



A Report from the University of Vermont Transportation Research Center

Using Remote Data Collection to Identify Bridges and Culverts Susceptible to Blockage During Flooding Events

Final Report

TRC Report 16-003
December 2016

Jim Sullivan, Jarlath O'Neill-Dunne, and Sean McFaden

Using Remote Data Collection to Identify Bridges and Culverts Susceptible to Blockage During Flooding Events

December 14, 2016

Prepared by:

James L. Sullivan
University of Vermont Transportation Research Center
Farrell Hall
Burlington, VT 05405

Jarlath O'Neill-Dunne
Sean McFaden
Tayler Engel
University of Vermont Spatial Analysis Lab
George D. Aiken Center
Burlington, VT 05405-0088

Acknowledgements

The authors would like to acknowledge VTrans for providing funding for this work and to senseFly for providing technical advice on the operation and processing of data collected using Unmanned Aerial Vehicles.

Disclaimer

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the UVM Transportation Research Center. This report does not constitute a standard, specification, or regulation.

Table of Contents

Acknowledgements	i
List of Tables	iii
List of Figures	iii
Executive Summary	1
Data Collection	1
Feature Extraction and Decision Support Methodology	2
Results and Implementation	3
1 Introduction	1
2 Background and Literature Review	3
3 Data Collection	6
3.1 Selection of Test Sites	6
3.2 Equipment	21
3.3 Flight Logging	21
3.4 Imagery Acquisition	35
4 Feature Extraction and Decision Support Methodology	43
5 Results	51
5.1 Evaluation of Threat and Risk	51
5.2 Web-Based Imagery Tool	55
6 Supplemental Analysis of Debris Dynamics	60
7 Conclusions and Implementation	65
7.1 Conclusions	65
7.2 Implementation	66
8 References	68
Appendix A	70

List of Tables

Table 1 Sites Chosen for Imagery Acquisition	21
Table 2 Summary of Flights at Each Crossing.....	35
Table 3 LWD Pile Inventory in Money Brook	45
Table 4 Summary of Large Woody Debris Piles.....	51
Table 5 Modified Inverse Distance Upstream for Each Crossing.....	52

List of Figures

Figure 1 Damage caused by debris blockage of a crossing structure	1
Figure 2 Location of Money Brook, State Route 100, and the Black River.....	7
Figure 3 Money Brook Looking Upstream from Route 100 in Plymouth (August 2012)	8
Figure 4 Development Along Great Brook at Mill Street in Plainfield, Vermont	9
Figure 5 Damage to Infrastructure from Great Brook at Mill Street in July 2015.	10
Figure 6 Road Crossings of Great Brook in Plainfield, Vermont	11
Figure 7 Great Brook in Plainfield (Follows Brook Rd to the north), Gunners Brook in Barre (Follows Lower Rd, Plainfield Brook Rd & State Route 14 to the southwest), and Honey Brook (Crosses Sierra Lavin Rd, Nuissi Rd & U.S Hwy 302 to the south) in East Barre.....	12
Figure 8 Five Road Crossings of Gunners Brook in Barre	13
Figure 9 Armoring of Gunners Brook Upstream of U.S. Hwy 302.....	14
Figure 10 Crossings of Honey Brook in Barre.....	15
Figure 11 Honey Brook Looking Upstream from U.S. Hwy 302	16
Figure 12 Flooding of Honey Brook at U.S. Hwy 302 in July 2007.....	17
Figure 13 West Branch Deerfield River at its Confluence with the Deerfield River in Readsboro.....	18
Figure 14 West Branch Deerfield River Crossing at Tunnel St. in Readsboro.....	19
Figure 15 Crossings of Concern at Test Sites Selected for Imagery Acquisition.....	20
Figure 16 Screen image from the eMotion 2 flight planning software showing the mission shape (A), the ground resolution and target height (B), and the overlap (C)	23
Figure 17 Screen image from the eMotion 2 flight planning software showing the working area radius (A) and the working area ceiling (B).....	24
Figure 18 Flight Log for Gunners Brook at Mitchell Road / Unnamed Brook at Lower Road	25

Figure 19	Flight Log for Gunners Brook at U.S Hwy 302	26
Figure 20	Flight Log for Honey Brook (North).....	27
Figure 21	Flight Log for Honey Brook (South).....	28
Figure 22	Flight Log for Money Brook (West).....	29
Figure 23	Flight Log for Money Brook (South)	30
Figure 24	Flight Log for Money Brook (North)	31
Figure 25	Flight Log for Great Brook (North).....	32
Figure 26	Flight Log for Great Brook (Mid)	33
Figure 27	Flight Log for Great Brook (South).....	34
Figure 28	Flight Log for West Branch Deerfield River.....	35
Figure 29	Orthophotos of (a) Gunners Brook at Mitchell Rd & Unnamed Brook at Lower Rd, (b) Gunners Brook at Harrington Ave and U.S. Hwy 302, (c) Honey Brook at U.S. Hwy 302, (d) Money Brook at Vermont Route 100, (e) Great Brook at Mill Street, and (f) West Branch Deerfield River at Tunnel St.....	42
Figure 30	Digital Terrain Model for the Money Brook Site.....	43
Figure 31	Locations of large woody debris piles in Great Brook (July 2015).....	44
Figure 32	Characterization of LWD Pile Relative Size.....	45
Figure 33	Comparison of UAV Imagery of a LWD Pile with Previously Available Imagery	47
Figure 34	Large woody debris piles identified in Great Brook (a-c) and Money Brook (d), with extracted thumbnail images (insets).....	50
Figure 35	LWD Piles Upstream of the first Great Brook Crossing by Brook Road and the first 2 LWD Piles (inset)	54
Figure 36	Threat-Vulnerability Matrix	55
Figure 37	Starting Page for the Web Application for Accessing Imagery from UAV Missions.....	56
Figure 38	Image Footprint for Money Brook in the Web Application.....	57
Figure 39	Download Options for Money Brook in the Web Application	58
Figure 40.	Online portal for the Great Brook woody debris mapping.....	59
Figure 41	Debris Counts in Great Brook before and after the July 20, 2015 Storm.....	61
Figure 42	Change in LWD Piles.....	62
Figure 43	LWD Pile Transitions in Great Brook before and after the July 20, 2015 storm	64

Executive Summary

Debris blockages of transportation-related river and stream crossing structures such as bridges and culverts can cause flooding at lower flow volumes than predicted by floodplain delineations. These types of flooding events contribute to the damage that was observed during both Tropical Storm Irene and the heavy rainfall in the spring and summer of 2013. Flooding occurs (1) when rain falls over a prolonged period of time, (2) when intense rain falls over a short period of time, or (3) when an ice or debris jam reduces the capacity of a crossing structure and causes a river or stream to overflow onto the surrounding area. The focus of this project is on the third type of flooding, specifically due to debris jams at crossing structures – culverts and bridges. Debris jams can also cause riverbank erosion, impede migration of aquatic creatures and adversely impact wildlife habitats.

A new approach to mapping potential debris blockages that can produce actionable information in a timely manner at a reasonable cost would be highly valuable to Vermont agencies at many levels of government. The objectives of this project were to pilot test the use of an unmanned aerial vehicle (UAV) to gather stereo imagery of streambeds upstream of crossing structures, and develop a process of rapidly transmitting actionable information about potentially blocking material to stakeholders.

A new system was developed in this project to identify potentially obstructing debris using a lightweight, easily-deployable UAV. The system was pilot-tested to provide safe, timely, and cost-effective information about potentially blocking material at vulnerable bridges and culverts. A process was also developed and tested for automating detection of these potential obstructions and outputting a data table containing an extracted thumbnail image of each identified obstruction.

Data Collection

The data collection phase of the project began by assembling the team of advisors from VTrans, ANR, and the Division of Emergency Management and Homeland Security (DEMHS) to assist in the selection of field sites for pilot tests. The test sites consisted of stream

reaches that are upstream of culverts or bridges on the network of public roadways in Vermont where debris collection and/or clogging has been a known or suspected problem.

The team identified the following test sites to include in this project:

Site	Town	Crossing Damage Event(s)	Length (mi.)	Avg. Slope
Gunners Brook	Barre	August 2011, July 2015	1.9	3%
Unnamed	Barre	August 2011, July 2015	2.4	5%
Gunners Brook	Barre	August 2011, July 2015	3.0	3%
Honey Brook	East Barre	July 2007	1.3	6%
Money Brook	Plymouth	Tropical Storm Irene	1.2	14%
Great Brook	Plainfield	Spring 2011, July 2015	6.2	2%
West Branch Deerfield River	Readsboro	August 2011	1.2	5%

At each site, a flight plan was uploaded to the UAV and flight operations were conducted. The number and timing of flights completed for each crossing were:

Site	Crossing-of-Concern	No. of Flights	Time of Flight(s)
Gunners Brook	Mitchell Rd	1	July 2015
Unnamed Brook	Lower Rd		
Gunners Brook	Harrington Ave	1	July 2015
	U.S Hwy 302		
Honey Brook	U.S Hwy 302	2	May 2015
Money Brook	State Route 100	3	
Great Brook	Brook Rd 1	6	May 2015, June 2015, July 2015
	Brook Rd 2		
	Brook Rd 3		
	Brook Rd 4		
	Brook Rd 5		
West Branch Deerfield River	Tunnel Street	1	March 2014

Feature Extraction and Decision Support Methodology

Once streambed imagery had been successfully collected using the UAV, the next step was to identify large woody debris (LWD) piles and

determine a method for disseminating actionable information about the piles to Vermont stakeholders. Decision-makers need to know the distance between each pile and the crossing and the relative size of each pile to assess the threat that the piles pose to the road infrastructure. In addition, the location and a visual image of each pile is necessary to plan for and conduct mitigation operations to protect crossings that are deemed to be at high risk.

As LWD piles were identified, the piles were classified according to the approximate number of trees present in each pile. Piles consisting of one to two trees were categorized as small piles, piles with three to six trees were categorized as medium piles, while piles containing more than 6 trees were categorized as large piles.

While sharing imagery of the debris pile itself is necessary in order to facilitate effective mitigation planning, transmitting the full ortho-rectified images directly is not feasible, due to the large file size of the high resolution imagery (between 400 MB and 2.5 GB each). Therefore, the team decided to extract only a thumbnail image of each pile, and to include only the required descriptive characteristics:

- Pile Longitude & Latitude
- Distance Upstream from Crossing (ft)
- Relative Size

Compiling the information in this way reduced the average file size (including the thumbnail and the supporting data) of the transmission to about 30 KB – a very manageable size for transmitting by email (typically a 10 MB limit) or text message (typically a 300-600 KB limit), using a smartphone network. This transmission provides all the information required to evaluate the threat and consider mitigation.

Results and Implementation

The number of piles identified at each crossing, and their average distance upstream of the crossing were:

- Gunners Brook - Mitchell Rd: 6 piles at 868 feet
- Unnamed Brook - Lower Rd: 17 piles at 760 feet
- Gunners Brook - Harrington Ave: 5 piles at 210 feet

- Gunners Brook - U.S Hwy 302: 6 piles at 290 feet
- Honey Brook - U.S Hwy 302: 17 piles at 1,503 feet
- Money Brook - State Route 100: 13 piles at 1,592 feet
- Great Brook - Brook Rd 1: 33 piles at 917 feet
- Great Brook - Brook Rd 2: 82 piles at 1,734 feet
- Great Brook - Brook Rd 3: 73 piles at 2,515 feet
- Great Brook - Brook Rd 4: 7 piles at 569 feet
- Great Brook - Brook Rd 5: 33 piles at 1,646 feet
- Great Brook - Mill Street: 1 pile at 499 feet

West Branch Deerfield was flown in late winter in an effort to determine how ice and snow affect the identification of debris (and ice). Identification of LWD was not possible due to snow cover.

A threat index was created that makes use of these assumed relationships, and inverts the distance upstream for each pile to align increasing threat with smaller distances. The modified inverse distance upstream (MIDU) can be calculated by weighting the inverses of the distances upstream for the large piles by a factor of 6, and the medium piles by a factor of 3. The MIDU provides an indication of threat that considers the quantity of piles, their individual sizes, and their distance from the crossing. The MIDUs for each of the river crossings tested were:

- Gunners Brook - Mitchell Rd: 0.01
- Unnamed Brook - Lower Rd: 0.24
- Gunners Brook - Harrington Ave: 0.24
- Gunners Brook - U.S Hwy 302: 0.04
- Honey Brook - U.S Hwy 302: 0.06
- Money Brook - State Route 100: 0.04
- Great Brook - Brook Rd 1: 0.73
- Great Brook - Brook Rd 2: 0.21
- Great Brook - Brook Rd 3: 0.12

- Great Brook - Brook Rd 4: 0.04
- Great Brook - Brook Rd 5: 0.09
- Great Brook - Mill Street: 0.01

From these MIDU values, it can be concluded that the most significant threat at the time of these flights was present at the first crossing of Brook Road by Great Brook

To get an indication of the overall risk of culvert or bridge obstruction from LWD, the vulnerability of the crossing itself must also be considered. The relative vulnerability of the crossings to being obstructed by LWD is created by the width of the opening through which water and debris can pass. Variables that will contribute to this vulnerability include:

- channel armoring
- floodplain availability
- bankfull width
- culvert or bridge width

Both threat and vulnerability should be considered together as an indication of risk.

The UAV can be deployed rapidly and output data can be provided in 24 to 48 hours. This fast turnaround is critical, based on the findings of the supplemental analysis of LWD changes in Great Brook. These changes highlight the importance of responsiveness of corrective actions. Corrective measures to mitigate high-risk crossings must be implemented promptly after the identification of LWD piles contributing to that risk – before the next significant storm event. At significant storm events, it appears that most or all of the LWD piles in a stream are either diminished, shifted or removed entirely, with many new piles appearing. These changes make previous LWD pile identifications obsolete. Therefore, it is recommended that the pre-mitigation UAV flight be deployed only once stakeholders are prepared to take relatively immediate corrective action.

1 Introduction

Debris blockages of transportation-related river and stream crossing structures such as bridges and culverts can cause flooding at lower flow volumes than predicted by floodplain delineations. These types of flooding events contribute to the damage that was observed during both Tropical Storm Irene and the heavy rainfall in the spring and summer of 2013 (Figure 1).



Figure 1 Damage caused by debris blockage of a crossing structure

The types of debris with the potential to block watercourses are numerous, ranging from tree trunks, branches, and shrubs to silt and gravel deposits. Identification of these materials is challenging. On-the-ground, manual field surveys are time consuming, costly, potentially dangerous, and infeasible in certain heavily forested regions. Traditional remote-sensing approaches, such as aerial surveys or satellite imagery, can be unworkable due to a combination of cost, resource availability, atmospheric conditions (e.g. cloud coverage), and sensor resolution. A new approach to mapping potential debris blockages that can produce actionable information in a timely manner at a reasonable cost would be highly valuable to Vermont agencies at many levels of government.

The objectives of this project were to pilot test the use of an unmanned aerial vehicle (UAV) to gather stereo imagery of streambeds upstream of crossing structures, and develop a process of rapidly transmitting actionable information about potentially blocking material to stakeholders.

A new system was developed to identify potentially obstructing debris using a lightweight, easily-deployable UAV. The system was pilot-tested to provide safe, timely, and cost-effective information about potentially blocking material at vulnerable bridges and culverts. A process was also developed and tested for automating detection of these potential obstructions and outputting a data table containing an extracted thumbnail image of each identified obstruction. The resulting model will support assessment of the corrective measures needed to address debris before it is transported downstream.

Although the project originally called for only two to three test sites, synergies between this project and an ongoing project from 2013 to 2017 for the Research and Innovative Technology Administration at U.S. DOT allowed additional sites to be included, resulting in a total of 6 test sites with 8 crossings. These synergies also allowed the research team to extend our focus at one of the sites (Great Brook) to examine the movement of specific debris piles in the streambed after a significant storm event. The U.S DOT project, entitled Rapid Exploitation of Commercial Remotely Sensed Imagery for Disaster Response & Recovery, automated the process of identifying road damage locations after a major storm, especially in places that were difficult or impossible to access by vehicle. This process will improve the quality of repairs made after major storm events and increase the speed with which the transportation network returns to its functional state. The U.S DOT project was provided supplemental funding in May 2015 to extend its duration another 2 years and extend its focus to explore the use of a UAV to address a wider variety of needs of state and local transportation agencies. These additional needs include four areas that have been determined to be of high interest by stakeholders: 1) stream geomorphic assessment 2) construction management and phasing, 3) resource allocation during disaster response, and 4) cost decision support during disaster response. The work funded in this project by VTrans applies synergistically to areas 1) and 4) of the supplemental US DOT funding scope.

Other significant costs incurred by the U.S DOT project that provided mutual benefit to this project were (1) the purchase of the UAV and its support software, (2) the development of flight planning and pre-flight operations expertise, and (3) development of expertise with image processing software necessary to accomplish the goals of this project.

2 Background and Literature Review

Flooding occurs (1) when rain falls over a prolonged period of time, (2) when intense rain falls over a short period of time, or (3) when an ice or debris jam reduces the capacity of a crossing structure and causes a river or stream to overflow onto the surrounding area. The focus of this project is on the third type of flooding, specifically due to debris jams at crossing structures – culverts and bridges. Debris jams can also cause riverbank erosion, impede migration of aquatic creatures and adversely impact wildlife habitats.

Vermont's Agency of Natural Resources (ANR) distinguishes large woody debris (LWD) from sediment in its assessment of the risk that debris poses to natural stream systems (Schiff et. al., 2014). LWD is beneficial in natural stream systems as it contributes greatly to the roughness of the stream channel, reducing the overall velocities and the stream power acting on the bed and banks of the stream. LWD also provides critical ecological benefits.

The generation, storage, and transport of woody debris from trees falling into a river influence channel equilibrium and stability and improves instream habitat (Brooks et al., 2006). For example, wood can create stable step-pools in steep mountain channels (Wohl and Merritt, 2008). Wood influences sediment storage, spacing of riffle-pool sequences, and vertical channel stability (Thompson, 1995). LWD forms physical holding locations for fish, and serves as the base of the aquatic food web (Allan, 1995).

Therefore, removal of LWD can remove an important mechanism for long-term channel bed and bank stability and future instream habitat structure. Effective river management must strike a balance between removing debris that pose a significant risk to infrastructure and leaving debris in the channel or floodplain to perform beneficial functions. The level of risk created by LWD accumulations should be assessed prior to removal. Specific procedures for assessing risk from LWD in a channel and removing the proper amount of LWD are established in the Vermont Standard River Management Principles and Practices (Schiff et. al., 2014). These principles recommend removal of debris only when debris jams span the entire channel, alter flow paths, and create a high risk of avulsion, or when remobilization of debris downstream is likely.

Information about the natural geomorphology of channels and floodplains is required for post-flood assessment, alternatives analysis, and design. Without geomorphic data that describe the natural form and function of the river and floodplain, flood recovery can turn into guesswork that may or may not reduce future flood risks, and flood-mitigation effectiveness is greatly reduced. Geomorphic data are available through the state's Stream Geomorphic Assessment (SGA) program, and data about the presence of LWD

at bridges and culverts is available through the Bridge and Culvert Assessment program. Both of these programs also gather information about the potential for bridges and culverts to be blocked by debris.

However, both of these assessments are resource-intensive efforts designed to completely describe the geomorphology of a stream reach. Debris loading in rivers and streams is a very dynamic process, so tools are needed to facilitate the rapid assessment of debris and sediment loads to allow immediate response when and where risks are high. Focusing risk assessments on specific locations with LWD in rivers and streams can make the removal of debris more efficient, especially when the accessibility of many of these mountainous stream reaches are considered.

Remote sensing data sources have the capability of automating geomorphology assessments, which is a needed step toward making rapid assessments of debris loads a reality. Semmens et. al. (2006) developed a GIS-based tool that capitalizes on the availability of high-resolution digital elevation models (DEMs) to derive channel morphology at the reach scale. Williams et. al. (2013) make use of DEMs along with other data sources to first characterize stream reaches into hydrogeomorphic patches and then output a variety of useful measures describing them. Biron et. al. (2013) advanced these methods further, also using a GIS platform, with a specific focus on estimating stream power for identifying areas of high streambank erosion. However, these tools rely on the availability of 1-m resolution LiDAR, with the ability to convey meaningful information about the cross-sectional features of the stream, like bankfull width and slope. Although these features are useful for geomorphological assessments, higher resolution DEMs (10-cm or less) are needed to extract meaningful information about debris loads in streams. This information is needed at higher temporal resolutions to determine the fate of LWD in streams that might pose a risk to downstream bridges and culverts.

Advances in digital photogrammetry have made it possible to rapidly generate DEMs from aerial imagery. At the same time, UAVs are making it easier and less costly to obtain the high-quality aerial imagery required for such applications. Although systems as simple as kites and balloons have been used to capture imagery suitable for such workflows more advanced, programmable platforms like the one used in this project are required if the data are to be accurate enough for precise mapping. Supplementing mobile LiDAR scanning with DEMs derived from UAV photogrammetric point clouds has been shown to provide bathymetric accuracies of under 10 cm, which are critical for accurate geomorphology (Flener et. al., 2013). A study of coastal environments found UAV-based photogrammetric methods to be comparable in their accuracy to terrestrial LiDAR, and to be better suited to obtaining data rapidly and in submerged environments (Mancini et. al., 2013).

Discrepancies between the two were found to be under 22 cm in resolution (by root mean square error), but closer to 5 cm, with accuracies at around 10 cm when compared with a “ground-truth” global navigation satellite system (Mancini et. al., 2013). A specific application to fluvial dynamics in a mountain stream showed spatial resolutions of 2 cm and an exceptional ability to identify shifting stream-bank erosion and make volumetric estimates of sediment loads (Mirijovsky and Langhammer, 2015). This study, in particular suggests that the application tested in this project is extremely feasible. However, the study by Mirijovsky and Langhammer (2015) made use of imagery obtained from a hexacopter, making coverage of the river system limited. The study by Mirijovsky and Langhammer (2015) also highlighted the need to study stream geomorphology in a time-series manner. They repeated their data collection every 6 months for 2 years, in 2013 and 2014.

