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Remote Sensing in Complex Terrain – A Review

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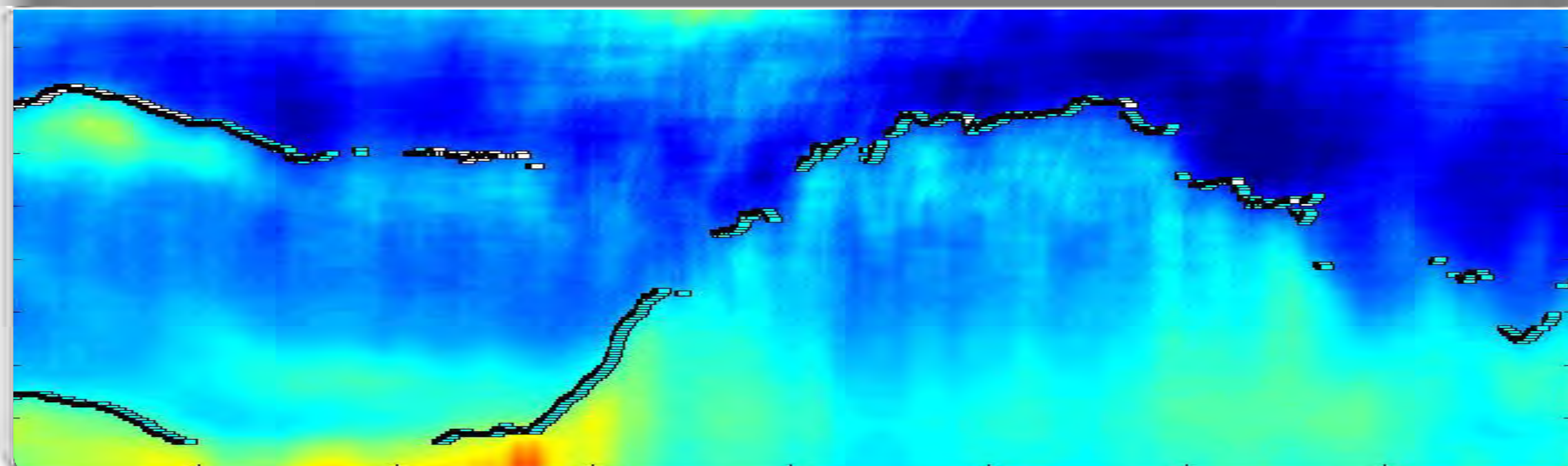
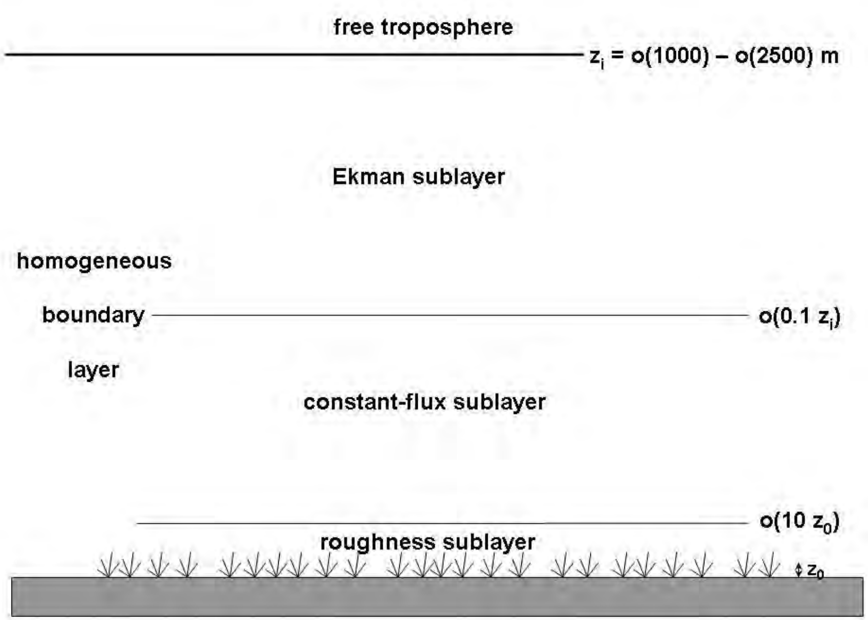


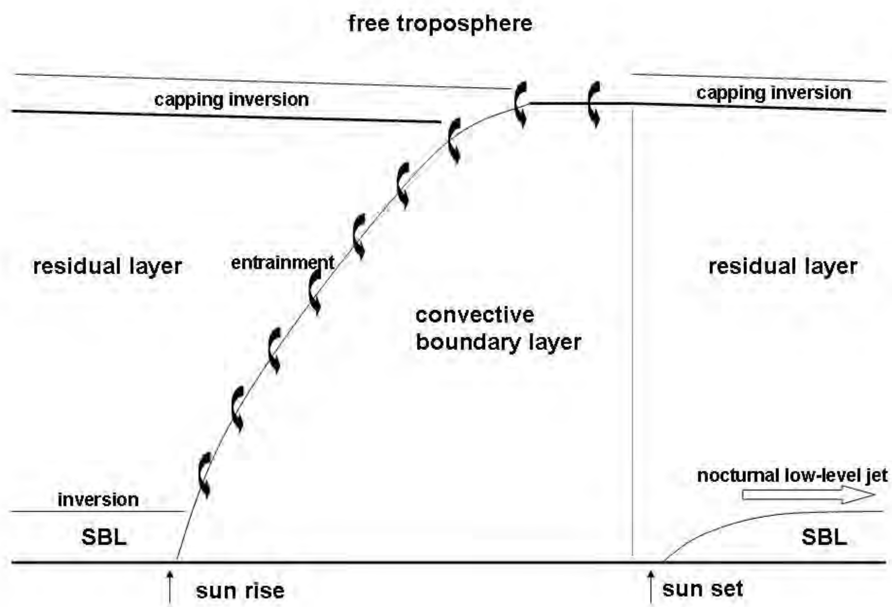
Boundary-layer types

over different surfaces
and
complex terrain

simplest situation: level terrain



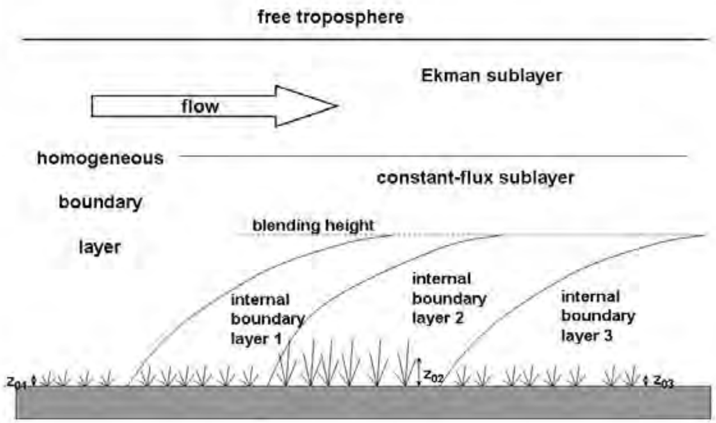
vertical structure

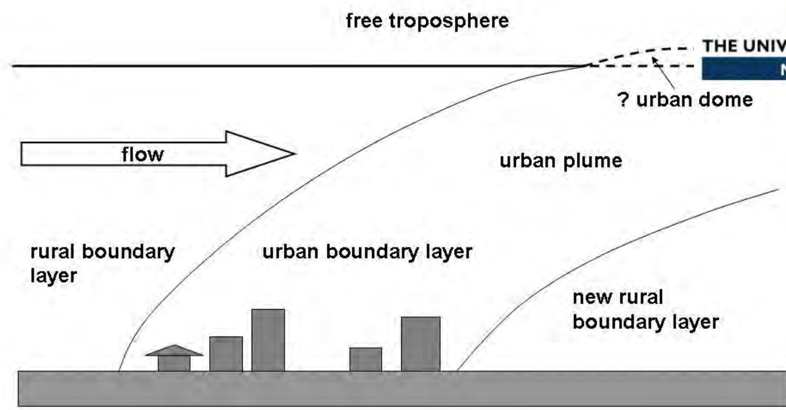


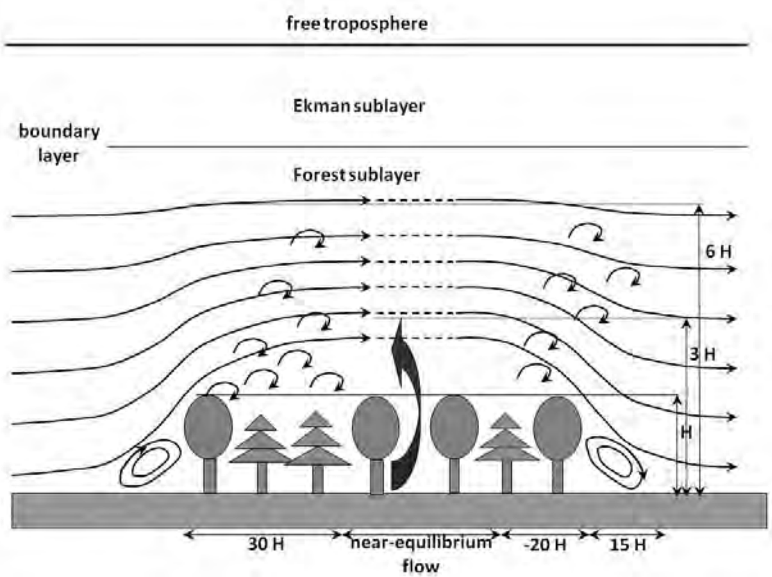
Source: modified from Stull (1988)

