

A New Lagrangian-Acoustic Drogue (LAD) for Monitoring Flow Dynamics in an Estuary: a Quantification of its Water-Tracking Ability

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ABSTRACT

SCHACHT, C. and LEMCKERT, C. J., 2007. A New Lagrangian-Acoustic Drogue (LAD) for Monitoring Flow Dynamics in an Estuary: a Quantification of its Water-Tracking Ability. *Journal of Coastal Research*, SI 50 (Proceedings of the 9th International Coastal Symposium), 420 – 426. Gold Coast, Australia, ISSN 0749.0208

We describe a novel in situ measuring drogue device developed for the investigation of near-surface sediment and flow dynamics in an estuary. The Lagrangian Acoustic Drogue (LAD) comprises a unique configuration of instruments including a downward-facing 600 kHz Broadband Acoustic Doppler Current Profiler mounted on a Lagrangian float; a Differential Global Positioning System; and a (Conductivity, Temperature, Depth sensor. Open ocean studies have revealed the necessity of understanding the Lagrangian nature of the drifter or drogue. As the ocean and estuarine systems are two vastly distinct environments, a separate study was conducted using the LAD in an estuarine environment. The main objective of this study was to directly quantify the LAD's ability to track and monitor a Lagrangian parcel of water over a slack-water period. It was found that the LAD confidently tracked a parcel of water to a depth of 4.5 m. It was also found that the water tracking ability (slippage) was directly related to the magnitude of tidal velocity. This study also revealed characteristics about the physical state of the estuary itself, and gave positive outlook for the future of drogue-based studies in estuaries.

ADDITIONAL INDEX WORDS: *Drogue, estuarine dynamics, current meter*

INTRODUCTION

Direct measurements of suspended sediment settling velocity and suspended sediment concentrations [SSC] are typically limited to Owen tube configurations (EISMA et al, 1997) and on-board settling chambers. The various limitations of these devices are well known. Probably the most common is associated with the observation of particle flocculation and reflocculation as a result of residual turbulence and convection currents (eg. CURRAN et al, 2003). From a physical science perspective, there is also the additional fact that the still water environment of a settling column is not representative of an estuarine environment.

Alternatively, indirect estimations of settling velocity via SSC measurements may be made by a number of instruments and have the advantage of gathering actual in situ data. Some of these include: optical methods and devices such as optical backscatterance sensors (OBS) and transmissometers; laser diffraction instruments such as the LISST-100 or Laser In Situ Scattering and Transmissometry profiler; and acoustic backscatterance devices, such as the Acoustic Doppler Current Profiler (ADCP). Previously these instruments have been under-utilised in their application for determining settling velocity. For example, ADCP measurements of mean river velocity (in estuaries only) have been typically limited to investigations from either a moving vessel (via cross-sectional transects of the estuary for spatial data), or from a fixed bed location for temporal data (MUSTE et al, 2004a,b).

Two approaches are commonly used for modelling and observing flow dynamics and suspended sediment transport:

namely the Eulerian and Lagrangian approaches. Most field measurements are conducted within the Eulerian framework (COULLETTE and MARSDEN, 2001) at fixed locations, moored at either specific heights to obtain temporal data, or longitudinally, at discrete spatial locations (often kilometres apart) of an estuary. However, this (Eulerian) method does not directly evaluate phenomena occurring between stationary points such as localised flocculation/settling and resuspension 'hotspots'. The term 'hotspot' is used to describe observed cloudy patches of increased turbidity caused by tidal resuspension and horizontal advection with the tide. One of the most difficult tasks in sediment transport studies is discerning the difference between local resuspension and horizontally advected suspended sediment as they both are detected by an increase (or decrease) in SSC (even if only the bottom-boundary layer is considered) (PRITCHARD, 2005). This change in SSC cannot easily and confidently be measured in the field at fixed Eulerian points, as the advected (sediment transport) is essentially Lagrangian, and so often the advected component can only be estimated from the synoptic tidal current or background levels (HILL et al, 2003).

On the other hand, a Lagrangian approach adopts a frame of reference that follows or tracks the motion of a particular parcel of fluid over time, and so not only shows the ultimate fate of a water mass, but gives an insight into the transport pathways of the water parcel. In this paper a Lagrangian drogue (LAD – Lagrangian Acoustic Drogue, see Figure 1) was developed so a parcel of estuarine water could be followed (with the advection of the tide)



Figure 1. Photograph of LAD before deployment (b). Note the Greenspan CTD is not shown in this photograph

and its properties monitored over time, thus eliminating the complication of advected and resuspended components.

