

# Turbulence spectral estimates from motion-sensor equipped ADVs on compliant moorings

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## ABSTRACT

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### 1. Introduction

Since their invention more than twenty years ago acoustic Doppler velocimeters (ADVs) have been used to measure turbulent velocities in a wide range of environments. Originally designed to make point-measurements in laboratory flumes and tanks, ADVs have become an increasingly useful tool in the oceanic environment. They have been deployed, for example, on the seafloor to measure fluxes in the oceanic bottom boundary layer, in the surf-zone to measure Reynold's stresses, and from ships on downward protruding masts to measure surface mixing (Lohrmann et al. 1994; Voulgaris and Trowbridge 1998; Kim et al. 2000; Trowbridge and Elgar 2003; Elgar et al. 2005; Geyer et al. 2008, e.g.).

Why is the turbulence spectrum important? – Captures motion at all scales. ADCPs 1) History of ADV use. How are they used? In what turbulence levels? What is their noise-floor? 1a) How do they compare to other turbulence tools? Compared to profilers, ADVs are: - Lower precision than profilers at high f? - Capture low-frequency information. - can be fixed in space. Compared to ADCP, ADVs can capture the turbulence spectrum: - Higher precision at high f - Higher resolution (down to cm scales) - Lower noise

A primary limitation of ADVs is that it has been challenging to place them at mid-depths (i.e. away from the seafloor and the surface). In the oceanic environment they have either been deployed on fixed platforms anchored to the sea-floor, or deployed near the surface from a ship. Until now, there has been no method for deploying these instruments at mid-water depths, or near the surface without a ship. This work describes a new approach for measuring turbulence spectra from ADVs mounted on moorings. Until recently this approach has been limited by the fact that mooring motion contaminates the velocity measurements. The frequency and amplitude of this contam-

ination will depend on the characteristics of the mooring and of the turbulent environment in which it is deployed. In most cases mooring motion will—over some range of frequencies—be similar to or greater than the turbulence velocities one would like to measure. This ‘motion contamination’ reduces usefulness of the ADV measurements.

Over the last decade, the cost of inertial motion sensors (IMUs)

However, this being said, In many cases the motion of the mooring Depending Because When the mooring (and ADV head) moves with the flow the measured velocity will be reduced, and when it moves against the flow it will enhance the it. is often equal to the turbulent velocities one would like to measure. contaminates the velocity measurements equipped with

In energetic environments ADVs provide

In energetic environments, where turbulence levels ADVs provide are Throughout

Velocity measurements have been made from

As flexible and useful as these instruments are, one limitation

are useful tools for making point-measurements of water velocity in labarotory and field environments. robust and versatile tools

ADV velocity measurements from compliant moorings will be contaminated by mooring motion. When an inertial motion unit (IMU, also known as a magnetic, angular rate, gravity or MARG sensor) is rigidly attached to, and tightly synchronized with, acoustic Doppler velocimeter (ADV) measurements the IMU’s orientation and motion measurements can be used to reduce motion contamination. Microstrain IMU on-board the Nortek Vector is equipped with a 3-axis accelerometer, a 3-axis rotation-rate sensor, and a 3-axis magnetometer. The Microstrain samples these signals at 1000Hz and performs integration and Kalman filtering operations to produce stable estimates of its orientation, change in velocity, and change in rotation-rate. and can be configured to output estimates of,

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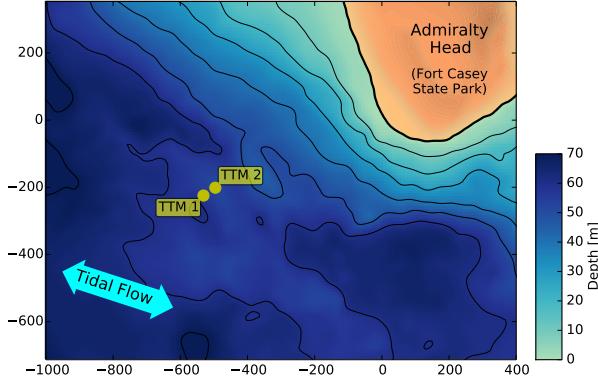


FIG. 1. Bathymetry of Admiralty Inlet at Admiralty Head.

## 2. Measurements

This work is focused on measuring turbulence spectra from moored ADVs that are equipped with inertial motion sensors (IMU). The ADVs utilized for these measurements were all equipped with Microstrain 3DM-GX3-25 IMU sensors that captured all 6 components of the ADV motion (3 components of angular rotation and 3 components of linear acceleration), as well the orientation of the ADV pressure-case. The sampling of the motion sensor is tightly synchronized with the ADV measurements. The IMU measures its motion at 1kHz and uses internal signal integration (Kalman filtering) to output the motion signals at the same sample rate as the ADV's velocity measurements. This reduces aliasing of the IMU's motion measurements above the ADV's sample-rate MicroStrain (2010).

