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HiWASE: instrument alignments

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ABSTRACT

Alignment offsets between anemometers and motion-sensing instruments are a source of uncertainty for eddy correlation flux measurements made at sea. A previously described laboratory technique (Brooks, 2008) has been utilised to determine the pitch, roll and yaw offsets between flux instruments installed on the weathership Polarfront as part of the HiWASE project. Pitch and roll offsets were determined with an uncertainty of between 0.02° and 0.08°. Yaw offsets were determined with an uncertainty of between 0.5° and 1.2°.

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HiWASE: Instrument alignments

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Abstract

Alignment offsets between anemometers and motion-sensing instruments are a source of uncertainty for eddy correlation flux measurements made at sea. A previously described laboratory technique (Brooks, 2008) has been utilised to determine the pitch, roll and yaw offsets between flux instruments installed on the weathership *Polarfront* as part of the HiWASE project. Pitch and roll offsets were determined with an uncertainty of between 0.02° and 0.08°. Yaw offsets were determined with an uncertainty of between 0.5° and 1.2°.

Contents

1. Instrument alignments

1.1. Background

The Eddy Correlation (EC) method for determining fluxes of momentum or scalar properties requires measurement of fluctuations in the vertical wind speed. Wind speed measurements for use in EC flux calculations are typically made in 3 dimensions using an instrument such as a sonic anemometer. On a moving platform such as a ship at sea, a flux-determining anemometer is either gimbaled or fixed relative to the platform. If the anemometer is fixed, then the instruments will be subject to the motion of the platform. The reference frame of the anemometer's wind velocity measurements must be rotated into the Earth's surface reference frame in order to determine the true vertical wind speed.

In order to rotate the anemometer's reference frame, measurements of the tilt of the instrument, the angular velocity and the platform velocity are all required at a rate that encompasses the frequency of platform motion (Edson *et al*, 1998). These measurements can be obtained from a dedicated motion instrument such as a Systron Donner MotionPak, which consists of three accelerometers and three angular rate gyros, mounted coaxially to give complete three dimensional motion measurements.

In order to minimize the linear velocity imposed at the point of wind measurement by its rotation around the motion sensor, it is desirable to locate the anemometer and motion instruments close together. The vector offset between the two instruments (specifically, the offset between the centre of the anemometer's measurement volume and the centre of the motion instrument) should be determined to a degree of accuracy less than the resolution of the anemometer. Taking the resolution of the anemometer as 0.01 $m.s^{-1}$ (as for a Gill R3 Sonic Anemometer) and a typical rotation rate of $10^{o}.s^{-1}$, the required vector offset accuracy is 0.057 m, an accuracy that necessitates the instruments being positioned near to one another (Brooks, 2008).

Uncertainty in the alignment of the anemometer's measurement axis with the axis of the motion instrument will cause error in the determination of the vertical wind speed and thus error in the EC momentum and scalar fluxes. A recent analysis of MotionPak – anemometer instruments determined that the error in the along wind momentum flux is 3.2% for a pitch misalignment of 1°, 3.7% for a roll misalignment of 1°, and 0.7% for a yaw misalignment of 1°. (Brooks, 2008). Note that the relative importance of the pitch, roll and yaw offsets shown here is likely a result of the particular platform motion experienced during the experiment.

This report details the process to determine the pitch, roll and yaw alignments between two principal components of the 'Autoflux' flux measurement system (Yelland et al, 2009). These instruments are a Gill R3 sonic anemometer (hereafter R3) and a Systron Donner MotionPak (hereafter MotionPak). For the HiWASE project (Brooks et al, 2008), the 'Autoflux' instrumentation made continuous measurements of momentum, sensible heat, latent heat and CO_2 fluxes onboard the ocean weather ship *Polarfront* from September 2006 to December 2009.

1.2. Methods

1.2.1. MotionPak accelerometer calibration

The MotionPak measures acceleration in three axis using three internal accelerometers, and determines its own rate of rotation using three internal angular rate gyros. The tilt of the instrument is determined from the accelerometer's measurement of gravitational acceleration through each axis.

The MotionPak's accelerometers output their signal as a current. The current is converted to voltage using an external 1500-Ohm resistor, and is passed through a low pass filter prior to data acquisition. Potential scaling or offset in the signal caused by the current to voltage conversion, filtering or logging was examined using the manufacturer's calibration data.