The objectives of this paper are two-fold. The first is to describe a novel technique of utilising an ADCP as a Lagrangian, non-obtrusive in situ monitoring device for the investigation of suspended sediment dynamics; we call this the LAD (Lagrangian Acoustic Drogue). The second is to investigate and understand the LAD's behaviour and ability to behave as a Lagrangian particle tracking device within an estuarine environment.

DROGUES

Lagrangian Framework and Slippage

Lagrangian drifters are particularly valuable for observing the spatial structure of a flow field and provide an insight into the flow dynamics which cannot be revealed using Eulerian data (JOHNSON et al, 2003). The LAD was therefore designed with an ADCP (facing downwards) so as to capture and thus understand the Lagrangian temporal flow dynamics and circulation patterns of the estuary as it tracks a parcel of water over time.

Devices such as drogues and drifters that are deployed within the ocean or estuary will experience a combination of complex tracking errors (referred to as, slippage). These are mainly due to environmental forces such as the wind, waves and tide.

According to the best knowledge of the authors, to date there has been no extensive theoretical analysis or empirical study into the ability of drogues to track a water parcel within an estuarine environment. The dominant physical driving forces acting in such environments are wind-stress, gravity (in the form of tidal currents) and buoyancy (a vertical force that is effected by the density and temperature of water masses). In previous open-ocean drifter investigations it has been the effect of wind stresses (more than 10 ms^{-1}) and wind waves that produce the largest slip force. In macrotidal estuaries such as the Fitzroy River estuary, Queensland, the most significant physical driving force is tidal velocity. Typical macrotidal estuarine velocities exhibit more than 0.4 ms^{-1} , while on a global basis, 90% of the area mean velocities exhibited by drifters in the open ocean are $0.04\text{--}0.1 \text{ ms}^{-1}$ (PADUAN and NIILER, 1993). Given these inherent differences between the estuarine and ocean environments, this study has developed specific methodologies to investigate the water tracking ability of drifters within an estuarine environment.

LAD Description and Deployment Specifications

The LAD drogue was designed to track a parcel of water with minimal influence from surface winds, small surface undulations and rotation. The overall size and design of the drogue was limited by the area available to re-construct the drogue in the deployment vessel (construction space area 1 m^2). The air-sea ratio of the drifter design (surface area ratio of drogue above water: to drogue below water) was kept to a minimum to reduce the effects of wind and surface waves on the exposed portions of the LAD (i.e. that above sea level). The LAD consists of a self-contained 600 kHz ADCP (facing down with transducer head approx 1 m from surface), an external Trimble® GeoXM DGPS - Differential Global Positioning System (for submetre accuracy) and a Greenspan CTD (CTD P300 - Conductivity, Temperature and Depth sensor) mounted at a depth of 40 cm from the surface.

For open ocean studies, drifters are made to withstand rough conditions for periods of up to several years. They are therefore constructed from more robust materials and are substantially larger than the drogue developed in this study. The LAD vanes, baseplate and connections are constructed out of aluminium and marine grade stainless steel. The weight of these members combined with the weight of the instruments (e.g. ADCP and battery pack etc.) were used to size a float which ensured that the top of the drogue float would be at the surface (i.e. neutrally buoyant). The LAD float is comprised of a high-density polystyrene buoy coated in a thick urethane spray for waterproofing. The housing for the DGPS is a PVC container with a clear Perspex lid and threaded o-ring for complete waterproofing and to enable unobstructed DGPS signals. Additionally, a very light and thin tether (of 3 m length) with floating waterproof strobe-light was attached for visual observation.

According to SPAIN (2003), there is a trade-off between the resolution, range and noise for the configuration of the ADCP. The most important set-up configuration in this study was the depth resolution (25 cm bin size) for the latter calibration of SSC samples. Secondly, it was important to configure the drogue to account for the unwanted random velocity error (noise) which was counter-balanced by adopting more pings per ensemble. Averaging reduces the standard deviation (SD) of the velocity error by the square root of the number of averaged pings (N), because random error is uncorrelated from ping to ping. This study used 120 pings per ensemble, which gave a small velocity standard deviation of 3.2 cm s^{-1} . Given the nature of the study site and frequent observations of random sediment plumes and hotspots, the ADCP ensembles were averaged over 1.5 minutes. The ADCP was configured to operate in mode 1: the most robust method with the highest profiling range and precision within a few cm s^{-1} (SPAIN, 2003)

The Trimble GeoXM DGPS receiver was synchronised with ADCP and attached separately on the top of the LAD float. This receiver was operated at a frequency of 1 Hz . Initialisation and satellite acquisition is automatically achieved by the DGPS, which records with a verified accuracy of 2 to 5 m .

