Detailed Inflow Measurements for Kinetic Hydropower Systems in a Tidal Strait

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Introduction

Over the past several years, Verdant Power has worked to develop and demonstrate operation of its Kinetic Hydropower Systems (KHPS) that capture energy from naturally occurring river, tidal, and ocean current flows. During 2006-2008, at its Roosevelt Island Tidal Energy (RITE) Project in the East River in New York City, Verdant installed and operated the world's first array of grid-connected tidal power turbines. Verdant Power's KHPS turbine uses an axial-flow turbine designed to capture the kinetic energy of tidal or river currents without the use of dams. During turbine operation, i.e. energy generation, water currents turn the 5 m diameter 3-bladed rotor at a slow and nearly constant rate (about 36 rpm), driving a gearbox and generator enclosed within a waterproof nacelle. Electricity from the generator is carried by an underwater cable to shore-based switchgear for grid connection. In a different generation and control version, the KHPS can power a stand-alone load.

Figure 1. Verdant Power KHPS

To ensure the reliability and survivablility of the KHPS turbine, the accurate prediction of loads on both the stationary and dynamic components is essential. Verdant has partnered with Sandia National Laboratory (SNL) and the National Renewable Energy Laboratory (NREL) to develop advanced models of the loads on a KHPS rotor, with focus specifically on the instantaneous and fatigue loads. The accurate characterization of inflow parameters, particularly their variation with depth and time, is essential to this modeling effort. Verdant has conducted extensive water velocity measurements in the East Channel of the East River to determine these characteristics. These measurements were taken using an Acoustic Doppler Current Profiler (ADCP) deployed in the East River for various durations of time. Measurements from stationary, bottom-mounted ADCPs include instantaneous and time-averaged velocities, vertical velocity profiles and turbulence intensities, among others. Detailed analysis of the vertical velocity profile (shear) and turbulence intensity (TI) across the rotor disk is presented for both ebb and flood tides. The influence of ADCP bin height (size), and the resulting degree of spatial averaging, is examined for both the shear profile and the TI. Based on the large set of experimental data acquired, Verdant will present some initial results and conclusions as well as lessons learned for future resource measurements.

Previous efforts to accurately characterize inflow conditions for tidal and river turbines have included similar ADCP measurements. Shear measurements taken at the RITE site previously published for 100 cm bins suggested that flood and ebb tides have different shear exponents, n, with evidence that a shear exponent, $n > 1/5$, is appropriate for the ebb tide inflow [1]. However, the effect on the shear exponent of neither the ADCP bin height nor mean hub height water velocity was examined. Further, little data exists on measured hub height turbulence intensities in tidal flows similar to that of the East River or other sites suitable for KHPS deployment.

Experimental Set-Up

The detailed inflow measurements presented below were acquired with a stationary, bottom-mounted Acoustic Doppler Current Profiler (ADCP). A Teledyne RD Instruments, 1200 kHz Workhorse Monitor, ADCP was deployed on the bottom of the East Channel, within the existing footprint of the RITE Pilot Project, and cabled to shore for continual data monitoring from a control room. Raw ASCII serial ADCP data was recorded and stored on-site for post-processing. Data was acquired using WinRiverII software and post-processed using Matlab R2010a.

The ADCP nominal deployment orientation and bin definitions (100 cm bins) are shown in Figure 2, including the 20^{o} beam expansion angle. The influence of both data rate (Hz) and ADCP bin height (cm) on both flood and ebb tide vertical velocity profiles and turbulence intensities were examined over a number of tidal cycles. Data acquisition specifications and flow parameter definitions are given below.

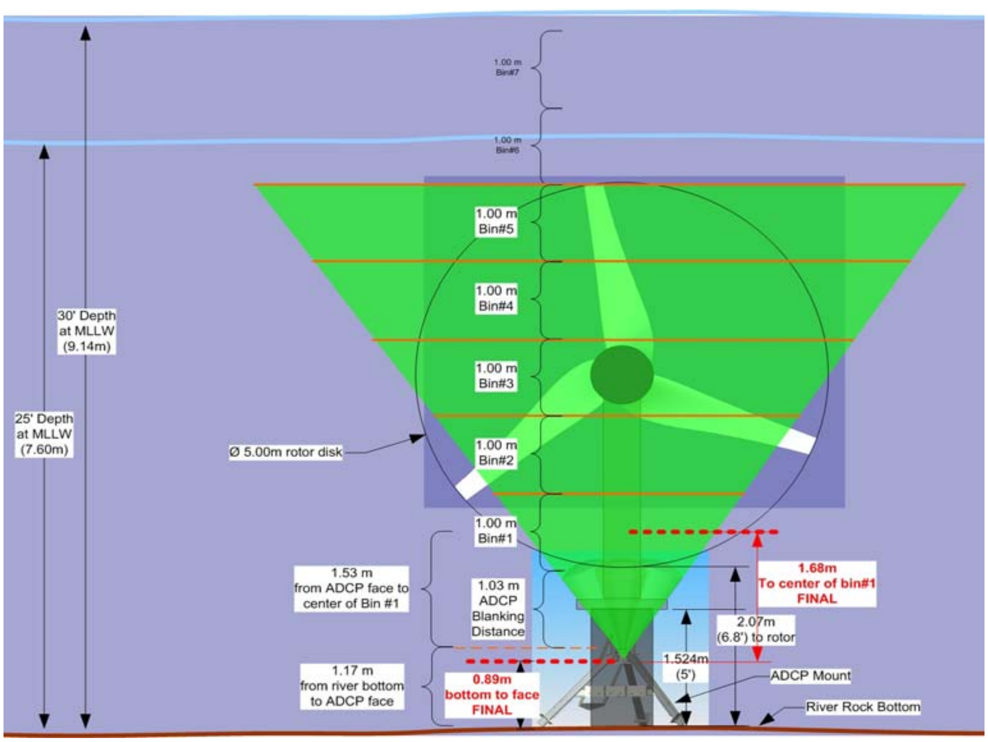

Figure 2. Schematic of the Stationary, Bottom Mounted ADCP Deployed in the East River, New York City

