NOAA Pacific Marine Environmental Laboratory
OCS / Saildrone

TECHNICAL NOTE 2-1

Direct Flux Measurements on Saildrone

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Project goal: To investigate the feasibility/accuracy of direct flux measurements on the Saildrone.

Principles: Use high-frequency samples from Gill 3D Anemometer (R3-50?), Inertial Nav System (INS & IMU) mounted on Saildrone to calculate wind stress and buoyancy flux through eddy covariance calculation. The calculation must account for motion of the platform as well as flow distortion. Field tests will be designed to test these calculations; calculations will be done by project scientists using delay-mode data. If successful, this study may guide future efforts to automate these calculations for real-time delivery of fluxes. This automation, however, is not part of this project.

Fundamentals of Direct Flux Measurements:

The Gill 3D anemometer R3-50 and R3-100 are designed for measuring the momentum (τ) and buoyancy flux (H_f) on a fixed platform via calculation of eddy covariance:

$$\tau_x = -\rho_a \overline{w'u'}$$
$$\tau_y = -\rho_a \overline{w'v'}$$
$$H_f = \rho_a C_p \overline{w'T'}$$

where $\overline{}$ denotes the time/space average of the records generally obtained in the first 20 minutes of every hour; (*u', v', w'*) and *T'* are respectively the three-dimensional wind and virtual temperature fluctuations relative to this average; ρ_a is the air density; and C_p is the heat capacity of air.

On a moving platform like the Saildrone (SD), however, a significant part of the fluctuating velocity (u', v', w') derived from anemometer measurements by simple averaging is due to the SD motion, which have to be removed before calculating the fluxes. This motion contamination in the anemometer records are caused by: 1) instantaneous tilt of the platform due to the pitch, roll, and heading variations of the SD; 2) angular velocities at the anemometer due to rotation of the SD; and 3) translational velocities of the SD.

To keep track of the anemometer motion, accurate INS/IMU with data output rate the same as the anemometer can be fixed next to the wind sensor. The IMU system measures the platform's attitude angles, angular velocity, and translational velocity due to SD motion in a right-handed coordinate frame, in which roll ϕ (rotation about *x* axis) is positive when the instrument port side is tilted up, pitch θ (rotation about *y* axis) is positive when the bow is tilted down, and yaw ψ (rotation about *z* axis) is positive counterclockwise. Note that ψ is defined positive for a right-handed rotation around the z axis, so a minus sign is applied to the compass reading. The motion-corrected wind velocities can therefore be expressed in Earth coordinates as:

$$\mathbf{U}_{\text{true}}^{\text{earth}} = \mathbf{T}(\phi, \theta, \psi)[\mathbf{U}_{\text{obs}} + \mathbf{\Omega}_{\text{obs}} \times \mathbf{R}] + \mathbf{V}_{\text{hp}} + \mathbf{V}_{\text{lp}}^{\text{earth}}, \quad (1)$$

$$\mathbf{T}(\phi,\theta,\psi) = \begin{bmatrix} \cos(\psi)\cos(\theta) & -\sin(\psi)\cos(\phi)+\cos(\psi)\sin(\theta)\sin(\phi) & \sin(\psi)\sin(\phi)+\cos(\psi)\sin(\theta)\cos(\phi) \\ \sin(\psi)\cos(\theta) & \cos(\psi)\cos(\phi)+\sin(\psi)\sin(\theta)\sin(\phi) & \sin(\psi)\sin(\theta)\cos(\phi)-\cos(\psi)\sin(\phi) \\ -\sin(\theta) & \cos(\theta)\sin(\phi) & \cos(\theta)\cos(\phi) \end{bmatrix} \quad (2)$$

where U_{obs} is the 3D vector wind recorded by the anemometer in the platform coordinate system, and $T(\phi,\ \theta,\ \psi)$ is the transformation matrix that rotates the platform frame into the reference frame (i.e. the earth) using the Euler angles; Ω_{obs} is the angular velocity vector measured by the IMU; R is the position vector from the IMU to the wind sensor; V_{hp} is the high-pass-filtered wave-induced platform velocity measured by the attitude sensors; V_{lp}^{earth} is the low-pass-filtered platform velocity relative to the earth.

