PREP
Piscataqua Region Estuaries Partnership

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Great Bay Estuary 2019 Drone Program for Remote Sensing of Estuarine Habitats Quality Assurance Project Plan

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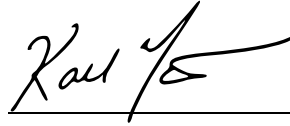Follow this and additional works at: https://scholars.unh.edu/prep

Great Bay Estuary
2019 Drone Program for Remote Sensing of Estuarine Habitats
Quality Assurance Project Plan

May 2019

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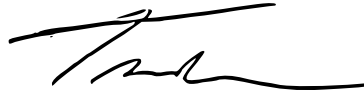
Project Manager: _____ **7-19-2019**
Signature / Date
Kalle Matso, PREP

Project QA Officer _____ **7-19-2019**
Signature / Date
Trevor Mattera, PREP

Scientist/Field Operations Manager: _____ **7-19-2019**
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Supporting Scientist: _____ **7-19-2019**
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David Burdick, JEL/UNH

US EPA Project Officer: Erik H. Beck 7/23/19 _____
Signature / Date
Erik Beck, US EPA

US EPA QA Officer: Nora J Conlon/July 23, 2019 _____
Signature / Date
Nora Conlon, US EPA

A2 – Table of Contents

List of Tables

List of Figures

Appendix

Appendix A: Quality Report Template from Pix4D Software

A3 – Distribution List

Table 1 presents a list of people who will receive the approved QA Project Plan (QAPP), the QAPP revisions, and any amendments.
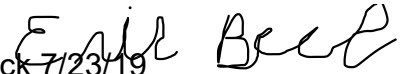
Table 1: QAPP Distribution List

QAPP Recipient Name	Project Role	Organization	Telephone Number and E-mail Address
Kalle Matso	Project Manager	PREP	603-781-6591 kalle.matso@unh.edu
Trevor Mattera	Project QA Officer	PREP	603-862-1310 trevor.mattera@unh.edu
Gregg Moore	Scientist/Field Operations Manager	JEL/UNH	603-862-5138 gregg.moore@unh.edu
David Burdick	Supporting Scientist	JEL/UNH	603-862-5129 david.burdick@unh.edu
Ted Diers	Data User	NHDES	603-271-3289 ted.diers@des.nh.gov
Erik Beck	US EPA Project Officer	US EPA	617-918-1606 beck.erik@epa.gov
Nora Conlon	US EPA QA Officer	US EPA	617-918-8335 conlon.nora@epa.gov

Based on EPA-NE Worksheet #3

A4 – Project/Task Organization

The project will be completed by the Piscataqua Region Estuaries Partnership (PREP), which will also provide funding for the project.

The Project Manager will be responsible for coordinating all program activities and communicating with EPA. The Project Manager will coordinate data analysis and will be responsible for all final products. The Project QA Officer will ensure that all QA steps are adhered to, and will be responsible for documenting any deviations from the procedures in the QAPP, the results of the quality control (QC) tests, and whether the reported data meet the data quality objectives of the project. The Field Operations Manager will manage all field staff and be responsible for "stop/go" decisions in the field.

The principal user of the data from this project will be PREP for State of Our Estuaries Reports. The scientists and the Project Manager will work together to prepare a report at the end of the project with all the data and the QA summary report.

Figure 1: Project Organizational Chart

| Erik Beck |
| US EPA Project Officer |

| Nora Conlon |
| US EPA Project QA Officer |

| Kalle Matso |
| Project Manager |

| Trevor Mattera |
| Project QA Officer |

| Gregg Moore |
| Scientist/Field Operations Manager |

| David Burdick |
| Supporting Scientist |
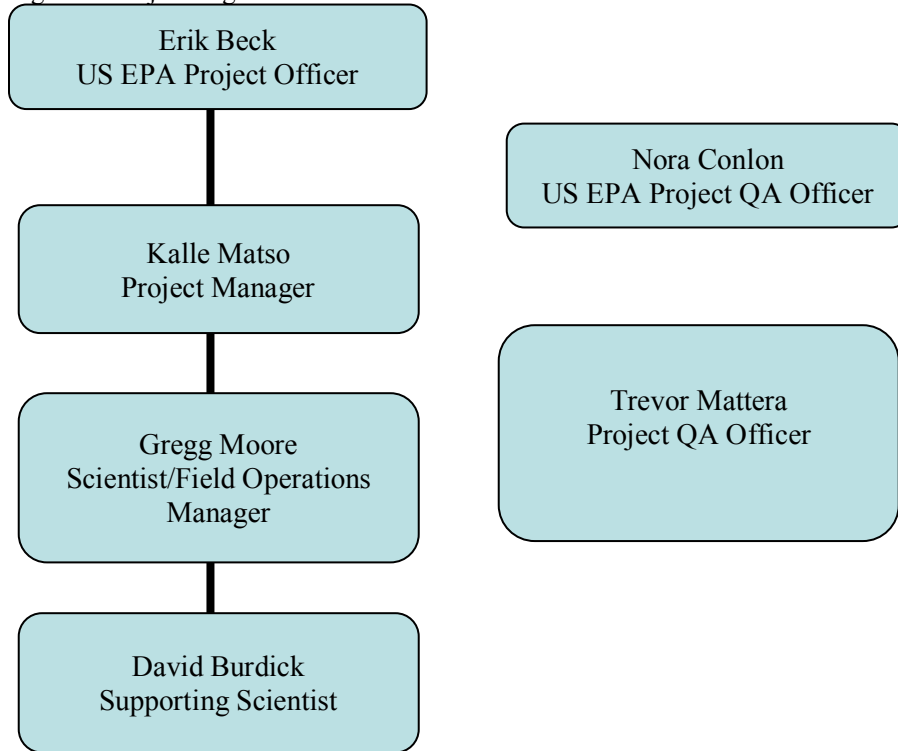
A5 – Problem Definition/Background

Seaweed blooms can be a sign of estuarine ecosystem impairment because they can occur in response to elevated nitrogen inputs, as well as other environmental factors. In addition, seaweed can entangle and ultimately outcompete eelgrass in subtidal environments. Therefore, PREP aims to track the abundance of both seaweed and eelgrass in the Great Bay Estuary as an indicator of estuarine health.

