Ultrasonic Anemometer Instrumentation at Steep Slopes
Wind Tunnel Study - Field Intercomparison - Measurements

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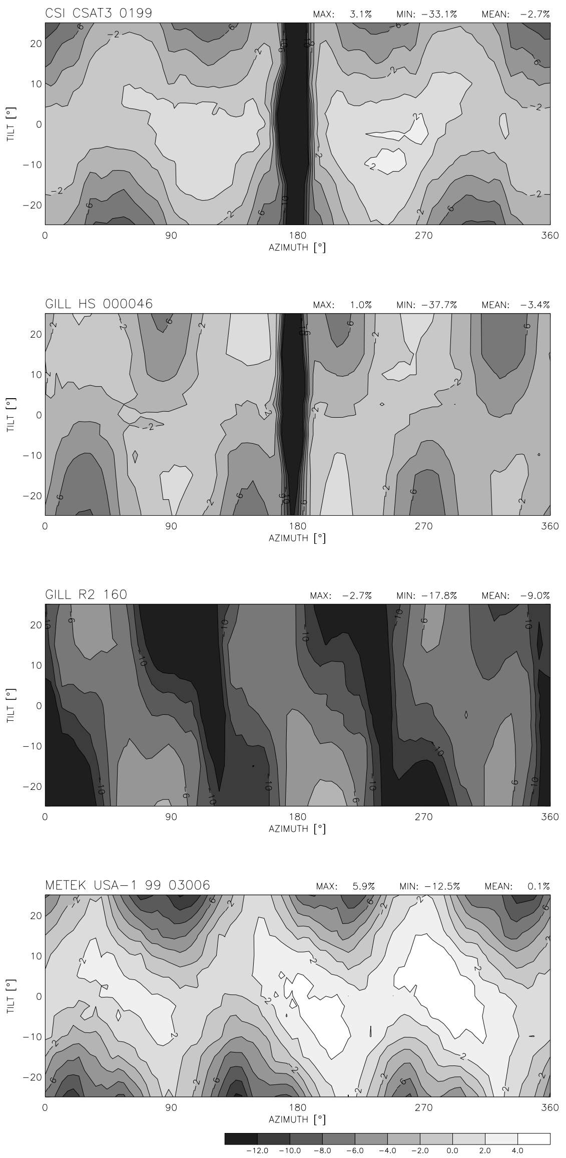


Fig. 1: Difference of wind speed measurement (vector mean) between wind tunnel and sonics at 4 m s^{-1} dependent from azimuth and tilt in %. The plots illustrate the effects of different sensor types with an azimuth resolution of 4° and 11 tilt positions. Gill R2 (omnidirectional) and Gill HS were operated in "uncalibrated mode". The high underestimations at 180° of the asymmetric instruments CSAT3 and HS correspond to the spar/fixing.

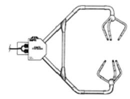
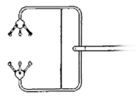
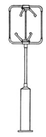
As part of the MAP-Riviera Project in 1999 turbulence and eddy covariance profile measurements at steep slopes (30°-40°) were carried out with state-of-the-art ultrasonic anemometers (Rotach et al., 2000). Micrometeorological studies in such complex terrain cannot be anymore reduced to classical one dimensional approaches and standard measurement methods. Therefore, it is of interest if the instrumentation can cope with these complex requirements. To have a closer look at the suitability of the instrumentation, a wind tunnel study and a field intercomparison were carried out with a large number of different ultrasonic anemometers (sonics) before setting up the slope stations.

Wind Tunnel Study

10 sonics were compared in the wind tunnel of the Institute of Fluid Dynamics at ETH Zurich in April 1999: 3 Campbell CSAT, 1 Gill HS, 1 Gill R3, 3 METEK USA-1, 2 omnidirectional Gill R2 and 1 asymmetric Gill R2. The sonics were exposed to 4 wind speeds (2, 4, 6, 8 m s^{-1}) by rotating them continuously around their vertical axis at eleven different tilt positions between ±25° with a tilting and rotation device. The wind vectors measured by the sonics were compared to the wind speed in the tunnel and the differences were analysed in dependence of azimuth and instrument tilt (Fig. 1).

The wind tunnel results point out that an angle of attack less than 10° from the horizontal plane (tilt) leads to more precise wind speed values than higher tilts, where systematic effects due to flow distortion are increasing. "High-end" instruments like Gill HS and CSAT3 show a more accurate measurement. However inter-instrumental differences are higher with higher tilts. This supports the advantage of a slope-normal setup for sonic measurements at steep slopes (Geissbühler et al., 2000).

