What's Z_0 got to do with it? Part 2: Considerations for Collecting Wind Profiling Data from Landed Vehicles

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Introduction: With apologies to Tina Turner, the title indicates that this report is a continuation of an abstract submitted to the 7th International Planetary Dunes Workshop [1], here focused on considerations for future spacecraft missions that may include the collection of wind profiling data to constrain z_0, the height at which a logarithmic wind speed profile is zero. A remarkable paper by Wieringa [2] describes several conditions that should be considered when collecting wind profile data to derive z_0.

Background: Bagnold [3, pg 47-49] plotted wind data on a linear velocity scale versus a logarithmic height scale; on this plot the wind data project along a straight line to a height of zero velocity for multiple wind conditions over the same surface, each line with a slope dependent on the shear stress (or friction speed). Bagnold further said that Prandtl related the height of the focus point (on a semi-log plot) to the roughness over which the fluid is moving; the height of the zero-velocity point is 1/30 the diameter of the roughness elements of the surface [3, pg 50]. The semi-logarithmic relationship between height and velocity is called the Prandtl-von Karman equation, or 'the Law of the Wall' [4, pg 44]. Wieringa [2] describes several conditions that affect the usefulness of wind profile data, and he makes the following important statement: The popular saying "z_0 is the height at which the wind speed becomes zero" is true in a purely algebraic sense only, since it implies extrapolation of the (Law of the Wall) equation below its limit of validity [2, pg 325].

Methodology: Wind profile measurements are typically collected using anemometers logarithmically spaced in height along a tower. Weiringa [2] states that the lowest anemometer height should be >20X the anticipated z_0 for the surface, the tower should be downwind of the nearest obstacle at a distance >15X the obstacle height, the fetch upwind of the tower should have consistent roughness elements for at least >80 m, at least four anemometers should be used for moderate roughness (z_0 ~10 cm) and preferably five or more over terrain smoother than this, and times near sunrise or sunset are to be avoided. A least-squares logarithmic fit is applied to the average wind speeds documented during time intervals where the wind increases systematically with height. The least-squares fit is then used to calculate the height at which the wind speed becomes zero (z_0).

Considerations for landed spacecraft: Caution is required to avoid spacecraft components from compromising the use of wind measurements to infer z_0 from wind profiling data (e.g., Fig. 2). This measurement can be done, as was demonstrated during the Pathfinder mission [5], but it involves a non-trivial effort to constrain results to winds coming from a direction that minimizes spacecraft structure from affecting the upwind flow. There may be little control over the final surface orientation of the sensor array on a fixed lander, but on a rover, attention should be paid to the rover orientation relative to anticipated wind direction at stops planned for wind profiling data collection.

Heights of anemometer sensors above the spacecraft are less important than the height of the lowest sensor above the surface. A tower fixed to a landed spacecraft should place the lowest sensor considerably higher than Wieringa's suggested lowest height (twenty times the estimated z_0 at the measurement location). If the spacecraft structure near the anemometer tower lacks significant obstacles, the lowest anemometer height could be as low as 10 cm above a smooth spacecraft deck. The height of the uppermost anemometer is not critical, but the anemometer array should be spaced logarithmically.

The estimated z_0 of 3 cm at the rocky Pathfinder site [5] implies that most 'safe' landing sites on Mars likely will have z_0 considerably smaller than 10 cm, the value used as a minimum by Wieringa [2]. Wieringa also suggested use of a minimum of four anemometers where z_0 is around 10 cm; consequently, five or more anemometers should be planned for future Mars landers at typical 'safe' sites. The smaller the anemometers, the more can be used on a tower of modest total length. Aerodynamic roughness z_0 can be constrained using only two anemometers [3, pg 50], but the more sensors on the tower, the stronger the confidence of documenting a logarithmic wind profile.

The choice of anemometer tower location on the spacecraft should be guided by using both wind tunnel tests with a high-fidelity spacecraft model and numerical modeling to optimize positions of minimal disruption of the logarithmic wind profile for winds coming from many directions. The landed anemometer array also should include temperature, pressure, and wind direction sensors.

