ESTIMATES OF ROUGHNESS LENGTH FROM MINISONDE PROFILES IN THE ATHABASCA OIL SANDS AREA

RMD Report L-87

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ESTIMATES OF ROUGHNESS LENGTH FROM MINISONDE PROFILES IN THE ATHABASCA OIL SANDS AREA

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by

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INTERA Technologies Ltd.

for

RESEARCH MANAGEMENT DIVISION
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ABSTRACT

Minisonde data collected in the Athabasca Oil Sands area from 1975 to 1979 were analysed to determine regional values of roughness length (Z_o). A rigorous selection procedure reduced the working data set to a small fraction of the original size. A least squares technique was used to determine Z_o from profiles of wind and temperature typically measured near the 50, 100, and 150 m levels.

Mean Z_o values calculated with allowance for diabatic and displacement height effects ranged from about 8 m downwind of the Syncrude plant site to about 1 m in the Athabasca River valley. Uncertainties in the estimates were of the same magnitude as the mean values. No differences in Z_o were found with wind direction. The large values for Z_o were attributed primarily to form drag from terrain features in the area during slightly unstable conditions. The study suggested that, where form drag is important, Z_o may be stability dependent.

An error analysis using reasonable uncertainties for wind speed, balloon height, and temperature gradient measurements showed that probable errors in the estimate of Z_o were comparable to the observed variability in Z_o.

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1. INTRODUCTION

The roughness length is a parameter relating wind drag at a surface to the vertical gradient of horizontal wind speed. It indicates the extent to which mechanically-induced turbulence is generated by wind flow over particular surfaces. For air quality studies, the roughness length enters the dispersion formulation either directly or by means of site-specific empirical parameters. For example, in the Gaussian frequency distribution model developed by Davison et al. (1981a), the roughness length (Z_o) is used explicitly to calculate the friction velocity and, hence, the fluctuations of the wind for the dispersion formulation.

The general study of wind profiles and surface stress, of which measurement of roughness length is a part, has proceeded from uniform, flat terrain to various types of topography and surface conditions. Walmsley et al. (1982) and Taylor et. al. (1983) described the application of a three-dimensional numerical model based upon Mason and Sykes (1979) to a small-scale terrain feature (Kettles Hill, Alberta). An extensive low level wind profile measurement program at Kettles Hill (Taylor et al. 1982) provided encouraging experimental support for the model predictions. However, the results indicated a need for spatially varying roughness lengths.

Generally, the effective roughness length has been found to be both direction- and height- dependent. Beljaars et al. (1983) found that the friction velocity (u_*) changed with height in response to changes in upstream roughness and that the vertical velocity fluctuations tended to scale with a "local" u_* at 3.5 m whereas horizontal fluctuations tended to scale with global values of u_* measured at 22.5 m. Ming et al. (1983) analysed routine wind profiles from three towers over 100 m high in various types of complex terrain in New England. They calculated effective roughness lengths for upper and lower parts of the profile and attempted to relate the values obtained to surface features various distances upstream using Hojstrup's (1981) relationship between height on a tower and upstream distance of influence. Ming et al. attributed some of the large roughness lengths in the upper layers (as large as 11 m) to form drag effects due to low hills (100 to 200 m) upstream of the tower site.

In the present study, minisonde data from the Athabasca Oil Sands area were used to estimate a value of roughness length appropriate to the region. The minisonde profiles were collected and processed by various groups and made available by Alberta Environment as a digital data set.

2. IMPORTANCE OF THE ROUGHNESS LENGTH IN THE ATHABASCA OIL SANDS

Mechanical mixing is thought to be an important (although perhaps not dominant) process occurring frequently in the Athabasca Oil Sands area. During daylight hours throughout late spring to early autumn, thermal mixing will also be important; however, mechanical mixing will still be important when winds at plume height are greater than approximately 6 to 8 ms^{-1}.

In a sensitivity and validation study of a Gaussian frequency distribution model, Davison et al. (1981b) showed that changing Z_o from 0.3 to 0.9 m caused marked changes in both the location and magnitude of the maximum ground level concentration (GLC) values. The changes were functions of the source characteristics, the thermal stability, and the wind speed. For example, at a downwind distance of 5 km in mechanically dominated mixing, the sector-averaged GLC values were increased by over 40% when Z_o was increased from 0.3 to 0.9 m. This was a greater effect than changing the wind speed from 10 to 15 ms^{-1}.

In stable conditions, the effect of changing Z_o from 0.3 to 0.9 m was to increase the GLC value by more than a factor of two and to change the location of the maximum by many kilometres. The sensitivity study also showed that adopting a value for Z_o of 0.9 m largely removed any systematic discrepancies between predicted and observed GLC values within the limits of the available data.

3. CHARACTERISTICS OF THE MINISONDE DATA BASE

3.1 DATA SOURCES

The minisonde data base used to determine Z_o was collected in the Athabasca Oil Sands area from 1975 to 1979. Many of the releases took place during intensive field studies in 1976 and 1977. Both single and double theodolite readings were taken; most of the single theodolite measurements were taken prior to 1977. Data from about 2000 minisondes released during daylight hours were available. For the double theodolite releases, observational intervals were 15 to 30 s which provided spatial resolutions of about 50 m.

3.2 DESCRIPTION OF SITES

The Athabasca Oil Sands area is characterized by a river valley within a region of rolling terrain. The major topographical features are the Birch Mountains running southwest to northeast about 40 km northwest of the site, Stoney Mountain about 40 km to the south, and a gradual rise to Muskeg Mountain in the east. The ground cover is a mixture of white spruce and aspen and open black spruce stands within fen and bog areas (Thompson et al. 1978).

The minisonde data examined in this report were from two sites, Syncrude and Lower Syncrude (see Figure 1). The Syncrude minisonde site is located about 50 m southeast of the Syncrude plant. To the south through west to northeast (170° to 040°) within about 1.5 km from the release site are plant buildings of one to several stories in height and the main stack which is over 180 m high. Beyond about 2 km are scattered strip mines free of vegetation intermixed with semi-open white spruce and aspen forest. Southeast of the release site, the land drops away slowly with a slope of about 10 m in 4 km and is covered by semi-open white spruce and aspen forest ranging in height up to 10 m.