3 Data Collection

3.1 Selection of Test Sites

The data collection phase of the project began by assembling the team of advisors from VTrans, ANR, and the Division of Emergency Management and Homeland Security (DEMHS) to assist in the selection of field sites for pilot tests. The test sites consisted of stream reaches that are upstream of culverts or bridges on the network of public roadways in Vermont where debris collection and/or clogging has been a known or suspected problem. Based on a literature review and stakeholder feedback, it was determined that multiple flights at one of the sites would also be useful in describing the dynamic processes involved with debris loads in rivers and streams in Vermont. Synergy between the activities on this project and the activities on the U.S.DOT project allowed the inclusion of these extra flights.

The advisor team identified Money Brook in Plymouth, Vermont as a test site. Money Brook is a steep brook running through a narrow, actively-incising ravine that crosses under State Route 100 where it meets the Black River (Figure 2). One of the prime reasons for selecting the site is that the topographic and vegetative characteristics make it challenging to both operate a UAV and generate accurate geospatial products from the imagery. Thus, if the proposed imagery acquisition was successful for Money Brook, it would demonstrate that operations in similarly challenging landscapes are possible.



Figure 2 Location of Money Brook, State Route 100, and the Black River

This brook is known to transport debris frequently to the box culvert spanned by Route 100. This box culvert clogged during Tropical Storm Irene due to the significant debris that was transported from upstream, and the overflow flooding destroyed portions of the roadway and caused damage to structures near the crossing (see Figure 3).



Figure 3 Money Brook Looking Upstream from Route 100 in Plymouth (August 2012)

Better information about debris in the brook upstream of the culvert in advance of the storm may have provided the ability to predict the amount of bedload likely to be delivered to the crossing-of-concern with State Route 100 during an extreme storm event.

Great Brook, in Plainfield was identified as a second test site. This stream has highly-eroded banks and typically high concentrations of uprooted trees and other woody debris. Near its confluence with the Winooski River, this brook becomes more confined by development along its banks in the Village Center of Plainfield (see Figure 4).



Figure 4 Development Along Great Brook at Mill Street in Plainfield, Vermont

A flash flood in spring 2011 severely damaged adjacent transportation infrastructure in numerous locations in Plainfield, so this waterway was identified as an ideal site for evaluating potential threats to downstream bridges and culverts. The Mill Street crossing in particular seemed particularly vulnerable, as it was damaged again in July 2015 during a severe storm (Figure 5). The town had contracted with Milone and Macbroom to evaluate options for the bridge, a key component of which was developing an understanding of woody debris movement in the Great Brook.



Figure 5 Damage to Infrastructure from Great Brook at Mill Street in July 2015

Great Brook was analyzed from its confluence with the Winooski River in Plainfield Village Center upstream past 4 bridges, where its potential for causing flooding is evident (Figure 6).

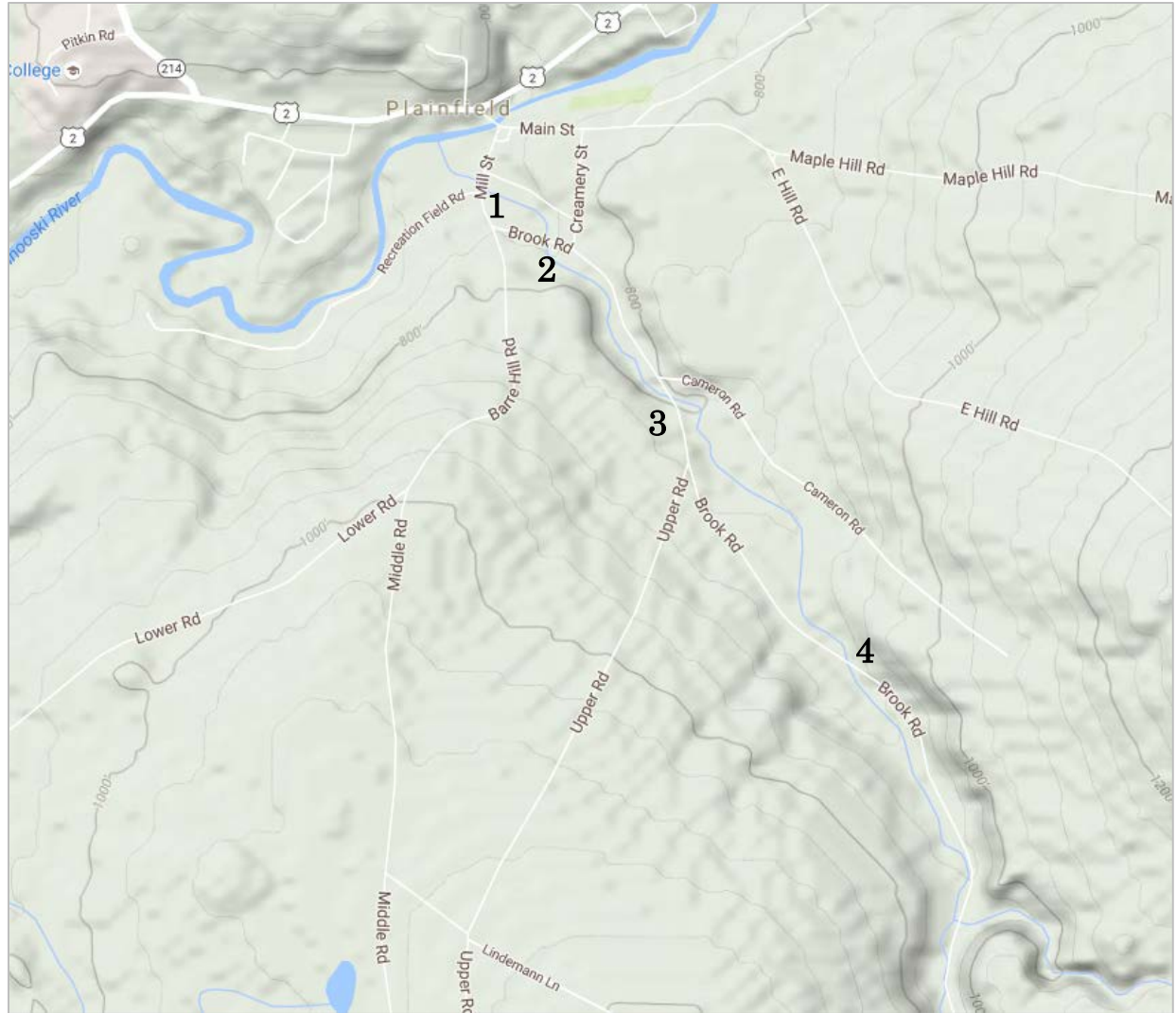


Figure 6 Road Crossings of Great Brook in Plainfield, Vermont

The first crossing, at Mill Street, is the crossing-of-concern, but damage has been reported at the other three as well. The team also decided that Great Brook would make an ideal site to analyze a time-series of images through multiple seasons. The time-series data for this site would likely show transitions in changing ice conditions, the potential for ice jams behind bridges and other choke points, along with the woody debris changes during each 3-month period of seasonal transition.

Three other sites near Great Brook were also selected where debris transported to road crossings were a known problem. Gunners Brook and Honey Brook in Barre both flow from the west side of the ridge that separates them from Great Brook, to the south into Stevens Branch and Jail Branch along U.S. Hwy 302 (Figure 7).

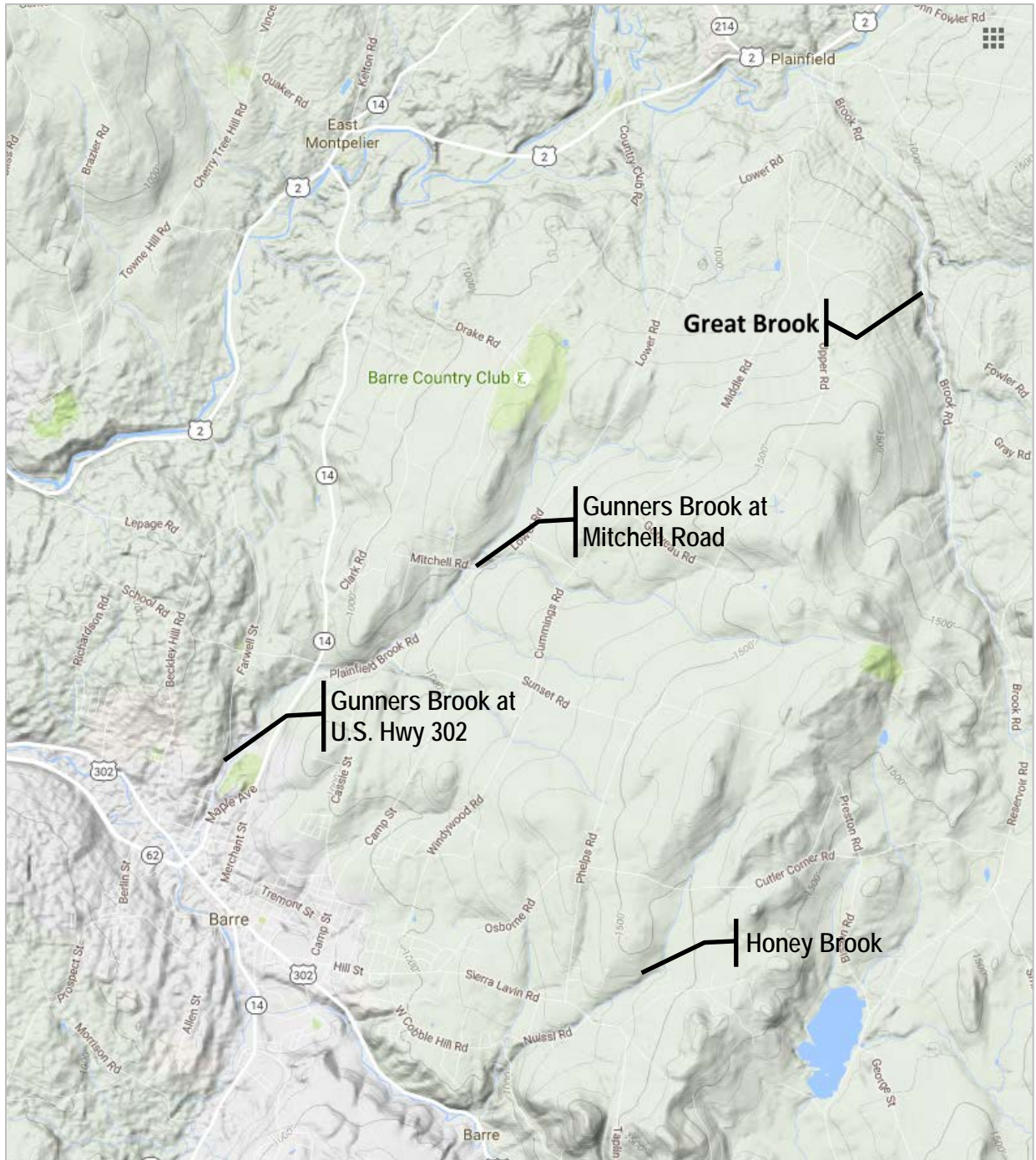


Figure 7 Great Brook in Plainfield (Follows Brook Rd to the north), Gunners Brook in Barre (Follows Lower Rd, Plainfield Brook Rd & State Route 14 to the southwest), and Honey Brook (Crosses Sierra Lavin Rd, Nuissi Rd & U.S Hwy 302 to the south) in East Barre

Gunners Brook parallels Lower Road, Plainfield Brook Road, and then State Route 14 into Stevens Branch after passing under U.S. Hwy 302. A severe storm on July 19, 2015 caused flooding from Gunners Brook at two crossings – one upstream at the Mitchell Road crossing and one near the downstream

edge at the U.S. Hwy 302 crossing. In fact, including the U.S Hwy 302 crossing, there are a total of 5 crossings in the last half mile of Gunners Brook in downtown Barre (Figure 8).

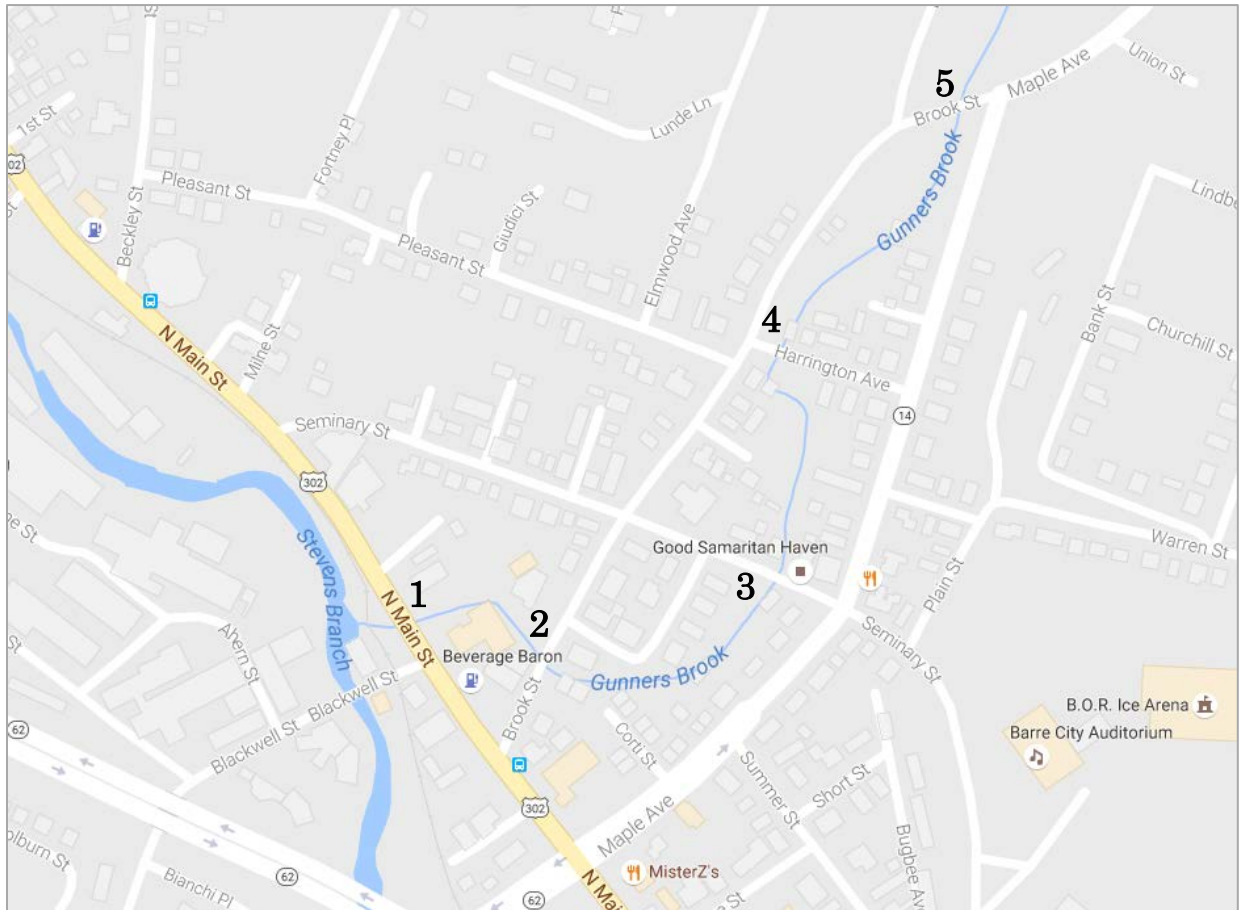


Figure 8 Five Road Crossings of Gunners Brook in Barre

Looking upstream from the crossing of Gunners Brook under U.S Hwy 302, heavy armoring of the channel that could also make the crossing more vulnerable to blockage is evident (Figure 9).



Figure 9 Armoring of Gunners Brook Upstream of U.S. Hwy 302

Honey Brook originates at Osborne Road and crosses Sierra Lavin Rd, Nuissi Rd and U.S Hwy 302 into Jail Branch (Figure 10).



Figure 10 Crossings of Honey Brook in Barre

It descends steeply from the heavily wooded slopes of Cobble Hill before flattening out just before its crossing at U.S. Hwy 302 (Figure 11).



Figure 11 Honey Brook Looking Upstream from U.S. Hwy 302

A significant storm passed through the Barre area on July 9th and 11th, 2007, with nearly four inches of rain on those two days. The storm was extremely localized; nearly two inches of rain fell in Barre on July 11th and only trace amounts of rain fell 9 miles away in Plainfield. The storm caused excessive flooding near the crossing at U.S Route 302. The role of debris in causing Honey Brook to flood was reported later that month (Duffy, 2007) and documented in the photograph of the same area during the flooding in Figure 12.



Figure 12 Flooding of Honey Brook at U.S. Hwy 302 in July 2007

Although upstream crossings of minor roads are a concern for debris loads in these brooks, each of them also has the potential to impact a significant urban federal highway (U.S. Hwy 302) at its downstream edge, so these are the crossings-of-concern.

A sixth site, the West Branch of the Deerfield River in Readsboro, was added to the list of test sites because it had caused significant debris-related damage during Tropical Storm Irene in 2011. The West Branch Deerfield River flows along State Route 100 south into Readsboro where it meets the Deerfield River after passing under Tunnel St (Figure 13).



Figure 13 West Branch Deerfield River at its Confluence with the Deerfield River in Readsboro

The bridge which spans Tunnel Street over the West Branch Deerfield River was obstructed with LWD during the storm, and the slopes of the adjacent roadway were damaged. Figure 14 provides an aerial view of the crossing in August 2012, nearly a year after the damage.



Figure 14 West Branch Deerfield River Crossing at Tunnel St. in Readsboro

Locations of the sites selected for testing are provided in Figure 15.

Table 1 summarizes the sites chosen for imagery acquisition.

Table 1 Sites Chosen for Imagery Acquisition

Site	Town	Crossing Damage Event(s)	Length (mi.)	Avg. Slope
Gunners Brook	Barre	August 2011, July 2015	1.9 ¹	3%
Unnamed	Barre	August 2011, July 2015	2.4	5%
Gunners Brook	Barre	August 2011, July 2015	3.0 ²	3%
Honey Brook	East Barre	July 2007	1.3	6%
Money Brook	Plymouth	Tropical Storm Irene	1.2	14%
Great Brook	Plainfield	Spring 2011, July 2015	6.2	2%
West Branch Deerfield River	Readsboro	August 2011	1.2 ³	5%

Notes:

1. From the head of the brook to Mitchell Road
2. From Mitchell Road to U.S. Hwy 302
3. From Howe Pond Brook to the crossing-of-concern

3.2 Equipment

The team used a SenseFly eBee UAV, which had been purchased in support of the U.S DOT project, to acquire stereo imagery of each river or stream reach extending from the crossing at least 1 km upstream. The eBee works with specialized flight-planning software, eMotion2, which allows all flight operations and imagery acquisition to occur without manual intervention. Derivation of the orthorectified imagery and digital terrain models (DTMs) was accomplished using the Pix4D photogrammetric software package. The DTMs are crucial for orthorectification of the imagery and are valuable when integrated into a GIS for identification of protrusions in the streambed.

3.3 Flight Logging

For each flight, airspace clearance was coordinated through the VTrans Aviation Program Administrator by providing a mission profile which included:

- Location of departure and landing zones
- Extent of flight area
- Proposed flight path

- Maximum in-flight altitude
- Flight duration

Each of the flights was operated in accordance with FAA regulations, which included flying below 400 ft above ground level (AGL), avoiding nighttime flights, and maintaining positive line of sight with the UAV at all times. Restricted Vermont airspace – areas within five miles away of designated airports and Camp Johnson – was also avoided. Local and state agencies were also notified, and outreach efforts were conducted to obtain permission from local landowners.

