XVIIèmes Journées Nationales Génie Côtier – Génie Civil
Chatou, 2022
DOI:10.5150/jngcgc.2022.102 *© Editions Paralia CFL*
disponible en ligne – http://www.paralia.fr – available online

Field velocimetry for sediment transport studies in water and air

Callum GRAY [1], Christy SWANN [2], Joe CALANTONI [2], Blake LANDRY [2], Carlo ZAMALLOA [2]

1. LaVision Inc, Ypsilanti, MI, USA.
   callum@lavisioninc.com
2. Ocean Sciences Division, Naval Research Laboratory, Stennis Space Center, MS, USA.
   christy.swann@nrlssc.navy.mil; joe.calantoni@nrlssc.navy.mil; Blake.Landry@nrlssc.navy.mil; Carlo.Zunigazamalloa.ctr.pe@nrlssc.navy.mil

Abstract:
Rates of sediment transport predicted by models differ significantly from field observations in both aeolian and underwater environments. Refinement of predictive models requires high quality ground truth data to discern if the discrepancy between models and field observations lie in a given model's ability to properly represent the physics of motion, or if our field observations are inadequately sampling the sediment transport process. Identifying the sources of error can only partially be achieved in a laboratory wind tunnels or wave flumes. The limited length and scale of turbulence recreated in wind tunnels do not follow those of natural boundary layer conditions that exist on a windy beach. Similarly, wave amplitudes and spectral content resulting in seabed sediment transport can only be recreated in limited scope in a wave flume or oscillating water column. Ruggedised point measurement tools are available for measuring fluid velocities in a field environment but are of limited spatial and temporal resolution. Here we describe the adaptation of two high resolution full field velocimetry techniques that fully transition laboratory methods to quantify sediment transport by wind and waves for use in field environments. To measure subaqueous sediment transport, we developed a Stereo Time Resolved Particle Image Velocimetry (SPIV) system that utilizes submersible enclosures for remote operation in an undersea environment at depths of up to 15 meters for a period of several weeks. The system was deployed off the coast of O'ahu near the Makai Research pier. To measure sediment transport by wind in a natural boundary layer, we developed a Time Resolved Volumetric Velocimetry system based on Shake-the-Box 4D Particle Tracking (STBPT). We deployed this system on a secure beach at NASA Wallops Flight Facility in Wallops Island, Virginia. Adapting valuable and sensitive equipment to measure sediment transport by waves and wind in an outdoor environment presents substantial technical and logistical challenges. This paper will describe the two systems mentioned above including design considerations, technical

innovations, experiences gleaned from the measurement campaigns and examples of data obtained.

Keywords:
Sediment transport, Aeolian, Maritime hydraulics, Stereo PIV, Shake-The-Box particle tracking, Maritime works, Coastal environment, Coastal ecosystems.

1. Introduction

There are certain advantages and disadvantages associated with making experimental measurements in the field versus the coastal Engineering laboratory. The first and most obvious is that in the field you experience "real" phenomena which incorporates all the subtle nuances of the real world that cannot be easily or sometimes ever reproduced in the laboratory. At local scales (near field) it is typically straight forward to reproduce magnitudes of velocity that are of the same or very similar magnitudes of velocity observed in the field. However, what cannot be reproduced is the "far field" physics. We cannot, for example, simulate the modulation of energy from short period waves to infragravity waves with periods of the order of minutes. Additionally, in the lab everything is "unidirectional" whereas in the field directions are oscillating all the time and there is a directional spectrum. Also, complex sedimentology beyond a mean grain size and local geology cannot be reproduced in the lab. On the other hand, the range of conditions that can be sampled in the field is limited by the prevailing weather occurring across the time window available. Also, one cannot rely on conditions remaining stable to collect statistically convergent data and real-world conditions may be much more complex than a deliberately simplified lab experiment. For these reasons it can be much more difficult to develop "theoretical" or more easily generalizable knowledge from field measurements. Lab based experiments are much better suited to theoretical studies and for isolating one or two processes to determine their respective impact on the outcome. Lab experiments are less expensive to perform, can be repeated many times and are better suited to numerical modelling to close the picture. In the lab you can essentially know everything. All details and boundaries etc whereas in the field it is impossible to know everything that may influence your results. In our experience working in the field is usually necessary when you have a very specific application that is be explored or developed.

The rest of this paper describes two separate field deployed velocimetry systems that have been adapted directly from laboratory-based equipment originally implemented in the costal engineering lab of the Naval Research Laboratory at the Stennis Space Center.

The first system to be implemented was a Stereo Time Resolved PIV system (ADRIAN & WESTERWEEL, 2011; RAFFEL *et al.*, 1998) designed to operate at sea depths of 10-15 meters and at distances from shore of up to 1.5km. The system is self-contained requiring only a 300V DC power source and optical fibre to communicate to shore. The

cameras, light source and control system were protected from the undersea environment by mounting into heavy duty enclosures with windows which themselves were mounted under a rotatable plate which was supported under a "quadpod". The orientation of the stereo light sheet could be selected to suit the prevailing wave direction. The system was deployed off the coast of O'ahu near the Makai Research pier during the summer of 2018. The design and implementation of the system started in 2016.
The second project that brought a traditionally laboratory technique into the field was a volumetric velocimetry system based on the Shake-The-Box 4D particle Tracking method (SCHANZ *et al*., 2016). The system was deployed on a secure beach on Wallops Island Virginia in October 2021 and designed to measure with high spatial and temporal resolution the turbulent boundary layer across the beach with the aim of understanding the relationship between the aerodynamic flow field and the "streamers" of saltating sand. Here again the system was designed to be resistant to the environment and allowing it to be utilised for extended periods of time (weeks).

