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Measurements of tidal flow variability in Ramsey Sound, Pembrokeshire

Jon Miles, Daniel Coles, David Simmonds, Magnus Harrold, Alex Paine, Sue Barr

Abstract— **The nature of the flow at in-stream tidal energy sites is particularly important for predicting array and device performance, and also for operations and maintenance planning. Flow characteristics of Ramsey Sound, based on analysis of 2 weeks of Acoustic Doppler Current Profiler (ADCP) data from the site of the Deltastream device are presented here, alongside tide gauge data from the nearby Standard Port of Milford Haven. The ADCP was located approximately 300 m across the channel, at the northern end of Ramsey Sound, where the channel width was 1200 m and the mean depth was approximately 33 m. The flow dynamics were examined specifically to look at times potentially suitable for offshore operations. Results demonstrate that flow velocities exhibited clear asymmetry, with stronger flows on the northerly directed flood tide than on the ebb. Cross correlation indicated that the flow speed generally led the elevation by 20 minutes. In contrast to the expected theory, the current strength at mid-depth was stronger than at the surface on the maximum flood tide. The maximum flow speed in the tide was reasonably predictable from the tide range at Milford Haven. A threshold-based analysis of the ADCP measurements allowed the duration of slow-moving water to be identified for operation planning.**

Keywords—**Tidal energy, ADCP measurements, Ramsey Sound.**

I. INTRODUCTION

THE nature of the flow at in-stream tidal energy sites is particularly important for predicting array and device performance [1], and also for operations and maintenance planning. Previous developers have reported issues such as the choice of vessel, cost of operations, and the limits of operation of deployment vessels affecting deployment, maintenance and recovery [2]. The dynamics of the flow around slack water has been of particular interest at Ramsey Sound in Pembrokeshire (UK) for recovery of an existing turbine, the Tidal Energy Limited 'Deltastream' (Figure 1), and also for deployment of future turbines using locally sourced vessels, such as the KML vessel 'Sarah Grey' (Figure 2).

Fig. 1. Tidal Energy Limited 'Deltastream' device prior to deployment in Ramsey Sound. Source [3].

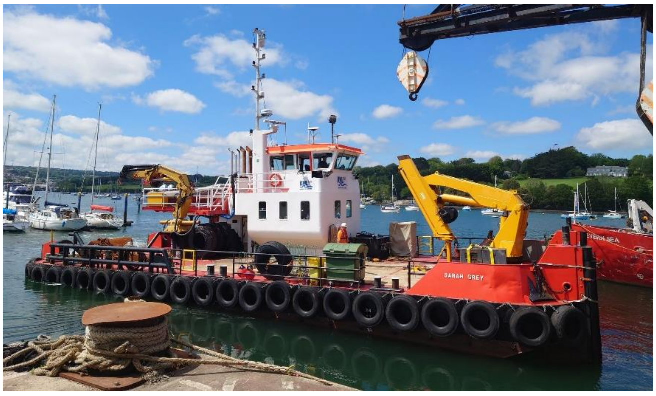

Fig. 2. Local vessel: Sarah Grey. Source: KML

Ramsey Sound is of variable geometry, measuring approximately 2-3 km long, 0.8-1.5 km wide, and with depths up to 69 m below Chart Datum (Figure 3). The tidal dynamics of West Wales are macro-tidal, semi-diurnal and largely dominated by the M2 component [4], with Ramsey sound sitting within a partially standing wave system in the Irish sea [5]. The tidal range at Milford Haven (to the South) is 6.29 m, and 4.02 m at Fishguard (to the North). Peak flows at the northern end of Ramsey Sound have

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been measured using an ADCP at up to 3 m/s, and flows are flood dominated [6]. Data from both ship-based ADCP transects [7] and numerical modelling [8, 9] indicates considerable spatial variability in the flow, due to features such as Horse Rock, a mid-channel trench, bed roughness variability, and rocks on the western side of the channel known as The Bitches.