Using an adjustable frame, the maximum positive or negative voltage for each axis, a, was recorded with the MotionPak stationary. The scaling factor, *sf,* (volts/g) and bias, b, (g) in each axis (denoted by the subscript i) could then be determined via:

$$g = \left(a_i / sf_i\right) - b_i \quad (1)$$

Where g is gravitational acceleration, taken either as positive or negative depending on the instrument's orientation. Note that the scale factor must first be converted from *mA/g* to *volts/g* using Ohm's law. The values determined for the two MotionPak instruments used on *Polafront* are shown in Table 1. The gravitational values through each axis are converted to tilt angles. The error in producing 1g and -1g in the three axes gives a measure of bias in the accelerometer signal output (Table 2).

The alignment of the MotionPak's rate gyros with its accelerometers is an additional source of potential bias in the MotionPak measurements (Brooks, 2008). This is a smaller error than that resulting from misalignment between the MotionPak and the R3. Determination of any such misalignment has not currently been performed and is intended as possible future work.

1.2.2. Instrument internal bias

In order to determine any bias in the MotionPak's pitch and roll accelerometers, the MotionPak is removed from its weatherproof housing and placed flat on an adjustable tilting frame. The frame is leveled using a calibrated bubble level, accurate when level to ~ 0.02°. The bubble level is itself calibrated using its internal adjustments so that the bubble level gave the same repeated measurement when turned 180º about its vertical axis.

The MotionPak accelerometer readings are taken with the instrument in four different orientations, rotated about its vertical axis. The average of the readings was used as the measure of bias in the MotionPak's x and y-axis. The MotionPak bias for the two instruments used in this report are shown in Table 3.

Inside the R3 casing is a wire inclinometer measuring the instrument's tilt in two dimensions (pitch and roll). The R3 outputs two orthogonal tilts in degrees.

The offset of the inclinometer from the R3 casing was found in a similar way to above. The casing base was levelled using the bubble level and the output from the inclinometer was recorded. The inclinometer is aligned with the R3 sonic sensor head as part of the manufacturer's calibration procedure, with the inclinometer having a specified accuracy of 0.3º for tilts of up to 10º.

The internal offsets as detailed here are not required for the following instrument offset calculations, as it is the offset between the measured frames of reference that is required. These offsets will be necessary for alignment of the instrument pair with other reference frames such as platform axis.

1.2.3. Instrument alignment calculation

The alignment of the motion and wind velocity instruments was determined following Brooks, (2008). The MotionPak and R3 instruments are mounted together on a metal plate (Figure 2, Photo 1). The mounting used here to measure the alignment is the same as that used to install the instruments onboard the *Polarfront*. The metal plate is fixed to an adjustable tilting frame. To determine the pitch, roll and yaw offsets between the Motionpak and R3, the MotionPak's x-y plane accelerometers are first leveled. The pitch and roll offsets of the R3's inclinometer can then be obtained directly. In order to minimize any directional bias in the instruments, this process is repeated with the instruments being brought level in the MotionPak's x-y plane from different initial tilt directions, and the average taken.

The yaw angle between the two instruments is determined by raising one of the MotionPak's x-y axis to a significant angle (here, between 10° and 16°) whilst keeping the other axis level. The yaw is then determined using ratios of the MotionPak and Sonic tilts. The formulae given here refer to particular instrument axis, corresponding to the instrument orientations used onboard *Polarfront,* shown in Figure 2 and Photo 1. The appropriate axis substitution is required to apply these formulae to other cases. With the nominal front of the instrument raised, corresponding to a negative increase of the MotionPak y-axis, a_y, the yaw angle, γ, can be determined from:

$$\sin\gamma = \sin I_y / \sin - a_y \tag{2}$$

$$\cos\gamma = \sin I_x / \sin - a_y \tag{3}$$

$$\tan\gamma = \sin I_y / \sin I_x \tag{4}$$

where I is an axis of the inclinometer, and a is an axis of the accelerometer, the axis indicated by subscript. To minimize any directional bias, the instruments were raised and lowered through several degrees of tilt (10° - 16°), the process repeated and the average taken.