2. Implementations

2.1 Underwater Time Resolved Stereo PIV System

The motivation for this project is to provide high-fidelity, laboratory-type measurements of the seabed 2D 3C velocity field and sediment motion across a representative range of real ocean conditions. The intention is to gain a more complete understanding of how near bed turbulent fluctuations initiate the mobility and burial of unexploded ordinance (UXO) and to calibrate and validate predictive models. The Imaging System for Littoral Environments (ISLE) was developed at the US Naval Research Laboratory and is a ruggedised Time Resolved Stereo Particle Image Velocimetry mounted under a quadpod along with other optical, electronic, and acoustic sensors. To facilitate long term deployment of up to one month ISLE was cabled to, and operated from, the shore. Repeat dive operations were conducted to provide in-situ maintenance. This includes mitigation of biofouling and to position and reposition different types of UXO in the test area. Particle Image Velocimetry (PIV) is a well-known technique for flow mapping and has been used extensively in the lab for this purpose. The principles of PIV are well documented (ADRIAN & WESTERWEEL, 2011; RAFFEL *et al*., 1998) and will not be covered here. The requirement for 3 components of velocity requires Stereo PIV (SPIV) necessitating the use of two cameras. Several wave periods of >10 seconds were to be acquired at a frequency sufficiently high to capture the characteristic timescales of the flow across a range of real ocean conditions. High Speed CMOS cameras were used to capture the stereo images and a scanned CW laser was used to illuminate the region of interest. The combination of high frame rate CMOS cameras and continuous scanning permits acquisition frequencies up to 3.5 kHz though in practice lower frequencies were sufficient to capture the temporal features of interest. The desired field of view was 1.2

meters wide and approx. 50cm high. Wide enough to simultaneously image several sand ripples and high enough to capture the flow structures from the interaction between bed ripples and wave/current. Another important consideration is that the submerged components should not impede or modify the flow field being studied and should have a small profile to minimise drag on the structure. The enclosures were designed to be deployed for extended periods of time in sea water to resist biofouling and be capable of tolerating a range of temperatures from a hot ship deck to cold under sea conditions.
The concept that was developed is based on the use of four separate watertight enclosures containing the cameras, the light sheet generator and the control enclosure that contains an embedded PC, Timing Unit and power supply. These four enclosures are rigidly mounted to a circular metal plate which itself is mounted under a "Quadpod". A schematic of the whole system is shown below in figure 1.

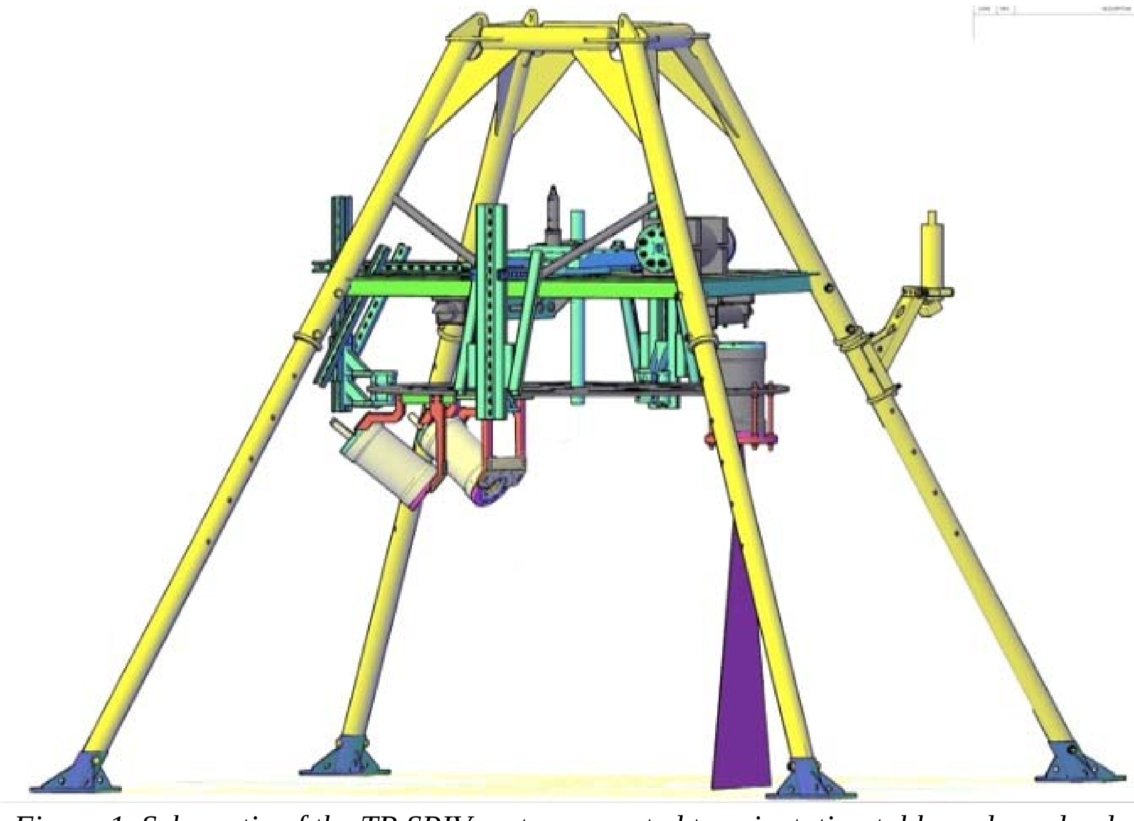

Figure 1. Schematic of the TR SPIV system mounted to orientation table and quadpod.

As can be seen the two camera enclosures are mounted looking down at the measurement area and inwards providing a stereo angle. The scanning light sheet enclosure is mounted vertically projecting the laser sheet downwards to the seabed. The "control" enclosure is mounted on the top shelf and provides power, timing and a data interface to the camera and laser enclosures. The positioning of the camera and laser enclosures are high enough above the bed to avoid modifying the flow being measured.

2.1.1 Camera Modules

All the enclosures were designed and built by Proteus Technologies from Slidell, LA and were of similar design to reduce complexity of manufacture.

