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Height Extrapolation of Short- and Long-Term Averaged Wind Data

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ABSTRACT

Various models that are used for height extrapolation of short and long-term averaged wind speeds are discussed. Hourly averaged data from 3 tall meteorological towers (the NOAA Erie Tower in Colorado, the Battelle Goodnoe Hills Tower in Washington, and the WKY-TV Tower in Oklahoma), together with data from 17 candidate sites (selected for possible installation of large WECS) were used to analyze the variability of short-term average wind shear with atmospheric and surface parameters, and the variability of the long-term Weibull distribution parameter with height.

The exponents of a power law model, fit to the wind speed profiles at the three meteorological towers, showed the same variability with anemometer level wind speed, stability, and surface roughness as the similarity law model. Of the four models representing short-term wind data extrapolation with height (1/7 power law, logarithmic law, power law, and modified power law), the modified power law gives the minimum rms for all candidate sites for short-term average wind speeds and the mean cube of the speed. The modified power law model was also able to predict the upper-level scale factor for the WKY-TV and Goodnoe Hill Tower data with higher accuracy. All models were not successful in extrapolation of the Weibull shape factors.

1. INTRODUCTION

The extrapolation of wind speed data measured at a certain height (e.g., anemometer height) to another height (e.g., hub height) is a point of interest to many wind energy applications. The extrapolation of wind speed data to different heights varies considerably depending on whether the extrapolation is conducted over complex or relatively flat terrain. It is also dependent on whether short-term averaged (e.g., 10 minute - 1 hour) or long-term averaged (e.g., monthly, annual) wind data are considered. Each averaging period presents a distinctly different problem. The long-term averaged wind data are functions of the statistics of occurrence of various atmospheric parameters and can only be predicted through empirical models. The extrapolation of short-term average wind speeds over flat terrain is well understood by the Monin-Obukhov similarity theory (1). The theory applies to the inertial sublayer, where the turbulent shear stresses and heat fluxes are independent of height. The depth of this layer can vary from 20 to 200 m (2) depending on the stability conditions.

2. EXTRAPOLATION OF SHORT-TERM AVERAGE WIND SPEEDS OVER RELATIVELY FLAT TERRAIN

2.1 The Similarity Model

The similarity model is based on the Monin-Obukhov similarity theory. It only applies for relatively flat terrains and within the depth of the inertial sublayer of the atmospheric boundary layer. To express the relationship in a power law form between heights Z and Z_a, the wind speed U is given by

$$U(Z)/U(Z_a) = (Z/Z_a)^{\alpha_e} , \qquad [1]$$

where the effective exponent α is given by

$$\alpha_e = \frac{\phi(Z_g/L)}{\ln(Z_g/Z_o) - \psi(Z_g/L)} \qquad [2]$$

where

ϕ and ψ are universal functions of (Z_g/L) (3)

Z_g is the geometric mean height $(Z \cdot Z_a)^{1/2}$

Z_o is the surface roughness length

L is the Monin-Obukhov length.

The surface roughness length is a physical parameter that determines the impedance to the wind flow. Water and ice have lower surface roughness lengths than wooded and urban areas. L is a measure of the combined mechanical and thermal turbulence in the atmosphere. This quantity is in turn physically related to surface layer turbulence caused by wind shear, surface heat flux, and surface roughness length. By examining wind speed temperature profiles and surface radiation from various meterological towers, a universal function relating L to the anemometer level wind speed, net radiation, and surface roughness is established (4). Figure 1 gives the effective exponent for different 10-m level wind speeds, surface roughness lengths, and radiation indices. A negative index indicates outgoing radiation (nighttime), and a large positive index indicates a high incoming radiation. The graph shows clearly that as the anemometor level wind speed increases beyond a certain value, which is a function of surface roughness and insolation, the effective exponent converges to the 1/7 power law value.