Offsets determined for the pairs of instruments installed on *Polarfront* are shown in Table 4. The R3 could be mounted on the plate twisted against its mounting bolts either hard anticlockwise (twisted to port) or hard clockwise (twisted to starboard). For the periods shown here when the R3 and MotionPak were installed fixed together on *Polarfront*,, the R3 was twisted anti-clockwise against its mounting bolts. For one sensor pair, the offsets when the sensor was mounted clockwise are also shown for reference.

Prior to January 2008, the MotionPak and the R3 were not mounted fixed together on a plate (Photo 2). Hence for this period alignments were determined by visual examination of the instruments in situ.

The means and uncertainties shown are the mean and standard deviation of the measurements obtained from each of equations 2, and 3, and hence include instrument uncertainties from each axis of the MotionPak's accelerometers and the R3's inclinometer, as well as measurement uncertainty. Equation 4 is not independent of equations 2 and 3, and would reduce the degrees of freedom if used in the calculation of mean or standard deviation.

1.3. Discussion

The yaw alignments determined for each set of instrument are relatively constant for the differing angles of tilt through which they were raised (Figure 1). Significant error in the determined pitch and roll offsets would lead to a bias in the yaw measurements that would vary with a_y. This bias is not apparent in the determined yaw offsets.

The uncertainty in the yaw measurements is noticeably larger for the instrument pair MP682 SON227, particularly when the instruments are raised (Figure 1). This may be due to measurement error, or due to the characteristics of the wire-inclinometer internal to the R3. The pitch and roll offsets determined for this instrument have a greater uncertainty than for the other R3 (Table 4). Determining the pitch and roll offsets is a more easily repeatable process than determining the yaw. The increased uncertainty in R3 227's pitch and roll offsets is therefore likely due to the instrument's characteristics.

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Tables

Table 1

MotionPak serial n'	Channel	Scale Factor	Bias
682	Rotation X	0.049823	0
682	Rotation Y	0.05019	0.11
682	Rotation Z	0.050113	-0.14
682	Acceleration X	1.905	0.00366
682	Acceleration Y	1.944	0.00405
682	Acceleration Z	1.9485	0.00335
791	Rotation X	0.049898	0.04
791	Rotation Y	0.049995	-0.18
791	Rotation Z	0.050112	-0.03
791	Acceleration X	1.914	0.0086
791	Acceleration Y	1.9185	-0.00434
791	Acceleration Z	1.9635	0.008

MotionPak calibrations. Acceleration scale factors and biases determined in laboratory analysis at NOCS. Rotation scale factors and biases are the manufacturers quoted values.

Table 2

MotionPak serial n'	Channel	Maximum g	Minimum g
682	Acceleration X	1.00159	-1.00209
682	Acceleration Y	1.00264	-1.00919
682	Acceleration Z	1.00153	-1.00207
791	Acceleration X	1.00076	-1.00311
791	Acceleration Y	1.00585	-0.99842
791	Acceleration Z	0.99701	-0.99927

MotionPak maximum measured accelerometer values through each axis.

Table 3

Instrument (serial n')	X channel bias	Y channel bias
MotionPak (682)	0.22°	0.27°
MotionPak (791)	0°	-0.02°
Anemometer (391)	0.33°	0.02°
Anemometer (227)	0.34°	-0.18°

Instrument internal alignments biases when placed on a flat surface. Surface leveled with a bubble level accurate to ~ ±0.02°.

Table 4

Date installed (jday of year)	MotionPak sn	Sonic sn	Sonic facing	Sonic bolts	Sonic fore-aft offset (°)	Sonic port-starboard offset (°)	Yaw offset (°)
7-09-2006 (250)	791	391	Fore	-	-	-	-
6-09-2007 (249)	791	391	60° starboard	-	-	-	-
24-01-2008 (24)	682	227	60° starboard	Clockwise	0.07 ±0.03	-0.35 ±0.08	65.9 ±1.2
			60° starboard	Anti-clockwise	-0.06 ±0.08	-0.23 ±0.06	51.7 ±0.9
19-05-2009 (139)	682	391	60° starboard	Anti-clockwise	-0.04 ±0.02	-0.08 ±0.02	52.4 ±0.5

R3 and MotionPak alignment offsets for instrument pairs installed on *Polarfront*. Sonic facing is the approximate alignment relative to the ship fore.

