PNNL-Tech-Report

ThermalTracker-3D

Offshore Validation Technical Report

April 2022

Shari Matzner
Thomas E. Warfel
Ryan Hull
Nolann Williams

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor Battelle Memorial Institute, nor any of their employees, makes **any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights**. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or Battelle Memorial Institute. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

PACIFIC NORTHWEST NATIONAL LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC05-76RL01830

Printed in the United States of America

Available to DOE and DOE contractors from the
Office of Scientific and Technical Information,
P.O. Box 62, Oak Ridge, TN 37831-0062;
ph: (865) 576-8401
fax: (865) 576-5728
email: reports@adonis.osti.gov

Available to the public from the National Technical Information Service
5301 Shawnee Rd., Alexandria, VA 22312
ph: (800) 553-NTIS (6847)
email: orders@ntis.gov <https://www.ntis.gov/about>
Online ordering: http://www.ntis.gov

ThermalTracker-3D

Offshore Validation Technical Report

April 2022

Shari Matzner
Thomas E. Warfel
Ryan Hull
Nolann Williams

Prepared for
the U.S. Department of Energy
under Contract DE-AC05-76RL01830

Pacific Northwest National Laboratory
Richland, Washington 99354

Summary

Wind energy is a sustainable source of electricity, and offshore winds are a particularly rich resource. To harness this energy with minimal impacts on the environment requires understanding the effects of offshore wind development on wildlife such as seabirds and bats. Quantifying these effects on seabird and bat populations is challenging due to the remoteness of and harsh conditions at offshore locations.

DOE's Wind Energy Technology Office has funded the development of technology for understanding wildlife impacts to accelerate the development of offshore wind energy in the US. The ThermalTracker-3D (TT3D) technology was developed by the Pacific Northwest National Laboratory (PNNL) with DOE funding as a method for continuously monitoring bird and bat activity at remote locations, such as those offshore. Its detection and 3-D tracking capabilities were validated on land in 2019. To validate its performance offshore, in 2021 a marinized prototype TT3D was integrated with a Wind Sentinel™ buoy and deployed offshore. This report describes that initial offshore validation of the TT3D system for monitoring and quantifying bird and bat activity at offshore wind energy sites.

The buoy was deployed with the integrated ThermalTracker-3D at an area planned for wind energy development, 25 nautical miles off the coast of northern California. The buoy's primary mission is to characterize the wind energy resource by measuring the wind speed and direction in the air column, up to 250 meters above the water surface. It provided a platform with power and a data link to shore for the TT3D. The TT3D camera assembly was mounted atop a camera stabilization system to hold the cameras relatively steady as the buoy was subjected to wave motion. The stabilizer stopped functioning early in the deployment; however, the TT3D continued to operate, and the situation provided an opportunity to study platform motion effects on the TT3D performance.

The prototype TT3D system operated continuously from May 4 through Aug 13, 2021 (14 weeks), at which time the buoy generator failed. Using data collected during the operational period, the technology was evaluated in terms of its reliability, output data quality, motion effects, hardware component performance, and platform integration.

The software operation and reliability largely exceeded expectations. The software ran autonomously without failure throughout its deployment and the associated scripts managing the disk space successfully maintained a healthy margin of free space, while those composing the status messages transmitted to shore through the buoy system ran reliably, providing continuous insight into the TT3D system's health and status. Hardware – cameras, GPS, computer -- performed reliably and the platform integration worked well; the mechanical integration was secure and no failures of any connections or attachment points have occurred to date.

During the operational period, the TT3D recorded 2,440 valid 3D flight tracks, many of which were recorded during non-daylight hours. A review of a sample of the TT3D data revealed that the detection rate was lower than expected – 44% compared to 89% from previous testing. The settings that control the sensitivity of the detection algorithm were tuned remotely during the deployment, and the detection rate increased to 52%, indicating that further tuning could possibly have produced additional improvement. The platform motion may also have reduced the detection rate. A random sample of 205 detections was reviewed and 80% were recognizably birds. The other 20% appeared to be blurred by motion and were unrecognizable.

Camera motion was characterized by the rate of pitch, roll and yaw in degrees per second that occurred as an animal flew through the field of view. Most detections occurred with motion rates less than 15 deg/sec. The detections during motion greater than 5 deg/sec were more likely to be blurred and/or unrecognizable. The validity of the 3D tracks as determined by the geometry of the stereoscopic field of view was found to be more affected by the animal's distance from the camera than by the camera motion. The distance effect is expected due to the nature of the stereo vision processing, which becomes less accurate for far away small objects. Extreme camera motion greater than 30 deg/sec did reduce the probability of a 3D track being valid.

This study successfully built an offshore prototype capable of autonomous long-term operation in an offshore environment, successfully integrated the prototype with a buoy, confirmed the reliability of the software, improved our understanding of the effects of motion, and collected seabird data for analysis and species identification, including data not previously available such as nocturnal activity and flight heights. Recommendations for future efforts and system improvements are as follows:

- Improve the detection rate by developing a workflow for tuning the detection sensitivity to the operating environment prior to deployment.
- Improve camera stabilization and add motion compensation in the software, as needed, to minimize motion effects from a floating platform.
- Optimize the computer and storage for constrained environments using the latest technology to increase the flexibility of the system.
- Develop automated taxonomic identification using data collected during this study combined with human observer data collected during a coincident survey of species in the buoy location.

Acknowledgments

This work was funded by the U.S. Department of Energy, Wind Energy Technology Office.

The buoy integration work was performed by AXYS Technologies, Inc. of Sidney, BC, Canada.

Acronyms and Abbreviations

BOEM	Bureau of Ocean Energy Management
DOE	Department of Energy
GPS	Global Positioning System
IMU	Inertial Measurement Unit
OSW	Offshore Wind
PH	Perfect Horizon camera stabilization system
PNNL	Pacific Northwest National Laboratory
RSZ	Rotor-Swept Zone
TBD	To Be Determined
TT3D	ThermalTracker-3D

Contents

Figures

Tables

1.0 Introduction

1.1 Background

Wind energy is a relatively clean, sustainable source of energy for generating electricity compared to fossil fuels. However, wind turbine presence and operations do affect wildlife. To make informed decisions that weigh the costs and benefits of developing offshore wind energy at a particular location, accurate characterization of the wildlife presence is needed. The potential effects of offshore wind energy development on the species and ecosystem of the site must be understood by data collection and analysis. The relevant data are the abundance and occurrence patterns of species, and their behavior in the proposed development area. For example, the flight behavior of seabirds – altitude, speed, direction and responses to wind conditions – all factor into quantifying the potential risk posed by offshore wind energy development (Masden and Cook, 2016). By collecting the right data from the start, we can learn as we go and continue to develop ways to generate clean, sustainable energy from wind.

Quantifying seabird and bat activity at offshore locations is challenging. Traditionally, such data were collected by conducting ship-based surveys with trained observers. Over the years, surveys have provided valuable data on large-scale population patterns and seasonal movements. However, the data that can be obtained from surveys is limited. Surveys can only be conducted during fair weather and during daylight. Many seabird species are active at night, and their nocturnal behavior may be influenced by light levels (Regular and Hedd 2011). There is evidence the seabird flight height varies in response to wind speed (Ainley et al 2015), but even trained observers cannot accurately estimate flight height at the higher altitudes relevant to offshore wind turbines. More recently, airborne surveys using both observers and digital video are conducted to collect baseline wildlife data at proposed wind energy development areas. Although airborne surveys, especially with digital images, have advantages over ship-based surveys, they suffer from the same limitations in terms of being limited to daylight and fair conditions. To overcome these limitations and fill in the gaps left by surveys, there is a need for remote sensing technology that can collect data continuously, both night and day, and in a range of weather conditions to fully understand and quantify offshore seabird presence and behavior.

Over the last decade, the US Dept. of Energy (DOE) has funded research and development of technology to meet this need, including the ThermalTracker-3D. This report describes the initial offshore validation of the ThermalTracker-3D technology for monitoring and quantifying bird and bat activity at offshore wind energy sites. The goal of the validation was to assess the system suitability for its intended purpose and the system readiness for offshore operations. The results will inform future deployments.

This report is intended for researchers, regulators and conservationists interested in understanding the effects of offshore wind energy development on seabirds, who need technology for collecting baseline data at a proposed site prior to construction and for monitoring post-construction effects.

1.2 ThermalTracker-3D Technology

The ThermalTracker-3D (TT3D) technology is software that generates 3D tracks of animals moving through a volume of space. From these data, statistics can be calculated such as the number of animals present by time of day, flight speeds, flight height, and the number of animals passing through the rotor-swept zone (RSZ) of a hypothetical or actual wind turbine. The statistics can then be used as inputs to collision risk models for siting and pre-construction risk assessments. The data also provide a pre-construction baseline of abundance and occurrence that can be compared to post-construction data to quantify avoidance behaviors that may reduce collision risk but lead to displacement and habitat loss.