During a 2 month period, ADCP data was collected at two different data sampling rates and three different ADCP bin heights. Details of the data acquired, including duration and ADCP settings, are presented in Table 1 below. All data was collected contiguously in the absence of rotating KHPS turbines:

Table 1. Stationary ADCP Experimental Parameters, RITE Project, 3/17/2009 to 4/15/2009

Data Set	Bin Height (cm)	Data Rate (Hz)	Ping per Ensemble	Duration (Days)	Total Number of Bins	1st Bin Center Height (m)	Hub Height Bin Number
1	10	1	1	11	98	1.32	34
2	20	1	1	3	49	1.42	17
3	100	½	7	15	5	2.57	3

To accurately characterize the inflow conditions for KHPS operating in tidal flows, the hub height TI and shear profile on both ebb and flood tides are two essential parameters. Instantaneous data collected from the ADCP in each bin throughout the water column was averaged over four minute windows. From these four minute averages, the turbulence intensity, TI, and shear exponent, n, were determined for both ebb and flood tides. The dependence of these 2 parameters on both mean hub height water speed and ADCP bin height are examined below for the East Channel tidal strait. Definitions of both TI and n are presented in Equations 1 through 4, where $\hat{U}_i$ is the measured instantaneous axial water velocity magnitude in any single bin, N equals the number of total data points in a particular averaging interval, e.g. N = 240 for 4 minute averages of 1 Hz data. The turbine hub height, Z_{Hub}, is 4.6 m above the river bottom and the turbine rotor diameter, D_{Rotor} = 5 m.

<u>Turbulence Intensity (TI)</u>

(1) $$TI = \frac{U}{u'} * 100$$ where:

(2) $$U = \frac{1}{N}\sum_{i=1}^{N} \hat{U}_i$$ (Mean Velocity)

(3) $$u' = \sqrt{\frac{1}{N}\sum_{i=1}^{N} \left(\hat{U}_i\right)^2}$$ (RMS Velocity)

Shear Exponent (n)

$$U(z) = U_{Hub}\left(\frac{z}{Z_{Hub}}\right)^{n} \tag{4}$$

Results

The ADCP is ideally suited to assess the vertical profile, or shear, of the velocity in a given natural flow. The instantaneous velocity is measured in bins from the near river bottom to the surface, as seen in Figure 2. Examples of vertical velocity profiles from the East River, both ebb and flood tides, are shown in Figure 3 and Figure 4. 4 minute mean hub velocities, U_{Hub} = 1.5 m/s, for 10 cm, 20 cm and 100 cm bin height data are presented for six total tides, along with power law curve fits and the associated shear exponent (n), seen in Equation 4 above. All curve fits were made using the Nelder-Mead method, an unconstrained nonlinear minimization of the sum of square residuals [2].

Figure 3 shows the ebb tide shear profile for three ebb tides, each with a mean hub height water velocity, U_{Hub} = 1.5 m/s. It is clear that a power law vertical velocity profile is an appropriate approximation of the natural boundary layer; however, the ADCP bin height plays an important role in the measured profile, and thus, the interpolation of the shear exponent. With smaller bins, 10 cm, the shear exponent is reduced, suggesting a less gradual change in velocity from the river bottom towards the surface. Using 100 cm bins, the predicted shear exponent, n = 1/3. However, using 10 cm bins, the shear exponent, n = 1/4. Both of these values are significantly different than those used for wind turbines, i.e. atmospheric boundary layer flow, n = 1/7 to n = 1/9 [3]. The accurate prediction of the shear exponent is essential to understand the variation in mean axial velocity across the rotor disk, shown from top to bottom as the dashed lines with the hub shown as the solid line. As the shear exponent increases, the variation in mean velocity from the rotor disk bottom to the rotor disk bottom increases. This leads directly to increasingly variable loading on each rotor blade during one rotation, as the flow speed changes roughly 50% from the top of the rotor disk to the bottom. To accurately predict the turbine fatigue loads, it is essential to capture this variation in water velocity across the rotor disk.