Enclosure material: Machined aluminium bronze alloy C955. This material is of the order 90% copper which is toxic to living organisms, and this reduces biofouling which is a problem when submerged in sea water for extended periods of time. The mechanical strength of the enclosures without a glass window would have permitted use at depths of 1000 meters. However, the pressure rating of the housings with the quartz window recessed into forward end caps and glued was 50 meters with failure at 150 meters. This far exceeds the target depths of 10-15 meters. The bronze material also has reasonable thermal properties to conduct heat.

Enclosure Design: The smallest possible cylinder diameter was used to reduce drag. The fore and aft end caps were designed to incorporate double o Rings. This is based on a past design and used many times to submerge other kinds of instrumentation (acoustic) to significant ocean depths.

The cameras (VEO340L Vision Research) were fitted with 50mm f1.8 Canon lenses with remote focus and aperture control. The Scheimpflug angle was calculated for the orientation of the cameras relative to the light sheet. A "compound" Scheimpflug angle is used to tilt the focal plane of the camera looking inward and downwards. This compound angle is used when the stereo viewing angle is not just in the horizontal plane bit also in the vertical. Due to the remote aperture and focus it was not possible to incorporate an adjustable Schiempflug adapter and so a fixed angle device was designed that could fit between camera and lens without increasing the lens sensor distance and so the full range of focussing including infinity was preserved, figure 2.

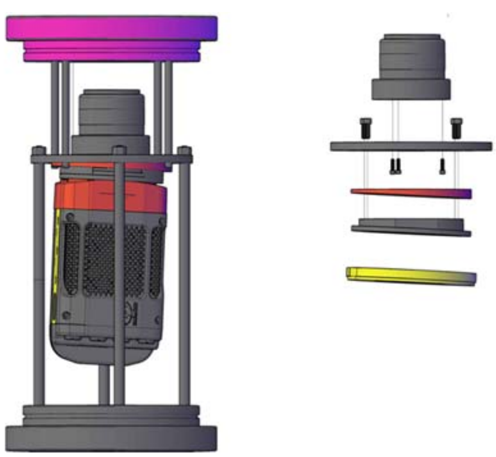

Figure 2. Fixed angle Schiempflug adapter.

The non-window end caps all had “pass-through” connectors that completely seal the enclosures but permit the required lines for power, triggering and data. The connectors were Subconn underwater mate able connectors apart from the fibre umbilical going into the control enclosure and that was GISMA fibre/copper connector, figure 3.
To avoid condensation of trapped humidity within the enclosures when sealed and put into cold water the enclosures were evacuated to low pressure and then backfilled with dry nitrogen. Humidity sensors were installed in all encloses to detect water ingress.

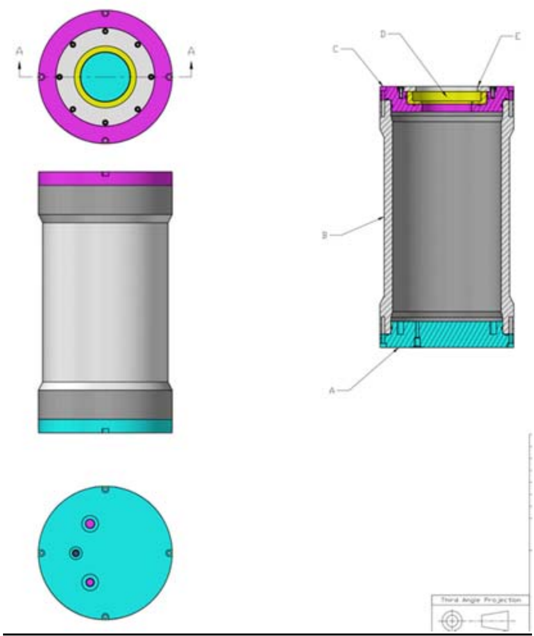

Figure 3. Camera enclosure showing the cylinder, end caps with pass through connectors and window.

2.1.2 Laser Module

As mentioned, the laser sheet system was based on a scanned CW laser beam from a CW YAG laser module outputting >6 watts at 532nm. Laboratory based PIV systems have the benefit of laboratory infrastructure specifically including access to ready cooling. Most PIV systems utilize a pair of flashlamp pumped, q-switched, frequency doubled laser cavities that typically generate 100-200mJ of energy in pulses of < 10ns duration. These kinds of lasers are efficient but require a considerable amount of active cooling which is provided in the lab by a water to air or water to water chiller. Additionally, the need for active water cooling adds bulk to the laser head. The solution to this is to use a laser that is compact, has only one cavity, does not require active cooling and coincidentally is a fraction of the cost of a double cavity pulsed PIV laser. We used a 6.51W (measured) DPSS CW YAG laser. This is possible for relatively low velocity flows by using the scanning beam method (GRAY *et al*., 1991). The scanning beam light sheet was developed for wave studies and is known to work for significant fields of view up to 1 meter so long as the maximum velocities are in the range of a few m/s. This approach would not be suitable for higher velocities or PIV in air but in this case permits a very compact light sheet with repetition rates up to 3000 scans per second. In the actual trial of the system scan rates < 1kHz were used and so well within the operating range of the system, figure 4.