The Lower Syncrude site is located within the Athabasca River valley flood plain about 200 m west of the river and 1 km east of the west bank of the valley. The bank rises about 60 m in 200 m and the the bank axis is oriented north-northwest to south-southeast for

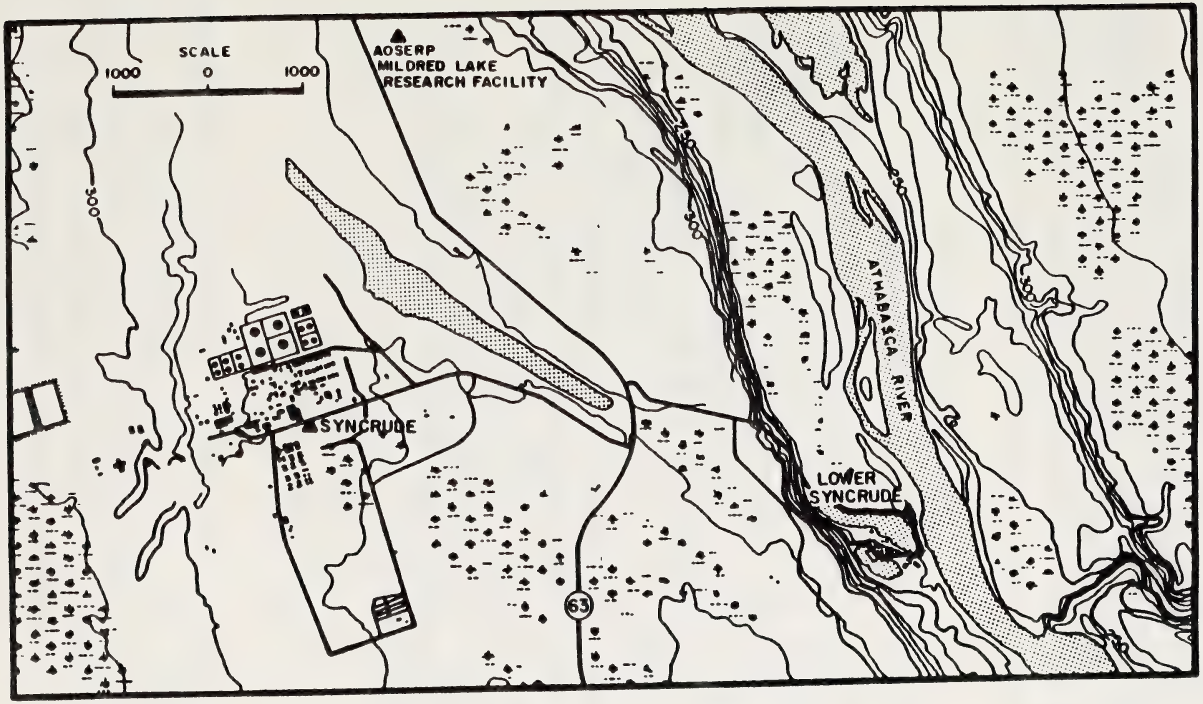

Figure 1. Map of Syncrude and Lower Syncrude minisonde release sites in late 1976. Contour intervals are 10 m. Horizontal scale is in metres.

several kilometres in either direction from the release site. To the north for 1 km and northwest for several kilometres is a flat bog/fenland. Similar vegetation exists to the east for 200 m; beyond that lies the river which is approximately 800 m wide. About 100 m to the southeast and south of the release site is a small lake about 300 m wide; beyond the lake is a grouping of low buildings typically 10 m or less in height.

3.3 UNCERTAINTIES IN THE MINISONDE MEASUREMENTS

Uncertainties inherent in calculations of wind speed and direction, temperature lapse rate, and balloon height from double theodolite minisonde techniques were examined by Schaefer and Doswell (1978) and extended by Netterville and Djurfors (1979). Measurement errors were shown to accumulate with time since release; errors associated with readings below 200 m (less than two minutes from release with typical ascent rates of 2 ms^{-1}) were less than 10%. Note that this is the minimum expected error; observer error and lack of instrument resolution will increase this value.

Atmospheric turbulence introduces additional uncertainties into estimates of the ensemble-average profile measurements. Following Netterville and Djufors (1979),

$$\varepsilon_u{}^2 = 1/T\ (\sigma_u/U)^2 \int_0^T R_L(t)\ (1 - t/T)\ dt \tag{1}$$

where ε_u is the relative wind error, T is the averaging time between consecutive position fixes, σ_u/U is the along-wind turbulent intensity, and R_L is the Lagrangian autocorrelation coefficient. The typical averaging times for minisondes are significantly less than the Lagrangian integral time scales and so the error estimate is approximately

$$\varepsilon_u \sim 0.7\ \sigma_u/U \tag{2}$$

The value of σ_u/U is a function of roughness length and stability and also involves low-frequency contributions which do not obey Monin-Obukhov scaling (Panofsky 1973). A typical value in strong winds (neutral conditions) at a height of 100 m with $Z_o = 1$ m is

$$\sigma_u/U = \sigma_u \, k/(u_* \ln Z/Z_o) \sim 0.2 \qquad (3)$$

where k is von Karman's coefficient. Combining (2) and (3) and noting that the error estimates associated with the minisonde readings are independent leads to a probable error of about 20%.

Much of the minisonde data produced in the Athabasca Oil Sands area has been examined by Davison and Leavitt (1979) who cited several cases of profiles that were likely incorrect based on known meteorological conditions and on comparisons with other profiles. They also estimated errors in wind speed to be about 20%.

Some of the minisonde data, especially prior to 1977, are based upon single theodolite measurements with an assumed rise rate. The error associated with single theodolite measurements over the first several hundred metres is probably largely dependent upon the precision of balloon inflation by the minisonde technician.