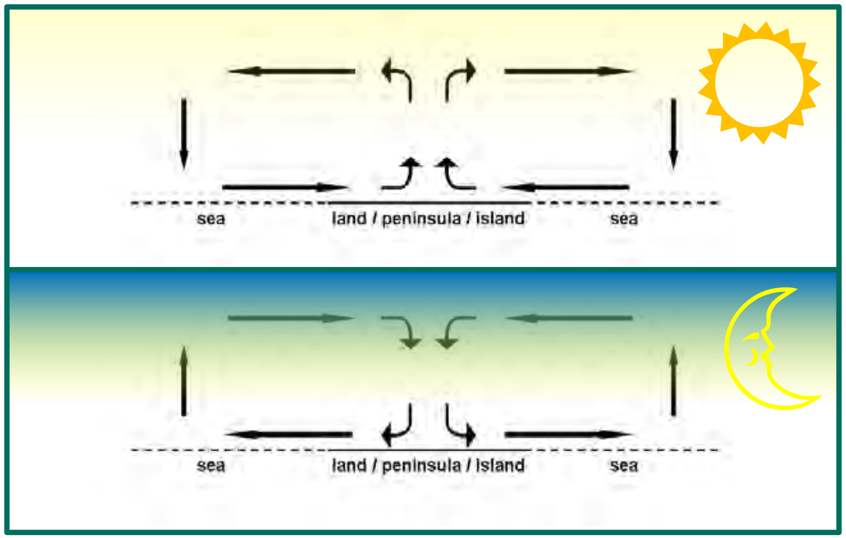
diurnal variation (clear sky)

complexity of the first kind: land use changes





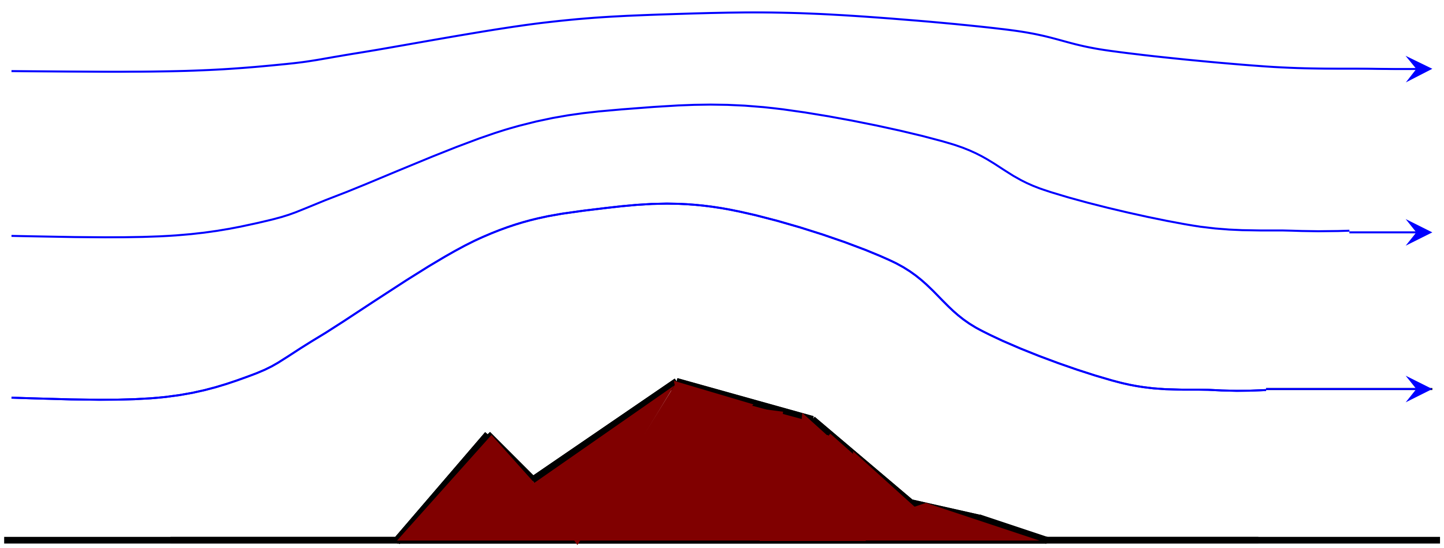




Warm cities influence local and regional weather (New York, May 28, 2011)

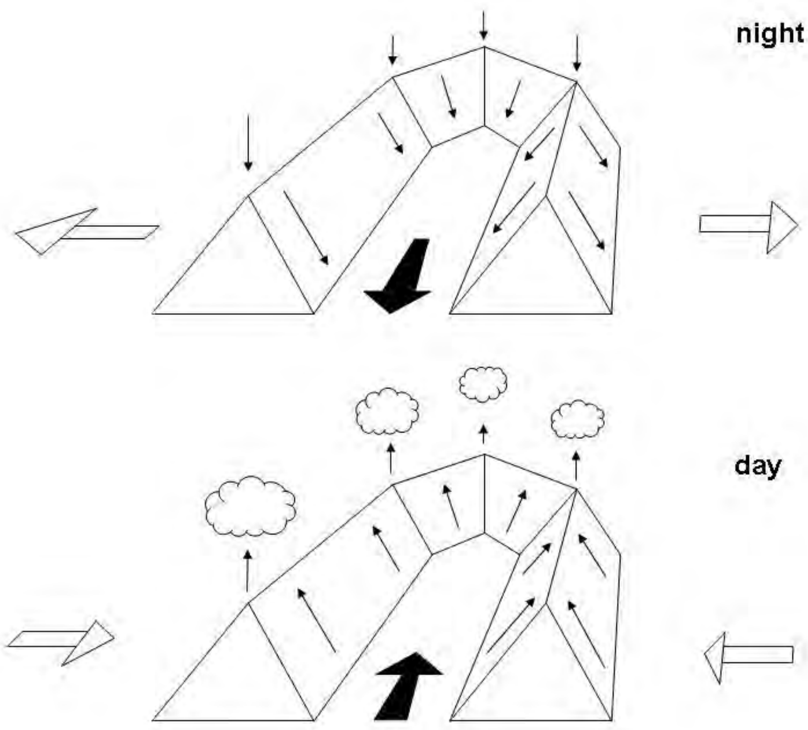
complexity of the second kind: orography