Current efforts to monitor subtidal seaweed rely on boat-based observations using snorkeling and snorkeler-held video. (See the QAPP at: https://scholars.unh.edu/prep/422/). Current efforts to monitor eelgrass occur at two scales. First, the entire estuary is remotely sensed using aerial photography in order to monitor the number of acres where eelgrass has at least 10% cover. (See the QAPP at: https://scholars.unh.edu/prep/421/). Second, detailed eelgrass health parameters are collected along two sets of three transects, according to the SeagrassNet protocol. (See the QAPP at: https://scholars.unh.edu/prep/420/

The objective of this project is to add an additional layer of remote sensing information to augment the on-the-ground seaweed sampling, for several reasons. First, the current method for assessing sub-tidal seaweed is highly accurate but constrained spatially, thus limiting the amount of area that can be surveyed. By relating drone surveys to on-the-ground surveys, scientists hope to build a remote sensing model that could allow assessment of greater areas. This will require understanding the accuracy of drone surveys as compared with on-the-ground surveys. Second, acquiring aerial imagery from high altitude flights is becoming more and more difficult due to deteriorating environmental conditions (e.g., more summer storms; more cloudiness; more turbid waters); aerial image acquisition can be expensive and drones may represent a better alternative; while drone imagery may not offer as comprehensive (i.e., large-scale) a picture of sub-tidal habitat, it can produce higher quality imagery over smaller areas.

Therefore, a pilot-scale effort to collect data will offer a foundation for improving future monitoring efforts; this is true whether it is done in tandem with aerial imagery, or as a standalone. In 2019, aerial imagery will be collected (if conditions permit) so the intent is to use drone imagery in tandem with aerial imagery. However, if the aerial flight does not happen, the drone imagery will still offer a valuable remote sensing counterpart to the on-the-ground data collection.

Trends of eelgrass and seaweed abundance are published in PREP State of Our Estuaries reports (PREP, 2017) and are of interest to the EPA, the NH Department of Environmental Services (NHDES), and other partners. This QAPP will apply to the year 2019.

A6 – Project/Task Description

Table 2: Project Schedule and Timeline

| Activity | Dates (MM/DD/YYYY) | | Product | Due Date |
	Anticipated Date(s) of Initiation	Anticipated Date(s) of Completion		
QAPP preparation	4/1/19	6/1/19	Approved QAPP	6/10/19
Acquire Imagery*	6/15/19	9/6/19	Drone-Captured Imagery	9/9/19
Post-Processing of Drone Imagery	6/16/19	10/10/19	Post-Processed, Ortho-	10/17/19

			Rectified Images	
Image Interpretation (using field verification)	6/17/19	11/10/19	Draft Estimates of Percent Cover for Seaweed and Eelgrass for Mapped Areas	12/1/19
QA Report	12/1/19	2/1/20	QA Report	3/1/20
Final Report	1/1/20	4/1/20	Final Report and Files	4/15/20

Based on EPA-NE Worksheet #10.

* Imagery acquisition is planned to be concurrent with the aerial flight for monitoring eelgrass distribution. The first attempt for this flight will be in mid-June; however, if conditions are not acceptable for the aerial flight, this may get delayed as late as the first week in September. Therefore, all the dates from the image acquisition stage and beyond should be regarded as estimates only.

A7 – Quality Objectives and Criteria

Table 3: Data Quality Objectives, Criteria, and Quality Control Protocols for the Drone Survey

Data Quality Objective	Criteria	Protocol
Imagery Completeness	Imagery obtained for 100% of study area. (i.e., less than 100% will fail to meet objectives)	Extent of imagery will be compared to study area.
Ground Pixel Resolution	Ground resolution is dependent on camera resolution, focal length, and UAV height. For this project, the minimum resolution will be 10 cm. Each pixel will be classified as either unvegetated, eelgrass or seaweed.	Pixel size of imagery will be compared to criteria.
Spatial Accuracy	Horizontal positional accuracy less than or equal to 0.62 meters (2 feet) Root Mean Square Error following guidance from National Standard for Data Spatial Accuracy.	The positions of at least 3 known locations (*i.e.* temporarily fixed buoys or rod-mounted QR code panels) in the orthorectified imagery will be checked against the known coordinates.
Environmental & Timing Conditions	- Tidal stage should be +/-2hrs MLW - Calm winds (<10 mph) - Sufficient water clarity*	Environmental & timing conditions during flight will be compared to criteria.

* "Sufficient water clarity" denotes conditions where the bottom features of the sampling area are distinguishable at the appropriate tidal stage. "Distinguishable" means that the human eye can differentiate between eelgrass, seaweed, and unvegetated bottom. Secchi disk measurements will also be taken to build up a dataset over time of requisite water transparency values required for successful monitoring.

A8 – Documents and Records

QA Project Plan

The Project Manager will be responsible for maintaining the approved QAPP and for distributing the latest version to all parties on the distribution list in section A3. A copy of the approved plan will be made available on the PREP publications web page (https://scholars.unh.edu/prep/).

Reports to Management and the Public

The Project Manager will post the final report on the PREP website. See Section C2 for details about the final reports.

Archiving

The QAPP and final reports will be kept on file with PREP (in electronic formats) for a minimum of 10 years and/or the duration of the EPA grant.

B1 – Sampling Process Design

The sampling process for this project is based on the the sub-tidal portion of the seaweed monitoring protocol (https://scholars.unh.edu/prep/422). Four sites will be sampled in 2019. The stations that will be sampled as part of this study are provided in Table 4. A map of the stations is provided in Figure 2. Annual sampling dates are shown in Table 5. If possible, the team will try to conduct one of the sampling events on the same day as the aerial flight for eelgrass mapping, but this cannot be guaranteed because the flight dates are themselves impossible to plan with 100% certainty.

Table 4: Sample Locations

Station ID	Town, State	Latitude	Longitude	Elevations (m above MLW)	Years Sampled
Adams Point (AP)	Durham, NH	43.09019	070. 86735	0.0, 0.5, 1.0, 1.5	2014-2018(all years)
Lubberland Creek (LC)	Newmarket, NH	43.07427	070. 90339	0.5, 1.0, 1.5	2013, 2015, 2017 (odd years)
Depot Road (DR)	Greenland, NH	43.05611	070. 89682	0.5, 1.0, 1.5	2013-2018 (all years)
Sunset Hill Farm (SHF)	Newington, NH	43.05751	070. 83443	0.75, 1.0, 1.5	2014, 2016 (even years)