The effect of stability is also clearly demonstrated at low radiation index value (nighttime) compared to high radiation index value (daytime). To eliminate the effect of stability on the effective power law exponent, limits of equation 2 are taken as $1/L \longrightarrow 0$ or $L \longrightarrow \infty$ for neutrally stable conditions, and the resulting exponent is the logarithmic power law model exponent.

$$\alpha_e = 1/\ell_n\,(Z_g/Z_o) \qquad [3]$$

Hence, the 1/7 power law is the limit of the similarity model for high anemometer level wind speeds, and the logarithmic law is the limit of the similarity model for neutrally stable conditions. Figures 2 and 3 show the exponent variability for the Goodnoe Hills and the Erie Towers, respectively. Goodnoe Hills and Erie Towers had a surface roughness length of 0.05 and 0.11 m (estimated by Battelle-Pacific Northwest Laboratory), respectively; a geometric mean height of 32.7 and 38.7 m, respectively; and an anemometer level of 10 m. Figure 4 compares the variability of the theoretical Monin-Obukhov wind speed exponent for Z_o= 0.1 m and Z_g = 22.3 m with the WKY-TV tower exponent for the hourly averaged data with Z_g = 25 m and Z_o= 0.07 m for nighttime and daytime. There is fairly good agreement between the observed and the predicted exponents. The slight variance is due to lumping all the stability categories into nighttime and daytime for the WKY-TV Tower data, while the stable and unstable curves represent stability categories -2 and 2 on a scale of -2 (stable) to 6 (unstable).

2.2 Power Law Model

The power law model (5) is an empirical model based on the height variability of long-term averaged data in four sets of meteorological tower data: Kennedy Space Flight Center (Florida); Wallops Island (Virginia); Hanford (Washington); and the WKY-TV Tower data in Oklahoma City (Oklahoma). The power law model is given by

$$U(Z)/U(Z_a) = (Z/Z_a)^{\alpha_p} \qquad [4]$$

where

$$\alpha_p = a + b\ \ell_n[U(Z_a)]\ ;$$

$$a = 0.37/[1 - 0.088\ \ell_n(Z_a/10)]$$

$$b = -0.088/[1 - 0.088\ \ell_n(Z_a/10)]\ .$$

The coefficients a,b were obtained by equating the probability of occurrence of an upper level wind speed at height Z that corresponds to a lower level wind speed at height Z_a for the four sets of tower data.

2.3 Modified Power Law Models

To combine the accuracy of a theoretical model with the simplicity of an empirical model, the modified power law model was suggested (3). The model is surface roughness, anemometer level wind speed, and height dependent. However it represents average stability conditions (Figure 1). The model is based on the power law model and the similarity model. The modified power law is given by

$$\alpha_m = a_m + b\ell_n[U(Z_a)] \qquad [5]$$

where

$$a_m = 1/\ell_n(Z_g/Z_o) + [0.088/$$
$$1 - 0.088\ \ell_n\ (Z_a/10)]\ .$$

Data taken at the U.S. candidate sites, for possible installation of large DOE turbines, were used to compare the performance of the modified power law model with the frequently used 1/7 power law and logarithmic models. Since stability information was not available for candidate sites, the similarity model was not used. Table 1 shows the observed average wind speed at hub height $\overline{VO}$ versus the average predicted wind speed at the hub height using the modified power law model $\overline{VM}$; the power law model $\overline{VP}$; the logarithmic model $\overline{VL}$; and the 1/7 power law model $\overline{V7}$. The table also gives the observed and predicted mean cube of the wind speed at hub height

$$\overline{VO^3},\ \overline{VM^3},\ \overline{VP^3},\ \overline{VL^3},\ \overline{V7^3}.$$

The modified power law model gives the minimum rms error for all candidate sites for the wind speed (0.28 m s^{-1}, 5.9%) and for the mean cube of the speed (115.2 $m^3\ s^{-3}$, 16.6%). Although the logarithmic law seems to perform as well as the modified power law