Tab. 1: Inter instrumental differences between sonics of different designs and different calibration methods during the field intercomparison at San Vittore. The table shows mean differences to a reference instrument (CSAT3 0199) in % of the absolute values over 22 h of raw data fulfilling the criteria described in the text.

									
Sonic Type	**CSI CSAT3**		**Gill HS**		**METEK USA-1**		**Gill R2** (2)		
Serial No	(0112, 0118)		(000046)		(99 03006)		(0043, 0160, 0212)		
Calibration	*Pure*	*Matrix*	*Pure* (2)	*Matrix*	*Pure*	*Matrix*	*Pure*	*Manuf.*	*Matrix*
Mean wind speed	-3.2 %	-0.4 %	+1.2 %	-1.9 %	+2.1 %	-1.6 %	-7.8 %	+0.5 %	-1.0 %
σ_w	-4.1 %	+0.2 %	-0.6 %	-1.8 %	-9.9 %	+3.0 %	-9.9 %	+0.4 %	+0.5 %
u_* (3)	-3.9 %	-1.2 %	+1.8 %	-3.1 %	-6.3 %	+10.1 %	-4.0 %	+6.3 %	+5.7 %
$\overline{w'\theta'}$ (4)	-6.4 %	-1.0 %	+2.1 %	-0.3 %	-17.5 %	-5.6 %	+1.1 %	+19.5 %	+13.0 %

(1) R2 0043: asymmetric head; R2 0160 and R2 0212: omnidirectional head

(2) HS in “uvw calibrated” mode.

(3) $u_* = \sqrt[4]{(\overline{u'w'})^2 + (\overline{v'w'})^2}$. Only values with $\overline{u'w'}$ < -0.05 m² s⁻².

(4) Only values with H > 30 W m⁻².

Two dimensional correction matrices were calculated from the tunnel-data according to Vogt (1995) for all 10 instruments separately to correct the systematic effects of the flow distortion.

Field Intercomparison

In a field intercomparison over five mostly clear-sky days in July 1999 wind and acoustic temperature measurement, fluxes and second order moments were compared under the influence of different sensor types and different calibrations (Christen et al., 2000). 19 sonics were operated at San Vittore Airfield (Mesolcina Valley, Switzerland) in a large valley wind system. The daily wind maximum was 5 m s^{-1} with TKE/m values up to 3 m^2 s^{-2}.

All sonics were mounted at a height of 1.8 m over homogenous grassland. 20 Hz raw data were collected (USA-1: 10 Hz). 30 min block means were calculated from 120 hours of raw data after a rotation into mean wind ($\overline{v}$ = 0 and $\overline{w}$ = 0). Only data with a wind speed higher than 1 m s^{-1} and a direction from undisturbed sectors were selected for further analysis.

Different calibrations were applied: “pure” means data collected from the sensor without any further calibrations (uncalibrated or instrument internal calibrated data), “Manufacturer” is the Gill-calibration applied to the R2 and “Matrix” refers to data corrected with the sensor-specific two dimensional matrix from the wind tunnel study (Tab. 1).

Applying the best calibration, wind speed measurement of the vector mean m can be improved to be over the whole intercomparison within ±2%. Three R2 show extreme offsets, so that they were not included in further analysis. Standard deviations σ_u and σ_v are within ±3% (except R2 ±5%). σ_w of USA-1 and R2 shows slightly higher uncertainties, that alters also w-spectra (Fig. 2). However, some stable nocturnal situations with low wind speed and low turbulence result in differences for m, σ_u, σ_u and σ_w up to ±15% over 30 min. Because stable situations were associated with lower wind speeds, the stable spectra show also higher uncertainties.

The virtual acoustic temperature measurement of HS and some R2 show offsets up to +12K, while CSAT3 and USA-1 agree well with the reference temperature. However, for most applications a precise absolute acoustic temperature is not of interest. The more problematic error source is σ_θ that contributes to the kinematic heat flux and showed significantly more inter-instrumental scatter than σ_u, σ_v and σ_w at San Vittore. USA-1 underestimates σ_θ with higher values by -10% but lower values with σ_θ < 0.5 K and high frequency fluctuations were overestimated. The θ-spectra of the USA-1 show extreme overestimations in the high frequency range faster than 0.5 s caused by the instrument noise and/or the slower sampling frequency. The HS overestimates all σ_θ-values by 13% (r^2=0.96) and R2 overestimate σ_θ by +10% to +30% with high scatter.