Figures

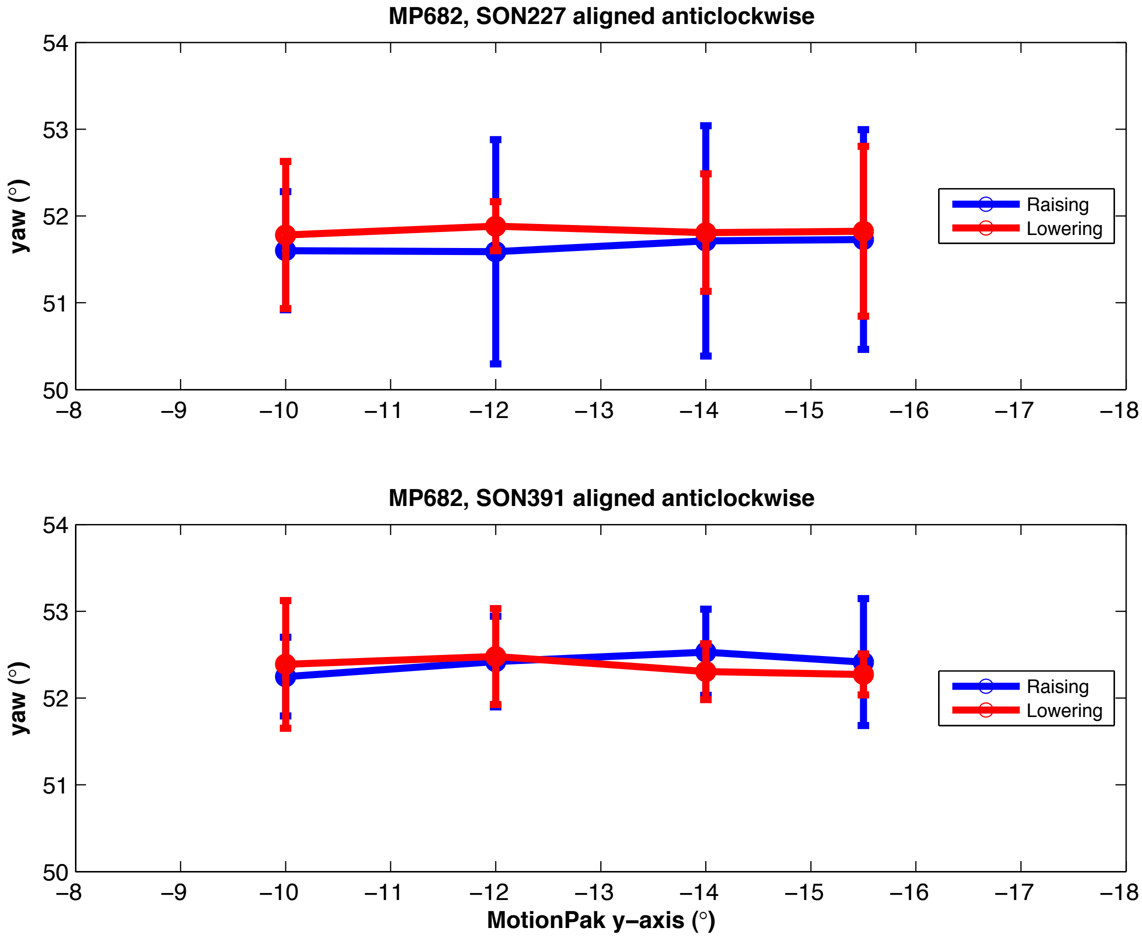

Figure 1. Yaw measurements determined for two instrument pairs. Each point is an average of four values: Two runs each comprising a sine and a cosine based calculation of the yaw (equations 2 and 3). The instrument pairs were either raised or lowered through the MotionPak's yaxis, with a negative value corresponding to a raise of the nominal front of the instrument pair.