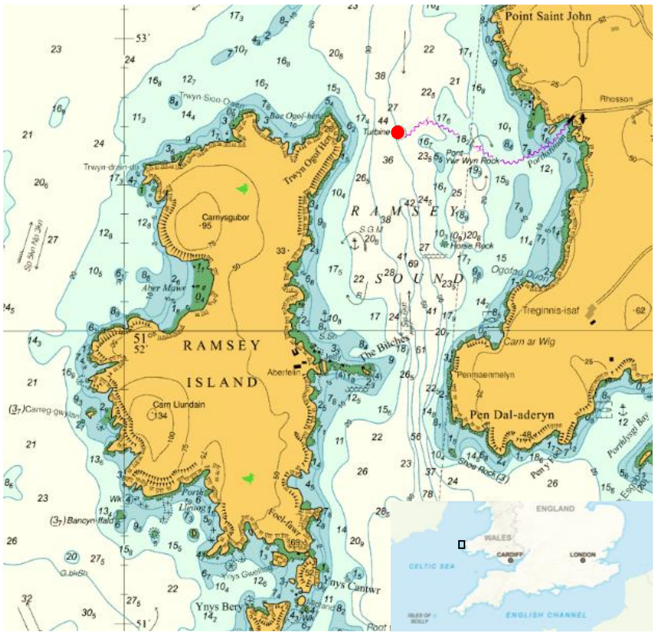

Fig. 3. Location of Ramsey Sound (inset) and ADCP position in the sound (red dot). Figure components sourced from Edina Digimap. Chart is UK Admiralty Chart 1482.

The seabed is made up of bedrock, gravel and coarse sand [10, 11]. The flow is roughly bi-directional, with dominant flood flows heading to the North [3, 6, 7]. Analysis of turbine scale Turbulent Kinetic Energy (TKE) has shown TKE is larger on the flood tide, and there are longer turbulent lengthscales (up to ~15 m) on the flood tide than on the ebb (up to ~11 m) [9]. The peak energy flux through the sound has been estimated at up to 180 MW, although the extractable power was estimated in the region 7.2 to 21.8 MW [7].

During 2015 a 400 kW tidal energy device was placed in the sound in a depth of approximately 35 m. The device was a 3 bladed fixed pitch rotor with 12 m diameter, mounted on a gravity base, standing 18.1 m tall overall and with a hub 12.1 m above the bed [3, 12]. The effect of the turbine on the flow has been modelled using similar geometry and flow speeds to the Ramsey Sound deployment and indicates flow recovery by 10 turbine diameters (D) downstream [13]. In-situ ADCP measurements on the device measuring flows arriving at the turbine indicate that the flow is affected up to 0.75 D upstream [12].

This paper examines data from Ramsey Sound from the perspective of operations management and planning for tidal energy device deployment, operation, maintenance, and recovery.

II. METHOD

Flow characteristics of Ramsey Sound were analysed, using simultaneous ADCP measurements from the Sound and tide gauge data from Milford Haven, which is the closest Standard Port. The ADCP was located approximately 300 m across the channel, at the northern end of Ramsey Sound, where the channel width was 1200 m and the mean depth was approximately 33 m. The ADCP was adjacent to the location of the Deltastream tidal energy device. The flow dynamics were examined specifically to look at times potentially suitable for offshore operations, but also in response to operational questions about the flow dynamics raised by developers at the site. The ADCP (Figure 4) was an RDI 600 kHz Workhorse Sentinel.

Fig. 4. ADCP in deployment housing from a similar deployment at the same location in Ramsey Sound. Source: [12].

Two weeks of data from 18th February 2009 to 21st March 2009 were used in the analysis, spanning a complete spring-neap cycle. For the majority of the analysis, mean flow values were used, calculated at 10-minute intervals over 33 x 1 m depth bins, from 2.27 m above seabed to the surface.

III. RESULTS

Results demonstrate that ADCP data can reveal a range of information that is relevant to marine operations. In particular, the work at Ramsey has found that flow velocities exhibited clear asymmetry, with stronger flows on the flood tide (northerly) than on the ebb (Figure 5).

Peak mean flows on the spring flood appear to reach 3.19 m/s, consistent with [6], however analysis of the data against rank suggests the highest three measurements are slightly greater than the general data distribution, and a maximum of 2.75 m/s is possibly more realistic. The ebb (southerly) maximum was 2.01 m/s. The residual tide (average over the two weeks) was 0.14 m/s in a northerly direction. The spring–neap variability was clearly visible, with neap tide northerly flows peaking at 1.68 m/s and southerly flows reaching 1.29 m/s The maximum depth recorded at the ADCP was 35.4 m. The minimum was 30.39