FIELD STUDY

The Fitzroy River, Australia, has an estuarine area that extends approximately 60 km from its mouth (Figure 2) to a tide-limiting barrage, with a number of minor tributaries. The location and nature of the barrage essentially forces the river to behave as an enclosed bay (with minimal freshwater input), with the exception of seasonal flooding events when the river receives its primary natural freshwater inflow (SCHACHT and LEMCKERT, 2006). There is however, a constant minor source of freshwater from the three

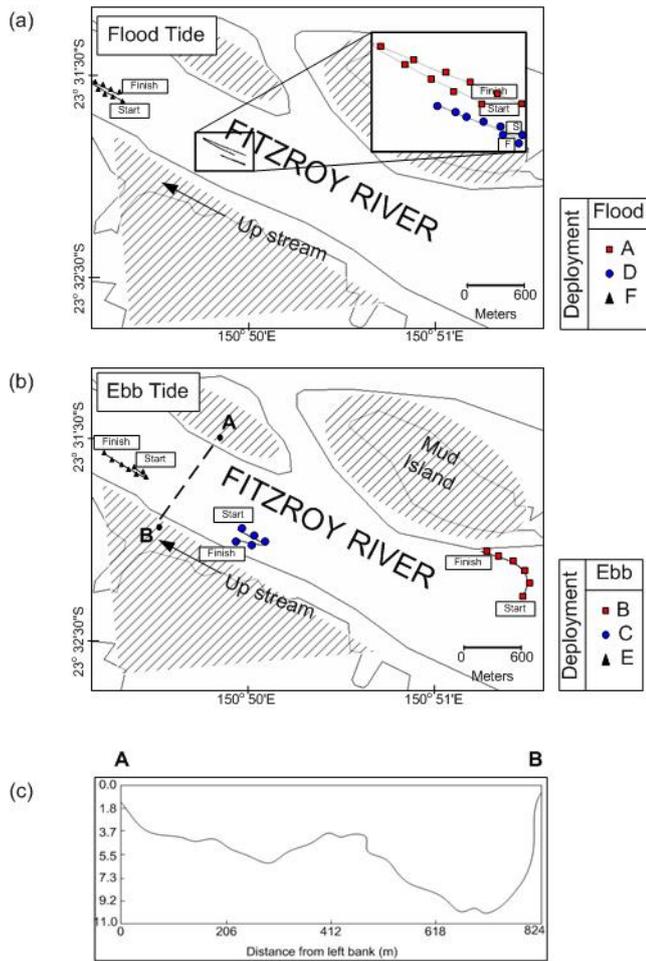


Figure 2. LAD tracks of the six deployments, separated into (a) Ebb tide and (b) Flood tide. Note a typical cross-sectional transect as per the Boat mounted 1200 kHz ADCP in (c).

sewage treatment plants and fish ladder, located at the barrage (approximately 35 ML day⁻¹).

The semidiurnal tidal regimes are macrotidal, with a mean tidal range from 0.3 to 4 m and marked spring and neap differences. The estuary exhibits shorter and faster tidal velocities during the flood tide than the ebb, which is a reflection of the estuary’s flood-asymmetry. This action is known to induce sediment resuspension, making it a naturally highly-turbid system.

Due to the natural undulations of the combined sand and silty-clay sea-bed topography, the induced resuspension (at the onset of mid-tide, which typically exhibits high velocities) occurs at ‘hot-spots’. In some localised areas these spots are indicated by large visual plumes, which exhibit turbidity more than four times that of the surrounding water (August 2004, Schacht unpublished observations).

Drogue Deployment

Six LAD deployments were completed over the flood and ebb slack water period of three separate surveys during the dry season of 2004 (August). The three survey periods were required to capture a selection of distinct tidal ranges (spring, neap and intermediate range) so as to clarify the effects of tidal velocity on the water-tracking ability of the drogue. As NILER et al. (1995)

confirmed the most important slip-producing force in oceans to be wind, it was assumed that the tidal velocity and ability of the LAD to react to the changes in tidal velocity would convey the greatest slip-producing force in the present estuarine investigation.

Preliminary site investigations found that moderate wind conditions (more than 10 – 15 knots) exist during the day and cause wind-waves in the region. These conditions created an unsafe and undesirable environment to deploy the LAD, and caused the LAD to travel in the direction of the wind, rather than the current; thus all deployments were conducted over night as minimal wind conditions were present (less than 5 knots). The individual deployments and specific conditions for each individual release (A – F) are described in Table 1. Note that each individual deployment is grouped in a pair (A and B, C and D, E and F) corresponding to the flood and subsequent ebb (or vice versa) for the specific survey.