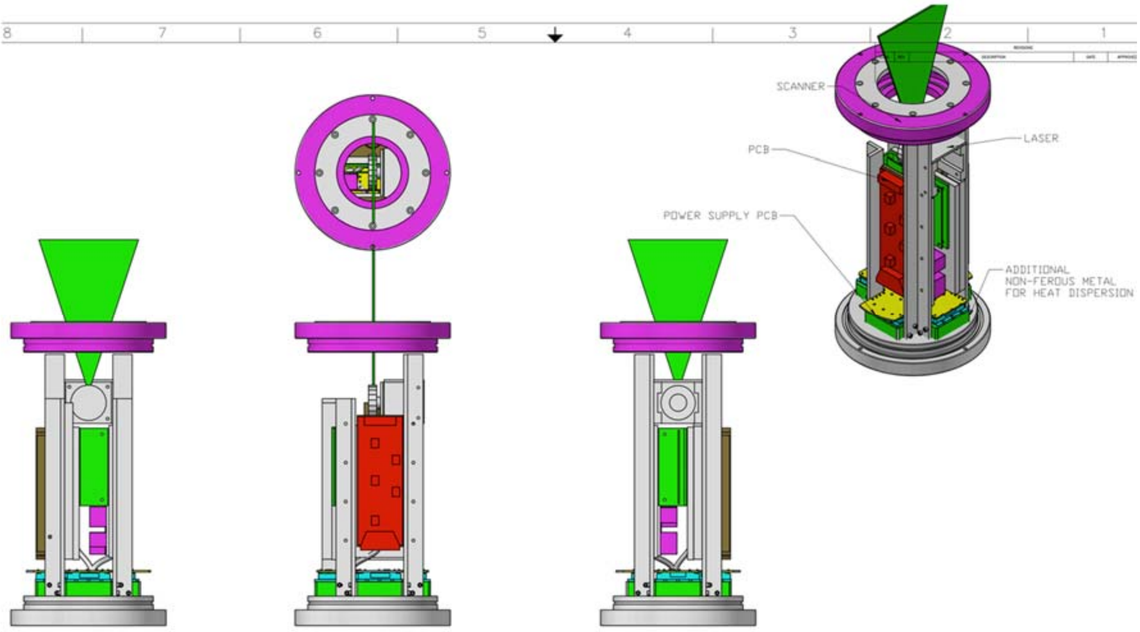

Figure 4. Laser sheet enclosure showing laser, 20 facet scanning mirror and driver.

2.1.3 <u>Control Module</u>

The control module contains a host PC (embedded compact PC), a timing unit (LaVision PTU X) which had been extracted from its enclosure, a “smart” power supply that takes 300V DC and converts to 24V, 12V, 8V to suit the requirements of the cameras, remote lens control, humidity sensors, laser, scanner, PTU X etc. The power supply has a controller that has a software interface that is used to control and monitor the power supply and ensures that the laser is not turned on until the scanner mirror is spinning. This avoids burning the mirror surface. The controller also provides feedback of the internal temperature of the enclosures from a thermocouple in each. Even though the heat generated by the CW laser was not great it was automatically switched off between runs as extended use would trip the lasers own temperature interlock. To increase passive cooling of the laser the base of the laser was connected to a metal bridge to the inside surface of the enclosure. Thermal conductivity was enhanced by using a thermal paste between laser base and heatsink, figure 5.

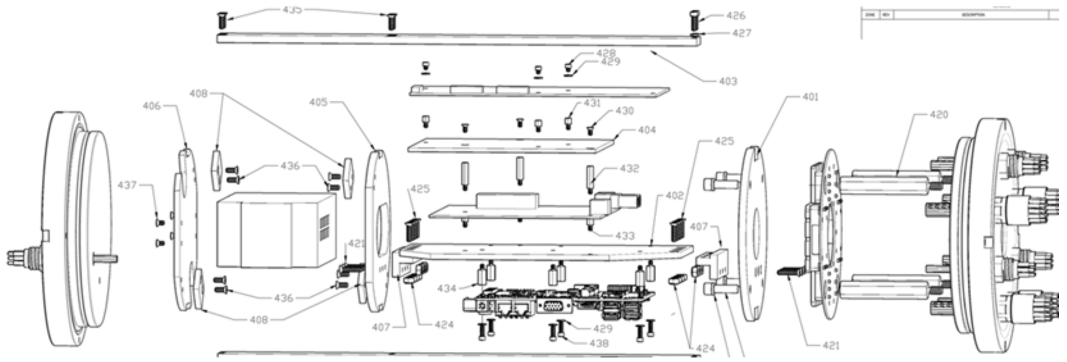

Figure 5. Control enclosure showing embedded PC, Timing unit (PTU X), power supply and control electronics board.

2.2 <u>Deployment</u>

The system was assembled at Stennis Space Centre in Mississippi where the Naval Research Laboratory have facilities and subjected to several tests concluding with a full immersion test. Once the integrity of the cannisters was confirmed the system was initialized and started acquiring images. The outdoor tank shown in figure 6 was seeded with 20-micron polyamide spheres and an induced circulation flow in the tank measured after performing a stereo calibration. This test confirmed that cameras, laser, and scanner were all operating as expected without overheating and that the embedded PC could be accessed by remote desktop via the 1500 meters fibre optic ethernet cable.

Figure 6. Immersion test of system at Stennis Space Center.

Following these tests made in March 2018 the system was disassembled and packed for shipment to the Makai Research Pier on the island of O'ahu, figure 7. In July 2018 the system was assembled under cover of the pier building. An electronics test was performed to ensure everything is operating correctly tested and then lowered into the sea through the removable floor of the pier.

Figure 7. Makai Research Pier O'ahu.

The quadpod was fitted with several flotation balloons that rendered the quadpod neutrally buoyant in the sea water. With the quadpod suspended under the pier and maintained in position by the pier crane it was left for several hours with the cameras and the laser operated periodically. The humidity sensors in the cannisters were monitored to verify that everything was watertight. A minor leak in one of camera cannister was detected after some time. The quadpod was lifted out of the water and the suspect cannister removed inspected, figure 8. A crack had developed in the glue that held the quartz window in place. This was repaired and the same "dunk test" performed and this time everything checked out. When no water ingress was detected after 8 hours in the water the system was left submerged under the pier overnight but monitored by a researcher from the remote desktop overnight just in case a leak developed again.
The next morning a team of divers manoeuvred the quadpod out from under the pier and out into open water to the test location. The Makai research pier was selected because it was a secure location with facilities well adapted to these kinds of activities. However, the pier is also located near to protected sea life and because we were using a class 4 laser

it was a requirement that the quadpod be fitted with 360-degree colour cameras that could be used to detect any protected species that may come close to the test site, figure 9.