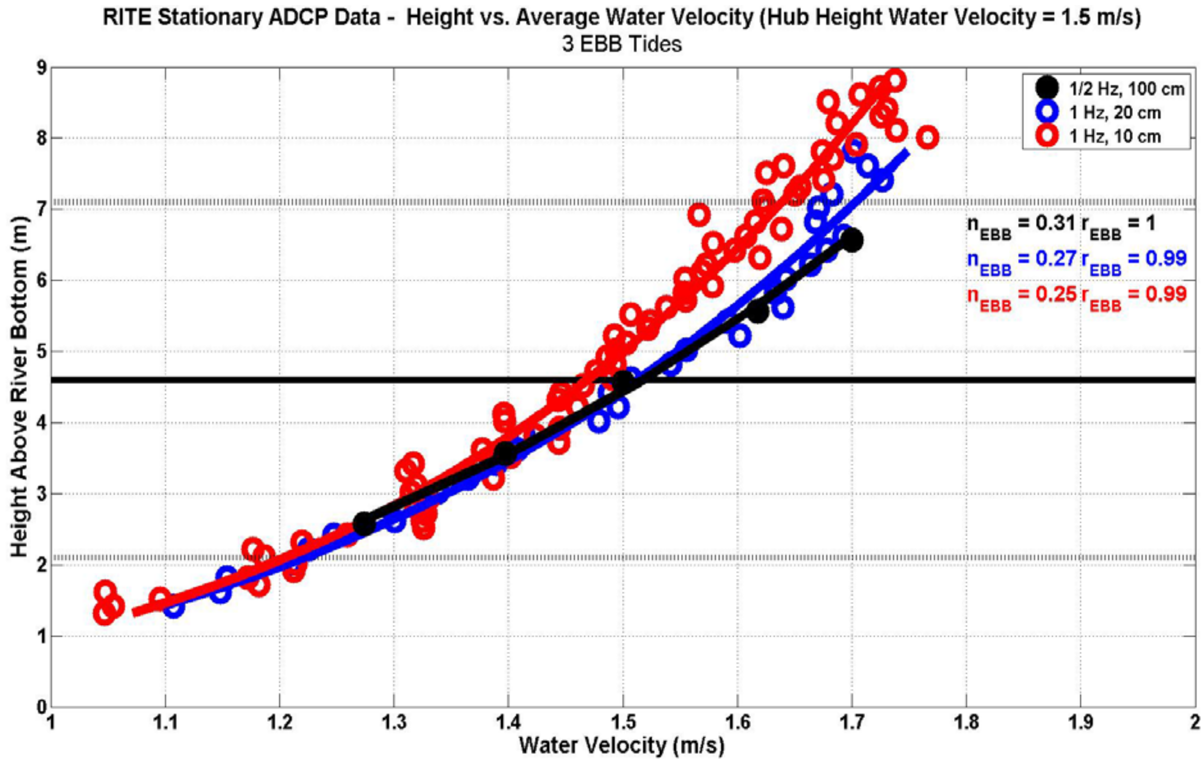

Figure 3. Three Individual Ebb Tides, Vertical Velocity Profile with Power Law, U_{Hub} = 1.5 m/s

Figure 4 shows the flood tide shear behavior for three flood tides, each with a mean hub height water velocity, U_{Hub} = 1.5 m/s, similar to the ebb tides shown above. Unlike the ebb tides, however, it is clear that a power law model is not an appropriate approximation for the shear profile on a flood tide at the RITE site. The n = 1/5 curve-fits shown do not capture the actual flow behavior, particularly across the rotor disk. While the flow below 3.5 m appears to fit the classic power law development, flow through and above the hub does not agree with the curve-fits shown. Instead, what would be a power law appears disturbed, with a reduction in velocity at the rotor hub and apparent flow acceleration towards the river surface. One likely explanation for this flow structure is geographic; in the East Channel, about 250 feet to the south of the stationary ADCP on a flood tide is the Roosevelt Island Bridge. This bridge is supported by two large concrete piers, surrounded by wooden fenders. The affect of these two piers is to reduce the cross-sectional area of the river, and since the western pier is less than 100 feet offset towards the shore from the ADCP location, they likely producing a jet-like structure within the channel flow. The influence of this near-surface jet is clearly seen at heights above 6 m from the bottom. Across most of the rotor disk, generally centered on the hub, is the highly turbulent mixing layer between the boundary layer and jet flows. Recognition and characterization of inflow conditions, such as those shown in Figure 4, is critical to ensure turbine, rotor and blade survivability.

Given the unique nature of the flood tide in this location, the influence of ADCP bin height on the measured velocity profile is generally reduced. The boundary layer, jet interaction is clearly captured for all three flood tides (i.e. all three bin heights). This may be a result of the increase in flow stability from the jet. As the mean flood velocity increases, the jet gains strength and acts to damp flow variations in the developing flood boundary layer. While the dynamics within the mixing layer itself are highly turbulent, the location of the mixing layer within the water column is quite stable. As such, the mean velocity values show good agreement independent of ADCP bin height. In the mixing layer, the vertical variation in the horizontal velocity is reduced, reducing the variable loading during a single blade rotation. However, the increase in turbulent fluctuations in the mixing layer, discussed below, will likely increase both the instantaneous and fatigue loads on the turbine rotor and blades.