Following approval for the flight from VTrans, flight planning was undertaken using the eMotion2 software. The flight planning included the following steps:

1. Select a background map
2. Select the take-off location
3. Setup the real-time kinematic (RTK) satellite navigation to enhance the precision of GPS data
4. Place the estimated landing approach and the home and start waypoints
5. Select mission shape to fit the entire area of interest
6. Adjust desired ground resolution ensuring the target height is below 400ft. Suggested values are between 3.0-4.0 cm/pixel.
7. Specify imagery overlap – more lateral overlap is needed for parallel flight lines than is needed for perpendicular flight lines.
8. Upload the flight plan (Figure 16)

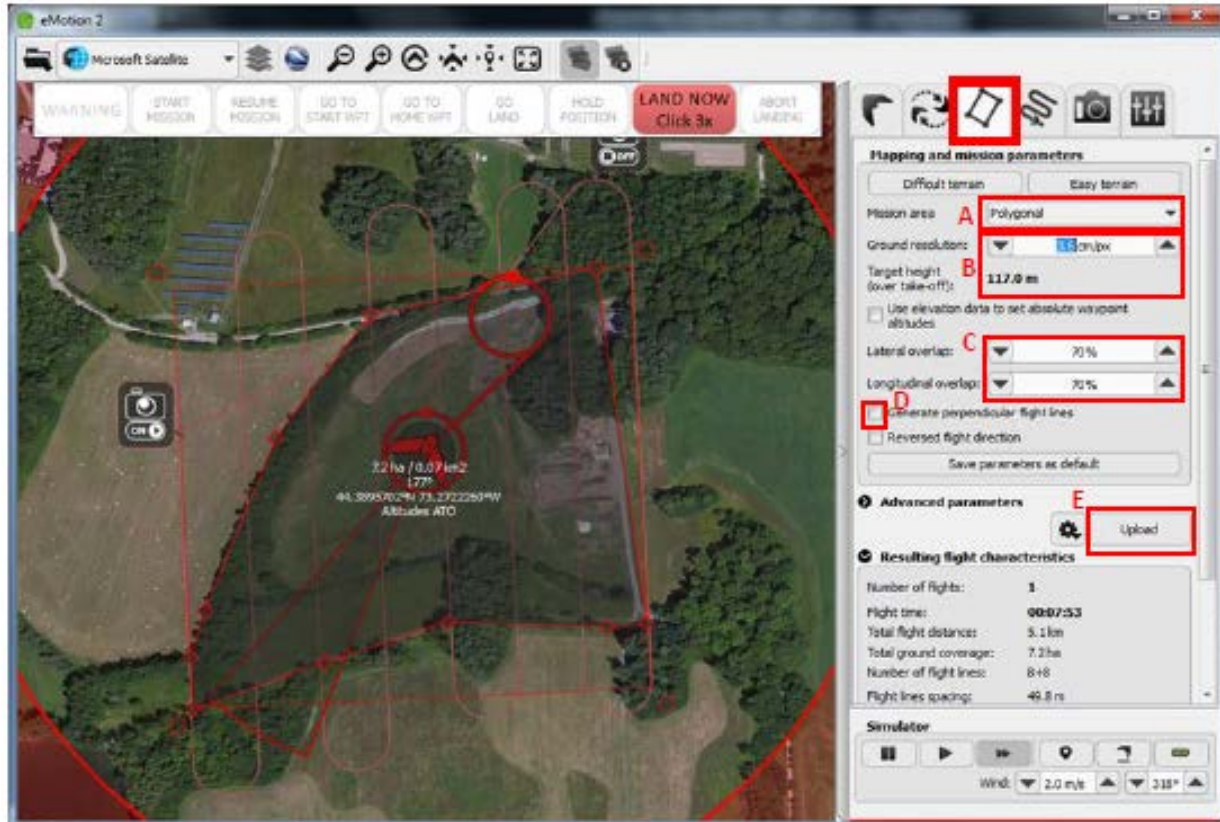


Figure 16 Screen image from the eMotion 2 flight planning software showing the mission shape (A), the ground resolution and target height (B), and the overlap (C)

11. Adjust working area radius so that the flight path of the eBee is fully within the circle (Figure 17)

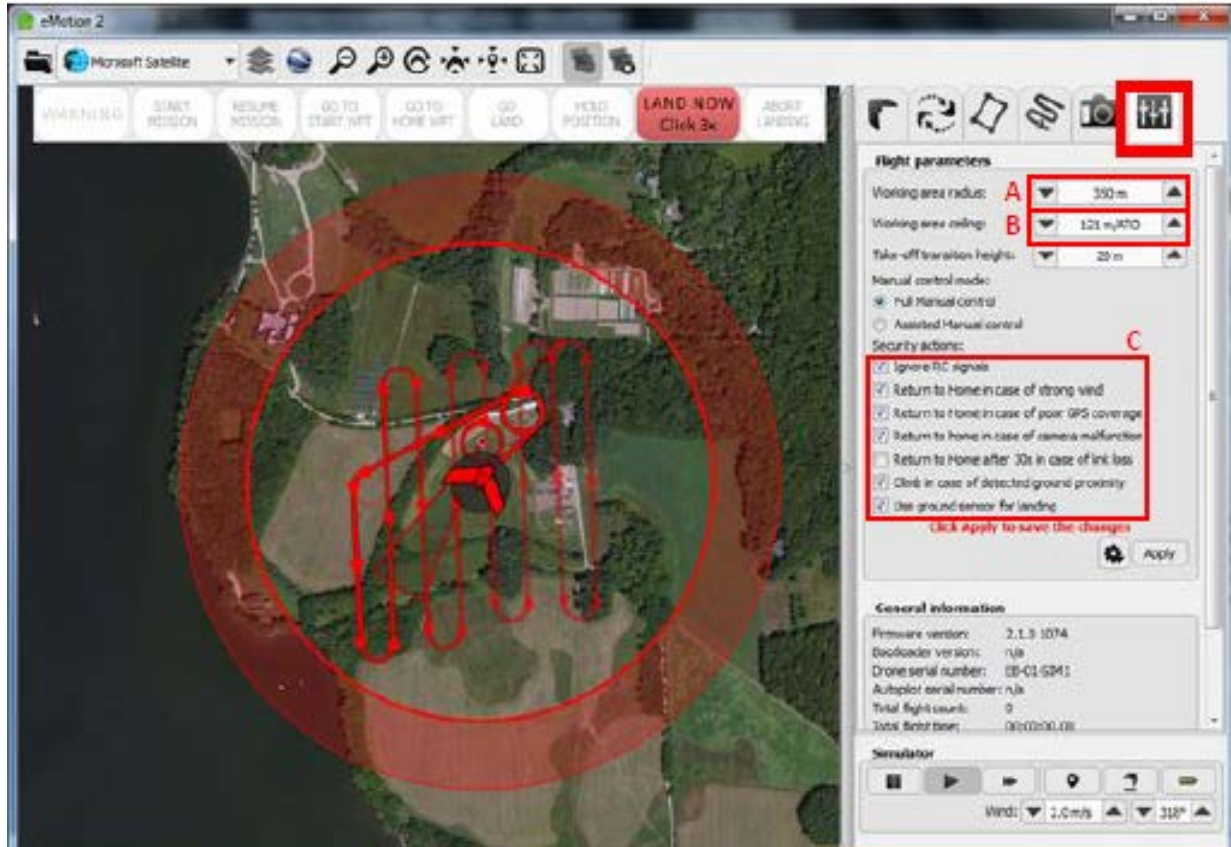


Figure 17 Screen image from the eMotion 2 flight planning software showing the working area radius (A) and the working area ceiling (B)

12. Adjust working area ceiling to 400 ft or less

Following the development of the flight plan, the UAV was brought to the site and the standard operating procedure for conducting the pre-flight checks were followed, as described in Appendix A. A checklist for the operating procedure was created in an Android app for use in the field to ensure that all steps in the procedure are completed prior to the launch of the UAV.

For several of the sites, line-of-sight restrictions required the team to plan multiple flights to gather imagery for 1 kilometer upstream of the crossing of concern. A total of 11 flights were planned to gather imagery for the 5 sites, including 7 crossings of concern. Final flight logs for each site are provided in Figures 18 thru 28.

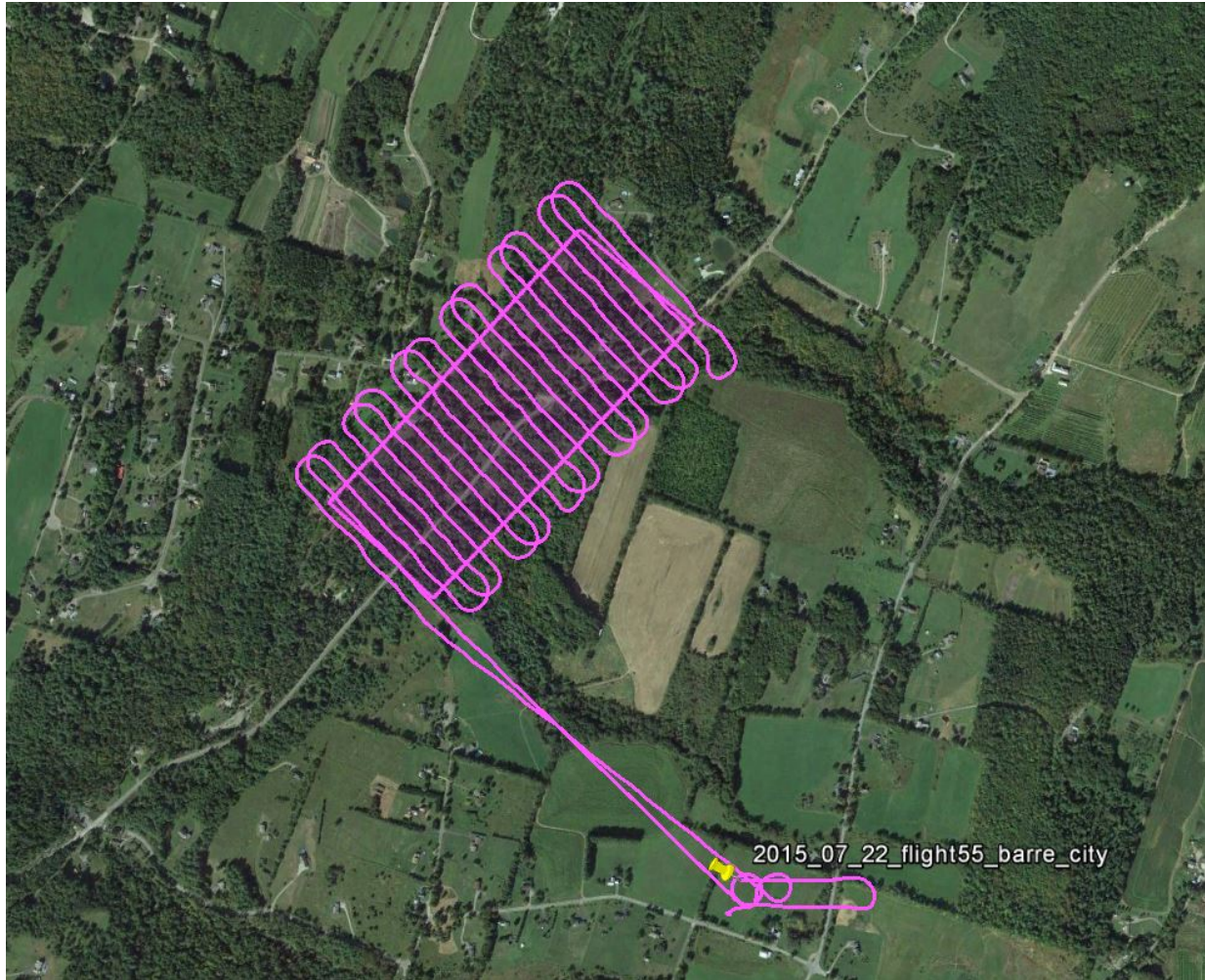


Figure 18 Flight Log for Gunners Brook at Mitchell Road / Unnamed Brook at Lower Road

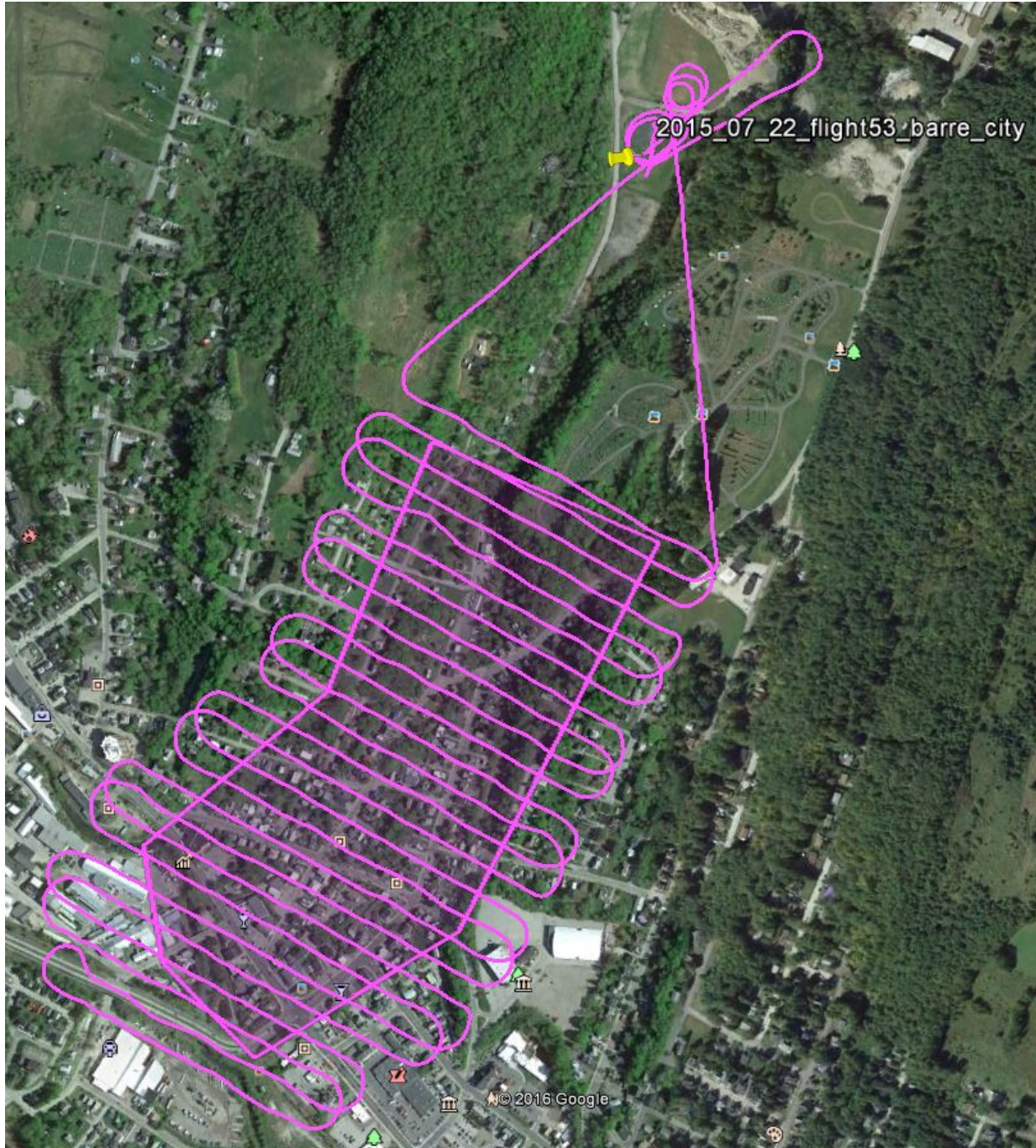


Figure 19 Flight Log for Gunners Brook at U.S Hwy 302

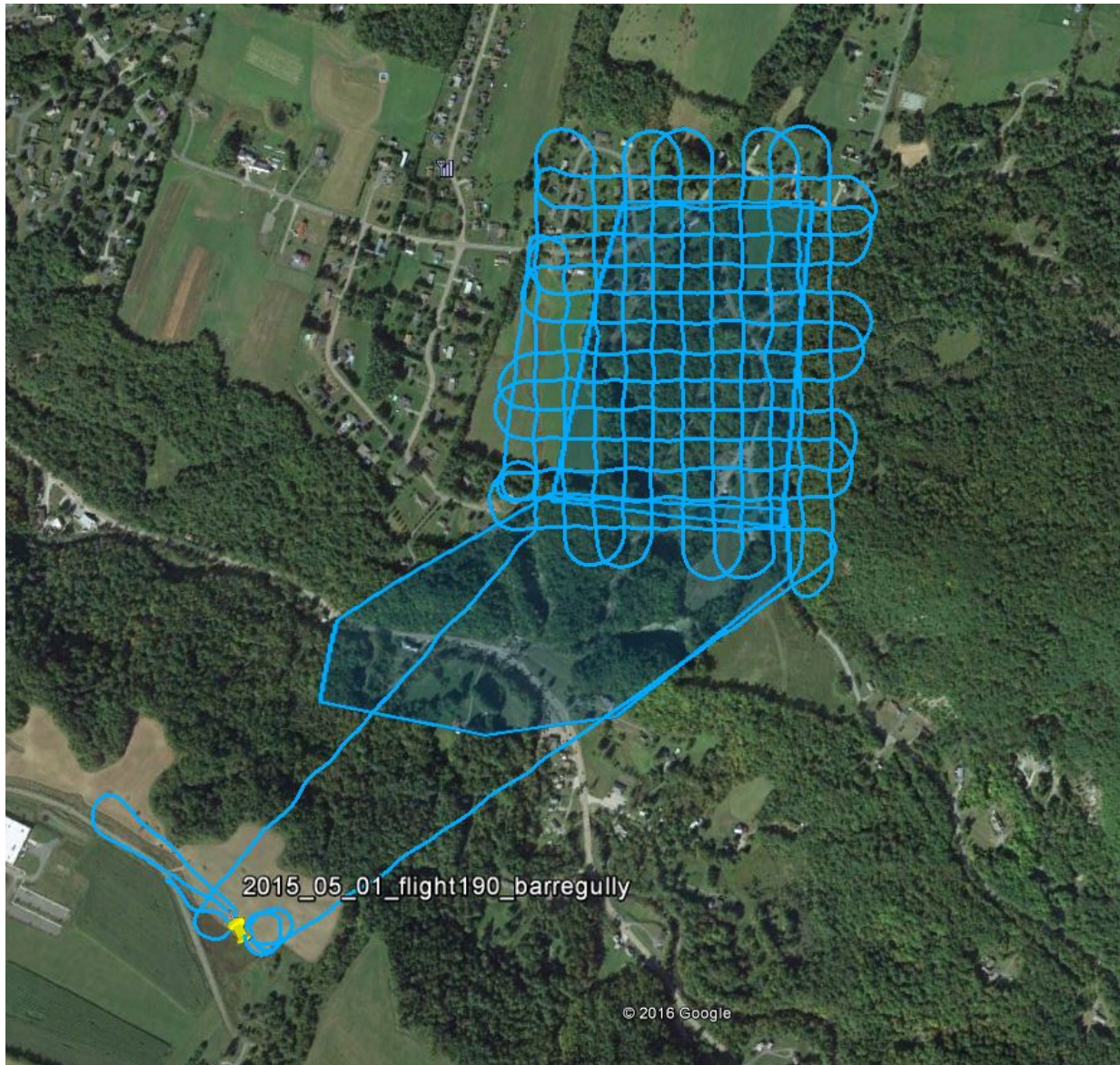


Figure 20 Flight Log for Honey Brook (North)

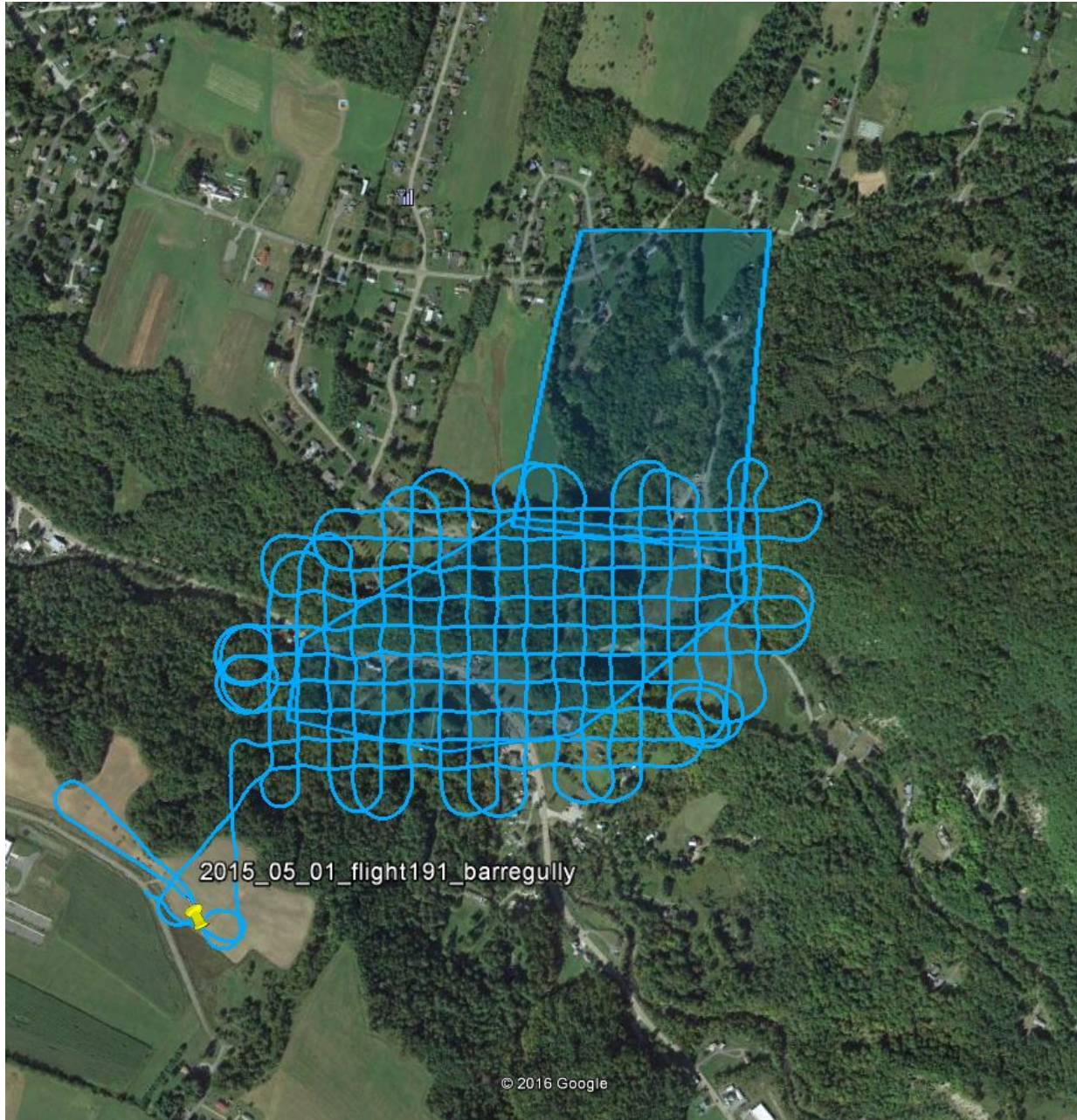


Figure 21 Flight Log for Honey Brook (South)

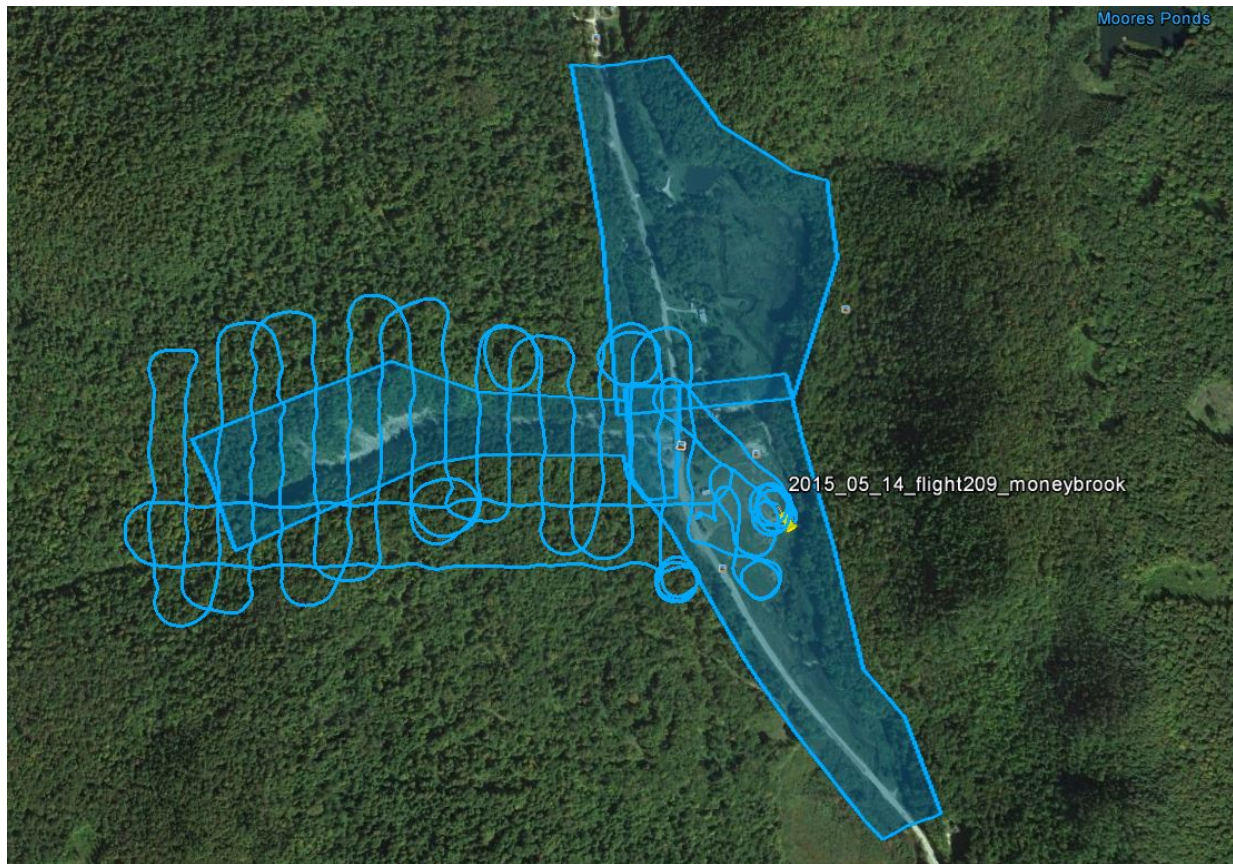


Figure 22 Flight Log for Money Brook (West)

