of Z_{21} and Z_{23} is used with I_{1b} to obtain V_{oc}, the open circuit voltage at the receiving dipole terminals. Input impedance of the receiving dipole is calculated and used with V_{oc} and the receiver impedance to obtain P_F. Again, the mutual impedance is assumed to be unaffected by the current in the receiving dipole's finite load impedance. This assumption results in an approximation to the value of P_F by reducing the number of mutual impedance relations to the four shown in Fig. 2.

The input impedances for the dipole antennas over perfect ground are given by

$$Z_{\text{int}} = Z_t \pm Z_{13} \tag{2}$$

for the transmitting dipole at a fixed height, and

$$Z_{\text{inr}}(h) = Z_r \pm Z_{24}(h) \tag{3}$$

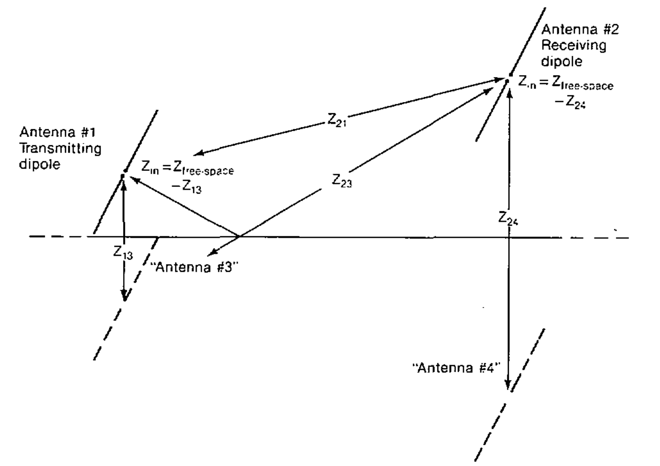


Fig. 2. Test range geometry and impedance relationships for horizontal dipole antennas.

for the receiving dipole at a variable height h. The sign of the mutual impedance is determined by the reflection coefficient of the ground plane, -1 for horizontal polarization and $+1$ for vertical polarization.

The power transmitted is given by

$$P_T = P_I(1 - |(Z_{\text{int}} - Z_G)/(Z_{\text{int}} + Z_G)|), \quad (4)$$

where Z_G is the generator impedance. The current required in (1) is given by

$$I_{1b} = (P_T/\text{Re}\ (Z_{\text{int}}))^{1/2}. \quad (5)$$

The total mutual impedance between the dipoles is given by

$$Z_m(h) = Z_{21}(h) \pm Z_{23}(h). \quad (6)$$

The receiving dipole open-circuit voltage is obtained using the definition of mutual impedance as

$$V_{\text{oc}}(h) = -I_{1b}|Z_m(h)|, \quad (7)$$

and the final received signal level (load power) delivered to the receiver at the dipole terminals is given by

$$P_F(h) = Z_R(V_{\text{oc}}(h)/|Z_R + Z_{\text{inr}}(h)|)^2 \quad (8)$$

where Z_R is the receiver impedance.

Finally, site attenuation (minimum insertion loss) for a pair of dipoles is given by

$$S_{\text{NBS}} = 10\ \log_{10}\ (P_I/P_F(H)),\quad \text{dB} \quad (9)$$

where $P_F(H)$ is the maximum value of $P_F(h)$ occurring at a height H in the range of heights over which the receiving dipole is scanned.

For the calculations, it is assumed that the generator and receiver impedances are real and equal to 100 ohms, and that $P_I = 1$ W.

Insertion loss between a receiving monopole and a fixed height transmitting dipole is calculated as above except for the following differences:

1) $Z_R = 50$ ohms;
2) $Z_{\text{inr}} = Z_r/2$;
3) $Z_m = Z_{21}$;
4) $h = H$ (the height of the dipole is fixed).