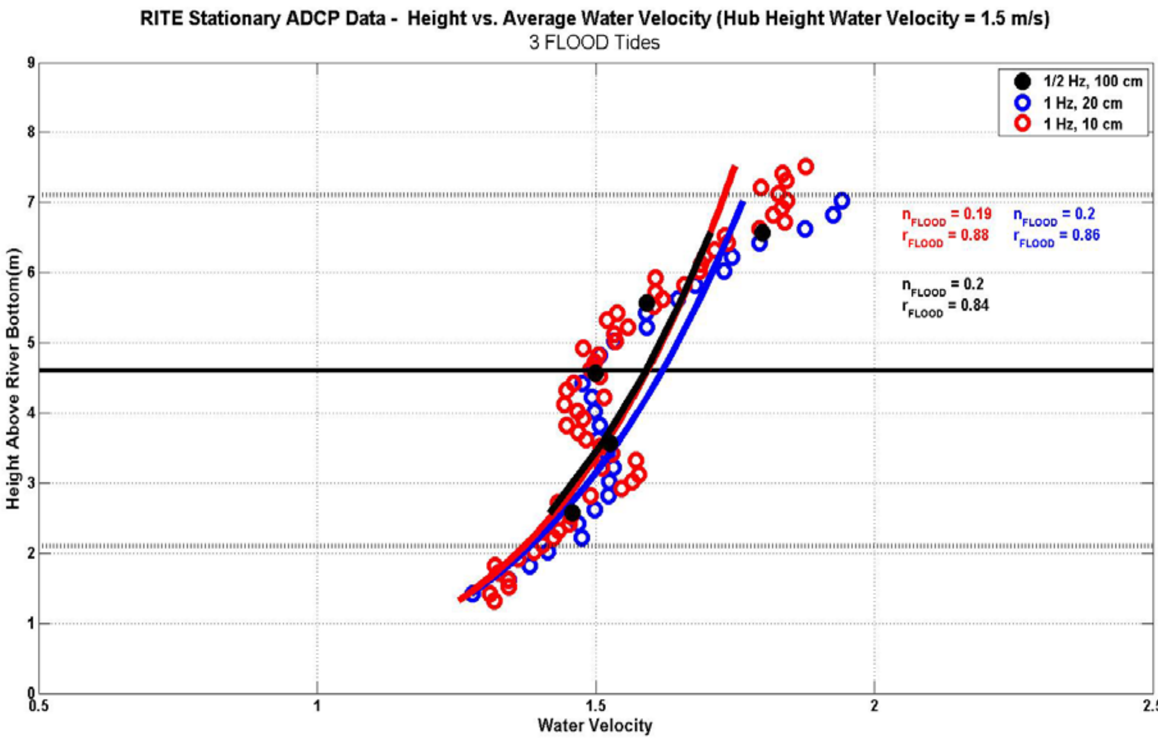

Figure 4. Three Individual Flood Tides, Vertical Velocity Profile with Power Law, U_{Hub} = 1.5 m/s

During each tide, the mean hub height water velocity varies from near zero (slack) to a peak value and returns to near zero. As such, a turbulent boundary layer develops and dissipates on every tide. At the RITE site, the flood tide is about 6 hours long, on average, while the ebb tide is closer to 6.5 hours. However, peak flood velocities are generally larger than peak ebb velocities. To characterize this boundary layer growth and decay, the variation in shear exponent, n, with hub height water velocity is examined on both ebb and flood tides. The Verdant Power KHPS begins rotation and energy generation at U_{Hub} = 1.0 m/s and remains parked at slower water speeds. It is important to remember the jet/boundary layer interaction seen on the flood tide when considering the results presented below.

To determine the variation in shear exponent, n, on ebb and flood tides with hub height water velocity, the four minute average hub height water velocity values were sorted into velocity classes, from 0.5 m/s to 2.5 m/s, 0.1 m/s width, labeled bin center. An average value for the shear exponent was calculated from the shear exponents in each velocity class, and the results for both ebb and flood tide are presented in Figure 5 and Figure 6 below. All vertical error bars show the 1st standard deviation for each velocity class of data.

As with Figure 3, Figure 5 clearly shows the influence of bin height on the calculated average shear exponent for ebb tides. As the bin size is reduced, the shear exponent is reduced as well. However, the difference between 10 cm and 20 cm bins is statistically insignificant. In addition, the variation in average ebb tide shear exponent is very small over a wide range of average hub height velocity. For 10 cm bins, the shear exponent varies from n = 1/5 to n = 1/4 as the hub height velocity increases from U_{Hub} = 1.0 m/s to U_{Hub} = 2.1 m/s. In a more narrow flow speed range, from U_{Hub} = 1.5 m/s to U_{Hub} = 2.0 m/s, however, the shear exponent remains constant, n = 1/4. The use of 100 cm bins predicts a shear exponent, n = 1/3, for all water speeds. This over prediction in the shear exponent at large ADCP bin size leads to an over prediction in the vertical variation in velocity, and thus, an over prediction in the variable turbine loading during a single rotation. This, in turn, leads to the over design of the turbine system, including the blades and rotor. From this analysis, it is evident that the East River ebb tide shear profile, particularly in the velocity range of greatest interest is well characterized by a power law with a shear exponent, n = 1/4. This result is significantly different than results from atmospheric flows. This difference confirms the need to modify existing prediction tools for wind turbine loads to accurately predict total loads on KHPS deployed in river and tidal situations.