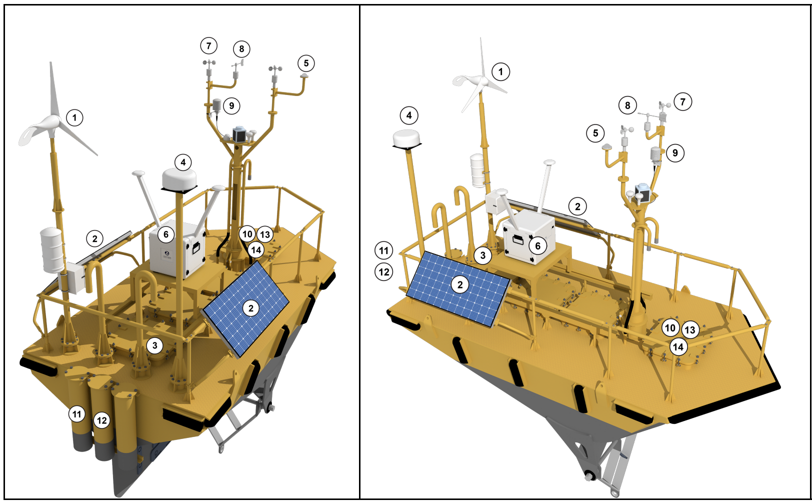
The TT3D software processes the video streams from a stereo-pair of thermal cameras in real-time, extracting animal flight track data to quantify animal activity with high resolution, both spatially and temporally. The thermal sensors are equally effective both night and day and in most weather conditions (exceptions include heavy rain or dense fog).

The TT3D was designed primarily to quantify the seabird activity at offshore wind energy sites before and after construction. In 2020, the Bureau of Ocean Energy Management (BOEM) partnered with the DOE and PNNL to deploy two Wind Sentinel buoys in potential lease areas off the coast of California. The buoy deployment afforded an opportunity to validate the TT3D performance in an offshore pre-construction environment.

1.3 DOE Lidar Buoys

A major impediment to persistent baseline data collection at proposed sites is the lack of infrastructure to support remote sensing technology. One solution is buoys large enough to support multiple instruments, such as wind-profiling buoys. These buoys are typically deployed in in areas being considered for wind energy projects to characterize the wind energy in fine spatial and temporal detail for a year or so prior to development. In 2014, the DOE purchased two WindSentinel™ buoys (AXYS Technologies, Sidney, BC, Canada) for this purpose (Figure 1-1) The buoys are outfitted with a suite of oceanographic and meteorological instruments, the primary being a wind-profiling lidar. The buoys provide a robust offshore platform and sophisticated power and data management systems. Data from the buoys are transmitted to shore regularly and archived on DOE's Atmosphere to Electrons Data Portal[1] hosted by PNNL. These data are available to the public.

This report describes the first trial of integrating a wildlife sensor, the TT3D, with a wind-profiling buoy. The addition of wildlife sensing technology to the buoys would add value to the already highly valuable data archive. Wildlife activity could then be correlated with weather conditions, especially wind speeds and direction, to inform planning and permitting.



Power & Data Communications

1. Turbine
2. Solar panels
3. Diesel generator (compartment)
4. Satellite antenna

Meteorological

5. Solar radiation
6. Wind profile
7. Wind speed
8. Wind direction
9. Air temperature & relative humidity
10. Barometric pressure (compartment)

Oceanographic

11. Water velocity profile (stern)
12. Conductivity and water temperature
13. Wave spectrum (compartment)
14. Sea surface temperature (compartment)

Figure 1-1. DOE Wind Sentinel buoy

---

[1] https://a2e.energy.gov/data

2.0 Validation Methods

For the offshore validation of the TT3D technology, an offshore prototype was designed and built by PNNL. The prototype system was then integrated with the WindSentinel™ buoy by AXYS Technologies, Inc. (Sidney, BC, Canada). The buoy was deployed by AXYS in the California Humboldt Wind Energy Area.

2.1 Offshore Prototype

An offshore prototype ThermalTracker-3D system was designed and built at PNNL (**Error! Reference source not found.**). A complete list of components including model numbers is provided in Appendix A.

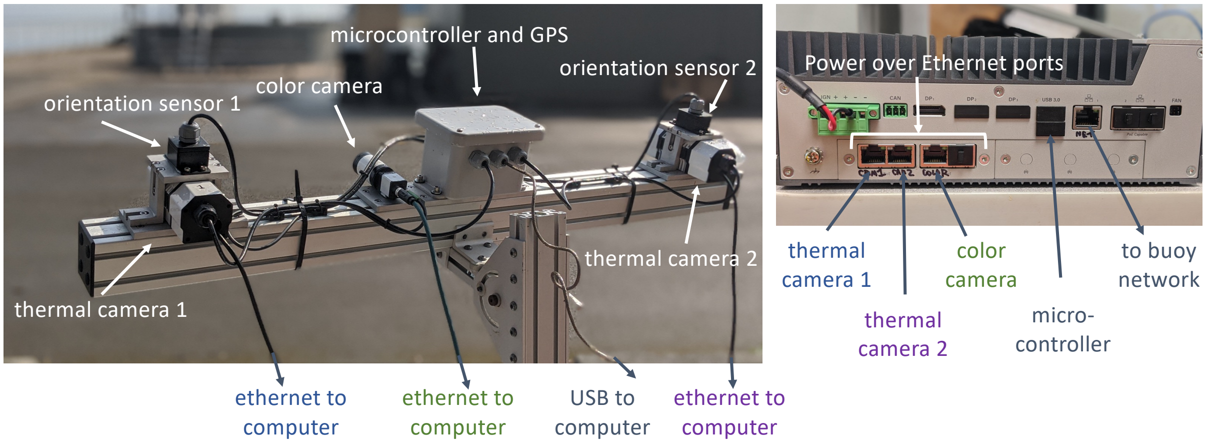


Figure 2-1. ThermalTracker-3D offshore camera assembly (left) and computer (right).

Previously, a prototype system had been assembled for validating the 3D tracking capability on land (Matzner et al, 2020). Several design changes were implemented for the offshore prototype. A color camera, microcontroller, GPS and two inertial measurement units (IMUs) were added. The camera assembly mounting bar, brackets, cables and connectors were upgraded to marine-grade standards. A dedicated computer was added to replace the laptop used for the previous validation study. Scripts were developed to monitor the system health and status, to manage data and to facilitate updating the software remotely.

The color camera was added to capture images of detected animals to aid in species identification. A triggering mechanism was added to the TT3D software to save images from the color camera during times when animals were detected in the thermal video.

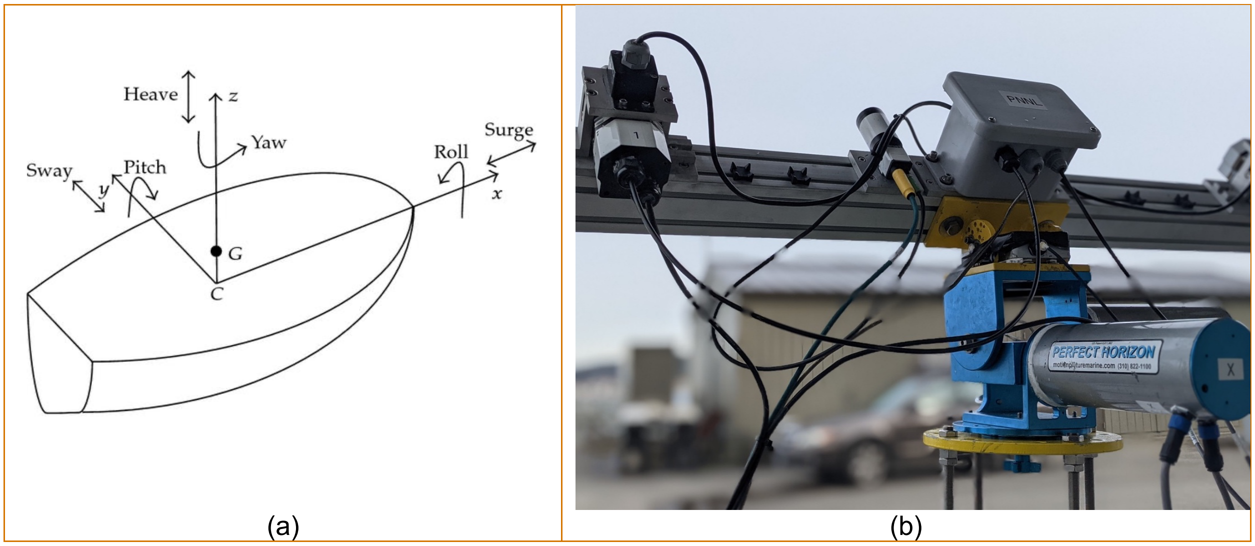
The microcontroller uses the GPS to obtain a precise timing signal to synchronize the frame capture of all the cameras and to timestamp the acquired images with millisecond precision. The previous prototype relied on software frame synchronization and the computer system clock for timestamps, which was not accurate over time. Precise frame synchronization is necessary for optimizing the accuracy of the stereo-vision processing that calculates the 3D position of objects in the 2D imagery. Precise timestamping of the data makes it possible to combine the TT3D data with that of other sources, such as the buoy's lidar wind profiler and other buoy instruments.