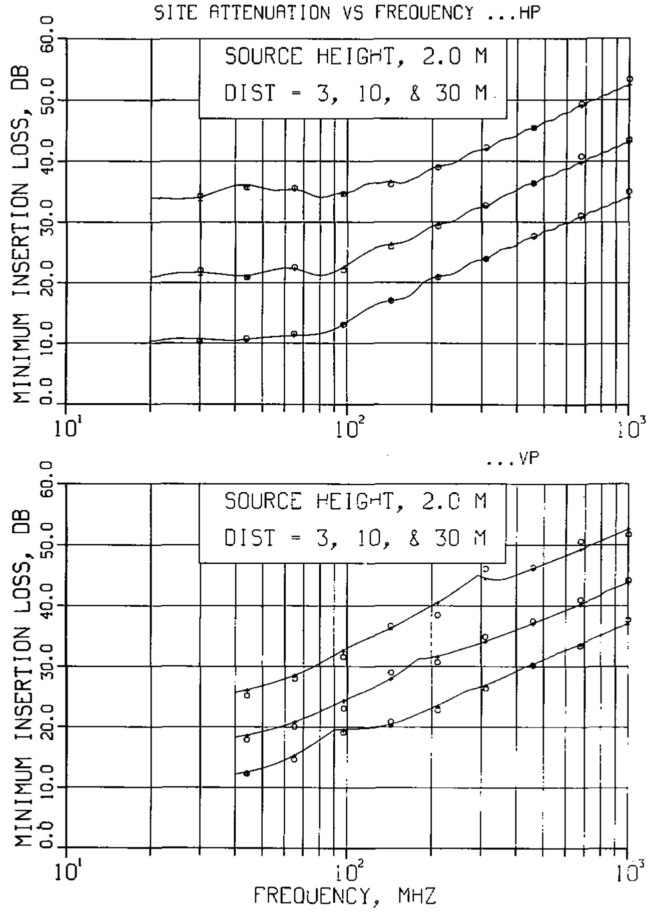


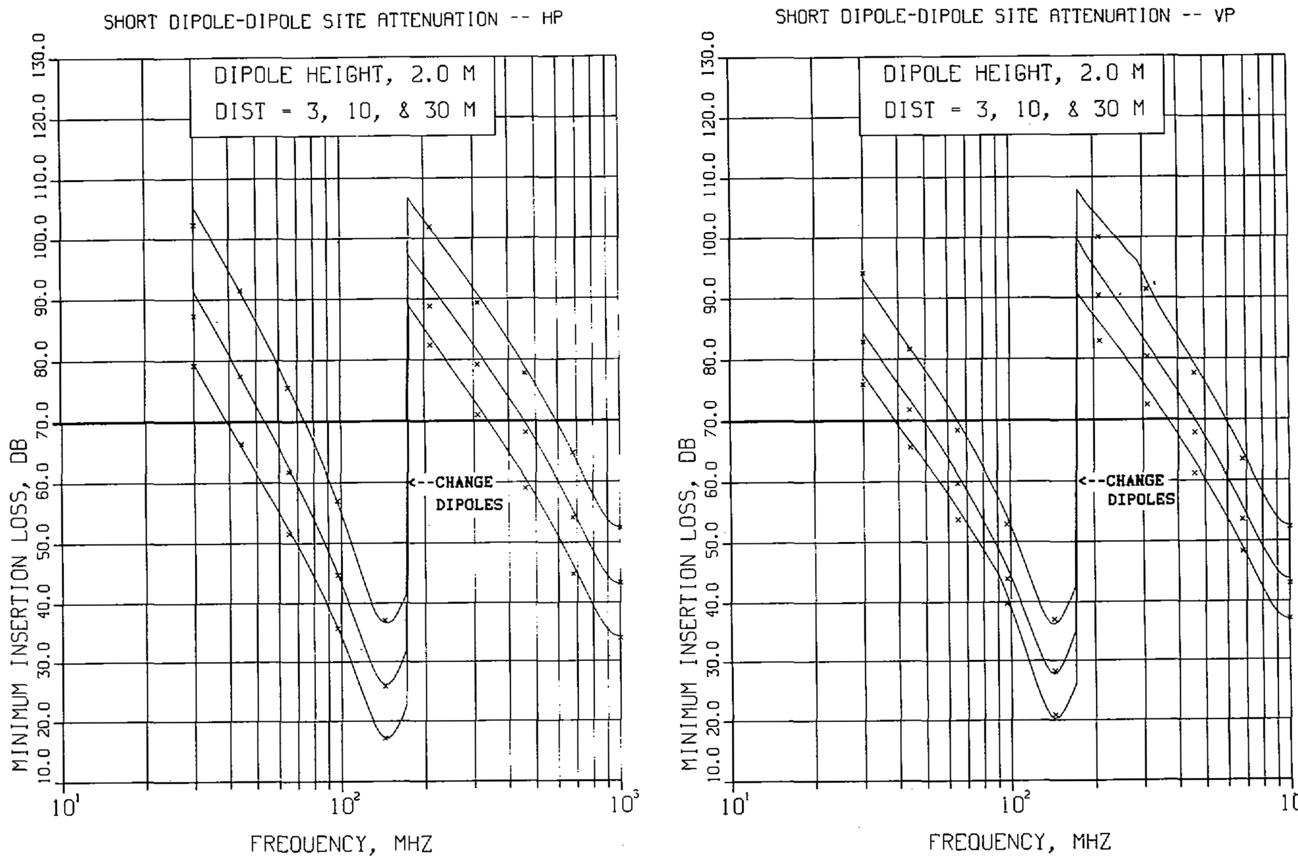
Fig. 3. Minimum insertion loss versus frequency for λ/2 dipoles horizontally polarized HP, and vertically polarized VP. Scan heights are 1–4 m for 3 and 10 m distances and 2–6 m for the 30 m distance. (This is data set 2). Solid line—calculated for infinitely thin λ/2 dipoles. + + + + + —calculated using real dipole dimensions. ○○○○○—measured using real dipoles.