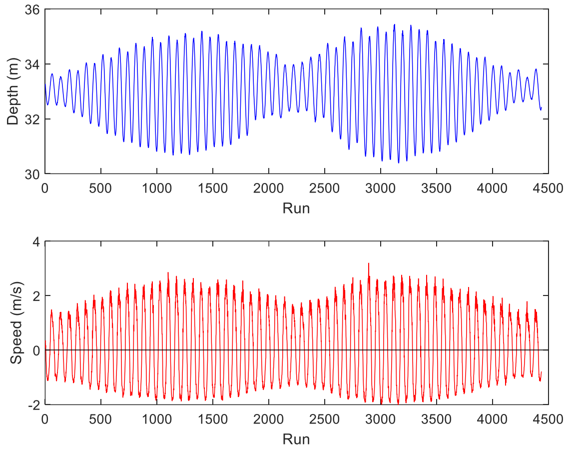

Fig. 5. Depth and flow velocity over a 2-week cycle.

m, giving a range of 5.05 m. The mean measured depth was 33.01 m. For the same period, the range at Milford Haven was 7.08 m. Generally, the range in Ramsey Sound was smaller than that at Milford Haven by a factor of 0.68. The two were approximately linearly related, with an r^2 of 0.96.

The current strength in the water column was stronger than at the surface (Figure 6). On a typical spring, the flow was maximum at 20.27 m above bed at 2.85 m/s, whilst near the surface (29.27 m above bed) it was 2.66 m/s, suggesting the surface velocity is reduced by a factor of 0.93. A similar effect was evident on the ebb tide although the reduction was less, with a factor of 0.95. The precise reason for this is unclear, however the implication is that (a) surface-based measurements may underestimate the velocity slightly and (b) both the log profile and the $1/n^{th}$ power law profiles [14] may give inaccuracies if the surface layers are used to predict the velocities over the profile.

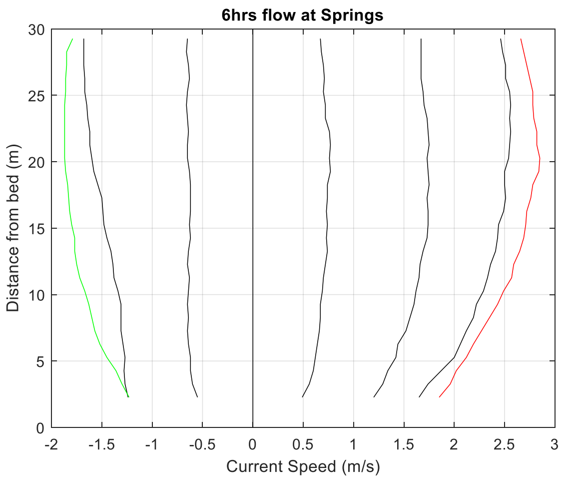

Fig. 6. Velocity profiles for a Spring tide.

The flood (northerly) current maximum was approximately in phase with high water at the nearby standard port of Milford Haven (Figure 7). This is consistent with the tide being a progressive wave at Ramsey. This is in agreement with previous modelling and analysis of the Irish Sea region [15].

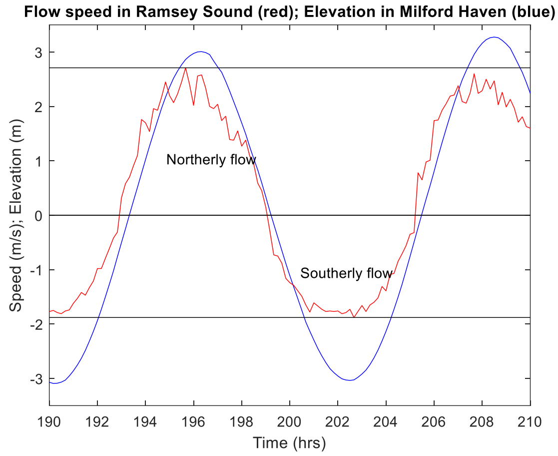

Fig. 7. Velocity (red) and tidal elevation (blue).

There was considerable variation in the measured current speed around the time of the maximum (Northerly) flow, suggesting large scale turbulence. This also makes identification of the timing and magnitude of the peak northerly flow awkward. This variability may emanate from either the line of rocks known as the 'Bitches', or from an underwater feature called 'Horse Rock'. Both of these features are to the South of the ADCP location. Cross-correlation indicated that the flow in Ramsey Sound led HW Milford Haven by 20 minutes (Figure 8).