4. ROUGHNESS LENGTH CALCULATIONS

4.1 PROFILE ANALYSIS

Monin-Obukhov similarity theory has proven to be effective for interpreting atmospheric boundary layer wind profiles. The wind shear can be expressed as follows (Businger 1973):

$$\Phi_m = kZ/u_* \, \partial U/\partial Z \tag{4}$$

$$\Phi_m = (1 - 15\ Z/L)^{-1/4} \quad \text{for } Z/L < 0 \text{ (unstable)} \tag{5}$$

$$\Phi_m = 1 + 5\ Z/L \quad \text{for } Z/L > 0 \text{ (stable)} \tag{6}$$

where k is von Karman's constant and L is the Monin-Obukhov length. Explicit expressions for the wind profile (Paulson 1970) are, for $Z/L < 0$:

$$U/u_* = (\ln Z/Z_o - \Psi_1)/k \tag{7}$$

$$\Psi_1 = \ln\left[(1+X)^2(1+X^2)/8\right] - 2\tan^{-1}(X) + \pi/2 \tag{8}$$

where

$$X = \Phi_m^{-1} = (1-15\ Z/L)^{1/4} \tag{9}$$

and for $Z/L > 0$:

$$U/u_* = (\ln Z/Z_o - \Psi_2)/k \tag{10}$$

where

$$\Psi_2 = -4.7\ Z/L \tag{11}$$

Because fluxes were not directly measured, the bulk Richardson number was used to estimate Z/L (following Arya 1982)

$$Z/L = Ri \quad \text{when } Ri < 0 \tag{12}$$

$$Z/L = Ri/(1-5\ Ri) \quad \text{when } Ri > 0 \tag{13}$$

where

$$Ri = g/\theta\ (\Delta\theta/\Delta Z)\ \bar{Z}^2/U_T^{\,2} \qquad (14)$$

and θ is potential temperature, $\overline{Z}$ is the geometric mean height, and U_T is the wind speed nearest the 150 m level. These equations have been found to be generally valid to heights as high as 150 to 200 m (Lumley and Panofsky 1964).

The Richardson number and the Monin-Obukhov length were calculated from the minisonde data. The Z_o was estimated by a least squares fit of U versus (in Z $-\Psi$) for each profile. Since the first temperature value was typically at 50 or 60 m (surface data were not provided) the diabatic influence for convective conditions could be significantly underestimated, even through diabatic effects may be large enough to mask Z_o effects on the profiles. Minisonde selection criteria and profile-by-profile examination were used to ensure that candidate profiles were indeed mechanically dominated and coupled to the surface.

4.2 MINISONDE SELECTION CRITERIA

The 2000 minisonde profiles used in the study were subjected to a selection process to produce well-behaved candidate profiles for roughness length calculations. Required profile attributes included:

1. Wind speeds in access of about 5 ms^{-1} and temperatures decreasing with height to ensure that the flow was coupled to the surface; and
2. Wind speeds increasing approximately logarithmically with height after compensation for diabatic effects.

Three data points were considered a minimum number to define a profile. A constraint was also required on the wind turning with height as a large turning could indicate the presence of a stable layer and hence decoupling of the winds from the surface.

The data selection criteria that produced these requirements included:

1. At least three measurements below a maximum height;
2. Minimum wind speeds greater than a specified value;
3. Monotonically increasing wind speeds and decreasing temperature with height;

4. variability constraint on wind direction, wind speed, and temperature profiles;
5. temperature lapse rate;
6. date of data collection (to stratify by season).

Table 1 shows the number of qualifying profiles for various combinations of selection criteria. The requirements of a minimum wind speed of 5 ms^{-1} at all levels with reasonable constraints for a uniform profile of wind speed, wind direction, and temperature resulted in a very large reduction in the number of qualifying profiles. This reduction is consistent with the climatologically light wind speeds of the area (Longley and Janz 1978). Further constraints on the temperature lapse rate and the maximum height for the lowest three measurements were considered to be prudent for estimating roughness lengths. The selection criteria adopted for the roughness length calculations are shown in Table 1 and consisted of 150 m maximum height and a lapse rate within 0.5°C/100 m of adiabatic. Note that lapse rate had little effect on the number of profiles chosen. The criteria which most reduced the data set were 5 ms^{-1} minimum wind speed and the three-level profile. No attempt was made to stratify by season because of the small number of selected profiles. While the small number of profiles might have increased the uncertainty of the mean Z_o values, rigorous selection ensured that only well behaved profiles were used.

4.3 ROUGHNESS LENGTH ESTIMATES

Roughness length estimates for profiles meeting the selection criteria are shown in Table 2. Included are estimates with no diabatic effects, with diabatic effects but no displacement heights, and with diabatic effects for a range of assumed displacement heights.

Bulk Richardson numbers near zero in Table 2 resulted in Z_o values corrected for diabatic effects being approximately equal to neutral Z_o values. When gradient Richardson numbers were used for comparison, as in Ming et al. (1983), increased variability in both R_i and Z_o were noted. Gradient R_i tended to be larger in absolute value, with some exceeding the assumed critical value of 0.20. Thus, the bulk formulation for R_i was used exclusively.

Table 1. The number of qualifying minisonde profiles from a total of 2000 as a function of selection criteria.[a]

Min. Height (m)	Lapse Rate (°C/100m)	Date	Qualifying Profiles
200	-1 ± 0.5	All	33
200	-1 ± 0.5	1977	18
150	<0	All	37
150	-1 ± 0.5	All	20 [b]
150	-1 ± 0.5	1977	6
150	-1 ± 0.25	All	15
150	-1 ± 0.1	All	9
150	-1 ± 0.1	1977	3

[a] Additional criteria applied to all subsets were:

(i) wind speed at lowest level (about 50 m) greater than 5 ms^{-1};
(ii) wind speeds monotonically increasing with height;
(iii) wind direction variation less than 15°;
(iv) temperature within ± 1°C of the temperature derived for that level from the mean linear lapse rate; and
(v) wind speed within ± 1 ms^{-1} of the wind speed derived for that level from the mean logarithmic profile.

[b] Finally selected criteria.

Table 2. Calculated roughness lengths for qualifying minisonde profiles.