Weiringa [2] described three flow types for wind blowing over surface roughness elements (Fig. 1). Surfaces involving closely spaced particles are consistent with 'skimming flow', which occurs 'when the surface is so closely covered with obstacles that flow in the spaces between obstacles has a regime quite separate from the bulk flow above' [2]. In this situation roughness height is less a result of the size of the individual particles than it is the cumulative effect from many closely spaced particles. Wind profiling over gravel-covered surfaces in the Puna of Argentina gave z_0 of ~1 cm regardless of whether gravel-covered megaripples were present in the upwind direction, suggesting that the closely spaced gravel particles caused skimming flow with only minimal influence from form flow over megaripples [6]. It is unclear how the atmosphere behaves in between closely spaced surface particles; use caution when inferring the 'average' particle size of the surface roughness elements to be 30 times the value of z_0.

Discussion: Weiringa [1] defines three flow types for wind blowing over surface roughness elements (Fig. 1). Sand and granule-gravel-covered surfaces are consistent with 'skimming flow', which occurs 'when the surface is so closely covered with obstacles that flow in the spaces between obstacles has a regime quite separate from the bulk flow above' [1]. In this situation, roughness height is less a result of the size of the individual particles than it is the cumulative effect from many closely spaced particles. As the scale of bedforms like large ripples or megaripples increases, wind flow over the bedforms may locally increase $z_{0,}$ but results thus far indicate this does not appear to produce a dramatic increase in z_0 if the tower is well outside of the 'wake' region downwind of obstacles (avoid locations with 'wake-interference flow', Fig. 1). The most useful wind profiling data comes from settings with a 'semi-smooth flow' regime (Fig. 1), where obstacle spacing is more than fifteen times the height of the obstacles. Since it is unclear how the atmosphere behaves among closely spaced surface particles, use caution in inferring the average particle size to be 30 times the value of z_0. The above should be considered when planning to collect wind speed data using future spacecraft, to avoid spacecraft components from compromising the potential use of wind measurements for possible wind profiling and z_0 analysis.

It is instructive to consider how changes to the least-squares logarithmic fit coefficients affect the extrapolated wind field (Table 1, Figs. 3 and 4). Coefficients similar to those resulting from fits to field measurements in Argentina [6] were used as the starting condition for the fit expression. The first lines in both sections of the table give z_0 values. In general, small changes to either coefficient can affect the derived z_0, but in general any change to z_0 translates to small percentage changes in the calculated wind speed at heights above the top anemometer; this could be important to modelers who use z_0 to estimate wind speeds at large heights above the surface.

Summary: Roughness height (z_0) can be constrained from tower-mounted anemometers on either fixed or roving landers if the data used are restricted to winds coming from a direction that minimizes possible upwind effects caused by spacecraft hardware. Rover mission planners should consider tower location relative to anticipated wind direction when selecting orientation for planned stops.