Table 5: Annual Sampling Schedule

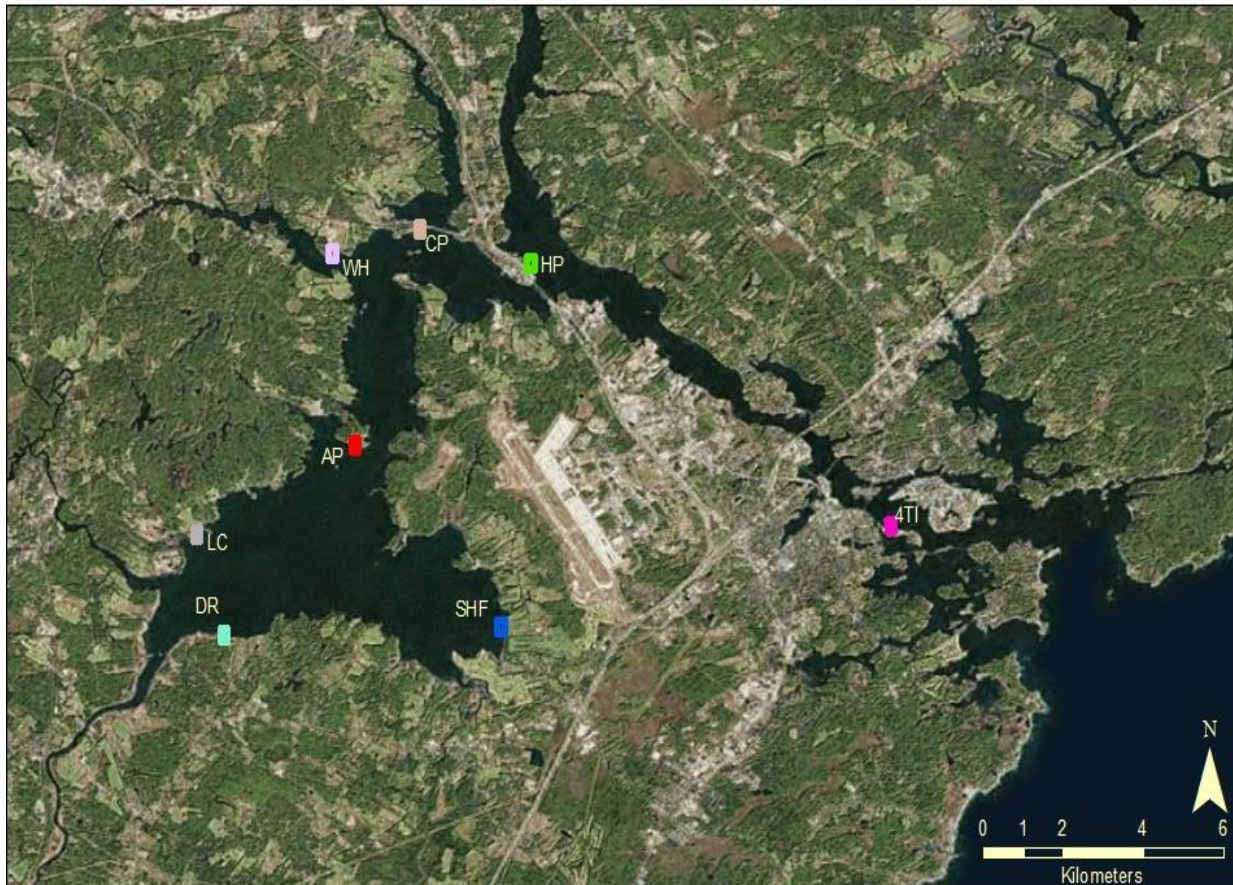| Month	Intertidal vs. Subtidal	Week	# Days Required	Site
July	Subtidal	Week 4	4	AP, DR, LC, SHF
September	Subtidal	Week 1	4	AP, DR, LC, SHF

Figure 1: Location of the four sampling sites for monitoring seaweeds in the Great Bay Estuary: Adams Point, Lubberland Creek, Depot Road, and Sunset Hill Farm. The other sites will not be part of the drone project.

B2 – Sampling Methods

The sample sites will be extensions of the existing intertidal transects, continuing into deeper water and accessed by small, shallow draft vessel. For more on these methods, please see the most recent QAPP for seaweed monitoring, available at: https://scholars.unh.edu/prep/

The objective of the drone work is to classify the survey area into cover classes comprised of the following categories: unvegetated; eelgrass; and seaweed. It is not currently expected that different types of seaweed will be differentiated.

Imagery will be captured at low tide and in the morning before the winds pick up to allow for best water clarity and visibility of the vegetation, thus maximizing the potential for mosaicking of full water images.
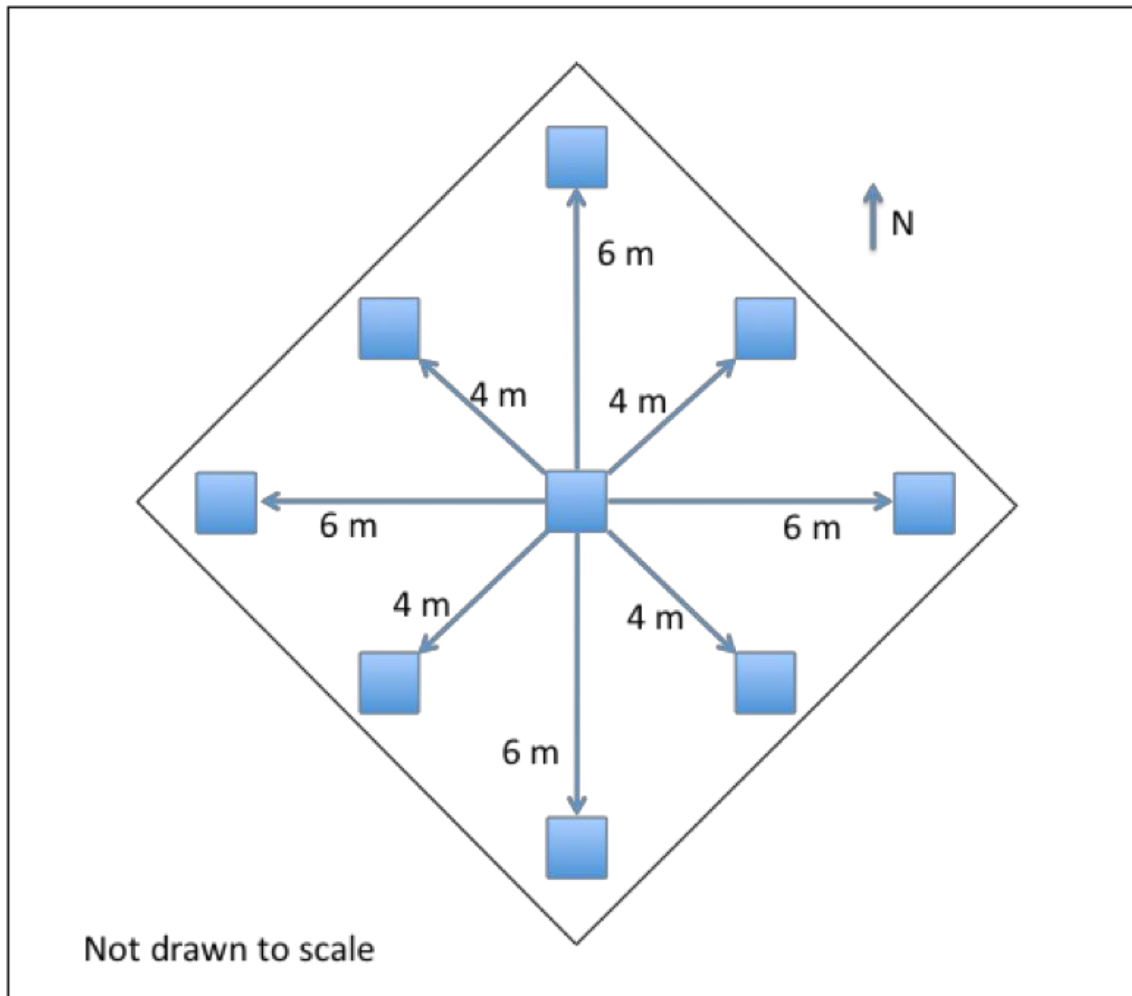
Figure 3: Subtidal sample arrangement of nine plots (0.5 by 0.5 m in size) that represent an area of 100 m^2. This approach is used for seaweed monitoring, and drone work will use the same configuration.