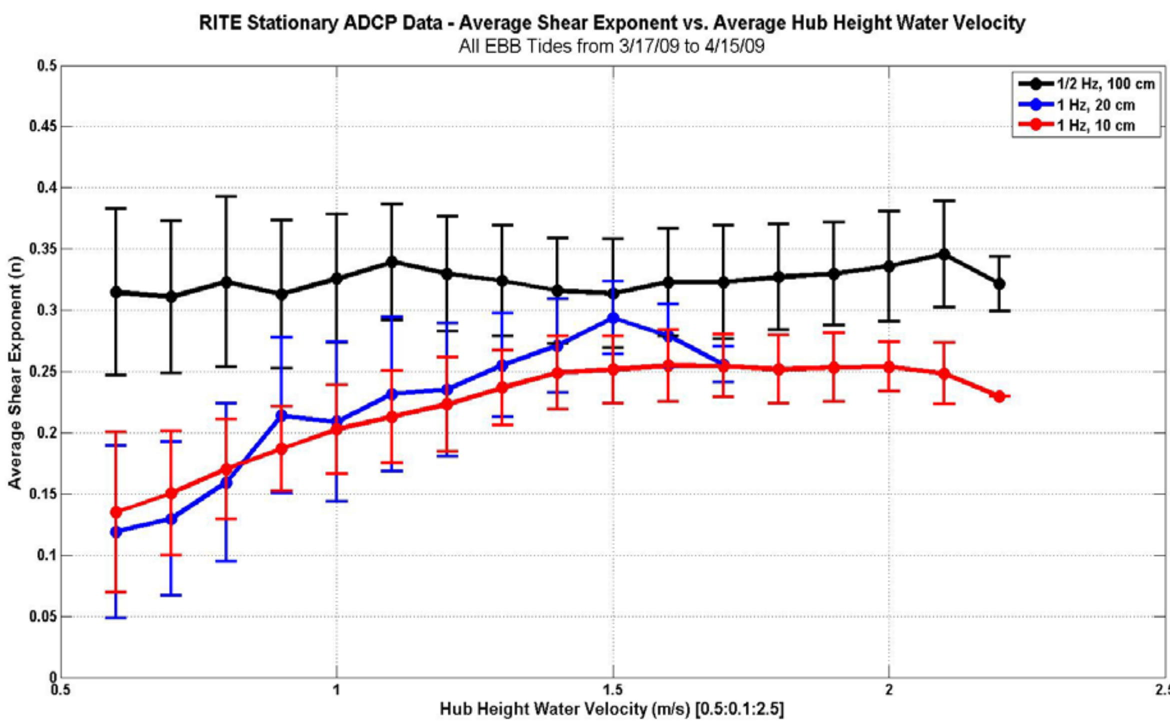

Figure 5. Ebb Tides, Shear Exponent vs. Hub Height Water Velocity

Figure 6 shows the variation in the flood tide average shear exponent with hub height water velocity. Unlike the ebb tide shown in Figure 5, the 10 cm, 20 cm and 100 cm bin height data agree well, particularly above U_{Hub} = 1.0 m/s. However, as discussed previously, the influence of the Roosevelt

Island Bridge on the flood tide prevents the applicability of a power law vertical profile. The shear exponent for the 10 cm bin height data appears independent of mean water velocity, suggesting the jet/boundary layer interaction is prevalent even at flow speeds less than the generator cut-on speed, U_{Hub} = 1.0 m/s. This flow behavior is considered anomalous and not representative of most sites for future project development. As such, the RITE ebb tide should be considered as representative of the axial velocity shear profile in open channel flows for both tidal and river applications. Unlike the wind industry, a shear exponent, n = 1/4, should be used to model the velocity variation across the rotor disk. Further, it is recommended that narrow ADCP bins, less than 25 cm, be used to measure this variation.