This work utilizes data from two distinct mooring systems to demonstrate the advantages and limitations of each platform. Both mooring systems were deployed in Admiralty Inlet, Washington, approximately 500 meters (m) WSW of Admiralty Head–Fort Casey State Park—in 60 m of water at latitude 48.153 north and longitude 122.687 west (Figure 1). Admiralty inlet possesses a large semi-diurnal tidal energy flux as it is the largest waterway connecting Puget Sound to the Strait of Juan de Fuca. The site is approximately 6 kilometers (km) east of Port Townsend, and 1 km north of the Port Townsend – Coupeville ferry route.

The first mooring system was a simple fin suspended between a clump-weight anchor (2700lbs dry weight) and a spherical steel buoy (700lbs buoyancy). The ADVs pressure case (body) was hose-clamped to one side of the fin and the ADV sensor head was positioned in 10cm in front of the fin's leading edge (Figure 2). The leading edge of the fin is fastened inline with the mooring line. This configuration was designed to work similar to a weather-vane, such that the drag on the fin held the ADV head upstream

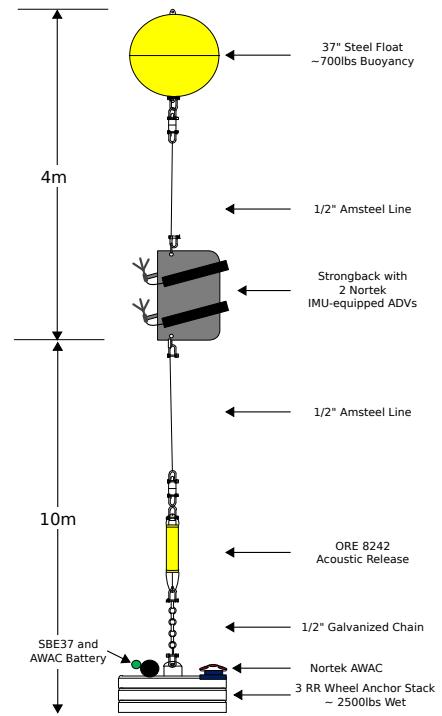


FIG. 2. Schematic diagram of the TTM, not to scale.



FIG. 3. TTM components on the deck of the R/V Jack Robertson. The TTM includes two ADVs, with pressure-cases mounted on opposite sides of the fin. The anchor stack includes a pop-up buoy for retrieval.

of the mooring components. The ADVs were inclined at an angle of 18° to the leading edge of the fin to account for mooring blow-down during strong currents (Figure 3).

The second mooring system was a cylindrical syntactic foam buoy that was anchored to a clump weight that weighed 2700 lbs (Figure 4). The buoy is 3.5 m long and 0.45 m in diameter with a tail ring that is 0.76 m in diameter. It weighs 295 kg in air, and has a buoyancy of 185 kg in water. An ADV head was positioned 0.1 m in front of the buoy nose. The buoy was equipped with a 300 kHz

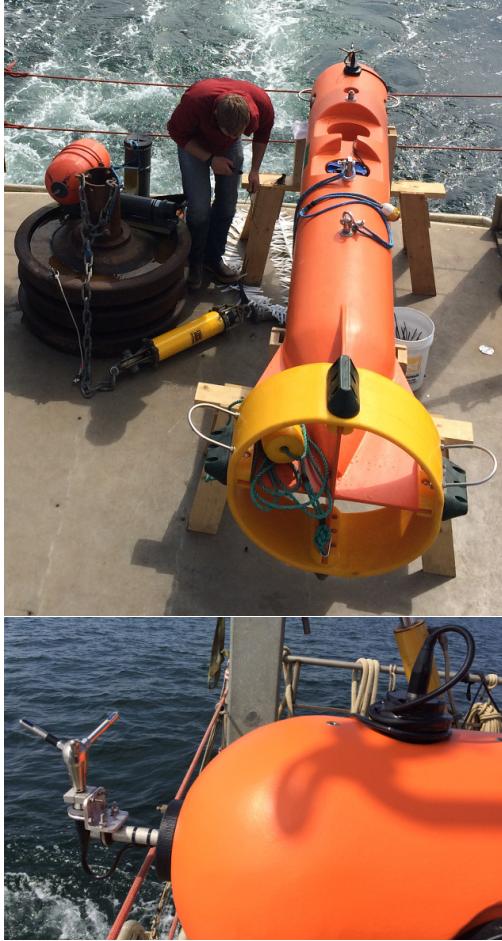


FIG. 4. Alex DeKlerk checks to ensure that the StableMoor buoy is properly fastened to its anchor; the RDI workhorse ADCP can be seen in the rear instrument bay (top). A bridle is draped across the top of the buoy for deployment and recovery, and a small marker buoy fastened to the tail aids in recovery. A close-up of the StableMoor nose shows the ADV head and the top of its pressure case (bottom).