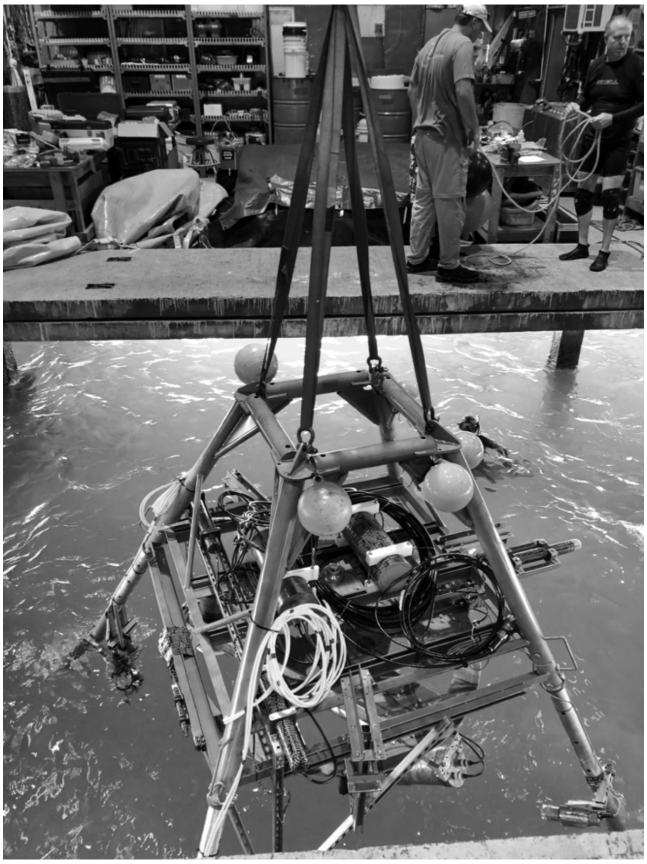

Figure 8. The quadpod being lowered into the sea through the removable floor of the pier.

At this point we were able to start operating the system. A piece of decommissioned ordinance (a shell) was placed under the quadpod in a position that the laser sheet intersected. Divers positioned a 3D calibration target in the plane of the laser sheet and the system was calibrated. In a lab-based PIV experiment seed particles will be added to the fluid. In air an aerosol of oil or helium filled soap bubbles will be used to provide neutrally buoyant tracers. In water seed particles made from glass or polyamide are commonly used. In many cases the particles will be fluorescent to be used with high pass filters on the cameras to exclusively image the particles and improve image quality for PIV processing. However, in the sea it is not practical to artificially seed the flow. Sea water contains a relatively high density of naturally occurring suspended particles which we anticipated would be sufficient for PIV. Operating the system while suspended under the Makai pier it was confirmed that a sufficient number density of particles was present and visible. The laser scanner was operated at scan rate of 330 scans per second. This gives a PIV delta T of just over 3ms and resulted in particle displacements of around 8-10 pixels.

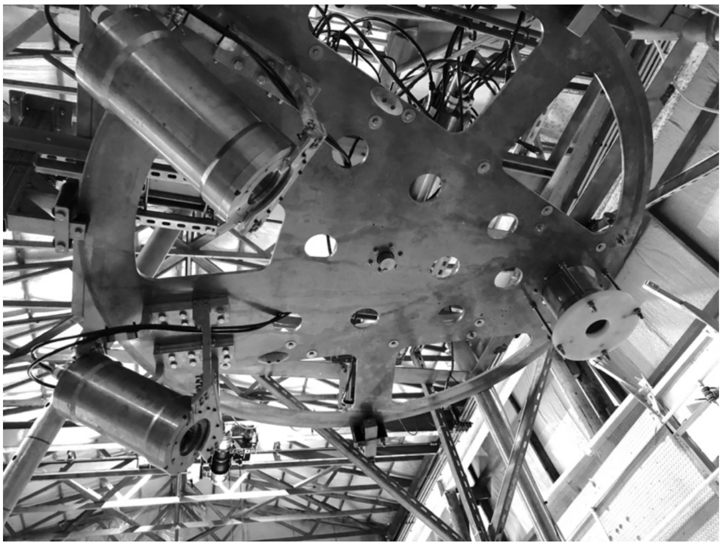

Figure 9. Camera and laser cannisters mounted under the quadpod on rotation table.

Stereo PIV Images were acquired to the memory of the CMOS cameras and when the 18Gigabytes of memory in each camera was full the sequences were downloaded to a networked disk for processing offline. The TR SPIV image acquisition and processing was performed from DaVis 10 with Stereo PIV processing module (LaVision GmbH). Image quality was considered good with contrast of nearly 1000 counts between particle images and background. Measurements taken during the middle of the day when the overhead sun was brightest tended to lose some contrast. Band pass filters on the camera lenses (532nm +/- 10ns, 95% transmission) were used to reduce most of the background ambient light. Most conditions of interest tended to be in the evening or at night in which case the background light was no issue.
Figure 10 below shows an example of the velocimetry data measured with the system. On the right shows the velocity field over a pair of sand ripples with vorticity as the colour code. The legend on the right shows the relationship between colour and vorticity magnitude