Profile	R_i[a] X10^{-2}	L[a] (m)	Wind Direction (° true)	Z_o Neutral (m)	Z_o with diabatic correction (m)			
					No Displacement Height	DIS1[b]	DIS2[c]	DIS1/2[c]
Lower Syncrude								
1	-0.015	-2800	14	4.0×10^{-4}	4.0×10^{-4}	4.0×10^{-4}	4.0×10^{-4}	4.0×10^{-4}
2	-0.21	-2400	359	2.7	2.8	2.8	2.8	2.8
3	0.78	23	211	0.18	0.15	0.093	0.053	0.12
4	0.65	150	292	1.0	0.94	0.64	0.41	0.78
5	-1.7	-120	342	0.62	0.78	0.78	0.78	0.78
6	0.20	730	281	0.59	0.57	0.38	0.24	0.47
Syncrude Site								
1	-0.14	-64,000	146	26	26	26	26	26
2	-0.29	-26,000	242	9.7	9.8	7.7	5.9	8.7
3	-0.40	-19,000	158	8.6	8.7	8.7	8.7	8.7
4	0.95	9,100	149	14	13	13	13	13
5	-0.52	-18,000	115	2.5×10^{-3}	2.9×10^{-3}	2.9×10^{-3}	2.9×10^{-3}	2.9×10^{-3}
6	0.078	120,000	110	5.3	5.2	5.2	5.2	5.2
7	-0.30	-26,000	229	8.6	8.7	6.9	5.2	7.8
8	-1.2	-7700	267	11	12	7.5	4.2	9.4
9	-0.23	-39,000	281	1.1	1.2	0.56	0.21	0.83
10	-0.39	-23,000	277	12	12	7.9	4.4	10
11	-1.2	-7,700	258	8.7	9.1	5.9	3.3	7.5

---

[a] Ri and L are Richardson Number and Monin-Obukhov length, respectively.

[b] DIS1 refers to the application of physically reasonable displacement heights as a function of direction. The assumed displacement heights for Lower Syncrude are 5 m for the wind direction range (150°, 340°) and zero elsewhere. The assumed displacement heights for the Syncrude site are 5 m for (180°, 250°), 10 m for (250°, 20°), and zero elsewhere.

[c] DIS2 and DIS1/2 refer to times 2 and times 1/2 those assumed displacement heights.

While diabatic effects were very small, terrain effects on minisonde profiles were larger. At Lower Syncrude, profile 6 could have been influenced by the valley wall located about 1 km westward, especially considering the apparently stable boundary layer. It appears to be the only profile at Lower Syncrude for which displacement heights were likely significant.

At the Syncrude site, winds blowing over the plant could have been affected by the increased roughness and might have experienced a displacement height. Physically reasonable displacement heights reduced the Z_o estimates by an average of about 15%. Calculating estimates of the displacement heights from the data was considered inappropriate based upon the probable error of the estimates as discussed in Section 5.

A summary of average Z_o estimates by release location is presented in Table 3. Because of large variations in Z_o (several orders of magnitude), both arithmetic and logarithmic averages are presented. Arithmetic averages of Z_o were near 1 m at Lower Syncrude and near 8 m at Syncrude with small differences among estimates using neutral, diabatic and displacement height effects. Arithmetic differences in Z_o between the two sites were large and were of the same order as the standard deviations. Site-to-site variations in Z_o were also large when logarithmic averages were used. It is evident that Z_o values from the selected profiles at Syncrude had less variability than at Lower Syncrude, as indicated by the relatively small difference between arithmetic and logarithmic averages at the Syncrude site and by the ratio of standard deviations to arithmetic averages. Logarithmic averages of Z_o at Syncrude were near 4 m. It should be noted that the use of standard deviations does not imply normally distributed Z_o values at either site; rather, the standard deviations give an indication of the variability of the data.

Spatial differences in Z_o between the two sites were evaluated using the non-parametric Mann-Whitney U test. This test makes no assumptions about the distribution of the Z_o values, ranking the values from highest to lowest. Very large or very small values of the statistic U imply a separation of the ordered values and indicate a

Table 3. Average roughness length estimates by release location.

Criteria	Number of Values	Z_o Neutral (m)	Z_o diabatic (m) No Displacement Height	Z_o diabatic (m) Assumed Displacement Height[c]
Arithmetic Averages of Zo				
Lower Syncrude	6	0.85 (0.97)[a]	0.87 (0.92)	0.78 (0.94)
Syncrude	11	9.5 (6.6)	9.6 (6.6)	8.1 (6.6)
Syncrude with directions (180, 20)[b]	6	8.5 (3.5)	8.8 (3.6)	6.1 (2.6)
All profiles	17	6.5 (6.7)	6.5 (6.8)	5.5 (6.4)
Logarithmic Averages of Zo				
Lower Syncrude	6	0.20	0.20	0.16
Syncrude	11	4.0	4.0	3.3
Syncrude with directions (180, 20)	6	6.5	7.2	4.7
All profiles	17	1.6	1.4	1.1

[a] Bracketed values are standard deviations.

[b] (180, 20) indicates wind direction from the sector 180° through 360° to 20°.

[c] As in DIS1, Table 2.

difference between the population distributions. Using sample sizes of 6 and 11 for Lower Syncrude and Syncrude, U values of 6 and 60 were found. Using the lower of the values, U = 6, as the test statistic (Seigel 1956) the one-tailed Mann-Whitney U test indicates that Z_o is smaller at Lower Syncrude than at Syncrude, at the 1% level.

Wind direction dependencies were also investigated, but no differences were found. A larger data set is likely required to resolve this.

5. DISCUSSION OF THE ROUGHNESS LENGTH ESTIMATES

The surprisingly large values of roughness length presented in Section 4 are discussed below in terms of uncertainties in the estimates, comparisons with other sites, independent support from other measurements in the oil sands area, and a possible stability dependence.

5.1 UNCERTAINTIES IN THE ESTIMATES

The most probable error (δF) of a derived parameter (F) which is a function of X_i constituent measurements is given by (see, for example, Baird 1962):

$$\delta F = \left\{ \sum_{i=1}^{N} (\delta X_i \quad \partial F/\partial X_i)^2 \right\}^{1/2} \tag{15}$$

Applying this formal methodology to the roughness length estimates is complicated by the least squares fitting of profiles and by the highly non-linear effect of velocity perturbations on the Z_o estimates.