The IMUs – one mounted on top of each thermal camera – provide the orientation of the camera in space. The orientation data, along with the GPS location, is used to translate the output 3D track data into geo-referenced coordinates, including altitude (flight height). The IMU data could also be used for software motion compensation, although we did not have time or resources to implement that for this validation study.

The dedicated computer runs the TT3D software and scripts. The computer also provides power to the cameras via power over ethernet. This simplifies the cabling and the whole system is powered by a single power input to the computer. The computer was configured with a 2 Tb solid state disk to provide fast, reliable storage capacity. The fanless design means the chassis is solid with no vents that could allow moisture inside.

2.2 Camera Stabilization

One of the primary technical challenges for offshore operation from a floating platform like the Wind Sentinel buoy is platform motion. The TT3D algorithms assume that the cameras are stationary relative to the Earth's reference frame. When the buoy is deployed offshore, it is subject to wave motion that results in rotation and translation of the buoy and its instruments (Figure 2-2a).



(a) (b)

Figure 2-2 a) Types of Vessel Motion (Ibrahim and Grace, 2010) b) The TT3D camera assembly mounted on the Perfect Horizon stabilization system.

A commercial camera stabilization system, the Perfect Horizon, was selected to stabilize the TT3D camera assembly during the deployment (Figure 2-2b). The Perfect Horizon (PH) was originally developed for use by the movie industry for filming from a boat. To support the validation deployment, the PH was re-engineered for autonomous operation. The PH corrects for pitch and roll motion at rates up to 35 degrees per second.

2.3 Buoy Integration

The ThermalTracker-3D and the Perfect Horizon were integrated with DOE's Wind Sentinel buoy by AXYS Technologies. The camera assembly was mounted on a purpose-built mast at the bow of the buoy and the computer and electronics were mounted below deck in a watertight compartment (Figure 2-3). Cables from the below-deck enclosure were routed through the mast for power and data connections. Inside the enclosure, power relays were installed so that the power to the ThermalTracker and the Perfect Horizon could be controlled remotely. The ThermalTracker computer and the Perfect Horizon controller were connected to the buoy's internal network. Both systems could be accessed remotely via the buoy's satellite link. The TT3D was integrated with the buoy's data management system and configured so that the output data (bird detections) were transmitted to shore every hour and status data were transmitted every 15 minutes.

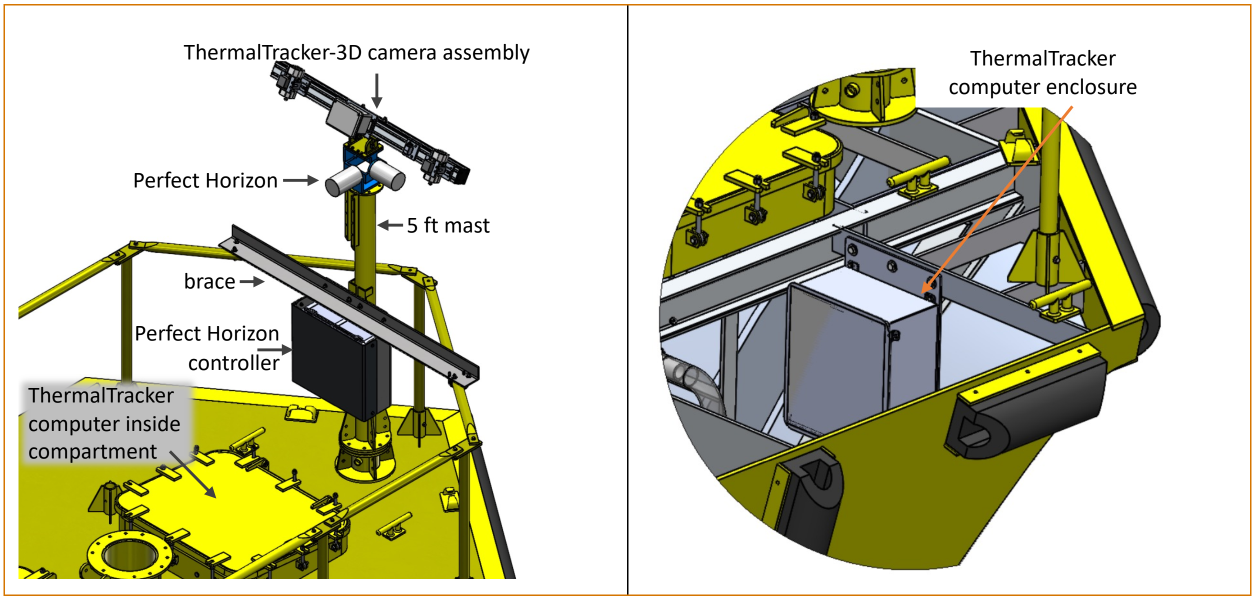
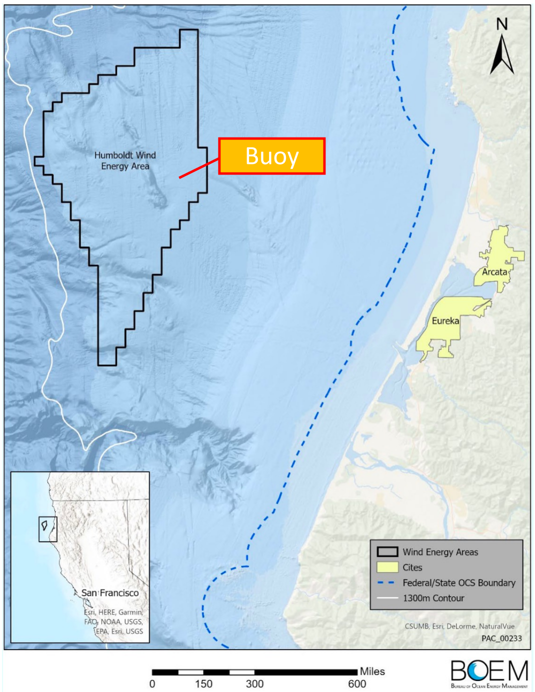


Figure 2-3. Buoy integration. The ThermalTracker-3D camera assembly and the Perfect Horizon were attached to the buoy deck at the bow (left) and the ThermalTracker-3D computer enclosure with power and data connections were mounted below deck (right). Cables were routed through the mast.

The TT3D camera assembly was mounted on the mast so that the cameras were looking up at about 55 deg off the horizon. This orientation angle maximized the camera field of view in the hypothetical RSZ.

2.4 Deployment Location

The deployment location was in BOEM's Humboldt Wind Energy Area. The area is in the Pacific Ocean, about 25 nautical miles west of the northern California coast (Figure 2-4). The water depth in the area is between 500 and 1100 meters, so wind turbines will need to be installed on floating platforms in the area if it is developed. The location is subject to strong winds, waves and large swell, especially during the winter and spring.



Significant Wave Height (meters)

	Percentile				
Year	10th	20th	30th	40th	50th
2018	1.2	1.5	1.7	1.9	2.1
2019	1.2	1.4	1.7	2.0	2.2

Dominant Wave Period (seconds)

	Percentile				
Year	10th	20th	30th	40th	50th
2018	15.4	14.3	13.3	11.8	11.1
2019	16.7	14.3	13.3	12.5	11.8

Figure 2-4. Buoy deployment location in BOEM's Humboldt Wind Energy Area (left) and historical wave statistics from nearby oceanographic buoy Station 46213 (right).

2.5 Evaluation Criteria and Metrics

Evaluation metrics were identified that could be quantified through data collected from the offshore deployment. The target values for the metrics were selected to be aspirational, representing target values for a fully matured system. The evaluation was broken down into the following areas.

Software Operation and Reliability

The ThermalTracker software was developed by PNNL. This area addresses the software's ability to operate unattended in a remote location for extended periods of time.

Table 2-1. Software Reliability Metrics

Metric	Calculation	Target
System Up Time	The time the software was running as a percentage of the total time it was expected to be running (*i.e.*, the system was powered on)	90%
Number of failures	The number of times the software unexpectedly stopped running or got stuck	2 in 6 mos.
Disk Space Available	Percentage of total disk space that remained free	25%

Output Data Quality

The outputs of the system are the detected 3D seabird flight tracks and orientation data needed to translate the 3D tracks into geo-referenced coordinates. The output data include image chips of detected birds from the thermal cameras and color camera images.