RDI workhorse acoustic Doppler profiler that was pointed downward and configured to measure water velocity below the platform in [how many bins?](#) and measure buoy motion ('bottom tracking') at 1 Hz. The buoy platform was ballasted to pitch upward a few degrees in zero-flow to avoid 'flying downward'. In the presence of an oncoming current the tail fins help to orient it into the flow. The anchor for this buoy is similar to that of the TTM, including an acoustic release so the mooring and anchor can be recovered separately.

#### [Need to describe the measurements for each data source.](#)

Periods of time during which the mooring interfered with a beam of the Doppler profiler were identified by inspection of the profiler's acoustic amplitude signal. Periods during which one beam of the profiler had  $> 5\%$

higher acoustic amplitude than the other beams were flagged as 'contaminated' and excluded from averaging. 5-minute averages in which more than 50% of the data was contaminated in this way are not shown.

#### [END: Add data sources](#)

Unless stated otherwise, vector quantities in this work are in a fixed 'principal-axes' coordinate system that is aligned with the bi-directional tidal flow: positive  $u$  is in the direction of ebb (310° True), positive  $w$  is vertically upward, and  $v$  is the cross-stream component in a right-handed coordinate system. The full velocity vector,  $\vec{u} = (\vec{u}, \vec{v}, \vec{w})$ , is separated into a mean and turbulent component as  $\vec{\bar{u}} = \vec{u} + \vec{u}$ , where the over-bar denotes a 5 minute average. All time series are linearly detrended and Hanning windowed prior to computing spectra—using fast Fourier transform routines—to reduce spectral reddening. All spectra are normalized to preserve variance (e.g.  $\int S(u)df = u^2$ ).

### 3. Methodology

Estimate time-series of velocity on a compliant mooring by obtaining an independent estimate of ADV head motion, and removing that motion from the measured signal. Nortek offers an ADV that is equipped with an IMU that measures the linear acceleration, rotational-motion, and orientation of the ADV pressure case (body). So long as the ADV head is rigidly connected to the ADV pressure case, it is possible to utilize the IMU motion signals to calculate the motion of the ADV head, and remove it from the measured velocity signal. The ADV head motion, is calculated as the sum of rotational and translational motion, which are each estimated from the IMU's angular-rate,  $\vec{\omega}$ , and acceleration,  $\vec{a}$ , signals as:

$$\vec{u}_h = \vec{u}_{\omega} + \vec{u}_a + \vec{u}_{low} \quad (1)$$

$$= \mathbf{R}^T \cdot \vec{\omega}^*(t) \times \vec{\ell}^* + \int \{\vec{a}(t)\}_{HP(f_a)} dt + \vec{u}_{low} \quad (2)$$

Here '\*' superscripts denote quantities in the ADV's locale coordinate system,  $\mathbf{R}^T$  is the IMU orientation matrix that rotates vectors from the IMU to the earth reference frame, and  $\vec{\ell}^*$  is the vector from the IMU to the ADV head. The notation  $\{\vec{a}\}_{HP(f_a)}$  indicates that the IMU's accelerometer signal is high-pass filtered (in the earth's stationary reference frame) at a chosen filter-frequency,  $f_a$ . This is necessary because accelerometers have known low-frequency noise, sometimes referred to as 'bias-drift' ([NEED CITATION for: Accelerometer noise](#)). This noise is amplified by integration of the acceleration signal such that it contaminates the motion correction, especially at low-frequencies (Figure 3).

