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16. ABSTRACT

This research project designed, built, and deployed a bathymetric survey system with Multi-Beam Echo Sounder (MBES) and Acoustic Doppler Current Profiler (ADCP) sensors for scour, Rock Slope Protection (RSP), and underwater riprap installation monitoring. Bathymetric data provides a preview of conditions and depths for Caltrans divers to plan their dive and supports underwater excavation for RSP installation. Moreover, this project experimented with an Unmanned Aerial System (UAS) based Large-Scale Particle Image Velocimetry (LSPIV) as well as topographic mapping with UAS aerial images using OpenDroneMap (ODM) and WebODM software. This report documents the experiences and lessons learned from deploying UAS to capture video for LSPIV processing. The bathymetric, topographic, and LSPIV data are also vital in hydraulic modeling using Surface-water Modeling System (SMS) software.

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Development of Data Collection Systems for Large-Scale Particle Image Velocimetry (LSPIV)

Kin Yen &
Dr. Ty A. Lasky: Principal Investigator:

Report Number: CA21-3183
AHMCT Research Report: UCD-ARR-21-06-30-01
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June 9,2021

California Department of Transportation

Division of Research, Innovation and System Information

Executive Summary

Problem, Need, and Purpose of Research

To calibrate hydraulic models used for bridge scour analysis and design, it is necessary to collect information about the flow characteristics of a river during flood events. However, using a manned boat can be difficult and time consuming to deploy. Deploying instruments from a bridge deck can also be challenging and may require lane closure due to space constraints.

A new method is needed to measure discharge, collect flow velocity (magnitude and direction) information at the water surface, and channel discharge in a river which can be used over a large spatial extent (1,000 - 2,000 feet) and is quick to use, safe for Caltrans personnel, and easily deployable.

The purpose of this research was to examine hardware, software, and deployment options to best implement current Large-Scale Particle Image Velocimetry (LSPIV) technology for estimate flood flows to meet Caltrans' hydraulic needs. Specifically, the most appropriate camera type (infrared and commercial off-the-shelf), Light Detection and Ranging, or other instrument for measuring the water slope, required camera accessories, post-processing LSPIV software and the hardware needed for deploying the system using both a retractable mast and an unmanned aerial system (UAS) were determined and implemented during this research project.

Background

The California Department of Transportation (Caltrans) Structure Maintenance and Investigations (SM&I) Hydraulic Branch uses hydraulic models for bridge scour analysis and design. The topographic and bathymetric terrain are vital for calibrating the hydraulic model and monitoring existing scour at bridge foundations. LSPIV technology enables Caltrans personnel to rapidly and safely collect important surface flow information that can assist hydraulic engineers in providing a more accurate evaluation of the scour potential at existing and new bridges. One objective of this research is to enhance the current Caltrans SM&I's topographic and bathymetric survey operations.

Overview of the Work and Methodology

This research examined hardware, software, and deployment options to best implement current LSPIV technology for estimating flood flows to meet Caltrans' hydraulic needs. Specifically, the research investigated the most appropriate camera, the required camera accessories, LSPIV post-processing software, and hardware needed for deploying the system using an Unmanned Aerial System (UAS). The research also included procurement and testing of a Multi-Beam Echo Sounder (MBES) for bathymetric surveys. Working with SM&I personnel, AHMCT provided technical support for deploying the MBES system in several bathymetric survey pilot projects.

UAS-based LSPIV can collect flow velocity (magnitude and direction) information at the water surface, and estimate channel discharge. This method provides valid information over a large spatial extent and can be quick to use, safe for Caltrans personnel, and easily deployed.

Major Results and Recommendations

This research project has successfully designed, integrated, and deployed a manned boat-based bathymetric survey system composed of Global Navigation Satellite System/Inertial Measurement Unit (GNSS/IMU) positioning system, MBES, Acoustic Doppler Current Profiler (ADCP), and single-beam echo sounder sensors. SM&I has deployed the newly integrated bathymetric survey system in several pilot projects to monitor scour, Rock Slope Protection (RSP), and underwater riprap installations. Furthermore, Caltrans divers have used the 3D images of piers and surrounding bathymetry to plan their dives and supplement their inspections at locations too deep for diving. SM&I has also inspected underwater excavation before RSP installation for Caltrans Construction. The pilot project results were presented at a Caltrans Area Bridge Maintenance Engineers meetings.[1,2]

Moreover, this project experimented with UAS-based LSPIV as well as topographic mapping with UAS aerial images using OpenDroneMap (ODM) and WebODM software. This report documents the experiences and lessons learned in capturing UAS video with Ground Control Point targets and LSPIV processing. UAS was proven effective in collecting aerial images for a large area over a short time for topographic mapping using WebODM software. The combined bathymetric, topographic, and LSPIV data were applied in hydraulic modeling using Surface-water Modeling System software. The fusion of MBES, UAS-based topographic data, and surface flow data provides a comprehensive view for a data-driven decision making process.

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[1] Kevin Flora and Oscar Suaznabar, "Benefits of Utilizing Multibeam Sonar for Bridge Investigations in SM&I," SMI – South All Staff Meeting, 11-09-2020, http://ahmct.ucdavis.edu/pdf/caltrans/abmeSouthMeeting20201109.pdf

[2] Kevin Flora and Oscar Suaznabar, "UAS Applications in Hydraulics," ABME South Meeting, 04-12-2021, http://ahmct.ucdavis.edu/pdf/caltrans/abmeSouthMeeting20210412.pdf

Key Benefits

- The manned boat-based bathymetric survey system enables early detection and identification of bridge scour, improving the safety of the traveling public and reducing hazards and exposure for divers.
- The LSPIV system allows Caltrans personnel to rapidly and safely collect important water surface flow information during high flow events for hydraulic modeling.
- The final mapping system enhanced Caltrans SM&I's topographic and bathymetric survey capabilities and operational efficiency.
- With improved evaluations, the design of new construction could be more cost effective and the assessment maintenance needs for existing structures more focused, thereby improving the overall safety for the motoring public.

Primary Lessons Learned

- Overhead bridge structures often obstructed GNSS signal and degraded the Spatial Dual GNSS/IMU system positional accuracy and availability. GNSS/IMU system upgrade or replacement with a better system should be considered in the future.
- The battery run time was limited for the current rugged Dell laptop used for data collection. Additional battery run time is needed for eight hours of full day data collection. In addition, the laptop's low-resolution display limited the ability of users to view all live data from all sensors simultaneously.
- Caltrans lacks UAS pilot training facilities. Proficient UAS pilot training requires many flight hours and investment of personnel time. Training site(s) would facilitate this.
- Site reconnaissance may be required to ensure sufficient natural seeding/tracers are available. Otherwise, a practical plan should be made to spread artificial seeding. The amount of seeding materials and number of personnel involved would depend on the river flow speed and width.
- LPSIV GCP targets can be difficult to locate and see on the UAS controller display when recording color and IR video for LSPIV analysis. Target size, shape, color, and background play a major role. Larger targets may be required for a river over 150-ft wide. Alternatively, the operator may consider capturing video on half of the river at a time.
- Uneven lighting conditions, such as heavy shade on one side and strong directional sunlight on the other side, reduce the video quality

and GCP target visibility. Targets in shaded areas tend to be more visible. Video capture at different times of the day could mitigate the effect of lighting.

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List of Acronyms and Abbreviations

Acronym	Definition
ABME	Area Bridge Maintenance Engineers
ADCP	Acoustic Doppler Current Profiler
AHMCT	Advanced Highway Maintenance and Construction Technology Research Center
bps	bits per second
CAD	Computer-Aided Design
Caltrans	California Department of Transportation
COTS	Commercial Off–The-Shelf
CSV	comma-separated value
DOT	Department of Transportation
DRISI	Division of Research, Innovation and System Information
EDF	Électricité de France
FAA	Federal Aviation Administration
fps	frame per second
FTDI	Future Technology Devices International
GCP	Ground Control Point
GIS	geographic information system
GNSS	Global Navigation Satellite System
GPIO	general-purpose input/output
HDR	High Dynamic Range
IMU	Inertial Measurement Unit

Acronym	Definition
IR	Infra-red
LiDAR	Light Detection and Ranging
LSPIV	Large-Scale Particle Image Velocimetry
MBES	Multi-Beam Echo Sounder
MP	Megapixel
NAD	North American Datum
NMEA	National Marine Electronics Association
ODM	OpenDroneMap
PM	Project Manager
PPK	Post-Process Kinematic
PPS	pulse per second
RGB	red-green-blue
RIVeR	Rectification of Image Velocity Result
RSP	Rock Slope Protection
RTK	Real-Time Kinematic
SM&I	Structure Maintenance and Investigations
SMS	Surface-water Modeling System
SR	State Route
UAS	Unmanned Aerial System
UHMW	Ultra-High Molecular Weight
USGS	United State Geological Survey
USV	Unmanned Surface Vessel

Acronym	Definition
UTM	Universal Transverse Mercator

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Chapter 1: Introduction

Problem

The California Department of Transportation (Caltrans) Structure Maintenance and Investigations (SM&I) Hydraulic Branch uses hydraulic models for bridge scour analysis and design. To calibrate hydraulic models, it is necessary to collect information about the flow characteristics in a river during flood events as well as the topographic and bathometric terrain of an area.

Objectives

Caltrans needs a new method to measure the discharge, collect flow velocity (magnitude and direction) information, and estimate channel profiles. The new method must provide valid information over a large spatial extent (1000 - 2000 feet) and be quick to use, safe for Caltrans personnel, and easily deployable.

This research examined hardware, software, and deployment options to best implement current Large-Scale Particle Image Velocimetry (LSPIV) technology for estimating flood flows to meet Caltrans' hydraulic needs. Specifically, the research investigated commercial off-the-shelf (COTS) cameras (infrared [IR] and standard non-IR cameras), required camera accessories, LSPIV post-processing software, and hardware needed for deploying the system using an Unmanned Aerial System (UAS). The research also included the procurement of a Multi-Beam Echo Sounder (MBES) for bathymetric surveys to determine channel profile for flow rate modeling. Working with SM&I personnel, the Advanced Highway Maintenance and Construction Technology (AHMCT) Research Center provided technical support for conducting data collection using the MBES system in several bathymetric surveys pilot projects.

Background & Literature Review

A Caltrans Preliminary Investigation, [Flood Flow Estimation using Large Scale Particle Image Velocimetry (LSPIV) (https://dot.ca.gov/-/media/dot-media/programs/research-innovation-system-information/documents/preliminary-investigations/flood-flow-pi-0208171-a11y.pdf),](https://dot.ca.gov/-/media/dot-media/programs/research-innovation-system-information/documents/preliminary-investigations/flood-flow-pi-0208171-a11y.pdf) was completed in February 2017. It contains a detailed literature review on LSPIV and its applications with UAS. Moreover, it formed the basis of this research.

Research Methodology

A Project Panel (panel) consisting of SM&I personnel and AHMCT researchers was established early in the project, and regular meetings were held with the Project Manager (PM) and/or the panel. The panel worked collaboratively to best guide the research effort.

The work evaluated LSPIV for regular Caltrans use. The goal was to improve the safety of Caltrans Maintenance staff in obtaining flow data and subsequently, improve the safety of the traveling public. A sample of the issues addressed during the work includes:

- Availability and capabilities of LSPIV software
- Operational issues for LSPIV as identified during field testing with Caltrans Maintenance personnel, such as workflow documentation
- Ability to integrate LSPIV output data with Caltrans' Surface-water Modeling System (SMS) software

The project task included gathering information through review of COTS systems, evaluating UAS for LSPIV, assessing software, field testing, and providing related documentation. To successfully achieve the goals of this project, the following work was performed:

1. Review of COTS systems
2. Procurement of UAS and related components for evaluating UAS-based LSPIV
3. Deployment support of MBES system in pilot projects
4. Evaluation of available LSPIV software
5. LSPIV UAS testing and data post-processing
6. Project documentation and management

Overview of Research Results and Benefits

Development of an LSPIV system allows Caltrans personnel to rapidly and safely collect important flow information during high flow events. This information can assist hydraulic engineers in providing a more accurate evaluation of the scour potential of existing and new bridges. Improved evaluations support more cost-effective designs for new construction along with more focused assessment of maintenance needs for existing structures. Both these benefits improve the overall safety of bridges for the motoring public. Additionally, eliminating staff from operating a boat in high flows improves worker safety and increases the number of sites that can be monitored in a day during flood conditions.

The key deliverables of this project include:

- UAS for evaluating UAS-based LSPIV
- Integrated MBES system for bathymetric surveys
- Summary of LSPIV software evaluation
- Summary of system field testing, experiment results, UAS video data collection best practices, and LSPIV post-processing workflow
- Preliminary assessment of applicability of MBES for bathymetric surveys
- Final report

Chapter 2: Review of COTS Systems and Procurement

UAS Procurement

A literature review was completed in a previous Caltrans Preliminary Investigation on LSPIV.[3] AHMCT reviewed the available COTS systems related to UAS platforms with integrated thermal imaging and/or red-green-blue (RGB) color cameras for LSPIV video data collection. The UAS purpose is to collect images for topographic survey. Ideally, a few UAS would be purchased for evaluation first. With the limited budget, the procurement of the final UAS was based on the literature review and system specifications as well as discussion and feedback from other UAS users in the survey community.

The UAS with integrated camera(s) selection considerations were:

1. The UAS must have integrated global shutter color camera capable of recording 4K video at 30 frame per second (fps) and 12 megapixel (MP) or better resolution images
2. Commonly used for aerial topographic survey
    a. Widely supported by other COTS software
    b. Good community support
    c. Better after-market accessories, such as carrying case and battery charger
    d. Large number of resellers for competitive bids
3. UAS with collision mitigation sensors and software
4. UAS platform stable in cross wind
5. Compatible with existing Caltrans UAS models
    a. Simplified and standardized UAS training and software approval
    b. Sharing of spare batteries, chargers, UAS controller, and consumables, such as spare fan blades
6. Long-term manufacturer support

[3] Kin S. Yen, "Flood Flow Estimation using Large Scale Particle Image Velocimetry (LSPIV)", Preliminary Investigation for the California Department of Transportation,February 8, 2017.

This information was presented to the panel for consideration. Data on long-term manufacturer support is generally unavailable. Final procurement in late 2018 included a DJI Phantom 4 Pro Version 2 and a DJI Matrice 210 with FLIR XT2 IR camera (specifications available at: https://www.flir.com/products/xt2/), spare batteries, and rugged storage cases (see Figures 2.1-2.3).

Figure 2.1: DJI Phantom 4 Pro Version 2 in rugged carrying case

Figure 2.2: DJI Matrice 210 in rugged carrying case

Figure 2.3: FLIR XT2 IR and color camera

COTS UAS are rapidly improving. New, lightweight UAS models with real-time kinematic (RTK) and post-process kinematic (PPK) Global Navigation Satellite

System (GNSS) were available after the UAS procurement. These new UAS models, such as DJI Phantom Pro 4 RTK, DJI Mavic 2 Enterprise Advanced M2EA, DJI Matrice 300, and Parrot ANAFI USA, may be better choices for future procurement and use.

MBES Procurement

The equipment budget supported procurement of an MBES for bathymetric surveys. The PicoMBES 120 sensor was purchased based on user recommendations and available project funds (specifications available at: https://www.nautikaris.com/product/picomb-120/). Fully integrated MBES bathymetric survey systems with GNSS/Inertial Measurement Unit (IMU) are available but at a higher cost. In addition, a Valeport water sound velocity sensor was included in the PicoMBES 120 kit (model: UltraSV, S/N: 66056, specifications available at: https://www.valeport.co.uk/content/uploads/2020/04/UltraSV-Datasheet-April-2020.pdf). AHMCT provided system integration and deployment support of the MBES with the existing Caltrans GNSS/IMU system.