During the validation deployment, additional data were also transmitted to shore for validation and verification purposes. Those data were composite images that are formed during the initial stage of the onboard processing, which are then input into the detection stage of the processing. These pre-detection images were stored at one-minute intervals.

A detection is defined as a single flight track of an individual animal. The flight track consists of a time sequence of thermal image chips and 3D positions in x-y-z coordinates relative to the camera. The coordinates are transformed into georeferenced coordinates in post-processing using the output from the ThermalTracker's GPS and orientation sensors.

Table 2-2. Output Data Quality Metrics

Metric	Calculation	Target
Detection Rate	Review a sample of the available pre-detection thermal images and quantify the percentage of visible birds that were detected.	90%
Valid Flight Tracks	Calculate the percentage of reported flight tracks with valid x,y,z coordinates for at least 3 positions. Valid means the values are within the range determined by the camera system geometry.	90%
False Positive Rate	Examine the thermal image chips and quantify the percentage of valid tracks that were not birds.	10%

Camera stabilization and motion effects

Camera stabilization is critical for operating on a floating platform to maintain sufficient video quality for the TT3D algorithms to perform effectively. The mechanical stabilization system is independent of the ThermalTracker system. The system used for the offshore validation deployment had two axes of for motion compensation, pitch and roll. Other buoy motion such as yaw and heave can also affect video quality.

Table 2-3. Camera Stabilization Metrics

Metric	Calculation	Target
System Up Time	The time the stabilization system was running as a percentage of the total time it was expected to be running (*i.e.*, the system was powered on.).	90%
Pitch Deviation	Deviation from the configured camera pitch angle as measured from the IMUs on the cameras.	0 deg. Average, 2 deg. maximum
Roll Deviation	Deviation from 0 degrees in roll angle as measured from the IMUs on the cameras	0 deg. Average, 2 deg. maximum
Image Quality	The percentage of detections where the image was clearly recognizable as a bird (i.e. not blurred.)	90%

Hardware Component Performance

The offshore TT3D prototype was built by PNNL using commercial-off-the-shelf components, including:

- Thermal cameras (2)
- Color camera
- Computer
- Microcontroller with custom firmware
- GPS
- IMUs (2)

Each of these components was evaluated in terms of suitability for autonomous offshore operations. The particular model chosen for each component could be changed for future deployments to improve overall system performance.

Table 2-4. Hardware Component Metrics

Metric	Calculation	Target
Suitability	1 -- Excellent, no changes needed, would use again 2 -- Sufficient, but could be replaced with another model for better performance 3 -- Not acceptable, must be replaced with another model for future deployments	1

Platform Integration

The platform integration includes the physical attachment of the ThermalTracker system components to the platform, power supply and data connections. The platform integration is platform-specific, and this evaluation area addresses the suitability of the platform for the ThermalTracker system.

Table 2-5. Platform Integration Metrics

Metric	Calculation	Target
Power Availability	The time that adequate power was available as a percentage of the total time it was expected to be available.	90%
Data Loss	The percentage of transmitted data that was lost due to failures of the platform's data management system.	1%
Data Transfer Volume Used	The percentage of the total available data volume used to transmit ThermalTracker data to shore. This indicates the adequacy of the communication data plan.	90%
Computer Temperature	The percentage of the time that the computer temperature was < 90 degrees (vendor specified operating range)	99%
Mechanical Mounting Failures	The number of failures in the attachment of the ThermalTracker components to the platform.	0

3.0 Evaluation Results and Discussion

The TT3D system was installed on the buoy at the buoy staging area in Eureka, CA in April 2021. The installation was performed by the buoy contractor and supported by PNNL staff. On May 4, the buoy was lifted into the water and all systems were powered on, including the ThermalTracker. The buoy remained tied to a pier for a final system checkout until May 7, when an instrument failure required that the buoy be taken back out of the water. The instrument was repaired, and the buoy lifted back into the water to await a weather window for the deployment. On May 24, the buoy was towed to its mooring and deployed in the Humboldt Wind Energy Area.

On June 24, the Perfect Horizon stopped operating. Cycling the power did not restore it to an operational state. The TT3D system continued to operate but with no stabilization. On July 20, the ThermalTracker software was updated to increase the detection sensitivity. On August 13, the buoy generator failed. The buoy power was then limited to what could be supplied from the wind turbine and the solar panels. The instruments, including the TT3D, were powered off. On September 20, the TT3D was powered on again and remained on until September 22, during which time a survey of the seabirds near the buoy was conducted by HT Harvey & Assoc.

Given the timeline of events, the TT3D performance period was divided into four periods for evaluation (Table 3-1Table 3-1): nearshore, offshore with stabilization, offshore with no stabilization, and offshore with no stabilization -- upgraded. The number of detections per day during each period is shown in Figure 3-1.Figure 3-1. Timeline of events and detections per day.

Table 3-1. Performance Evaluation Periods

Period	Description	Start	End	Duration (days)
1	Nearshore with stabilization	2021-05-04	2021-05-23	20
2	Offshore with stabilization*	2021-05-25	2021-06-24	31
3	Offshore with no stabilization	2021-06-25	2021-07-19	25
4	Offshore with no stabilization, upgraded	2021-07-20	2021-08-13	24
			Total	100

*Data from the camera IMUs indicates the stabilizer may have stopped working before 6/24.

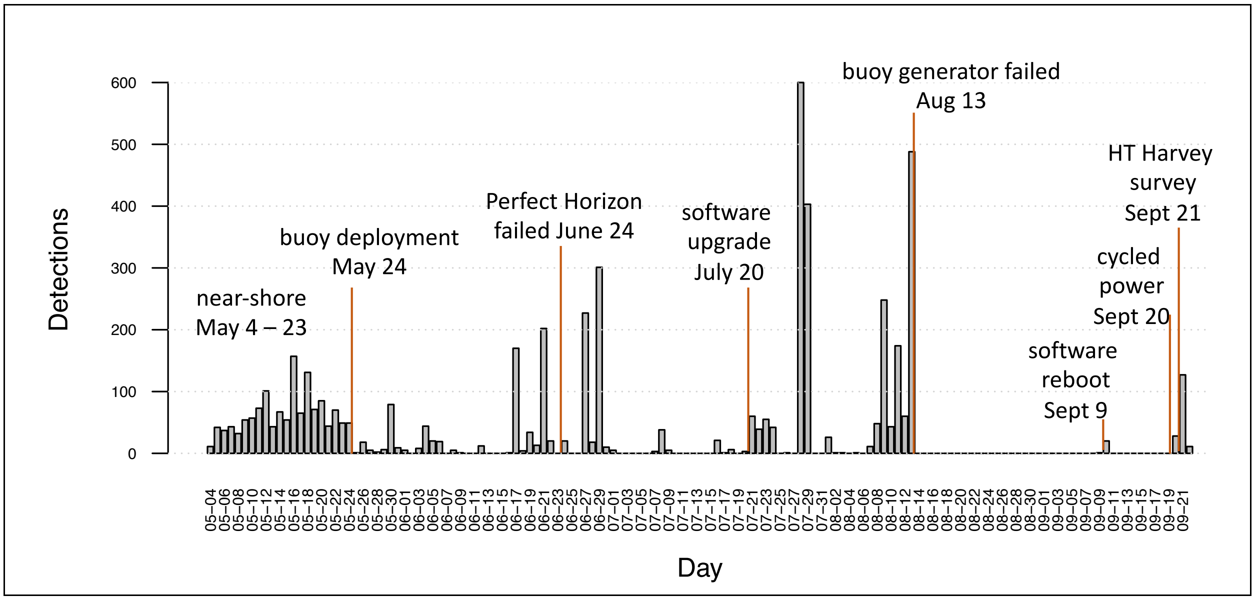


Figure 3-1. Timeline of events and detections per day.

3.1 Software Operation and Reliability

Overall, the software operation and reliability exceeded expectations (Table 3-2). The software continued running without failure throughout the deployment up until the buoy generator failed. The scripts managing the disk space successfully maintained a healthy margin of free space. The scripts composing the status messages transmitted to shore through the buoy system ran reliably, providing continuous insight into the ThermalTracker system's health and status. Some of the status data were more useful than others in hindsight, and the status data could be reduced for future deployments.