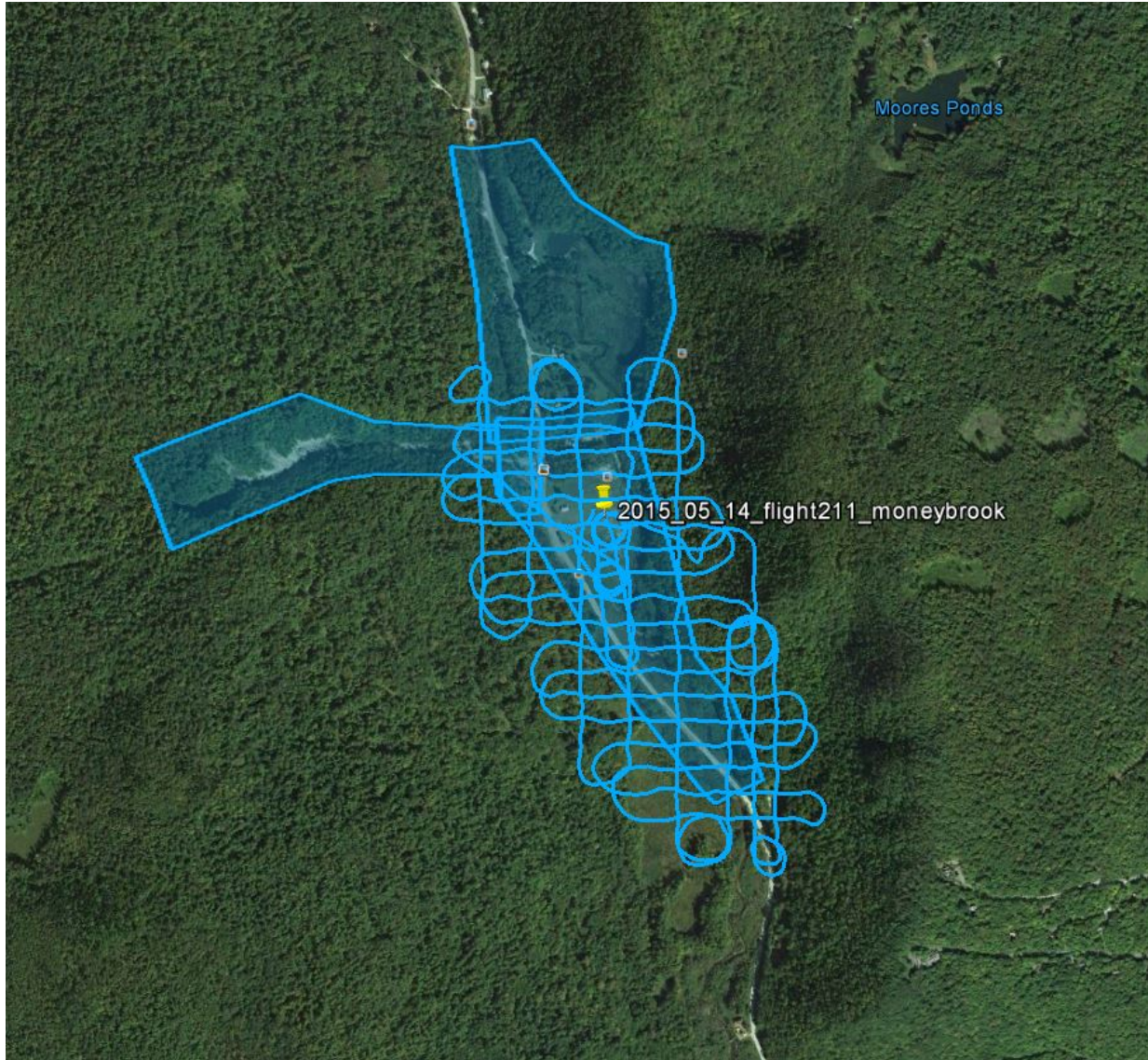


Figure 23 Flight Log for Money Brook (South)



Figure 24 Flight Log for Money Brook (North)

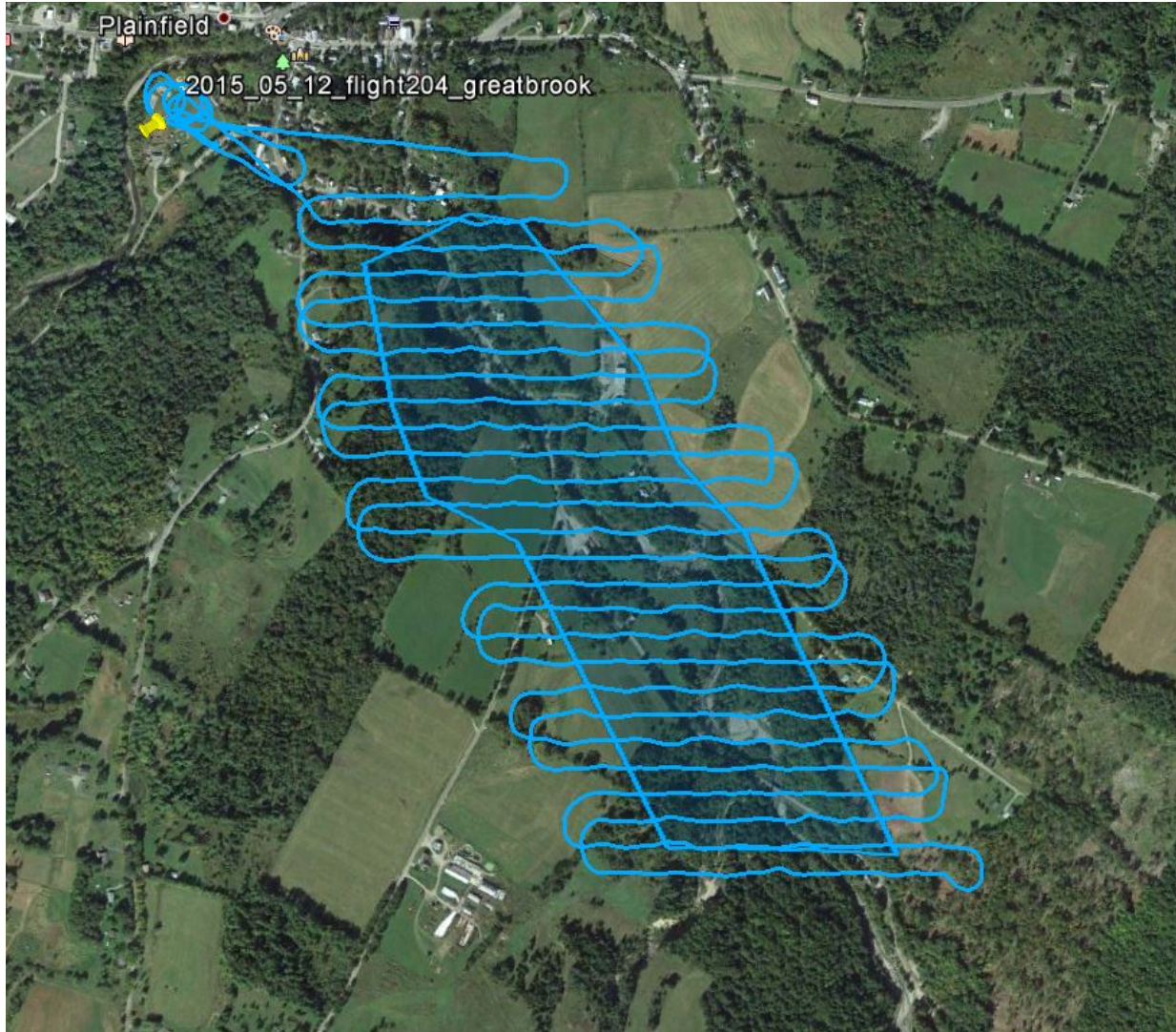


Figure 25 Flight Log for Great Brook (North)

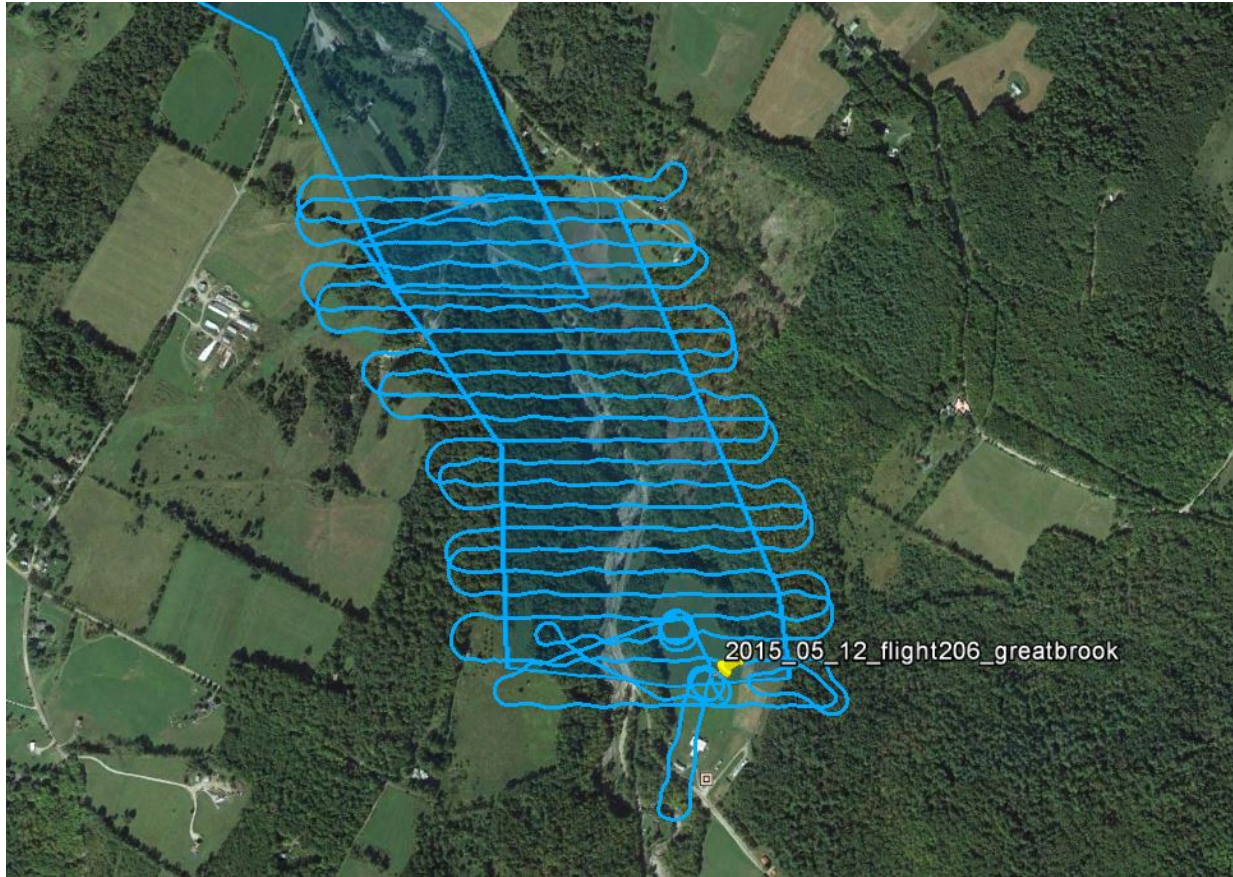


Figure 26 Flight Log for Great Brook (Mid)

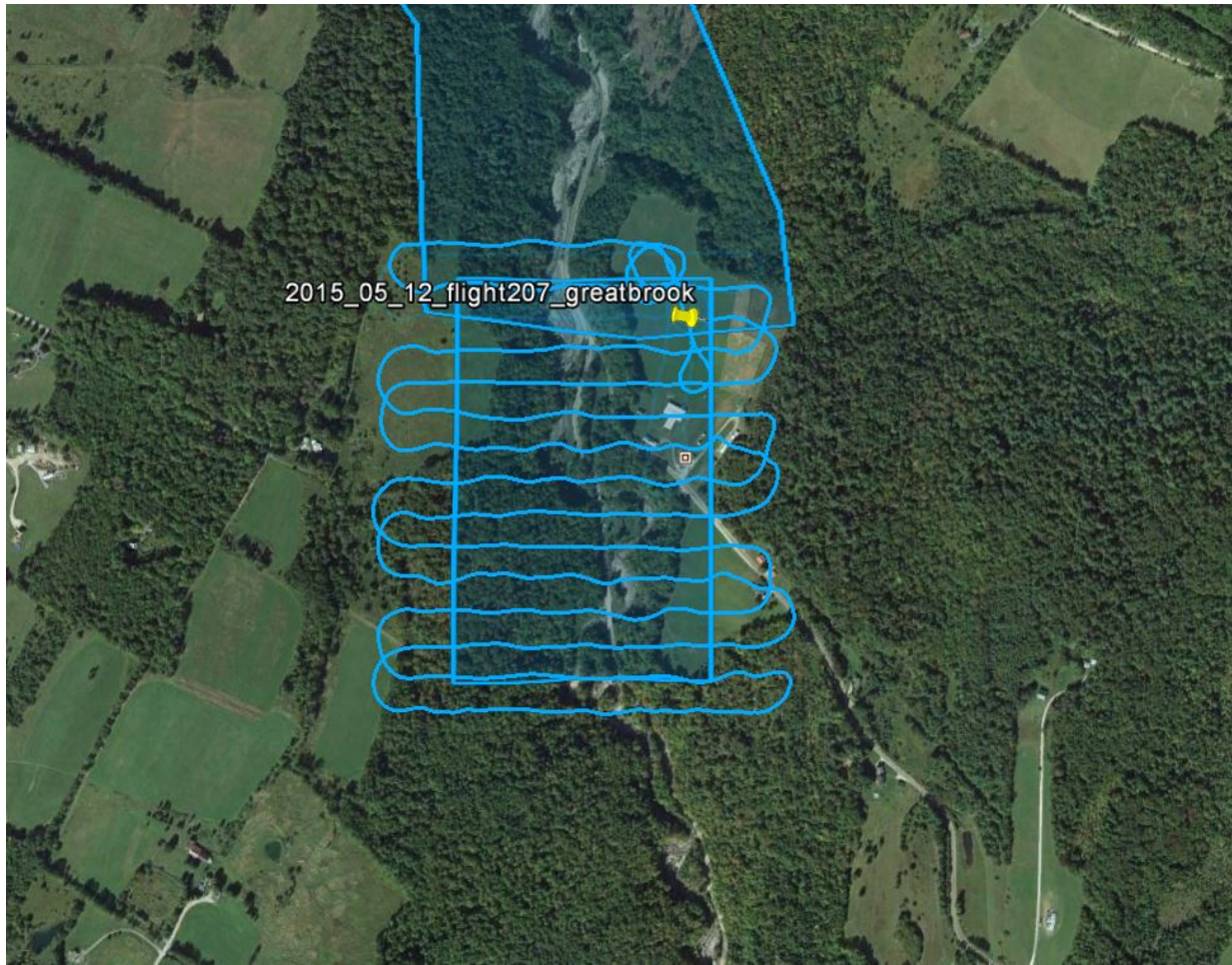


Figure 27 Flight Log for Great Brook (South)



Figure 28 Flight Log for West Branch Deerfield River

3.4 Imagery Acquisition

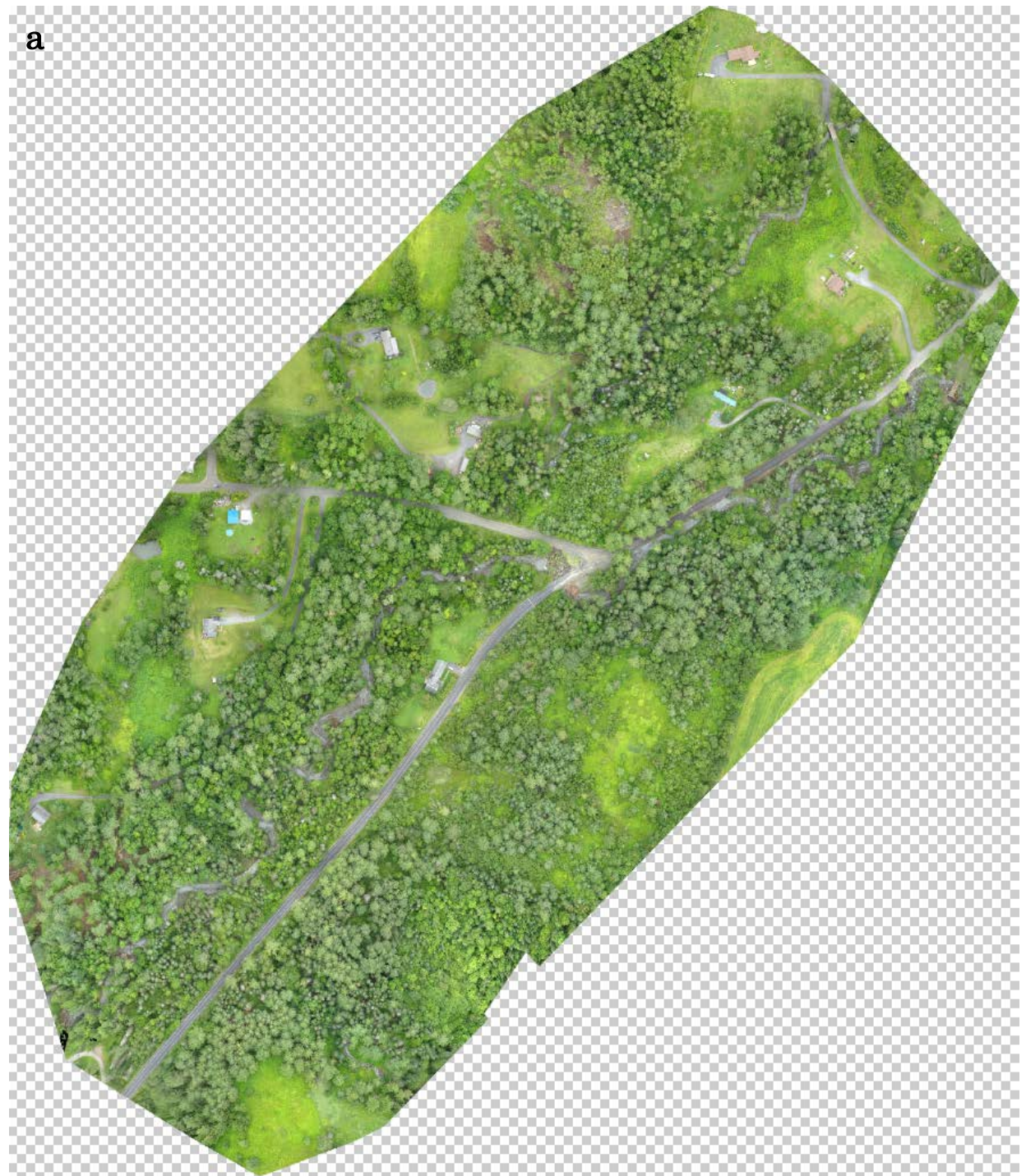
At each site, the flight plan was uploaded to the UAV and flight operations were conducted in accordance with the procedures described in Appendix A. Table 2 summarizes the number of flights completed for each crossing.