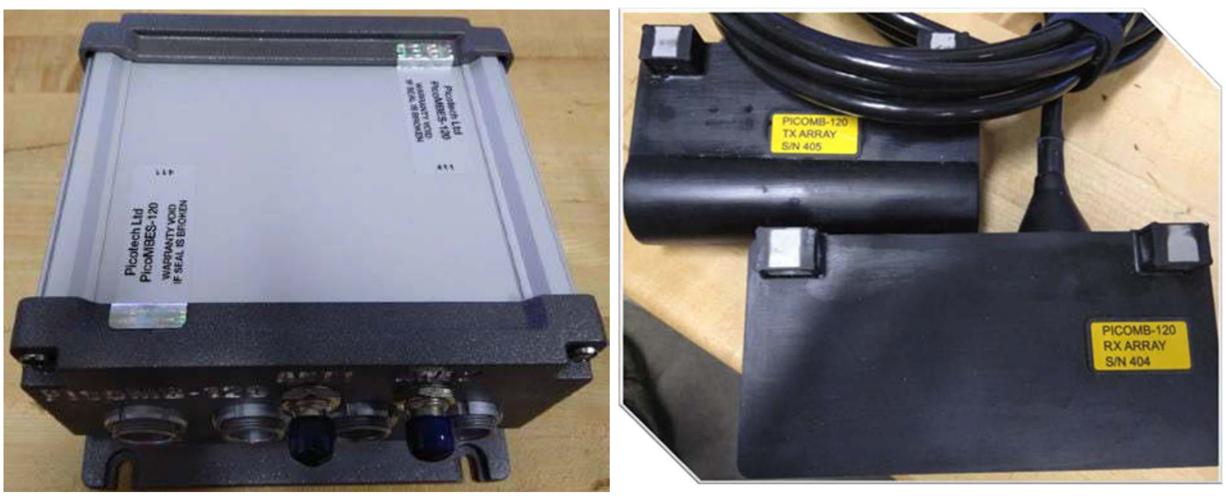

Figure 2.4: PicoMBES 120 system

Figure 2.5: Valeport sound velocity sensor, model: UltraSV and S/N: 66056

Chapter 3: Systems Integration and Deployment Support of Bathymetric Survey System

The following systems integration tasks were required to deploy the PicoMBES 120 sensor for bathymetric survey:

1. Design and fabricate component mounts to the Caltrans inflatable boat and the large diver boat
2. Design, procure, and make battery power system for components:
    a. PicoMBES 120 system
    b. Rugged Dell laptop
    c. External monitor
    d. Advanced Navigation Spatial Dual GNSS/IMU positioning system
    e. Teledyne Rio Grande Acoustic Doppler Current Profiler (ADCP) sensor
    f. CEE Echo single beam sounder sensor
3. Data integration of PicoMBES 120 system and Advanced Navigation Spatial Dual GNSS/IMU positioning system using HYPACK and BeamworX software
4. Data integration of Advanced Navigation Spatial Dual GNSS/IMU positioning system, Teledyne Rio Grande ADCP sensor, and CEE Echo single beam echo sounder sensors with WinRiver II software

Component mounts on a Caltrans Foldable Boat

Caltrans SM&I has a foldable inflatable boat primarily used for hydrographic survey in rivers and lakes. The small inflatable boat is normally folded and stored in a Caltrans truck for transporting to and from boat launch sites. A removable lightweight component mounting platform is needed to secure all the components in the small boat during hydrographic survey. No COTS mounting solution was found. The design was modified and enhanced based on observations and feedback from SM&I after field trials.

Computer-Aided Design (CAD) models of mounts and assemblies were created in SolidWorks CAD software to aid design, fabrication, modification, and documentation. The design is broken up into several sub-assemblies so that the system can be taken apart for transport and storage. The carbon fiber

GNSS/IMU antenna bar sub-assembly, shown in Figure 3.1, maintains a fixed offset between antennas located at each end and the IMU located in the middle of the antenna bar. The antenna bar is mounted on top of a 4-ft-long, 2-in-diameter carbon fiber pole with either the PicoMBES 120 sensor or the ADCP/echo sounder sensor assembly at the bottom end of the pole as show in Figure 3.2. This sub-assembly design resulted in a fixed offset between the GNSS/IMU system with the PicoMBES 120 sensor and the ADCP/echo sounder sensor assembly. The fixed offset eliminates the need to measure sensor offsets and reconfigure software during each deployment.

Figure 3.1: Advanced Navigation Spatial Dual GNSS/IMU positioning system SolidWorks sub-assembly CAD model

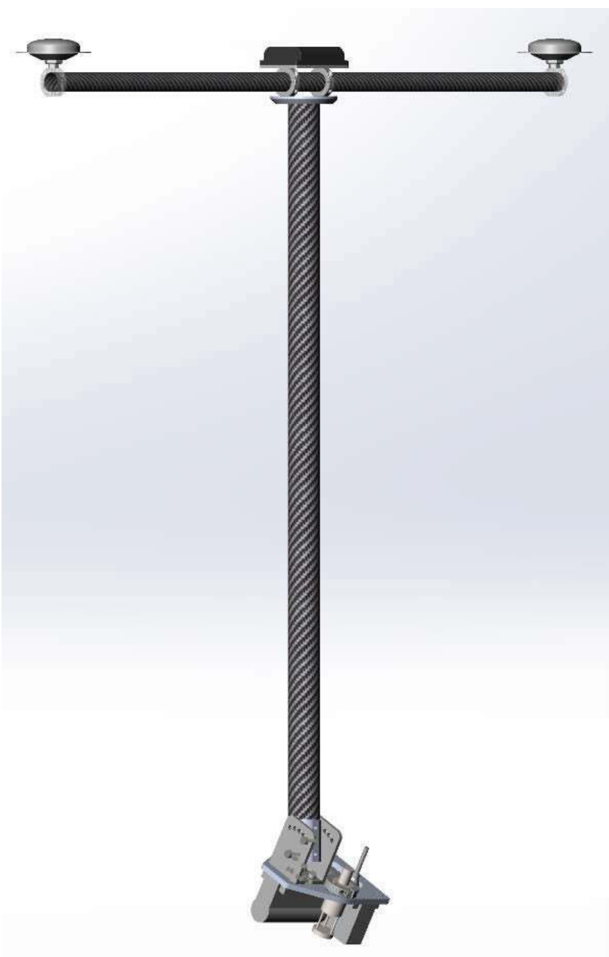

Figure 3.2: Antenna bar and PicoMBES 120 sensor assembly CAD model. The CAD model shows a 30-degree tilt of the PicoMBES 120 sensor assembly.

The PicoMBES 120 sensor assembly was originally designed to allow the sensor to tilt 30 degrees as shown in Figure 3.2 and Figure 3.4. It was later modified to enable a 15-degree tilt after a field trial deployment. Tilting the PicoMBES 120 sensor facilitates improved data capture near shores and piers. A protective cover, shown in Figure 3.5, was attached to the front of the sensor to maintain laminar flow. Caltrans SM&I had an ADCP and a single-beam echo sounder sensor before this project. To unify bathymetric surveys setup, a sensor mount for both the ADCP and echo sounder was designed and fabricated to mount at the end of the 2-in carbon fiber pole as shown in Figure 3.6. ADCP, in conjunction with an echo sounder, are used to measure streamflow. ADCPs measure water velocity by transmitting sound waves that are reflected off sediment and other materials in the water.

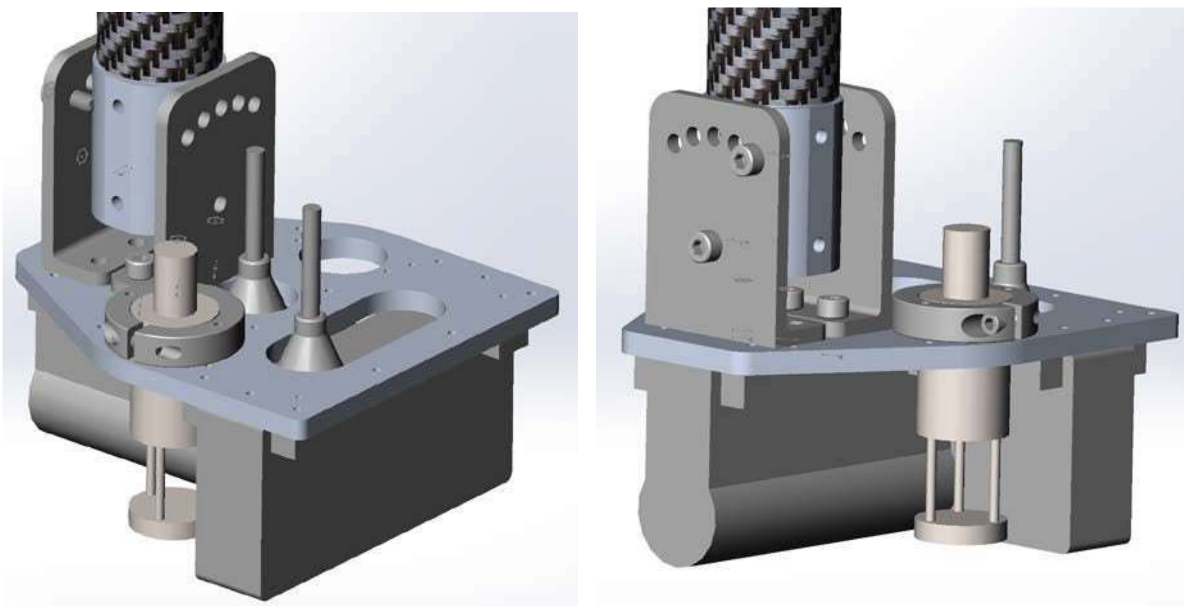

Figure 3.3: PicoMBES 120 sensor assembly CAD model

Figure 3.4: PicoMBES 120 sensor assembly with cover CAD model

Figure 3.5: PicoMBES 120 sensor assembly with protective cover CAD model

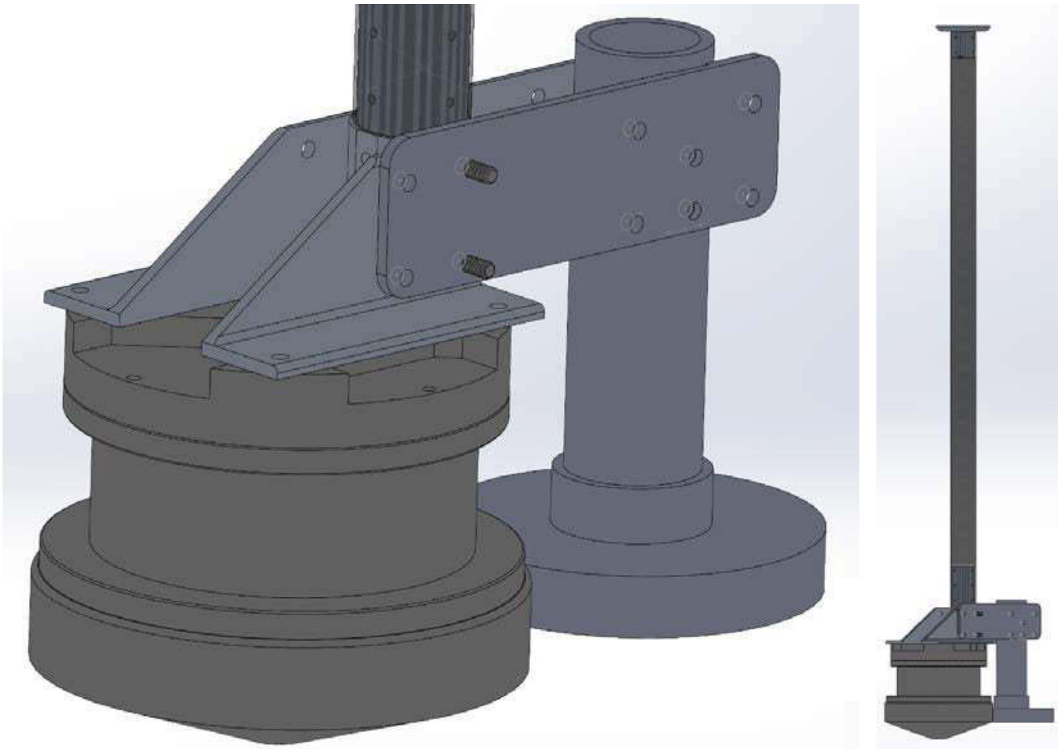

Figure 3.6: ADCP and echo sounder sensor assembly CAD model

Figure 3.7: ADCP (left) and CEE Echo sounder (right) assembly

Other bathymetric survey components, such as a rugged laptop, batteries, external monitor, sensor controller, and sensor mask, are secured to a component-mounting platform as shown in Figure 3.8. The component mounting platform is made out of aluminum T-slot elements, two ultra-high molecular weight (UHMW) polyethylene plastic plates, COTS parts, and custom parts. COTS components are employed when possible to reduce integration time and simplify future part replacement. The T-slot system allows users to reconfigure the platform to fit on another small boat in case the foldable boat is replaced. 316 stainless steel and titanium fasteners were used to mitigate corrosion. Two UHMW polyethylene plastic plates, located on top and bottom, have a grid of holes for mounting components in different positions. Velcro strips were added to provide a simple way to secure small parts quickly. In addition, the sensor mask is mounted on to the platform on a hinge so that the PicoMBES 120 or the ADCP/echo sounder sensors can be pivoted out of the water in transit as shown in Figure 3.9.

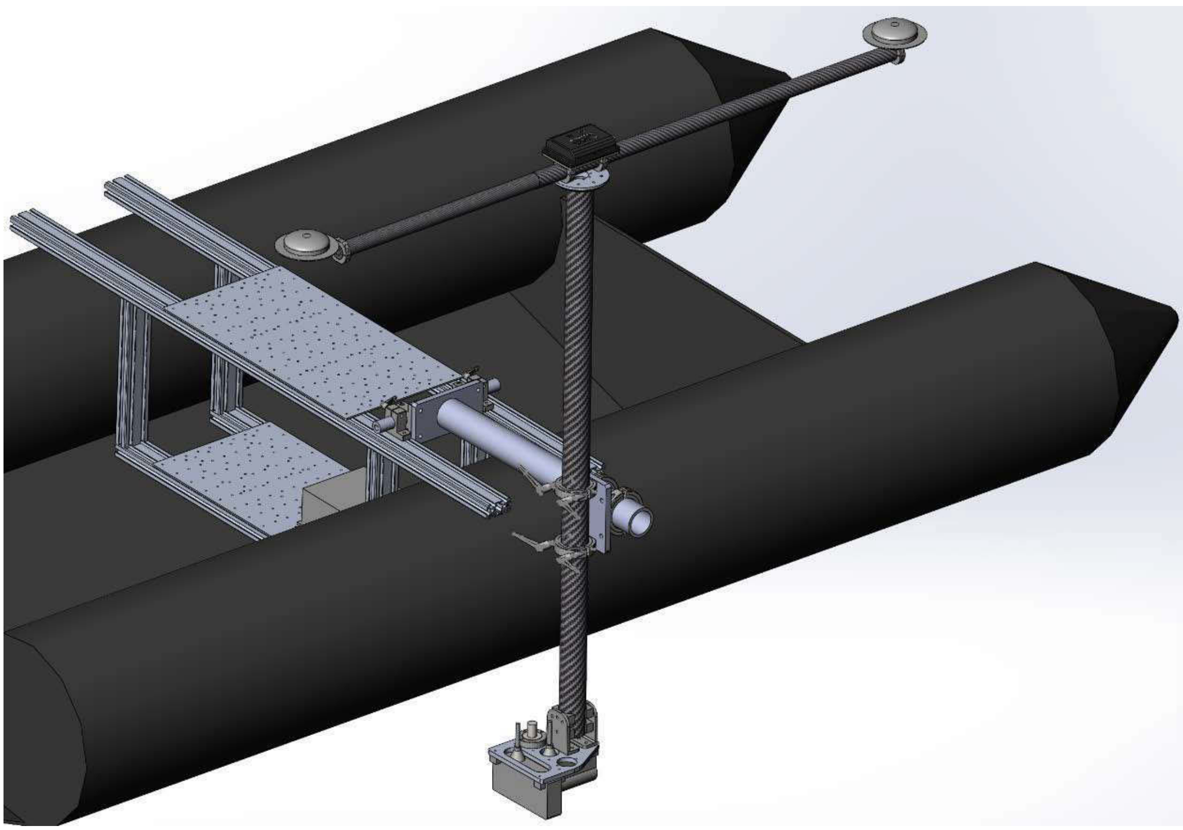

Figure 3.8: CAD model of component mounting platform in a foldable boat

Figure 3.9: SM&I foldable boat with PicoMBES 120 with 15-degree tilt at Discovery Park boat launch (10/15/2020). The sensor mask is rotated up before transit to into water.