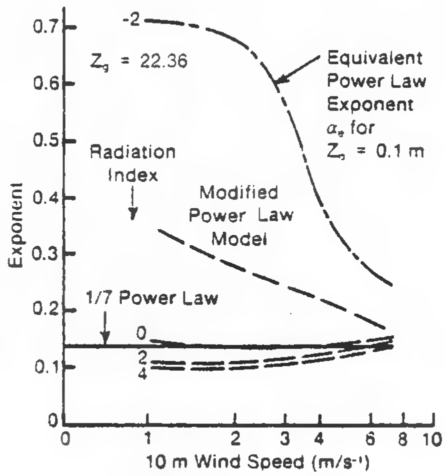

Figure 1. Effective Exponent for Various Parameters

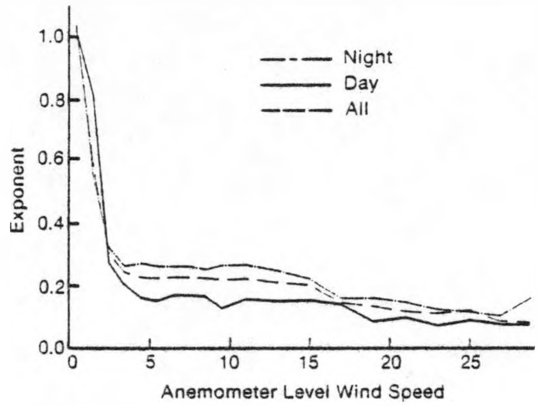

Figure 2. Exponent Variability for the Goodnoe Hills Tower

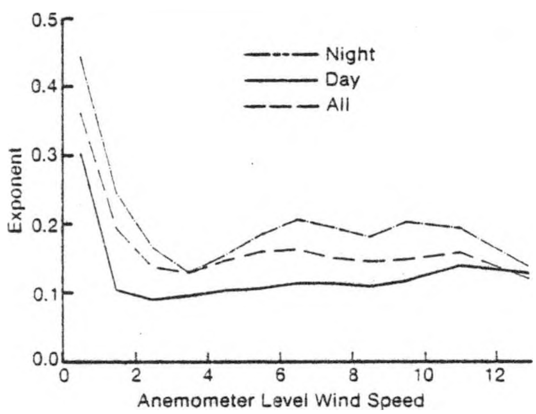

Figure 3. Exponent Variability for the Erie Tower

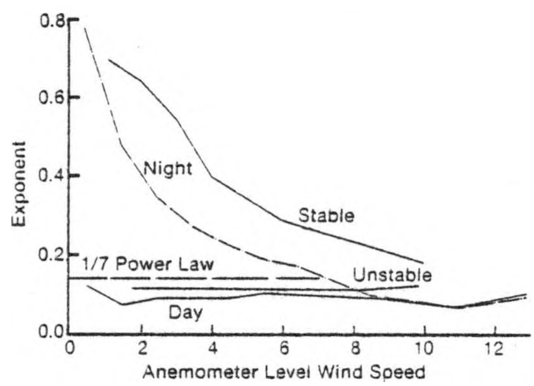

Figure 4. Exponent Variability for the WKY-TV Tower

in predicting the average wind speed, the error associated with predicting the mean cube of the speed is higher. This will have a direct effect in the estimation of power output at hub height.

3. EXTRAPOLATION OF LONG-TERM AVERAGE WIND DATA OVER RELATIVELY FLAT TERRAIN

Long-term average wind data include wind speeds averaged over a period of several hours or more and a long-term frequency distribution parameters. The Weibull distribution was found to adequately fit observed wind speed distributions. The Weibull distribution is given by:

$$P(V) = 1 - \exp\left[-(V/C)^k\right] \qquad [6]$$

where

- C is the scale factor
- k is the shape factor
- P(V) is the probability density function.

3.1 Model Descriptions

The extrapolation of long-term wind data, that includes average wind speed and Weibull distribution parameters, following the power law model (equation 4) is given by

$$C_2/C_1 = (Z_2/Z_1)^{\overline{\alpha}} , \qquad [7]$$

TABLE 1. OBSERVED VS. PREDICTED HUB HEIGHT WIND SPEEDS (m/s) AND MEAN CUBED WIND SPEEDS (m^3/s^3) FOR CANDIDATE SITE DATA