For the purpose of this study, the definition of ‘slack water’ was taken as the minimum point of velocity (close to 0 ms⁻¹) measured by the DGPS. This is the time at which the net current forces acting on the surface areas of the drogue cause it to slow to a near stop and progressively change direction (transition from ebb to flood, or flood to ebb tide). In this study, it is the difference between the slack water measured by the DGPS and the slack water measured by the first bin of the ADCP that later determines the slippage of the LAD.

The study site was located close to the mouth of the Fitzroy River estuary, and adjacent to Mud Island (Figure 2). Preliminary visual inspections showed this region was highly-turbid due to high tidal velocities. The DGPS track from each deployment (A – F) is shown in Figure 2, and are separated into the flood (a) and ebb (b) deployments. Figure 2c depicts a typical cross-sectional profile of the estuary.

The aim of each deployment was to capture the most data both before and after slack water, without the LAD running aground or drifting too far up or downstream. Therefore the LAD was deployed approximately 1½ hours before the predicted (ebb or flood) slack water and retrieved approximately 1½ hours after. This time period was selected to ensure there was a contingency window for the predicted variations, as there was sometimes a difference of up to 60 minutes between the predicted (at Port Alma station, Table 1) and measured tides. This discrepancy resulted in one of the deployments (i.e., E) being let out only 25 minutes before slack water.

Table 1: Observed LAD deployment conditions

Survey	Deployment	Tide	Tide heights			Total LAD dist. (m)		Conductivity range (µS/cm)	Temperature range (°C)
			(AHD)*	HW/LW	Slack water	ADCP	GPS		
1	A	Flood	4.19	00:39	01:27:07	763.0255	716.36	317	0.105
	B	Ebb	1.31	07:02	08:12:32	756.379	680.189	312	0.268
2	C	Ebb	1.97	21:31	22:30:52	521.0163	536.77	298	0.138
	D	Flood	3.53	02:56	03:36:12	485.9046	475.603	385	0.148
3	E	Ebb	1.39	00:39	01:14:57			458	0.308
	F	Flood	3.78	06:08	07:16:32	936.09	826.991	530	0.113

* Australian Height Datum (AHD) is 2.854 m above the Port Alma Station datum, Lowest Astronomical Tide (LAT).

Calibration and Other Instruments

A separate self-contained CTD profiler was primarily used for the calibration and verification of the LAD. This profiling instrument, containing a SEACAT SBE 19-03 CTD, with pump attached, nephelometer and Flowjet centrifugal pump (for bulk water collection) was deployed and lowered to the seabed at a steady rate of approximately 10 cms⁻¹ every 20 minutes to monitor

the dynamics over the changing tidal cycle and to account for the different turbulent fluctuations of various time-scales in the study area. All of the profiling instrument's measuring-sensors were located within the same 200 mm radius, so the same parcel of water was measured. The profiling instrument was deployed within a radius of no less than 7 m and no more than 15 m of the drogue (because of interference with the acoustic beam). For the last two deployments (E and F), a Sequoia LISST-100, with SBE 37-SI MicroCAT was used for profiling instead, primarily to investigate the in situ particle size distribution (though not within the scope of this project).

The deployment of the LAD and the profiling of the other instruments were conducted from a 5.5 m boat. Due to the nature of the fast-flowing currents, it was imperative that the boat stayed within 30 m radius of the drogues. Care was taken to minimise propeller-induced bubbles that could interfere with the ADCPs.

RESULTS AND DISCUSSION

LAD observations and tracks

The focus of this study was confined to a 5.7 km length of the river extending upstream from its mouth. The estuary consists of a main channel that extends along its southern bank, with a central intertidal mud-bank ridge, and a shallower channel on its northern bank (which is often unnavigable at low water), see typical cross-sectional diagram, Figure 2c.

The tracks from the six LAD deployments (Figure 2) give a clear representation of the short-term flow patterns occurring within the study region. The ebb tide deployments (Figure 2b) depict a noticeably larger radius of curvature than that of the flood-tide releases with a tendency to hug the estuarine banks. This observation is consistent with the findings from the drogue work conducted by RIDD et al. (1998) on axial convergence fronts. Axial convergence fronts (a form of secondary estuarine flow rotation) occur in well-mixed estuaries due to an 'interaction between the cross-channel gradient in the axial velocity and axial density gradient'. It is often denoted by a central convergence zone (often by an accumulation of floating debris in the middle of channel) during flood tides and central divergence zone on the ebb tide. Most LAD deployments were made in the deeper channel (towards the south); however, it must be noted that the LAD was deployed on the northern side of the channel during deployment B during an ebb flow. It is postulated that this is the reason the LAD drifted closer to the mud banks.