The choice of high-pass filter to be used to correct for low-frequency accelerometer noise issue depends on the application (e.g. deployment platform), and the turbulence level of the measurement environment. In particular, this

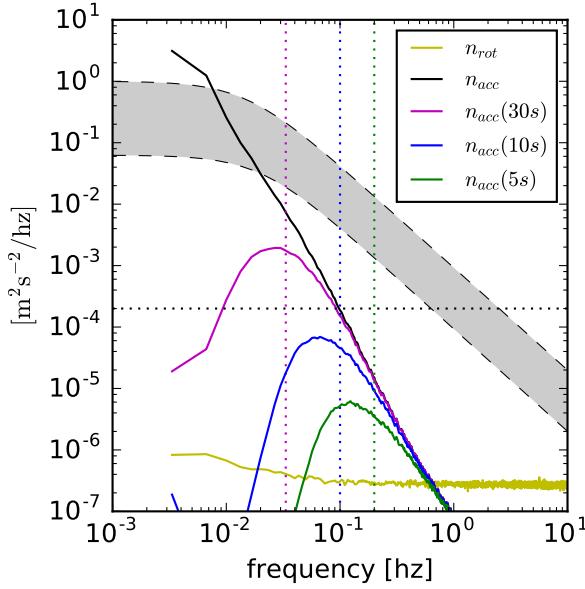


FIG. 5. Spectra of  $\vec{u}_\omega$  (yellow) and  $\vec{u}_a$  signals from the Microstrain IMU sitting on a motionless table. The  $\vec{u}_a$  signals are unfiltered (black), and high-pass filtered at 30s (magenta), 10s (blue), 5s (green). Vertical dotted lines indicate the filter frequency. The black horizontal dotted line indicates the noise-level of a Nortek Vector ADV configured to measure  $\pm 4$ m/s. The shaded region indicates the range of spectra presented herein ( $0.002 < \text{k}_{\text{TE}} < 0.03 \text{ m}^2/\text{s}^2$ ,  $1\text{e}-5 < \epsilon < 5\text{e}-4 \text{ W/kg}$ ).

involves a trade off between filtering-out this noise and not filtering measured motion (Figure 3). If an independent measure of low-frequency motion is available, it is possible to combine that signal with the IMU's high-frequency motion measurements to obtain a complete estimate of ADV motion. An example of this operation is presented in section ???. Lacking an independent measure of low-motion, the user may instead choose to neglect the portion of the spectrum below the filter frequency, or demonstrate that platform motion at those frequencies is small compared to the measured signal based on other considerations.

With this estimate of ADV head motion it is straightforward to correct the measured velocity,  $\vec{u}_m$ , to estimate the velocity in the earth's inertial reference frame:

$$\vec{u}(t) = \vec{u}_m(t) + \vec{u}_h(t) \quad . \quad (3)$$

Note here that the ‘+’-sign is correct because head motion,  $\vec{u}_h$ , induces a measured velocity in the opposite direction of the head motion itself ( $\vec{u}_m = \vec{u} - \vec{u}_h$ ).

#### 4. Results

A comparison of mean velocity measured by an IMU-ADV mounted on a TTM, to that of an upward-looking acoustic Doppler profiler mounted on the TTM anchor is

presented in Figure 6. This shows excellent agreement between the ADV and Doppler profiler measurements of velocity. The  $u$  and  $w$  components are always within 0.1 m/s, and the  $v$  component only has limited periods where the difference is as large as 0.4 m/s. This agreement between the magnitude and direction of these independent measurements indicates that the IMU-measured orientation matrix accurately resolves the ADV orientation in the Earth's reference frame. This is a highly encouraging result considering most ADV manufacturers previously assumed these instruments would be stationary and therefore relied on slow-response orientation sensors.

While it is encouraging that the moored IMU-ADV is capable of measuring mean velocity, it is not particularly useful considering that Doppler profilers accomplish this task more easily (upward looking from a bottom-lander or downward looking from a ship). As such, it

slow sample-rate were only capable of resolving amplitude of the ADV's motion on the mooring, and the Harding et al. (2016)

Though there are some periods where the  $v$  component of velocity differs by as much as 0.4m/s, the  $u$  component is always within 0.1m/s. and

data were than return amplitude was significantly larger than the other beams, and by inspection of t There were significant periods of time when the TTM mooring pass in front of a beam of the profiler. interfered with The periods In this figure, the The mean velocity vector from the TTM-based ADV measurements agrees remarkably well with the velocity measured by the upward looking, bottom-mounted Doppler profiler at the same depth (Figure 6). Comparison of the mean velocity The moored velocity measurements provide a reliable estimate of the mean velocity components.