forced flows



complexity of the second kind: orography

thermally driven flows

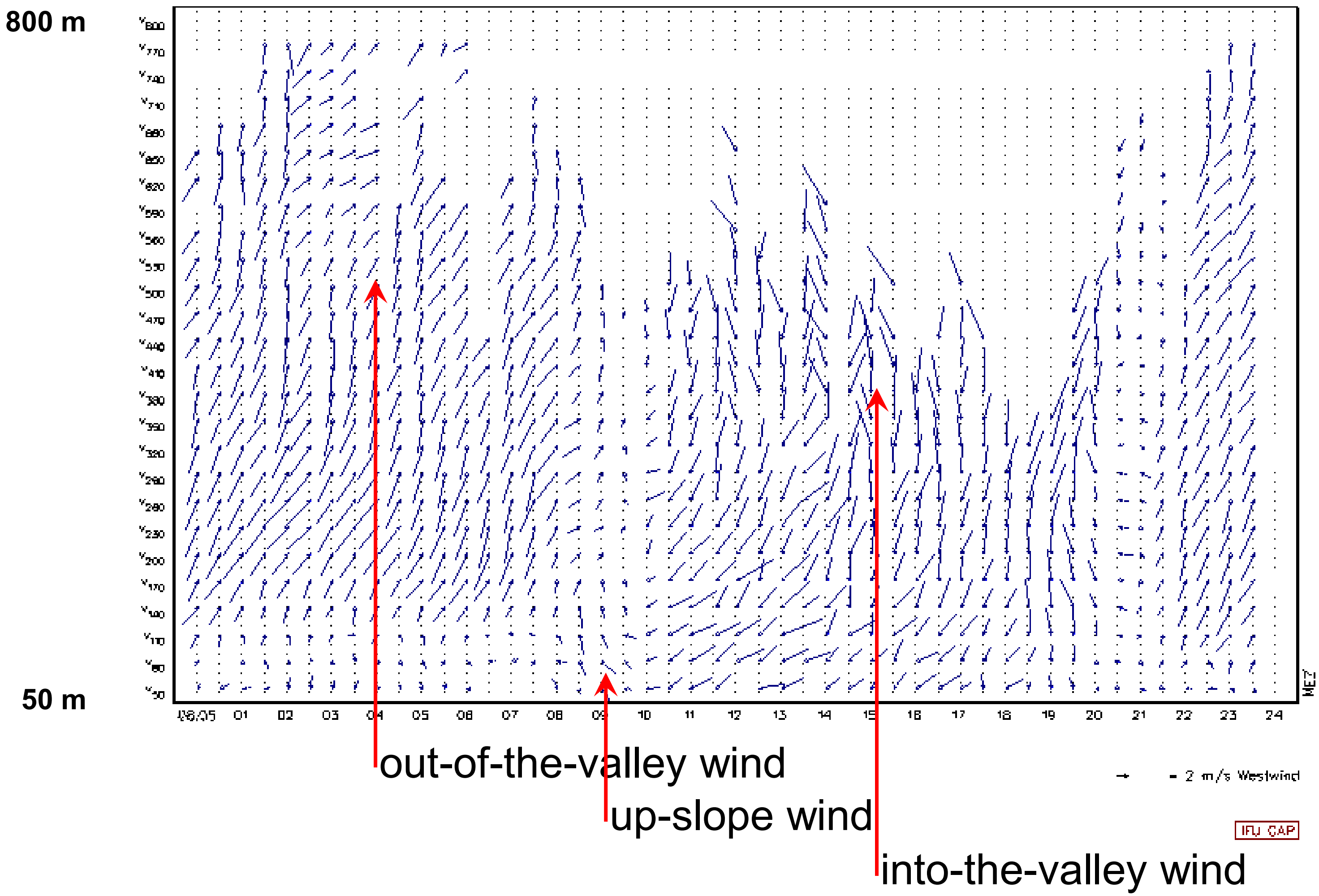


thin arrows: slope winds
night: downslope
day: upslope

full arrows: valley winds
night: out of the valley
„mountain winds“
day: into the valley
„valley winds“

open arrows: regional winds
(„Alpine pumping“)
night: into the planes
day: towards the mountains

valley wind system in an alpine valley (one day)



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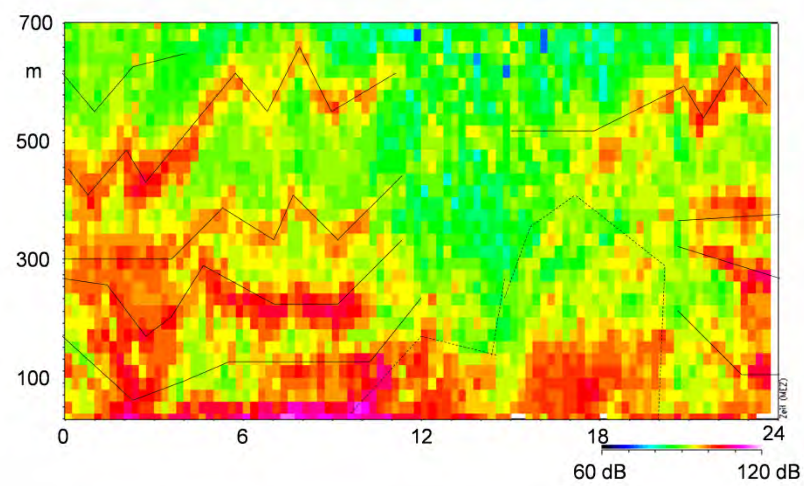
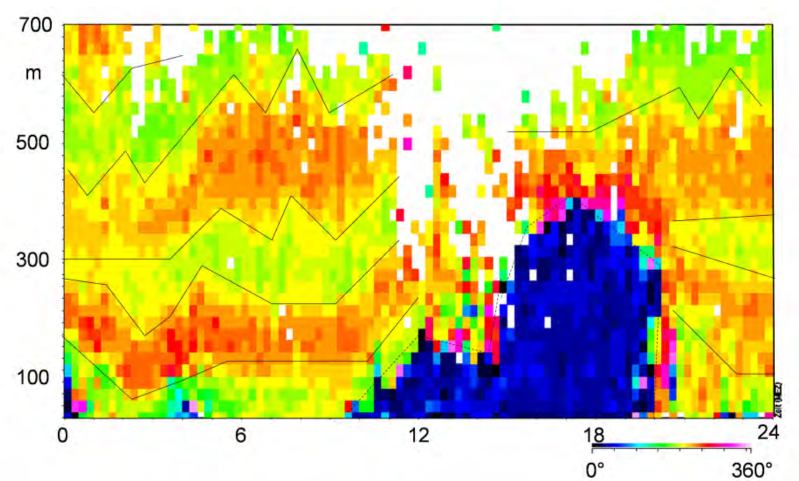
multiple layers in a wintry alpine valley



acoutic backscatter (vertical temperature gradients)



wind direction

problems of volume averaging measurements in complex terrain

existing studies

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some existing studies:

Bradley (ISARS 2008)	**based on a potential flow analysis (cylinder model)**
Bingöl et al. (MetZet 2009)	**based on the assumption of linearly varying wind components**
Bouquet et al. (ILRC 2010)	**theoretical considerations similar to Bingöl et al., CFD model to derive realistic corrections to lidar measurements**
Bradley et al. (BLM 2012)	**Myres Hill, Scotland, Zephir lidar, AQ 500 sodar**
Behrens et al. (BLM 2012)	**5-beam sodar measurements by Paul Behrens in complex terrain probing in two different directions**
Bradley (JTECH 2012)	**potential flow, bell-shaped hill and escarpment**

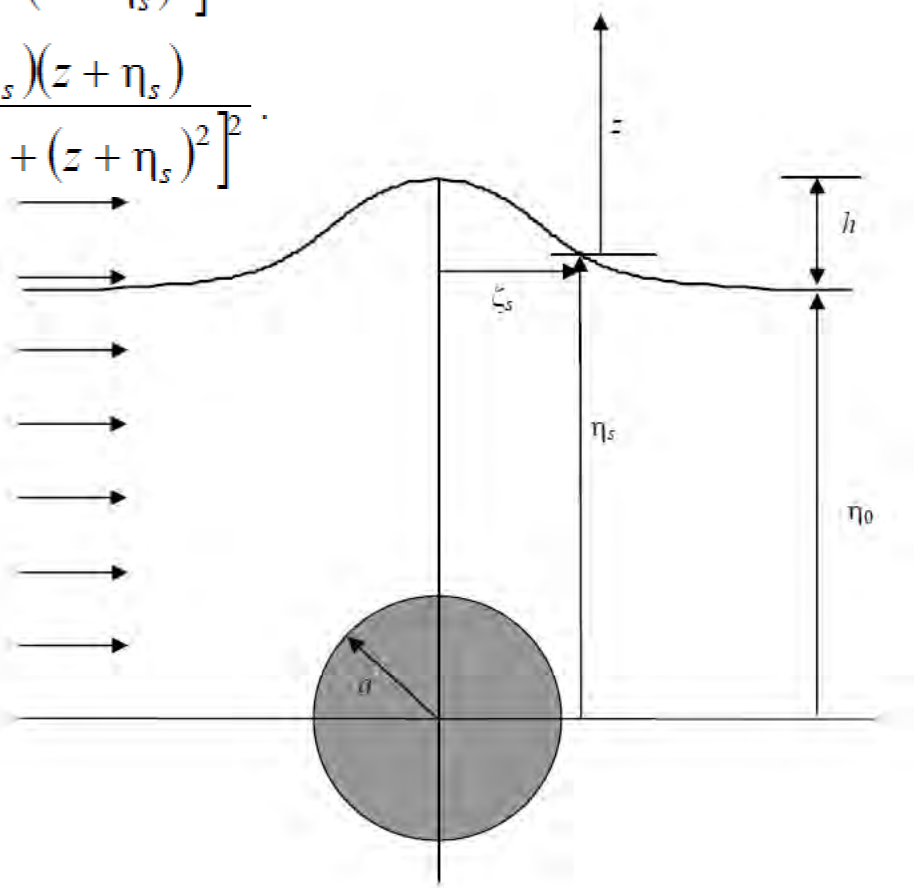
Bradley (2008) (ISARS 14, Risø)

potential flow, cylinder model

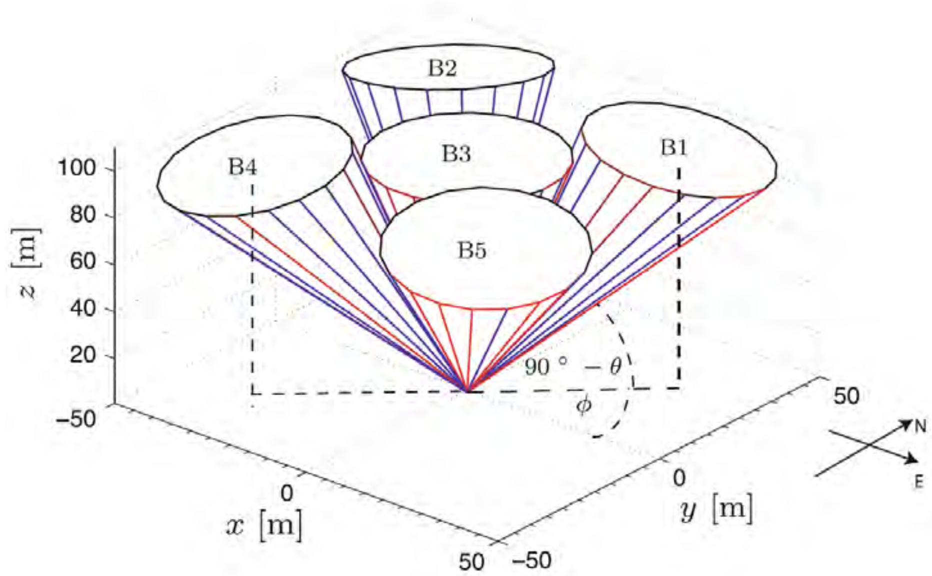
$$\frac{u}{U} = \frac{1}{U}\frac{\partial\psi}{\partial\eta} = 1 - h\left(L^2 + \frac{h^2}{4}\right)^{1/2} \frac{(x+\zeta_s)^2 - (z+\eta_s)^2}{\left[(x+\zeta_s)^2 + (z+\eta_s)^2\right]^2},$$