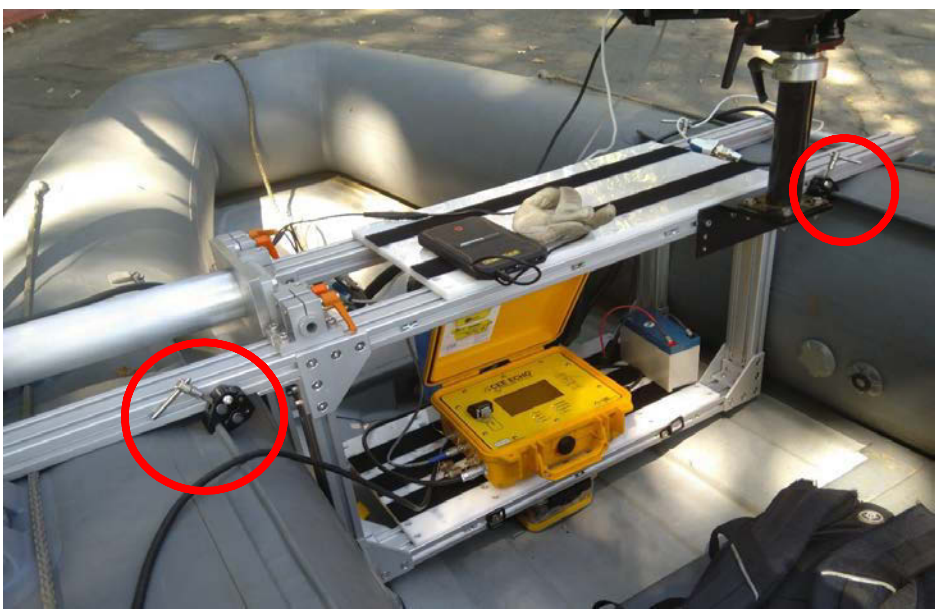

Figure 3.10: Component mounting platform secured in the Caltrans foldable boat with four clamps. Two of the clamps are visible and highlighted by red circles.

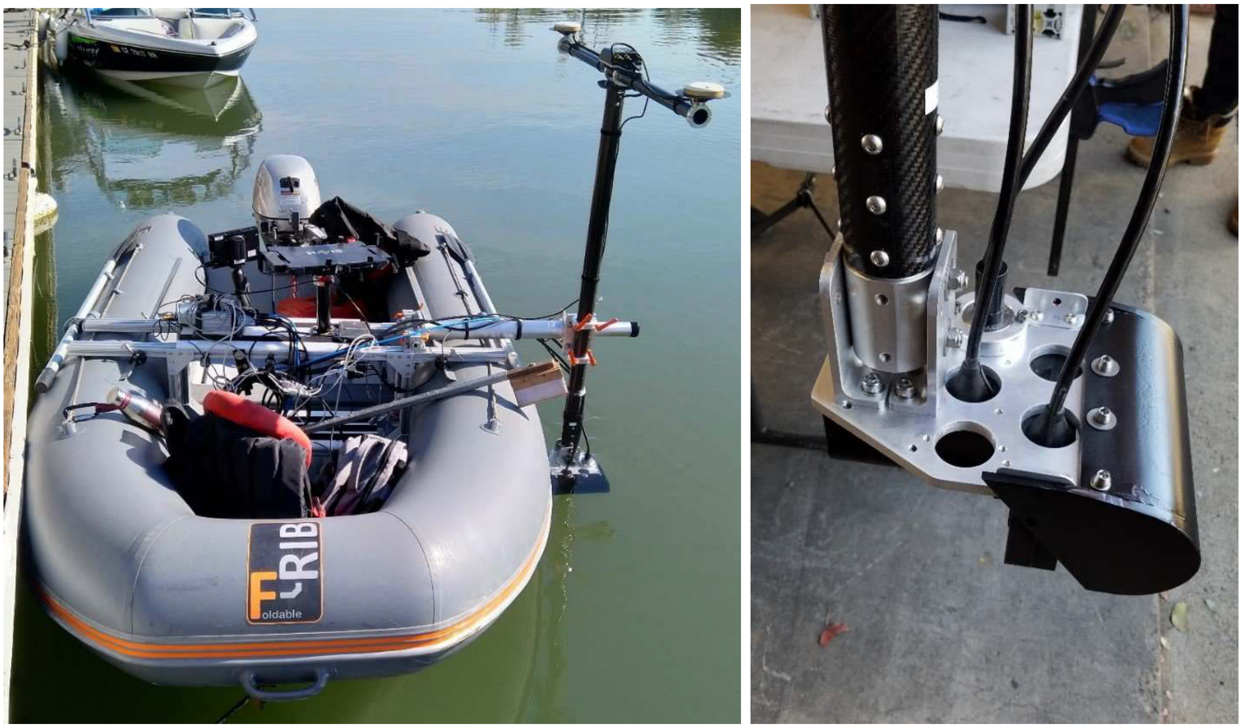

Figure 3.11: SM&I foldable boat with PicoMBES 120 sensor in water (bathymetric survey configuration). The data collection rugged laptop was removed.

Figure 3.12: PicoMBES testing on Caltrans boat at Napa River (05/22/2020). The top photograph shows the sensor mask pivoted up so that the PicoMBES sensor is out of the water (transit configuration).

Sensor Mount for Caltrans Dive Boat

Caltrans has a larger boat for divers. It is deployed to inspect bridges with foundations located in deep water. A sensor mount was also designed and fabricated to secure the GNSS/IMU and PicoMBES 120 system for bathymetric survey in the San Francisco Bay. The sensor mount was designed to clamp on to the boat rail as shown in Figure 3.14. The GNSS antenna bar assembly is mounted on top of a 9-ft-long, 2-in-diameter carbon fiber pole. The PicoMBES 120 sensor is mounted to the bottom of the 9-ft pole. The entire sensor mask is mounted on a pivot so that the PicoMBES sensor can be rotated out of the water in transit. The other bathymetric survey equipment, such as laptop and batteries, are located inside the cabin. The dive boat bathymetric survey setup was used and tested at the new SF-Oakland Bay Bridge on December 18, 2019 and February 12, 2020.

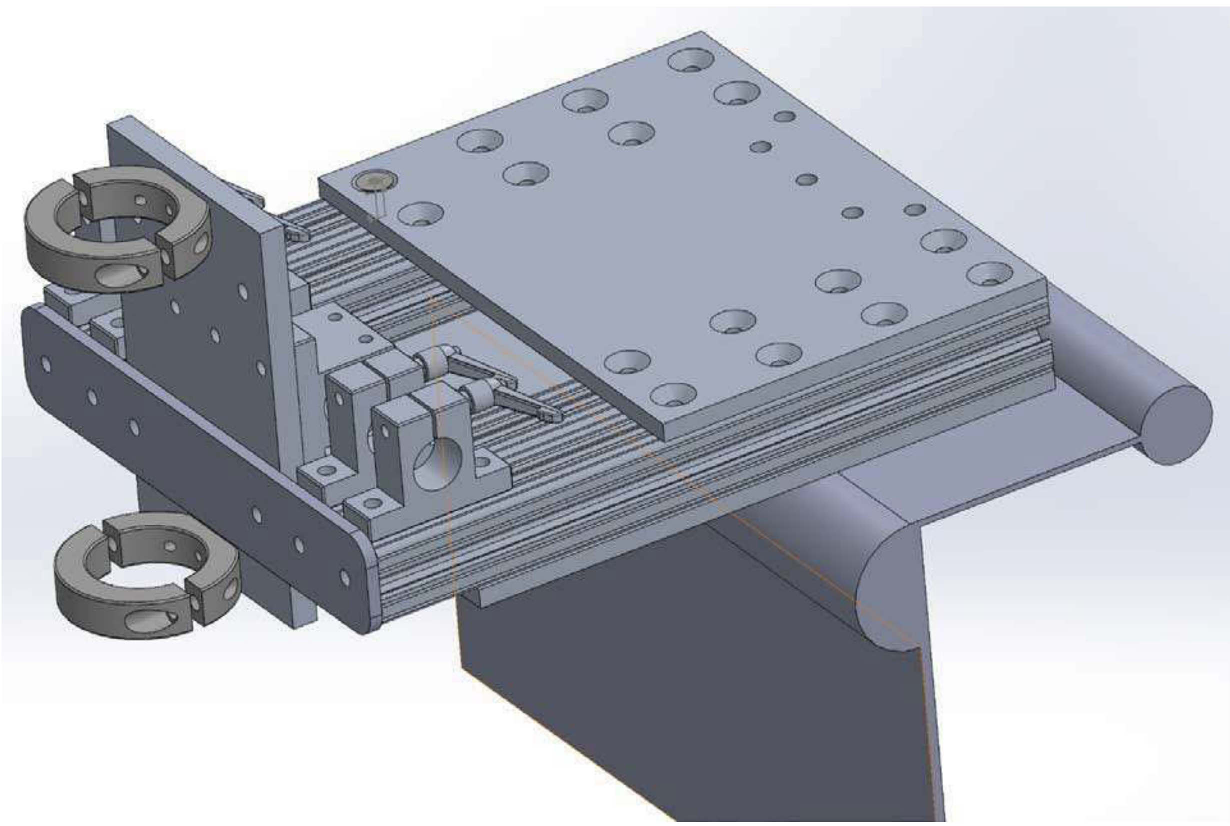

Figure 3.13: Sensor mount CAD model

Figure 3.14: Sensor mount on the large Caltrans dive boat

Figure 3.15: PicoMBES 120 testing on large Caltrans dive boat (2/12/2020)

Battery Power System

The PicoMBES 120 system and the Advanced Navigation Spatial Dual GNSS/IMU positioning system were originally powered by a 6,000-mAh 22.2-V Lipo Battery. After a few deployment pilot projects, a 16,000-mAh LIPO battery pack with XT90 connector was purchased for the MBES sensor power supply in order to support longer bathymetric survey operation (over six hours) without the need for changing the battery. The battery connections are fused, and the battery is enclosed in a clear, waterproof plastic box.

The Teledyne Rio Grande ADCP sensor is powered by a 12-volt lead acid gel cell battery, and the CEE Echo single beam sounder sensor is powered by an internal rechargeable battery.

The rugged Dell data collection laptop run time is extended by using two Dell Power Companion 4-Cell 12,000-mAh power packs. The Dell power pack should be plugged into the laptop before the internal battery is below 50%. The external monitor was powered by a Sony NP-F970 battery or 12-VDC via a 24-VDC to 12-VDC converter connected to the 6,000-mAh 22.2-V Lipo Battery. The laptop battery's energy capacity is now the limiting factor for surveys.

Data Integration and Data Collection Software

Advanced Navigation Spatial Dual GNSS/IMU Positioning System

The Advanced Navigation Spatial Dual GNSS/IMU positioning system has a built-in IMU and two GNSS receivers for orientation (yaw/heading, pitch, and roll) and global position output. It has two RS232 serial ports (one primary and one secondary serial port) and two general-purpose input/output (GPIO) pins. The Spatial Dual primary RS232 port is connected to the rugged laptop via a Future Technology Devices International (FTDI) Ltd US232R-100-BULK RS232-to-USB converter configured to communicate at 1,000,000,000 bits per second (bps) baud-rate. Only the FTDI US232R-100-BULK converter supports this baud rate. The Advanced Navigation Spatial Dual cable harness connector pin-out is documented in Appendix A. Advanced Navigation provides 64-bit Java Spatial Dual Manager software to allow the user to configure the Spatial Dual's data input and outputs and log raw GNSS/IMU measurement for post-processing. The user must install the 64-bit version of Java for the Spatial Dual Manager software to function properly. The Spatial Dual GPIO #2 pin is configured for 1 pulse per second (PPS) output to the PicoMBES 120, and the GPIO #1 pin is configured to be an RS232 transmit pin for National Marine Electronics Association (NMEA) messages at 115,200 bps baud rate. The Spatial Dual secondary RS232 port is also available for NMEA message output. NMEA messages are text serial data containing position, speed, and orientation information.

PicoMBES 120 System

The PicoMBES 120 system has a control box where the sensors, power, and data cable are connected. The PicoMBES 120 data cable is split into an Ethernet cable connected to the laptop, a 1 PPS input to the Spatial Dual, and an RS232 port for NMEA message input.

Figure 3.16: PicoMBES 120 system control box

Bathymetric Data Collection and Post-processing Software

[BeamworX (https://www.beamworx.com/)](https://www.beamworx.com/) and [HYPACK (https://www.hypack.com/)](https://www.hypack.com/) software were evaluated for data collection and post-processing of the multibeam data. Each software package requires a different cabling arrangement. A custom cable harness was made first for HYPACK software evaluation. The custom cable harness was then modified for BeamworX software. BeamworX was selected for subsequent pilot projects.

Data Integration with ADCP and CEE Echo Sounder Sensors and Data Collection Software

Caltrans SM&I owns an ADCP and CEE echo sounder. AHMCT supported SM&I in the deployment of the ADCP on the newly developed component mount platform. The previous ADCP sensor mount setup did not support co-location of the CEE echo sounder sensor. A new mount was designed and made to mount both ADCP and echo sounder sensors on the bottom of the carbon fiber pole below the Spatial Dual GNSS/IMU system. The sensor pole uses the same component mount platform for the PicoMBES 120. Teledyne WinRiver II software was used to collect, store, and analyze data from the GNSS/IMU, ADCP, and echo sounder. This configuration is different from SM&I's previous setup. The new setup required a new configuration in the WinRiver II software. Different cabling and configurations were evaluated to determine the best setup. The CEE echo sounder may be configured to output depth data via Bluetooth and/or the RS232 port on the CEE Echo computer (yellow box shown in Figure 3.10 and Figure 3.17). The Bluetooth connection from the CEE Echo computer to the laptop was found to be unreliable. The CEE Echo computer's RS232 serial output is more reliable and was connected to the laptop via the RS232-to-USB cable provided by the manufacturer. The serial data output port location is labelled inside the lid of the Echo computer box. The WinRiver II software requires two separate RS232 serial output data streams from the GNSS/IMU system. The position and speed GPGGA (GPS fix data) and GPZDA (date and time) data stream is connected to the laptop COM port, and the heading RS232 data stream is connected to the laptop via a RS232-to-USB converter. The WinRiver II software collected the ADCP sensor data output via RS232 directly connected to the laptop. The ADCP survey setup was field-tested multiple times.