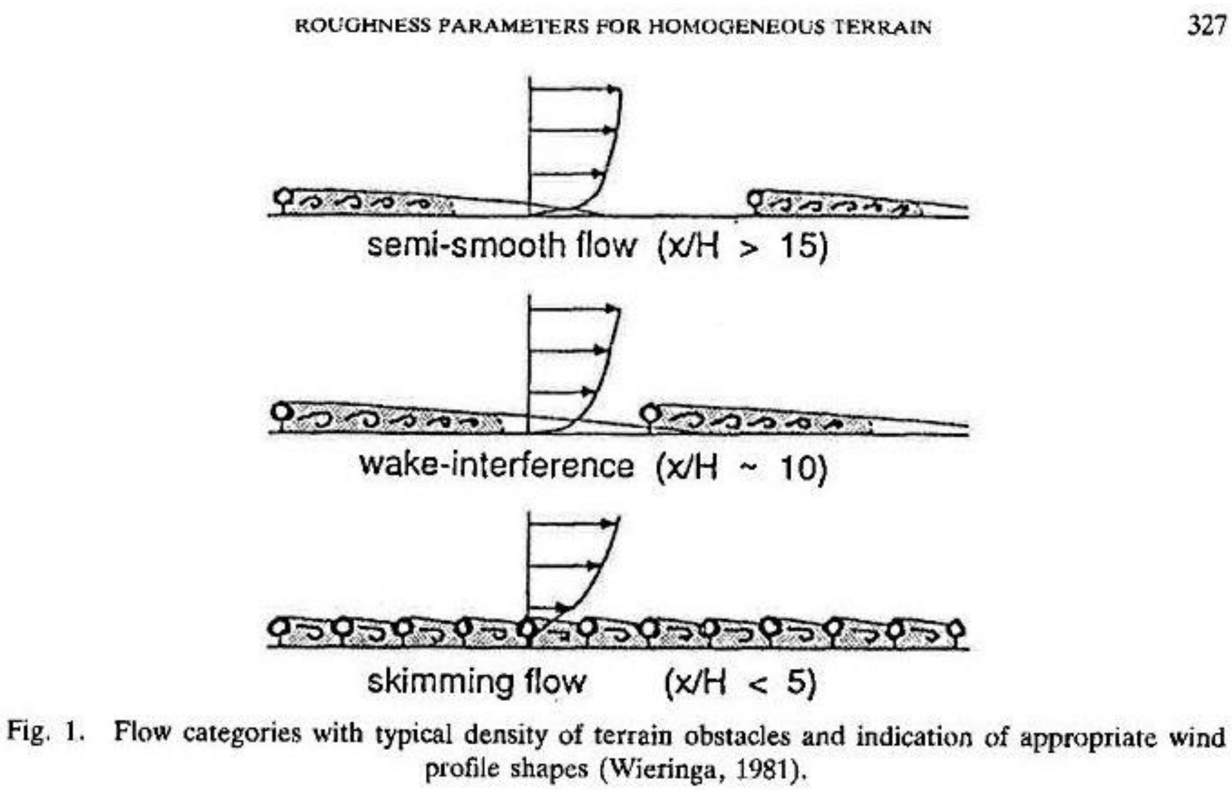

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Fig. 1. Flow categories with typical density of terrain obstacles and indication of appropriate wind profile shapes (Wieringa, 1981).

Figure 1. Flow categories over homogeneous terrain obstacles, from Fig. 1 of [2]. H is the height of a roughness element and x is the distance between obstacles.

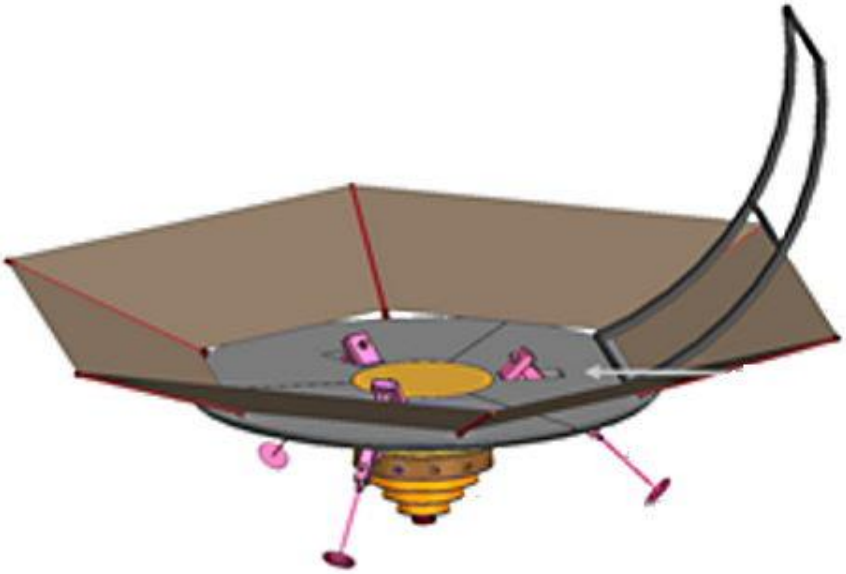

Figure 2. A proposed landed spacecraft concept which may be used for collecting wind profiling data, after a figure from [7]. Care should be used to place anemometers at locations having the least potential for interference to wind flow caused by spacecraft components. Both wind tunnel experiments and numerical models could aide in evaluating wind flow over the spacecraft structure.