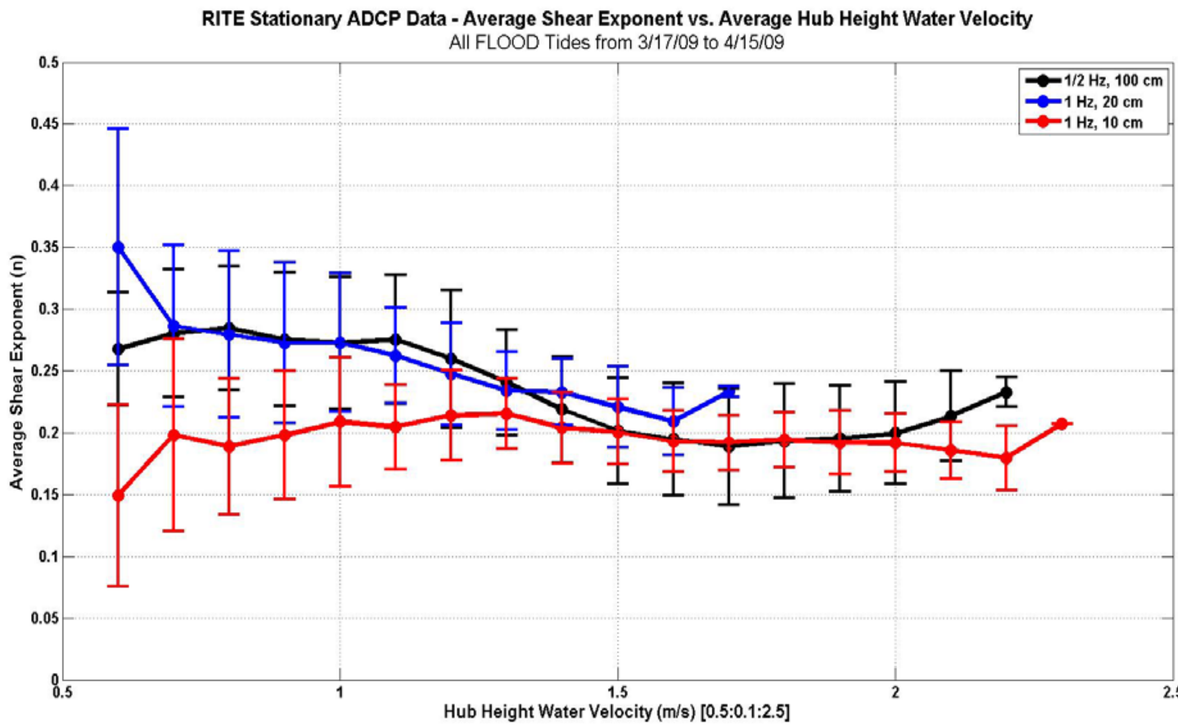

Figure 6. Flood Tides, Shear Exponent vs. Hub Height Water Velocity

In addition to the vertical variation in the mean axial velocity across the rotor disk, the turbulence intensity, TI, at the rotor disk center point is also a crucial parameter for inflow characterization and loads predictions. The variation in the TI across the rotor disk is also of importance. The TI quantifies the temporal fluctuations inherent in any turbulent flow and is critical in predicting the extreme loads on the turbine system and rotor/blades. The maximum forces on the turbine occur when turbulent fluctuations add cumulatively to maximum average water velocities. While these extreme events are generally short duration, the influence of turbulent fluctuations also increases the fatigue loading on the rotor and turbine. An under prediction of the inherent TI may compromise the structural integrity of the designed rotor; while an over prediction of the TI may result in excessively heavy, even impractical, blades.

Figure 7 shows the ebb tide turbulence intensity at three locations across the rotor disk vs. the measured hub height water velocity. The influence of ADCP bin height on the calculated ebb tide TI is significant. Further, the influence of beam expansion is apparent as the calculated turbulence intensity decreases from maximum values near the rotor disk bottom (minimum beam expansion) to minimum values at the rotor disk top (maximum beam expansion). As the volume of each ADCP bin increases, the amount of relative spatial averaging increases. This averaging effectively damps out small scale variations in the flow, resulting in the general under prediction of the turbulence intensity. This effect is significant for measurements within the water column, due to the inherent beam spreading, and in the selection of experimental parameters, such as bin height, and should be accounted for.

Using 100 cm bins, as seen below, the calculated turbulence intensity appears independent of water speed, but varies from 20% at the rotor disk bottom to 10% at the rotor disk top. The rotor disk bottom is closer to the river bottom, and thus, closer to the turbulent boundary layer, suggesting larger TI values. However, the ADCP bin volume at the rotor disk bottom, $V_{Rotor\text{-}Bottom} = 1.01\ m^3$ while the rotor disk top ADCP bin volume, $V_{Rotor\text{-}Top} = 12.1\ m^3$. While the bin cross-sectional area only increases 4 fold, the measuring volume has increased by more than a factor of 10 between these two bins. This difference in spatial averaging is seen directly in the drastic reduction in TI from rotor disk top to bottom, Figure 7, black curves.

If smaller bins are used instead, 10 cm or 20 cm, the calculated turbulence intensity clearly decreases with increasing water speed. In both cases, the magnitude is reduced by roughly half from 0.5 m/s to 2.0 m/s. Similar to the 100 cm bin condition, there is a reduction in turbulence intensity from the rotor disk bottom to the rotor disk top, likely associated with the spatial average due to beam spreading. The influence of spatial averaging is also clear from the comparison of 10 cm and 20 cm bin data. At all water speeds, the 10 cm bin turbulence intensity values are at least 30% greater than those measured with 20 cm bins. Further, 10 cm bin turbulence intensity values are 2 to 5 times as large as those measured with 100 cm bins. These differences in calculated turbulence intensities highlight a limitation of the ADCP for quantifying small scale flow phenomena throughout the water column. Spatial averaging inherent to the technology reduces the measured turbulent fluctuations, and thus, the calculated turbulence intensity. Further temporal averaging is likely to occur at slower data rates. Data acquisition with 10 cm bins at 1 Hz is near the limit of the Workhorse Monitor ADCP capabilities. As such, a single ping per ensemble was used, which increases the noise in each sample. However, the use of multiple pings per ensemble introduces additional averaging while reducing the maximum data acquisition rates.

One conceivable approach to discerning a more accurate TI value from ADCP measurements is to extrapolate the TI values based on the measurement bin cross-sectional area from the existing data to a bin area of zero. Figure 8 shows such an extrapolation for the 4 minute average TI values during the middle 60% of a single ebb tide for the 100 cm bin height data. While this represents the phenomenon qualitatively, the 20% TI result can only be considered provisional, and a reasonable suggestive starting point for better quantitative measurements using an Acoustic Doppler Velocimeter (ADV).