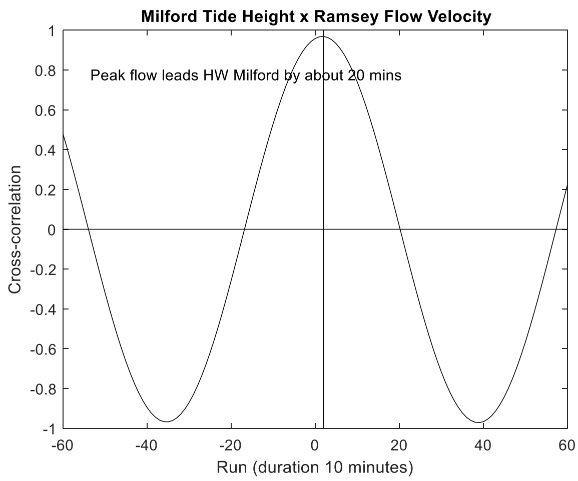

Fig. 8. Cross correlation between velocity and elevation.

This is useful information for tidal device operators because times of HW Milford are published by the UK Admiralty and generally available, while the timing of the maximum flow speeds are not.

The magnitude of the maximum flow speed (U_{max}) in the tide was reasonably predictable from the tide range at Milford (R), revealing separate linear relationships for the flood and ebb (Figure 9).

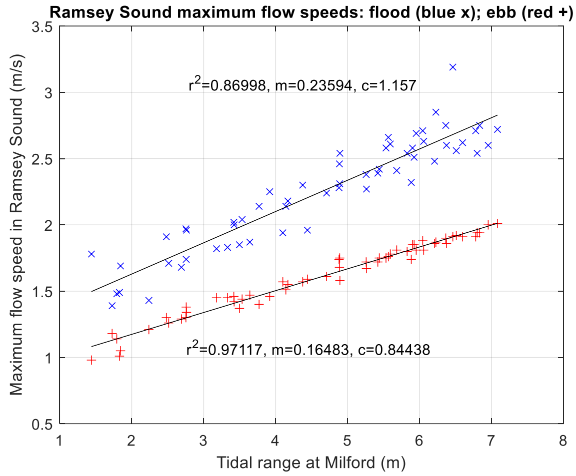

Fig. 9. Prediction of maximum flow rates from tide range.

Tidal asymmetry means that the flood and ebb velocities were of different magnitudes for the same tidal range.

$$U_{max,flood} = 0.24R + 1.16 \quad (1)$$

$$U_{max,ebb} = 0.16R + 0.84 \quad (2)$$

ADCP measurements allowed the duration of slow-moving water to be identified for operation planning. Using a threshold of 0.75 m/s, it was found that spring tides gave a working window of less than 1 hr, while neap tides gave a window greater than 2 hrs. (Figure 10).

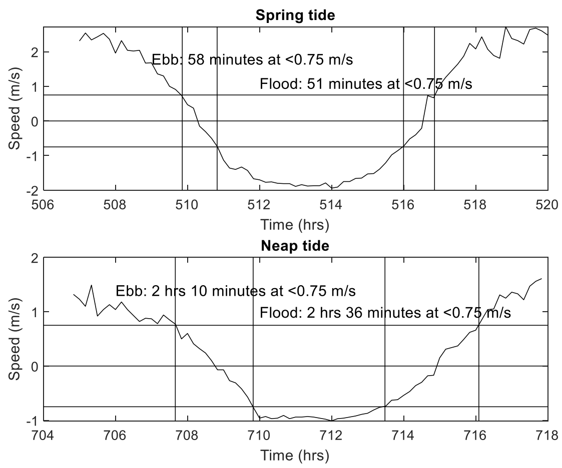

Figure 10: Identification of operation windows on Springs/Neaps.

In order to plan operations, it is useful to be able to predict the time of slack water on site from the tide times at a standard port. At Ramsey, slack water occurred generally at tide heights of approximately mid water level. To give predictability, the duration between slack water in Ramsey Sound and HW Milford Haven was identified both for the flood tide and the ebb tide (Figure 11).