An alternative procedure presented by Blanc (1983) involves explicit calculation of the parameter F for the error estimates of X_i. His procedure is especially convenient for computer-based analysis since the error perturbations can be treated by the same code used for the actual data analysis. Blanc's perturbation approach is given by:

$$\delta F_{xi} = \left(|F^{+}_{xi} - F| + |F^{-}_{xi} - F| \right)/2 \tag{16}$$

$$\delta F = \left\{ \sum_{i=1}^{N} (\delta F_{xi})^2 \right\}^{1/2} \tag{17}$$

where F_{xi} is the value of F calculated for a positive perturbation of the X_i constituent measurement. For this application, $F = Z_o$. Constituent measurements were wind speed, temperature gradient, and balloon height.

A "base case" was chosen and both positive and negative perturbations were applied. The base case was defined as having profile measurements at 50, 100, and 150 m with $U(50) = 5\ \mathrm{ms}^{-1}$ and a neutral lapse rate. The uncertainty estimates were calculated for Z_o values of 1, 5, and 10 m (from which the wind speeds at higher elevations were computed). Wind speed uncertainties were 20% and temperature and balloon height uncertainties were taken as 10% (from Netterville and Djurfors 1979). Table 4 presents a summary of results for $Z_o = 5$ m and a range of wind speed perturbations; Table 5 presents uncertainties for a range of Z_o. Uncertainty estimates detailing the contributions to the total probable error of individual measurements (wind speed, height, and temperature lapse rate) are given in the appendix. These estimates indicated that errors in wind speed were dominant for wind speed perturbations larger than about 5%.

For wind speed perturbations of 5 to 30%, the total probable error in Z_o (from Table 4) is shown to range from 4 to 24 m, for an initial Z_o of 5 m. A factor of six variation in the perturbation results in a factor of six variation in the probable Z_o error. The error in Z_o is sensitive to wind speed perturbation.

For wind speed perturbations of 20% and initial Z_o ranging from 1 to 10 m (Table 5), the range in Z_o error was much smaller. In fact, in the Z_o range from 1 to 10 m, the error was nearly constant at 11 m. This was expected since the wind speed component error appears to dominate and the wind speed perturbation was held constant. Note, however, that the error in $\ln Z_o$ did not remain constant but decreased with increasing $\ln Z_o$.

Roughness length estimates in Tables 2 and 3 can be compared to error estimates in Tables 4 and 5. Standard deviations of Z_o (from Table 3) ranged from 4 to 7 m with most near 7 m. Probable errors in Z_o (from Table 4) ranged from 3.7 m (5% wind speed perturbation) to 24 m (30% wind speed perturbation); a standard deviation of 7 m corresponded to a perturbation of about 13%. That this value (13%) is less than the 20% error suggested by Davison and Leavitt (1979) and by the σ_u/U analysis suggests that careful

Table 4. Roughness length uncertainty estimates as a function of perturbation in U(Z) for neutral profiles with U(50) = 5 ms^{-1} and Z_o = 5 m. Total error is the total probable error assuming independence of constituent errors. Uncertainty estimates are differences in metres from Z_o = 5 m (for Z_o).

Perturbed Parameter	Z_o Perturbation (%) 5	10	20	30	$\ln Z_o$ Perturbation (%) 5	10	20	30
U(50)	1.2	3.5	6.7	9.4	0.36	0.73	1.5	2.0
U(100)	0.35	1.4	6.2	14	0.066	0.25	0.80	1.3
U(150)	1.7	3.2	4.7	16	0.33	0.60	0.55	1.4
Errors due to Z and dT/dZ (10% perturbation)	2.7	2.7	2.7	2.7	0.60	0.60	0.60	0.60
Total error in Z_o(m) or $\ln Z_o$	3.7	5.7	11	24	0.78	1.1	1.9	2.9

Table 5. Roughness length uncertainty estimates as a function of Z_o for neutral profiles with U(50) = 5 ms^{-1} and 20% perturbation in U(Z). Total error is the total probable error assuming independence of constituent errors. Uncertainty estmates are differences in meteres (for Z_o) from indicated Z_o values).

Perturbed Parameter	Z_o			$\ln Z_o$		
	Z_o(m)			Z_o(m)		
	1	5	10	1	5	10
U(50)	4.3	6.7	7.5	2.2	1.5	0.83
U(100)	7.9	6.2	5.0	2.1	0.80	0.41
U(150)	9.5	4.7	6.1	2.3	0.55	0.51
Errors due to Z and dT/dZ (10% perturbation)	1.3	2.7	3.2	5.4	0.60	0.31
Total error in Z_o(m) or $\ln Z_o$	13	11	11	6.6	1.9	1.1

selection of candidate profiles helps to reduce apparent errors in measurement. The scatter in Z_o estimates in Table 3 can largely be accounted for by reasonable uncertainties in profile measurements.

5.2 COMPARISON OF Z_o VALUES MEASURED AT OTHER SITES

The Z_o estimates from this study can be compared to values in other regions. For example, Korrell et al. (1982) analysed profile data between 10 and 50 m from the Boulder 300-m instrumented tower. This site is reasonably flat with terrain slopes near 2% and low vegetation with occasional trees and houses within a radius of about 3 km. Z_o was found to be direction-dependent with values ranging from 4 to 35 cm. Ming et al. (1983) analysed profiles at three towers in New England. At one site, surrounded by tall and irregular trees in rolling terrain, Z_o values ranged from 1 to 11 m based on data at 46 and 99 m. At a second site, in forest and rolling farmland, Z_o values were near 1 m (21, 46, and 99 m measurements), while at a third site, with water, woods, farmland and buildings in different directions, Z_o varied from less than 1 cm to about 250 cm (10, 43, and 114 m measurements).