The flood-tide tracks and their sharp turning point reflect the estuary's flood asymmetry – where the duration of the falling tide exceeds the rising tide, resulting in a peak flood current. Maximum currents exhibited during this study were just under 0.3 ms^{-1} , although currents outside of the window period exceeded 0.35 ms^{-1} . Factors affecting the tidal asymmetry in the Fitzroy River estuary are the general hydrodynamics and morphology, and more specifically the bottom friction, location of tidal flats, tributary inflow, and tide-limiting barrage (WALTON, 2002).

LAD's Water-Tracking Ability

Water Parcel Properties

For the purpose of this investigation, a change in the properties of a tracked water parcel was considered as a marked change in the vertical velocity stratification (or increased slip past the LAD). That is a change in velocity of approximately more than 0.15 ms^{-1} . Other important parameters that describe the water tracking capability are the conductivity, temperature and suspended sediment concentration changes.

The conductivity and temperature of the water parcel have been investigated, and show little change during the window period of

each deployment (see Table 1). This demonstrates that the water parcel characteristics do not vary considerably with time during the short duration of the window period.

LAD water parcel lag (slippage)

NIILER et al. (1995) directly quantified the effects of environmental and design parameters on the water-tracking capability (slippage) of several designs of open ocean drifters. They did this primarily by attaching a vector measuring current meter (VMCM) to the top and bottom of the drifter and measured the velocity of the water that slipped past the drifter. A similar methodology is adopted in the present investigation, in that the slippage (or LAD water parcel lag) is measured from the difference between the top (DGPS) and bottom (first depth bin of the ADCP) of the LAD. In this study the ADCP was set to bottom track – so that all water velocities measured by the ADCP were relative to the moving bed.

The DGPS and ADCP were synchronised together so that both were making the same spatial (GPS locations) and temporal measurements. This then enabled a comparison between the two. The slippage of the LAD (within the physical extent of drogue) could then be calculated between the upper limit of the LAD using the DGPS (height datum = 0 m) and the lower limit, using the first bin from the ADCP (height datum = 0.65 m (length of vane) + 1.89 m (blanking distance until first bin) = 2.54 m). Note a distance of 1.89 m exists between the physical extent of the drogue and the first bin. For the purpose of this study the water parcel lag was therefore defined as the distance the tracked water parcel moved (as measured by the first bin of the ADCP) relative to the LAD (as measured by the DGPS).

To determine the water parcel lag, the point of zero velocity (at slack water) had to be determined for both the DGPS (previously described) and the upper bin of the ADCP, and their difference calculated. For consistency, the DGPS readings, averaged at 5 second intervals were then averaged every 1.5 minutes to match the corresponding ADCP velocity outputs. An example of how the water parcel lag is determined for deployment A (in the temporal domain) is included in Figure 3 and depicts the LAD velocities derived from the DGPS, and the velocity from the first bin of the ADCP over the window period of 84 minutes. Slack water (as measured by the min DGPS velocity) is at exactly 42 minutes after deployment, as this was the centre from which the window period (of 42 minutes) was measured either side. A second order polynomial equation for the measured ADCP velocity (V) as a function of time (t) was fitted to the data and yielded in, with correlation coefficient, $r^2=0.67$. Note that for the other deployments the correlation coefficient was well above $r^2=0.67$. To find the minimum velocity for slack tide, the minimum (turning point) of the polynomial function was found, $t = (-b/2a)$, where t is time in minutes from deployment; b is -0.008 ; and a is 0.0004 . The ADCP derived time of slack water for deployment A was approximately 40 minutes after deployment, as measured by the ADCP giving a water parcel lag of two minutes. The distance can easily be calculated by applying a simple filter to change the time domain to distance.