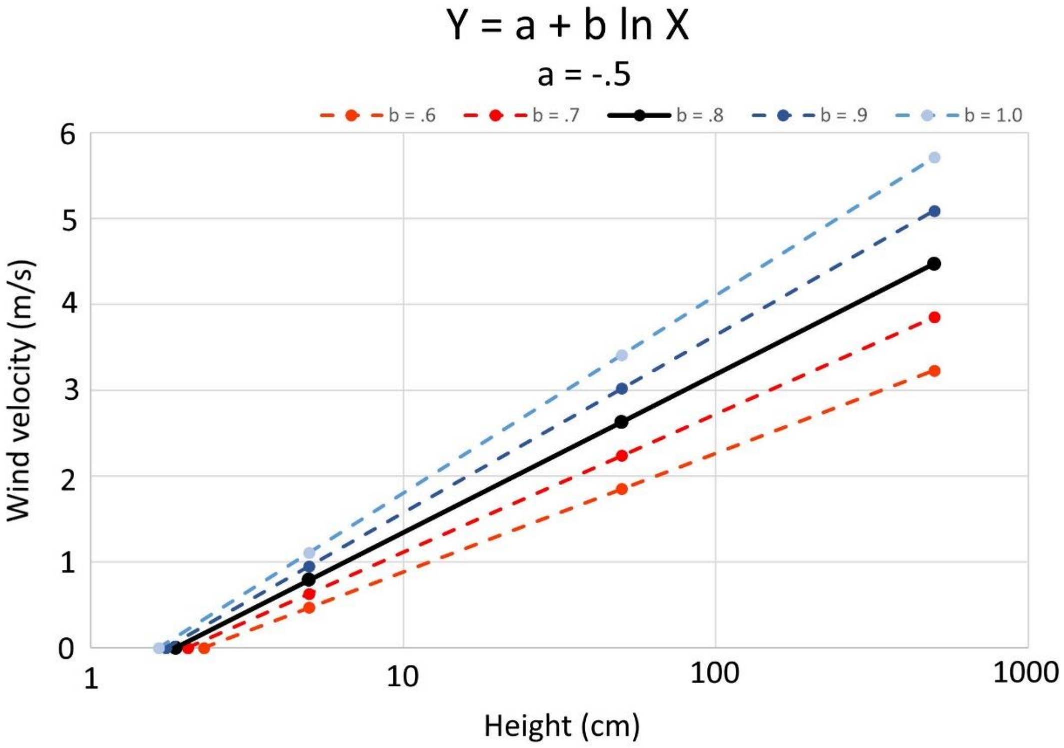

Figure 3. Changes to a typical logarithmic fit to wind profiling data, holding the first (a) parameter constant while varying the second (b) parameter. Changes in parameter b have a small effect on inferred z0 heights; the slight change in slope of the line indicate parameter b have a small effect on the derived friction speed.