5.3 THE IMPLICATION OF DISSIPATION MEASUREMENTS ON ROUGHNESS LENGTH

Independent supporting evidence for the existence of relatively large Z_o can be found in height-dependent turbulent dissipation values measured in the Athabasca Oil Sands area. Typically, the dimensionless dissipation rate ε_D decreases rapidly with height near the surface and then is approximately constant within the convectively mixed layer (see, for example, Kaimal et al. 1976); The dissipation rate is given by:

$$\varepsilon_D = \varepsilon T/(g\ Q_o) \qquad (18)$$

where

ε = turbulent energy dissipation;

T = mean temperature; and

Q_o = surface kinematic heat flux.

A constant ε_D requires ε to increase with height as T decreases. In the oil sands area, however, Davison and Grandia (1979) found ε near plume level on clear sunny days to consistently decrease with height. They concluded, therefore, that mechanical mixing was important at plume heights even in the presence of significant surface heat fluxes. Venkatram (1980), on the other hand, suggests that large surface heat fluxes in the oil sands area imply that free convection should occur frequently. These two pieces of evidence can be reconciled if Z_o is large. In that case, ε_D would decrease with height as surface effects are observed at higher levels, and therefore free convection would not be expected to occur frequently even with large heat fluxes.

5.4 A POSSIBLE STABILITY DEPENDENCE FOR ROUGHNESS LENGTH

The application of (large) Z_o values from this study to air quality modelling studies in the Athabasca Oil Sands area requires clarification. In slightly unstable conditions the data indicate Z_o values ranging from 1 to 8 m. These values seem reasonable when the contribution to Z_o from form drag is important. In this case Z_o will be representative of conditions over a wide area (up to a kilometre or more) including the effects of small terrain features.

The application of a large Z_o is more uncertain in stable conditions for several reasons. First, air tends to flow around obstacles rather than over them, causing a decoupling of the air from the surface and therefore a situation in which elevated winds are not determined by the underlying terrain. Second, air quality model sensitivity studies in the area by Davison et al. (1981b) suggest Z_o to be of the order of 0.5 to 1 m, neglecting dependence on stability. The use of $Z_o \sim 8$ m would introduce minor changes in their estimated GLC values in unstable conditions but would impose a large, systematic bias to large GLC values in stable conditions. Finally, the number of stable profiles analysed in this study was too small and the results were too variable to suggest a new Z_o estimate in stable conditions. The net result in stable conditions is suggested to be a smaller value of Z_o since the effects of form drag are reduced.

The results of this study suggest that, when form drag is an important determinant of Z_o, the roughness length may be a function of stability. This could occur because, while the ground cover component of Z_o is expected to vary little with stability, the effects of form drag might be expected to vary substantially.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

Roughness lengths were calculated from profiles of minisondes released in the Athabasca Oil Sands area from 1975 to 1979. A rigorous selection process to obtain well-behaved wind and temperature profiles resulted in only 20 suitable profiles at two sites from an original database of about 2000 minisonde releases.

Based on measurement levels typically near 50, 100, and 150 m, mean values of Z_o were found to range from 1 m at Lower Syncrude to 8 m at the Syncrude plant site. The Mann-Whitney U test showed these differences to be significant at the 1% level. These Z_o values were comparable to other values in similar terrain quoted in the literature and were consistent with height-dependent dissipation rates measured in the area. No differences with wind direction were found. It was suggested that Z_o may be stability-dependent in terrain where form drag is important, such that, in stable conditions, the effective roughness length is much smaller due to the decreased effectiveness of form drag.

An error analysis showed that the observed variations in the Z_o estimates were similar to the estimated uncertainties in the constituent measurements. It was also shown that uncertainties in the wind values were much more important for Z_o calculations than uncertainties in the balloon height or in the temperature gradient.

6.2 RECOMMENDATIONS

1. It is recommended that Z_o be determined from profiles from the 150 m tower located at Lower Syncrude. The tower profiles should provide a larger data base than the minisondes and should have smaller associated measurement errors (especially wind speed). The tower data analysis would emphasize Z_o calculation in slightly unstable conditions and should provide Z_o estimates representative of conditions in the Athabasca River valley.

2. It is recommended that a catalog of Z_o values be compiled for Alberta. This task would include synthesizing Z_o values where they exist and calculating them from existing profile data in regions where tower or other atmospheric sounding data are available. An instrumented research aircraft might be used in areas where no profile data exist. The catalog is recommended because of the spatial and stability dependence of Z_o suggested by the results of this study.

7. REFERENCES CITED

Arya, S.P.S. 1982. Atmospheric boundary layers over homogeneous terrain. In Engineering Meteorology, ed. E. Plate. Amsterdam: Elsevier Scientific Publ. Co. pp. 237-267

Baird, D.C. 1962. Experimentation, an introduction to measurement theory and experiment design. Englewood Cliffs, New Jersey: Prentice Hall. 198 pp.

Beljaars, A.C.M., P. Schotunus, and F.T. Nieuwstadt. 1983. Surface layer similarity under nonuniform fetch conditions. J. of Cli. and Appl. Meteorol. 22:1800-1810.

Blanc, T.V. 1983. An error analysis of profile flux, stability, and roughness length measurements. Boundary-Layer Meteorol. 26:241-267.

Businger, J.A. 1973. Turbulent transfer in the atmospheric surface layer. In Workshop on Micrometeorology, ed. D.A. Haugen. American Meteorological Society, Boston, pp 67-100.

Davison, D.S. and E.D. Leavitt. 1979. Analysis of AOSERP plume sigma data. Prep. for Alberta Oil Sands Environmental Research Program by INTERA Environmental Consultants Ltd. AOSERP Report 63. Edmonton, Alberta. 251 pp.

Davison, D.S. and K.L. Grandia. 1979. Plume dispersion measurements from an oil sands extraction plant, June 1977. Prep. for Alberta Oil Sands Environmental Research Program by INTERA Environmental Consultants Ltd. AOSERP Report 52. Edmonton, Alberta. 194 pp.

Davison, D.S., E. Leavitt, R. McKenna, R. Rudolph, and M.J.E. Davies. 1981a. Airshed management system for Alberta Oil Sands. Volume I: A Gaussian frequency distribution model. Prep. for Research Management Division, Alberta Environment by INTERA Environmental Consultants Ltd. and Western Research. AOSERP Report 119. Edmonton, Alberta. 132 pp.