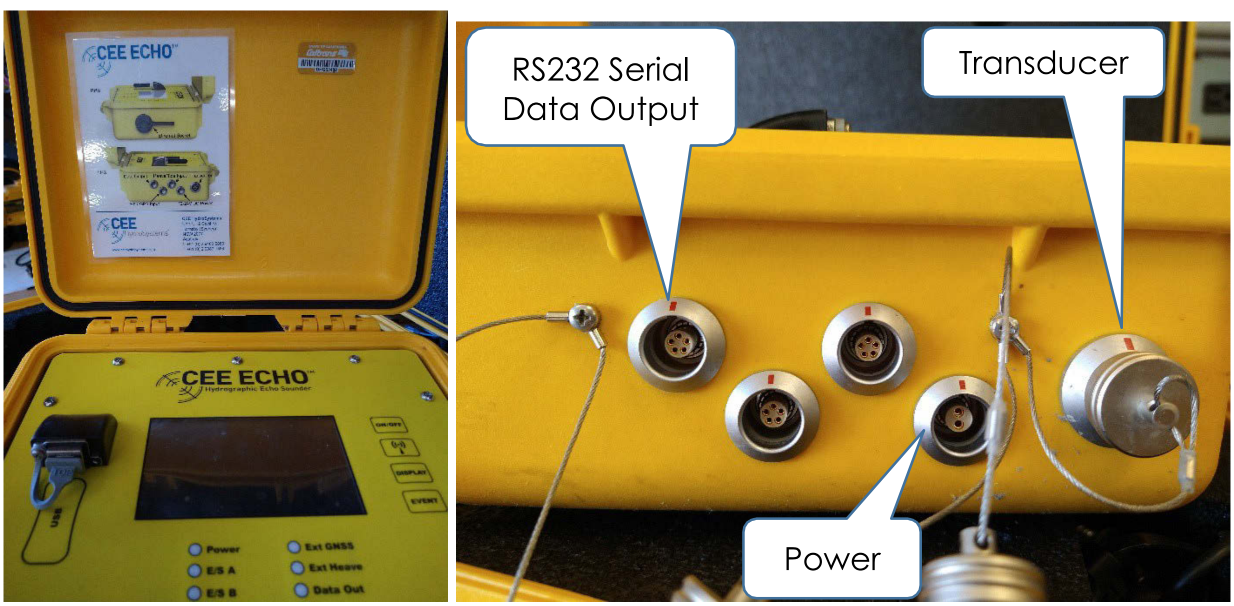

Figure 3.17: CEE Echo computer. Right image shows the RS232 serial port connection location.

Figure 3.18: SM&I personnel testing the ADCP and echosounder integration with WinRiver II software. ADCP and CEE Echo sounder sensors are under water.

Bathymetric Survey System Deployment and Pilot Project Results

The AHMCT researcher and SM&I personnel worked together to deploy the bathymetric system in multiple pilot projects for testing, evaluation, and support training. The task magnitude was larger than originally anticipated. However, field trial observations and feedback from SM&I personnel were critical in identifying deficiencies and improving the design. The design was enhanced multiple times throughout the deployment phase. Seafloor Systems personnel provided technical support and HYPACK software training. Seafloor Systems trained Caltrans personnel on the use of the PicoMBES system and HYPACK software from September 24 to 26, 2019. BeamworX personnel also provided technical support. Both HYPACK and BeamworX were evaluated, and BeamworX was selected for data collection and post-processing software due to its ease of use and lower cost.

Figure 3.19: Seafloor Systems personnel training SM&I on the use of HYPACK software

The PicoMBES 120 sensor mount was modified to support 15-degree tilt of the sensor head. The original sensor mount design supported 30-degree tilt. However, field test results suggested that a 15-degree sensor tilt may yield better results. The new 15-degree tilt mount was tested on October 15, 2020 on the American River near Discovery Park in Sacramento. The 15-degree tilt MBES sensor works well in mapping close to shore and near bridge foundations.

In addition, the Advanced Navigation Spatial Dual GNSS/IMU system was not performing as expected in previous pilot studies. The heading recovery time was longer than expected. Experiments were conducted to determine the cause(s) with support from Advanced Navigation. Two new GNSS antenna cables were made for the Spatial Dual GNSS/IMU system. The cables were tested using another GNSS receiver by comparing the L1/L2 signal strength with a commercially-made cable. L2 signals are generally weaker. The original assumption was that the previous cables may have failed to provide a good GNSS signal. The original Spatial Dual GNSS antennas were replaced with two Trimble Zephyr Model 2 antennas for performance comparison. The heading and position recovery time were measured by covering the antenna(s) with an aluminum plate in order to block the GNSS signal. The Trimble Zephyr antennas resulted in shorter heading and position recovery time. Advanced Navigation analyzed the raw GNSS data logs. One or both of the original antenna(s) may have been damaged, resulting in poor L2 signal reception. Two Trimble Zephyr antennas have temporarily replaced the original antennas while two Tallysman Wireless, Inc., triple-band (L1/L2/L5) VSP6337L-58 GNSS antennas will be used as permanent replacements upon funding availability. Working with BeamworX and SMI personnel, the GNSS/IMU system with Trimble Zephyr Model 2 antenna replacements and PicoMBES system with 15-degree tilt configuration were tested on the American River near Discovery Park on October 15, 2020. The GNSS/IMU performance in positioning and heading recovery was improved. The 15-degree tilt MBES results were examined by SM&I.

Pilot Projects Results

SM&I also deployed the system several times independently without assistance from AHMCT. The MBES bathymetric survey results from the pilot projects were presented at the Caltrans Area Bridge Maintenance Engineers (ABME) meeting on November 9, 2020.[4] The presentation was well received.

The pilot projects include:

- Scour and Rock Slope Protection (RSP) monitoring at Napa River Bridges and American River Bridges
- Long-term monitoring of underwater riprap installations
- Providing a preview of conditions and depths for Caltrans divers to plan their dive
- Extend and supplement data at depths lower than 100-ft which exceed the Caltrans dive depth limit
- Obtaining 3D image of piers and surrounding bathymetry
- Construction support for underwater excavation and RSP installation at American River State Route (SR) 160 westbound

Figures 3.20 to 3.25 were produced by SM&I and extracted from presentations at the ABME meeting and to Caltrans Division of Research, Innovation and System Information (DRISI).

[4] Kevin Flora and Oscar Suaznabar, "Benefits of Utilizing Multibeam Sonar for Bridge Investigations in SM&I," SMI – South All Staff Meeting, 11-09-2020, http://ahmct.ucdavis.edu/pdf/caltrans/abmeSouthMeeting20201109.pdf

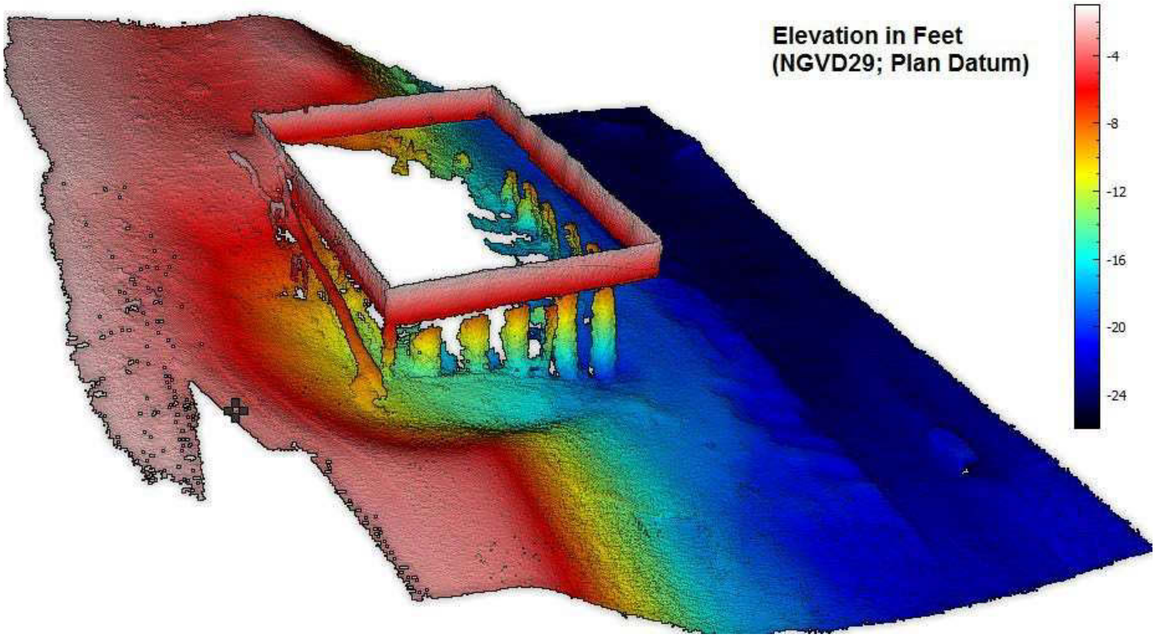

Figure 3.20: PicoMBES 120 survey of Napa River Bridge pier data using BeamworX software

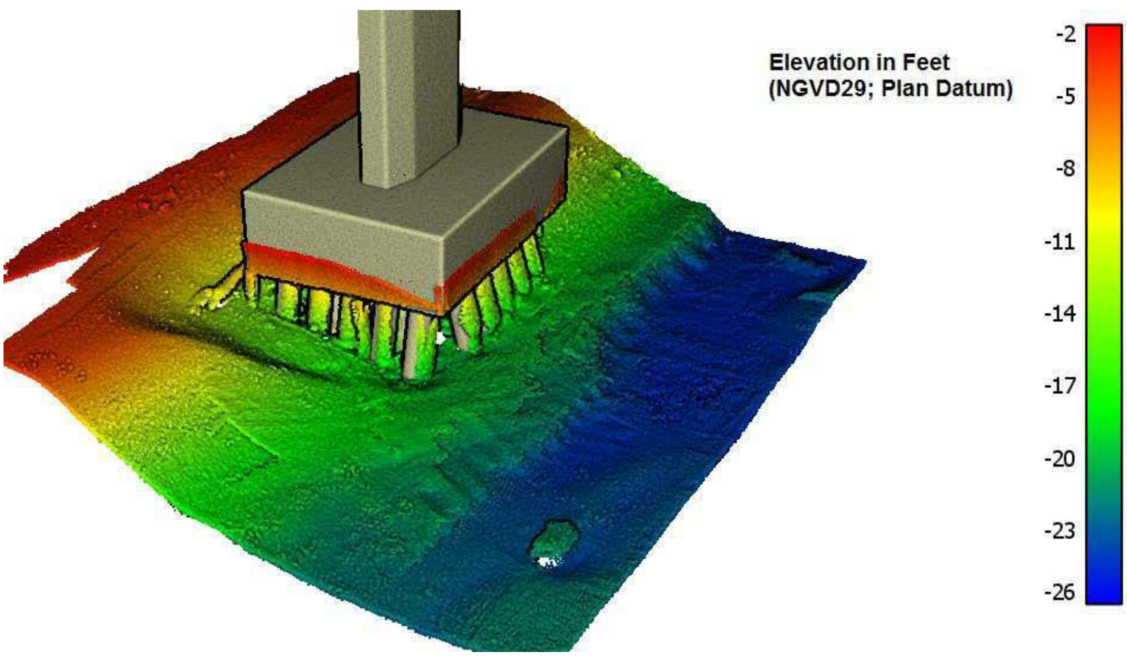

Figure 3.21: PicoMBES 120 survey of Napa River Bridge pier data overlaid on CAD model

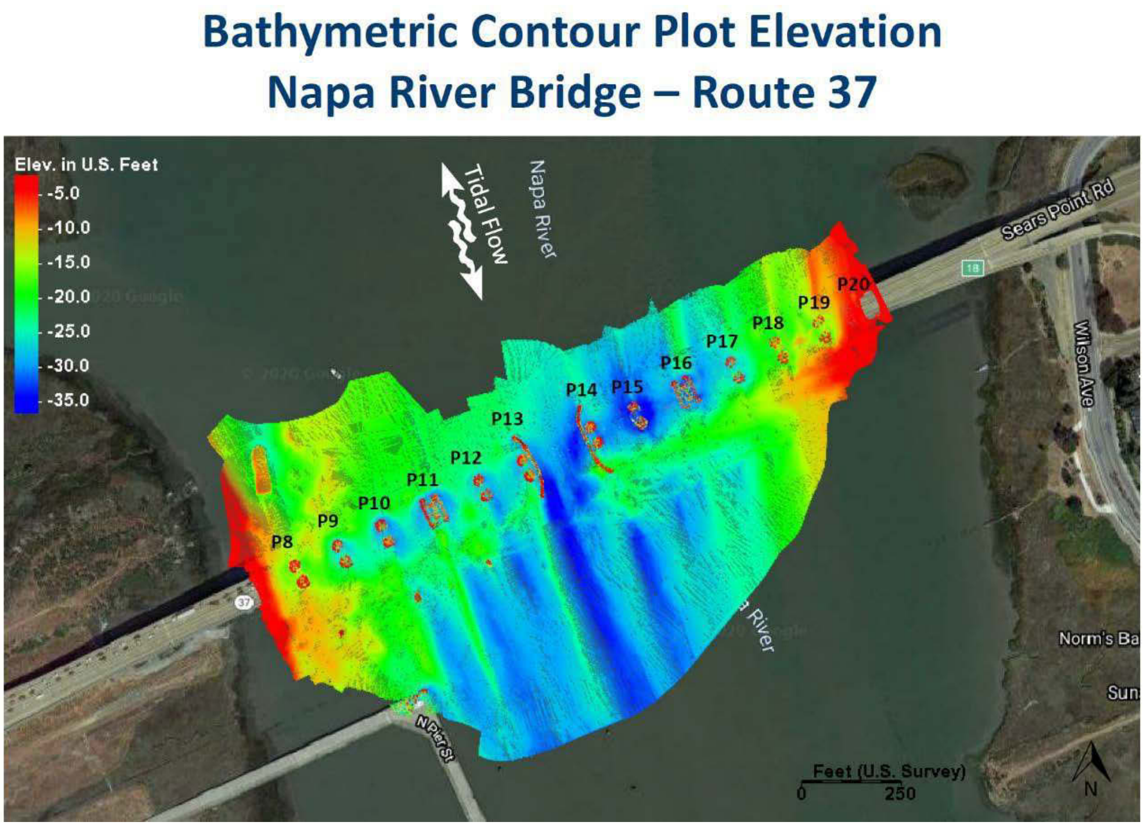

Figure 3.22: Example bathymetric survey result presented by SM&I in Caltrans ABME meeting

