A Revisited Motion and Tilt Correction for Direct Air-Sea Flux Measurements

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Eddy covariance principle

- The vertical flux of a quantity \((x)\) can be measured directly as the covariance of the vertical wind speed \((w)\) and \(x\):

\[ F_x = \langle wx \rangle \]

- The \(x\) can be anything, e.g.:
  - Horizontal wind speed \((u)\) → momentum flux
  - Trace gases: \(\text{CO}_2\), DMS, ...
  - Temperature, humidity, ...

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**Image Description:**

- The image illustrates the principle of eddy covariance with a diagram of wind flow and eddy currents. The diagram shows arrows indicating the movement of air and eddies, and there is a tower representing the measurement apparatus. The background consists of a grid pattern and water, symbolizing the environment where such measurements are typically made.

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**Explanation:**

Eddy covariance is a method used in meteorology and environmental science to estimate the flux of a quantity from one place to another. This method relies on the statistical relationship between the vertical wind speed and the quantity of interest. The equation above shows how the flux \(F_x\) is calculated as the covariance of \(w\) and \(x\). The diagram visually supports this principle by depicting the flow patterns and eddies associated with wind and air movement.
Eddy covariance platforms

Buoy (un-manned) moored or drifting (photo WHOI).

Ships, e.g., R/V-Saramiento de Gamboa (photo Brian Ward).

+ Ships are the more convenient place to work at
+ Most trace gas flux measurements require a lot of power (pump) and maintenance (no off the shelf equipment)
  - Distortion of the mean wind speed (can be corrected for)
  - Distortion of the turbulent fluxes $\approx 15\%$ (no correction available)
From the measured 3D wind speed \( (\mathbf{u}_{\text{me}}) \) to the true wind speed in natural coordinate system \( \mathbf{u} = (u, v, w) \).

1. Correct for platform motion \( \mathbf{v}_{\text{ship}} \), calculated from 3D accelerations & rates, speed, course, and heading (e.g. Edson et al. 1998; Miller et al. 2010.)

\[
\mathbf{u}_{\text{true}} = \mathbf{u}_{\text{me}} + \mathbf{v}_{\text{ship}}
\]

2. Find the natural coordinate system using the double rotation method (DR), first yaw by \( \psi \) to get \( \langle v \rangle = 0 \), then pitch by \( \theta \) to get \( \langle w \rangle = 0 \) (e.g. Anctil et al. 1994; Edson et al. 1998)

\[
\mathbf{u} = \text{DR}(\mathbf{u}_{\text{true}})
\]
Air-sea momentum flux measured with eddy covariance

- Wind stress
  \[ \tau = \rho_{\text{air}} (i \langle wu \rangle + j \langle wv \rangle) \]

- Friction velocity
  \[ u_* = (\langle wu \rangle^2 + \langle wv \rangle^2)^{1/4} \]

- Neutral drag coefficient
  \[ C_{DN} = \frac{u_*^2}{u_{10N}^2} \]

- Ship borne EC fluxes typically higher than fluxes from moored platforms (Edson et al., 1998). Is this due to flow distortion?

Drag coefficient as function of the wind speed (normalized to 10 m height and neutral atmospheric conditions), based on Edson et al., 2013.
“Calibration” of wind speed and wind direction ($\alpha$) measured on board the R/V-\textit{Saramiento de Gamboa} with the wind speed measured on the mooring.
Friction velocity measurements and flow distortion corrected wind speeds don’t match very well.

Does flow distortion affect the $u_*$ values?
A closer look at the tilt correction

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Flow distortion acts on the relative wind speed $u_{me} = A(A(A(u_{true} - v_{ship})$.

Double rotation of $u_{true}$ overestimates the pitch when $\langle v_{ship} \rangle > 0$.

Better to use $(DRx)_{DR} = DR(\langle v_{ship} \rangle)_{DR}$.

Individual $\theta_{DRx}$ still have high uncertainties.
A closer look at the tilt correction

- The wind vector is pitched when it passes the ship
- Why is \( \theta \) so variable?

Flow distortion acts on the relative wind speed \( u_{me} = \hat{u}_{true} - v_{ship} \). Double rotation of \( \hat{u}_{true} \) overestimates the pitch when \( \langle v_{ship} \rangle > 0 \). Better to use \( \theta_{DR} \) for \( u_{true} \):

\[
\theta_{DRx} = \theta_{DR} \left( u_{me} + v'_{ship} \right) \\
\left( v'_{ship} = v_{ship} - \langle v_{ship} \rangle \right)
\]

Individual \( \theta_{DRx} \) still have high uncertainties.
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- The wind vector is pitched when it passes the ship
- Why is \( \theta \) so variable?
- Fairall 1996: \( \theta < 10^\circ \)
- Pedreros 2003: \( \frac{v_{\text{ship}}}{u_{\text{me}}} < 0.2 \)
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  Pedreros 2003: $\frac{v_{\text{ship}}}{u_{\text{me}}} < 0.2$
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  $u_{\text{me}} = A(u_{\text{true}} - v_{\text{ship}})$
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- Better to use (DRx) $u = DR(u_{\text{me}} + v'_{\text{ship}})$ ($v'_{\text{ship}} = v_{\text{ship}} - \langle v_{\text{ship}} \rangle$)
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  \[ u = \text{DR}(u_{\text{me}} + v'_{\text{ship}}) \]
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The radial planar fit method (rPF).

- Radial Planar fit over wind direction sectors (whole data set):
  \[ \langle w_{me} \rangle = c_3 + \tan(\theta) \cdot \langle u_{mr} \rangle - \tan(\phi) \cdot \langle v_{mr} \rangle \]

- First correct for \( v'_{\text{ship}} \) then for pitch, roll (and yaw) then correct for \( \langle v_{\text{ship}} \rangle \) (The rPF method)
Using the rPF tilts significantly improves the correlation of $u_*$ and $u_{10N}$ when compared to classic DR method.
The rPF method significantly reduces the flow distortion effects when compared to the DR and DRx methods.

The residual flow distortion increases with the relative wind direction. Potentially the effect of the large tower at the bow.
Conclusions

- Ships and buoys have different (dis)advantages for direct eddy covariance flux measurements

- The large structure of a ship leads to distortion of the air flow

- The classic motion-tilt correction over-estimates the tilt of the wind vector for ships under-way and leads to biased EC fluxes

- The radial planar fit method accounts for the flow distortion tilts (pitch and roll) and can significantly improve the quality of ship borne EC flux measurements

Questions?