While the geometry transformation from the platform frame to the reference (earth) frame is well defined. The determination of Euler angles has been a difficult problem. The WHOI Direct Covariance Flux System (DCFS) includes an IMU (MotionPak II) attached 0.8m (R in Equation 1) below the wind sensor. In this strapped-down system, the measured accelerometer output is a combination of the gravitational component due to the pitching and rolling of the SD (i.e. due to tilting of the system) plus the accelerations from the SD motion along the accelerometer axes

$$\begin{pmatrix} \ddot{x}_{obs} \\ \ddot{y}_{obs} \\ \ddot{z}_{obs} \end{pmatrix} = \begin{pmatrix} \ddot{x} \\ \ddot{y} \\ \ddot{z} \end{pmatrix} + \begin{pmatrix} -g\sin(\theta) \\ g\sin(\phi)\cos(\theta) \\ g\cos(\phi)\cos(\theta) \end{pmatrix}$$

where $\ddot{}$ denotes second derivatives of the position vector $X = (x, y, z)$, and g is the gravitational acceleration. As described by *Edson et al.* [1998] and *Flügge et al.* [2016], θ and ϕ can be approximated as the sum of the high frequency of integrated angular rate ($\int \dot{\theta}\,(t)dt$ and $\int \dot{\phi}\,(t)dt$, high-pass filtered) and the low frequency $\theta_{lp} = LP\,\{\sin^{-1}(-\frac{\ddot{x}}{g})\}$ and $\phi_{lp} = LP\{\sin^{-1}[-\frac{\ddot{y}}{g}/\cos\theta_{lp}]\}$, respectively. ψ can be approximated as the low frequency ψ_{slow} (compass output) and high frequency of $\int \dot{\psi}\,(t)dt$. It is hoped that this complementary filtering removes unwanted drift induced by the angular rate sensors while retaining the low-frequency tilts from the accelerometers. The cut-off frequency for filtering is however platform and environment dependent, and will have to be determined by analyzing the variance spectra of timeseries from integrated rate sensors and normalized accelerometers.

The gravity-induced (tilt) accelerations will have to be removed from the accelerometer output in order to compute the wave-induced velocities V_{hp} of the SD. The accelerometer outputs are first rotated to the earth frame by applying the coordinate transformation matrix $T(\phi,\ \theta,\ \psi)$. The resulting values are integrated and high-pass filtered to find the platform velocities required in Equation (1). V_{lp}^{earth} of the SD can simply be determined by the GPS.

Finally, flow distortion over the SD will cause the streamlines to deviate from the horizontal, resulting in an additional tilt to the flow. To account for this, the above motion-corrected wind velocities are rotated into the streamwise wind to remove the mean lateral and vertical wind components:

$U(t) = \overline{U} + u'(t), V(t) = v'(t), W(t) = w'(t)$

where $\overline{U}$ is the mean streamwise wind speed (vector time averaged), (u', v', w') is the 3D instantaneous turbulent winds that can be used for the calculation of covariance fluxes.

Uncertainties:

Largest uncertainties are associated with the determination of Euler angles for the transformation matrix $T(\phi, \theta, \psi)$ and the flow distortion correction, both of which depend on the SD's response (in different transit modes) to different atmospheric conditions and sea states. The Euler angle determination is particularly complicated and may introduce large errors.

Are there any ways to directly measure the Euler angles? Would it be practical to have two IMU systems, one strapped-down and one gimbaled, to determine angular rates on the platform frame and Euler angles in transformation matrix $T(\phi, \theta, \psi)$*, separately?*

Process:

Step 1: Record data in high resolution on board, for post processing on shore.

High frequency data acquisition is essential for eddy covariance calculation. Test instrument sampling rates ranging from 20Hz to 50Hz. Test performance of data synchronization from serial ports. If experiencing problem with synchronization (often the case in higher frequency measurements), proceed with asynchronous data processing with every datum having its own time tag. Purpose is to verify that input variables are of adequate accuracy to produce good data.

Step 2a: Set up validation experiments to test removal of platform motion.

Self-consistent experiments will be performed to ensure that the wind fluctuations are not sensitive to orientation of the platform. These tests include "+" transects, with each transect averaged separately in delay mode. Eddy covariance fluxes will be compared to the bulk flux and therefore the SD should carry sensors to measure SST, air temperature, humidity, barometric pressure, and radiative fluxes, in addition to the high frequency three-dimensional wind sensor.

Optional Step 2b: Set up validation experiments to test removal of platform motion and flow distortion, by comparing with measurements on a fixed platform

Install Gill 3D Anemometer (R3-50) and bulk flux measurement suite used on Ocean Climate Stations (OCS) buoys on a pile in San Francisco Bay, sail SD around the pile in different transit modes (normal transit mode, change transit directions relative to winds, stationary mode, etc.), and in different atmospheric conditions and sea states.

Step 3: Analyze collected data and plan for next step

Data collected from SD will be analyzed as described in **Fundamentals of Direct Flux Measurements**, and compared to measurements from the Gill 3d anemometer fixed on the pile and the results from the bulk measurements. Investigate the accuracy and uncertainties in different SD transit modes and environmental conditions. Assess the feasibility and potential of using SD to directly measure the fluxes in real time. Draft plan for the next phase of development and new proposal for science questions.

Key References

[*Fairall et al.*, 2003][*Bourras et al.*, 2014]

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