The P2546A Cup Anemometer
with extended specifications

February 14, 2005

Standard Calibration:

$U = A_\circ + B_\circ \times f$

U: Wind speed in m/s

f: Output frequency in Hz

$A_\circ = 0.27$ m/s

$B_\circ = 0.620$ m

Non-linearity: $\Delta U < 0.03$ m/s in the interval 4.5 m/s $< U <$ 16 m/s

Variability among instruments in the interval 4 m/s $\leq U \leq$ 16 m/s:

$$\sigma_{A_\circ} = 0.01 \text{ m/s}$$
$$\sigma_{B_\circ} = 0.002 \text{ m}$$
$$\sigma_U = 0.003 \times U$$

Distance constant: $\ell_\circ = 1.81$ m

Angular response:

μ_1	=	0.05	asymmetry parameter
μ_2	=	-0.9	flatness parameter

Single-Instrument Calibration: $U = A + B \times f$

Standard error and correlation: in the interval 4 m/s $\leq U \leq$ 16 m/s:

$$\sigma_A = 0.01 \text{ m/s}$$
$$\sigma_B = 0.001 \text{ m}$$
$$\rho_{AB} = -0.94$$

Temporal stability under normal operation: 3 years

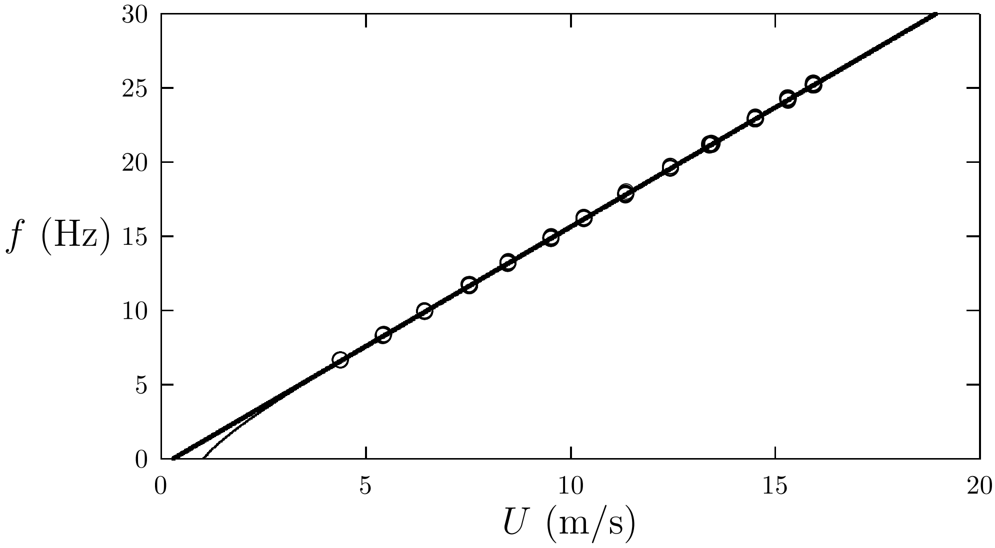

Figure 1: The linear calibration expression (thin line), the non-linear, hyperbolic calibration expression (thick line), and the 182 data points (open circles).

Comments:

1. The wind speed U is the velocity component perpendicular to the instrument axis.
2. The output frequency f is to be understood as the average rate of pulses over a user-chosen period of time. Two pulses are emitted for each rotor revolution.

   The angular velocity of the three-cup rotor is not constant for a constant wind speed. It fluctuates periodically with a period equal to the time for one full rotor revolution. Consequently, the best temporal resolution Δt is given by the duration of one revolution. This can be approximately 'translated' into a spatial resolution $2\pi\ell$ along the direction of the wind:

   $$2\pi\ell \equiv U\Delta t = \underbrace{A_\circ \Delta t}_{<0.1 \text{ m}} + B_\circ \underbrace{f \Delta t}_{=2} \approx 2B_\circ = 1.24 \text{ m}$$