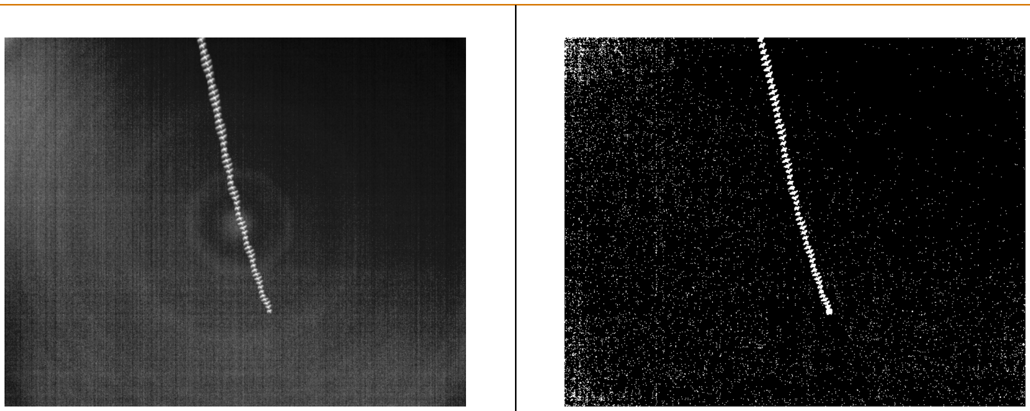
Table 3-2. Software Reliability Results

Metric	Target	Actual
System Up Time	90%	100%
Number of failures	2	0
Disk Space Available	25%	57%

3.2 Output Data Quality

3.2.1 Detection Rate

The detection rate was determined by reviewing the pre-detection imagery and matching visible birds with detections. The pre-detection images are composite images formed by superimposing consecutive video frames into a single image, where each pixel in the composite images is set to the maximum value obtained at the pixel location over the sequence of video frames (Figure 3-2). These images are formed in the initial stage of the ThermalTracker processing and the subsequent stage then detects the flight tracks of birds in the composite images. Composite images are formed every 6 seconds during the processing cycle and normally are not saved. For the deployment, a composite image was saved to disk once per minute and stored with the output data (detections) so that the detection rate could be estimated. A random sample of the available images was composed by selecting every 10th hour for which there were data and reviewing all the images for that hour. Note that the composite images were not saved until 5/19.


Composite Image

Detection Mask

Figure 3-2. A composite image of a bird flight track (left) and the associated detection mask (right). These images are from the first stage of ThermalTracker-3D processing; the subsequent detection stage uses these data as input.

Table 3-3. Detection Rate Based on a Random Sample

Period	Images Reviewed	Visible Tracks	Detected Tracks	Visible Tracks	Detected Tracks
1	322	17	3 (18%)	13	3 (23%)
2	415	6	0 (0%)		
3	237	12	8 (67%)	95	49 (52%)
4	653	83	41 (49%)		
Total	**1627**	**118**	**52 (44%)**		

The detection rate was 44%, much lower than the target rate of 90% (Table 3-3). There are several settings that affect the sensitivity of the detection algorithm. The settings can be tuned to achieve the desired balance between missed detections and false positives. This tuning must be done through trial and error, ideally in the target operational environment. Prior to the deployment, the opportunities for tuning were limited. The settings had been tuned previously for a cluttered environment to minimize false positives (less sensitive). During the deployment, the settings were adjusted during Period 2 based on the number of detections being reported, which seemed low compared to the number of detections that were seen during testing at PNNL's Marine and Coastal Research Laboratory which is in a near-shore environment. The adjustment does seem to have improved the detection rate based on the increase in Periods 3 and 4 over the earlier periods. However, the optimal settings were not achieved.

Another factor that may have affected the detection rate is the camera motion. Camera motion effects are discussed in Section 3.3.

3.2.2 Valid Tracks

Valid tracks are detections where the coordinates of the 3D track are within the valid range determined by the camera parameters and geometry (**Error! Reference source not found.**). The valid range of 3D position coordinates relative to the camera are determined by the camera's field of view angle and the limits of the stereo vision processing. The horizontal field of view angle of the thermal cameras is $\alpha_H = 24.6$ degrees and the vertical field of view $\alpha_V = 19.8$ degrees. The coordinates are estimated by the stereo-vision stage of the real-time processing. The 3D position of an object is calculated from the disparity in the position of the object in the images from each of the two thermal cameras. The accuracy of the coordinate estimates is affected by the accuracy of the pixel location of a detected bird in the thermal image, and thus by the quality of the video.

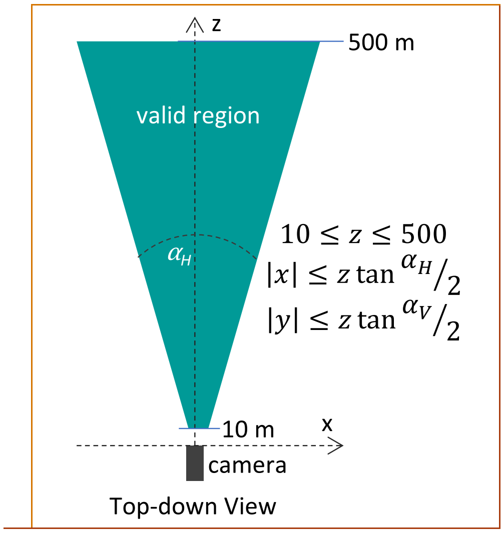


Figure 3-3. The valid range of 3D position coordinates relative to the camera.

Table 3-4. Valid Detections

Period	Detections	Valid Tracks
1	1198	955 (80%)
2	518	387 (78%)
3	266	254 (89%)
4	938	844 (90%)
Total	**2920**	**2440 (84%)**

The coordinates of the detected tracks were filtered according to the valid range equations in **Error! Reference source not found.**. For each position in a track, first the z coordinate was tested and if it was out of range, then all three position coordinates were marked out of range. If the z coordinate was within range, then the x and y coordinates were tested. If any of the positions in the track were valid, the track was considered valid. If all the positions were invalid, the track was considered invalid. Overall, 84% of the detected tracks were valid which is lower than the target of 90% (**Error! Reference source not found.**). As noted, the coordinate validity is affected by the accuracy of the stereo vision processing, which is affected by the pixel-level accuracy of the detection of a bird's thermal image in the video. The farther away a bird is from the cameras in the z direction, the less pixels there are available in the bird's image. The farther away a bird is from the cameras, the lower the probability of the position estimates being accurate, and therefore valid (Figure 3-5).

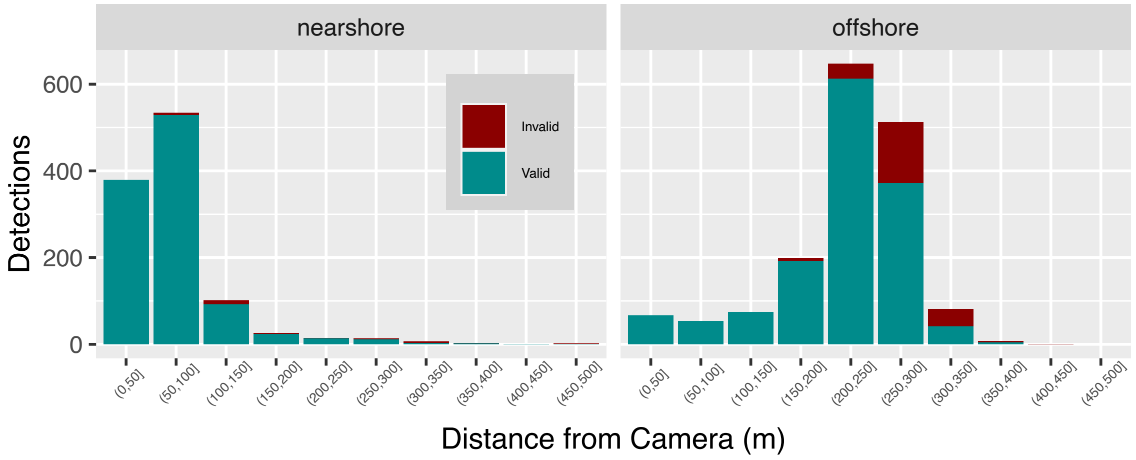


Figure 3-4. The distributions of detection distance from the camera for the nearshore period (period 1) and the offshore periods (periods 2-4) were different.