Site Code	H1	H2	$\overline{VO}$	$\overline{VM}$	$\overline{VL}$	$\overline{VP}$	$\overline{V7}$	$\overline{VO^3}$	$\overline{VM^3}$	$\overline{VL^3}$	$\overline{VP^3}$	$\overline{V7^3}$
LDG	18.2	45.7	7.56	7.31	7.36	6.52	6.07	815.6	807.9	924.8	571.4	518.4
CAO	9.1	45.7	7.50	7.35	7.42	7.75	7.01	698.7	693.8	830.5	815.3	699.6
AGP	18.2	45.7	8.92	8.48	8.69	8.57	8.15	1179.1	963.6	1112.7	995.0	916.7
CLB	9.1	45.7	6.77	6.47	6.57	8.66	7.88	415.7	361.4	411.8	864.5	710.4
KGS	9.1	45.7	6.84	6.64	6.73	7.99	7.26	611.7	518.6	635.3	903.0	796.9
RSL	9.1	45.7	7.56	7.64	7.72	7.82	7.07	710.5	763.6	918.0	820.1	705.2
PAA	9.1	45.7	6.67	6.35	6.35	7.34	6.57	578.2	441.7	507.1	680.5	562.3
SGN	9.1	45.7	8.02	7.95	8.29	8.71	8.14	1387.1	1105.7	1475.6	1454.2	1394.1
HON	9.1	45.7	6.94	6.68	6.64	7.05	6.27	600.3	518.0	590.2	608.8	497.2
BON	18.2	45.7	7.96	7.65	7.81	7.73	7.32	1011.7	959.4	1146.6	990.7	944.6
WTK	18.2	45.7	7.49	7.34	7.47	7.74	7.30	747.7	718.6	829.4	840.8	775.0
BID	9.1	45.7	7.46	7.28	7.22	6.86	6.06	696.1	536.4	710.3	530.9	420.3
HOL	18.2	45.7	7.32	7.33	7.34	6.35	5.87	771.4	684.9	751.2	444.2	385.2
AMA	9.1	45.7	8.04	7.92	6.55	8.73	6.47	795.0	715.0	523.0	958.9	504.0
BDN	9.1	39.6	5.16	5.84	5.73	5.99	5.30	308.5	398.9	440.0	428.3	348.6
BDN	9.1	70.1	5.48	6.40	6.23	6.82	5.75	357.9	494.1	565.4	596.0	445.3
KAN	9.1	27.4	7.40	7.16	7.28	7.43	7.01	837.7	677.8	776.7	756.4	692.0
KAN	9.1	54.9	7.79	8.20	8.43	8.52	7.74	971.4	963.8	1205.6	1083.1	932.1
RMS error				0.28 m/s 5.9%	0.48 m/s 6.8%	0.82 m/s 12.4%	0.83 m/s 11.1%		115.2 m/s 16.6%	131.0 m^3/s^3 22.3%	194.5 m^3/s^3 37.3%	188.0 m^3/s^3 28.5%

where

$$\overline{\alpha} = a + b\ \ell_n C_1 ;$$

$$k_2/k_1 = [1 - 0.088\ \ell_n\ (Z_1/10)]/[1 - 0.088\ \ell_n\ (Z_2/10)] ; \qquad [8]$$

and

$$\overline{V}_2/\overline{V}_1 = (Z_2/Z_1)^{\overline{\alpha}_1} , \qquad [9]$$

where

$$\overline{\alpha}_1 = a + b\ \ell_n\ V_1 ;$$

where C_1 and k_1 are the Weibull scale and shape parameters, respectively, corresponding to height Z_1; and C_2 and k_2 are the Weibull scale and shape parameters corresponding to height Z_2. $\overline{V}_2$ and $\overline{V}_1$ are long-term average wind speeds at height Z_1 and Z_2, respectively.

The height surface roughness, stability dependent, modified power law model is given by the same relation as equations 7-9 except coefficient a is replaced by a_m from equation 5.

Spera and Richards (6) developed a surface roughness dependent power law model for long-term average speeds and Weibull parameters. The exponent $\overline{\alpha}_2$ is given by

$$\overline{\alpha}_2 = \alpha_o \frac{1 - \log V_1/\log V_h}{1 - \alpha_o \log(Z_1/Z_r)/\log V_h} \qquad [10]$$

where

$\alpha_o = (Z_o/Z_r)^{0.2}$
α_o = surface roughness exponent
V_h = homogeneous wind speed ($\overline{\alpha}_2$ = 0) ($m\ s^{-1}$)
V_1 = steady wind speed at elevation Z_1 ($m\ s^{-1}$)
Z_r = reference elevation (10 m)
Z_o = surface roughness length (m)

and where the Weibull parameters C and k are related by:

$$C_2 = C_1(Z_2/Z_1)^{\alpha_c} \qquad [11]$$

where

$$\alpha_c = \alpha_o \frac{1 - \log C_1/\log V_h}{1 - \alpha_o \log\ (Z_1/Z_r)/\log V_h}$$

and

$$k_2 = k_1 \frac{1 - \alpha_o \log\ (Z_1/Z_r)/\log V_h}{1 - \alpha_o \log\ (Z_2/Z_r)/\log V_h} . \qquad [12]$$