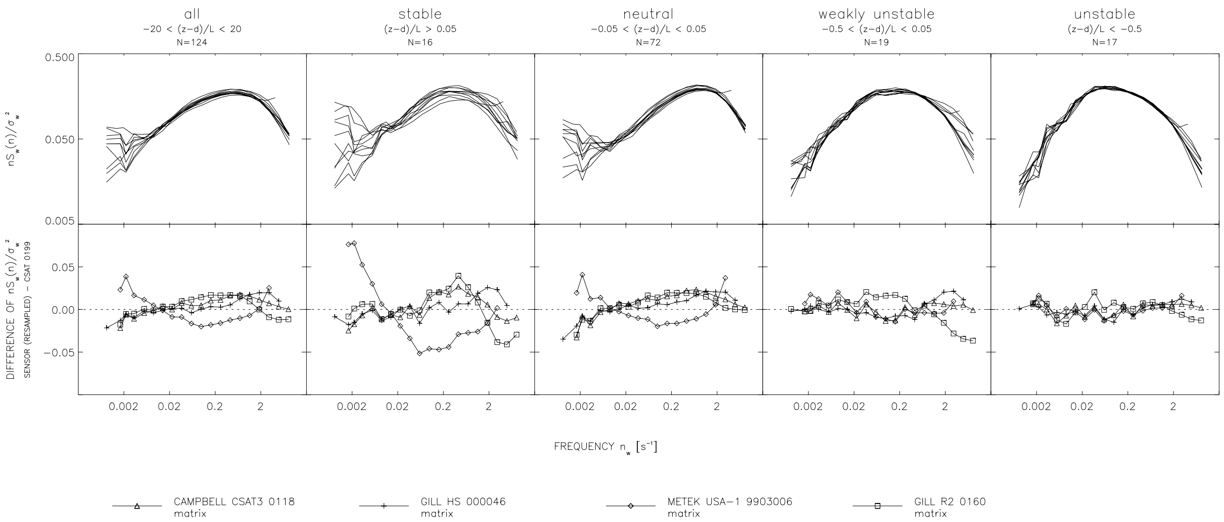


Fig. 2: Intercomparison of mean normalized vertical wind spectra of different sonics during the San Vittore field intercomparison. The upper row shows one mean spectra per sensors in the indicated stability class, the lower row visualizes differences between sensor and reference (CSAT 0199) as difference of $n \cdot S_u(n)/\sigma_u$. for four selected sensors according to the legend. A linear detrending was applied and the spectra are not normalized by mean wind.

Analogous to the wind tunnel, different classes of instrument performance can be formed: CSAT3 and HS show highest inter-instrument agreement, followed by USA-1 and then by R2. The field intercomparison points out, that USA-1 can be improved in most cases substantially by applying a matrix calibration, whereas the improvement of R2 by matrix calibration is in the same order as the suggested manufacturer calibration.

Measurements

The micrometeorological measurements at the slopes during the MAP-Riviera project were carried out under much more complex conditions, in terms of homogeneity, fetch, stationarity and forcings. For example, parameters like $\overline{v'w'}$ that are nearly zero in homogeneous terrain, contribute significantly to the momentum fluxes under the observed conditions (van Gorsel et al., 2000).

The stations were erected at the steep westward facing slope of the Riviera Valley, Ticino, Switzerland. At most slope-stations the sonics were tilted up to 40° to adjust them to the topography and therefore to minimize flow distortion. Figure 3 illustrates the observed angles of attack at the slope-station Monte Nuovo which was operated inside and above a birch forest of 35°. The station supported 6 sonics of different designs: At the topmost level (22 m, z/h=1.75) an HS was installed to get as accurate flux measurements as possible. In the lowest two levels inside the trunk space CSAT3 were mounted to sample more precisely the slow