Figure 4 shows the absolute water parcel lag (in the spatial domain) for deployments A, B, C, D and F, as a function of the total distance traveled. Note that deployment E cannot be compared or included in this figure, as the window period for this deployment is 20 minutes less than the others. As the window period was the same for each deployment and velocity was (essentially) symmetrical over the slack water axis, the tidal velocity during the study period was represented by the distance

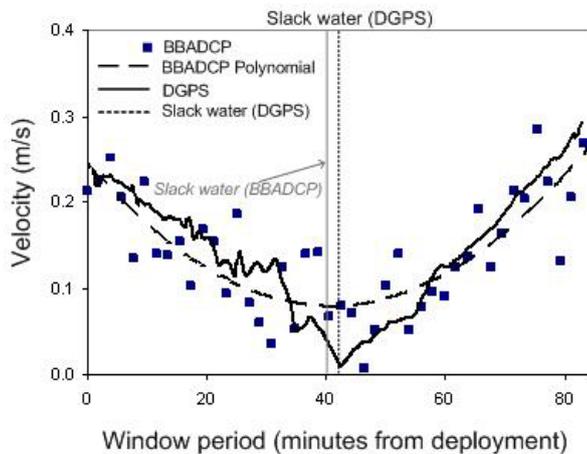


Figure 3. Determination of *water parcel lag* (slippage) for deployment A. Slack water is measured via the DGPS slack water, depicted by the dotted vertical line. A second order polynomial was fitted to the ADCP velocity and the minimum (slack water) was found at 40 minutes (grey vertical line). Deployment A had water parcel lag of 2 minutes.

the LAD travelled during each deployment. For example, during higher velocities the LAD traveled farther than during a lower velocity flow. A linear regression through the data points for each deployment revealed they are in extremely good agreement ($r^2=0.92$). The linear regression equation appears below.

$$y = 0.2x - 96 \quad (1)$$

Despite this level of correlation, it is interesting to note the deviation of deployment A, marked by data point (A). This point seems to be affected by the highest measured velocities (of this study) exhibited on this day, which suggests there could be a limitation of LAD water tracking capabilities at high tidal velocities. Note again that deployment E is omitted. The figure shows that water-tracking ability of the drogue is directly related to water velocity, and of course morphology. Thus, the faster the tidal velocity, the greater the water parcel lag.

Finding the LAD Vertical Limitation

The previous section demonstrated that the water-tracking ability of the LAD is directly related to the magnitude of the tidal velocity. Now the vertical (depth) limitation (outside the physical constraints of the LAD) of the LAD's ability to track a parcel of water in a Lagrangian fashion can be investigated. To achieve this, the ADCP has the advantage of measuring velocities at various depths within the water column at the same time.

The velocity difference between that of the first ADCP bin (located at a depth of 1.89 m) and every other bin (located every 0.25 m) was calculated and represented in Figure 5. This approach also enables us to investigate the presence of velocity gradients. This figure (Figure 5) shows a temporal and spatial representation of the velocity differences or slippage past the LAD (in ms^{-1}) for each deployment (labelled A – F). The 42-minute window period is shown either side of slack water, which is represented by a dashed line down the centre. Note that the range for velocity difference is only between 0.02 ms^{-1} and 0.22 ms^{-1} , and that the

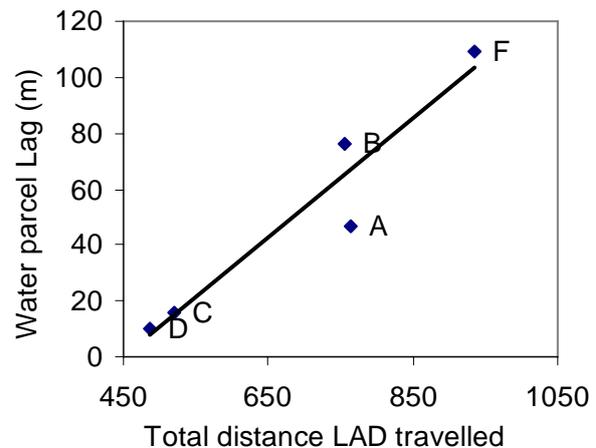


Figure 4. LAD water parcel lag in upper water column as a function of the total distance travelled during each deployment (A-F), with deployment E not included. A linear regression (marked by a solid line) agrees extremely well with the data points (correlation coefficient ~ 0.92). Note: This figure depicts the spatial domain so water parcel lag is defined as the absolute distance the tracked water parcel moved (as measured by the first bin of the ADCP) relative to the LAD (as measured by the DGPS).

theoretical velocity standard deviation from the initial configuration is 0.032 ms^{-1} .

Within each contour plot Figure 5a to f there are marked areas of increased velocity. Most of these areas (marked by a darker contour colour, i.e. darker than $0.02\text{--}0.07 \text{ ms}^{-1}$ depicted by the light grey shade) extend over the entire depth of the water column, showing that the LAD itself has moved synchronously with the tide. An example of slippage is shown in Figure 5d, where there is evidence of stratification (other than vertical) below 4.54 m. In this study, a marked change in velocity or demonstration of slippage was shown by a change of more than 0.15 ms^{-1} , depicted by the darkest contour plot shading.