Davison, D.S., M.J.E. Davies, R.C. Rudolph, and M.C. Hansen. 1981b. Airshed management system for the Alberta Oil Sands. Volume III: Verification and sensitivity studies. Prep. for Research Management Division by INTERA Environmental Consultants Ltd. and Western Research. AOSERP Report 124. Edmonton, Alberta. 129 pp.

Hojstrup, J. 1981. A simple model for the adjustment of velocity spectra. Boundary-Layer Meteorol. 21:341-356.

Kaimal, J.C., J.C. Wyngaard, D.A. Haugen, O.R. Cote, Y. Izumi, S.J. Caughey, and C.J. Readings. 1976. Turbulence structure in the convective boundary layer. J. Atmos. Sci. 33:2152-2169.

Korrell, A., H.A. Panofsky, and R.J. Rossi. 1982. Wind profiles at the Boulder tower. Boundary-Layer Meteorol. 21:295-313.

Longley R. and B. Janz. 1978. The climatology of the Alberta Oil Sands Environmental Research Program study area. Prep. for Alberta Oil Sands Environmental Research Program by Atmospheric Environment Service. AOSERP Report 39. Edmonton, Alberta. 102 pp.

Lumley, J.L. and H.A. Panofsky. 1964. The structure of atmospheric turbulence. New York: Interscience, Wiley. 239 pp.

Mason, P.J. and R.I. Sykes. 1979. Flow over an isolated hill of moderate slope. Quart. J. Roy. Meteorol. Soc. 105:383-395.

Ming, Z., H.A. Panofsky, and R. Ball. 1983. Wind profiles over complex terrain. Boundary-Layer Meteorol. 25:221-228.

Netterville, D.D.J. and S.G. Djurfors. 1979. Controlling inherent uncertainties in double theodolite measurements. J. Appl. Meteorol. 18:1371-1375.

Panofsky, H.A. 1973. Tower micrometeorology. In Workshop on Micrometeorology, ed. D.A. Haugen. American Meteorological Society. Boston. pp 151-176.

Pasquill, F. 1974. Atmospheric Diffusion. Chichester, U.K.: Ellis Horwood Ltd. 429 pp.

Paulson, C. 1970. The mathematical representation of wind speed and temperature profiles in the unstable atmospheric surface layer. J. Appl. Meteorol. 9:857-861.

Schaefer, J.T. and C.A. Doswell. 1978. The inherent position errors in double-theodolite pibal measurements. J. Appl. Meteorol. 17:911-915.

Seigel, S. 1956. Nonparametric statistics for the behavioral sciences. New York: McGraw-Hill Book Company. 312 pp.

Taylor, P.A., J.L. Walmsley, and J.R. Salmon. 1983. A simple model of neutrally stratified boundary-flow over real terrain incorporating wavenumber-dependent scaling. Boundary-Layer Meteorol. 26:169-190.

Taylor, P.A., R.E. Mickle, J.A. Salmon, and H. Teunissen. 1982. The Kettles Hill experiment: site description and mean flow results. Atmospheric Environment Service. Rep. AQRB-82-000-L. Downsview, Ontario.

Thompson, M.D., M.C. Wride, and M.E. Kirby. 1978. Ecological habitat mapping of the AOSERP Study area. Prep. for Alberta Oil Sands Environmental Research Program by INTERA Environmental Consultants Ltd. AOSERP Report 31. Edmonton, Alberta. 176 pp.

Walmsley, J.L., J.R. Salmon, and P.A. Taylor. 1982. On the applications of a model of a boundary-layer flow over low hills to real terrain. Boundary-Layer Meteorol. 23:17-46.

Venkatram, A. 1980. Evaluation of the effects of convection on plume behaviour in the AOSERP study area. Prep. for Alberta Oil Sands Environmental Research Program. AOSERP Report 95. Edmonton, Alberta. 75 pp.

8. APPENDIX

8.1 ROUGHNESS LENGTH UNCERTAINTY ESTIMATES

This section documents the contributions to total probable error of the individual constituent profile measurements. Probable errors for Z_o (differences from the original value) are in metres. The overbar indicates the mean of a positive and negative perturbation for a single parameter. The total probable error in Z_o and $\ln Z_o$ is given at the bottom of each table.

Table 6. Roughness length uncertainty estimates for Z_o = 5 m, U(50) = 5 ms^{-1}, and a neutral profile.

Perturbed Parameter	Perturbation %	δZ_{oi}	$\overline{\delta Z_{oi}}$	$\delta \ln Z_{oi}$	$\overline{\delta \ln Z_{oi}}$
U (50)	-20	8.9		1.1	
U (50)	+20	4.4	6.7	2.1	1.5
U (100)	-20	6.7		0.86	
U (100)	+20	5.6	6.2	0.74	0.80
U (150)	-20	0.39		0.081	
U (150)	+20	9.1	4.7	1.0	0.55
Z (50)	-10	1.4		0.33	
Z (50)	+10	1.7	1.6	0.30	0.31
Z (100)	-10	0.068		0.013	
Z (100)	+10	0.058	0.063	0.012	0.012
Z (150)	+10	1.2		0.21	
Z (150)	+10	0.86	1.0	0.19	0.20
dT/dZ	-10	2.6		0.72	
dT/dZ	+10	1.3	1.9	0.22	0.47

δZ_o = 11

$\delta \ln Z_o$ = 1.9

Table 7. Roughness length uncertainty estimates for $Z_o = 1$ m, $U(50) = 5\ \mathrm{ms}^{-1}$, and a neutral profile.