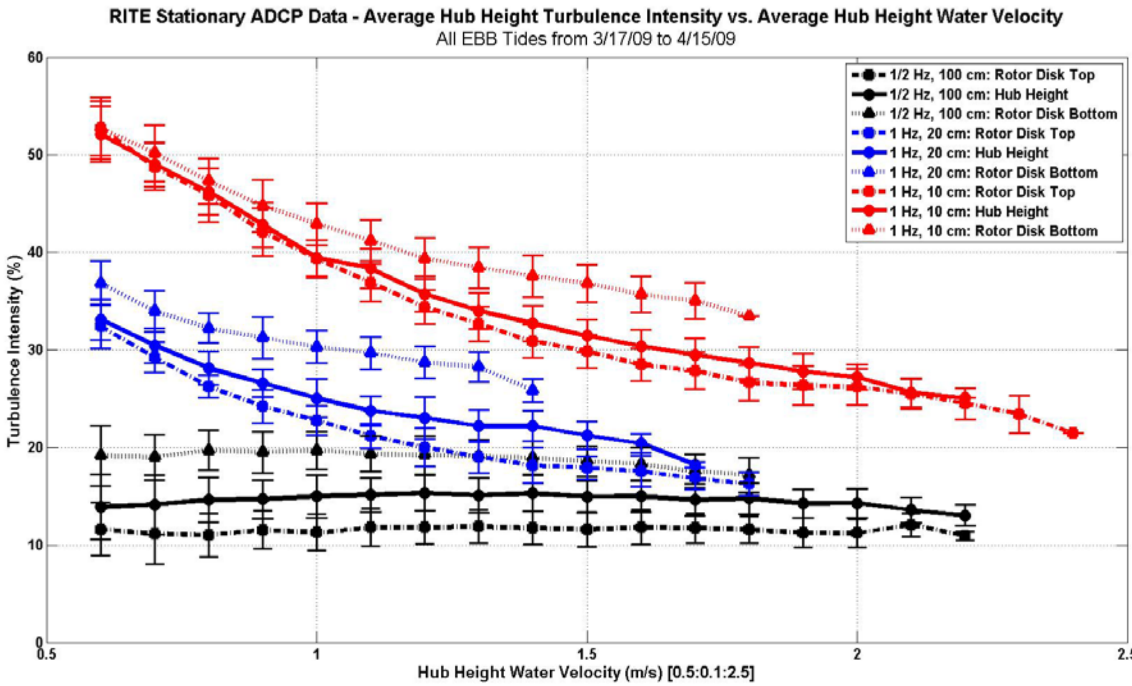

Figure 7. Ebb Tides, Turbulence Intensity vs. Hub Height Water Velocity

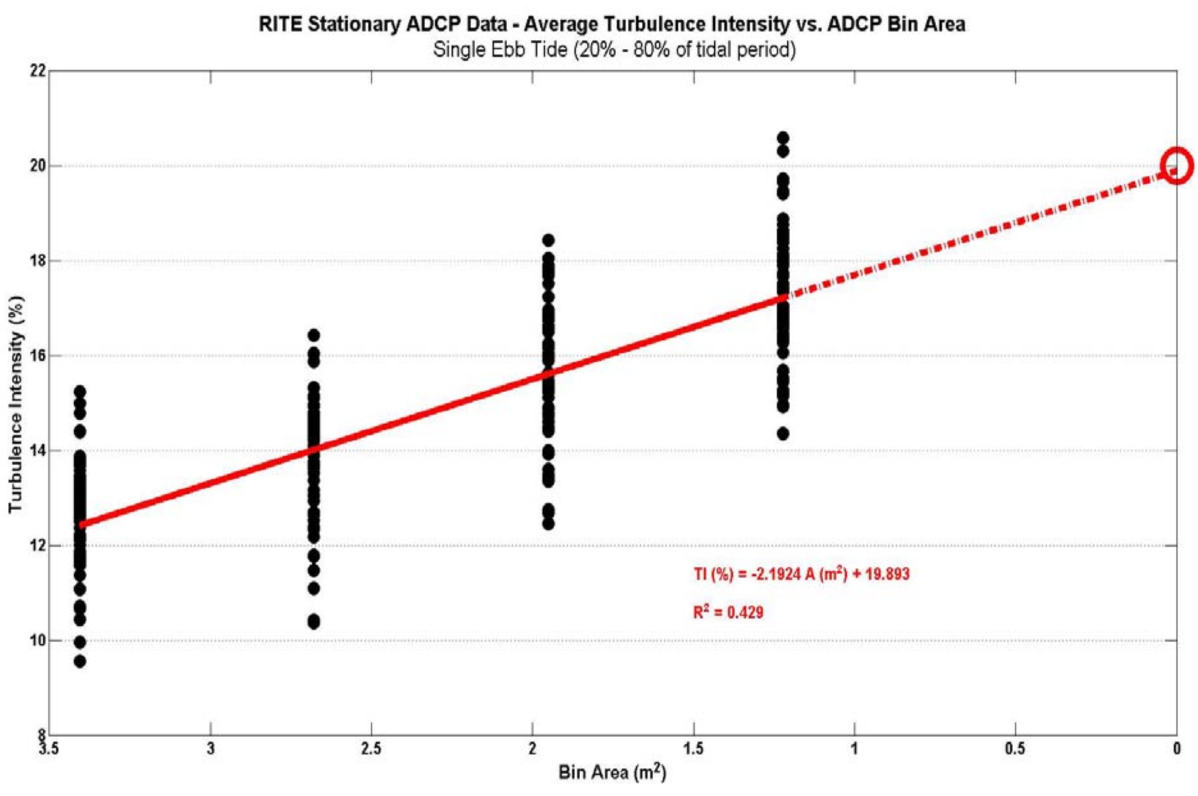

Figure 8. Single Ebb Tide, Turbulence Intensity vs. ADCP Bin Area

Figure 9 shows the flood tide turbulence intensity vs. measured hub height water velocity, with very similar results as those seen in Figure 7. However, the variation across the rotor disk is different on the flood tide, again, a likely result of the jet - boundary layer interaction addressed previously. Unlike for the ebb tide, the flood tide calculated turbulence intensities are almost identical for the rotor disk bottom and the rotor hub height, even with a larger measurement volume at the hub. This relative increase in turbulence intensity near the rotor hub confirms the presence of a strong mixing layer between the jet and the developing boundary layer. This turbulent mixing layer would result in increased instantaneous and fatigue loading on the rotor and turbine system during a flood tide, particularly at flow speeds greater than generator cut-on, U_{Hub} = 1.0 m/s. This analysis confirms the importance of detailed site analysis before approving the design of a tidal or river energy convertor for use at a given site. For the RITE site in particular, the ebb tide exhibits the classic turbulent boundary layer development according to a power law, n = 1/4. However, due to geographic constraints, the flood tide flow includes a jet - boundary layer interaction, with the resulting mixing layer nearly centered on the turbine rotor disk. From this, a representative tide can be developed based on the “undisturbed” ebb tide. However, for instantaneous and fatigue load calculations, the site specific flood tide conditions may dominate the extreme events. As such, two separate inflow models are needed to accurately capture the dynamic loads felt by a KHPS during operation in this portion of the East River. In other sites, similar measurements will be required to characterize the inflow conditions in support of reliable turbine and rotor load predictions.

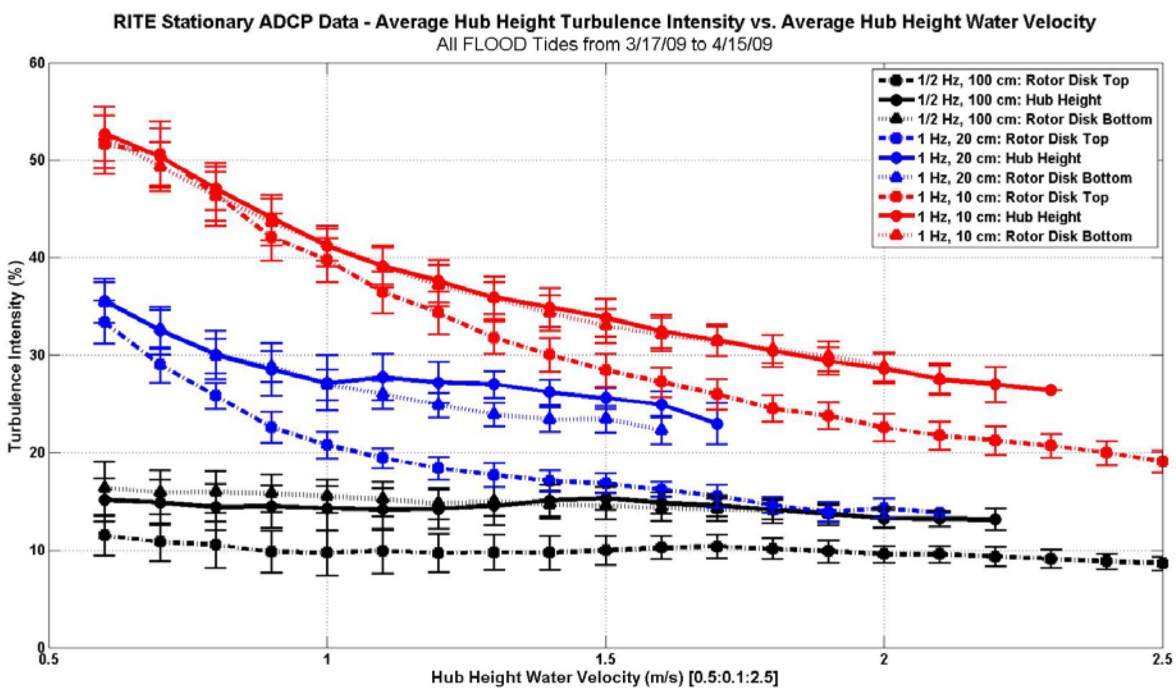