As part of the seaweed monitoring protocol, a fixed array of nine quadrat samples will be placed at each sampling location (Figure 3). Drone monitoring will take place as close as possible to the days of the on-the-ground subtidal sampling, scheduled for Week 4 of July 2019 and Week 1 of September 2019, and taking place at four stations: Adams Point, Depot Road, Lubberland Creek and Sunset Hill Farm (see Figure 2). Sampling events take about 4 days to complete (1 day per site). The drone-based survey area is expected to cover a square area at least ~100x that of the ground-based survey area (100m^2), estimated at 0.01km^2, allowing for extrapolation to subtidal areas adjacent to the ground-based surveys. Larger drone-based survey areas are possible and may be conducted as conditions allow. If possible, at least one survey will be conducted within 1 day before or after the plane-based photography is gathered.

The goal of the drone use is to generate high resolution, georectified photomosaics capturing the area of each of the four study sites.

To plan the survey, we will use 3DR's "Tower" software to set the survey flight path and associated parameters. This includes survey altitude, speed, flight path overlap, timing of photos, camera type, and focal length among other parameters, given the monitoring needs. Once the area is defined and parameters set, the resulting "mission" is uploaded to the drone. The survey will be conducted at the fixed elevation of 200 ft, at a speed of 6 mph, with an overlap of at least 70%, with cameras collecting geo-referenced photos every 3 seconds. The result is a well replicated series of photos that are georeferenced and share a high degree of similarity and commonalities (pixels) that facilitate point cloud generation and the creation of a single, high-resolution photomosaic of the survey area.

Drone flights will be conducted according to the guidelines set forth by The Federal Aviation Administration (FAA) rules for the operation of small Unmanned Aircraft Systems (UAS) in the National Airspace System (NAS) in accordance with Title 14 of the Code of Federal Regulations (14 CFR) part 107. Due to the proximity of several of the study areas to Pease International Airport, additional level of notifications and authorizations will be required to obtain the necessary permissions for flight, including contacting the Pease Flight Tower as well as the FAA. As of May 2019, flight restrictions for the four study sites are as follows: Adams Point (50 ft); Lubberland Creek (400 ft); Depot Road (200 ft); Sunset Hill Farm (200 ft).

The drone to be used for this project is a 3DR Solo. The Solo is preferred to other common consumer grade drones (e.g., DJI Phantom) due to its higher payload and widely available accessories for mounting additional cameras for survey and research purposes. However, technology and drone models and features are ever changing and growing, so there may be other units available that could achieve equally suitable results. The drone will be outfitted with three cameras (one gimballed and able to pan 90 degrees, two mounted in fixed location under the craft, pointed directly down). The gimballed camera is a GoPro 4 with Bluetooth communications to the UAV controller and tablet, providing real time 'view' of UAV flight. The bottom mounted cameras are MaPIR model Survey3 cameras, each 4k resolution. One records visible light (RGB), the other captures Normalized Difference Vegetation Index (NDVI). The benefit of the Survey3 cameras is their integrated GPS antenna, providing a geolocation stamp with each image gathered, greatly facilitating image processing and improving accuracy of the resulting orthomosaic.

Dr. Moore of JEL will be the drone pilot, holding a current FAA 14 CFR part 107 UAV (unmanned aerial vehicle) license (Certificate no. 4150258), along with an observer who may or may not hold UAV license (license not required for observer).

B3 – Sample Handling and Custody

Not applicable. No samples will be collected.

B4 – Analytical Methods

Once acquired, image processing is completed using Pix4D software that integrates Tower's flight logs and geographic positioning data linked to the MaPIR high definition cameras to produce high resolution orthomosaics that are georeferenced and viewable as GeoTiff format files in ESRI, GoogleEarth, or other open access mapping software. The quality (and accuracy) of the resulting mosaic is tied to drone speed, photo overlap, and prevailing weather conditions – thus the need to fly under light wind conditions is important.

Ground observations will be used to 'train' an algorithm for interpretation of the drone-based imagery within an image processing software. The field-based seaweed monitoring observations are the basis for a supervised classification algorithm that will discern different cover types ("unvegetated"; "eelgrass"; or

"seaweed.") for each pixel in the survey area. In some cases, we will rely on visual interpretation to discern cover types from the orthomosaics and will maintain a library of the original photo images, which may be referenced individually if further interpretation or analysis is required.

When completed, this remotely sensed interpretation of cover types will be tested for accuracy by generating random points and comparing the model to ground-based assessments of cover. The accuracy assessment seeks to have >75% agreement between the classification and field assessed plots.

B5 – Quality Control

The Project QA Officer will check that the data quality objectives are met using the criteria and methods from Table 3 in Section A7.

The Project QA Officer and the Field Operations Manager will verify that protocols are followed correctly during the field sampling audit (see Section C1).

QA/QC of ground-based observations are covered under the QAPP for Seaweed Monitoring. QA/QC of drone acquired imagery will be achieved via the georeferenceing software, Pix4D, which automatically issues a Quality Report (see "Appendix A") containing a summary of the mosaicking process. While the Quality Report discusses many criteria, this project is solely concerned with:

1) Keypoints Image Scale: Images have enough visual content to be processed.