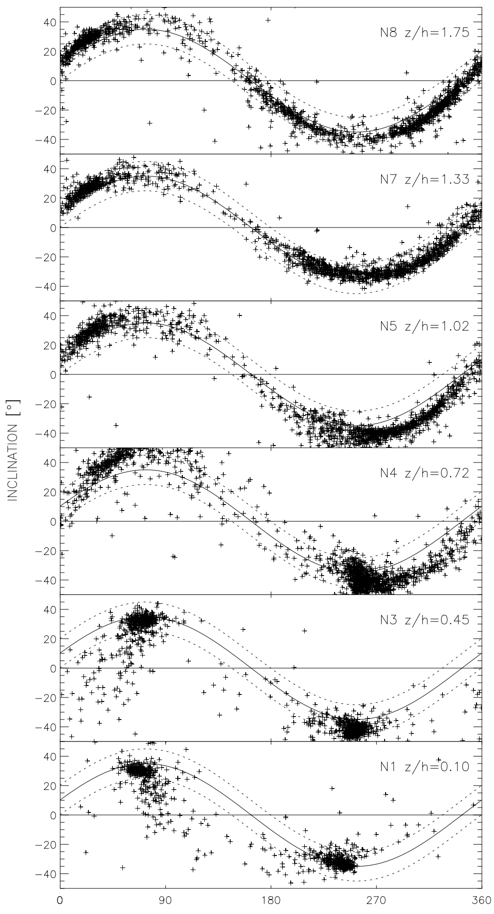


Fig. 3: Inclination of wind in function of horizontal azimuth of wind attack for all sonics at Monte Nuovo based on 10 min block averages from DOY 245 to 255. Inclination and azimuth refer to a horizontal aligned coordinate system. The solid sine function represents the horizontal plane of the tilted sonic (35°), the dashed lines border the region with has less than ±10° deviation to the horizontal plane of the sonic.

drainage flows. Additionally the profile was enhanced by 3 R2.

The highest deviations from the horizontal plane of the sonic were found at the instrument that was mounted directly inside the crown space (z/h=0.72) due to flow modifications caused by the dense plant structure. Overall, the probability density of wind direction and inclination attacks the tilted sonics in most cases inside the favorable sector of ±10° from the sonic horizontal plane (indicated by the thick sine-line). The situation inside the canopy is characterized by lower mean values of wind components and fluxes, therefore relative higher errors are expected for the sonic measurements.

When measuring fluxes at slopes, it is of interest, how the components are directed and if the

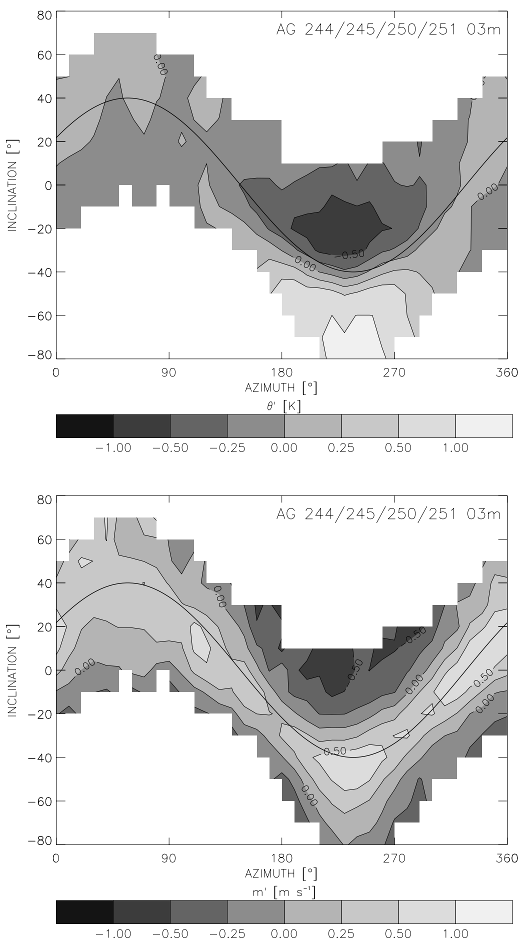


Fig. 4: Spatial distribution of the deviations from mean temperature (θ', upper plot) and the deviations from mean scalar velocity (m', lower plot) both relatively to 30 min block means. Data from four days at the station Alpe di Gagèrn are shown as a function of horizontal azimuth and inclination based on 1 Hz data. Inclination and azimuth refer to a horizontal aligned coordinate system. An azimuth of 240° is upslope wind and 60° represents downslope winds. The solid sine function indicates the horizontal plane of the tilted sonic (40°).

Fig. 3: The setup of the tilted R2 sonics at the slope station Alpe di Gagèrn (2100m).

sonic is aligned to measure the fluxes in an accurate way. Figure 4 illustrates the mean temperature and velocity fluctuations as a function of their spatial angle of attack at the 3 m level of the slope-station Alpe di Gagèrn. The data point out, that the tilted sonic represents also the plane that divides negative (drawn in dark) and positive heat contributions θ' (bright), at least in the turbulent upslope wind (240°). Slower wind velocities (negative m') are associated with higher inclinations towards the sonic, higher wind speeds (positive m') are observed in the slope normal plane (corresponds to negative $\overline{u'w'}$ and $\overline{v'w'}$).

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