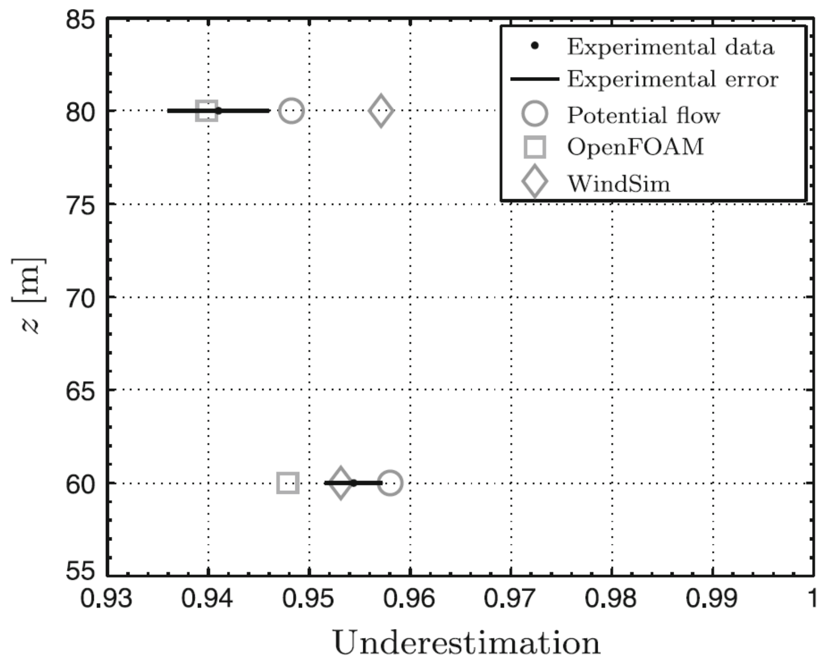
$$\frac{w}{U} = -\frac{1}{U}\frac{\partial\psi}{\partial\zeta} = -2h\left(L^2 + \frac{h^2}{4}\right)^{1/2} \frac{(x+\zeta_s)(z+\eta_s)}{\left[(x+\zeta_s)^2 + (z+\eta_s)^2\right]^2}.$$

$$L^2 = \left(\eta_0 + \frac{h}{2}\right)\left(\eta_0 + \frac{3h}{2}\right)$$



Behrens et al (2012) sodar observations versus potential flow (cylinder) model and two other models