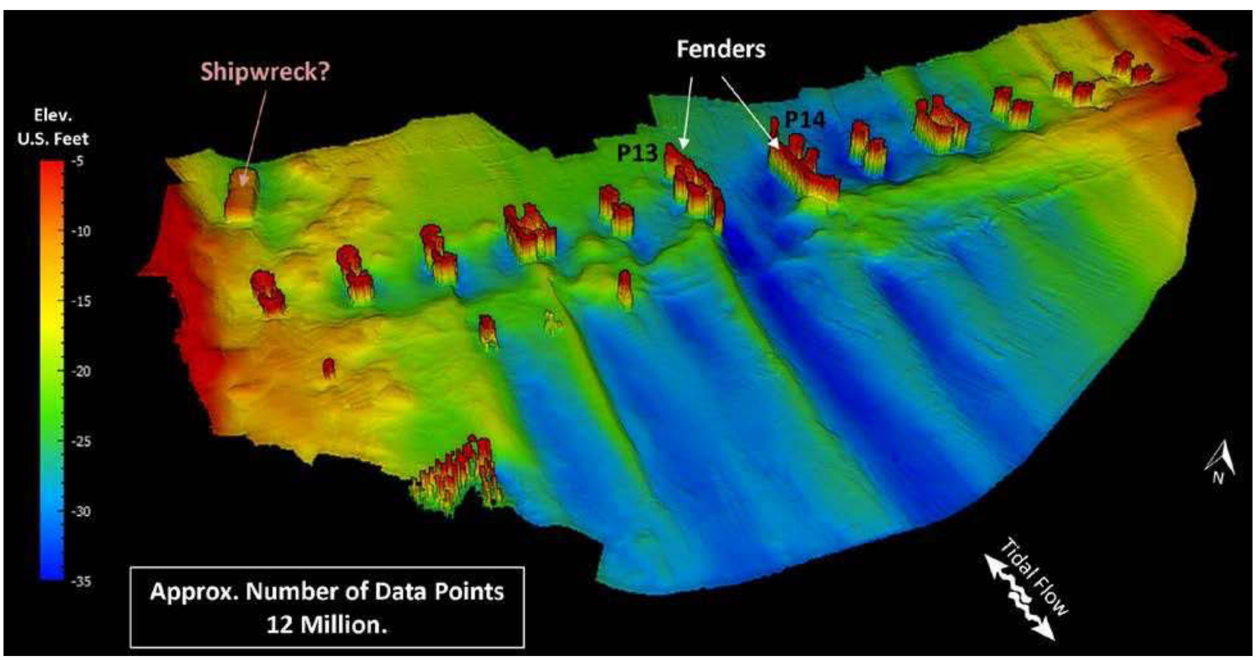

Figure 3.23: 3D view of bathymetric contour plot elevation Napa River Bridge SR37

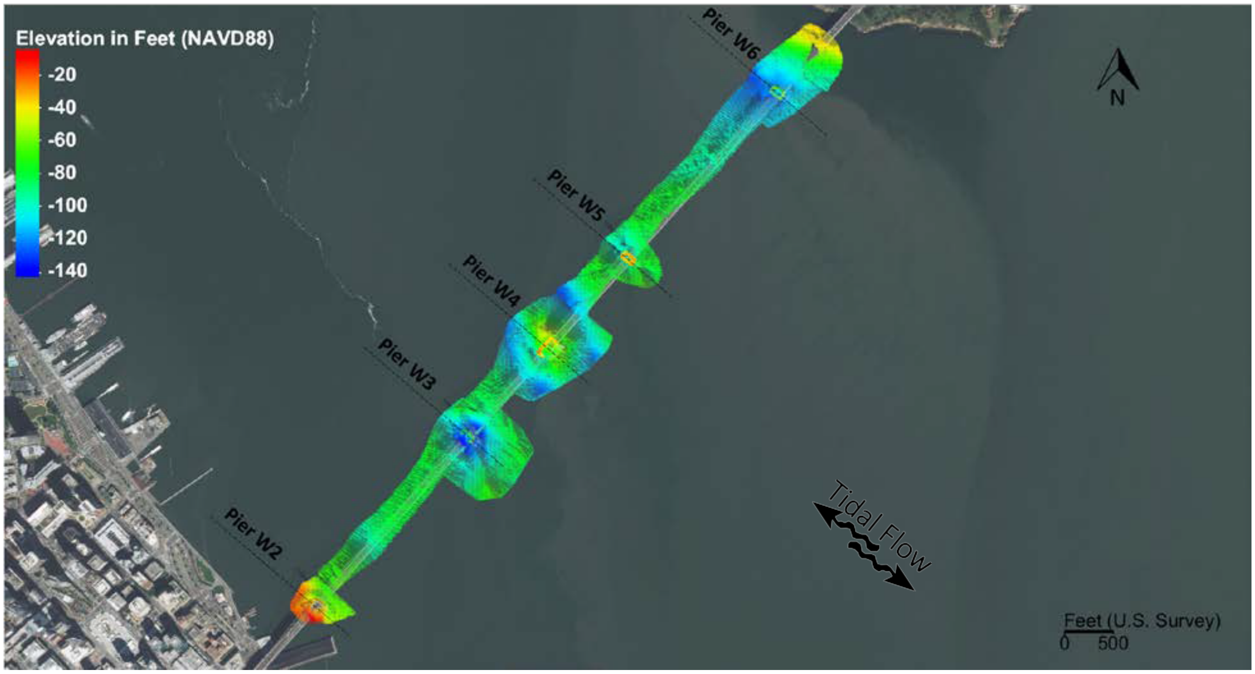

Figure 3.24: Bathymetric survey result of San Francisco-Oakland Bay Bridge, CA

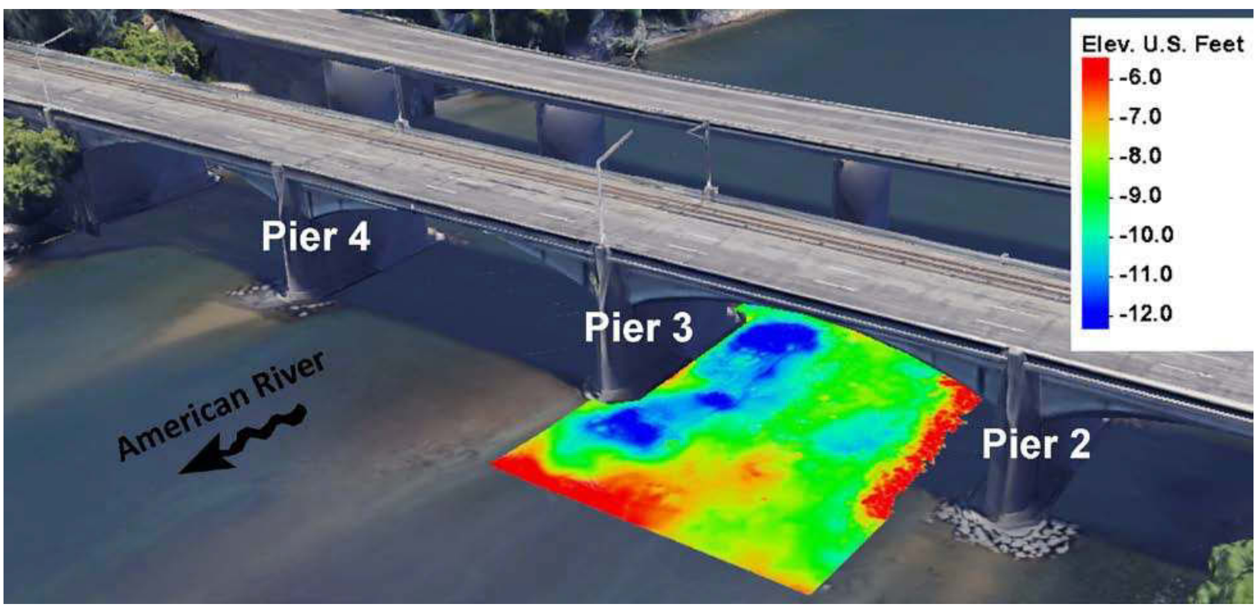

Figure 3.25: Underwater excavation before RSP installation at American River SR160 westbound

Chapter 4:
UAS, LSPIV, and Topographic Mapping Evaluation

Topographic Mapping

SM&I uses the Surface-water Modeling System (SMS) software (https://www.aquaveo.com/software/sms-surface-water-modeling-system-introduction) model to visualize water flow. Topographic elevation data input to the SMS software is vital for accurate modeling. COTS software are available for topographic mapping using aerial images from UAS, but they generally require a license fee. Free software were evaluated to determine if they would meet SM&I's topographic mapping needs.

DroneDeploy for Data Collection

The DroneDeploy App, available on Android and iOS App stores, was evaluated for flight path planning and control as well as triggering image capture for topographic mapping data collection. It can help users to create a flight path to ensure appropriate coverage and overlap of imagery, and it controls the UAS to follow the flight path and trigger the UAS onboard camera at the desired locations. The user can override the system at any time. DroneDeploy supported UAS are limited (see Recommended and Supported Drones [https://support.dronedeploy.com/docs/recommended-and-supported-drones] for details). Caltrans owns a few Mavic Mini2 UASs, which are not supported.

The DroneDeploy Google Android App was used to collect aerial images for topographic mapping with a DJI Phantom 4 Pro V2 UAS at Knights Landing SR113 over the Sacramento River as shown in Figure 4.1. Several detailed DroneDeploy training and tutorial videos are available on YouTube.

Figure 4.1: Aerial image of the SR113 Bridge (Pilot project site) over the Sacramento River at Knights Landing taken by the DJI Phantom 4 UAS

OpenDroneMap (ODM) and WebODM for Data Post-processing

ODM (https://www.opendronemap.org/) is an open-source processing engine that takes images as input and produces a variety of outputs, including point clouds, 3D models, and orthophotos for topographic mapping applications. The generated orthophoto can aid LSPIV processing by helping users to locate the ground targets in the LSPIV videos. WebODM (https://www.opendronemap.org/webodm/) is a free open-source software. It provides a web user interface to process UAS image in ODM and a user interface for selecting Ground Control Points (GCPs) from aerial images. Both ODM and WebODM are in active development and available on Windows, macOS, and Linux.

Both the Windows and Linux versions of WebODM were evaluated using the 679 aerial images collected at Knights Landing. Using the UAS aerial images and selected GCPs, the AHMCT researcher and SM&I personnel successfully used WebODM to generate an orthophoto and topographic point cloud. GCPs improve the resulting point cloud and orthophoto accuracy and allow users to check the resulting product's accuracy.

High-resolution (~2 to 4 cm) orthophoto was first produced by WebODM without any GCPs. The high-resolution orthophoto can help users to identify the location of the GCPs in the aerial image as well as each GCP's ID number. Each GCP has a unique ID number assigned by the user. The user must pinpoint the GCPs in the images and identify associated ID numbers, which can be difficult and time-consuming. The orthophoto can be overlaid with GCPs in Geographic Information System (GIS) software, as shown in Figure 4.2, to aid the target identification process.

Figure 4.2: SR113 pilot study site Ground Control Points (GCP) overlaid on top of orthophoto created by WebODM

An example aerial image with two GCP targets (24" x 24") is shown in Figure 4.3. Some users paint the GCP ID number next to the GCP target. In the case of the Knights Landing dataset, the GCP ID number was not painted next to the target to save field time and reduce environmental impact. Two different size targets (12" x 12" and 24" x 24") were used in the Knights Landing dataset. The 12" x 12" GCP target, shown in Figure 4.4, is 12-in solid black-and-white vinyl tile, which was sold in a pack of 20. A 3/8" hole was drilled at the center of each tile to temporarily secure them to the soft ground with nails. The 24" x 24" GCP targets, shown in Figure 4.3, are foldable and specifically designed and made for aerial mapping application. These are easier to see on a small UAS control screen when capturing LSPIV video. Nevertheless, it can be challenging to locate the GCP targets on screen when collecting video, depending on the background color and scene brightness. When the black-and-white GCP targets were placed on top of white rocks, the shadow cast by the rocks and the white rock background makes finding the black-and-white GCP targets difficult. As a result, some colored GCP targets, shown in Figure 4.5, were purchased for the next test.

Figure 4.3: Example aerial image for topographic mapping. A GCP target (24" x 24") is highlighted with a red square.

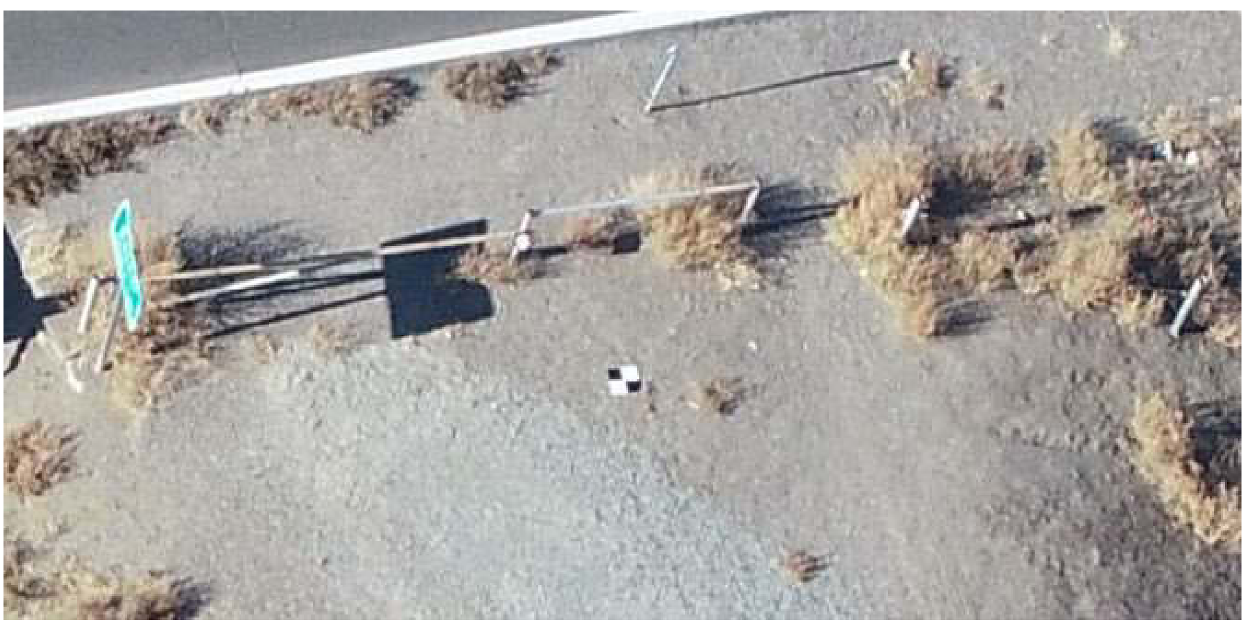

Figure 4.4: Cropped aerial image with a 12" x 12" GCP target

Target placement lesson learned:

- The 12" x 12" GCP targets are suitable to be placed in large open flat areas for topographic mapping
- The GCP targets are easier to identify when placed near large landmarks, such as intersections, light poles, road signs, etc.
- Targets should be placed away from trees and buildings as they obstruct the targets and GNSS signals
- 24" x 24" GCP targets are easier to see when collecting LSPIV video
- Color targets may be more suitable on white rocks

Figure 4.5: Aerotas 16" x 16" biodegradable GCP targets next to ice packs (10" x 13") used as thermal imaging GCP targets

Various WebODM settings were tested to find the best settings for SM&I applications. Online WebODM resources were studied for recommended processing settings. The Knights Landing dataset was processed several times. GCP were used to improve the point cloud accuracy and to check the final result. WebODM allows a user to define presets to automate processing settings. The following text can be copied and pasted into the WebODM preset user interface for a semi-optimized preset:

[{"name": "camera-lens", "value": "brown"}, {"name": "dem-resolution", "value": "2.0"}, {"name": "depthmap-resolution", "value": "1024"}, {"name": "dsm", "value": true}, {"name": "dtm", "value": true}, {"name": "feature-quality", "value": "ultra"}, {"name": "ignore-gsd", "value": true}, {"name": "mesh-octree-depth", "value": "11"}, {"name": "mesh-size", "value": "400000"}, {"name": "orthophoto-resolution", "value": "2.0"}, {"name": "pc-quality", "value": "ultra"}, {"name": "texturing-data-term", "value": "gmi"}, {"name": "use-3dmesh", "value": true}]

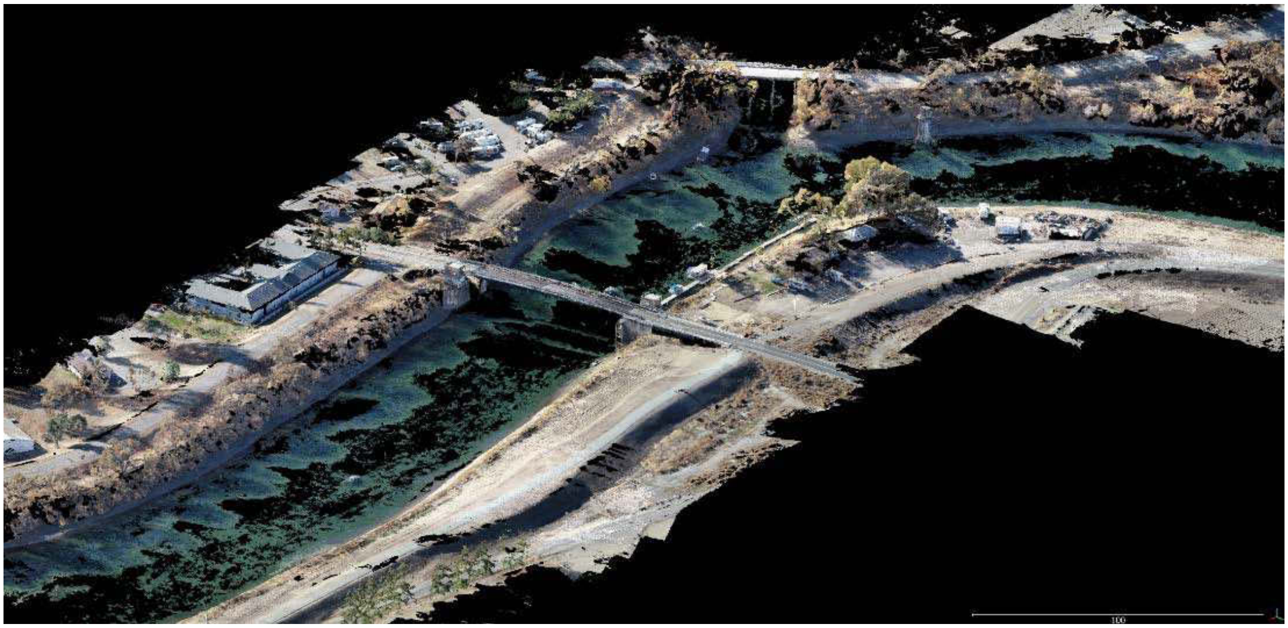

Figure 4.6: SR113 pilot study site point cloud (64 million points) created by WebODM software using 679 aerial images

Figure 4.6 shows the final point cloud of the pilot study site. The depth-map-resolution and orthophoto-resolution affect the computational time. Changing the "feature-quality" and "pc-quality" to medium would lower the computational time. The preset, shown above, is computationally heavy. The processing time ranges from 2 to 6 hours. Most online resources recommend enabling "ignore-gsd" and setting “camera-lens" model value to "brown.”

When processing the data with GCPs in North American Datum (NAD) 83 State plane coordinates, there seemed to be some coordinate conversion errors resulting in a large global coordinate shift in the point cloud. The large global coordinate shift was eliminated when using GCP Universal Transverse Mercator (UTM) coordinates in meters instead. The user should check the resulting point cloud accuracy by importing the point cloud and GCPs into a point cloud viewing software, such as the open-source software CloudCompare. In addition, the user should check the UTM coordinate values in the GCPlist.txt created by WebODM for conversion errors. The vertical errors of the pilot project point cloud were within 0.2 meters (~0.66 feet). New releases of ODM and WebODM are made frequently. Recommendations provided in this report may be outdated. Users should reference the latest online documentation.

ODM and WebODM Online Resources Links

[Tutorials — OpenDroneMap 2.4.7 documentation (https://docs.opendronemap.org/tutorials.html)](https://docs.opendronemap.org/tutorials.html)

[Drones for GIS – Best Practice (https://www.wildlabs.net/sites/default/files/community/files/drones_for_gis_-_best_practice_1.3_0.pdf)](https://www.wildlabs.net/sites/default/files/community/files/drones_for_gis_-_best_practice_1.3_0.pdf)

[DJI Phantom 4 Pro V2 camera calibration (https://community.opendronemap.org/t/dji-phantom-4-pro-v2-camera-calibration/2809)](https://community.opendronemap.org/t/dji-phantom-4-pro-v2-camera-calibration/2809)

[Ground Control Points (GCPs) for aerial photography (https://diydrones.com/profiles/blogs/ground-control-points-gcps-for-aerial-photography)](https://diydrones.com/profiles/blogs/ground-control-points-gcps-for-aerial-photography)

UAS Training

Operation of the UAS requires properly trained Caltrans personnel. At the time of this research, AHMCT did not have a properly trained UAS operator. AHMCT and SM&I used the previously procured UAS to evaluate the UAS-based LSPIV after Federal Aviation Administration (FAA) registration to support UAS pilot training. UAS training classes were conducted at various locations by Caltrans personnel for four new SM&I UAS pilots. The AHMCT researcher supported and attended UAS training sessions. Proficient UAS operation requires many UAS flight hours. SM&I personnel required more practical flight time after the training. Based on this resource gap in the research team, existing SM&I UAS operators operated the UAS to collect the aerial images and video at the pilot project site for topographic mapping and LSPIV analysis.

Figure 4.7: UAS pilot training in June 2020

Capturing UAS-Based LSPIV Video

A pilot study was performed at SR113 over the Sacramento River at Knights Landing in mid-December 2020. SM&I and AHMCT set various GCP targets on the ground and banks of the river before capturing images and videos. ADCP and echo sounder data were collected a day after the LSPIV video capture for comparison and analysis using data fusion of multiple data sources. The LSPIV videos are either 4K or 1080p resolution and are 30 sec to 2 min in length. Video of the same area were captured two to three times.

From the obtained LSPIV dataset, AHMCT performed LSPIV post-processing using both Rectification of Image Velocity Result (RIVeR) and Fudaa-LSPIV to determine river surface flow. AHMCT experimented with ways to geo-reference the LSPIV output export data and converted them into standardized format (comma-separated value [CSV] delimited text) for SMS and GIS software. The LSPIV results were compared with the ADCP measurements.

Figure 4.8: Pilot project site aerial view

LSPIV Software

AHMCT personnel evaluated two freely available LSPIV software: Rectification of Image Velocity Result (RIVeR) Toolbox[5] and Fudaa-LSPIV.[6] Both LSPIV software share the similar concept of operation and steps, but some of their step sequence orders are different.

RIVeR

RIVeR and RIVeR-STIV (http://riverdischarge.blogspot.com/) are tools developed in Matlab and aim to process large-scale water surface characterization like velocity fields or individual trajectories of floating tracers. RIVeR integrated PIVlab[7] (https://pivlab.blogspot.com/) and PTVlab[8] (http://ptvlab.blogspot.com/) as components for LSPIV processing. Based on the RIVeR release history, it is in active development. The latest RIVeR v2.5 was released in September 2020 and compiled with Matlab runtime environment 2015b. It embedded PIVlab 2.36, which was released in June 2020. A RIVeR manual is provided with the software.

In previous years, staff from the U.S. Geological Survey (USGS) Water Science Centers, the National Research Program, and the Office of Surface Water began experimenting with and adapting new surface velocity measurement technologies. They provided webinars (https://my.usgs.gov/confluence/display/SurfBoard/SurfBoard+Webinar+Series) and how-to instructions (https://my.usgs.gov/confluence/display/SurfBoard/How+to+process+a+video+with+RIVeR+Software) on RIVeR software. In addition, the USGS also provided Guidelines for the collection of video for Large Scale Particle Velocimetry (https://my.usgs.gov/confluence/pages/viewpage.action?pageId=546865360).

Other online video training resources are also available:

Calculating Fluid Velocity from a Video (https://www.youtube.com/watch?v=roV5yewOS4c)

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5 A. Patalano and C. García, "RIVeR—Towards Affordable, Practical and User-Friendly Toolbox for Large Scale PIV and PTV Techniques," in *River Flow 2016*, CRC Press. pp. 576-579, 2016.

6 J. Le Coz, M. Jodeau, A. Hauet, B. Marchand, and R. Le Boursicaud, "Image-Based Velocity and Discharge Measurements in Field and Laboratory River Engineering Studies Using the Free Fudaa-LSPIV Software," in River Flow, *Proc. 7th Int. Conf. on Fluvial Hydraulics*, Lausanne, Switzerland, 2014.

7 W. Thielicke and E. Stamhuis, "PIVlab–Towards User-Friendly, Affordable and Accurate Digital Particle Image Velocimetry in MATLAB," *Journal of Open Research Software*, **2**(1), 2014.

8 PTVlab Time-Resolved Digital Particle Tracking Velocimetry Tool for MATLAB (http://ptvlab.blogspot.com/)

Extracting Still Images from Video with FFMPEG (https://www.youtube.com/watch?v=JWNiQMzA3J0)

Tutorial PTVlab (https://www.youtube.com/watch?v=mMIJiRSOc00&)

PIVlab - Background and quick start guide (https://www.youtube.com/watch?v=Sp3Ounq07Qc&)

The USGS recommends approximately 15-25 pixels of movement of particles between consecutive frames. Assuming the computer monitor resolution is 270 dots per inch, 25 pixels of movement would result in 25/270 = .09-in or ~0.1-in of movement between sampling frames. The user can put a ruler on the screen to measure the consecutive frames' particle movement to ensure it is adequate. After the PIVlab processing, PIVlab provides statistics of the particle movement in pixels per sec. The user can adjust the video frame extraction frequency accordingly.

RIVeR allows the user to correct for camera lens distortions if the camera lens model is available. However, the DJI Phantom 4 Pro V2 camera lens model is not available from the RIVeR camera lens model library. There are OpenCV-based software tools available that a user can leverage to develop their own camera lens model.

- Camera Calibration Toolbox for Matlab (http://www.vision.caltech.edu/bouguetj/calib_doc/)
- Tutorial Camera Calibration (https://boofcv.org/index.php?title=Tutorial_Camera_Calibration)

Since the DJI Phantom 4 Pro V2 camera lens is not a super-wide-angle lens with large lens distortion, lens correction was not employed in the pilot project data analysis. Since the videos were captured with the UAS directly over the river with the camera pointing directly down, the two-point rectification method was used to map the pixel movement to velocity movement in meters per second.

The LSPIV results can be exported in a Microsoft Excel format to a file named Summary.xls. The exported Summary.xls Excel file contains four worksheets: X, Y, U, and V. The X worksheet contains the local X coordinates (meter), and the Y worksheet contains the local Y coordinates (meter) in the video orientation. The U worksheet contains flow rate in X-direction (m/s) and the V worksheet contains flow rate in Y-direction (m/s). The video image XY does not align with UTM X- and Y-axes.

Fudaa-LSPIV

The Fudaa-LSPIV open source software (https://riverhydraulics.inrae.fr/en/tools/measurement-software/fudaa-lspiv-2/) has been co-developed and distributed by Électricité de France (EDF) and

Irstea with DeltaCAD since 2010. User days have been organized every year in Lyon since 2017. Fudaa-LSPIV version 1.8.2, a 64-bit Java software, was released in December 2020. It may be downloaded for free from [Fudaa-LSPIV Files (https://forge.irstea.fr/projects/fudaa-lspiv/files)](https://forge.irstea.fr/projects/fudaa-lspiv/files). It requires the 64-bit version of Java to be installed first. There is a [Fudaa-LSPIV Youtube channel (https://www.youtube.com/channel/UCZ8HFyQBfXz1O_pHbiiR7Vg)](https://www.youtube.com/channel/UCZ8HFyQBfXz1O_pHbiiR7Vg) that provides instructional videos. In addition, a Fudaa-LSPIV manual, along with example data, is also provided from the software download site. The software usage steps are very similar to RIVeR.

While RIVeR supports selecting a polygonal shape area of interest, Fudaa supports selecting a quadrilateral shape area of interest. The Fudaa-LSPIV resulting data density is based on the grid that the user specifies. In the pilot project, 30 x 30 was used for Fudaa_LSPIV data, and 40 x 40 (default) was used to the RIVeR LSPIV data. RIVeR/PIVlab provides a graphical interface for filtering the raw results. Fudaa relies on manual input of the maximum and minimum limit value for filtering the raw results. The raw LSPIV result filter in the RIVeR LSPIV user interface is comparatively better and easier to use.

Fudaa-LSPIV can export analysis results into an Excel file format in a single table with Index, X, Y, Norm, Vx, and Vy columns. Norm is the magnitude of the flow rate in m/s. X and Y are the X and Y coordinates in local video frame, and Vx and Vy are the flow rate in X and Y direction in m/s.

Data Export to SMS and GIS Software

As part of the post-processing effort, AHMCT investigated development of a method to support importing LSPIV results into existing 2D hydraulic software, specifically SMS by Aquaveo. Both RIVeR and Fudaa-LSPIV results may be transformed and geo-referenced to a real-world coordinate system, such as UTM, and exported into a CSV-formatted text file.

A Python program can transform the RIVeR LSPIV export output (Summary.xls) and geo-reference the local XY to UTM X and UTM Y coordinates using two GCPs. Using the local XY and the corresponding UTM XY coordinate, the required global translation and rotation to the local XY coordinate can be determined. The local XY coordinate of a GCP may be obtained by using the "Data Cursor" tool. The Data Cursor tool icon is located next to the "Zoom in" icon and under the main "File" menu. The GCPs UTM X and Y coordinates are surveyed using GPS. The flow velocity in true north and east direction can be calculated by applying the rotation transformation to the U and V flow speed. The Python program then outputs the calculated values into text files with columns: UTMX, UTMY, Z, Vx, Vy, Vmag, and Vdir. Vmag is the magnitude of the water flow rate (m/s); Vdir is the water flow direction from the east direction (counterclockwise being positive). UTM_X is the UTM 10N WGS84 X coordinate, and UTM_Y is the UTM 10N WGS84 Y coordinate (EPSG: 32610). Alternatively, Microsoft Visual Basic programing and/or Excel functions can be used to transform and geo-reference the data in Excel depending on the user's skill and preferences.

Figure 4.9: RIVeR Data Cursor icon location (highlighted by a red circle)

A similar method can be used to transform and geo-reference Fudaa-LSPIV exported data using GCPs. The local XY coordinates are displayed at the lower left corner as shown in Figure 4.10. The user may obtain the GCP XY coordinate values by moving the mouse cursor over the GCP position in the extracted video frame. Using GCPs local and UTM coordinates, the user can translate and rotate the all-local XY to UTM XY coordinate values. Similarly, rotation is needed to apply to the Vx and Vy water flow speeds.