Note that all impedances are "referred to the base" or terminal currents [6], and the antennas need not have the same overall length.

IV. Results

Figs. 3–5 show the results of the insertion loss measurements at 3 m, 10 m, and 30 m separation distances for λ/2 dipoles, for two short dipoles, and for the λ/4 monopole − λ/2 dipole pairs, over the 30 to 1000 MHz frequency range. The two short dipoles are actually the 143 MHz λ/2 dipole, used from 30 to 143 MHz, and the 1000 MHz λ/2 dipole, used from 210 to 1000 MHz. Therefore, these dipoles are not short at all measurement frequencies, and the 143 and 1000 MHz data in Figs. 3 and 4 should be identical. The purpose of this particular measurement is to determine the feasibility of simplifying site attenuation measurements made over a wide frequency range.

Table I lists a simple set of statistics, mean $\bar{x}$, and standard deviation σ, of the difference between the calculated and measured site attenuation data expressed in dB. The λ/2 dipole



(a) (b)

Fig. 4. (a) Minimum insertion loss versus frequency for two short dipoles horizontally polarized. Scan heights are same as for Fig. 3. Solid line—calculated using real dipole dimensions; × × × × ×—measured using real dipoles. (b) Minimum insertion loss versus frequency for two short dipoles vertically polarized. Scan heights same as for Fig. 3. Solid line—calculated using real dipole dimensions; × × × × ×—measured using real dipoles.

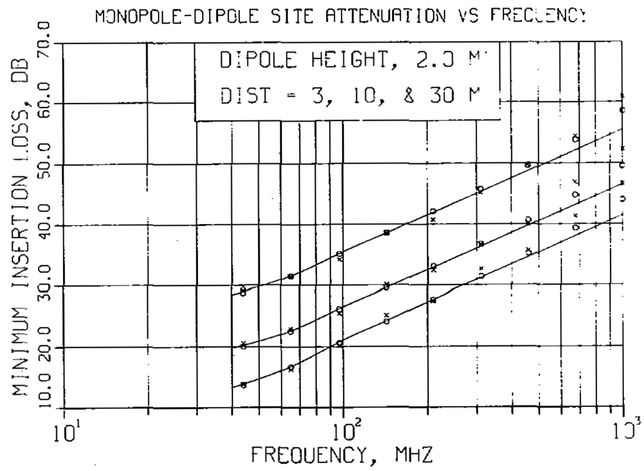


Fig. 5. Minimum insertion loss versus frequency for λ/2 dipole–λ/4 monopole antenna pair. Solid line—calculated for infinitely thin elements. ○○○○○—calculated using real antenna dimensions. × × × × ×—measured using real antennas.

data set 1 is not included because it was a preliminary set used to determine the suitability of the equipment. Some errors occurred in the results because the test site was not completely free of reflecting objects. Data set 2 was measured with an air supported fabric cover over the entire ground screen. Data set 3, the short dipole data, and the monopole-dipole data were measured without the cover. Additional sets of data are required to characterize the performance of these last two antenna geometries with more certainty.