3.2 Model Verification

The hourly averaged data were used to calculate the lower-level Weibull distribution parameters, and the suggested models were used to predict the upper-level Weibull parameters for the NOAA Erie Tower in Colorado, the Battelle Goodnoe Hills Tower in Washington, and the WKY-TV Tower in Oklahoma. The observed upper-level Weibull parameters were then compared with the predicted values from the power law and modified power law models with the velocity-surface roughness models (equations 10-12). The surface roughness length was 0.11 m for the Erie Tower, 0.07 m for the Goodnoe Hills Tower, and 0.05 m for the WKY-TV Tower.

Figures 5 through 7 show clearly that the modified power law model (roughness-, height-, and velocity-dependent) generally predicts upper-level parameters with higher accuracy than the roughness- and velocity-dependent NASA power law and the power law models. However, all models failed to accurately predict the scale factor for the upper levels of the Erie Tower. This might be attributable to the complex terrain for certain prevailing wind directions near the Erie Tower. The maximum observed error in the C value for the modified power law model is <2% for the Goodnoe Hills Tower data, 6% for the WKY-TV Tower data, and 28% for the Erie Tower data. Except for the WKY-TV Tower data, all tower data show an increase in the scale factor prediction error with height, which is attributable to the breakdown of the similarity assumption with the increase of height from the ground.

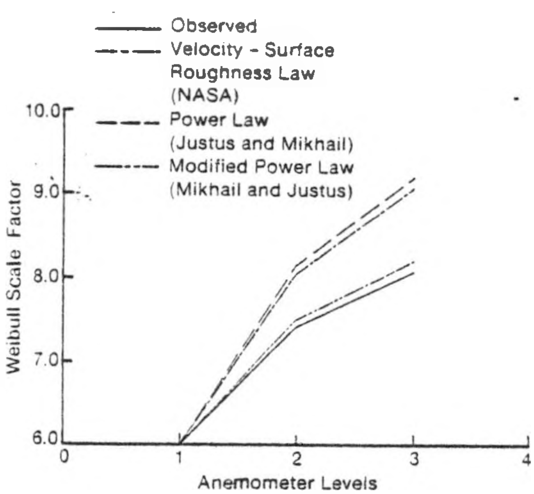

Figure 5. Upper-Level Weibull Parameters Predicted at the Goodnoe Hills Tower

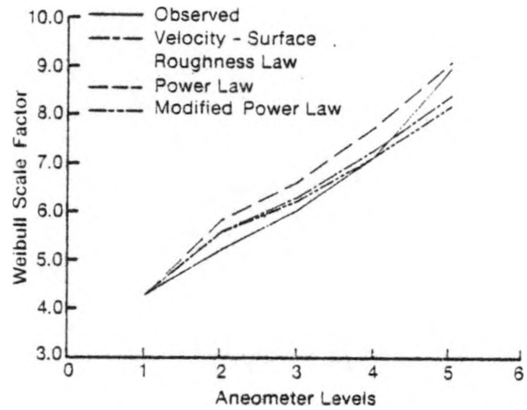

Figure 6. Upper-Level Weibull Parameters Predicted at the WKY-TV Tower

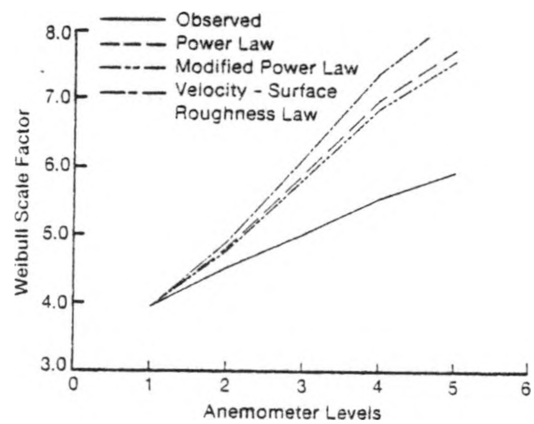

Figure 7. Upper-Level Weibull Parameters Predicted at the Erie Tower

Figures 8 through 10 show the predicted shape factor by the modified and power law models (identical k projection) and the NASA model. All models seem to overestimate the values for the Erie and Goodnoe Hills Towers, and underestimate the value for the WKY-TV Tower. The maximum error is about 25%, which can be significant in the prediction of turbine power output at hub height.