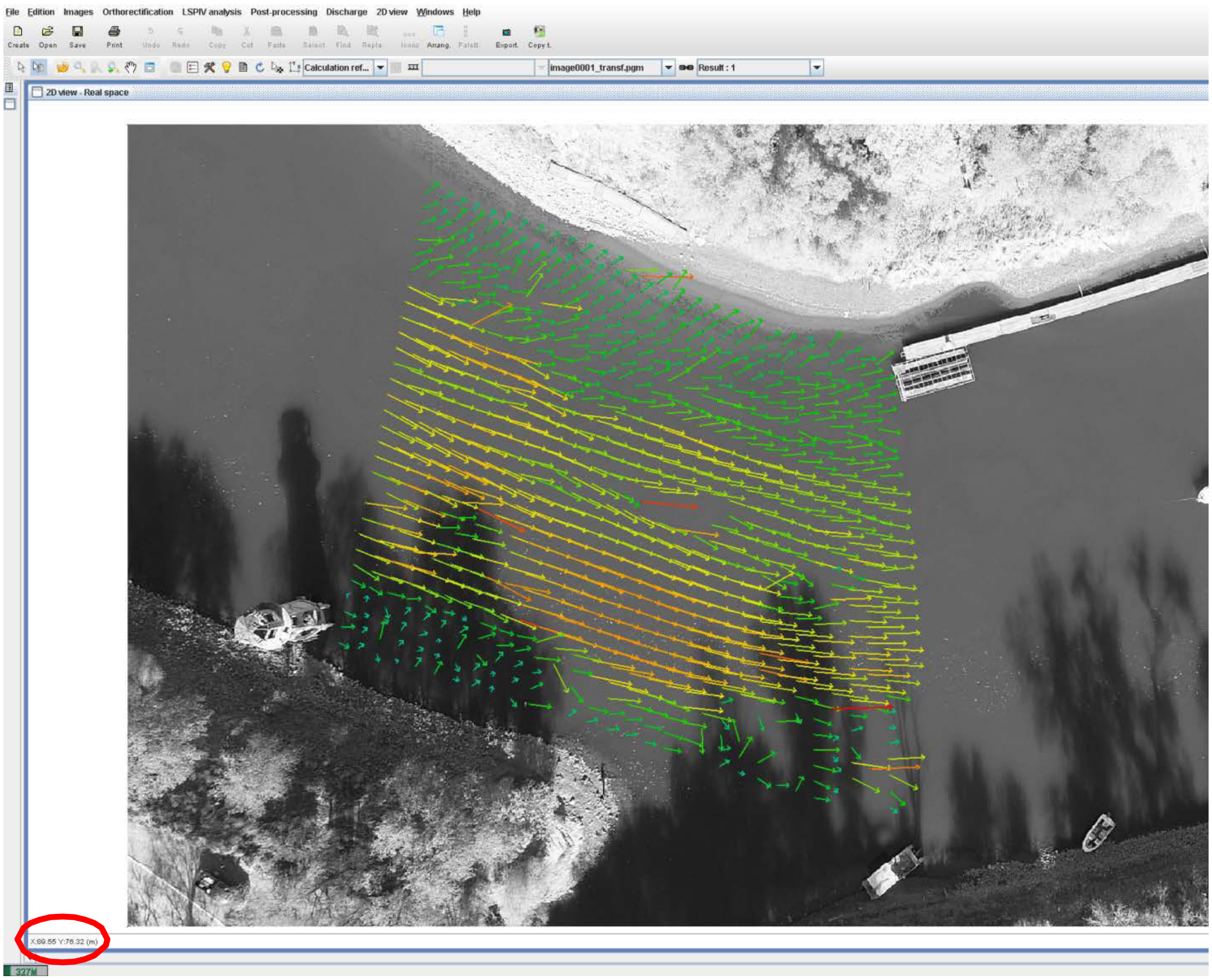

Figure 4.10: Fudaa-LSPIV GUI. The local XY coordinate values under the mouse cursor are displayed in the lower-left corner (highlighted by a red circle at the lower left corner)

Working cooperatively with Caltrans, example datasets were successfully imported into GIS and SMS software. The AHMCT researcher used QGIS (see Figure 4.11 and Figure 4.12) to import the geo-referenced data to check for any errors. Figure 4.11 shows two LSPIV datasets (light blue arrows and yellow arrows) resulted from two different 1080p videos taken a few minutes apart. RIVeR software was unable to provide LSPIV estimates in areas with no data points due to the lack of natural tracers/seeding.

Figure 4.11: RIVeR LSPIV result overlaid on georeferenced orthophoto in QGIS. Area with good natural tracers is highlighted by a white rectangle, and area with poor/no natural tracers is highlighted by a red circle.

Good seeding in the LSPIV video is critical for obtaining accurate and reliable water surface flow velocity. Figure 4.11 and Figure 4.13 show areas with good natural seeding/tracers. LSPIV estimate at the area with poor seeding is unreliable and has poor accuracy. Previous literature suggested various biodegradable materials, such as leaves and biodegradable packing materials, may be used as artificial seeding.[9] However, artificial seeding was not employed in the pilot project.

[9] I. Fujita and S. Aya, "Refinement of LSPIV technique for monitoring river surface flows," in *Building Partnerships*, pp. 1-9, 2000.

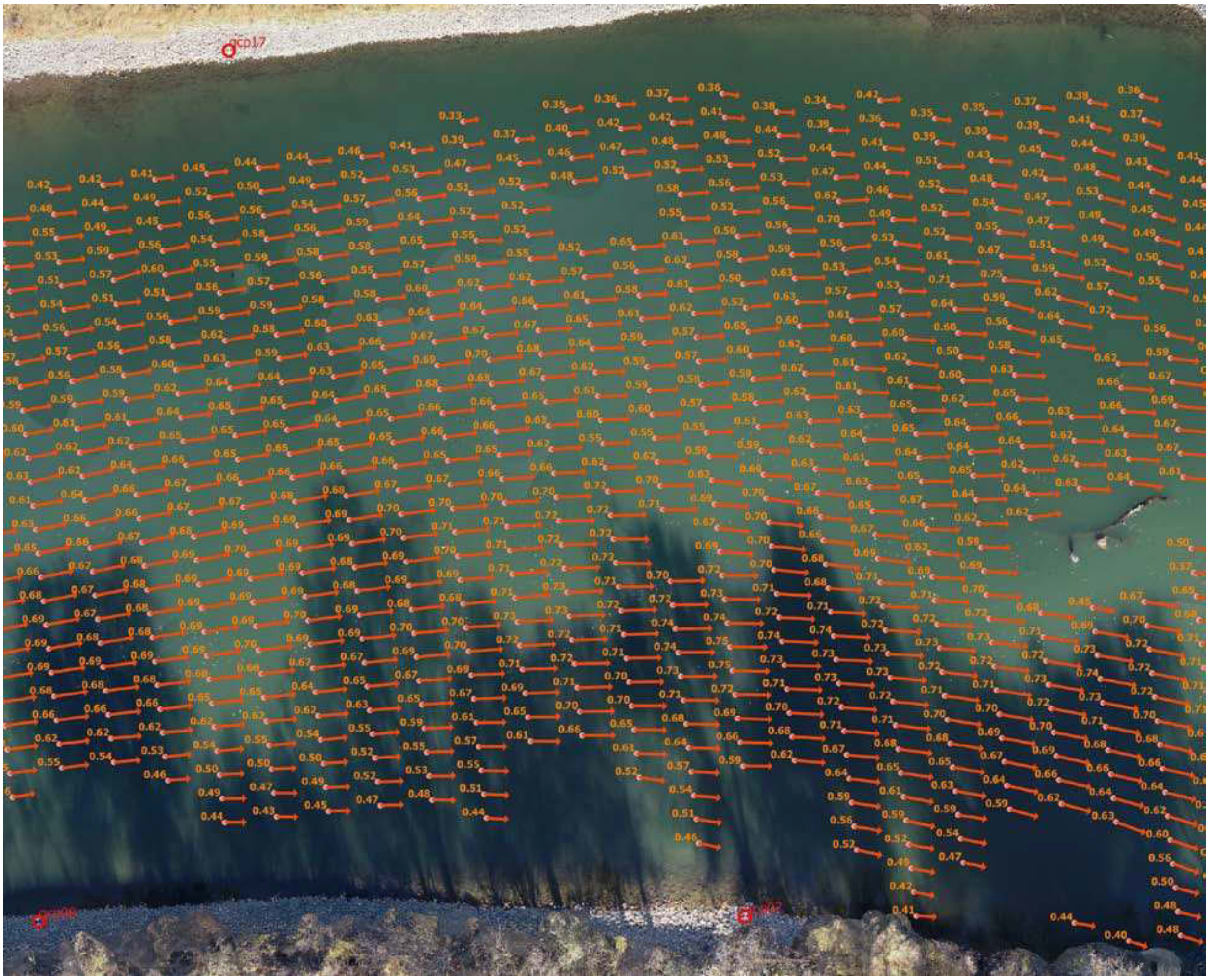

Figure 4.12: RIVeR LSPIV result from a 4K video overlaid on georeferenced orthophoto in QGIS

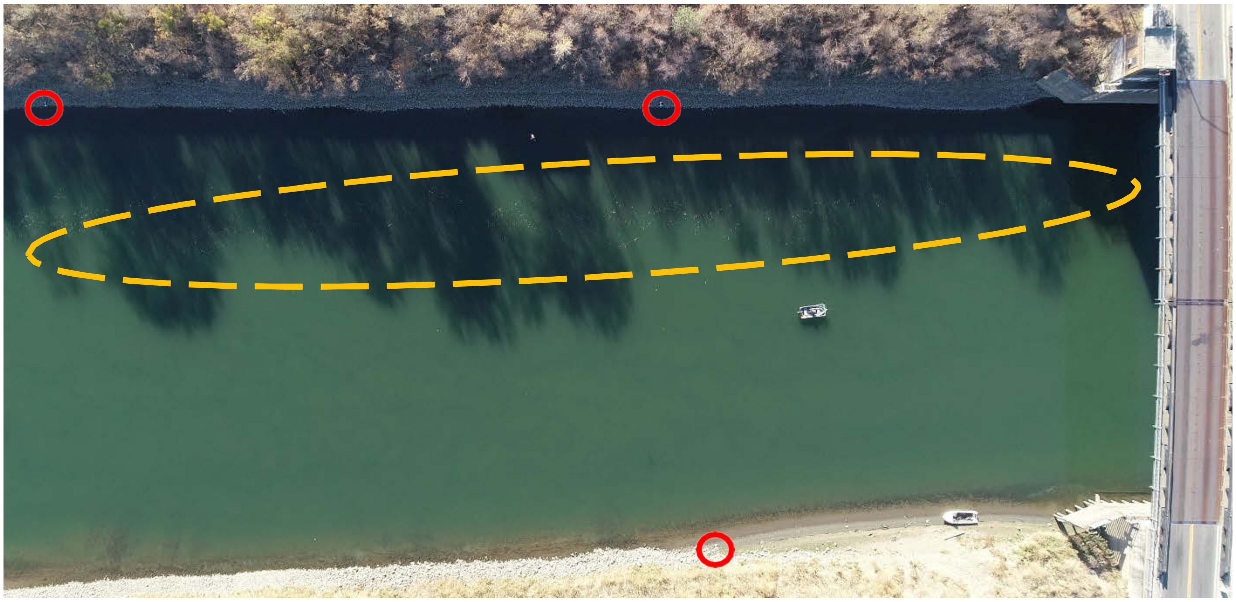

Figure 4.13: Example LSPIV 4K color video capture frame. Area with good, natural seeding is highlighted by a yellow dashed line, and red circles highlight the GCP targets.

Figure 4.14 shows an example of an IR video capture frame. Some natural seeding can be seen in the IR video. However, the majority of the area does not contain any natural seeding. Two 20 lb bags of ice cubes were used as artificial seeding. The ice cubes were roughly 1-in cubes. They were thrown into the river from the bridge at two locations continuously during the video recording. Only a small amount of ice cubes were detected in the video. Some ice cubes melted together and formed larger pieces. Due to the low resolution (640 x 512) of the IR camera, the smaller ice pieces were not detected. More experimentation is need to find a practical way to produce an even distribution of artificial seeding. However, applying artificial seeding to a river over 150-ft-wide will be logistically and practically challenging. Deploying ADCP may be a better option.

Furthermore, it is difficult to distinguish IR GCP targets (10" x 13" ice pack) from the background. The rocky shoreline also presented challenges in placing the ice packs flat and facing upward. Due to the low IR camera resolution, larger ice packs or two ice packs for IR GCP targets may be required. Several large ice packs can be heavy and difficult to transport through steep slopes.

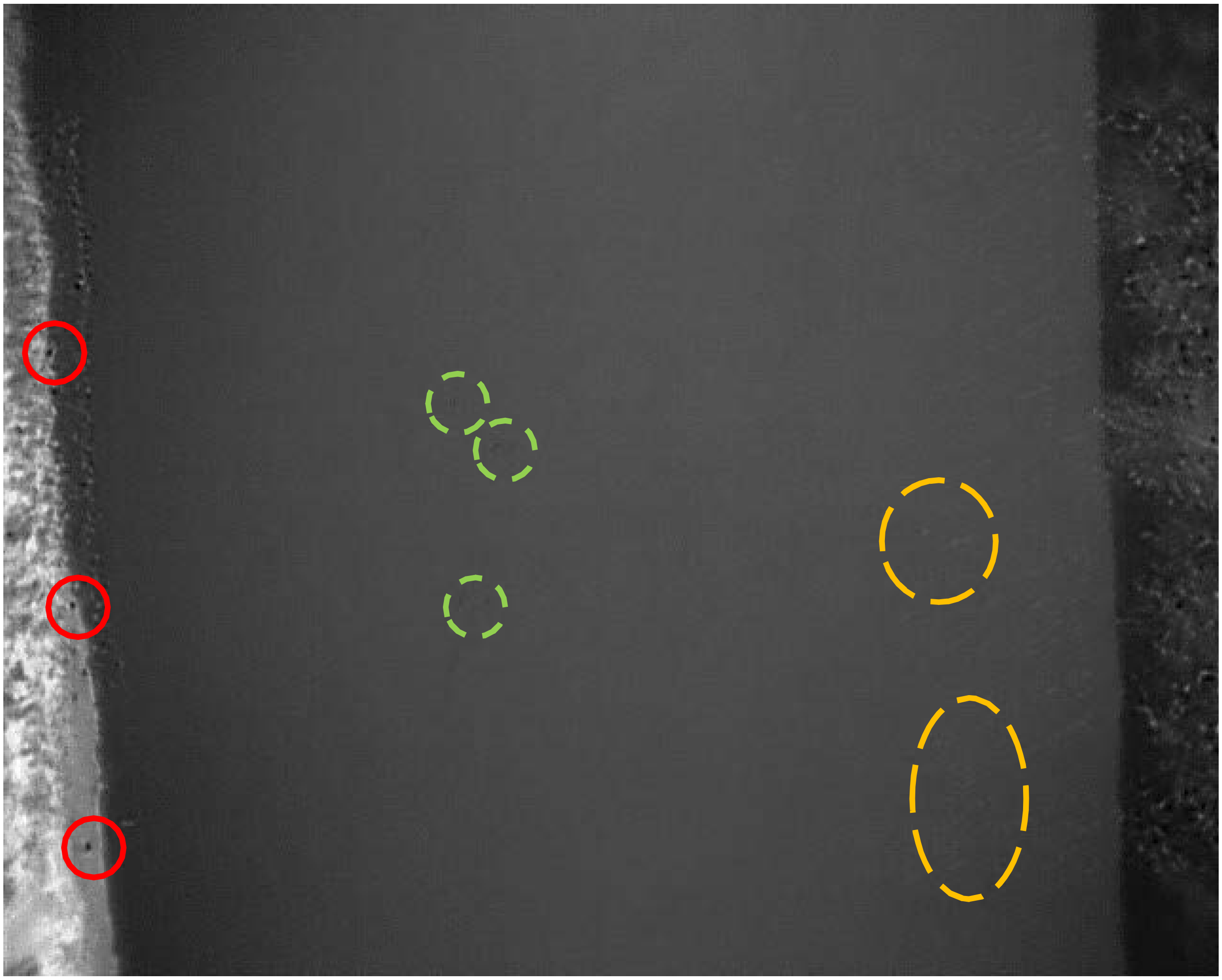

Figure 4.14: Example LSPIV IR video capture frame. Area with good, natural seeding is highlighted by a yellow dashed line. Red circles highlight the GCP targets. Green circles highlight artificial seeding using ice cubes.