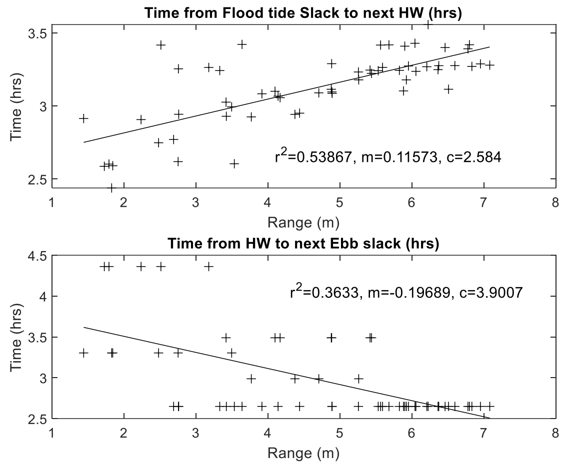

Fig. 11. Length of time between slack water (Ramsey Sound) and high water (Milford Haven) on the flood tide (top) and the ebb tide (bottom).

When considering the flood tide, the slack water was generally 'earlier' before HW when the tidal range was larger. However, what is notable for operations is that during neap tides (small range), the slack water varied in time from 2.5 hrs to 3.5 hrs before HW. A similar trend was observed for the ebb slack, but the duration was more variable, taking 2.6 hrs to 4.4 hrs to settle to zero. It is unclear exactly why there is this variability, however the implication for operations is that sufficient time has to be allowed in the timing of slack water. Slack water times may vary by an hour, and the time of slack is less predictable on neap tides than on springs.

Operators on site reported across channel oscillations in velocity, making vessel positioning difficult during operations. Spectral analysis of the across-channel flows allows the frequency of such oscillations to be identified. The spectral analysis of the ADCP velocity time series are presented tentatively here, because the beam separation angle leads to uncertainty in the instantaneous velocity time series.

The ADCP data was sampled at 1 Hz, and for this analysis was separated into runs of length 2048 points (34 minutes). Spectral analysis was applied to flood, slack and ebb tide data runs separately, following the approach of [16]. Each run was separated into four non-overlapping sections of 512 points, with 3 overlapping sections, giving a frequency resolution of 1.8 x 10^{-3} Hz up to the Nyquist frequency of 0.5 Hz. This results in 12.04 degrees of freedom. Lower and upper factors for the 95% confidence intervals on spectral peaks are therefore 0.5 and 2.7, respectively, following [17].

The across channel flows (East-West) were analysed at the time of maximum northerly flow, maximum southerly flow, and at the turn of the current (slack water). The analysis revealed the largest variance on the northerly flow, indicative of turbulence at this time, and the least variance at slack water. There was some evidence of low frequency oscillations in the current at f = 0.015 Hz. This peak was largest during the northerly flow and remained at slack water (Figure 12).

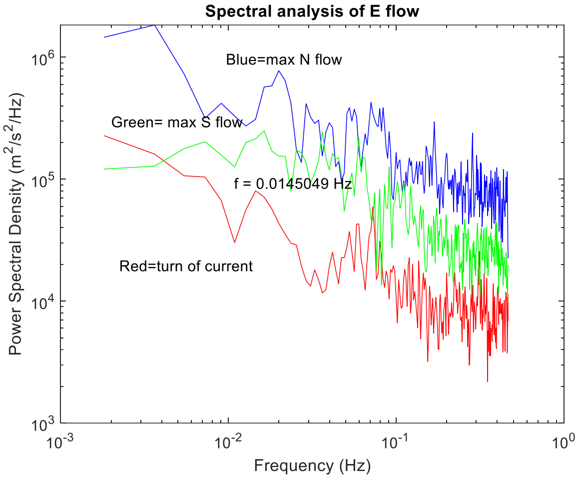

Fig. 12. Spectral analysis of cross-channel flow oscillations

The period of these across-channel flow oscillations was approximately 68.9 s, which is roughly consistent with the observations of operators. It is possible that there is an across-channel standing wave at this frequency. Shallow water approximations in depth 30 m would suggest a wave speed of 17 m/s, and a wavelength of 1,183 m. The ADCP and tidal energy device was located approximately 300 m across the channel, where the channel width was approximately 1200 m. The position of the ADCP would therefore correspond to a node in an across-channel standing wave (Figure 13), where across-channel velocity variations would be largest (Figure 14). Oscillations would be less evident in the surface elevation.

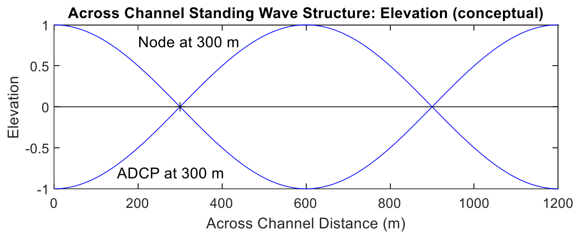

Fig. 13. Normalised elevation in a standing wave.