Table 2 Summary of Flights at Each Crossing

Site	Crossing	No. of Flights	Time of Flight(s)
Gunners Brook	Mitchell Rd	1	July 2015
Unnamed Brook	Lower Rd		

Site	Crossing	No. of Flights	Time of Flight(s)
Gunnery Brook	Harrington Ave	1	
	U.S Hwy 302		
Honey Brook	U.S Hwy 302	2	May 2015
Money Brook	State Route 100	3	
Great Brook	Brook Rd 1	6	May 2015, June 2015, July 2015
	Brook Rd 2		
	Brook Rd 3		
	Brook Rd 4		
	Brook Rd 5		
	Mill Street		
West Branch Deerfield River	Tunnel Street	1	March 2014

During the flight, the UAV takes still photographs of the ground at a pre-determined frequency. While the photograph is being taken the UAV motor turns off and the UAV enters a brief glide period to minimize vibration that might distort that photograph. After the flight post-processing using digital photogrammetric software (Pix4D) assembles the images into a single orthorectified image (orthophoto). Reproductions of each of the orthophotos assembled from the imagery are provided in Figure 29.



b









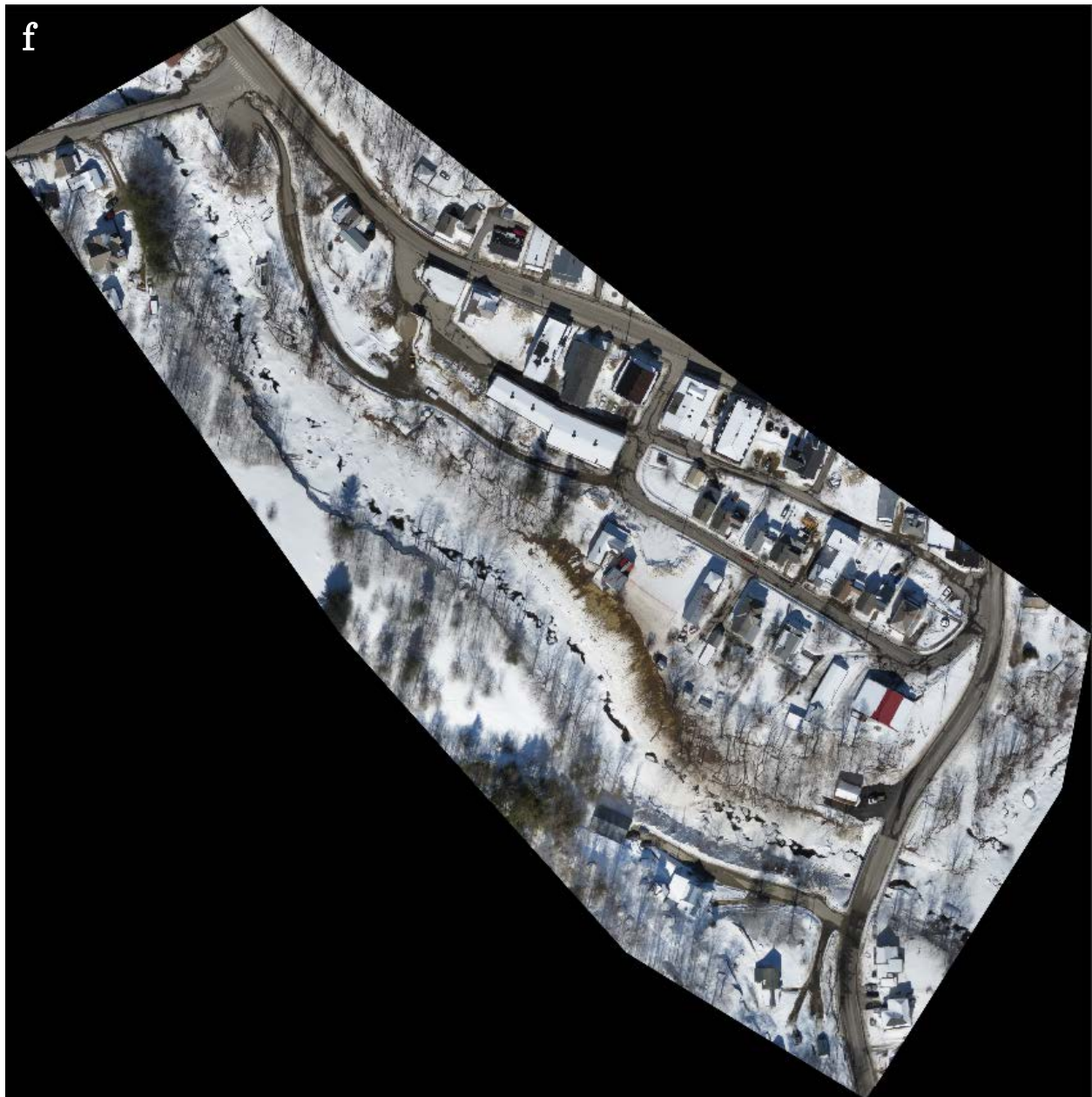


Figure 29 Orthophotos of (a) Gunners Brook at Mitchell Rd & Unnamed Brook at Lower Rd, (b) Gunners Brook at Harrington Ave and U.S. Hwy 302, (c) Honey Brook at U.S. Hwy 302, (d) Money Brook at Vermont Route 100, (e) Great Brook at Mill Street, and (f) West Branch Deerfield River at Tunnel St.

4 Feature Extraction and Decision Support Methodology

Once streambed imagery had been successfully collected using the UAV, the next step was to identify LWD piles and determine a method for disseminating actionable information about the piles to Vermont stakeholders. Based on conversations with VTrans and ANR personnel, the project team identified several pieces of information that are required to facilitate decision-making about LWD piles. Decision-makers need to know the distance between each pile and the crossing of interest and the relative size of each pile to assess the threat that the piles pose to the road infrastructure. In addition, the location and a visual image of each pile is necessary to plan for and conduct mitigation operations to protect crossing that are deemed to be at high risk.

In order to test the development of automated processes to identify LWD piles the DTMs generated as part of the photogrammetric processing were integrated into GIS. An example DTM created for the Money Brook site is shown in Figure 30. Once the test algorithm identified an LWD site, these sites were manually verified and thumbnail images of the debris pile were created for dissemination to stakeholders. In order to validate this algorithm, the complete orthophoto imagery was simultaneously manually reviewed by members of the project team. During this validation process, it became clear that the quality of the original imagery made the automation of the feature extraction routine unnecessary. Direct manual review of the full ortho-rectified imagery took a similar amount of time as the verification and extraction of automatically identified LWD sites, with better overall results. Therefore, it was decided that the best way to perform the identification of debris piles would be by direct manual review of the stereo imagery.

The Great Brook test site had more LWD piles than any other test site. In May of 2015, 408 distinct LWD piles were identified in Great Brook. After the July 2015 flooding event, 229 independent LWD piles were identified. A

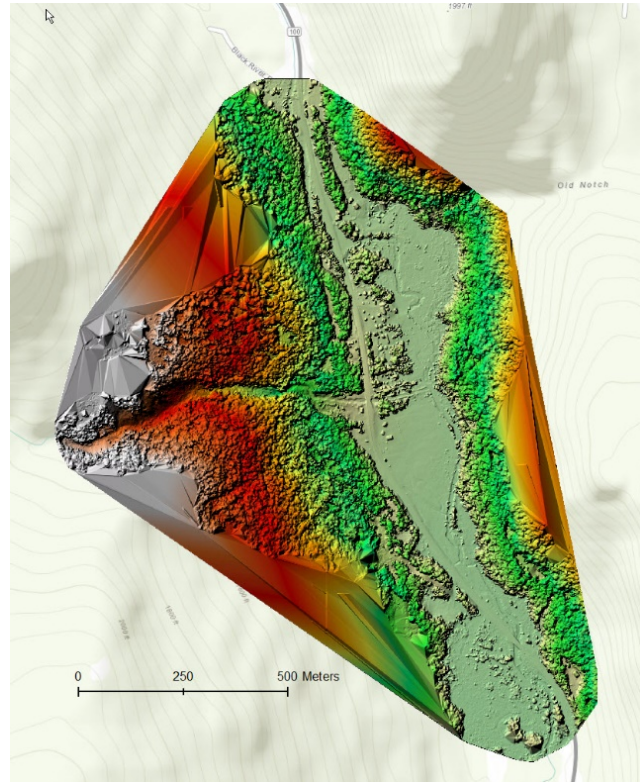


Figure 30 Digital Terrain Model for the Money Brook Site

map of the LWD piles identified after the July 2015 storm event is provided in Figure 31.



Figure 31 Locations of large woody debris piles in Great Brook (July 2015)

As LWD piles were identified, the piles were classified according to the approximate number of trees present in each pile. Piles consisting of one to

two trees were categorized as small piles, piles with three to six trees were categorized as medium piles while piles containing more than 6 trees were categorized as large piles. Figure 32 shows examples of small and large LWD piles.



Figure 32 Characterization of LWD Pile Relative Size

Table 3 lists the location, relative size, and distance to the crossing for all 13 LWD piles identified in Money Brook. This information is easily transmittable by personnel in the field by email, text, and a variety of apps available for smartphones and tablets.

Table 3 LWD Pile Inventory in Money Brook

GIS ID	Pile Location		Distance Upstream from Crossing (ft)	Relative Size
	Longitude	Latitude		
91552	-72.733034	43.515574	357	large
91553	-72.733634	43.515939	522	medium
91554	-72.734632	43.515959	785	large
91555	-72.735561	43.516037	1,033	medium
91556	-72.736965	43.515947	1,401	small

GIS ID	Pile Location		Distance Upstream from Crossing (ft)	Relative Size
	Longitude	Latitude		
91557	-72.737992	43.515407	1,673	medium
91558	-72.738701	43.515278	1,864	small
91559	-72.739015	43.515227	1,948	small
91560	-72.739504	43.515036	2,084	small
91561	-72.739731	43.514884	2,151	small
91562	-72.740079	43.514883	2,243	small
91563	-72.740233	43.514871	2,284	small
91564	-72.740509	43.514936	2,354	small

While sharing imagery of the debris pile itself is necessary in order to facilitate effective mitigation planning, transmitting the full ortho-rectified images directly is not feasible, due to the large file size of the high resolution imagery (between 400 MB and 2.5 GB each). Therefore, the team decided to extract only the thumbnail images of each pile, and to include only required descriptive characteristics shown in Table 3. Compiling the information in this way reduced the average file size (including the thumbnail and the supporting data) of the transmission to about 30 KB – a very manageable size for transmitting by email (typically a 10 MB limit) or text message (typically a 300-600 KB limit), using a smartphone network. This transmission provides all of the information required to evaluate the threat and consider mitigation.

Because of the high resolution of the UAV collected imagery, thumbnails extracted from these images provide exceptional detail on the LWD piles. Figure 33 provides a comparison of the thumbnails produced during this

project with an example of the aerial imagery available previously at a similar scale.

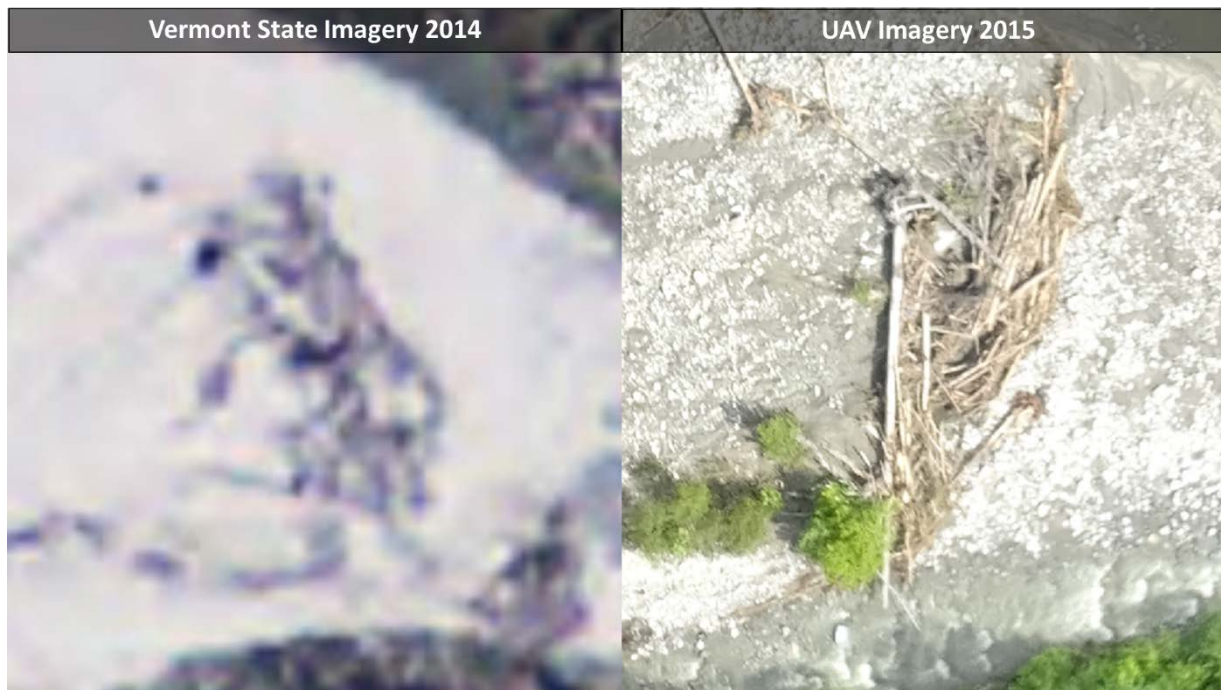


Figure 33 Comparison of UAV Imagery of a LWD Pile with Previously Available Imagery

A selection of thumbnail images extracted from the LWD pile-identification process for Great Brook and Money Brook are shown as the insets of the photographs shown in Figure 34.

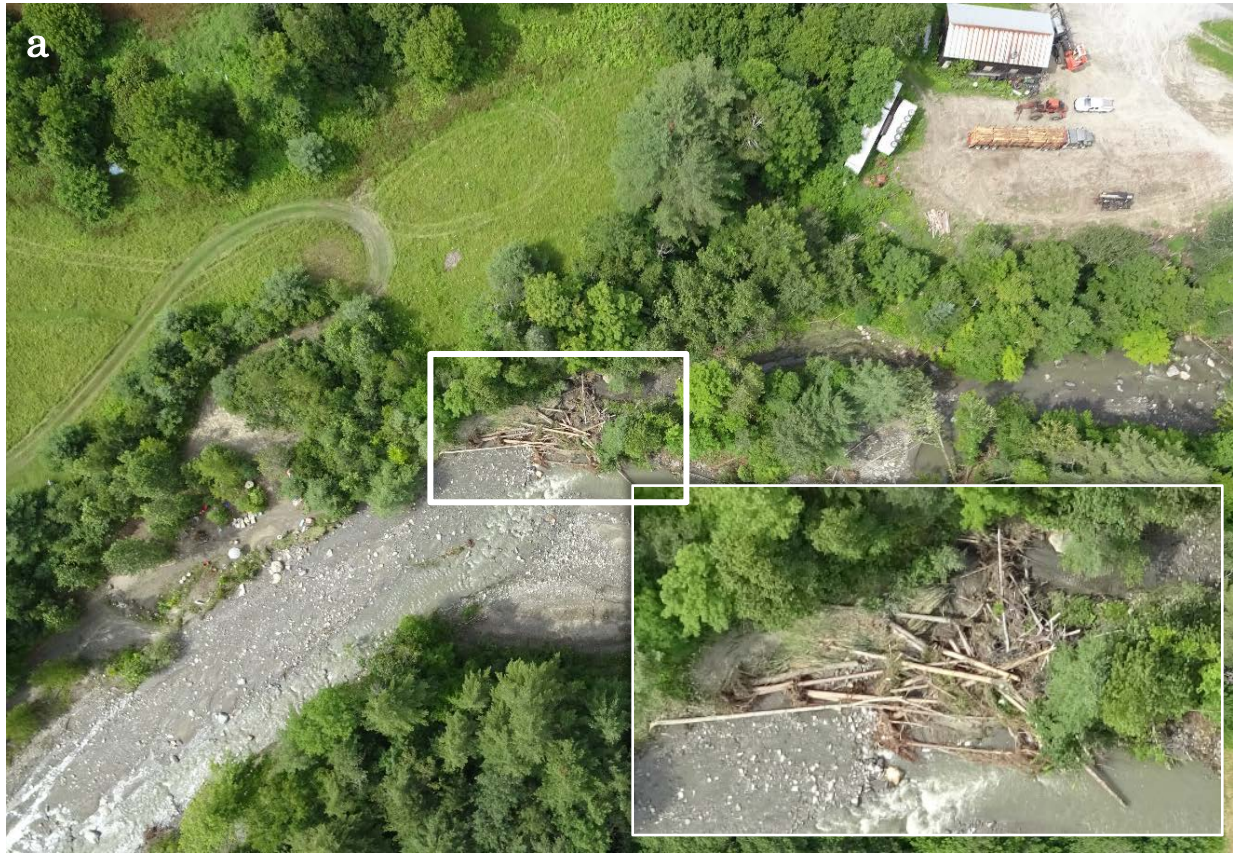






Figure 34 Large woody debris piles identified in Great Brook (a-c) and Money Brook (d), with extracted thumbnail images (insets)

5 Results

5.1 Evaluation of Threat and Risk

Table 4 contains a summary of the LWD piles identified at each of the crossings investigated for this project.

Table 4 Summary of Large Woody Debris Piles

Water Body	Crossing	Large Woody Debris Pile Summary		
		No.	Mode Size	Avg. Distance Upstream (ft.)
Gunners Brook	Mitchell Rd	6	small	868
Unnamed Brook	Lower Rd	17	small	760
Gunners Brook	Harrington Ave	5	medium	210
Gunners Brook	U.S Hwy 302	6	small	290
Honey Brook	U.S Hwy 302	17	large	1,503
Money Brook	State Route 100	13	small	1,592
	Brook Rd 1	33	medium	917
	Brook Rd 2	82	medium	1,734
	Brook Rd 3	73	medium	2,515
	Brook Rd 4	7	medium	569
	Brook Rd 5	33	medium	1,646
	Mill Street	1	medium	499
West Branch Deerfield River ²	Tunnel Street	-	--	--

Notes:

1. Great Brook values are for its July 2015 imagery

**Large Woody Debris Pile
Summary**

Water Body	Crossing	No.	Mode Size	Avg. Distance Upstream (ft.)
2. West Branch Deerfield was flown in late winter in an effort to determine how ice and snow affect the identification of debris (and ice). Identification of LWD was not possible due to snow cover.				

These 3 measures (count, size, and average distance upstream) of the LWD piles can be used to evaluate the threat for each crossing. Based on the assessment of the LWD pile sizes, the following assumptions were made:

- 1 medium pile \approx 3 small piles
- 1 large pile \approx 6 small piles

With these assumptions in mind, a threat index can be created that makes use of these assumed relationships, and inverts the distance upstream for each pile to align increasing threat with smaller distances. The modified inverse distance upstream (MIDU) can be calculated by weighting the inverses of the distances upstream for the large piles by a factor of 6, and the medium piles by a factor of 3:

$$MIDU_x = \sum \frac{1}{d_s} + \sum \frac{3}{d_m} + \sum \frac{6}{d_l}$$

Where $MIDU_x$ is the modified inverse distance upstream of LWD piles at crossing x , d_s is the distance upstream of each small LWD pile, d_m is the distance upstream of each medium LWD pile, d_l is the distance upstream of each large LWD pile. Using the formulation, the MIDU provides an indication of threat that considers the quantity of piles, their individual sizes, and their distance from the crossing. The MIDU was calculated for each of the river crossings tested and the results are provided in Table 5.

Table 5 Modified Inverse Distance Upstream for Each Crossing

Water Body	Crossing	MIDU
Gunners Brook	Mitchell Rd	0.01
Unnamed Brook	Lower Rd	0.24
Gunners Brook	Harrington Ave	0.24
Gunners Brook	U.S Hwy 302	0.04

Water Body	Crossing	MIDU
Honey Brook	U.S Hwy 302	0.06
Money Brook	State Route 100	0.04
Great Brook	Brook Rd 1	0.73
Great Brook	Brook Rd 2	0.21
Great Brook	Brook Rd 3	0.12
Great Brook	Brook Rd 4	0.04
Great Brook	Brook Rd 5	0.09
Great Brook	Mill Street	0.01
West Branch Deerfield River	Tunnel Street	--

From these MIDU values, it can be concluded that the most significant threat at the time of these flights was present at the first crossing of Brook Road by Great Brook. Upon further inspection of the results for the LWD piles upstream of the Brook Rd 1 crossing, it was discovered that the first 2 of the 33 piles are located within a few feet of the crossing, as shown in Figure 35.

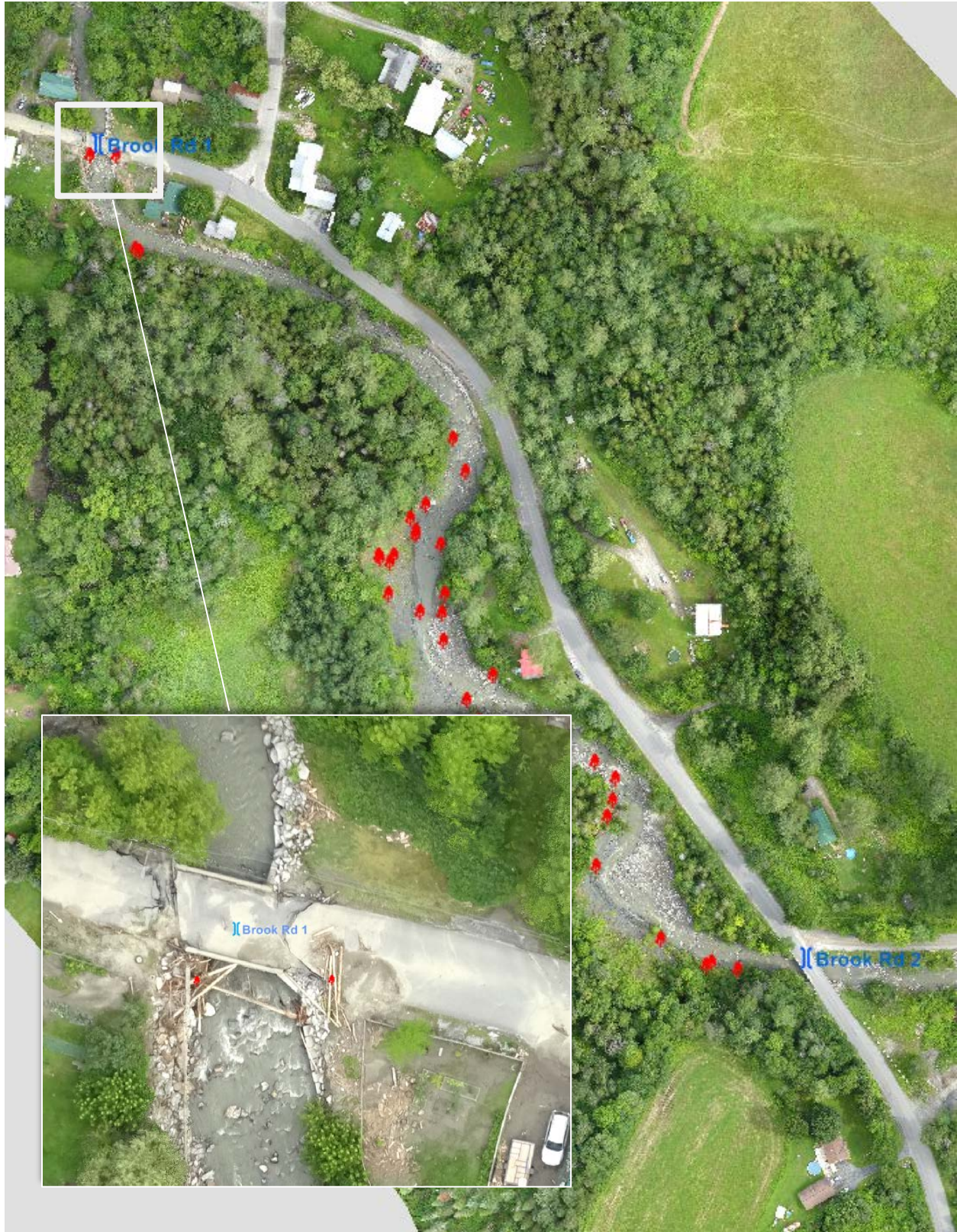


Figure 35 LWD Piles Upstream of the first Great Brook Crossing by Brook Road and the first 2 LWD Piles (inset)

Since these 2 medium piles are such a short distance from the crossing, they contribute to about 80% of the MIDU at this location. In fact, these piles are the remains of a flood event that occurred just a few days before the imagery was collected, when the bridge was obstructed at this location and the surrounding roadway was badly damaged. The indication of the MIDU is that debris still remains at the crossing and it is in danger of being obstructed again.