2) Data Set: All or almost all images have been calibrated in a single block.

3) Matching: This indicates that the results are likely to be of high quality in the calibrated areas. Figure 5 of the Quality Report is useful to assess the strength and quality of matches.

4) Georeferencing: For optimal results, Ground Control Points (GCPs) should be well distributed over the dataset area. Optimal accuracy is usually obtained with 5 - 10 GCPs.

B6 – Instrument/Equipment Testing, Inspection, and Maintenance

All equipment used for the drone survey shall be inspected prior to the flight to ensure proper operation.

B7 – Instrument/Equipment Calibration and Frequency

The Aerial Sensors/Camera(s) used to acquire project imagery shall have current USGS certification, or in the case of digital sensors a current Product Characterization Report.

B8 – Inspection/Acceptance Requirements for Supplies and Consumables

Not applicable.

B9 – Non-direct Measurements

Information on tides, sun angles, weather, water clarity, and precipitation will be used to decide on the date for the aerial survey. The data sources that will provide this information are:

- Tides: NOAA Tide Predictions at Fort Point, Dover Point, and the Squamscott River span the study area.

    - Fort Point (Portsmouth Harbor)
      http://tidesandcurrents.noaa.gov/noaatidepredictions/NOAATidesFacade.jsp?Stationid=8423898

    - Dover Point
      http://tidesandcurrents.noaa.gov/noaatidepredictions/NOAATidesFacade.jsp?Stationid=8421897

    - Squamscott River
      http://tidesandcurrents.noaa.gov/noaatidepredictions/NOAATidesFacade.jsp?Stationid=8422687

- Sun Angles: Sun angles for Portsmouth, NH are available from http://aa.usno.navy.mil/data/docs/AltAz.php.

- Weather: Weather predictions for Portsmouth, NH are available from http://forecast.weather.gov/MapClick.php?CityName=Portsmouth&state=NH&site=GYX&textField1=43.0568&textField2=-70.782&e=1

B10 – Data Management

Imagery from the survey will be stored on hard drives by the Field Operations Manager. The final imagery files will be transferred to the Project Manager on external hard drives. Draft imagery as a composite true-color compressed file in SID format, geolocated using direct georeferencing and assuming an average elevation.

- Final imagery as orthorectified 4-band (red, green, blue, near infra-red), 8-bit imagery for the entire area in uncompressed GeoTiff format using ¼ quadrangle tiles (1:24,000 scale) and a composite true-color compressed file in SID format.

- The imagery will be projected in New Hampshire State Plane-Feet NAD83 and shall have metadata meeting FGDC standards.

The Final Report (see Section C2) will include quantitative results on the accuracy of drone-based remote sensing assessment of percent cover for three cover classes: unvegetated, seaweed, and eelgrass.

C1 – Assessments and Response Actions

In order to confirm that the survey and analyses occur as planned, the Project QA Officer and the Field Operations Manager shall confer prior to and after the first sampling events in both July and September to discuss the methods being employed and to review the QAPP protocols. The Project Manager will have the authority to resolve any problems encountered.

The Project Manager will initiate appropriate response actions after each check, if needed.

C2 – Reports to Management

The final report for this project will have the following components:

- Introduction
- Methods
    - o Methods for surveys
    - o Methods for post-processing/algorithm development ("training")
    - o Methods for quality control checks
- Results
    - o Summary of cover classification
- References
- Appendix A (Quality Report from Pix4d Software)

D1 – Data Review, Verification, and Validation

The Project QA Officer will be responsible for a memorandum to PREP summarizing any deviations from the procedures in the QAPP and the results of the QA/QC tests. The Project QA Officer will review all field data sheets and/or final computer data files for completeness and quality based on the criteria described in Section A7. The Project QA Officer will also *affirmatively* verify that the methods used for the study followed the procedures outlined in this QAPP. If questionable entries or data are encountered during the review process (see methods in Section B5), the Project QA Officer will contact the appropriate personnel to determine their validity.

D2 – Verification and Validation Procedures

The Project Manager will compare the QA memorandum against the QAPP. Any decisions made regarding the usability of the data will be left to the Project Manager; however, the Project Manager may consult with project personnel or with personnel from EPA, if necessary.

D3 – Reconciliation with User Requirements

The Project Manager will be responsible for reconciling the results from this study with the ultimate use of the data. Results that are qualified through the QA process may still be used if the limitations of the data are clearly reported to decision-makers. Data for this project are being collected as part of a long-

term monitoring program. It is not possible to repeat sampling events without disrupting the time series. Therefore, the Project Manager will:

1. Review data with respect to sampling design.

2. Compare the QA memorandum with the QAPP.

3. If the data quality objectives from Section A7 are met, the user requirements have been met. If the data quality objectives have not been met, corrective action will be established by the Project Manager.

References

PREP. 2017. "State of Our Estuaries 2018" PREP Publications 391. http://www.stateofourestuaries.org/2018-reports/

Appendix A
Quality Report
Template from Pix4D Software

Images	
✅	*Keypoints Image Scale* > 1/4: More than 10'000 keypoints have been extracted per image. *Keypoints Image Scale* ≤ 1/4: More than 1'000 keypoints have been extracted per image.	Images have enough visual content to be processed.
⚠️	*Keypoints Image Scale* > 1/4: Between 500 and 10'000 keypoints have been extracted per image. *Keypoints Image Scale* ≤ 1/4: Between 200 and 1'000 keypoints have been extracted per image.	Not much visual content could be extracted from the images. This may lead to a low number of matches in the images (for more information: Matching Quality Check) and incomplete reconstruction or low quality results. This may occur due to several factors: • **Image content**: Large uniforms areas such as deserts, snow, fog, etc. **What to do**: In such cases, a high overlap is required. Flying at a higher altitude may also have a positive influence on the visual content of the images. • **Image quality**: Images are over/under exposed, blurry, or noisy. **What to do**: Camera parameters need to be adjusted (shutter speed, exposure time). For more information about the camera settings: Step 1. Before Starting a Project > 2. Configuring the Camera Settings. • **Image size**: The likelihood of extracting many features increases with the image size. **What to do**: Images smaller than one megapixel have very few features and require a large amount of overlap (>80%). Doubling the image size used to extract the features could also help: Menu Process > Processing Options... > 1. Initial Processing > General.
⚠️	*Keypoints Image Scale* > 1/4: Less than 500 keypoints have been extracted per image. *Keypoints Image Scale* ≤ 1/4: Less than 200 keypoints have been extracted per image.	**What to do**: Same as above, increasing the overlap (> 90%).