Note the overall background shading of the contour plot, accounting for more than 85% of the entire figure, is light grey, which depicts a velocity difference of $0.02\text{--}0.07 \text{ ms}^{-1}$. This in itself suggests the drogue was moving in parallel with a single parcel of water (Lagrangian). Generally, deployments during ebb tides (B, C and E) have shown better water-tracking capabilities, more specifically within the upper 4-5 m. The CTD casts depict a vertically well-mixed water column with little to no salinity or temperature stratification.

In Figure 5, deployment B exhibits a velocity anomaly (or velocity slippage) after 80 minutes. When compared with the track of deployment B in Figure 3, it can be observed that the LAD is in close proximity to Mud Island; a shallow mangrove-dominant region with high bottom velocities.

Deployment D had a higher velocity difference compared with the other deployments, especially when in close proximity to the seabed (4.54 – 5.54 m). Deployment D was the only track that travelled along the same path for the flooding and ebb tide: depicting the lack of a developed axial convergence front. However, after 23 minutes into the window period, the LAD had

to be repositioned (only 10 m and still within our 30 m rule) as it was touching the boat. This caused the increased velocity anomaly between 23 and 27 minutes.

Whilst deployed less than 2 km apart in the same main channel, deployments C and F demonstrate the best water-tracking ability. This is shown over their entire depth profile, with velocities rarely exceeding the range of $0.02\text{--}0.07\text{ ms}^{-1}$ and high percentage of velocities existing within the range of $0\text{--}0.02\text{ ms}^{-1}$ (depicted by the lightest grey shade).

Figure 5 demonstrates the LAD's ability to flow in a Lagrangian

manner. It displays the spectrum of velocities and slippage observed from the perspective of the LAD. The similarity of these panels (each deployment) demonstrates the LAD's ability to consistently track a parcel of water under different tidal velocity conditions.

From the results, the Fitzroy River estuary is a vertically well mixed estuary with little to no stratification forced by the constant fresh-water source of the three sewage outlets or rainfall events. Due to the case of strong bottom velocities clearly exhibited in deployments B and D at a depth of approximately 4 m, a