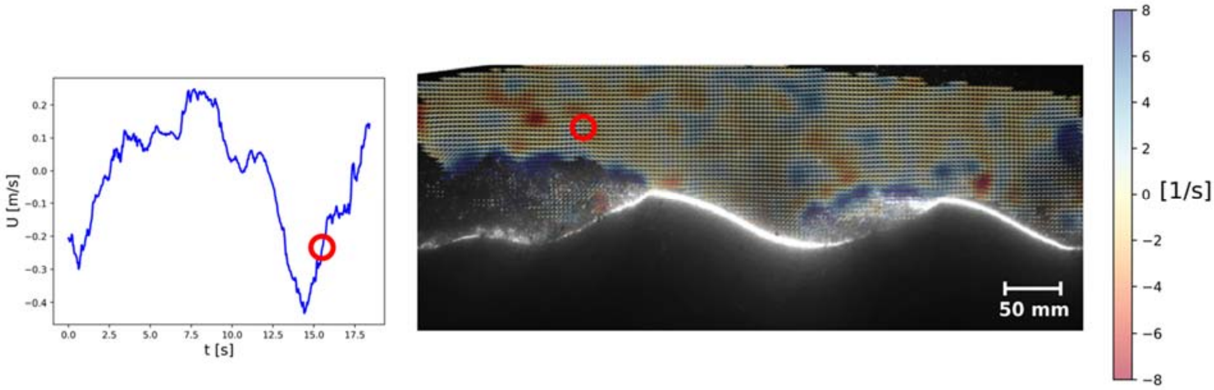

Figure 10. Example velocity plot acquired from ISLE showing vorticity as colour and on left a temporal trace taken from one point in the imaged field of view.

2.3 Aeolian Volumetric Velocimetry System

Existing aeolian transport models often fail in field environments. The discrepancy between models and prediction has been attributed to inadequate field measurements and uncertainty in the fundamental processes (turbulence) driving sand transport. The main challenges of measured and modelled aeolian transport include:

1) Coarse resolution measurements relative to the fluid -grain scale physics
2) An inadequate understanding of the fundamental physical relationship between turbulence and sand transport
3) The inability of aeolian transport models, derived from wind tunnel observations, to simulate natural boundary layer processes at the appropriate field scales (mm-cm)

The Field based Particle Tracking Velocimetry (F-PTV) system was developed at the Naval Research Laboratory (NRL) to address these challenges. Prior measurement techniques integrate over sample volumes on the order of cm to tens of cm and often cannot be placed in the saltation cloud. For example, ultrasonic anemometer. Or, in the case of cup anemometer, has a response time that precludes sampling turbulence at the relevant timescales. Also, these kinds of instruments measure turbulence at a point and as such as incapable of adequately sampling the spatial and temporal fluctuations and lags that cause turbulence induced transport.

The F-PTV system is based on components that are previously exclusively used in a laboratory and acquired images processed using the LaVision Shake-The-Box (STB) particle tracking algorithm. A detailed description of the STB method will not be given here (SCHANZ *et al*., 2016) though a general overview is helpful. Neutrally buoyant tracers are injected into the flow and illuminated by a pulsed light source to render the flow visible as with PIV. Unlike conventional PIV though a volume rather than a plane is illuminated. The light source pulses repeatedly and 4 high frame rate cameras synchronised with the pulsed illumination capture a sequence of images of the scattered light. The 4 cameras are calibrated using a flat dot target so that positions in the measurement volume can be accurately related back to positions on each of the 4 camera sensors. The camera mapping functions that are generated from the calibration images are further refined using a technique called Volume Self Calibration (WIENEKE, 2008) which uses the experiments data images to "tune" the mappings so that particle locations can be determined to better than 0.1 pixel. The Shake the Box (SCHANZ *et al*., 2016) algorithm uses the data images to triangulate particle positions in the real world from the 2D pixel images. The 3D coordinates of found particles are iteratively processed into trajectories which may then be converted from Lagrangian trajectories into a Eulerian grid of vector values. A simple but fast binning method can be used to re-grid the data, or a more sophisticated approach uses a 4D solver to come up with a solution constrained by the known trajectories. This is called Fine Scale Reconstruction (JEON *et al*., 2022) and is based on a solver called VIC#.

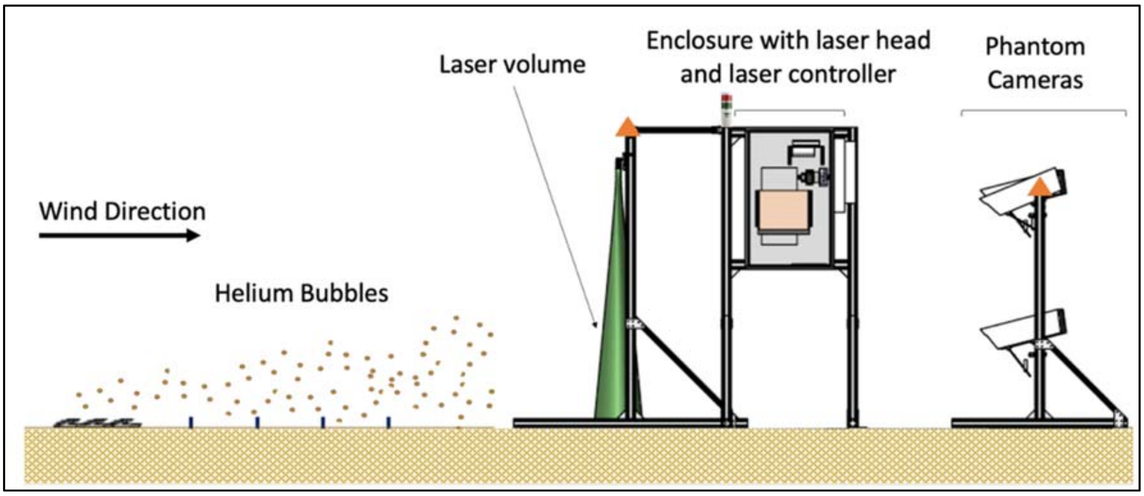

Figure 11. Schematic of the field PTV system showing Helium Filled Soap Bubble Generator (HSFBG), gantry with optical fibre fed volume optics and mounted cameras.

Figure 11 shows a schematic of the F-PTV system. Artificial seeding is injected into the flow upwind of the measurement system. The tracers drift through the measurement station which is a gantry from which the illumination is projected down to the beach The light scattered by the tracers is imaged by an array of 4 high speed cameras looking upwind at the illuminated seeding plume. The system is not completely non-invasive but minimally so.