Dataset	
✅	More than 95% of enabled images are calibrated in one block.	All or almost all images have been calibrated in a single block.
⚠️	Between 60% and 95% of enabled images are calibrated or more than 95% of enabled images are calibrated in multiple blocks.	Many images have not been calibrated (A) or multiple blocks have been generated (B). A) **Uncalibrated images** are not used for processing. This may occur due to several factors: • **Dataset with low overlap** or images not taken in a systematic way. Overlap can be assessed in figure 4 and figure 5 of the Quality Report. **What to do**: Increase the overlap. For more information about the flight plan: Step 1. Before Starting a Project > 1. Designing the Image Acquisition Plan > a. Selecting the Image Acquisition Plan Type.

- **Repetitive or complex dataset** (trees, forest, fields).
  What to do:
  - Increase the overlap (>80%).
  - Flying at a higher altitude often reduces visual complexity and improves the results, especially in forest and dense vegetation environments. For more information about the flight plan: Step 1. Before Starting a Project > 1. Designing the Image Acquisition Plan > a. Selecting the Image Acquisition Plan Type.
  - Process with lower Keypoints Image Scale: This processing option can lead to a higher number of calibrated images than the default original keypoint image scale. For more information: Menu Process > Processing Options... > 1. Initial Processing > General.
- **Dataset made from multiple flights** with images not similar enough (different time of capture, moving objects, different temperature, different lens).
  What to do: Process each flight individually and combine the projects together in a second step. For more information about how to merge projects: Merging projects.
- **Dataset containing multiple images** shot from the same position, or images taken during take-off or landing phase.
  What to do: These images should be manually removed.
- **Image quality not sufficient**: Camera parameters need to be adjusted (shutter speed, exposure time). For more information about the camera settings: Step 1. Before Starting a Project > 2. Configuring the Camera Settings.

B) **Multiple blocks**: A block is a set of images that were calibrated together. Multiple blocks indicate that there were not enough matches between the different blocks to provide a global optimization (see the graph 2D Keypoint Matches). The different blocks might not be perfectly georeferenced with respect to each other.

What to do:

- Enabling the option *Rematch* may improve the connection between the blocks. For more information about the *Rematch* option: Menu Process > Processing Options... > 1. Initial Processing > Calibration.
- Adding Manual Tie Points between the blocks and reoptimizing can connect the blocks together. For more information: How to import and mark Manual Tie Points (MTPs).
- Capturing new images with more overlap may be required.

⚠️ Less than 60% of enabled images are calibrated.

What to do: Same as above.

Such a low score may also indicate a severe problem in:

- **The type of terrain**: Water surface, oceans, mirrors and glass surfaces, moving lava, and moving landscapes do not contain the needed visual content for processing. To obtain results, these terrains need to be combined with areas that are easy to reconstruct. Flying at a higher altitude is recommended to map areas close to water: Step 1. Before Starting a Project > 1. Designing the Image Acquisition Plan > a. Selecting the Image Acquisition Plan Type.
- **Image acquisition process**: Wrong image geolocation, inappropriate flight plan, insufficient overlap, corrupted images, etc.
- **Project setup**: Wrong coordinate system definition, wrong images, etc.

Camera Optimization

✅ An initial camera model should is within 5% of the optimized value.

The focal length/affine transformation parameters are a property of the camera's sensor and optics. It varies with temperature, shocks, altitude, and time. The calibration process starts from an initial camera model and optimizes the parameters. It is normal that the focal length/affine transformation parameters are slightly different for each project. An initial camera model should be within 5% of the optimized value to ensure a fast and robust optimization.

⚠️ The percentage of the difference between the initial and optimized focal length for a perspective lens, affine transformation parameters C

What to do:

- Flat and homogenous areas that do not provide enough visual information for optimal camera calibration.
  - Process with lower Keypoints Image Scale: This processing option can lead to a higher number of calibrated images than the default original keypoint image scale. For more information: Menu

	and F for a fisheye lens, is between 5% and 20%	Process > Processing Options... > 1. Initial Processing > General.
		  • Enable Geometrically Verified Matching.
		  • Set "internal calibration parameters" to All Prior in Step 1 processing options.
		• The images have significant rolling shutter distortion.
		  • Calculate the Vertical Pixel Displacement and enable linear shutter optimization in the Image Properties Editor if needed.
		• Blurry images, a dataset with low overlap, damaged camera.
		  • Recapture Image Dataset
		  • Check the camera for any potential damage
		• Wrong initial internal camera parameters. The camera has been physically modified with a lens filter or similar accessory that affects the optic.
		  • Verify that the camera model defined is correct for the images used in the project.
		  • If the camera is not in the Pix4D database then it may be necessary to generate these values by following the instructions:
		    • Fisheye lens calibration
		    • Perspective lens calibration
		• Preprocessed or cropped images.
		  • Do not modify the images before importing into Pix4D for processing.

⚠️	The percentage of the difference between the initial and optimized focal length for a perspective lens, affine transformation parameters C and F for a fisheye lens, is more than 20%.	**What to do**: same as above.

Matching	
✅	*Keypoints Image Scale* > 1/4: More than 1'000 matches have been computed per calibrated image. *Keypoints Image Scale* ≤ 1/4: More than 100 matches have been computed per calibrated image.	This indicates that the results are likely to be of high quality in the calibrated areas. Figure 5 of the Quality Report is useful to assess the strength and quality of matches.
⚠️	*Keypoints Image Scale* > 1/4: Between 100 and 1'000 matches have been computed per calibrated image. *Keypoints Image Scale* ≤ 1/4: Between 50 and 100 matches have been computed per calibrated image.	A low number of matches may indicate that the results are not very reliable: changes in the initial camera model parameters or in the set of images may lead to improvements in the results. Figure 5 of the Quality Report shows the areas with very weak matches. **A low number of matches is very often related to low overlap between the images.** **What to do**: See the Dataset Quality Check section to improve the results. There might be needed to restart the calibration a few times with different settings (camera model, Manual Tie Points) to get more matches. To avoid this situation, it is recommended to acquire images with more systematic overlap. For more information about the flight plan: Step 1. Before Starting a Project > 1. Designing the Image Acquisition Plan > a. Selecting the Image Acquisition Plan Type.
⚠️	*Keypoints Image Scale* > 1/4: Less than 100 matches have been computed per calibrated image.	**What to do**: Same as above. The minimum number of matches to calibrate an image is 25.

Keypoints Image Scale ≤ 1/4: Less than 50 matches have been computed per calibrated image.

Failed Processing Report: always displayed as the information is not available.