Low measured P_F levels affect the accuracy of the short dipole insertion loss data, shown in Fig. 4, indicating that three short dipoles, not two, may be required for more accurate measurements over the entire 30 to 1000 MHz frequency range. Table I data indicate that the means are greater for the short dipole used from 210 to 1000 MHz than the means at the lower frequencies. The proportion of feed-point dielectric relative to the antenna element length may be too large for this antenna when it is electrically small.

There is no simple explanation for the large differences in measured and calculated monopole-dipole data at the two highest measurement frequencies shown in Fig. 5. The ground plane in the vicinity of the monopole may not be flat enough or a good enough conductor (a joint and 0.64 cm step are used between the aluminum mounting plate and the wire mesh ground screen).

Test range antenna heights and separation distances are set within ± 1 cm over a ground screen that is estimated to be flat within ± 1 cm. Dipole heights are measured at the feedpoint. Uncertainties in insertion loss caused by positioning errors are

TABLE I
STATISTICS FOR THE DIFFERENCE BETWEEN CALCULATED AND MEASURED DATA (S_{NBS} CALCULATED-S_{NBS} MEASURED), dB[1]

	Horizontal Polarization			Vertical Polarization		
Test Configuration	$\bar{x}$, dB	σ, dB	Sample Size	$\bar{x}$, dB	σ, dB	Sample Size
$\lambda/2$ dipoles						
(data set #2)	-0.02	0.40	30	0.03	0.86	27
(data set #3)	0.00	0.47	30	0.44	0.70	27
Short dipoles						
(all samples)	0.90	1.20	30	1.30	1.20	30
(30-143 MHz)	0.67	1.32	15	0.83	1.02	15
(210-1000 MHz)	1.14	1.05	15	1.79	1.09	15
$\lambda/4$ monopole - $\lambda/2$ dipole						
(all samples)				-0.44	1.12	27
(samples at 677 and 1000 MHz removed)				0.03	0.68	21

[1] These statistics are valid only when expressed as power ratios. For the small differences in measured and calculated data in this paper, the errors incurred in calculating these statistics using the dB values are considered negligible.

calculated to be $\leqq \pm 0.09$ dB. Horizontal $\lambda/2$ dipole droop at 30 MHz is calculated to cause a 0.05 dB uncertainty in mismatch loss at a 2 m height—an assumed worst case. Stability of the receiver and generator is evaluated as the repeatablity of P_I, measured as shown in Fig. 1(a), before and after each subset of measurement frequencies; each subset is determined by the frequency range of the three hybrid junctions required to cover the entire frequency range. This stability is typically $\leqq \pm 0.2$ dB, and results from connector mating, cable handling, and open-site environmental changes during the measurements. The inability of the 3 dB attenuators to force Γ_G and Γ_L to zero results in a difference between the calculated attenuation and the measured insertion loss of $\leqq \pm 0.27$ dB. This difference is calculated using the manufacturer's performance specifications for all components in Fig. 1(a). The largest source of uncertainty is the "cumulative fidelity" of the spectrum analyzer of $\leqq \pm 1.0$ dB over 0 to 80 dB display, 20–30° C. This uncertainty can be greatly reduced by calibrating the spectrum analyzer. A simple worst case uncertainty in these measurements is estimated to be $\leqq \pm 1.6$ dB assuming the automatic level control (ALC) in the generator maintains P_I constant for the two measurement conditions.

Bear in mind that Table I data, and the worst case uncertainty above, are for a *pair* of antennas. Even though the dipoles are identical, their heights over ground may be different when insertion loss is measured. The dipole and monopole are certainly not identical. Therefore, these data cannot be halved to obtain the performance uncertainty of a single antenna—but it is certainly a useful estimate.

V. CONCLUSION

One-half of the mean of the difference between measured and calculated $\lambda/2$ dipole insertion loss is $\leqq 0.22$ dB between 30 and 1000 MHz; for the short dipoles between 30 and 143 MHz it is $\leqq 0.42$ dB; and for the $\lambda/4$ monopoles between 44 and 459 MHz it is $\leqq 0.02$ dB. Note that the difference statistics are always better for horizontal polarization than for vertical polarization because of the small, unavoidable effects of the vertically oriented transmission lines. These results indicate the value of a very small part of the work of S. A. Schelkunoff and H. E. King.

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