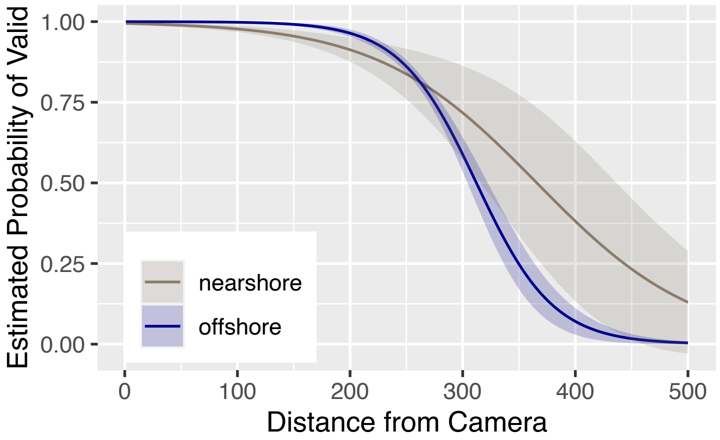
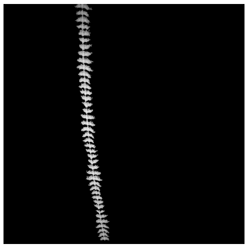
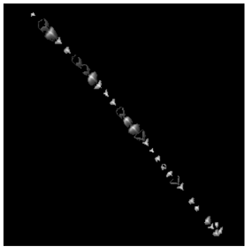
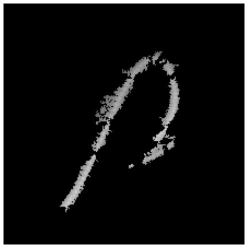
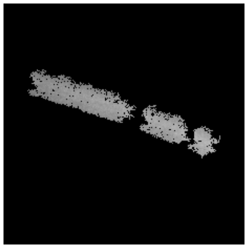
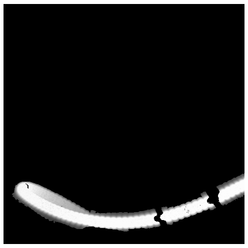
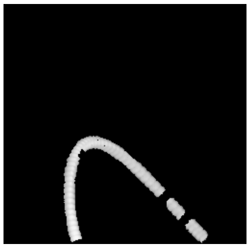
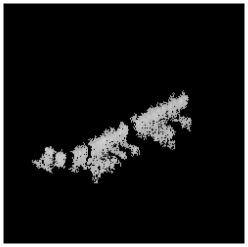


Figure 3-5. The probability of valid position data as a function of distance. The probability for the nearshore data is less certain because there were less distant detections.

3.2.3 False Positive Rate

The false positive rate was determined by reviewing the thermal image chips saved with each detected track and the flight track plot. A random sample of 8% of the valid detections (205 out of 2,440) was selected. For each track in the sample, the track data were examined, and the track was classified as one of four classes (Table 3-5). The thermal image chips were viewed first, which only contain the pixels that were included in the bird detection and no background. These image chips are not always easy to interpret due to the lack of context. If there was doubt then the closest saved composite image was reviewed to see the background, whether the sky was cloudy or clear and if there was evidence of motion blur.

Table 3-5. Detection Classifications

Class	Description	Examples	
Bird	Clearly a bird – bird shape with wings, individual image blobs line up in a line or smooth curve consistent with bird flight motion.		
Blurred Bird	A bird but shape is blurred by motion.		
Bright Bird	Clearly a flying animal but warmer (brighter thermal signature) than other bird detections and individual image blobs not distinguishable along the motion track.		
Unknown	Blurred image not recognizable, maybe a bird or maybe a cloud		

The majority of the detections in the sample were verified as being a bird or likely a bird (Table 3-6). The images from 20% of the sampled detections were not identifiable, likely due to motion blurring. A false positive rate cannot be estimated, therefore, due to the motion blurring and the lack of definitive "ground truth". Color images from a high-resolution camera were saved for each track but these data were not available at the time of this writing because they are stored on a physical hard drive located on the buoy, which is currently offshore. The images could not be transmitted to shore during the deployment due to bandwidth limitations so they were stored onboard and will be available when the buoy is brought back to shore.

Table 3-6. Detection Classification Results

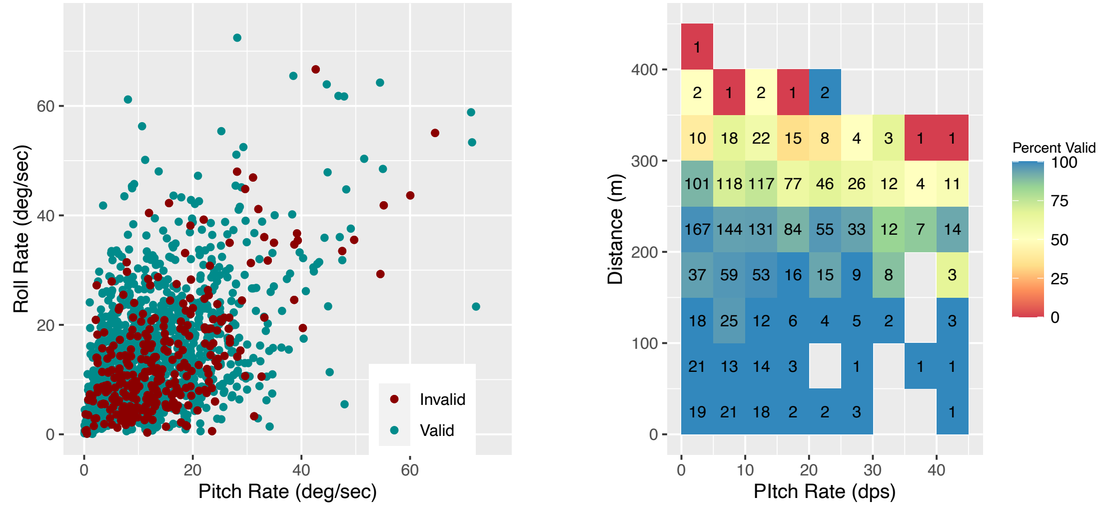
Class	Count	Percentage
Bird	92	44.9%
Blurred Bird	38	18.5%
Bright Bird	34	16.6%
Unknown	41	20.0%
Total	**180**	**100%**

3.3 Camera Stabilization and Motion Effects

The camera stabilization solution used for the deployment was a custom version of the Perfect Horizon (PH), a camera stabilization system used in the motion picture industry for filming from a boat. The PH corrects for pitch and roll motion, up to 35 degrees per second, and was designed to maintain a level position within +/- 2 degrees. The PH stopped reporting status messages to the TT3D computer on June 24, 2021. Although the PH microcontroller was accessible via remote login, the control software failed to run, exiting with an error message. Cycling the power to the system did not resolve the issue. The PH had occasionally exhibited unstable behavior during testing prior to the deployment. The system was observed to oscillate around the roll axis and would have to be powered off in order to recover. The system control parameters were adjusted and the problem was thought to be resolved. However, at some point the system became stuck at the limit of the roll axis. Based on the data from the TT3D IMUs, it appears that the PH may have actually stopped working prior to June 24. Despite the lack of active camera stabilization, the TT3D continued to operate and record seabird activity.

To quantify the camera motion effects, the camera motion was characterized by the rate of change in degrees per second of the pitch, roll and yaw angles over the duration of a detected flight track. The camera orientation angle data was measured by the IMUs and recorded at 30 Hz, synchronized to the camera frame capture. When a detection occurred, the camera orientation data for every frame that has the detected animal in view was saved as part of the output flight track detection data. The range of values of the orientation over the course of the flight track indicates the amount of camera motion.

The validity of the detected flight tracks appears to be more affected by the distance of the detected bird from the camera than by the camera motion (Figure 3-6). However, the validity of the flight track coordinates may not be a sufficient indicator of data quality and the algorithm effectiveness. The recorded camera motion was 15 deg/sec or less for most of the detections (Figure 3-7). This may indicate that camera motion reduced the detection rate of the algorithm. A detection requires first finding pixels brighter than the background in each camera, and then matching the detections in both cameras to form a 3D track. The background is calculated as the average intensity of each pixel. If the video images are blurred by motion, then the bright signature of a bird in the scene would be smeared across many pixels, reducing the contrast between the bird pixels and the background.



The camera motion affected the interpretability of the image data. An image from a detection with camera motion of 5 deg/sec or less was much more likely to be clearly recognizable as a bird, with defined body and wing shapes, than an image with camera motion greater than 5 deg/sec (Figure 3-7).

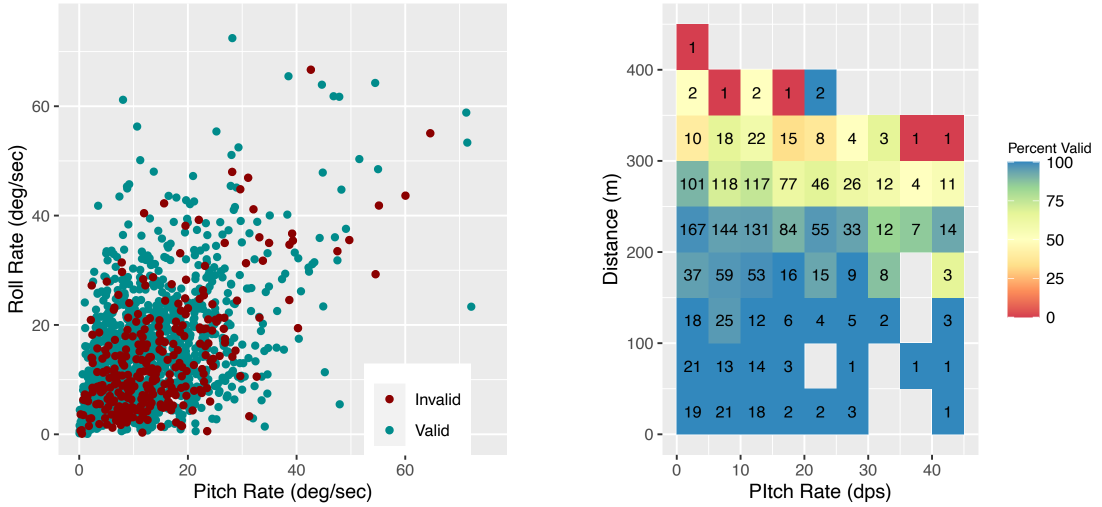


Figure 3-6. Camera motion and track validity. The camera motion alone is not a predictor of the validity of the detected flight tracks (left). Camera motion may reduce the distance at which detected tracks have a high probability of having valid coordinates (right).