Georeferencing	
✅ GCPs are used and the GCP error is less than the average GSD.	For optimal results, GCPs should be well distributed over the dataset area. Optimal accuracy is usually obtained with 5 - 10 GCPs. For more information about GCPs: Step 1. Before Starting a Project > 4. Getting GCPs on the field or through other sources (optional but recommended).

⚠️ GCPs are used and the GCP error is less than 2 times the average GSD.
 	
 or
 	
 no GCPs are used
 	
 Failed Processing Report: always displayed whether GCPs are used or not.
	A) **GCPs are used**
	
	 • **Not enough GCPs** were used given the size of the project.
	   • Add additional GCPs. A minimum number of 3 GCPs is required but we recommend including at least 5 to 10 GCPs. When the topography of the area is complex adding more GCPs could lead to a more accurate reconstruction.
	 • **Accuracy values for GCPs are not properly set**.
	   • If the accuracy of the GCPs is known then it should be entered instead of the default values in the GCP/MTP Manager.
	   • When using the default accuracy values in projects that are set to imperial (ft) then the GCP accuracy should be adjusted to 0.066.
	 • **Poor GCP marking:** The quality of GCP marks can be estimated by reviewing the projection error for each GCP shown in the quality report. All projection error values should be less than 1 pixel.
	   • If the values reported are greater than 1 pixel then carefully remark the images.
	 • **GCPs are not marked on enough images.**
	   • Add additional GCP mark on the project images. Each GCP should be marked in at least 2 images but we recommend marking the GCPs on more project images.
	
	 B) **No GCPs are used**
	 There are two cases where No GCPs are displayed:
	
	 • **No GCPs were entered**. This means that the project is georeferenced using the position of the computed image positions. GPS devices used to geolocate the original images may suffer from a global shift, leading to a global shift in the project of several meters.
	 • **The GCPs were discarded** by the software due to errors with the GCPs (e.g. wrong GCP coordinate system, wrong GCP coordinates, GCPs not marked correctly on the images). For more information: *Ground Control Points*.

🔺 GCPs are used and the GCP error is more than 2 times the average GSD.	A GCP error superior to 2 times the Ground Sampling Distance may indicate a severe issue with the dataset or more likely an error when marking or specifying the GCPs. **What to do**: Same as above.

Preview

The displayed images are the low resolution preview of the Orthomosaic and the DSM before step 2. They allow a visual inspection of the quality of the initial calibration. If the orthomosaic is skewed, there might be an error with the project orientation and GCPs may be required. If the DSM contains large seams or artifacts, there might be due to multiple blocks in the reconstruction. If there are holes in the Orthomosaic and DSM, check the Quality Checks section and the 2D Keypoint Matches graph.

Initial Image Positions

This graph is useful to review the images geolocation. If this graph does not correspond to the flight plan, there might be problems with the matching, and the orientation, scale and/or the geolocation of the results. Check that the images' coordinate system and the images coordinates are correct.

Computed Image/GCPs/Manual Tie Points Positions

This graph shows the difference between the initial and computed image positions, the difference between the initial and computed GCPs/Check Points positions (if any), the MTPs positions (if any) and the uncertainty ellipses of the absolute camera positions.

Images: There might be a small offset between the initial and computed image positions because of image geolocation synchronization issues or GPS noise. If the offset is very high for many images, it may affect the quality of the reconstruction and may indicate severe issues with the image geolocation (missing images, wrong coordinate system, and/or coordinate inversions).

A bended/curved shape in the side and front view may indicate a problem in the camera parameters optimization. Ensure that the correct camera model is used. If the camera parameters are wrong, correct them and reprocess. If they are correct, the camera calibration can be improved by:

- Increasing overlap/image quality.
- Removing ambiguous images (shot from the same position, take-off or landing, too much angle, image quality too low).
- Introducing Ground Control Points.
- Enable linear shutter optimization in the Image Properties Editor.

GCPs/Check Points: An offset between initial and computed position may indicate severe issues with the geolocation due to wrong GCP/Check Point initial positions, wrong coordinate system, and/or coordinate inversions, wrong marks on the images, wrong point accuracy.

Uncertainty Ellipses: The absolute size of the uncertainty ellipses does not indicate their absolute value because they have been magnified by a constant factor noted in the figure caption. In projects with GCPs, the uncertainty ellipses close to the GCPs should be very small and increase for images further away. This can be improved by distributing the GCPs homogeneously in the project.

In projects only with image geolocation, all ellipses should be similar in size. Exceptionally large ellipses may indicate calibration problems of a single image or all images in an area of the project. This can be improved by:

- Adding Manual Tie Points in the area.
- Rematching and optimizing the project.
- Removing images of low quality.

Absolute Camera Position and Orientation Uncertainties

In projects only with image geolocation, the absolute camera position uncertainty should be similar to the expected GPS accuracy. As all images are positioned with similar accuracy, the sigma reported in the table should be small compared to the mean. In such projects, the absolute camera position uncertainties may be bigger than the relative ones in the table "Relative position and orientation uncertainties".

In projects with GCPs, a large sigma can signify that some areas of the project (typically those far away from any GCPs) are less accurately reconstructed and may benefit from additional GCPs.

Overlap

This graph shows the number of overlapping images for each pixel of the orthomosaic. It only takes into account the calibrated images. Red areas indicate too low overlap. This may lead to low-quality 3D reconstruction in these areas. The overlap is an important parameter for the overall quality. For precise 3D modeling and mapping applications, the overlap should be in green, i.e. each pixel should be visible in more than 5 images.

Internal Camera Parameters

Perspective lens: The principal point should be around half the resolution of the camera, and that the radial distortion values R1, R2, R3 should each be smaller than 1. The uncertainties on the focal length and the principal point should be only a few pixels. The uncertainties on the distortion parameters should be close to

zero. For more information about how to edit the initial camera parameters: How to use the Editing Camera Model Options.

Fisheye lens: The principal point should be around half the resolution of the camera. The optimized values for the affine transformation parameters C and F should be close to each other. The optimized values for the affine transformation parameters D and E should be close to 0. The uncertainties on the affine transformation parameters C, D, E, and F should be only a few pixels. The uncertainties on the polynomial parameters should be close to zero. For more information about how to edit the initial camera parameter: How to use the Editing Camera Model Options.

For more information: Camera Optimization section in the Quality Check table.

Parameters Correlation: The highest quality calibration is characterized by decorrelated parameters. However, having some type of correlation between parameters is sometimes expected:

- In projects with nadir images, a correlation between the radial distortion parameters and between the coordinates of the principal point is expected.
- In close-range projects with oblique images, a correlation between the focal length and the coordinates of the principal point is expected as well as between the coordinates of the principal point and the tangential distortions.