The reliability of the IMU's orientation matrix is demonstrated shown by The moored IMU-equipped ADV provides a reliable estimate of mean velocity (Figure 6). The I The mean velocity is well resolved by the moored orientation matrix of the IMU provides a reliable estimate of the earth-frame

This section presents IMU corrected ADV measurements from the Tidal Turbulence Mooring (TTM) and Stalemoor (SM) platforms. These platforms have different motion characteristics that result in Harding et al. (2016)

##### a. Turbulence Spectra

Estimates of spectra

##### b. Massive Body

*Acknowledgments.*

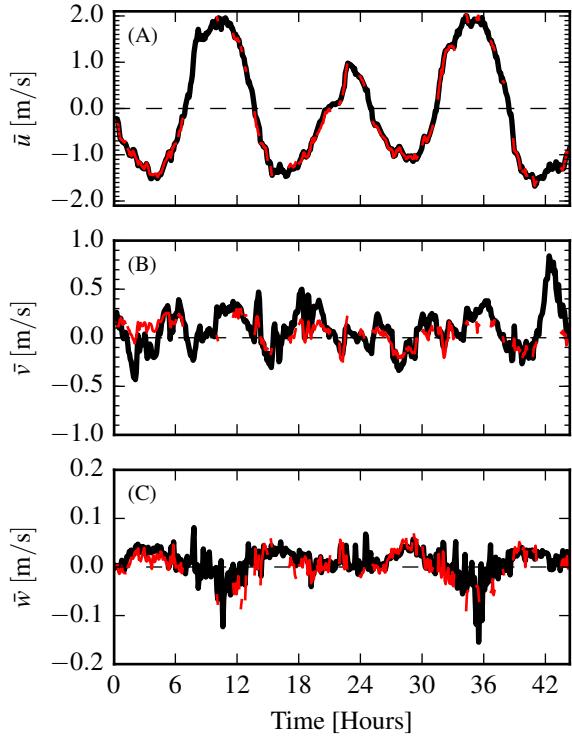


FIG. 6. Time series of tidal velocity at Admiralty Head from TTM measurements (black), and an acoustic Doppler profiler (red). The profiler measurements—taken at the same depth as the ADV on the TTM—were contaminated by acoustic reflection from the strongback fin when it was inline with one of the profiler's beams. Note that the vertical scale on the three axes vary by more than an order of magnitude (the small ticks in A and B are equivalent to the ticks in C).

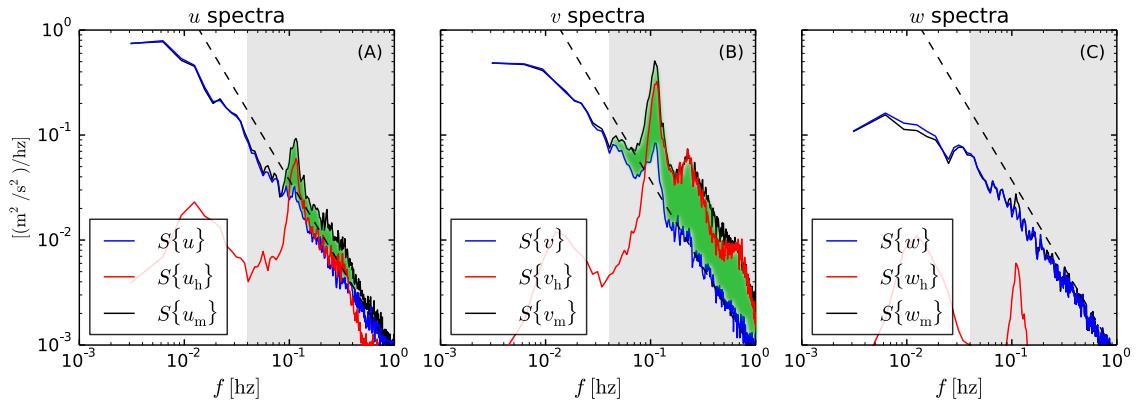
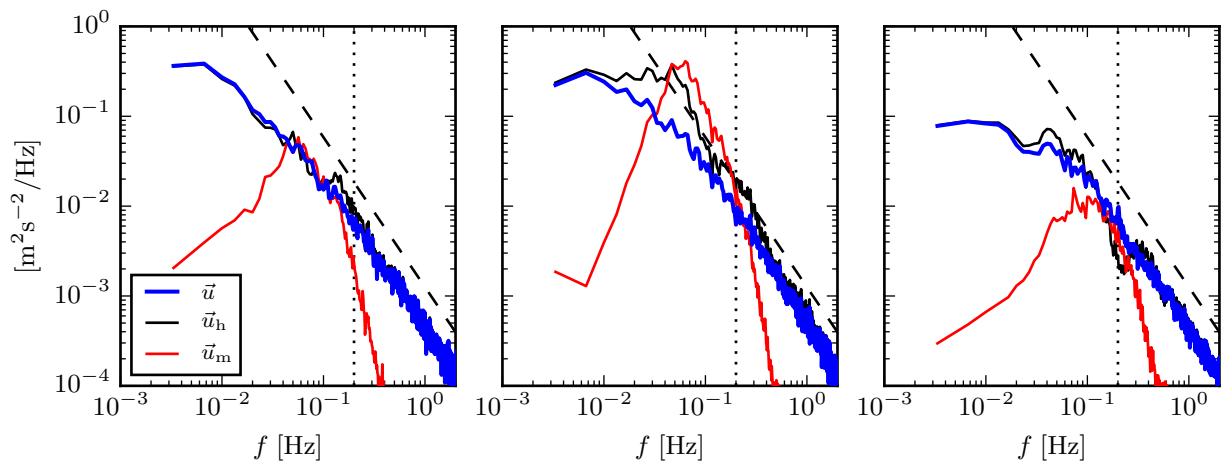