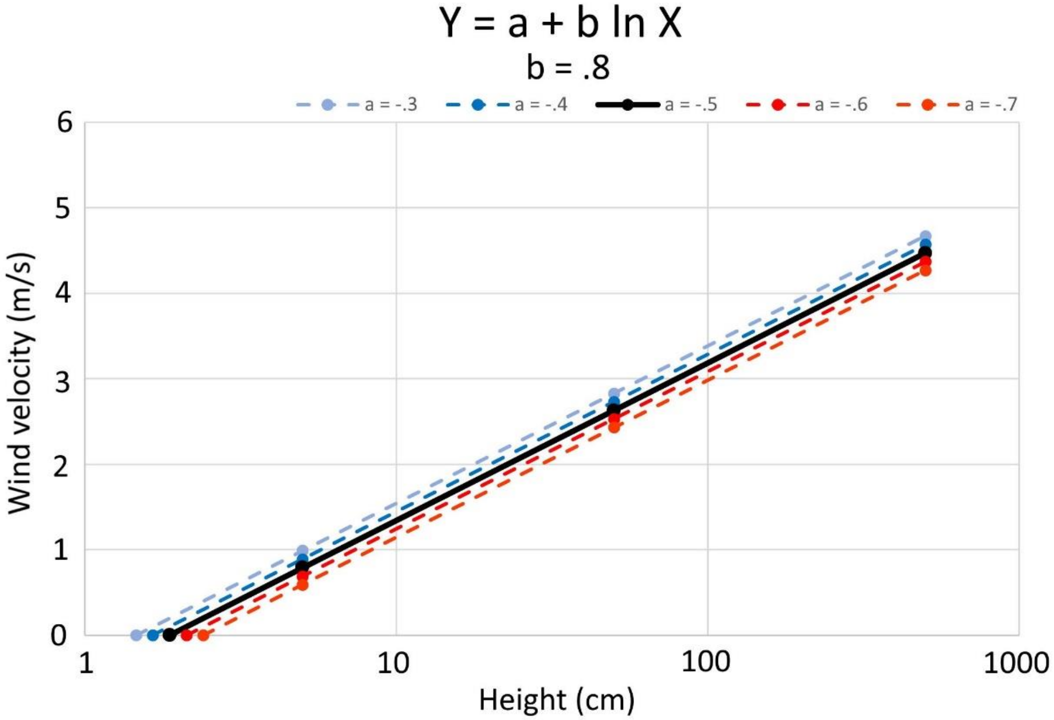

Figure 4. Changes to a typical logarithmic fit to wind profiling data, holding the second (b) parameter constant while varying the first (a) parameter. Changes in parameter a have a small effect on inferred z0 heights; no change in slope of the line indicates parameter b has no effect on the derived friction speed.

Table 1. Changes to logarithmic best-fit parameters relative to a **reference condition** (values inside parentheses are percentage change from reference value shown in **bold** in each line). Both parameters influence the derivation of z_0, but parameter ‘a’ has a stronger effect on estimated wind speed above the tower than does parameter ‘b’. Changes to z_0 translate to relatively small percentage changes in the calculated wind speed at heights above the top anemometer.

$Y = a + b \ln X$ [where Y is wind velocity, X is height]

a = -.5*

b = .6		b = .7		b = .8*		b = .9		b = 1.0	
X (cm)	**Y** (m/s)	**X** (cm)	**Y** (m/s)	**X** (cm)	**Y** (m/s)	**X** (cm)	**Y** (m/s)	**X** (cm)	**Y** (m/s)
(+23%) 2.30	0	(+9%) 2.04	0	**1.87**	0	(-7%) 1.74	0	(-12%) 1.65	0
5.0	(-41%) 0.47	5.0	(-20%) 0.63	5.0	**0.79**	5.0	(+20%) 0.95	5.0	(+41%) 1.11
50	(-30%) 1.85	50	(-15%) 2.24	50	**2.63**	50	(+15%) 3.02	50	(+30%) 3.41
500	(-28%) 3.23	500	(-14%) 3.85	500	**4.47**	500	(+14%) 5.09	500	(+28%) 5.71

b = .8*

a = -.3		a = -.4		a = -.5*		a = -.6		a = -.7	
X (cm)	**Y** (m/s)	**X** (cm)	**Y** (m/s)	**X** (cm)	**Y** (m/s)	**X** (cm)	**Y** (m/s)	**X** (cm)	**Y** (m/s)
(-22%) 1.46	0	(-12%) 1.65	0	**1.87**	0	(+13%) 2.12	0	(+28%) 2.40	0
5.0	(+25%) 0.99	5.0	(+13%) 0.89	5.0	**0.79**	5.0	(-13%) 0.69	5.0	(-25%) 0.59
50	(+8%) 2.83	50	(+4%) 2.73	50	**2.63**	50	(-4%) 2.53	50	(-8%) 2.43
500	(+4%) 4.67	500	(+2%) 4.57	500	**4.47**	500	(-2%) 4.37	500	(-4%) 4.27

References: [1] Zimbelman, J. R. (2022) 7th IPDW Abs. 3011. [2] Wieringa J. (1993) *Bound. Layer Meteorol*., 63, 323-363. [3] Bagnold, R. A. (1941). The Physics of Blown Sand and Desert Dunes. Chapman and Hall, London. [4] Lorenz, R. D. and J. R. Zimbelman (2014) Dune Worlds: How Windblown Sand Shapes Planetary Surfaces. Springer/Praxis, New York. [5] Sullivan R. et al. (2000) JGR, 105, 24547-24562, doi: 10.1029/1999JE001234. [6] Zimbelman, J. R. et al. (2022) *Lunar Planet. Sci*., 53, Abs. 1502. [7] Diniegia, S. (2022) 7th IPDW Abs. 3025.