4. CONCLUSIONS

The observed power law exponent for all three towers showed strong dependence on the anemometer level wind speed and atmospheric stability (nighttime and daytime). It also exhibited a high degree of dependence on extrapolation height with respect to

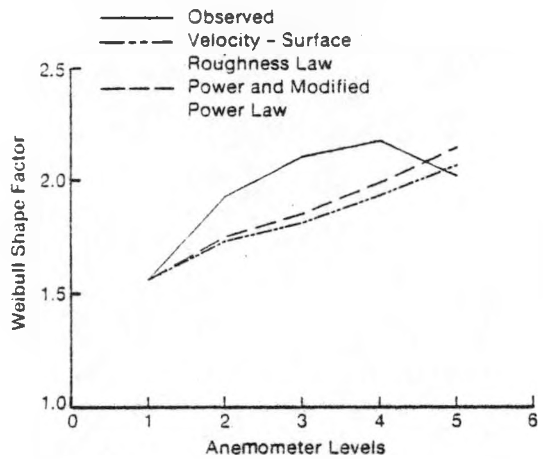

Figure 8. Predicted Shape Factor of the WKY-TV Tower

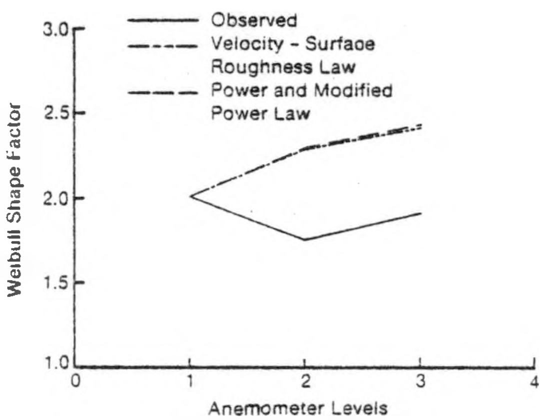

Figure 9. Predicted Shape Factor of the Goodnoe Hills Tower

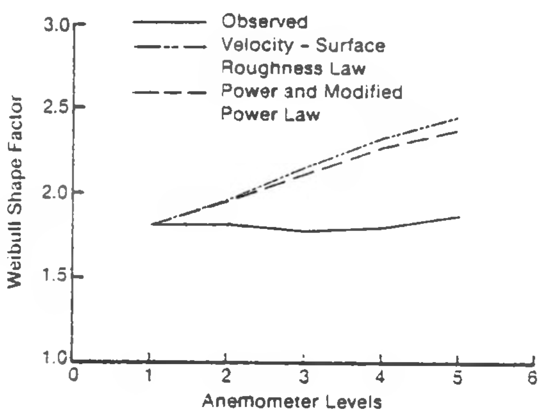

Figure 10. Predicted Shape Factor of the Erie Tower

anemometer height. These dependences became less severe as the anemometer level wind speeds were increased due to the dynamic mixing of the atmospheric boundary layer.

The data from candidate sites were used to compare the performance of the 1/7 power law model, the logarithmic law model, the power law model, and the modified power law model. The 1/7 power law and the surface roughness dependent logarithmic law are commonly used for height extrapolation. The power law is an empirical model that is dependent on the lower level wind speed. The modified power law is a semi-empirical model that is height, surface roughness, and lower wind speed dependent. The modified power law model had the minimum rms error for all candidate sites for wind speed (0.28 $m\ s^{-1}$, 5.7%) and for mean cube of the speed (115.2 $m^3\ s^{-3}$, 16.6%).

The three models used for Weibull distribution parameters extrapolation were the power law, the modified power law, and the velocity-surface roughness dependent models. The models projected the scale parameter C fairly accurately for the Goodnoe Hills and WKY-TV Towers and were less accurate for the Erie Tower. However, all models have overestimated the C value. The maximum error for the modified power law model was <2% for Goodnoe Hills, 6% for WKY-TV, and 28% for Erie. The error associated with the prediction of the shape factor (k) was similar for the three models. It ranged from 20% to 25%.

5. Acknowledgment

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