FIG. 7. Spectra from Tidal Turbulence Mooring IMU-ADV measurements.



## APPENDIX

### Coordinate Systems

#### a. IMU uncertainty

#### b. Measurement frames

Tracking coordinate systems ('reference frames', or simply 'frames') is critical to accurately correcting for platform motion of ADV measurements. In general, two three-dimensional, orthogonal, right-handed coordinate systems 'a' and 'b' are related by the equation:

$$\vec{r}^b = \mathbf{R}_b^a \cdot (\vec{r}^a - \vec{l}_b^a)$$

The vectors  $\vec{r}^a$  and  $\vec{r}^b$  point to the same point in space, but in the two distinct coordinate systems. Superscripts denote the coordinate system that the quantity is measured in and · indicates standard matrix multiplication. The vector  $\vec{l}_b^a$  is the 'translation vector' that specifies the origin of coordinate system 'b' in the 'a' frame, and  $\mathbf{R}_b^a$  is the 'orientation matrix' of 'b' in 'a'. Note that the equation that maps vectors - as opposed to points in space - from one frame to the other does not include  $\vec{l}_b^a$ :

$$\vec{u}^b = \mathbf{R}_b^a \cdot \vec{u}^a \quad (A1)$$

Also note that for the orthogonal, right-handed coordinate systems considered here the inverse rotation matrix is simply the transpose,  $\mathbf{R}_a^b = (\mathbf{R}_b^a)^{-1} = (\mathbf{R}_b^a)^T$ , and the determinant of the rotation matrix is 1,  $\det(\mathbf{R}_b^a) = 1$ . The coordinate systems for doing so can be broken into two categories: 1) the 'inertial' or 'stationary' ones into which it is the goal to transform the measurements, and 2) the moving coordinate systems in which sensors make measurements.

The purpose of this appendix is to clearly document and define the relationships between all of the coordinate systems necessary for quantifying turbulence using moored ADVs. This appendix starts with general definitions of coordinate systems and the relationships between them (c), then details the stationary and measurement frames used herein (?? and b, respectively).

1. the earth reference frame is the inertial coordinate system in which it is desirable to have measurements of turbulence velocity
2. the IMU reference frame is the reference frame in which that sensor measures platform motion
3. the ADV-head reference frame is the reference frame in which the velocity measurements are obtained.

In addition to measuring platform motion the Microstrain IMU provides an estimate of the orientation of its coordinate system in the earth's reference frame. Provided that the position and orientation of the ADV-head is known and fixed in the IMU frame (i.e. they are rigidly connected), it is possible to estimate the motion of the ADV-head in the earth reference frame.

#### c. Defining coordinate systems

##### d. The earth frame

The earth coordinate system is the coordinate system in-which the orientation of the ADV is measured (see 2), and is the coordinate system in-which motion correction is most easily calculated and discussed (section ??). This work utilizes 'e' superscripts to denote an 'ENU' earth coordinate system with basis vectors,

$\hat{x}$ : East,

$\hat{y}$ : North, and

$\hat{z}$ : Up.

To combine signals from an IMU with those of an ADV to perform motion correction the coordinate systems in which each of the measurements are made must be carefully accounted for.

For the Nortek Vector instruments that were used for this work the 'ADV-body' coordinate system is defined as being centered on the cylinder-body axis at the point where the head-cable meets its end-cap. The basis vectors of this coordinate system are defined as (Figures A1 and A2B):

$\hat{x}^*$ : points from the center of the 'head' end-cap toward the notch in that end-cap,

$\hat{y}^*$ : is defined by the right-hand-rule based on the other two basis vectors, and

$\hat{z}^*$ : points from the 'head' end-cap toward the 'battery' end-cap along the body-cylinder (pressure case) axis.