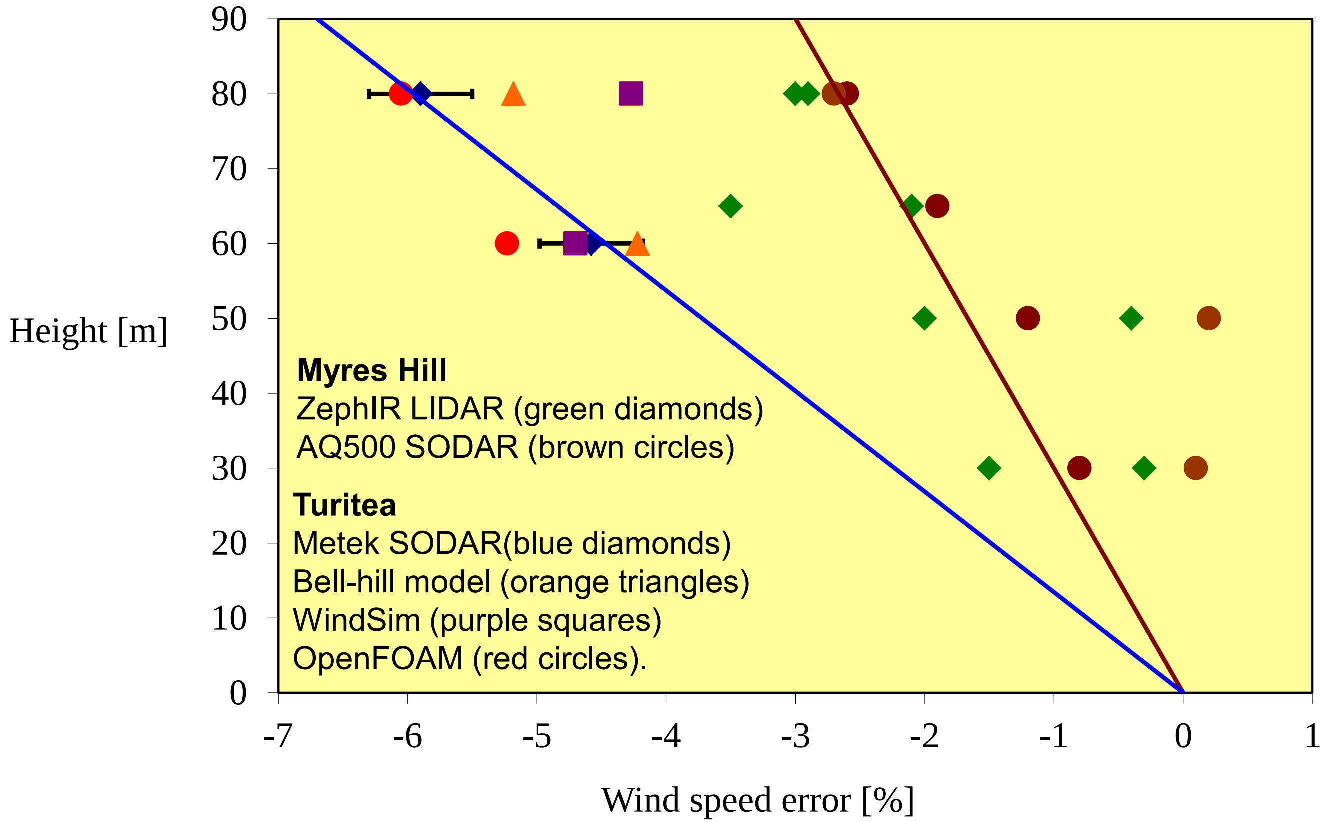




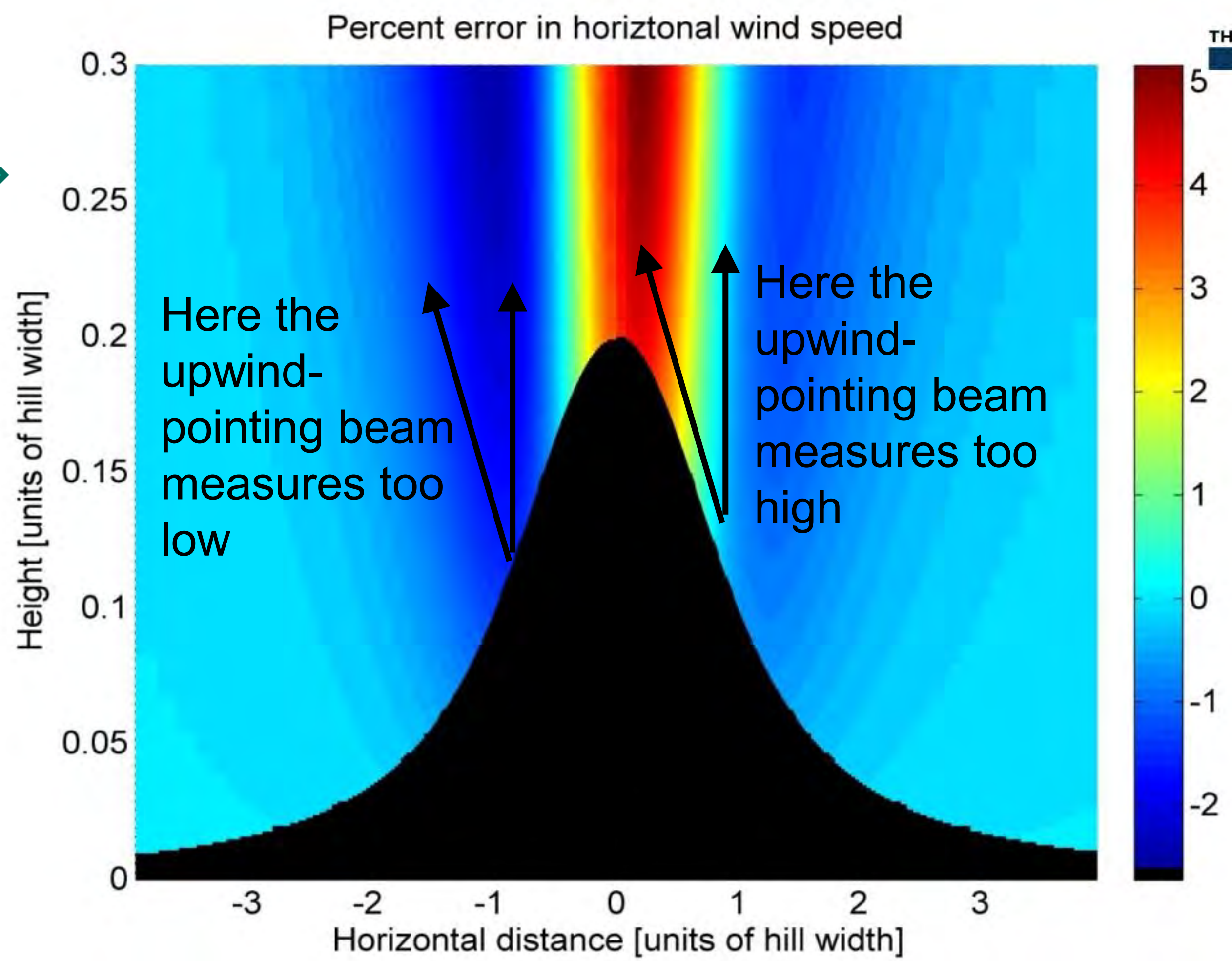
Behrens P, O'Sullivan J, Archer R, **Bradley SG**. Underestimation of monostatic sodar measurements in complex terrain. *Boundary Layer Met.*, **143**, 97-106. DOI 10.1007/s10546-011-9665-6, 2012.

Bradley (2012)

potential flow (cylinder) model, for higher complexity more than one cylinder can be used, bell-shaped hill



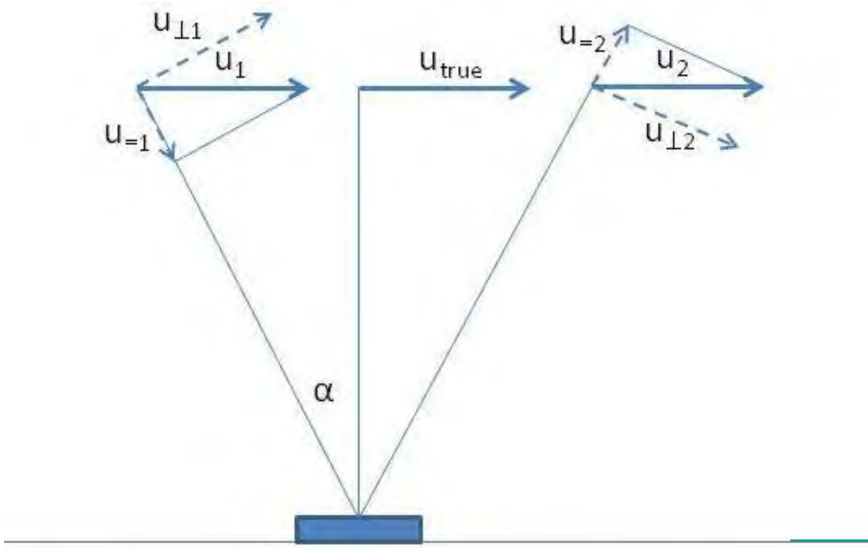
Bradley SG, Perrot Y, Behrens P, Oldroyd A. Corrections for wind-speed errors from sodar and lidar in complex terrain. *Boundary Layer Met.*, **143**, 37-48. DOI 10.1007/s10546-012-9702-0, 2012



Percent error in horiztonal wind speed
0.3
0.25
0.2
0.15
0.1
0.05
0
Height [units of hill width]
-3
-2
-1
0
1
2
3
Horizontal distance [units of hill width]
5
4
3
2
1
0
-1
-2
Here the upwind-pointing beam measures too low
Here the upwind-pointing beam measures too high

problems of volume averaging measurements in complex terrain

dimensional analysis

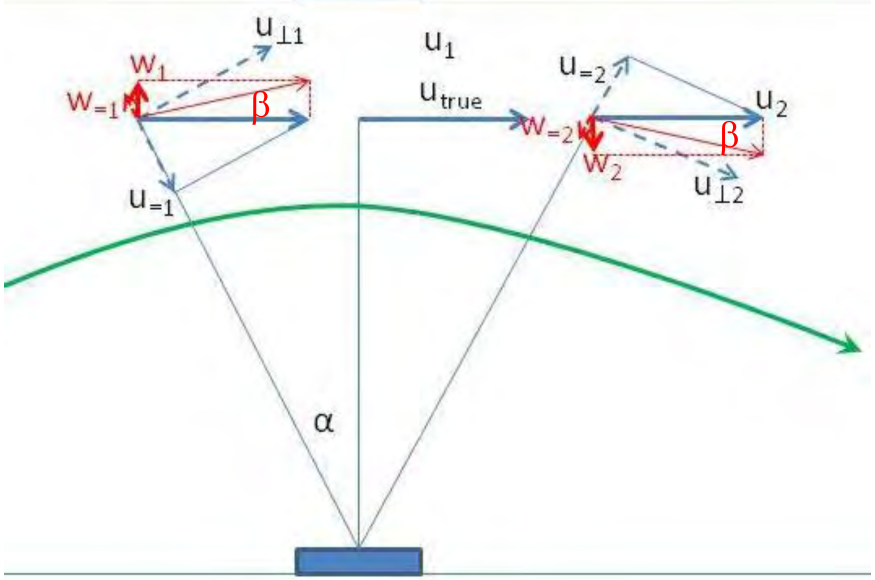


$$u_1 = \frac{|u_{=1}|}{\sin\alpha}$$

flat terrain

$$u_2 = \frac{|u_{=2}|}{\sin\alpha}$$

$$u_{Lidar} = u_{true} = \frac{u_1 + u_2}{2} = \frac{|u_{=1}| + |u_{=2}|}{2\sin\alpha} = \frac{|u_{=}|}{\sin\alpha}$$



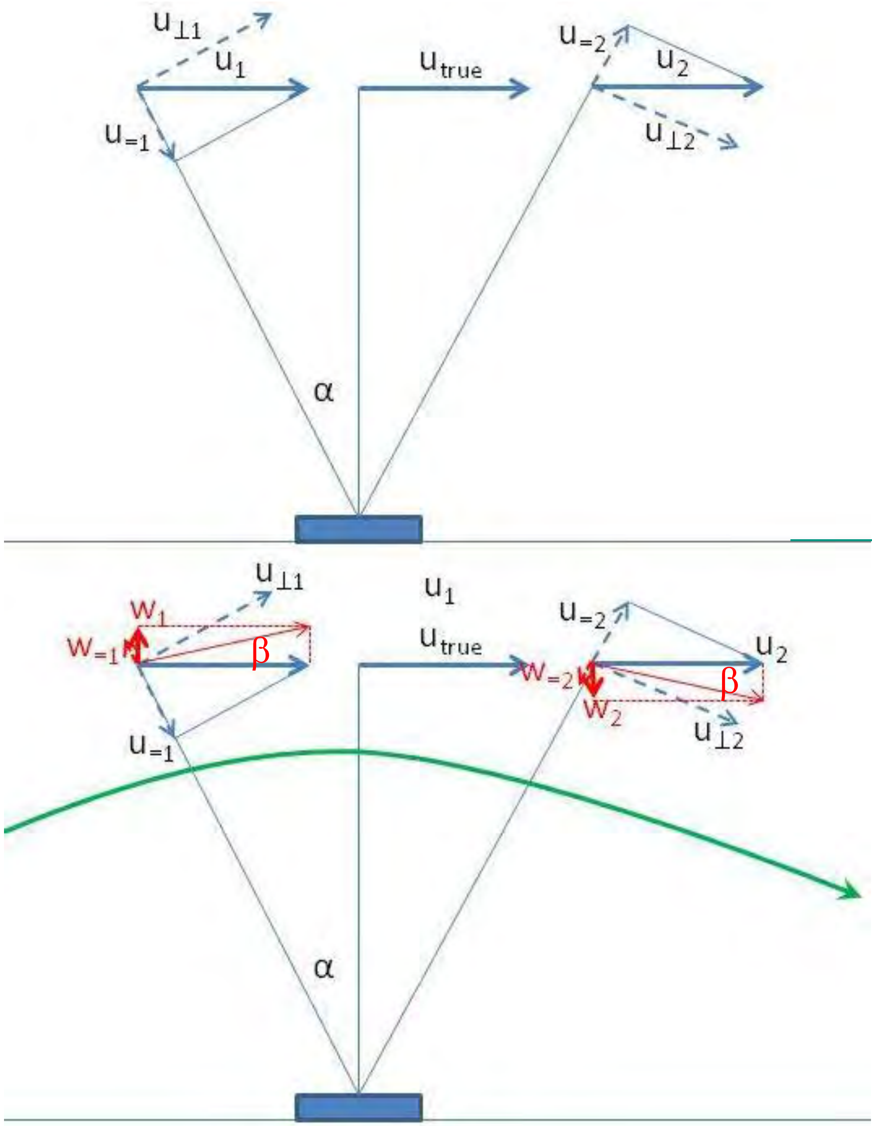
$$u_1 = \frac{|u_{=1}| - w_{=}}{\sin\alpha}$$