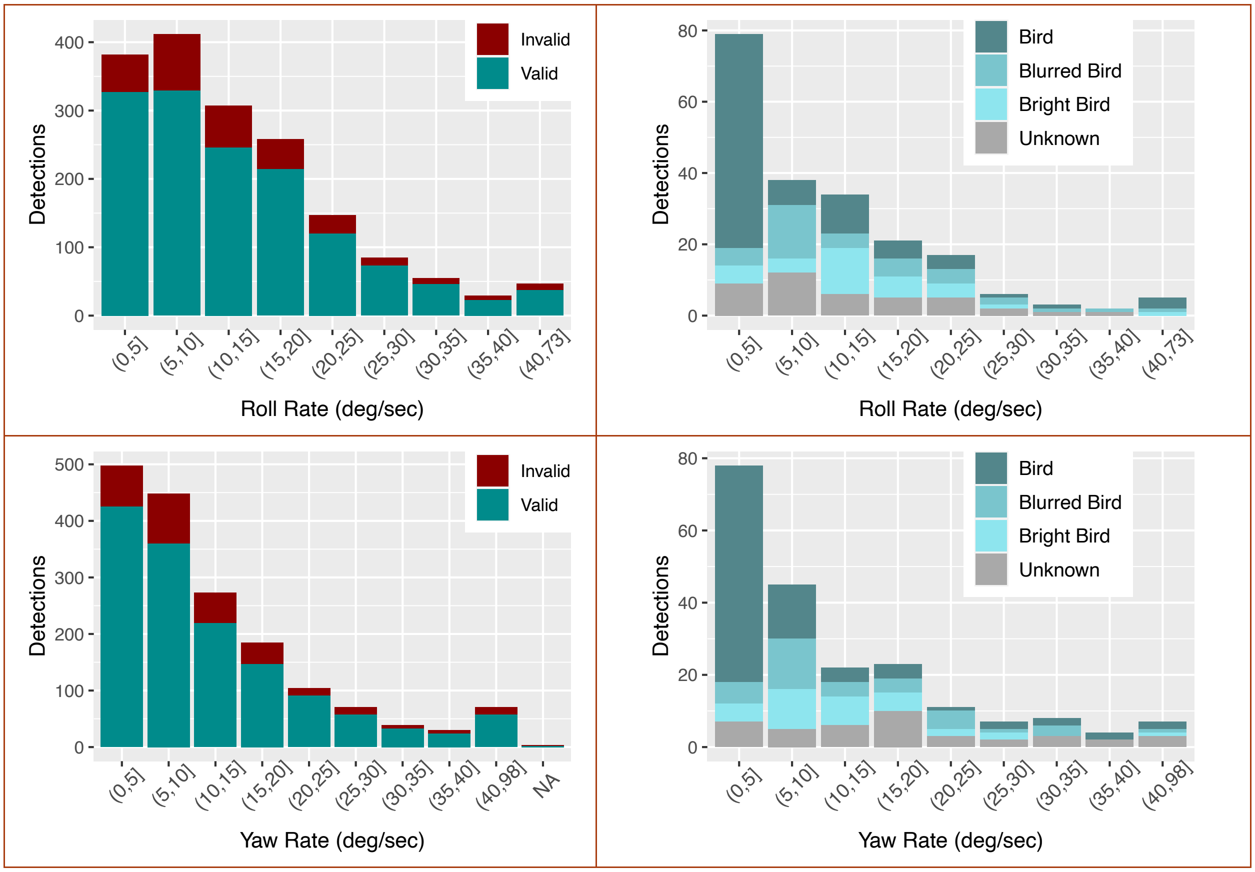


Figure 3-7. Camera motion and its effect on image quality. The camera motion was less than 15 deg/sec for most of the detections (left). A detection was most likely to be recognizable if the camera motion was less than 5 deg/sec (right).

3.4 Hardware Component Performance

The hardware performance overall met expectations. There were no failures or issues with any of the components.

Table 3-7. Hardware Performance Results

Component	Suitability[(a)]	Notes
Thermal cameras	1	The cameras were reliable and recorded good quality video throughout the deployment, as evidenced by the composite images that were reviewed to calculate the detection rate.
Color camera	TBD	The performance of the color camera cannot be assessed until the color image data is retrieved from the onboard computer.
Computer	2	The computer performed reliably throughout the deployment. However, industrial computers and single board computers are constantly evolving; newer solutions should be considered for future deployments.
Microcontroller	1	No issues.
GPS	1	No issues.
IMU	2	The IMUs operated reliably throughout the deployment. However, the quality of the data has not been fully evaluated. These sensors were at the low end of the market and could be replaced with more accurate sensors.

(a) Suitability rankings:
1. Excellent, no changes needed, would use again.
2. Sufficient, but could be replaced with another model for better performance.
3. Not acceptable, must be replaced with another model for future deployments.

3.5 Platform Integration

Overall, the platform integration worked well. The mechanical integration was secure and there were no failures of any of the attachment points to date. The height of the mast kept the TT3D camera assembly from being inundated by crashing waves, and the cameras had a clear view of the sky. The electrical integration included relays so the power could be cycled remotely to the TT3D and to the PH, independently. This capability was useful when the issue with the PH was detected, and the power was cycled in an attempt to restore its function. The TT3D seemed to have adequate power supplied during the deployment up until the generator failure, based on the continued operation of the software and reported detections. The buoy’s Data Management System, originally developed by AXYS Technologies, ensured that there was no data loss. Data from the TT3D was archived with the rest of the buoy instrument data on the A2E Data Access Portal with no issues.

Table 3-8. Platform Integration Results

Metric	Target	Result	Notes
Power Availability	90%	100%*	
Data Loss	1%	0%	This result does not include the color image data, which is stored onboard the TT3D computer. Some color image data has been downloaded ad hoc, but the data volume has not been quantified as of yet.
Data Transfer Volume Used	90%	60%	The volume used was estimated from the size of the dataset on the DAP. Additional data was used for remote logins and transfers to update the software.
Computer Temperature < 90 deg. C	99%	70% (estimated)	The temperature was close to the rated maximum operating temperature at times, but this did not appear to cause any issues.
Attachment Failures	0		

M

* Up until the generator failed on 8-14-2021.

There was some concern prior to the deployment about the temperature of the compartment and the enclosure where the TT3D computer was mounted. The computer is a fanless design and depends on heat exchange for cooling. The compartment does not have any active temperature control and is sealed against water intrusion. To monitor the situation, the temperature of the CPU and the solid-state hard disk were reported hourly using the AXYS Technologies' SmartWeb. The historical data shows that the temperature of the CPU and the disk did "run hot" at times, but that the ambient temperature of the compartment remained sufficiently cool for keeping the computer within its operating temperature range (Figure 3-8).

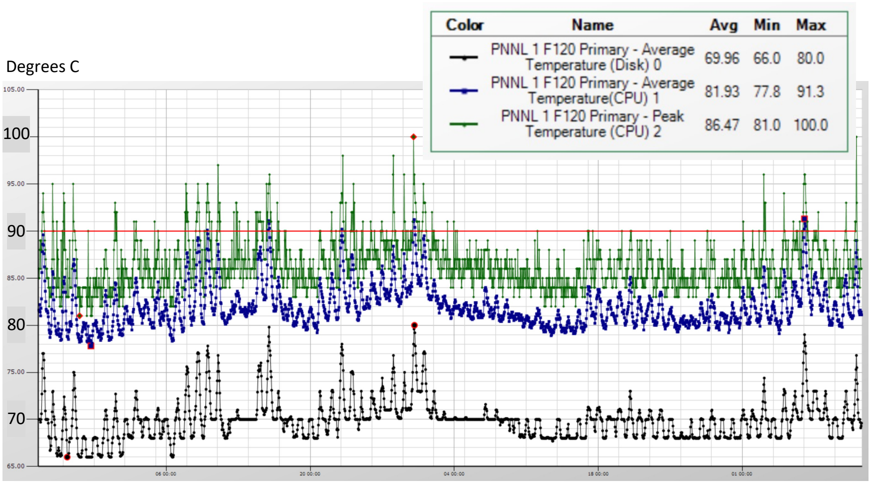


Figure 3-8. CPU and disk temperature data from the TT3D computer. Shown is the average disk temperature (black line), the average CPU temperature (blue line) and the peak CPU temperature (green line) over 1-hour intervals.