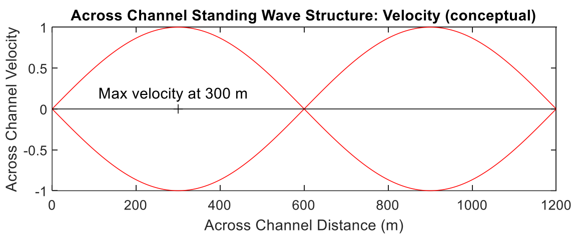

Fig. 14. Normalised velocity in a standing wave.

IV. Discussion

The measurements reported here give similar values of flow speed to those measured previously [6, 7]. The general phase relationship between the tidal elevation and the along-channel flow velocity in the sound indicates a progressive tidal wave locally in this region, sitting within the larger scale system indicated by [5], and modelled by [4]. A mid-depth maximum in flow speed identified here, consistent with previous measurements [9], particularly during peak flows on the flood tide. The fine lengthscales of turbulence of order 1-15 m identified by [9] are not investigated further here, however the data here supports the observation of a lower frequency across channel oscillation with a scale ~1 km not previously mentioned in the literature. While prior work focusses largely on the power production potential from maximum flow speeds in the peak ebb and flood (e.g. [4]), the work here gives some focus to the slack tide window, due to the interest in this time for operations on site.

Numerical models also have great potential for predicting regional flows near tidal energy devices (e.g. [8, 10], and such models may be interrogated to obtain slack water periods. Further to this, ADCP deployment and data analysis offers the opportunity to gain insight into the variability of timing and duration of potential operation windows, and also for better understanding the dynamics of the site. Variability in the flows may occur from a range of variable driving forces (such as wind, waves and barometric pressure) that are awkward to include in regional flow models in this context, because of the relatively short durations of prediction capability of weather systems compared to tidal flows.

The low frequency oscillations in the flow were first reported by operators on site, making some vessel-based operations very challenging. While initial data analysis and an across channel resonance is suggested here, driving mechanisms including eddies and shear driven instabilities in the currents arising from the morphology are possible (e.g. [18]). Further work is required to investigate the process in more detail.

It is noted that in analysing the time series from the ADCP, the beam separation may lead to some uncertainty in the instantaneous values of current at any point. For fine scale turbulence analysis, careful analysis of the data is required (e.g. [9]). Larger scale flow structures which are coherent across spatial scales much greater than the ADCP beam spacing are likely to be less sensitive to this issue.

Operations and planning in light of sound understanding of hydrodynamics at tidal energy sites is critical for future economic success of the tidal energy sector [19]. The results shown here from an ADCP deployment in Ramsey Sound have demonstrated the capability to give useful tools for planning deployment, maintenance and recovery operations at the site, when used in conjunction with tide data from a local standard port. The observations here illustrate some of the range of analyses that is possible, to help quantify some of the conditions on site for operators.

Further investigation of Ramsey Sound data and data from other sites will help identify how the approaches and analyses used here may be applied to other sites. While understanding the dynamics of such channels is of critical importance for planning, installation, maintenance, and recovery of large-scale installations, it is also important for smaller deployments to support isolated island community projects [20], where financial margins may be smaller.

V. Conclusions

Analysis of an ADCP data set from Ramsey Sound has shown that (i) the data set can be analysed specifically to inform operations planning and (ii) gives specific insight into new hydrodynamic features. Results demonstrate that flow velocities exhibited clear asymmetry, with stronger flows on the northerly directed flood tide than on the ebb. Cross-correlation indicated that the flow speed in Ramsey Sound generally led the elevation at the local standard port of Milford Haven by 20 minutes. At peak flow, the current strength in the mid water column was stronger than at the surface. The maximum flow speed in the tide was reasonably predictable from the tide range at Milford Haven. An assumed working window, defined by a threshold when the current speed was < 0.75 m/s, indicated that there was a ~1 hr working window on spring tides, compared to ~2 hrs on the ebb. The neap flood tide working window was the longest, due to tidal asymmetry. The time of slack water compared to HW indicated some variability, and could be up to an hour different for similar tide ranges. This variability was greatest for smaller tide ranges when recovery/deployment/maintenance operations would be most favourable. Initial indications supported the observation of a low-frequency across-channel motion.

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