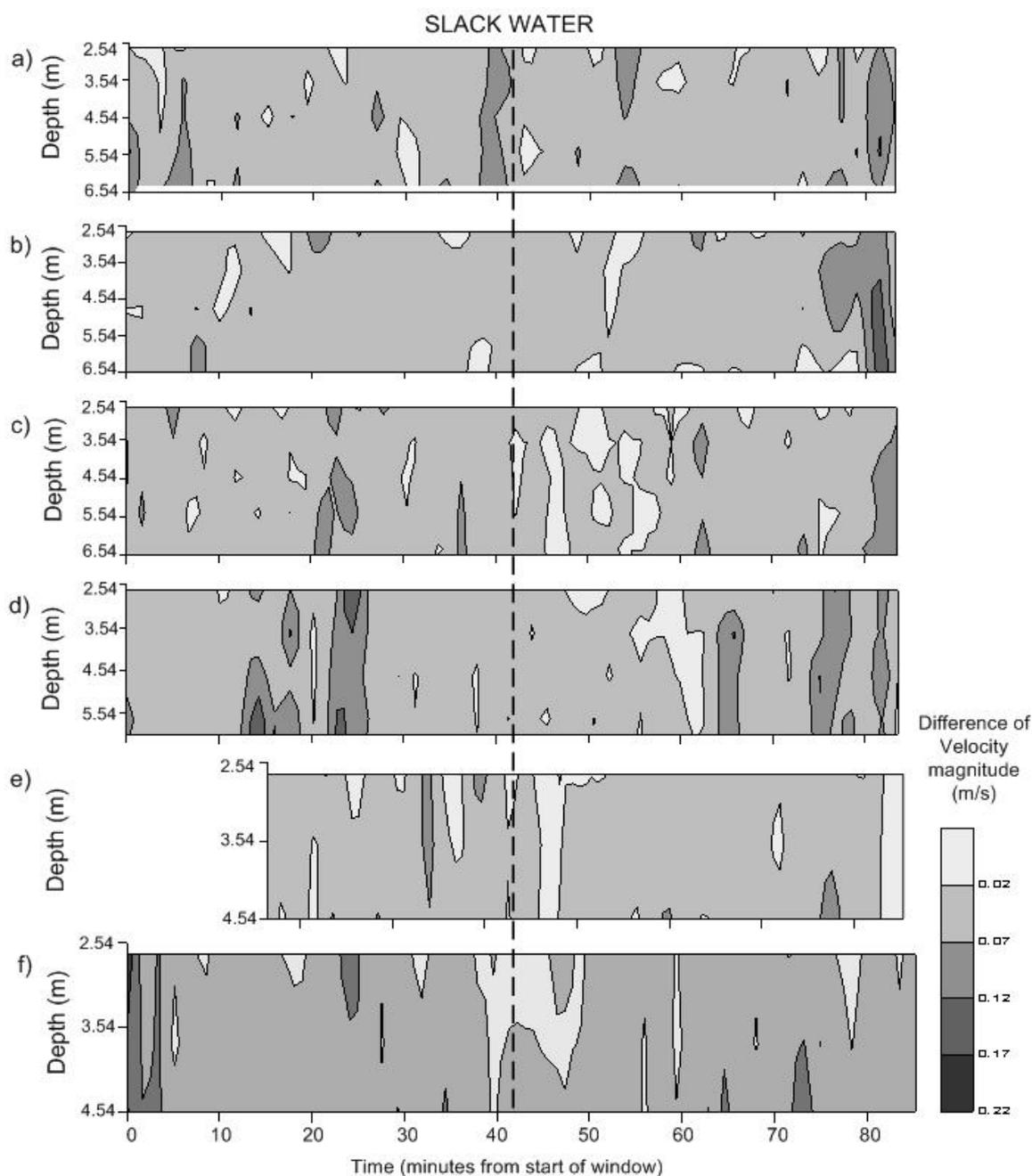


Figure 5. Deployment profiles (A – F) respectively, (a) – (f) of velocity difference (between that of the first bin and subsequent others) over the duration of the 84 minute window period. Note the time of *slack water* as measured by the DGPS is marked by the dashed line down the centre and in the middle of each deployment.

conservative 5 m was assumed to be the vertical limit of the tracked water parcel. This value is assumed applicable for the overall Lagrangian tracking ability of the LAD; for different tidal regimes.

CONCLUSION

This paper specifically investigated the ability of a novel estuarine device, the LAD to follow a parcel of water over time for the further and unique application of measuring SSC within a Lagrangian framework. The benefits of conducting sediment transport investigations through a Lagrangian framework is that direct settling measurements (without the complication of advected SSC) can be made as transport is naturally Lagrangian.

Ocean drifter studies, in particular NIILER et al. (2005) revealed the importance of quantifying and understanding errors such as slippage that affect the Lagrangian path of the drifter/drogue. From a number of experimental design and environmental variables, they attributed the greatest slip-producing force to be from wind. Using a similar criterion, but with a rigid and set drogue design and, in an environment of negligible wind conditions, we found the greatest slip-producing force in estuaries to be tidal velocity.

The LAD was deployed over the slack water period of three distinct tidal conditions and velocities for both the flood and subsequent ebb tide (or vice versa). We found that during all deployments the slippage was directly proportional to the velocity of the LAD. Thus, faster currents exhibited more slippage than slower currents. We then measured the extent to which the LAD measured a Lagrangian parcel of water. We found that as a holistic and conservative limitation over the variety of tidal velocities, the LAD follows a Lagrangian parcel to a depth of 4.5 m.

This investigation also gave us an insight into the preferred conditions (no wind) and logistical constraints for the deployment of the drogues in estuaries and led to the focus of night work for calmer conditions and less boat traffic. It has proved its capability to follow a parcel of water, and has also provided an insight into the flow patterns within the study site. It also revealed that during the three surveys, the Fitzroy River estuary was in a vertically well-mixed state, with no major velocity or density stratification. Until now, a Lagrangian ADCP drogue (LAD) has not been used to quantify its water-tracking ability within an estuarine system. This study has provided positive insight into the capability of drogues to follow Lagrangian parcels in the upper water column of estuaries.

Given the already wide application of ADCPs for flow velocity and now SSC measurements, this study demonstrates the need to further explore other methods of measuring sediment transport in the field, such as measurement via a Lagrangian framework.

ACKNOWLEDGEMENTS

The authors would like to thank our funding and support body – the CRC for Coastal Zone Estuary and Waterway Management, and the School of Engineering, Griffith University, for their use of facilities and equipment. A special thanks to our research team: Nathan Benfer, Adam Brook, Chris Scraggs and Ryan Dunn for their tireless efforts and ability to function without sleep for the duration of the study.

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