   so that $\ell \approx 0.2$ m. The quantity $2\pi\ell$ can be interpreted as the length of the column of air which has to pass through the rotor to make it turn one revolution.
3. The non-linearity is difficult to determine and the specification here is rather pessimistic. For one anemometer the number of data points are too few. Consequently, we have taken all 13 calibration points for each of 14 anemometers and fitted these 182 points the linear expression

   $$f_L(U) = a_\circ \times U + b_\circ$$

   and the hyperbolic expression

   $$f_H(U) = a \times U + \frac{b}{U}$$

   We found $a_\circ = 1.6095 \pm 0.0009\,\text{m}^{-1}$, $b_\circ = -0.4257 \pm 0.0099$ Hz, $a = 1.5868 \pm 0.0006\,\text{m}^{-1}$, and $b = 1.67 \pm 0.05$ m/s^2.

   The two fits and the data points are displayed in Fig. 1.

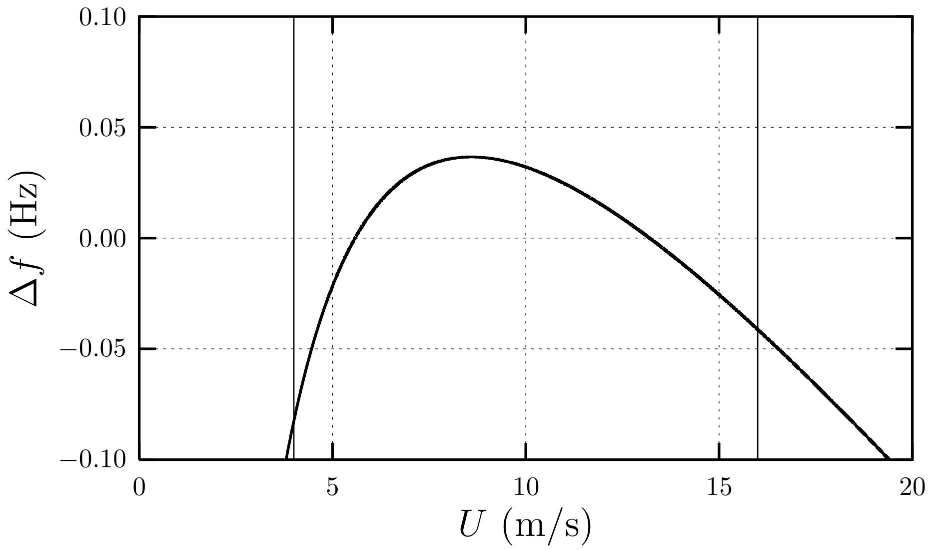

Figure 2: The difference Δf. Vertical thin lines indicate the wind speed interval from 4 m/s to 16 m/s.

We use the difference

$$\Delta f = f_H(U) - f_L(U)$$

as an expression for the non-linearity and find

$$\Delta U = A_\circ \times \Delta f \approx 0.02 \text{ m/s},\ 5 \text{ m/s} < U < 15 \text{ m/s}$$

The difference Δf as a function of wind speed U is shown in Fig. 2.

4. The standard-calibration constants $A_\circ$ and $B_\circ$ are average values of the calibration constants for about 80 anemometers. The variabilities $\sigma_{A_\circ}$, $\sigma_{B_\circ}$, and σ_U correspond to 68.3% confidence limits (95.4% confidence limits for twice these variabilities). This means that 68.3% of all single instrument calibration constants A and B are closer than $\sigma_{A_\circ}$ and $\sigma_{B_\circ}$ to $A_\circ$ and $B_\circ$, respectively, and that 68.3% of all measured wind speeds in the range $4 \text{ m/s} \leq U \leq 16 \text{ m/s}$ are within $\pm\sigma_U$ from each other.

5. The dynamic response is represented by the distance constant $\ell_\circ$. It corresponds to the velocity dependent time constant $\tau_\circ = \ell_\circ / U$ which characterizes the anemometer as a first-order temporal filter. A sudden change ΔU in wind speed will cause the anemometer frequency output $\Delta f(t)$ to change according to

$$\Delta f(t) = \frac{\Delta U}{B} \left(1 - \exp\left(-\frac{t}{\tau_\circ}\right)\right)$$

This means that a column of air with a length equal to $\ell_\circ = 1.81$ m must pass through the rotor before its angular velocity has changed 63.2% towards its new equilibrium output.