The seeding system used was a LaVision Helium Filled Soap Bubble Generator (HFSBG) (FALEIROS *et al.*, 2019) which generates 230-micron helium filled soap bubbles. At this specific size they are neutrally buoyant and have the primary advantage for this application that they are large and scatter approximately 10,000 X more light intensity than the aerosol commonly used in wind tunnels. The HFSBG consists of a controller with a soap reservoir which is connected to Helium and Nitrogen tanks. The controller ensures the correct pressure and flow rate of soap, He and N2 is maintained to generate the bubbles and 40,000 are produced per second from each nozzle. There are 20 nozzles per linear nozzle array (LNA) and as many as 10 linear nozzle arrays can be supported from one controller, figure 12. For the tests at Wallops Island 3 LNA's were used. A custom case was designed to protect the controller from sand and salt. To avoid the LNA from altering the flow being measured the LNAs were laid sideways into wooden boxes which were lowered into a trench dug into the sand up wind of the gantries.

Figure 12. Helium Filled Soap Bubbles being generated from Linear Nozzle Array.

Pulsed illumination is provided by Diode Pumped solid state YLF laser (Photonics Industries DM Dual head YLF). The laser is a sensitive instrument and is protected from the elements by mounting into a weatherproof cabinet along with the other sensitive components such as the timing unit (LaVision PTU X HS) and the fibre optic beam launch optics. The cabinet itself was mounted onto the side of the gantry (see figure 13) that supports the volume optics and the other pieces of instrumentation such as cup anemometers, sonic anemometers, moisture probes, saltation sensors and saltation traps. The instrument gantries are shown below in figure 13. The main gantry mounts the laser volume optics and the other probes mentioned. The camera gantry provides a rigid platform for the cameras. The cameras are protected from the sand, salt, and rain by camera enclosures like those used for outside video surveillance. Extra vents were installed in the back of these enclosures to enhance cooling of the cameras. Each camera was fitted with the same remote focus and aperture controllers as used in the underwater PIV system described in the first section. This permits control of focus and aperture on the lenses of the enclosed cameras.

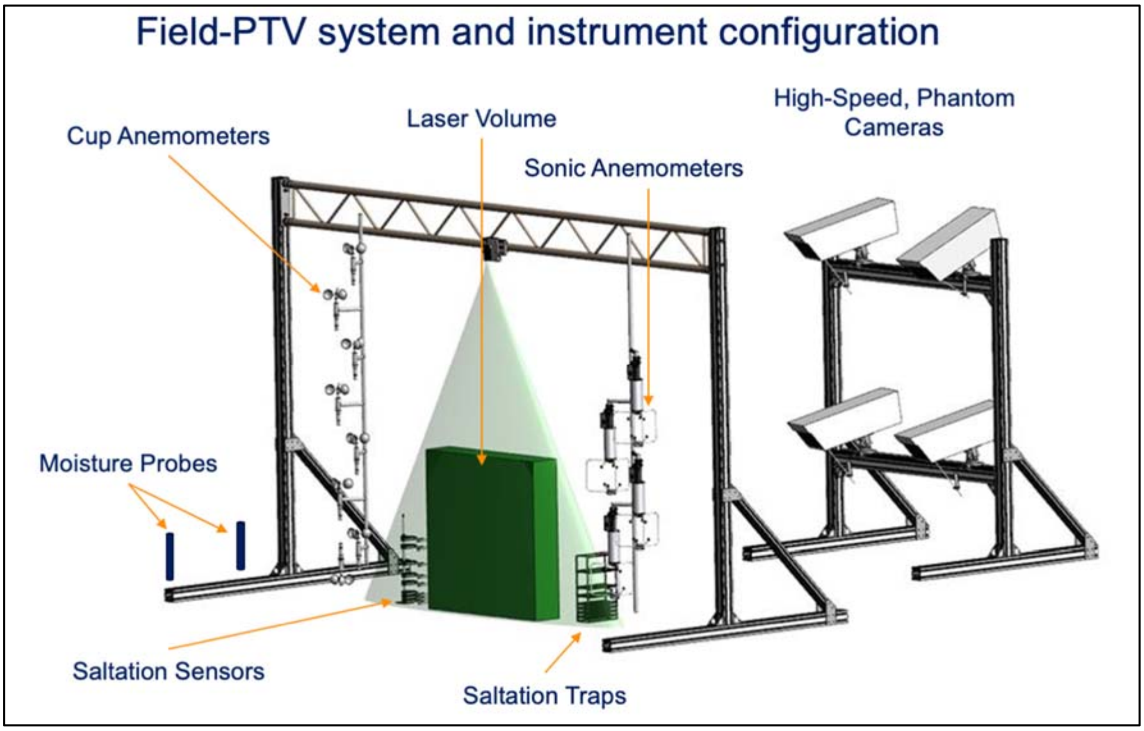

Figure 13. Schematic of the Field PTV System layout.

The cameras are VEO340 L CMOS high frame rate cameras from Vision Research. A 1-meter x 1-meter calibration target was mounted along the mid-section of the illuminated volume and used to generate camera mapping functions for each of the 4 cameras. Once the standard calibration was captured then a test series of images of helium bubbles was captured and used to perform volume self-calibration. Volume Self-Cal is used to enhance the accuracy of the mapping functions down to below 0.1 pixel required for reliable detection and tracking of the 3D bubble trajectories.

Figure 14. Picture of the F-PTV system on the beach at Wallops Island. Weatherproof cabinet shown on right attached to the instrumentation gantry.