complex terrain

$$u_2 = \frac{|u_{=2}| - w_{=}}{\sin\alpha}$$

$$u_{Lidar} = \frac{u_1 + u_2}{2} = \frac{|u_{=}|}{\sin\alpha} - \frac{w_{=}}{\sin\alpha} = u_{true} - \frac{w_{=}}{\sin\alpha}$$

$$u_{Lidar} = u_{true}(1 - \frac{\sin\beta}{\tan\alpha})$$



$$u_{Lidar} = u_{true}(1 - \frac{\sin\beta}{\tan\alpha})$$

complex terrain

example:

α = 15°

β = 0.5° ➔ sin β / tan α = 0.032
β = 5° ➔ sin β / tan α = 0.32

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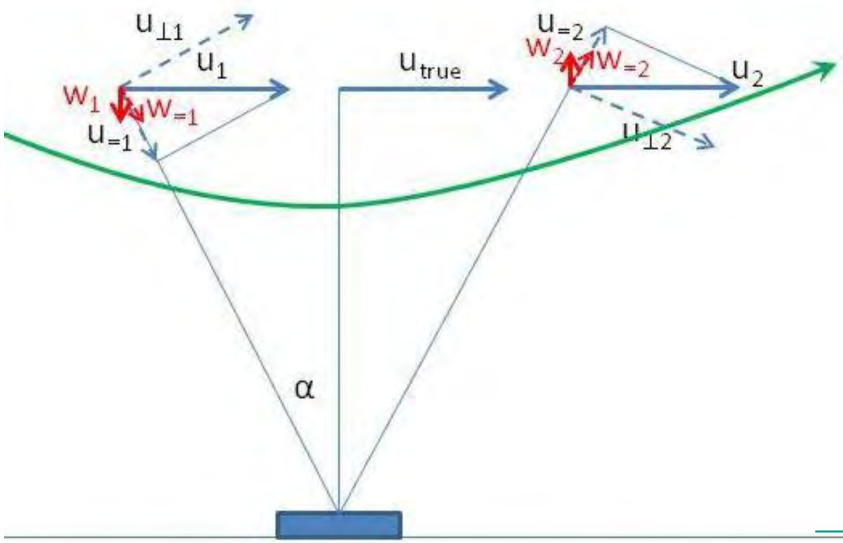
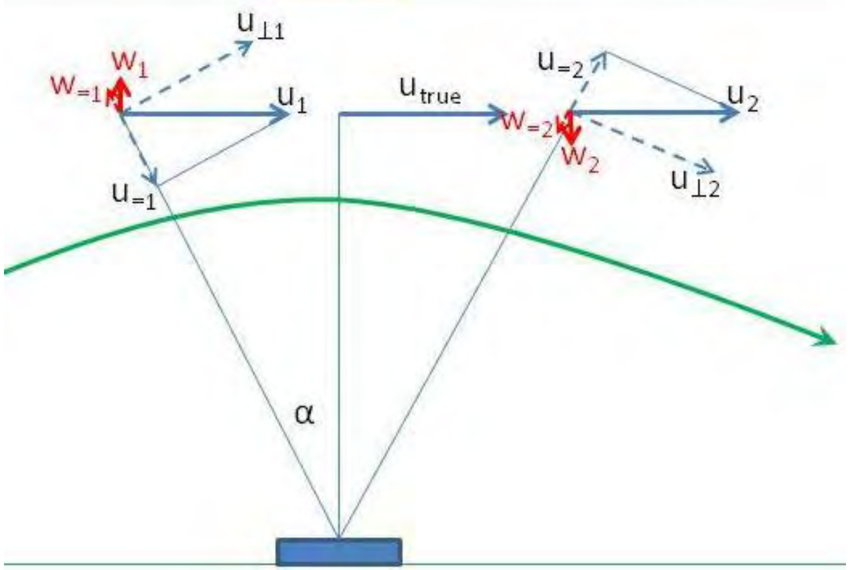


valley:

w-component adds to u-component

➔ SODAR/LIDAR measures too much wind

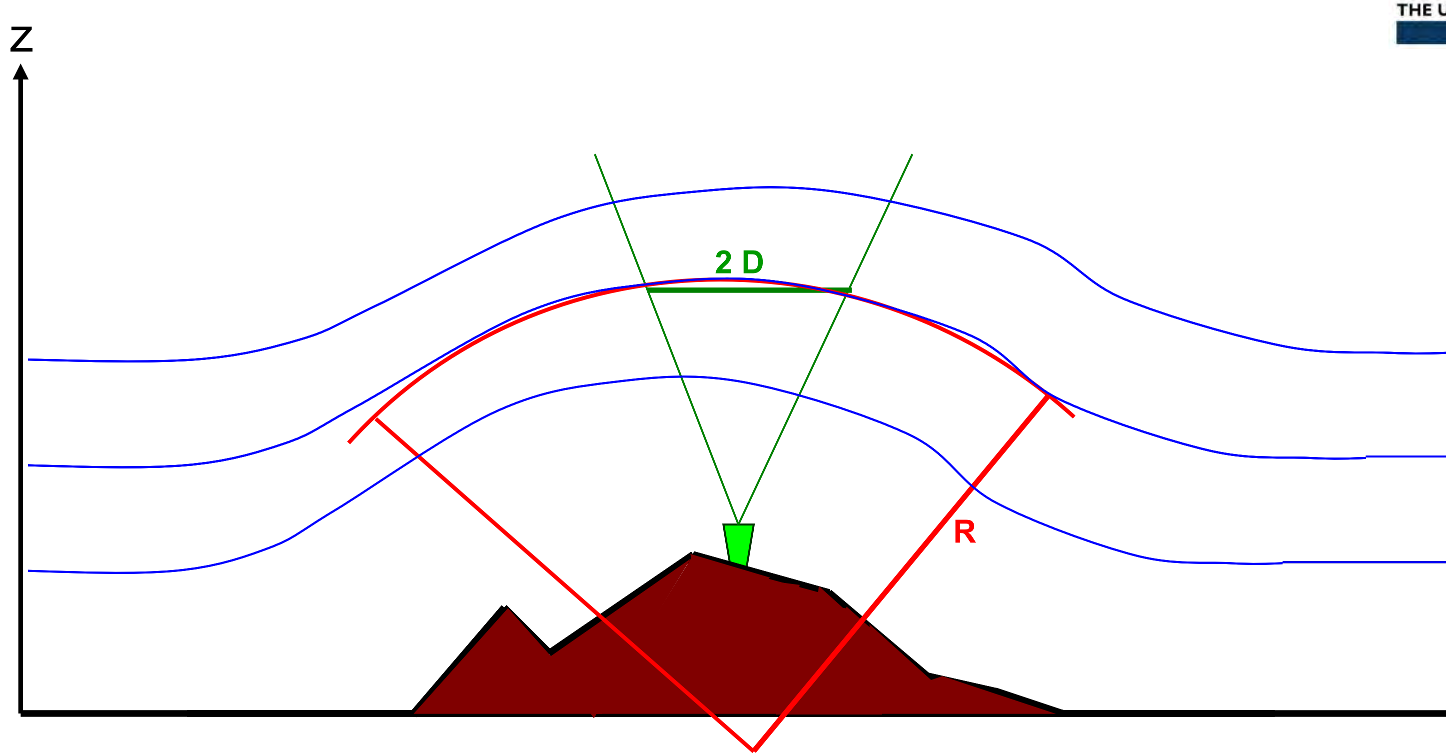


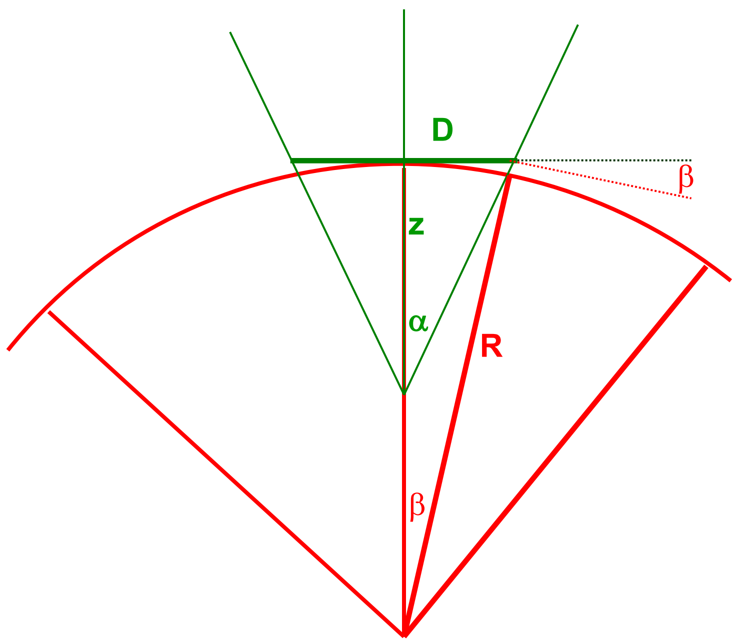
hill top / pass:

w-component reduces u-component

➔ SODAR/LIDAR measures too little wind

attached flow: how large is β?