6. The angular response $g(\theta)$ is a function of the angle θ (in radians) between the wind direction and the plane perpendicular to the instrument axis. An upward wind velocity corresponds to a positive value of θ. The ideal angular response is the so-called cosine response where

$$g_\circ(\theta) = \cos\theta \approx 1 - \frac{\theta^2}{2}$$

In this case the anemometer is insensitive to the vertical velocity component. The power-law expansion is accurate within 1% if $|\theta| < 0.7$ (this corresponds to $\pm 40^\circ$). A real angular response can conveniently be presented as

$$g(\theta) = 1 + \mu_1\theta - (1 - \mu_2)\frac{\theta^2}{2}$$

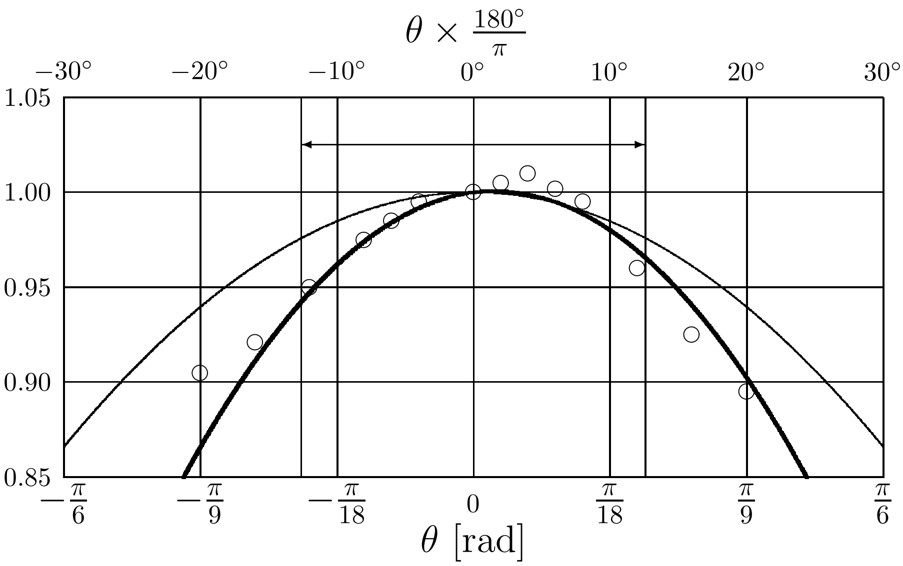

Figure 3: The open circles are measurements, the thick line the fit according to the equation for $g(\theta)$, and the thin line the ideal cosine response $g_{\circ}(\theta)$. The vertical lines at about $\pm 12°$ indicate the fitting interval.

The two constants are wind-speed independent. The first represents asymmetry with respect to up-down wind direction whereas the second will be responsible for the bias on the measured mean-wind speed when there is vertical-component turbulence. The bias will be positive/negative when μ_2 is positive/negative. When $\mu_1 = \mu_2 = 0$ the angular response is ideal. Figure 3 shows measured angular response.

The fit has not been possible to satisfactorily capture the strange behavior of the angular response in the interval $0 < \theta \lesssim 0.15$. As a consequence μ_1 and μ_2 have standard errors of about 30% and 18%, respectively.

7. The standard error of the single-instrument constants are 68.3% confidence limits. The correlation ρ_{AB} is needed to estimate how errors in A and B propagate to functions $G(A, B)$ of A and B. The standard error of $G(A, B)$ is

$$\sigma_G = \sqrt{G'_A(A, B)^2 \sigma_A^2 + 2G'_A(A, B) G'_B(A, B) \rho_{AB}\, \sigma_A \sigma_B + G'_B(A, B)^2 \sigma_B^2}$$

8. Temporal stability means that A and B over time change less than σ_A and σ_B, respectively.