The F-PTV system was deployed at NASA Wallops Flight Facility on the eastern shore of Virginia from September 29^{th} through October 28^{th}, see figure 14. The instrument gantry was located approximately 6 meters shoreward of the of the base of the dune and 20 meters from the shoreline. Initially, the system was operated to test for the optimal locations of the HFSBG LNAs to distribute the helium bubbles. LNA locations turned out to be a critical parameter for successful seeding of the measurement volume. Changes in wind direction sometimes required relocation of the LNAs and if operated at night required some choreography. Future measurement campaigns will benefit from having more LNAs and having them more closely spaced and across an arc upwind of the measurement station. With the limited LNAs available at the time many of the captured image sequences had inhomogeneous seeding giving dense results in some location and times but infrequently uniformly seeding the whole imaged volume. A range of conditions were sampled and some of those required operating at night. Data captured at night-time had the advantage that less image pre-processing was required to remove the bright background scene captured during the day. Work is ongoing to process all the data captured and to contextualize it with the other data sets sampled at the same time. An example of the trajectories and the remapped Eulerian data is shown in figures 15 and 16.

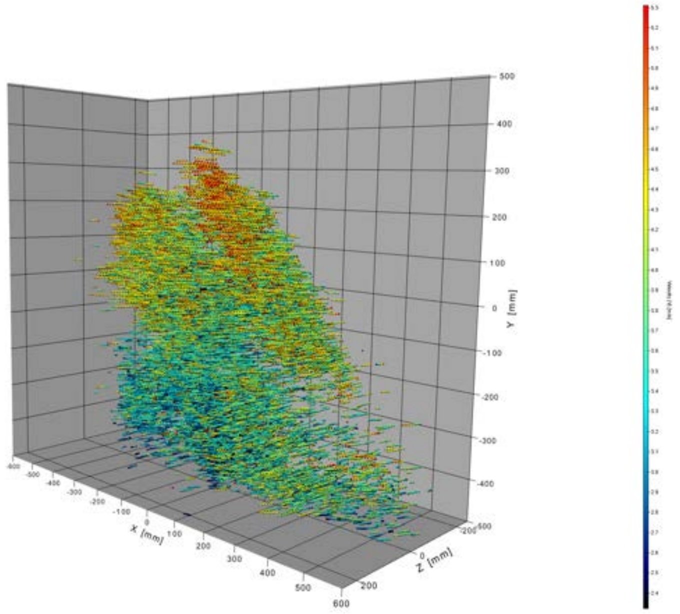

Figure 15. Example map showing trajectories across much of a 1 m x 1m x 40cm volume.

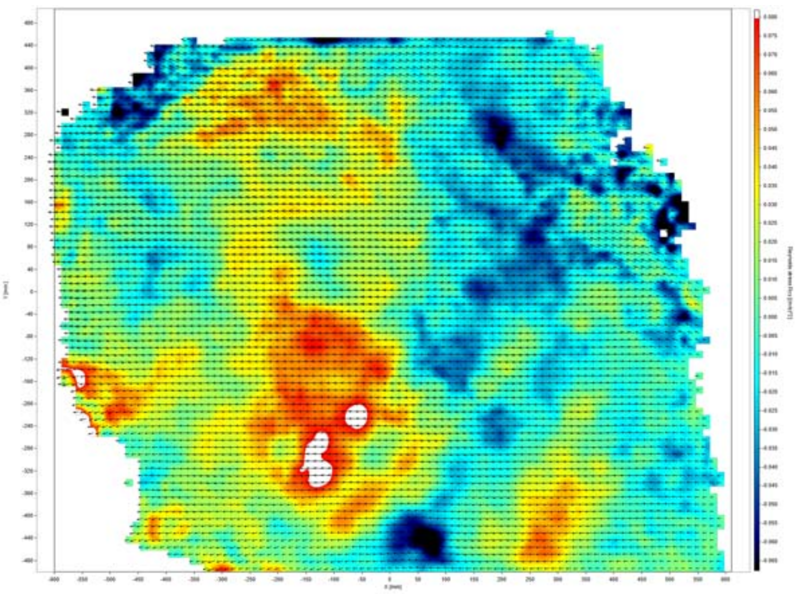

Figure 16. Lagrangian trajectories remapped to Eulerian grid showing central plane within the measured volume.

3. Conclusions

The two examples of field velocimetry systems show that laboratory techniques such as PIV and 4D PTV can be taken into the field and implemented to obtain laboratory like results. The trials performed in Hawaii and Virginia will serve as templates for future campaigns. Insights obtained from these initial trials will help guide future field exercises both in terms of optimising the measurement systems as well as guiding what conditions are of prime interest.

4. References

ADRIAN R.J., WESTERWEEL J. (2011), *Particle image velocimetry*, Cambridge University Press, New York, 558p. ISBN:9780521440080 and 0521440084

RAFFEL M., WILLERT C.E., KOMPENHANS J. (1998). *Particle image velocimetry – A practical guide*, Springer, Berlin, 255p. https://doi.org/10.1007/978-3-662-03637-2

GRAY C., GREATED C.A., MCCLUSKEY D.R., EASSON W.J. (1991). *An analysis of the scanning beam illumination system*, Meas. Sci. and Techno., vol. 2, no 8, pp.717-724. https://iopscience.iop.org/article/10.1088/0957-0233/2/8/003

SCHANZ D., GESEMANN S., SCHRODER A. (2016). *Shake-The-Box: Lagrangian particle tracking at high particle image densities,* Exp Fluids, 57:70, https://doi.org/10.1007/s00348-016-2157-1

WIENEKE B. (2008). *Volume self-calibration for stereo PIV and tomographic PIV*, Exp Fluids, 45:549–556. https://doi.org/10.1007/s00348-008-0521-5

JEON Y.J., MULLER M., MICHAELIS D. (2022). *Fine scale reconstruction (VIC#) by implementing additional constraints and coarse-grid approximation into VIC+,* (2022), Exp Fluids, Vol. 63, Issue 4. https://doi.org/10.1007/s00348-022-03422-9

FALEIROS D.E., TUINSTRA M., SCIACCHITANNO A., SCARANO F., (2019). *Generation and control of helium-filled soap bubbles for PIV*, Exp. Fluids, Vol. 60, Issue 3. https://doi.org/10.1007/s00348-019-2687-4