#### 1) THE ADV HEAD

In order to transform measured velocities into a meaningful reference frame (and to perform motion correction) the orientation (and position) of the ADV head in terms of the body coordinate system must be known. To facilitate this the orientation matrix of the ADV head,  $\mathbf{H}$ , and translation vector<sup>1</sup>,  $\vec{l}_{\text{head}}^*$ , are defined according to,

$$\vec{x}^{\text{head}} = \mathbf{H} \cdot (\vec{x}^* - \vec{l}_{\text{head}}^*) \quad , \quad (A2)$$

where  $\vec{x}^{\text{head}}$  and  $\vec{x}^*$  are the same point in the head and body coordinate systems, respectively. Combined with the math notes in the previous section, the velocity vectors in the head frame can be transformed into the body frame by,

$$\vec{u}^* = \mathbf{H}^T \cdot \vec{u}^{\text{head}} \quad . \quad (A3)$$

For Nortek Vectors, the coordinate system of the ADV head is centered on the transmit transducer face, and the

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<sup>1</sup>The position of the ADV-head origin (transmit transducer) in the body coordinate system.

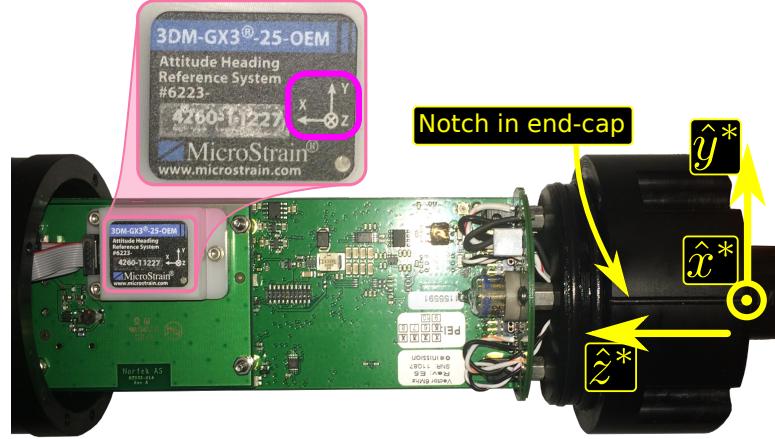


FIG. A1. The circuit-board and pressure-case end-cap of a Nortek Vector equipped with a Microstrain IMU. The ADV-body coordinate system (yellow) is depicted on the right. The notch in the end-cap defines the  $\hat{x}^*$  direction (out of the page), and the  $\hat{z}^*$  direction points back along the pressure case axis. A zoom-in on the Microstrain chip highlights its coordinate system (magenta) relative to the body.

coordinate-directions are defined by (Figure A2B, Nortek (2005)):

$\hat{x}^{\text{head}}$ : the direction of one of the transducer ‘receive’ arms (marked with tape or paint)

$\hat{y}^{\text{head}}$ : is defined by the right-hand-rule based on the other two basis vectors, and

$\hat{z}^{\text{head}}$ : is into the transducer face.

For fixed-head Nortek Vector ADVs, the body-frame and head-frame have parallel coordinate systems ( $\mathbf{H}$  is the identity matrix), and the ‘head-frame’ is translated 21cm along the  $z$ -axis. That is,  $\vec{l}_{\text{head}}^* = (0, 0, -0.21)\text{m}$  (Nortek 2005).

For cable-head ADVs, the position and orientation of the ADV head is arbitrary. This means that when preparing to make measurements using cable-head ADVs, **the orientation and position of the ADV head must be accurately recorded** in order to allow the ADV measurements to be transformed into the body frame during post-processing. For the example in Figure A2A,  $\vec{l}_{\text{head}}^* = (254, 64, -165)\text{mm}$ , and

$$\mathbf{H} = \begin{pmatrix} 0 & 0 & -1 \\ 0 & -1 & 0 \\ -1 & 0 & 0 \end{pmatrix} .$$

In general  $\mathbf{H}$  will not necessarily be symmetric nor will it have so many zero-elements (i.e. these characteristics are specific to the head-body alignment of the example).