To get an indication of the overall risk of culvert or bridge obstruction from LWD, the vulnerability of the crossing itself must also be considered. The relative vulnerability of the crossings to being obstructed by LWD is created by the width of the opening through which water and debris can pass. Variables that will contribute to this vulnerability include:

- channel armoring
- floodplain availability
- bankfull width
- culvert or bridge width

Both threat *and* vulnerability of each crossing should be considered together as an indication of risk (Figure 36).

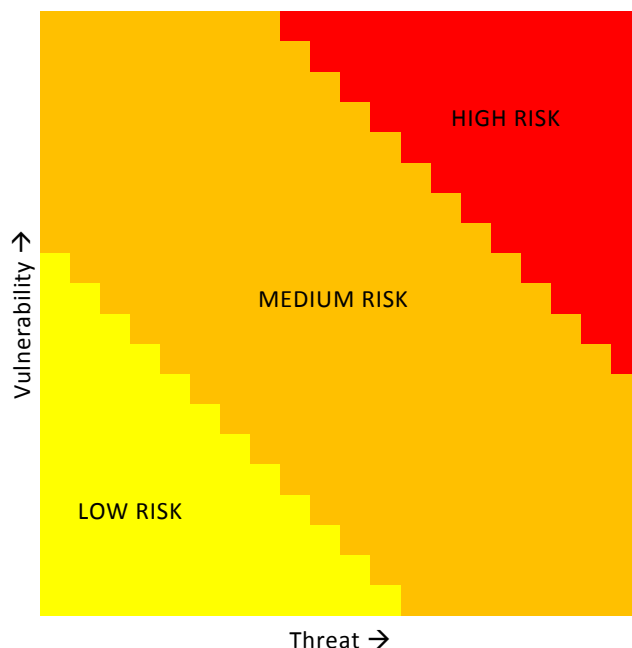


Figure 36 Threat-Vulnerability Matrix

5.2 Web-Based Imagery Tool

An interactive, web-based ESRI application was created to make the imagery obtained for this project, and for the U.S. DOT projects, easily accessible. This interactive web map can be found at <http://goo.gl/H3MFuy>.

The starting page provides a map of Vermont showing all of the locations where imagery has been obtained using the UAV for these projects (Figure 37).

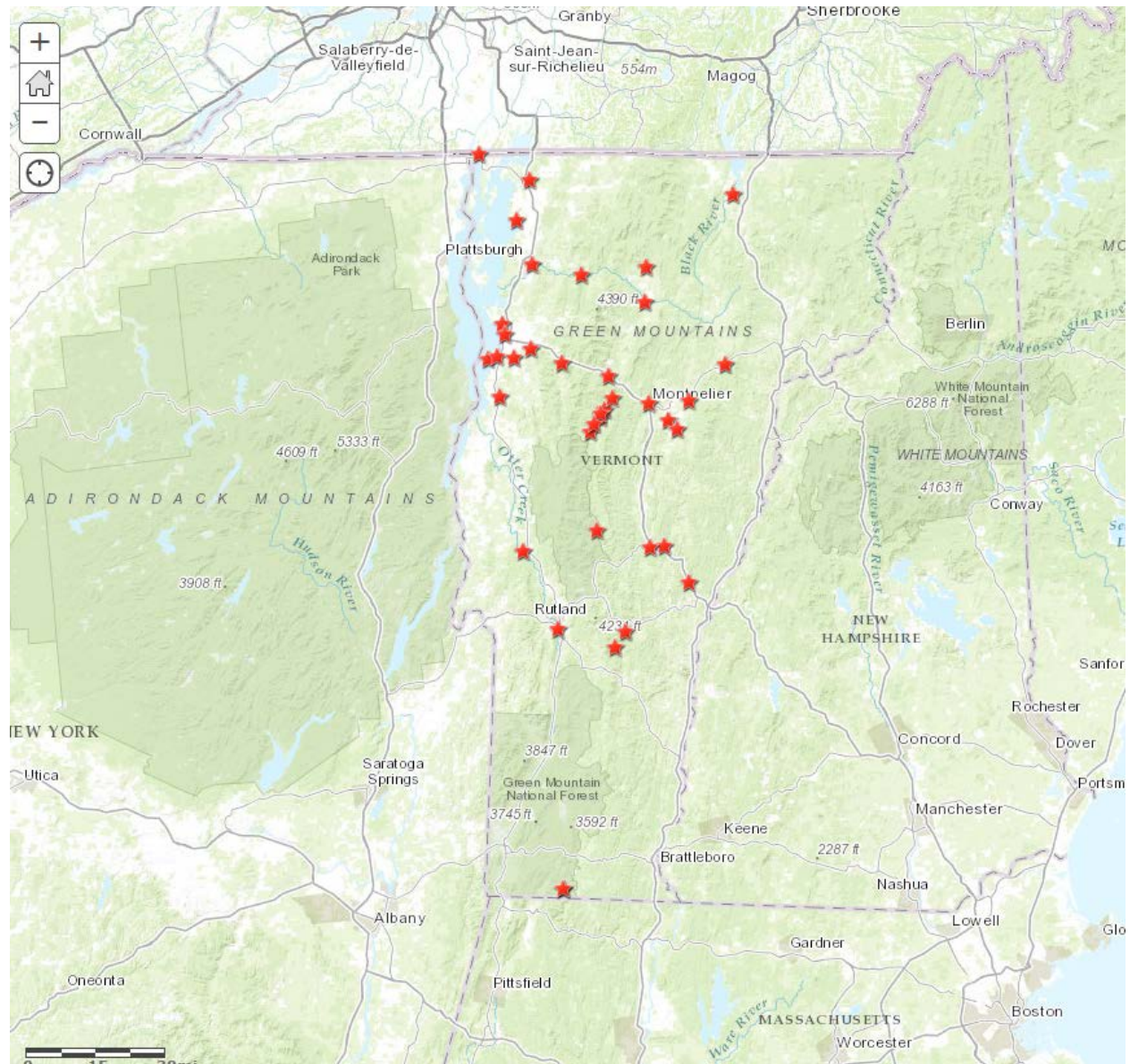


Figure 37 Starting Page for the Web Application for Accessing Imagery from UAV Missions

Selecting one of the missions allows the user to zoom to a closer view of the mission location, providing a polygon whose borders roughly indicate the boundary of the final image footprint, as shown in the selection for Money Brook in Figure 38.

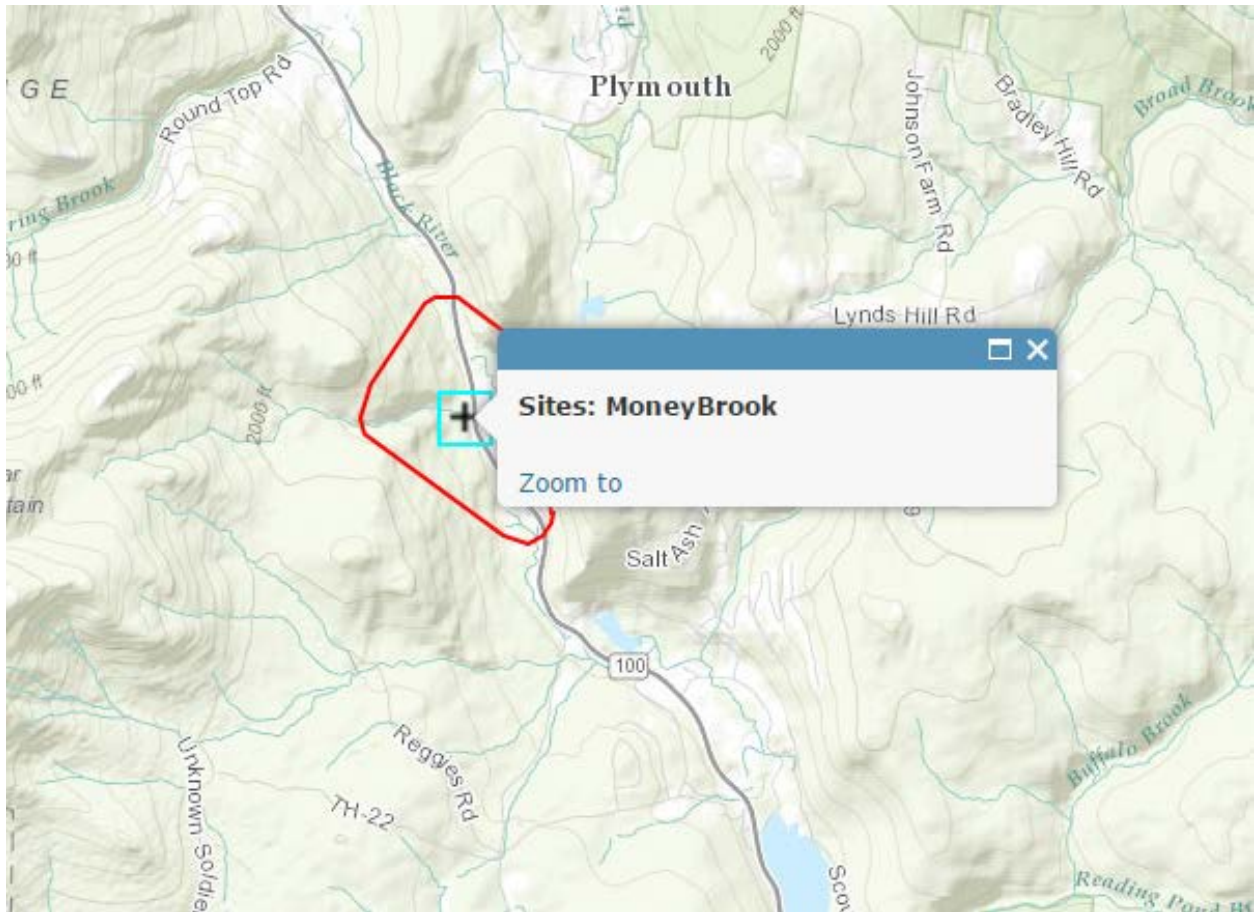


Figure 38 Image Footprint for Money Brook in the Web Application

Selecting the “+” sign in the middle of the polygon allows the user access to the DMT or the orthophoto for download, initiated by selecting the “More info” links shown in Figure 39.

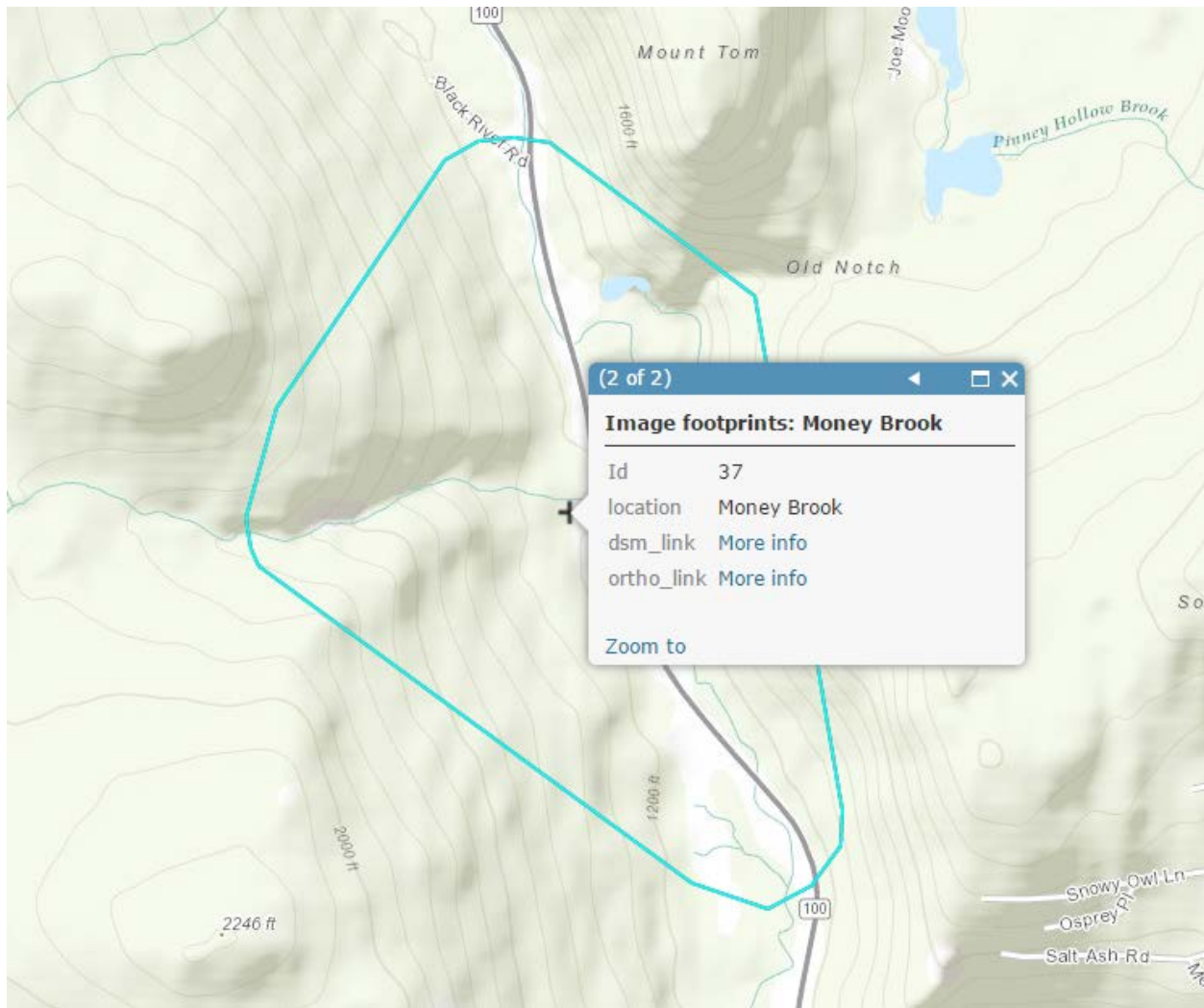


Figure 39 Download Options for Money Brook in the Web Application

A web-based woody debris map was developed specifically for the Great Brook project to showcase how an online portal could enhance decision support (<http://go.uvm.edu/naymz>). This portal includes the orthorectified imagery from before and after the summer 2015 storm event along with the locations of all the woody debris attributed with time series presence/absence information (Figure 40).

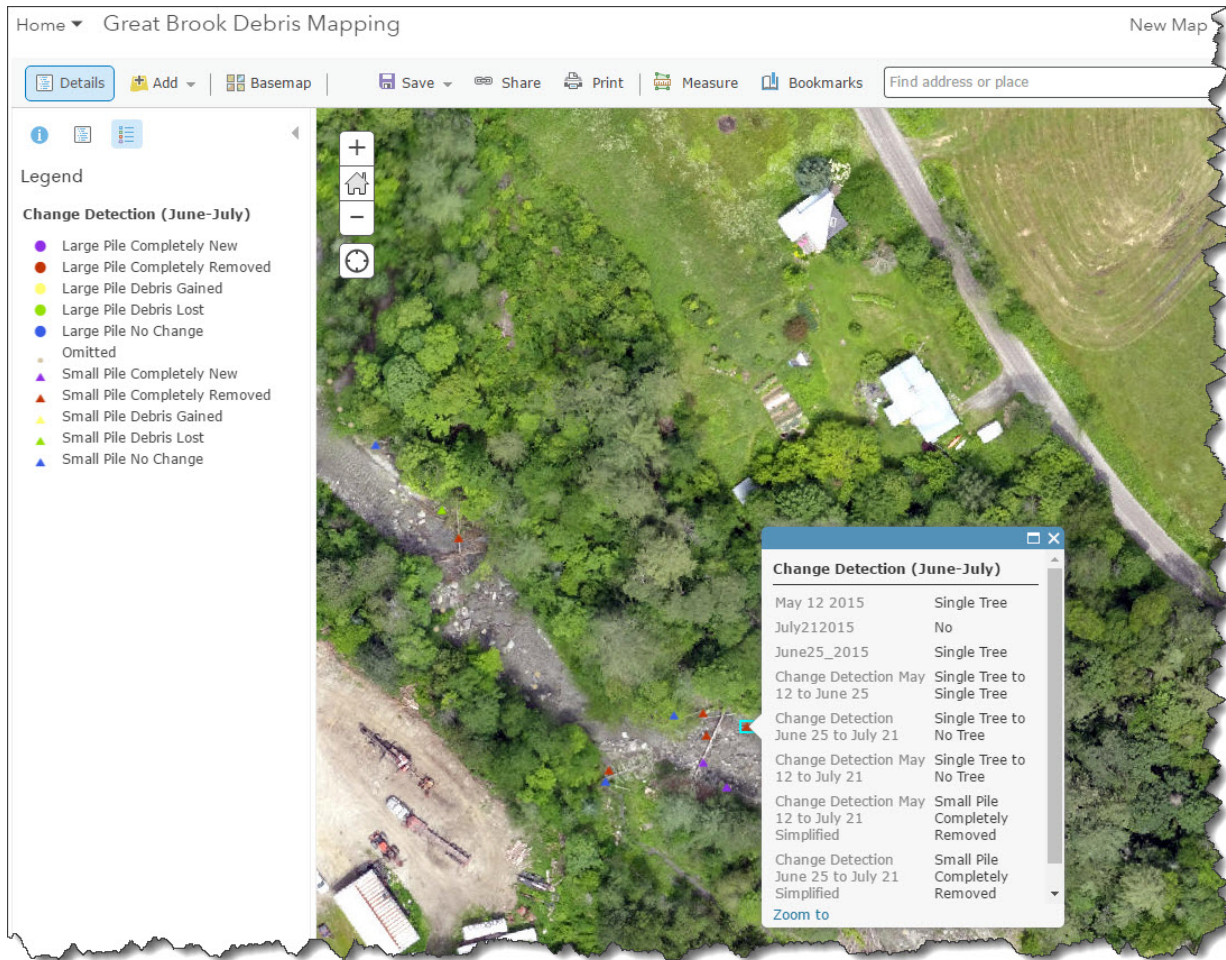


Figure 40. Online portal for the Great Brook woody debris mapping

6 Supplemental Analysis of Debris Dynamics

Considering the timing of corrective action for high-risk crossings, the team conducted a supplemental analysis of debris dynamics at the Great Brook site by conducting the analysis before and after a major storm event, when LWD piles were known to have moved within the brook, causing extensive flooding of downstream crossings. This analysis was conducted on the Great Brook site because the presence of LWD piles and the opportunity for storm impacts in a developed area were both very high. The initial flights at the Great Brook site in May 2015 were followed up with a set of flights in late July 2015, after a severe storm dumped up to 4 inches of rain on central Vermont on July 20th, causing flooding and damage in Plainfield and Barre.

These two sets of flights allowed the research team to evaluate dynamic changes in LWD piles through the course of a major storm event, by repeating the analysis before and after the storm. From these repeated analyses, it was discovered that the changes in the number, location, and size of LWD piles was far greater than the team had anticipated. Before the storm, the process identified 408 LWD piles in Great Brook. After the storm, it identified 604. Additionally, few of the original LWD piles were confirmed to have persisted in the brook after the storm swept through. A comparison of the debris counts before and after the storm is provided in Figure 41.

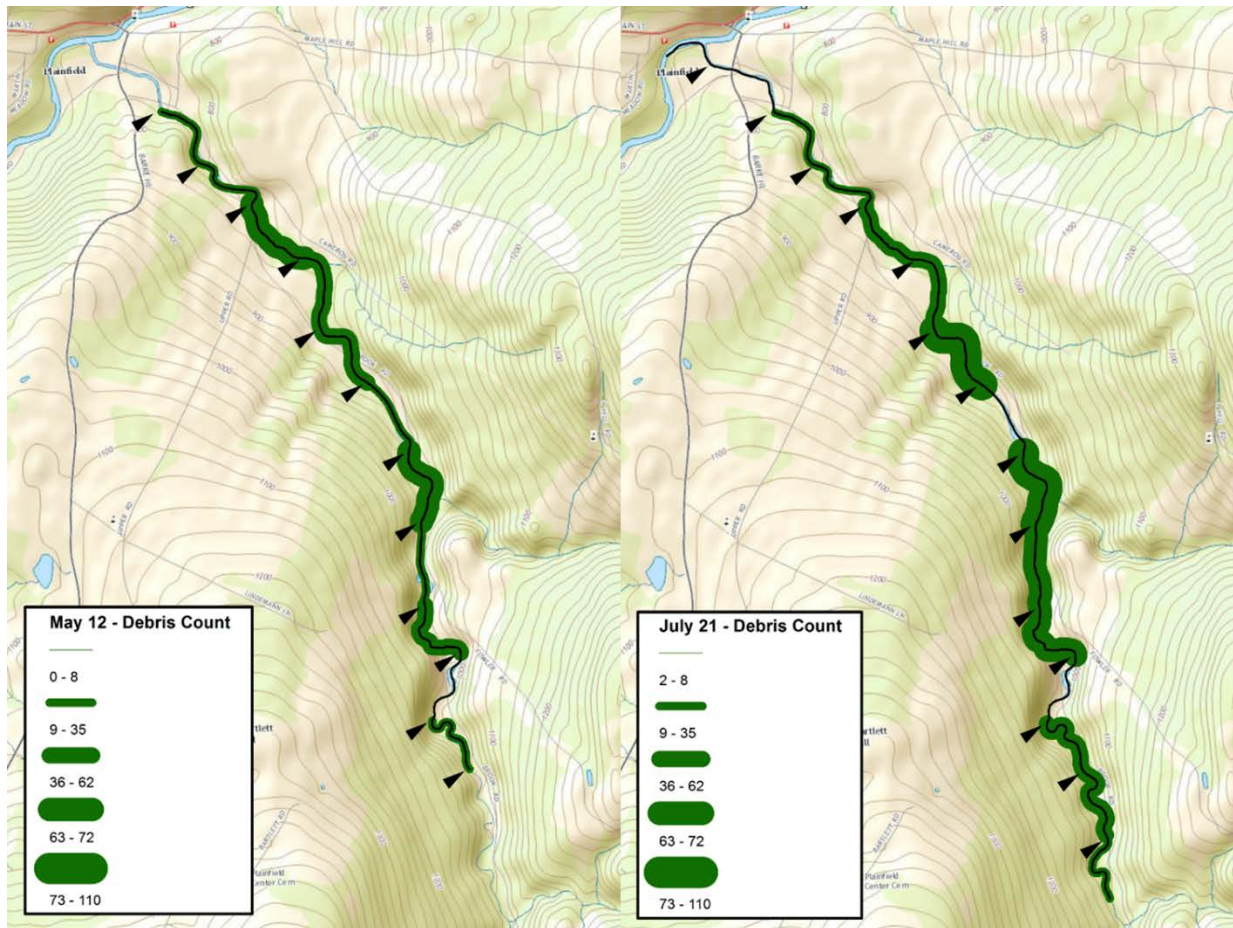


Figure 41 Debris Counts in Great Brook before and after the July 20, 2015 Storm

Figure 42 provides an illustration of the change in the number of LWD piles along different sections of Great Brook.