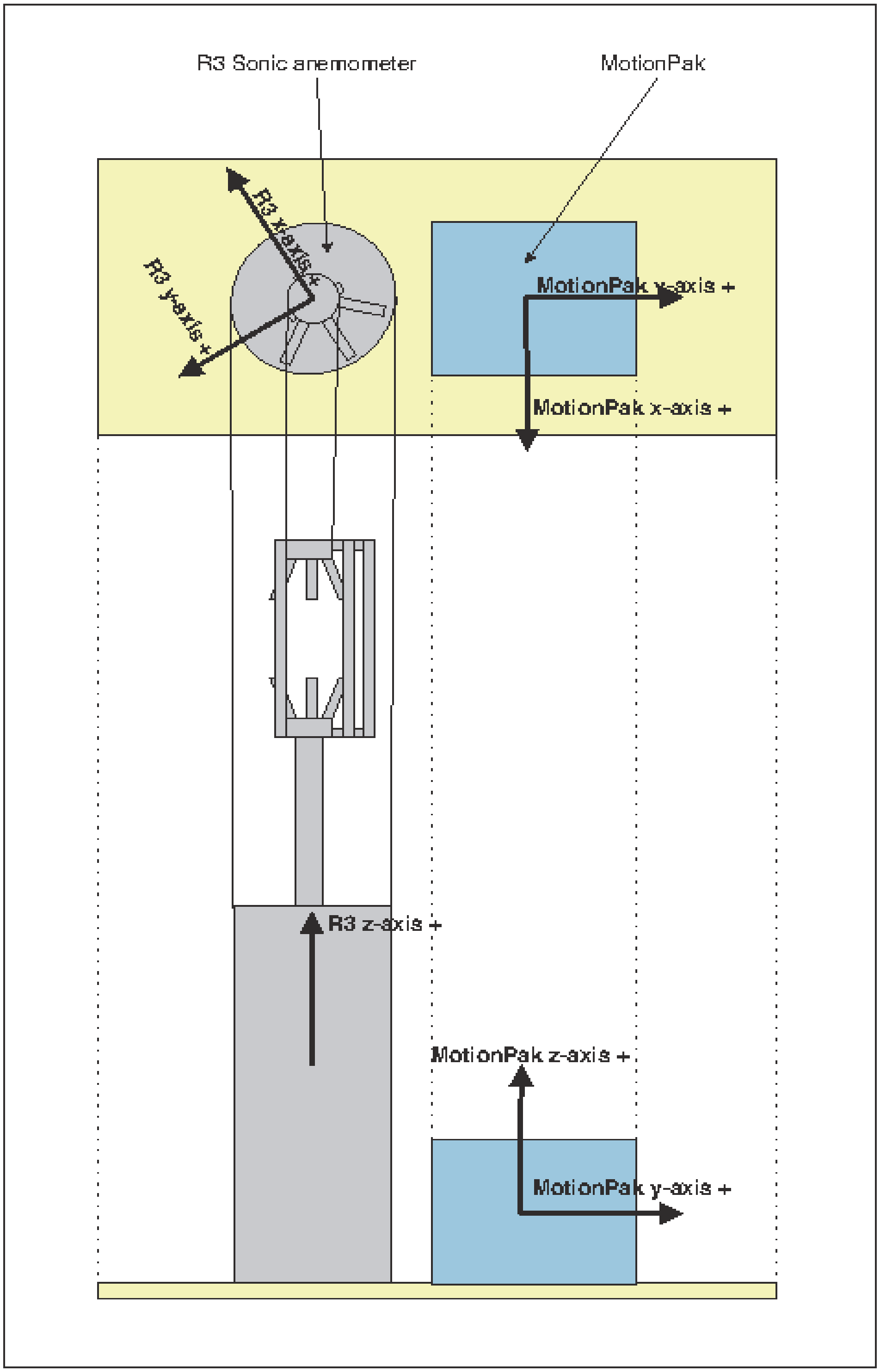

Figure 2. Side and plan view schematic of an R3 and a MotionPak as mounted on *Polarfront* from January 2008. Instrument co-ordinate axis for accelerometer and inclinometer outputs are shown. Axis direction indicates the direction of a raise corresponding to the axis.

Photo 1. *Polarfront* foremast R3 anemometer (227) and MotionPak (682) installation as of January 2008.

Photo 2. *Polarfront* foremast R3 anemometer (391) and MotionPak (791) installation from September 2006 to January 2008.