Perturbed Parameter	Perturbation %	δZ_{oi}	$\overline{\delta Z_{oi}}$	$\delta \ln Z_{oi}$	$\overline{\delta \ln Z_{oi}}$
U (50)	-20	7.7		2.1	
U (50)	+20	0.96	4.3	2.3	2.2
U (100)	-20	9.2		2.3	
U (100)	+20	6.5	7.9	2.0	2.1
U (150)	-20	12		2.5	
U (150)	+20	7.5	9.5	2.1	2.3
Z (50)	-10	0.41		0.48	
Z (50)	+10	0.58	0.49	0.44	0.46
Z (100)	-10	0.048		0.044	
Z (100)	+10	0.038	0.043	0.037	0.040
Z (150)	-10	0.41		0.33	
Z (150)	+10	0.26	0.34	0.28	0.31
dT/dZ	-10	1.1		10.0	
dT/dZ	+10	1.2	1.1	0.75	5.4

$\delta Z_o = 13.0$

$\delta \ln Z_o = 6.6$

Table 8. Roughness length uncertainty estimates for $Z_o = 10$ m, $U(50) = 5\ \mathrm{ms}^{-1}$, and a neutral profile.

Perturbed Parameter	Perturbation %	δZ_{oi}	$\overline{\delta Z_{oi}}$	$\delta \ln Z_{oi}$	$\overline{\delta \ln Z_{oi}}$
U (50)	-20	8.6		0.62	
U (50)	+20	6.5	7.5	1.0	0.83
U (100)	-20	5.7		0.45	
U (100)	+20	4.4	5.0	0.36	0.41
U (150)	-20	3.2		0.38	
U (150)	+20	9.0	6.1	0.64	0.51
Z (50)	-10	2.3		0.26	
Z (50)	+10	2.7	2.5	0.23	0.25
Z (100)	-10	0.014		0.0014	
Z (100)	+10	0.010	0.012	0.0010	0.0012
Z (150)	-10	1.6		0.15	
Z (150)	+10	1.3	1.5	0.14	0.14
dT/dZ	-10	1.6		0.18	
dT/dZ	+10	0.87	1.3	0.083	0.13

$\delta Z_o = 11$

$\delta \ln Z_o = 1.1$

Table 9. Roughness length uncertainty estimates for $Z_o = 5$ m, $U(50) = 5$ ms^{-1}, and a neutral profile.

Perturbed Parameter	Perturbation %	δZ_{oi}	$\overline{\delta Z_{oi}}$	$\delta \ln Z_{oi}$	$\overline{\delta \ln Z_{oi}}$
U (50)	-5	1.9		0.33	
U (50)	+5	1.6	1.8	0.40	0.36
U (100)	-5	0.27		0.053	
U (100)	+5	0.42	0.35	0.080	0.066
U (150)	-5	1.5		0.34	
U (150)	+5	1.9	1.7	0.32	0.33
Z (50)	-10	1.4		0.33	
Z (50)	+10	1.7	1.6	0.30	0.31
Z (100)	-10	0.068		0.013	
Z (100)	+10	0.058	0.063	0.012	0.012
Z (150)	-10	1.2		0.21	
Z (150)	+10	0.86	1.0	0.19	0.20
dT/dZ	-10	2.6		0.72	
dT/dZ	+10	1.3	1.9	0.22	0.47

$\delta Z_o = 3.7$

$\delta \ln Z_o = 0.78$

Table 10. Roughness length uncertainty estimates for Z_o = 5 m, U(50) = 5 ms^{-1}, and a neutral profile.

Perturbed Parameter	Perturbation %	δZ_{oi}	$\overrightarrow{\delta Z_{oi}}$	$\delta \ln Z_{oi}$	$\overrightarrow{\delta \ln Z_{oi}}$
U (50)	-10	4.1		0.60	
U (50)	+10	2.9	3.5	0.87	0.73
U (100)	-10	1.4		0.24	
U (100)	+10	1.5	1.4	0.26	0.25
U (150)	-10	2.3		0.60	
U (150)	+10	4.2	3.2	0.60	0.60
Z (50)	-10	1.4		0.33	
Z (50)	+10	1.7	1.6	0.30	0.31
Z (100)	-10	0.068		0.013	
Z (100)	+10	0.058	0.063	0.012	0.012
Z (150)	-10	1.2		0.21	
Z (150)	+10	0.86	1.0	0.19	0.20
dT/dZ	-10	2.6		0.72	
dT/dZ	+10	1.3	1.9	0.22	0.47

$\delta Z_o = 5.7$

$\delta \ln Z_o = 1.1$

Table 11. Roughness length uncertainty estimates for $Z_o = 5$ m, $U(50) = 5\ ms^{-1}$, and a neutral profile.

Perturbed Parameter	Perturbation %	δZ_{oi}	$\overline{\delta Z_{oi}}$	$\delta \ln Z_{oi}$	$\overline{\delta \ln Z_{oi}}$
U (50)	-30	14.0		1.3	
U (50)	+30	4.7	9.4	2.7	2.0
U (100)	-30	17.0		1.5	
U (100)	+30	12.0	14.0	1.2	1.3
U (150)	-30	19.0		1.6	
U (150)	+30	14.0	16.0	1.3	1.4
Z (50)	-10	1.4		0.33	
Z (50)	+10	1.7	1.6	0.30	0.31
Z (100)	-10	0.068		0.013	
Z (100)	+10	0.058	0.063	0.012	0.012
Z (150)	-10	1.2		0.21	
Z (150)	+10	0.86	1.0	0.19	0.20
dT/dZ	-10	2.6		0.72	
dT/dZ	+10	1.3	1.9	0.22	0.47

$\delta Z_o = 24$

$\delta \ln Z_o = 2.9$

9. LIST OF AOSERP RESEARCH REPORTS

1. AOSERP first annual report, 1975.
2. Walleye and goldeye fisheries investigations in the Peace-Athabasca Delta--1975.
3. Structure of a traditional baseline data system. 1976.
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12. Very high solution meteorological satellite study of oil sands weather: "a feasibility study". 1977.
13. Plume dispersion measurements from an oil sands extraction plant, March 1976.
14. None published.
15. A climatology of low-level air trajectories in the Alberta oil sands area. 1977.
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45. Interim report on physiology and mechanisms of air-borne pollutant injury to vegetation, 1975 to 1978.

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65. A review and assessment of the baseline data relevant to the impacts of oil sands development on black bear in the AOSERP study area. 1979.

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