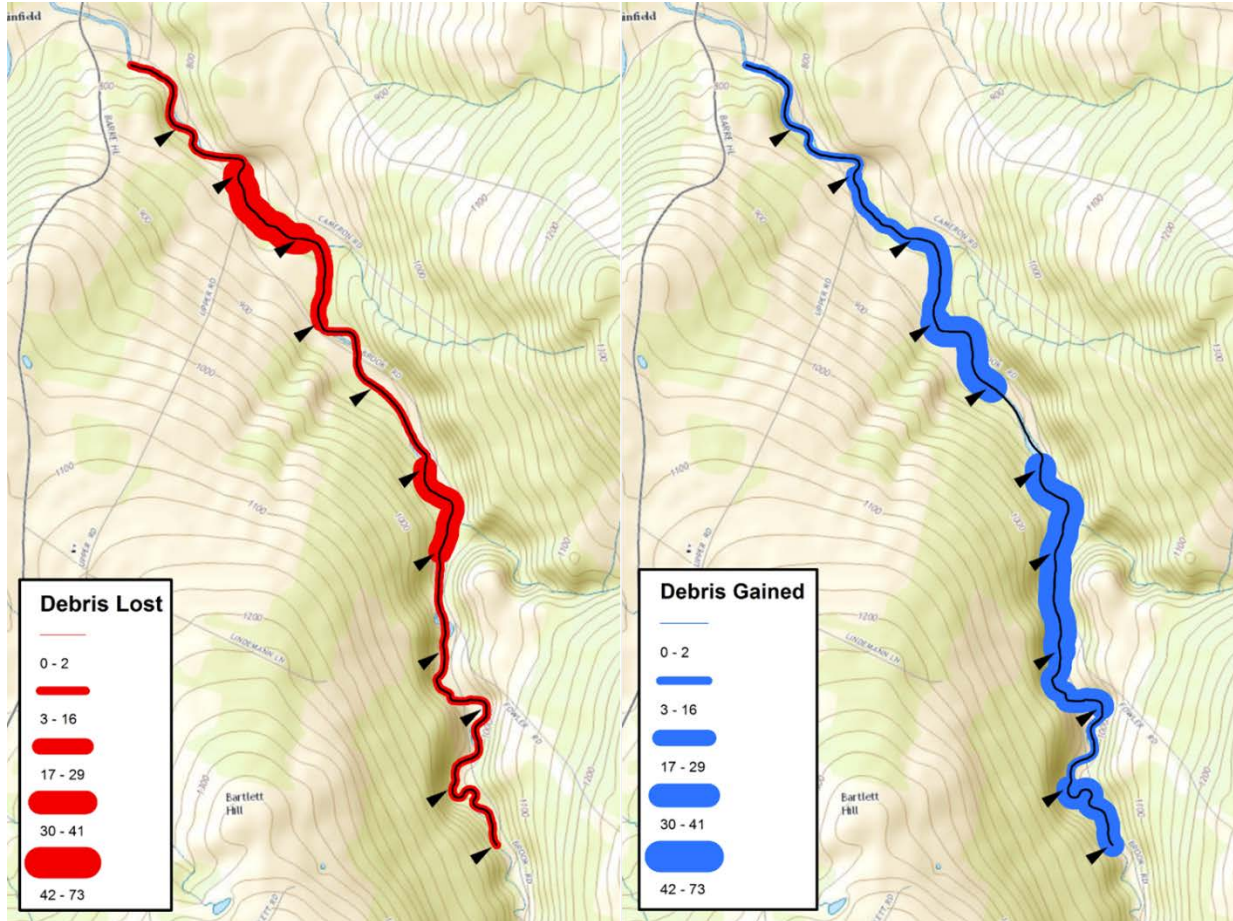


Figure 42 Change in LWD Piles

The dramatic changes that occurred over a period of a few months are evident in the figure. New LWD was introduced throughout the upstream reach of the brook, and existing LWD was transported downstream out of the brook. A close-up view of how these changes appeared at 3 specific locations in the brook can be seen in Figure 43.

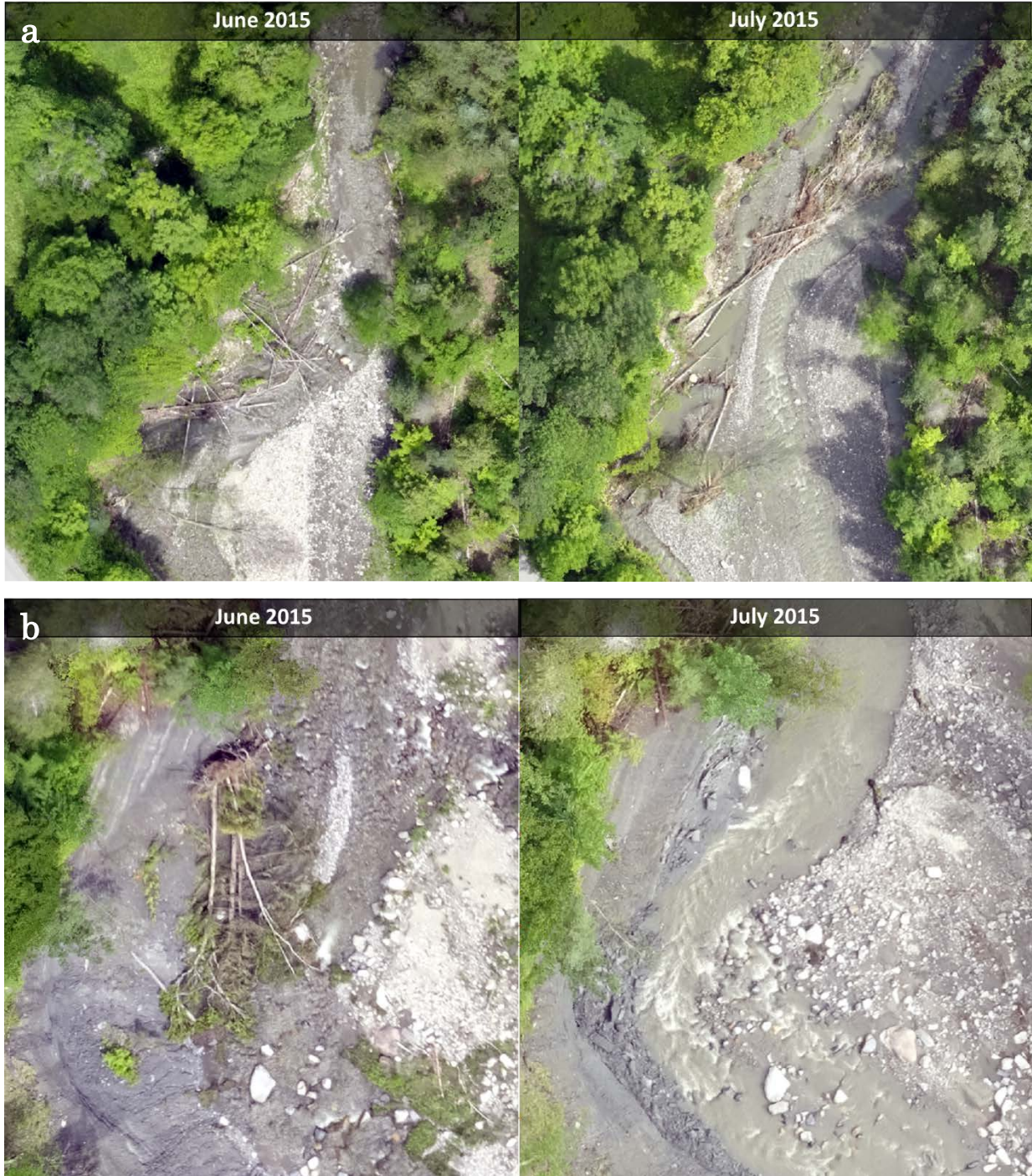




Figure 43 LWD Pile Transitions in Great Brook before and after the July 20, 2015 storm

From these images, the extent of the changes are even more evident. In Figure 43a, all of the original trees appear to be gone, and a pile with a new size and shape has taken its place. In addition, the course of the brook has changed, likely as a result of the flow obstruction caused by the initial LWD pile. In Figure 43b, a small LWD pile is removed and no new trees are present. Only in Figure 43c is some trace of the original pile, well up the stream bank, still present after the storm. But the rest of the large LWD pile appears to be new.

7 Conclusions and Implementation

7.1 Conclusions

The goal of this project was to pilot-test a new system for providing responsive, timely, and cost-effective information about the threat posed by upstream LWD to vulnerable bridges and culverts in Vermont. The system made use of an unmanned aerial vehicle (UAV) to gather stereo imagery of streambeds upstream of a vulnerable crossing. A process was developed for identifying specific LWD piles upstream of a vulnerable crossing and outputting descriptive data with an extracted thumbnail image of each pile. The system allowed LWD piles to be identified, described, and rapidly transmitted via email or text message to support threat evaluation and assessment of corrective measures that may be needed to address debris before it is transported downstream. The system was demonstrated for 8 different stream-road crossings at 6 different sites in Vermont where culverts or bridges are known to be vulnerable to blockage or debris-related flooding.

Two significant challenges were encountered during this project, in the post-processing of imagery and data transmission to stakeholders. Automation of the feature-extraction process in GIS was initially thought to be imperative to getting actionable results from the DTMs as quickly as possible. However, due to the extremely high resolution of the raw images and the need to check the results of the automated process, it became clear that the fastest method of getting actionable results was to visually scan the images for LWD piles, which are relatively easy to discern in the streambed and on the stream banks. So a visual orthophoto review process was used preferentially to obtain the results described in this report. In addition, transmission of data from the field to critical stakeholders was originally not thought to be a critical aspect of the project. The file sizes that are typical of the high-resolution orthophotos and DTMs that would be obtained from a UAV flight normally preclude their transmission with anything but a hosted file transfer service or by delivering the data on a portable storage device, like a thumb drive. However, as interactions with stakeholders progressed, it became clear that, in many instances, it would be beneficial for the team collecting data in the field to be able to transmit actionable information on the location and extent of LWD piles as rapidly as possible, without having to return to the office at UVM. To overcome this challenge, the team developed a procedure for extracting a small thumbnail image of each LWD pile and its relevant data, reducing the file sizes to make them transmittable as an attachment to an email or text message.

7.2 Implementation

The UAV can be deployed rapidly and output data can be provided in 24 to 48 hours. This fast turnaround is critical, based on the findings of the supplemental analysis of LWD changes in Great Brook. These changes highlight the importance of responsiveness of corrective actions. Corrective measures to mitigate high-risk crossings must be implemented promptly after the identification of LWD piles contributing to that risk – before the next significant storm event. At significant storm events, it appears that most or all of the LWD piles in a stream are either diminished, shifted or removed entirely, with many new piles appearing. These changes make previous LWD pile identifications obsolete. With these considerations in mind, the implementation should proceed in the following steps:

1. A series of sites (5 to 10) are selected for initial risk assessment: the site-selection process will include stakeholders from VTrans and ANR who have witnessed flooding events at crossings where LWD obstruction occurred or are familiar with the site-specific characteristics of specific bridges and culverts that may contribute to this type of flooding:
2. The sites are flown by the UAV and the LWD pile-identification process is conducted
3. The MIDU is calculated for each of the sites and the sites are ranked according to the threat from LWD piles upstream
4. Those sites identified with the most imminent threats are evaluated further for vulnerability of the crossing structure (bridge or culvert) to being blocked
5. Threat and vulnerability are considered together to identify the site with the highest risk of flooding from LWD jams at the crossing structure
6. One or more sites are identified for risk mitigation
7. If corrective measures are planned for the specific LWD piles in the stream or river, then a pre-mitigation flight may need to be conducted to identify the specific locations and sizes of the piles to be removed, unless no significant precipitation has fallen since the initial flights in Step 2.
8. Corrective measures are implemented before the next significant precipitation event

Therefore, it is recommended that the pre-mitigation UAV flight be deployed only once stakeholders are prepared to take relatively immediate corrective action. ANR's *Guidance on the Removal of Instream Woody Debris* should be modified to incorporate this procedure. Standard Operating Procedures for deploying a UAV flight are provided in Appendix A.

This type of deployment can be a significant benefit to both ANR and VTrans in the future. Making a UAV flight a standard part of the implementation of corrective action as problematic stream/road crossings can focus the mitigation efforts to significantly reduce resources and time needed to address the problem. Focusing these mitigations efforts will make the corrective measures more effective, and allow more problematic crossings to be fixed before the damage is done.

8 References

- Allan, J. D., 1995. *Stream Ecology: Structure and Function of Running Waters*, Kluwer Academic Publishers, Boston, MA.
- Biron, Pascale M., Guénolé Choné, Thomas Buffin-Bélanger, Sylvio Demers and Taylor Olsen, 2013. Improvement of streams hydro-geomorphological assessment using LiDAR DEMs. *Earth Surface Processes and Landforms* 38(15), November 2013.
- Brooks, A. P., T. Abbe, T. Cohen, N. Marsh, S. Mika, A. Boulton, T. Broderick, D. Borg, and I. Rutherford, 2006. *Design Guidelines for the Reintroduction of Wood into Australian Streams*. Land & Water Australia, Canberra, Australia.
- Duffy, Kate, 2007. Does Development Cause Flood Damage? Accessed at <http://www.wcax.com/story/6847860/does-development-cause-flood-damage> on September 19, 2016.
- Flener, Claude, Matti Vaaja, Anttoni Jaakkola, Anssi Krooks, Harri Kaartinen, Antero Kukko, Elina Kasvi, Hannu Hyyppä, Juha Hyyppä and Petteri Alho, 2013. Seamless Mapping of River Channels at High Resolution Using Mobile LiDAR and UAV-Photography. *Remote Sensing* 2013, 5: 6382-6407.
- Mancini, Francesco, Marco Dubbini, Mario Gattelli, Francesco Stecchi, Stefano Fabbri and Giovanni Gabbianelli, 2013. Using Unmanned Aerial Vehicles (UAV) for High-Resolution Reconstruction of Topography: The Structure from Motion Approach on Coastal Environments. *Remote Sensing* 2013, 5: 6880-6898.
- Miřijovský, Jakub and Jakub Langhammer, 2015. Multitemporal Monitoring of the Morphodynamics of a Mid-Mountain Stream Using UAS Photogrammetry. *Remote Sensing* 2015, 7: 8586-8609.
- Schiff, R., E. Fitzgerald, J. MacBroom, M. Kline, and S. Jaquith, 2014. *Vermont Standard River Management Principles and Practices (Vermont SRMPP): Guidance for Managing Vermont's Rivers Based on Channel and Floodplain Function*. Prepared by Milone & MacBroom, Inc. and Fitzgerald Environmental Associates, LLC for and in collaboration with Vermont Rivers Program, Montpelier, Vermont.
- Semmens, D. J., S. N. Miller, and D. C. Goodrich, 2006. Towards an automated tool for channel-network characterization, modeling and assessment. *Proceedings of the Third Federal Interagency Hydrologic Modeling Conference*, Reno, Nevada. April 3-6, 2006.

Thompson, D. M., 1995. The Effects of Large Organic Debris on Sediment Processes and Stream Morphology in Vermont. *Geomorphology* 11(3):235-244.

Williams, Bradley S., Ellen D'Amico, Jude H. Kastens, James H. Thorp, Joseph E. Flotemersch, Martin C. Thoms, 2013. Automated riverine landscape characterization: GIS-based tools for watershed-scale research, assessment, and management. *Environ Monit Assess* (2013) 185: 7485–7499.

Wohl, E. and D. M. Merritt, 2008. Reach-Scale Channel Geometry of Mountain Streams. *Geomorphology* 93(3-4):168-185.

Appendix A

Standard Operating Guidelines: Unmanned Aerial Vehicle Deployment



University of Vermont

Contents

- Administrative Preparation1
- Notifications2
- Equipment Acquisition2
- Equipment Checklist3
- Battery Information and Safety5
- Pre-flight Tasks6
- Data Management.....6
- Flight Planning8
- Pre-flight Field Tasks..... 22
- Flight Operations 28
- Data Processing 30
- Equipment Return 39

Administrative Preparation

After obtaining written permission to use the UAV from Jarlath O'Neil-Dunne, users will be required to obtain approval from Vermont Agency of Transportation (VTrans) Aviation Program Administrator, Guy Rouelle, in accordance with the following steps.

- Guy Rouelle at the Vermont Agency of Transportation should be contacted at the onset of the project and provided with a project summary and scope of work.
- Flight will require a Mission Profile. During this initial conversation, Mr. Rouelle will tell you exactly what information to include in the Mission Profile and how far in advance to submit it. Also, depending on where you want to fly and at what altitude, you may need a Certificate of Authorization (COA) for the flight. If your organization is not an Agency of the State, we recommend that you choose flight paths that are outside of restricted airspace and below 400ft AGL to avoid the COA requirement. Confirm with Mr. Rouelle as to whether or not your project will require a COA. If necessary, Guy Rouelle will contact FAA and Portland FSDO and/or obtain a Special Airworthiness Certificate (SAC).
- Send a Mission Profile to Guy Rouelle a minimum of 1 week prior to the scheduled flight. Generally, the Mission Profile should include the following information:
 - Location of departure and landing zones
 - Extent of flight area
 - Proposed flight path
 - Maximum in-flight altitude
 - Flight duration

Some additional factors to consider when creating the Mission Profile:

- Restricted airspace: The general rule of thumb is that UAVs should be flown 5 or more miles away from designated airports and Camp Johnson. However, different airports have different requirements and some additional restricted airspace exists within Vermont. Work with Guy Rouelle when selecting a flight location.
- Flight altitude: The UAV should be operated below 400ft (121m) above ground level (AGL) to avoid the need for FAA clearance.

Notifications

In addition to the Vermont Agency of Transportation, the following entities should be contacted prior to the proposed flight:

- Local Police Department associated with the flight location
- State Police Department, if flying over or adjacent to state highways
- Property owners adjacent to flight location
- Local Municipality associated with flight location

Equipment Acquisition

The necessary equipment can be obtained from:

Spatial Analysis Laboratory
Rubenstein School of Environment & Natural Resources
220 George D. Aiken Center
Burlington, VT 05405-0088
Tel: (802) 656-3324

Equipment Checklist

- Backpack
 - Laptop (Dell M6700)
 - Surface Tablet
 - Laptop charger
 - Laptop batteries (x2 – blue/red)
 - Mouse (with AAA battery and USB plugin)
 - Camera Bag
 - Canon S110 camera (NIR)
 - SD Card
 - Battery
 - Canon S110 camera (RGB)
 - SD Card
 - Battery
 - Backup SD cards (x2)
 - Lens cleaner
 - ButterFox Binder
 - Extra *eBee* batteries (x3)
 - USB Cables (x2 black, x1 orange)
 - MicroSD Card Reader
 - Thumbdrive
 - senseFly Radio Tracker Manual
 - Verizon Jetpack Mobile Hotspot – MiFi and charger
 - External hard drive with cable
 - Automobile power outlet adapter (x2)
 - Handheld wind meter
 - Radio Transmitter
 - GPS unit
 - Antennas and bases
 - Compass
 - AA 1.5 V batteries (x4), AAA batteries (x2)
 - Velcro, Twisty Ties, and Orange Ribbon
 - Standard Operating Guidelines (SOG)
 - Car Antennas and Bases
 - Pens and pencils
- *eBee* carry case:
 - *eBee* body
 - *eBee* wings (x2 – left/ right)
 - *eBee* batteries (x3)
 - Battery charger & transformer (x3)
 - *eBee* propeller (x1)
 - *eBee* propeller bands
 - Canon IXUS 127HS camera (NC)
 - SD card

- Battery
 - Battery Charger
 - SenseFly USB radio modem
 - Mini-USB male to USB-A male cable (x1 black and white)
 - Styropor Glue
 - *eBee* Manual
- *eBee* RTK carry case:
 - *eBee* body
 - *eBee* wings (x2 – left/ right)
 - *eBee* batteries (x3)
 - Battery charger & transformer (x1)
 - *eBee* propeller (x1)
 - *eBee* propeller bands
 - Sony WX camera (RGB)
 - SD card
 - Battery
 - Battery Charger
 - Power Cable
 - SenseFly USB radio modem
 - Mini-USB male to USB-A male cable (x1 black)
 - Styropor Glue
 - *eBee RTK* Manual
- Duffel Bag
 - Motorola Talkabout handheld radios (x6)
 - Motorola Talkabout handheld radio chargers (x6)
 - Radio Tracker Receiver
 - Hi-vis vests (x6)
 - Hi-vis hats (x2)
 - Hard hats (x3)
 - Ground control points (GCPs) (x2)
 - White trash bags for GCPs
 - Camera battery and Tablet charger bag
 - Charger for S110 RGB
 - Charger for S110 NIR
 - Charger for Tablet
 - Monopod
 - Screen Protector
 - Long USB Cable (extra)
 - Car antenna
 - Electrical tape (Black and multi-colored)
 - LiPo Guard charge bags (x4)
 - Binoculars

- Paper Towels
- Extra batteries in Ziploc bag
- First Aid Kit
- Other
 - Tripod
 - Camera Tripod
 - Stop signs (x2)
 - Traffic cones (x3)
 - Hi-vis Jackets (x2)
 - Tarp
 - Umbrella
 - Standing Table
 - Car traffic hazard roof light
 - Keys to vehicle

Battery Information and Safety

The lithium polymer (LiPo) battery is composed of three cells. Each cell has a voltage capacity between 3 and 4.2 volts (V). When the battery is empty it is at 9 V (3 V per cell). When full, the battery is at 12.6 V. The ‘healthy’ voltage for each cell is between 3 and 4.2 V, so it should not be at any level outside of this range. If the battery cells’ voltage levels are unbalanced the battery charger will balance its levels between the cells.