$D = z \tan \alpha$

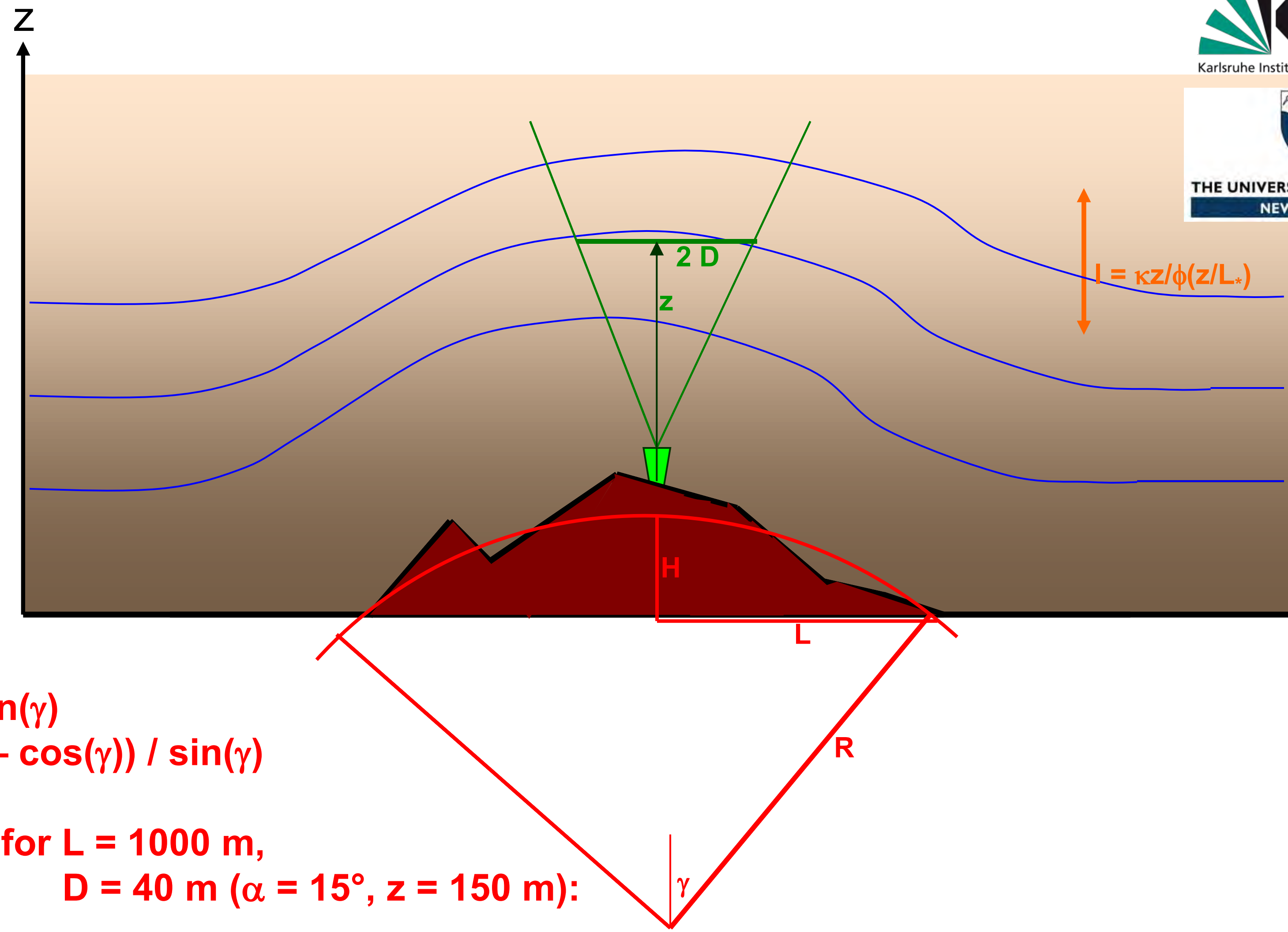
$\beta = \arctan (D/R)$

$= \arctan (z \tan \alpha / R)$

D is given by the instrument geometry

i.e., we still have to determine R

attached flow



$R = L / \sin(\gamma)$

$H/L = (1 - \cos(\gamma)) / \sin(\gamma)$

example for L = 1000 m,
D = 40 m (α = 15°, z = 150 m):

H/L = 0.1 → 11.42° → R = 5051 m → β = 0.46° → 3.0 % error
H/L = 0.2 → 22.62° → R = 2600 m → β = 0.89° → 5.8 % error
H/L = 0.3 → 33.40° → R = 1817 m → β = 1.27° → 8.2 % error

More general: preliminary parameter analysis

Influencing length scales

instrument:	**scan conus diameter**	**D**
orography:	**radius of curvature**	**R**
	surface roughness	z_0
atmosphere:	**thermal stability**	**L**
	height above ground	**z**

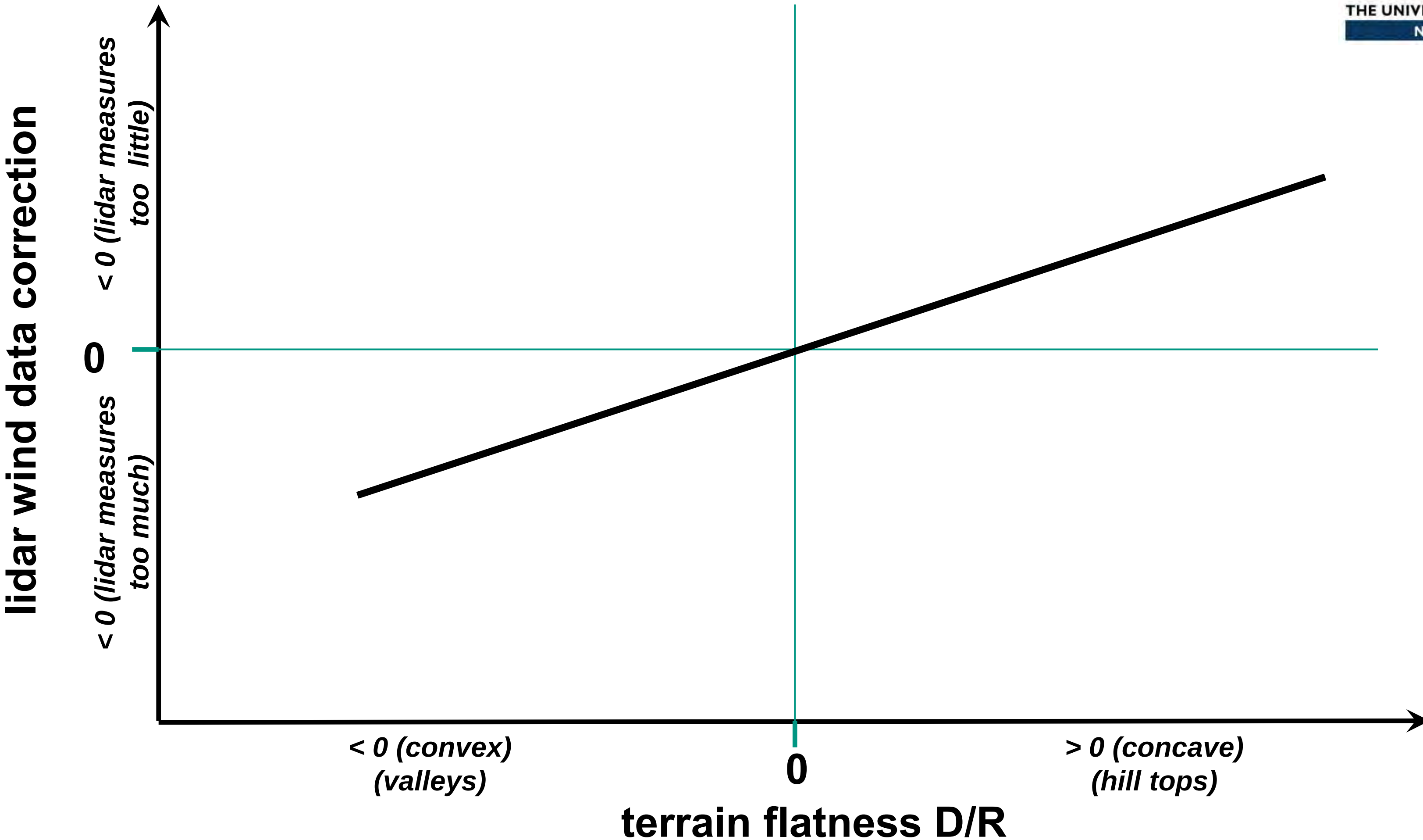
...