## 2) THE IMU COORDINATE SYSTEM

Like the ADV head, the coordinate system in which the IMU measurements are made must be clearly defined and

documented. In general, the IMU frame is related to the body coordinate system by,

$$\vec{x}^{\text{imu}} = \mathbf{A} \cdot (\vec{x}^* - \vec{l}_{\text{imu}}^*)$$

For the Microstrain 3DM-GX3-25 (IMU) as it is integrated into the Nortek Vector (Figure A1),  $\vec{l}_{\text{imu}}^* = (0.006, 0.006, 0.150)\text{m}$  and,

$$\mathbf{A} = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ -1 & 0 & 0 \end{pmatrix} .$$

### The orientation matrix

In order to use the orientation matrix to rotate velocity measurements into an earth-fixed coordinate system it is important to understand how the orientation matrix is defined. The Microstrain IMU outputs an orientation matrix,  $\mathbf{R}_{\text{imu}}$ , such that:

$$\vec{u}^{\text{imu}} = \mathbf{R}_{\text{imu}} \cdot \vec{u}^{\text{NED}}$$

Where  $\vec{u}^{\text{imu}}$  and  $\vec{u}^{\text{NED}}$  are vectors in the IMU’s local coordinate system and a ‘north-east-down’ (NED) earth-fixed coordinate system, respectively (MicroStrain 2012). However, this NED earth coordinate system is different from the ENU earth coordinate system used here (and typically used by Nortek (Røstad 2011)). That is,

$$\vec{u} = \mathbf{B} \cdot \vec{u}^{\text{NED}}$$

where,

$$\mathbf{B} = \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & -1 \end{pmatrix} .$$

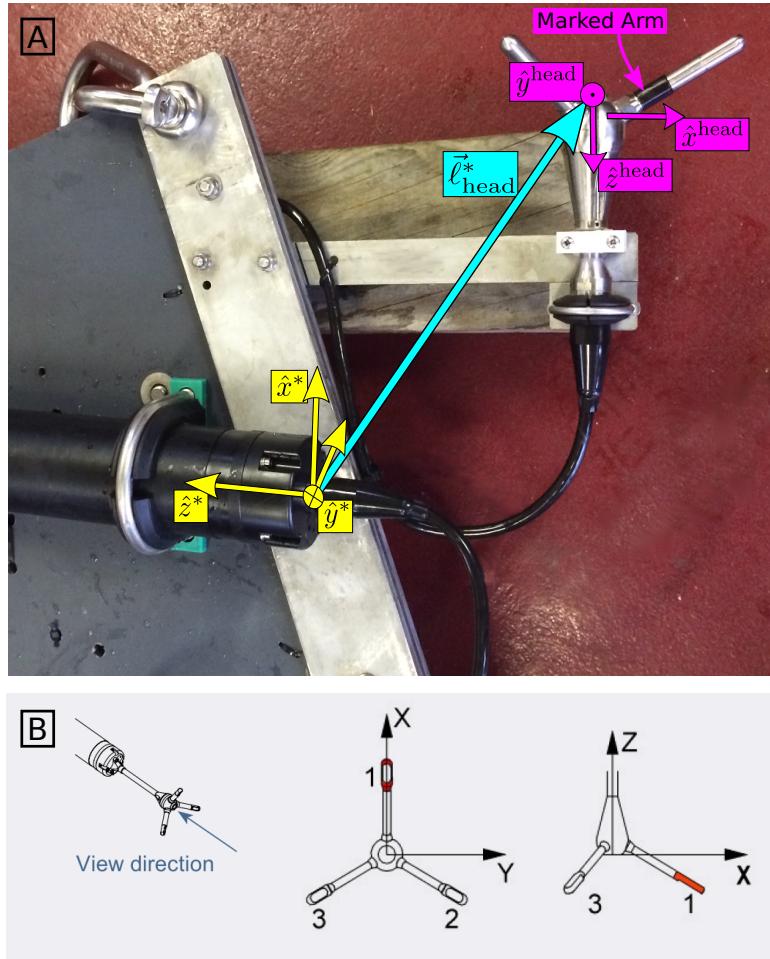


FIG. A2. Coordinate systems of the ADV body and head. A) A strongback with an ADV rests on a block of wood. Coordinate systems of the ADV head (magenta) and body (yellow) are shown. The  $\hat{x}^{\text{head}}$ -direction is known by the black-band around the transducer arm, and the  $\hat{x}^*$  direction is marked by a notch on the end-cap (indiscernible in the image). The cyan arrow indicates the body-to-head vector,  $\hat{x}_{\text{head}}^*$ . The perspective slightly distorts the fact that  $\hat{x}^{\text{head}} \parallel -\hat{x}^*$ ,  $\hat{y}^{\text{head}} \parallel -\hat{y}^*$ , and  $\hat{z}^{\text{head}} \parallel -\hat{z}^*$ . B) Coordinate system of the ADV head as defined in the Nortek Vector manual (Nortek 2005).

From this, and the above discussion of the orientation of the IMU in the ADV, it is simple to show that the orientation matrix of the ADV body in a ENU earth frame is

$$\mathbf{R} = \mathbf{A} \cdot \mathbf{R}_{\text{imu}} \cdot \mathbf{B}$$

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