4.0 Conclusions

The initial offshore validation study of the ThermalTracker-3D technology achieved the following technical objectives:

- **Successful integration with buoy.** A key use case for the TT3D technology is to collect baseline data on seabird (and bat) activity at a potential offshore wind energy site, pre-construction. Generally, such a site lacks infrastructure to support remote sensing. However, lidar buoys such as the Wind Sentinel are usually deployed at the site to characterize the wind energy resource prior to development. This validation study demonstrated that the TT3D can be integrated with a Wind Sentinel buoy, making it possible to collect seabird activity data in conjunction with wind energy resource data. The design and components for integration developed for this study can now be leveraged for future deployments.
- **Validation of offshore prototype design.** The TT3D offshore prototype withstood harsh offshore conditions during the deployment, including strong winds, big waves, salt spray and intense sunlight. The design used commercial off-the-shelf components that cost less than $50,000. All of the components performed as expected with no failures. Additional prototypes can be built based on the design used for this study at a lower cost in terms of engineering time and by realizing bulk discounts on component costs.
- **Validation of software reliability**. The TT3D software operated autonomously without the need for user intervention throughout the deployment. The software ran continuously, status was reported regularly, and detection data was transmitted to shore. Disk space was managed effectively to maintain a healthy amount of free space. The mechanism for updating the software remotely was tested and verified. The software reliability has been validated.
- **Improved understanding of motion effects.** In preparing for the offshore validation, camera motion was identified as the primary technical challenge for operating the TT3D from a floating platform. In practice, the camera motion did impact the video quality and made the images difficult to interpret but did not result in excessive false positives. The specific effects of each type of motion – pitch, roll, yaw, heave, surge, sway – can be analyzed further using the data collected during this study.
- **Collection of seabird data for analysis and species identification.** The goal was to collect good data at least 30% of the time at sea, where “good” means that the detections are valid and minimally affected by motion blur so that the geo-referenced 3D tracks can be used to estimate passage rates through a hypothetical RSZ and the thermal image chips provide some information for species identification. During the 100 days that the buoy power system was operational, 2,440 valid flight tracks were detected, with detections occurring continuously at all times of day throughout the study period. Additional data were collected from 9-20-2021 01:00 UTC to 9-22-2012 07:15 UTC when the buoy’s batteries were charged by wind and solar power. During that time, on 9-21, a survey of the seabirds in the area was conducted by H.T. Harvey and Associates. The TT3D data and the survey data will be analyzed and the results reported in a future publication.

4.1 Recommended Next Steps

The results of this study will inform future deployments and further maturation of the TT3D technology. Based on the findings reported here, the following next steps are recommended:

- **Improve detection rate**. The detection rate during the buoy deployment was lower than expected. Previous testing with other datasets demonstrated higher detection rates, e.g., 89% (Matzner et al 2015). The difference in performance can be attributed to differences in the environments where the datasets were collected. The previous datasets were collected near shore, and included moving clouds and choppy water surface in the field of view. Based on these data the detection algorithm was tuned to be less sensitive to reduce the probability of false positives. There are a number of parameters within the software that determine the sensitivity of the detection algorithm. For future deployments, these parameters should be tuned for the specific environment in accordance with deployment objectives (e.g., maximize detections or minimize false positives).
- **Improve camera stabilization** and add motion compensation in the software as needed, based on data from this study. A robust stabilization system is needed that can operate reliably for at least one year in an offshore environment, subject to frequent extreme wave motion. The stabilization system must limit camera motion to less than 5 degrees per second. The motion and image data from this study can be used to develop processing to compensate for residual motion not handled by the mechanical stabilization system, such as yaw and heave motion.
- **Optimize the compute and storage for constrained environments.** The computer used for this study was mounted inside a compartment on the buoy and both the disk and the CPU were close to their rated maximum operating temperature range much of the time. Although there were no system failures due to overheating, the latest commercial offerings for both processing and storage should be investigated to identify a solution that may be more appropriate for the constrained environment of an oceanographic buoy.
- **Develop automated taxonomic identification**. During this study, the thermal composite pre-detection images were found to be useful for verifying detections and interpreting the flight track data due to the context provided by the background pixels. This implies that the thermal image chips saved as part of the flight track data could be made more useful by including background pixels. The color image data could be cropped and more aggressively compressed so that it could be included with the output data transmitted to shore. The animal size estimates and other clues, such as the flight pattern (Cullinan et al, 2015), flight height and speed could be developed into a taxonomic prediction model incorporated into the software.

References

Ainley, D. G., E. Porzig, D. Zajanc, and L. B. Spear. 2015. “Seabird flight behavior and height in response to altered wind strength and direction.” *Marine Ornithology*, *43*, 25-36.

Cullinan, V. I., S. Matzner, and C. A. Duberstein. 2015. "Classification of birds and bats using flight tracks." *Ecological Informatics* 27: 55-63. https://doi.org/10.1016/j.ecoinf.2015.03.004.

Ibrahim, R. A., and I. M. Grace. 2010. "Modeling of Ship Roll Dynamics and Its Coupling with Heave and Pitch." *Mathematical Problems in Engineering* 2010: 1-32. https://doi.org/10.1155/2010/934714.

Masden, E. A., and A. S. C. P. Cook. 2016. "Avian collision risk models for wind energy impact assessments." *Environmental Impact Assessment Review* 56: 43-49. https://doi.org/10.1016/j.eiar.2015.09.001.

Matzner, S. V. I. Cullinan, and C. A. Duberstein. 2015. "Two-dimensional thermal video analysis of offshore bird and bat flight." *Ecological Informatics* 30: 20-28. https://doi.org/10.1016/j.ecoinf.2015.09.001.

Matzner, S., T. Warfel, and R. Hull. 2020. "ThermalTracker-3D: A thermal stereo vision system for quantifying bird and bat activity at offshore wind energy sites." *Ecological Informatics* 57. https://doi.org/10.1016/j.ecoinf.2020.101069.

Regular, Paul M., A. Hedd, and W. A. Montevecchi. 2011. "Fishing in the dark: a pursuit-diving seabird modifies foraging behaviour in response to nocturnal light levels." *PLoS One* 6.10: e26763.

Appendix A – ThermalTracker-3D Offshore Prototype Components

Component	Quantity	Vendor Link
Flir A65 thermal cameras	2	https://www.flir.com/products/a65
Workswell thermal camera enclosures	2	https://workswell-thermal-camera.com/protective-case-for-thermal-camera-flir-ax5
Lucid Vision Labs Triton TRI028S-CC optical camera	1	https://thinklucid.com/product/triton-2-8-mp-imx429
Lucid Vision Fujinon 12 mm lens and IP67 lens tube	1	https://thinklucid.com/accessories/#lenses
Yost Labs 3-Space USB sensors	2	https://yostlabs.com/product/3-space-usbrs232
Bud Industries aluminum enclosures for Yost sensors	2	https://www.digikey.com/product-detail/en/bud-industries/AN-2811-AB/377-2336-ND/5775315
PJRC Teensy 4.0 USB development board	1	https://www.adafruit.com/product/4323
Adafruit Ultimate GPS FeatherWing	1	https://www.adafruit.com/product/3133
Enclosure for microcontroller	1	https://www.mcmaster.com/7583K111
Custom 8020 frame for mounting cameras	1	Solidworks files available on request
Logic Supply Karbon 700 industrial computer with 4 PoE ports	1	https://www.logicsupply.com/k700-se/?configuration=6d28190d9b72921a5bfad95439927914

Appendix B – ThermalTracker-3D Output

For each detection, an output json file is generated that contains all the information about the detected flight track. A sample file is given below.

```
{
   "cam1TrackId": 19019770,
   "cam2TrackId": 20738475,
    "startTime": 1624226827801,
    "endTime": 1624226828902,
    "blobs": [
      {
         "cam1_blob": {
               "timestamp": 1624226827801,
                "topleft_x": 631,
                "topleft_y": 0,
                "width": 9,
                 "height": 12,
                 "image": […] list of pixel values, floating point between 0 and 1
          },
          "cam2_blob": {
                 "timestamp": 1624226827801,
                 "topleft_x": 623,
                 "topleft_y": 2,
                 "width": 14,
                 "height": 14,
                 "image": […] list of pixel values, floating point between 0 and 1
          },
         "frameIndex": 265,
         "x": 101.82075500488281,
         "y": -41.543479919433594,
         "z": 315.81719970703125

      },

 {…} more blobs. …]
}
```

Pacific Northwest
National Laboratory

902 Battelle Boulevard
P.O. Box 999
Richland, WA 99354
1-888-375-PNNL (7665)

www.pnnl.gov