What helps with decorrelation:

- Accurate camera positions (e.g. RTK, or at least GPS), combined with GCPs.
- MTPs at multiple depths and near image edges for oblique projects.
- Different camera orientations (e.g. rotate at ends of grid rows, so images will be at 180°), especially when the coordinates of the principal point are correlated.
- Using All Prior for the internal parameters: Menu Process > Processing Options... > 1. Initial Processing > Calibration.

2D Keypoints Table - 2D Keypoint Matches graph

See the Matching and Dataset Quality Check sections in the Quality Check.

The *2D Keypoints Table* displays some statistics of the keypoints and the matches of the project. Keypoints are points of interest (high contrast, interesting texture) on the images that can be easily recognized. The number of keypoints depends on:

- The size of the images.
- The visual content.

A 14MP image will generate between 5'000 and 50'000 keypoints per image. If the number of keypoints is less than 1'000, the image may not have enough content to be calibrated (Images section in the Quality Check). The number of matches will be very low if:

- The number of keypoints is low.
- Visual content is too repetitive.
- Overlap between the images is too low.
- There are too many changes in the scene during the image acquisition (moving shadows, cars, etc).

The minimum number of matches to calibrate an image is 25. The recommended number of matches is at least 1'000 per image. In the *2D Keypoint Matches* graph, it is possible to visualize the areas with weak matches. It might be necessary to acquire images again in these areas to increase the image overlap.

The Uncertainty Ellipses describe how precisely each image is located with respect to the other images by means of the Manual and Automatic Tie Points. Usually, the ellipses in the center of the project are smaller than at the outside, as these images have more matches that bind them to the surrounding images. Large ellipses in parts of the project may indicate problems calibrating these parts of the project and typically correspond to areas with few matches.

Relative Camera Position and Orientation Uncertainties

The mean relative camera position uncertainty should be within a few multiples of the GSD, the mean orientation uncertainty should be less than 0.1 degree. A large sigma may indicate that some parts of the project are not well calibrated.

In projects with RTK-GPS or with many GCPs the relative camera position and orientation uncertainties reported in this table may be worse than the ones reported in the table "Absolute Camera Position and Orientation Uncertainties". This is expected as this table provides information on how well the Tie Points constrain the images.

2D Keypoint Table for Camera

This table is displayed if more than one camera model is used. It displays some statistics of the keypoints and the matches for each camera model. The same

analysis as above applies.

Median / 75% / Maximal Number of Matches Between Camera Models

This table is displayed if more than one camera model is used. It shows the median, 75% quartile, maximum number of matches between two different cameras models and between the images of one camera model. The same analysis as above applies.

3D Points from 2D Keypoint Matches

Multiple 2D matching keypoints are triangulated together using the camera parameters to generate a 3D point. 3D points generated from 2-3 images are less precise than 3D points generated from a higher number of images.

Manual Tie Points

This section is displayed if MTPs have been used. For a good calibration Manual Tie Points should have an error around 1 pixel. The Manual Tie Points image marks should also be *Verified*. High *Projection Error* and/or many not *Verified* marks may indicate an issue with the marking or the calibration.

Ground Control Points

This section is displayed if GCPs have been used. GCPs are used to assess and correct the georeference of a project. For more information: Georeferencing. 3 GCPs is the minimum to geolocate (scale, orient, position) a project. Optimal accuracy is usually obtained with 5 - 10 GCPs. For more information about GCPs: Step 1. Before Starting a Project > 4. Getting GCPs on the field or through other sources (optional but recommended).

Scale Constraints

This table is displayed if the project has Scale Constraints. It displays the *Computed Length Error* for the scale constraint. Verify that the mean error is close to 0 and the sigma error is close to 1. If not, verify that:

- The *Initial Length* accuracy for the scale constraint is correct.
- The image geolocation accuracy is correct if the images are geolocated.
- The GCPs accuracy is correct if the project has GCPs.

Orientation Constraints

This table is displayed if the project has Orientation Constraints. It displays the *Computed Angular Error* in degrees for the orientation constraint. Verify that the mean error is close to 0 and the sigma error is close to 1. If not, verify that:

- The *Angular Accuracy* for the orientation constraint is correct.
- The image geolocation accuracy is correct if the images are geolocated.
- The GCPs accuracy is correct if the project has GCPs.

Absolute Geolocation Variance

This table displays the percentage of geolocated and calibrated images with a geolocation error in X,Y,Z within a predefined error interval. There are ten predefined intervals between -1.5 and 1.5 times the maximum accuracy A_{max} of all images. If the percentage of images with an error lower than -1.5 × A_{max} or higher than 1.5 × A_{max} is big, the *Accuracy* values might not have been set correctly. Verify if the *Accuracy* of the image geolocation and the GCPs needs to be adjusted.

This table also evaluates the quality of the image geolocation. A high percentage of images with a high error may indicate:

- Noise in the GPS device.
- Poor synchronization between the GPS device and the camera.
- Errors in the geotagging process.

Geolocation Coordinate System Transformation

This table is displayed if a *Site Calibration* transformation is defined and enabled and if the output coordinate system is an arbitrary coordinate system. It defines the transformation from the input coordinate system to the output arbitrary coordinate system.

It can be used in projects where the images are in a known coordinate system and no GCPs are used in order to define the transformation to an arbitrary output coordinate system. For more information: How to compute the Site Calibration for GCPs in an Arbitrary Coordinate System.

Relative Geolocation Variance

This table displays the percentage of geolocated and calibrated images with a *Relative Geolocation Error* between -1 and 1, -2 and 2 and -3 and 3. A high percentage of images with a *Relative Geolocation Error* lower than -3 or higher than 3 may indicate an incorrect value for the *Accuracy* of the image geolocation (given by the user). Verify if the *Accuracy* of the image geolocation and the GCPs needs to be adapted.

In projects without GCPs:

- If less than 99.6% of the geolocated and calibrated images have an error between -3 and 3, then the geolocation *Accuracy* might be overestimated. Try to increase the value for the geolocation *Accuracy*.

Rolling Shutter Statistics

This section is displayed if the *Linear Rolling Shutter* model has been selected. The graph contains the vector between the initial camera position and the final camera position during the readout time (time needed to take the image). The vector should have the same direction as the flight direction and the *Median camera speed* should correspond to the drone speed during flight. If this is not the case, there might be a problem with the calibration. Check the number and quality of matches, camera parameters, the overlap of the project.

The table displays the

- Median camera speed.
- Median rolling shutter displacement(during sensor readout).
- Median rolling shutter time.

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