Figure 4.15 shows RIVeR LSPIV and ADCP results overlaid on the orthophoto using QGIS. The average ADCP data are represented by light blue arrows, and the orange arrows represent LSPIV results from the 4K UAS color video. The ADCP measures flow velocity at depth, and WinRiver II software measures flow velocity at average depth. The water surface flow velocities are higher than ADCP results. Previous research suggested that a correction factor (Mean Velocity coefficient) of 0.85 should be applied to the surface velocity to match the ADCP results. In Figure 4.15, the Mean Velocity coefficient of 0.85 was applied to the ADCP measurements. The pilot test site LSPIV estimates are generally lower than the ADCP results in an area with good, natural seeding. However, they are within the error limit suggested by the literature.

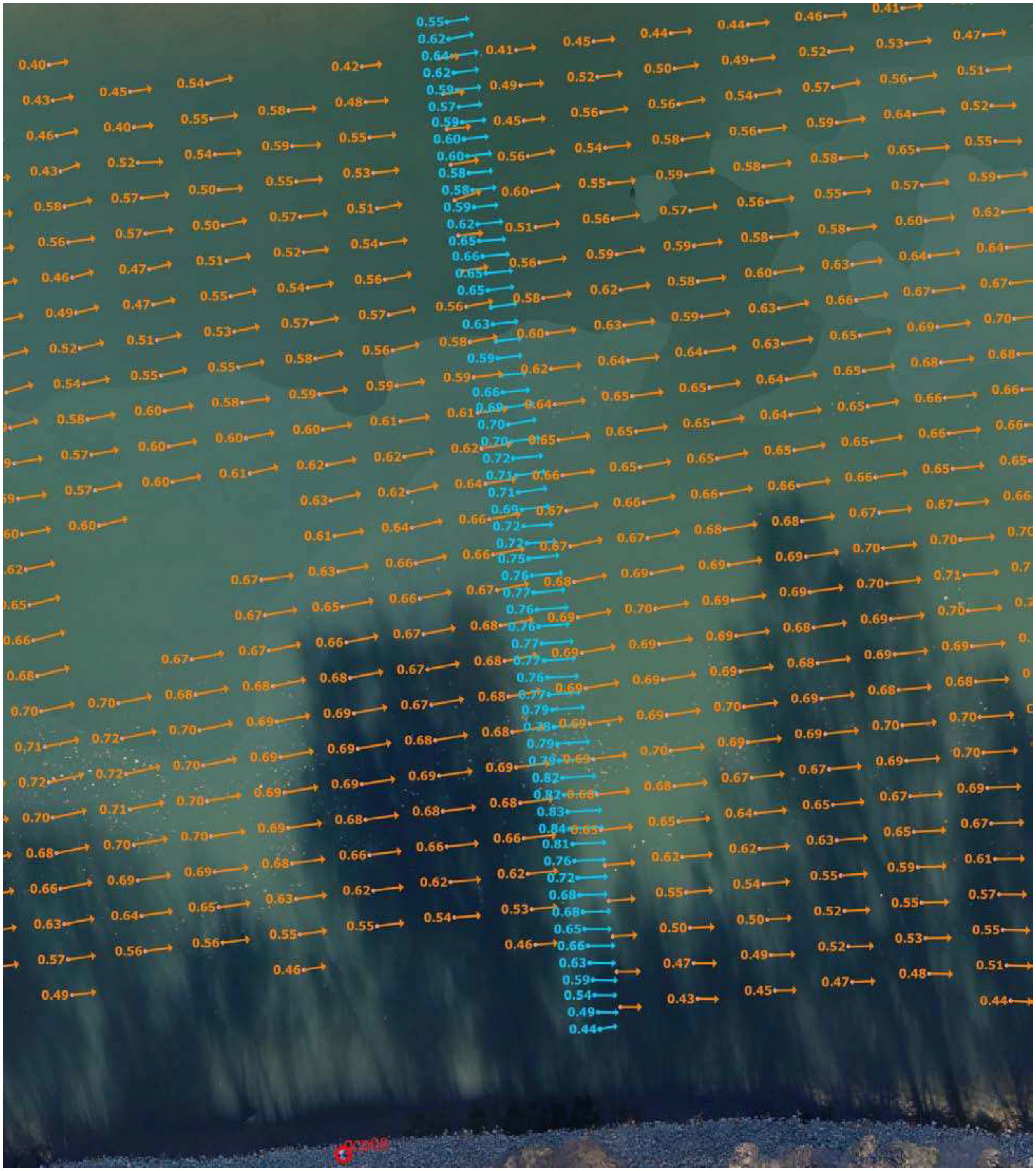

Figure 4.15: RIVeR LSPIV and ADCP result overlaid on the orthophoto. The average ADCP data are represented by light blue arrows, and the orange arrows represent LSPIV results from the 4K UAS color video. The blue text represent the surface flow estimate calculated from the average ADCP measurement values, and the orange text represents the LSPIV estimates.

Lessons Learned

Experiments were conducted to measure water surface flow velocity using UAS equipped with a color camera and a thermal IR camera. The surface flow velocity estimates helped improve hydraulic modeling with SMS software. The DJI Phantom 4 UAS was easy to deploy. However, UAS-based LSPIV has its limitations.

- UAS battery-powered flight time is limited. Six battery packs were used in capturing LSPIV video and topographic images at the pilot test site. Having several fully-charged battery packs is crucial before field operation.
- The Phantom 4 UAS can usually maintain a fixed position during video capture. However, it started to slowly rotate after 20 to 30 seconds of video recording during the pilot study. Better initial UAS IMU calibration may reduce the rotational speed during a fixed position hold. UAS rotational speed increases an LSPIV estimate error and limits the length of video that can be used for LSPIV analysis.
- Lack of natural seeding on the water surface hindered the LSPIV software's abilities to provide accurate results. Special attention must be made to confirm accuracy. When using the RIVeR software for post-processing, the user should consider disabling the interpolate missing data option and Standard Deviation filter if seeding in the video is limited during the Post-processing Vector Validation step in PIVlab. By default, both options are enabled in PIVlab.
- An environmentally-friendly, low-cost, safe, and practical way to spread artificial tracers/seeding in a medium to large river is needed to obtain desired flow velocity accuracy.
- The current Phantom 4 UAS does not support High Dynamic Range (HDR) video recording. Areas in full sunlight tend to be overexposed, and areas in the shade tend to be underexposed. The overexposure of GCP targets in the video hindered determining target location by the user during video recording and post-processing.
- Current LSPIV software does not support combining LSPIV estimates from multiple videos.

Advantages of topographic mapping using UAS images include:

- Low cost (equipment, software, and time) compared to using a Light Detection and Ranging (LiDAR) scanner and other traditional survey methods
- Suitable for use in mapping large areas

- Improved worker safety by eliminating the hazard of workers traversing through difficult terrain with heavy survey equipment, such as a LiDAR scanner, tripod, and batteries

Disadvantages of topographic mapping using UAS images include:

- Not suitable in areas with heavy vegetation. Data collection in fall or winter time may result in better data.
- FAA and Caltrans policies may restrict the use of UAS in some areas

Chapter 5: Deployment and Implementation

Problems and Issues that Affected Product Deployment

Manned Boat Bathymetric Survey Platform

1. The Advanced Navigation Spatial Dual GNSS/IMU system did not perform as expected in pilot studies. The original Spatial Dual GNSS antennas were determined to be broken. Funding for Two Tallysman Wireless, Inc., triple-band (L1/L2/L5) VSP6337L-58 GNSS antennas is needed to replace the broken antennas.
2. Overhead bridge structures often obstructed GNSS signal and degraded the Spatial Dual GNSS/IMU system positional accuracy and availability.
3. The battery run time was limited for the current rugged Dell Laptop used for data collection. Additional battery run time is needed for eight hours of full day data collection. In addition, the laptop's low-resolution display limited the ability of users to view all live data from both the GNSS/IMU system and the bathymetric sensors at the same time.
4. The sensor mount was damaged when the MBES sensor collided with a shallow sandbar during data collection. It was repaired afterward.

UAS

1. LPSIV GCP targets can be difficult to locate and see on the UAS controller display when recording color and IR video for LSPIV analysis. Target size, shape, color, and background play a major role. Larger targets may be required for a river over 150-ft wide. Alternatively, the operator may consider capturing video on half of the river at a time.
2. Uneven lighting conditions, such as heavy shade on one side and strong directional sunlight on the other side, reduces video quality and GCP target visibility. Targets in shaded areas tend to be more visible. Video capture at different time of the day could mitigate the effect of lighting.

Solutions to Noted Problems and Issues

1. The Spatial Dual GNSS receiver board firmware can be upgraded to enable Galileo GNSS signal, which would improve its performance in

GNSS-challenged conditions, such as near a bridge. SM&I is pursuing funding for GNSS receiver upgrade as well as antenna replacements.

2. Replacing the current rugged laptop with a laptop with higher-resolution sunlight-readable display and hot-swappable batteries would increase system runtime and improve operation. The use of a laptop docking station may reduce setup time and cabling complexity.
3. Enhanced manned boat bathymetric sensor platform design would reduce system setup and breakdown time in the field. Sensor mount enhancement could mitigate damages that may be caused by collision with shallow sandbars.
4. UAS with built-in RTK or PPK capability may reduce the need for placing and surveying GCP targets in topographic survey.

Issues Expected to Affect Full Implementation

None

Other Considerations for Reaching Full Product Deployment

Equipment Issues

1. A backup camera on the equipment truck would aid and speed up the recovery of the foldable boat with a trailer.
2. Optimization of the battery power supply system of the bathymetric survey system would simplify power connections and extend duration of usage.

Operational Issues

1. Caltrans lacks UAS pilot training facilities. Proficient UAS pilot training requires many flight hours and investment of personnel time. Training site(s) would facilitate this.
2. Site reconnaissance may be required to ensure sufficient natural seeding/tracer is available. Otherwise, a practical plan should be made to spread artificial seeding. The amount of seeding materials and number of personnel involved would depend on the river flow speed and width.

Policy Issues

FAA and Caltrans UAS flight policies may restrict the use of UAS in some areas. Traditional bathymetric survey methods and LiDAR may be the only solution in UAS flight-restricted areas.

Chapter 6: Conclusions and Future Research

The primary objective was to enhance the current Caltrans SM&I topographic and bathymetric survey operations. Topographic and bathymetric surveys are vital for modeling water channel flow and early detection of bridge scour. This research project successfully designed, integrated, and deployed a manned boat-based bathymetric survey system composed of GNSS/IMU positioning system, MBES, ADCP, and single beam echo sounder sensors. This task was more substantial than originally anticipated. SM&I utilized the newly integrated bathymetric survey system in several pilot projects to monitor scour, RSP, and underwater riprap installations. Furthermore, Caltrans divers have used 3D images of piers and surrounding bathymetry to plan their dives. SM&I has also inspected underwater excavations before RSP installation for Caltrans Construction. There may be more potential Caltrans use cases that could benefit from the MBES bathymetric survey results. The pilot project results were presented at a Caltrans ABME meeting.

In addition, this project deployed COTS UAS to:

1. Collect aerial images to generate topographic point clouds and digital terrain maps as well as high-resolution orthophotos
2. Capture videos to measure water surface flow using LSPIV technology

This report documented the experiences and lessons learned in capturing UAS video with GCP targets and LSPIV processing. UAS proved effective in collecting aerial images for a large area over a short time for topographic mapping using WebODM software. The combined bathymetric, topographic, and LSPIV data were applied in hydraulic modeling using SMS software.

UAS pilot training remains challenging due to lack of facilities and ample personnel time investment to complete a sufficient amount of practice flight hours. UAS-based LSPIV is a complementary tool to ADCP with echo sounder for measuring water flow velocity. UAS-based LSPIV works well for rivers with high flow rate and a large amount of natural seeding/tracers on the water surface.

Benefit of the Research

The manned boat-based bathymetric survey system enables Caltrans' early detection and identification of bridge scour, improving the safety of the traveling public and reducing hazards and exposure for divers. This research improved worker safety and efficiency of estimating flood flows using LSPIV technology to meet Caltrans' hydraulic needs. The final mapping system enables Caltrans SM&I to perform topographic and bathymetric survey efficiently. This research has enhanced SM&I's topographic and bathymetric mapping capabilities, resulting in enhanced stewardship and efficiency as well as directly supporting Caltrans' goals of System Performance and Organizational Excellence.

Future Work

- Develop a camera lens model to improve LSPIV accuracy
- Enhance existing manned boat-based sensing platform
  - Improve the battery power system to support full-day operation of the topographic and bathymetric mapping system
  - Explore the integration of LiDAR to provide topographic mapping capabilities in areas where UAS operation is prohibited
- A small Unmanned Surface Vessel (USV) platform with integrated topographic and bathymetric mapping sensors (GNSS/IMU, MBES, and LiDAR) may enable surveys to be conducted in challenging environments, such as high-flow flood conditions and shallow water where using a manned boat may infeasible or hazardous. LiDAR enables topographic mapping in areas where UAS operation is prohibited due to policies and regulations. In addition, a small USV could be rapidly deployed near bridges without the need for a boat launch, and the boat launch could potentially take place at a distance from the bridge. Small USV would shorten deployment time and traveling time to the site. Thus, measurements can be made quickly and efficiently, enabling mapping of scour of multiple sites in one day during a flood. This is critical since flood conditions may not last for long.
- Evaluate the use of a small USV-based topographic and bathymetric sensing system
  - Evaluate the use of MBES on a small USV
  - Pilot test USV deployment near bridges in flood and non-flood conditions for bathymetric mapping
  - Experiment and document best practices for safe and secure deployment, operation, and retrieval of small USV

Appendix A:
Cable Pin-out Documentation

Table A.1: Advanced Navigation Spatial Dual cable harness connector pin-out

Pin	Color	Function	Primary DB9 Socket Pin	Auxiliary DB9 Socket Pin	GPIO DB9 Socket Pin	BNC	Power
1	Black	Signal Ground	5	5	5	Shield / Ground	NC
2	Brown	Power	NC	NC	NC	NC	1
3	White	GPIO1	NC	NC	2	NC	NC
4	Green	GPIO2 (1 PPS)	NC	NC	NC	Center Conductor	NC
5	Red	Primary RS232 TX	2	NC	NC	NC	NC
6	Orange	Primary RS232 RX	3	NC	NC	NC	NC
7	Yellow	Auxiliary RS232 TX	NC	2	NC	NC	NC
8	Blue	Auxiliary RS232 RX	NC	3	NC	NC	NC
9	Pink	Power Ground	NC	NC	NC	NC	2