Figure 9. Flood Tides, Turbulence Intensity vs. Hub Height Water Velocity

Conclusions

Measurements from a bottom-mounted stationary ADCP at the Verdant Power RITE site were presented for a range of experimental conditions and water speeds. From this data, it is clear that the ADCP is well suited to measure the vertical variation in horizontal velocities from the near river bottom towards the surface. Specifically, the turbulent boundary layer development on the ebb tide is well captured, as is the jet - boundary layer interaction on the flood tide. However, due to significant spatial averaging associated with both beam expansion and bin height, the ADCP is not well suited to capture the small-scale turbulent fluctuations. Significant variation in measured turbulence intensity, both across the rotor plane and between measurements, is seen. While the mean velocity values are well captured, measurements of the fluctuating velocity component are very sensitive to ADCP settings.

Based on ADCP measurements, the ebb tide at RITE should be considered a typical representative inflow condition, with a constant shear exponent, n = 1/4. A provisional turbulence intensity value at the turbine hub height, TI = 20% should be chosen until more appropriate measurements can be taken. Specifically, small measurement volume, high frequency Acoustic Doppler Velocimeter (ADV) data will be taken to address the spatial and temporal averaging issues associated with the ADCP.

For future ADCP measurements, choosing a bin height equal to or smaller than 20 cm is recommended to accurately capture the shear profile and reduce spatial averaging. Maintaining a sampling rate of at least 1 Hz, and minimizing the pings per ensemble, is also recommended to reduce the influence of temporal averaging before post-processing. Depending on the frequency of flow variation (tidal vs. river for example), averaging windows from 4 to 10 minutes may be appropriate for post-processing.

References

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[2] MATLAB 7.10.0 (R2010a)

[3] "Wind Energy Handbook", Burton T., et al., Jon Wiley and Sons, New York, NY 2001.