non-dimensional numbers

orography:	**terrain flatness**	$P1 = D/R$
	terrain roughness	$P2 = z_0/R$
atmosphere:	**stratification**	$P3 = z/L$

...

hypothetical influence terrain flatness D/R



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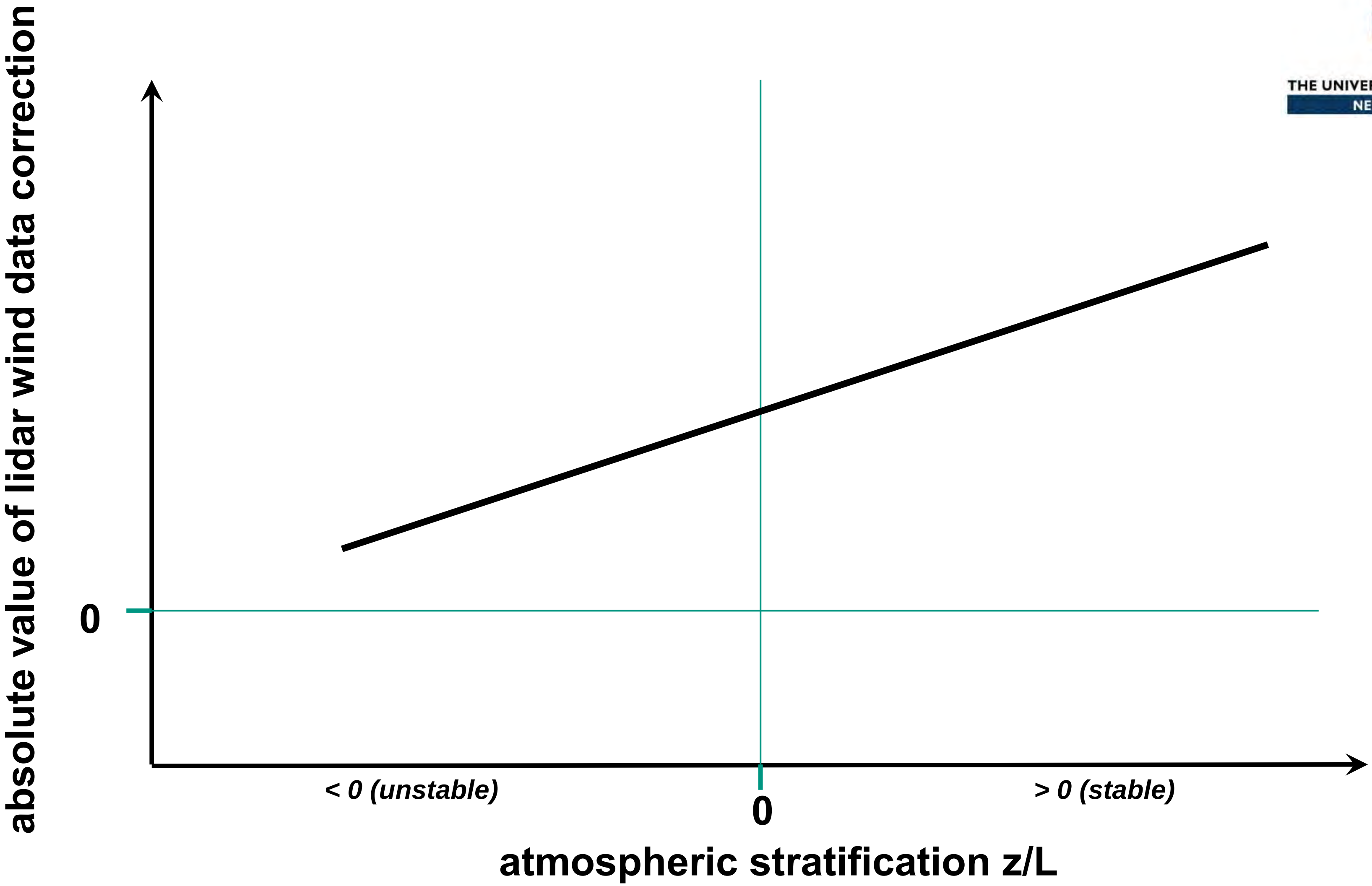
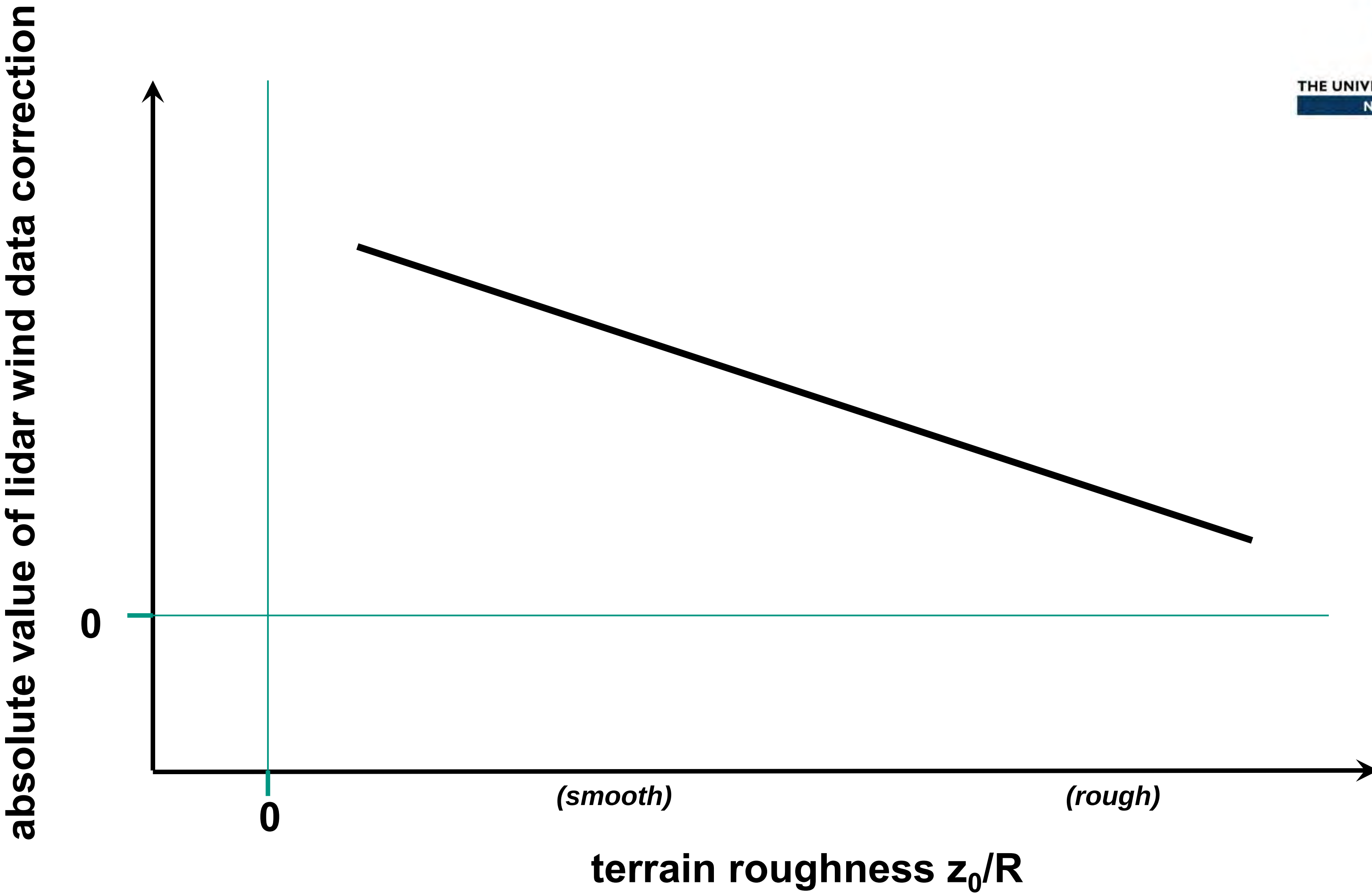
hypothetical influence atmospheric stability z/L



hypothetical influence terrain roughness z_0/R



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Conclusions:

non-homogeneous flow is a challenge
for volume-averaging measurement strategies

examples shown were for vertical curvature,
but horizontal curvature would cause problems as well

assessment by comparison of in-situ and volume-averaging measurements
or by numerical experimentation

main influencing parameter: radius of curvature of streamlines
secondary parameters: atmospheric stability
surface roughness
land use
...

First approaches for adjusting remote sensing wind data for spatial inhomogeneities exist, but further research is necessary.

Thank you very much for your attention