The status of the batteries are indicated by LED lights on the senseFly battery chargers. There are 4 lights: the “status” light as well as three lights, each representing a battery cell. While the battery is charging the status LED light is red, and when complete it will turn green. Towards the end of the charging process, the charger checks and balances the battery’s cells. During the process, red lights will appear next to each indicated cell. If the battery is overcharged the “status” LED light will flash.

Charge Safety

Do not use any other charger besides the provided senseFly *eBee* charger. Charge the LiPo batteries in an open, ventilated area on top of a cool and non-flammable surface. Pyrex dishes and plant pots with sand are simple and safe surfaces to charge your batteries on. Never leave your batteries charging unattended.

If the charge exceeds 12.6 V the charger will indicate a red flashing LED and the battery should be immediately discarded. Overcharging the battery may cause irreversible damage and can be too dangerous to charge again. Leaving a damaged battery charging may cause them to catch fire. Do not attempt to charge an already over-charged battery. Contrarily, if the battery is left *discharged* to a level below 9 V, damage will be caused. It is not safe to charge again. In either case of battery damage, dispose of the battery safely.

Storage

Voltage and temperature are two vital factors to determining LiPo battery life.

It is best to leave the LiPo batteries in storage with about 50% charge (10.8 V total, 3.6 V per cell). Storing the battery at 100% charge will result in loss of battery capacity. Some battery chargers will charge LiPo batteries to a “storage level”, but the *eBee* chargers do not have this feature, so be sure to check the charge levels before storage.

LiPo battery life will last longer if stored in colder temperatures. Ideal storage temperature ranges between 32 – 40° F – about the average temperature of a kitchen refrigerator. If storing them in a refrigerator keep the batteries in a Ziploc bag. When you take them out of the refrigerator keep the batteries in the Ziploc bag until they are at room temperature. This prevents moisture from condensation forming on the batteries. **Note: Lithium batteries do not last as long in below freezing weather.**

Having the right storage voltage and temperature will result in a longer battery life.

Pre-flight Tasks

1. Charge batteries

- *eBee* battery packs (x9)
- Camera battery (x4 – RGB, NIR, IXUS, WX)
- Handheld radios (x6)
- Laptop battery (x2)
- Tablet Battery
- Check battery & operation of handheld wind meter

2. Ensure *eMotion2* software and UAV firmware are up to date

1. Check for software updates: <http://www.sensefly.com/support/download.html> and log in to my.senseFly
2. Connect *eBee* battery
3. Connect *eBee* to PC via USB cable
4. Run ‘Updater *eBee*’ program (Start Menu->*eMotion2*-> Updater *eBee*)
5. Upon completion, unplug USB and disconnect battery
6. Connect battery to *eBee* & radio modem to PC
7. Open *eMotion2* to ensure successful UAV/software connection
8. DO NOT update the *eBee* with the camera plugged into the drone

Data Management

It is important that all data associated with UAV operations is organized in a consistent manner. General guidelines for spatial data management apply, including the absence of spaces or periods within file or folder names. All final and backup data must be saved in the network O: drive. The folder layouts are organized as follows:

Main folder: Named by location of flights. Contains three subfolders: **Data**, **Docs**, and **Maps**.

Data: Contains missions and planning folders.

Mission folder: All post-flight processing data. See naming convention below.

Planning: Contains preliminary flight plans (.afp, .xml, .kml) saved from *eMotion*. If there are unique missions and dates, separate accordingly.

Docs: Contains important notes and information about flight. Screenshots of flight plans, word documents, non-spatial data.

Maps: Arcmap maps, .mxd files, and PDFs of maps.

Naming conventions and information for mission folder:

Mission folder: Folder containing all data associated with a day's mission.

Convention: [Day][Month][Year]_[Project location or description]

Example: 07December2013_SampleMission

NOTE: For the RTK, the naming convention should look like:
'2015-06-04_flight15_RTK_Burlington' when using *eMotion*.

Subfolders for individual flights are formatted by eMotion, and use the following naming convention:

<Date>_<User name>_<flight name>_<project name>

Example – 2014_08_03_flight87_mount_philo

The following folders will be created automatically within this main directory during processing:

- dsm
- mosaic
- params
- pointcloud
- report
- temp
- tiles
- trianglemodel

eBee laptop local data: All data stored in the D: drive

- Flight plans and pre-flight data located under (D:\eMotion\routes).
- *eMotion* flight processing goes in (D:\UAV_Missions_Local\Missions).
- Follow the mission folder naming convention above when creating new mission folder. All flight subfolders are automatically created by *eMotion* formatting.

Surface Tablet C: drive and external E: drive

- The tablet's internal hard drive is for storing flight plans only. *eMotion* defaults its flight plans to pathname: C:\Users\Drunken Raven\Documents\eMotion\routes
- All other data, such as post-flight flight folders should be stored in the external hard drive, which follows folder organization above. Pathname: E:\eMotion\Missions

Flight Planning

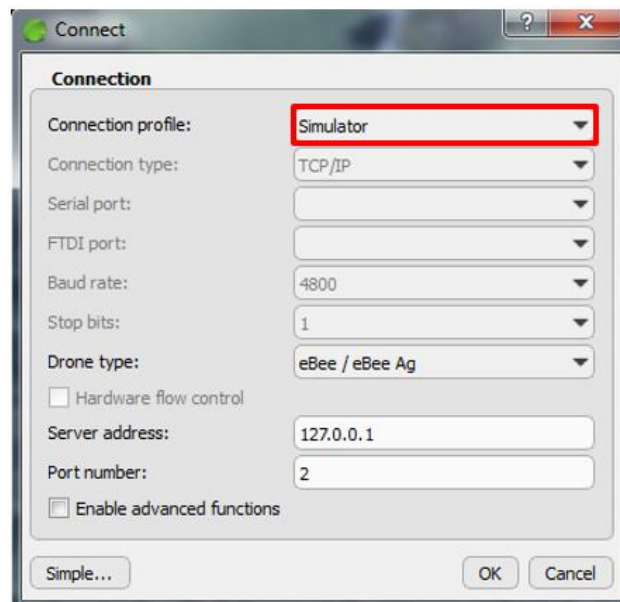
Creation of a flight plan should be accomplished at least 1 week prior to the date of proposed field operations to ensure timely notification and approval. Flight plans can be updated or created on site during operations, if necessary.




Check flight area weather and be prepared to monitor weather in the field.

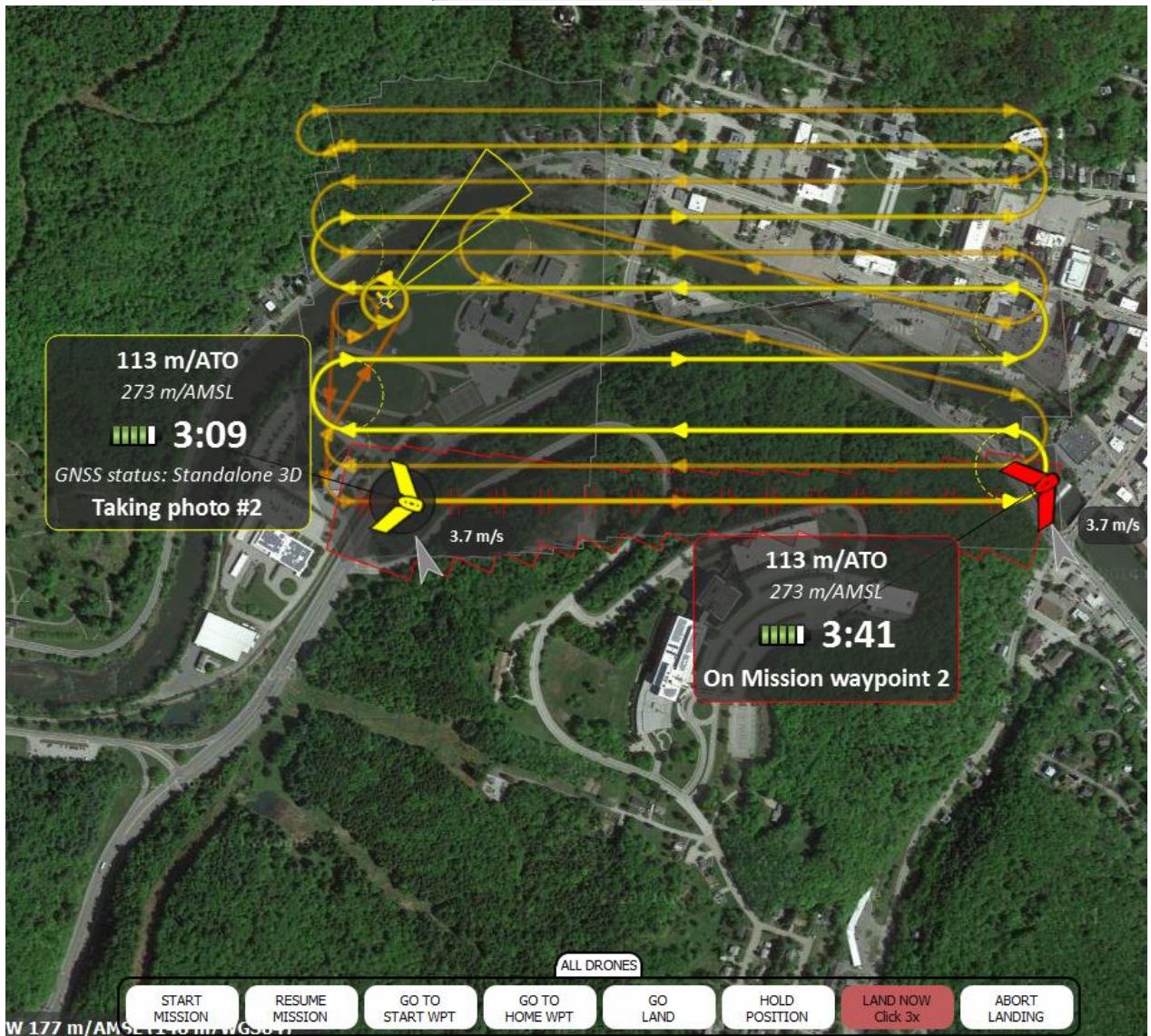
Check area to ensure there are no Notice to Airman (NOTAMS), flight restrictions, or other flight operations that would impede a safe flight operation.

1. **Launch *eMotion 2* software**
2. **Select “Simulator” option as shown and select ‘OK.’**

If a connection error warning is displayed, repeat this process (this is a known bug in the software). To switch between simulating the *eBee* and the *eBee RTK*, select the preferred drone in the Drone type drop down selection menu. **NOTE:** If you want to fly multiple drones, go through the same connection steps are before after connecting the first drone, selecting the preferred drone type from the drone type dropdown menu. This will result in a new panel appearing on the screen displaying important data about each drone. Selecting either of the drones from this menu will allow the same full control and information displayed during a standard single drone flight. The bottom control bar at the bottom of the display screen controls both drones at the same time now, unlike the control bar at the top of the screen which controls whichever drone is currently selected.



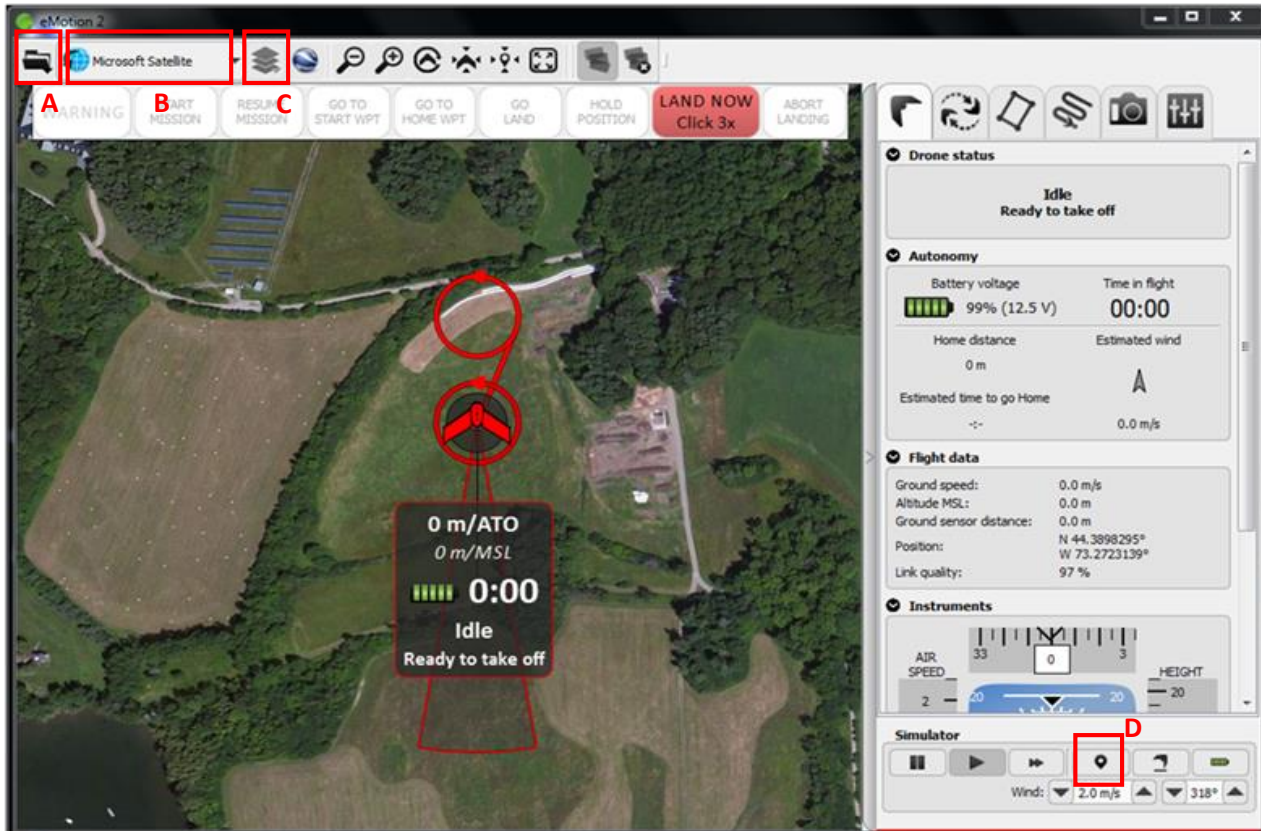
	ER-01-008 Ref alt.
	Taking photo
	EB-01-009 Ref alt.
	Mission
	<input type="button" value="Sort by"/>



3. Load base map and place proposed UAV start location

- Select a background map from the dropdown list [B] and pan to the area of interest for the flight.

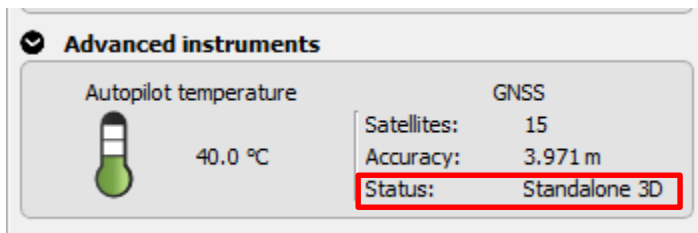
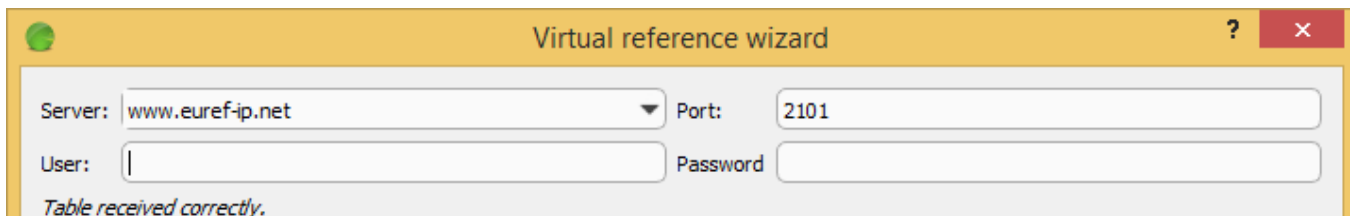
- Select the marker icon in the lower right corner [D] of the drone status tab and use the crosshairs to select the proposed take-off location of the UAV.
- It is possible to import KML files as a custom basemap or for other planning purposes by selecting “Import KML (ctrl+j)” from the file dropdown menu [A] in the top left.
- The KML files available for viewing can be toggled on or off in the layers dropdown menu [C].



4. Setup of RTK

- In the field, a Wi-Fi connection is required using the MiFi.
- Select the RTK button on the top of the screen [B]. This brings up a window with three tabs. Select the right most one labeled “Virtual reference (VRS).”
- If a Virtual Reference is not already added, select the “+” icon at the bottom right side of the window, bringing up the Virtual Reference Wizard.
- In this menu, make sure the Server is “170.222.32.141”, the Port is “2101”, the User is “UVMSAL”, and the Password is “KdhEfnBK7Ft”. In the Table menu below the entry fields, select the “VRS_RTCM3” option by clicking on the “+” icon on the right hand side and select OK.
- In the RTK Source dropdown menu [A], select the “Virtual: VRS_RTCM3” option. The GPS and Glonass options should now both be listed as “Ok.”

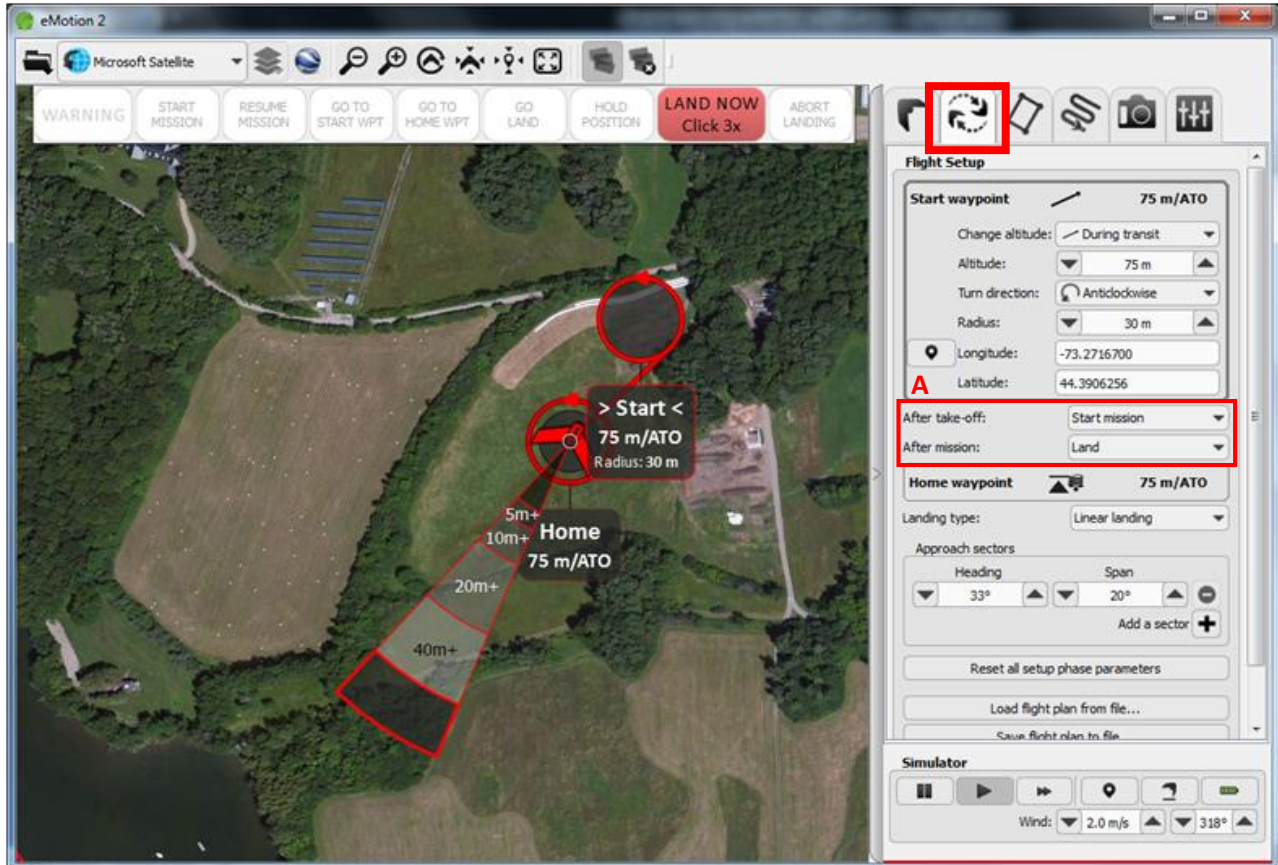
- The GPS and the Glonass should now both read “Ok” instead of “Not Sufficient” [C].
- On the Flight Monitoring tab (the left most one), under Advanced Instruments at the bottom of the screen, check to make sure that the Status now reads “RTK Fixed” and not “RTK Float” or “Standalone 3D.”



5. Place the estimated landing approach and home and start waypoints (Flight Setup tab)

- **Home waypoint:** UAV landing location. Variable radius, 30m recommended.
- **Start waypoint:** UAV circles this location before initiating mission to gain altitude. Variable radius, 30m recommended.
- **Landing approach sector:** Zone of potential landing paths. Variable span and heading. Depending on field conditions, multiple approaches may be added. The *eBee* will select the best approach path based on wind conditions.
- By default, *eBee* will start mission after take-off and land immediately after mission completion. These actions can be adjusted with the dropdown menus [A].

These parameters can be adjusted by dragging with the mouse or by changing the associated values in the flight setup tab (highlighted). Generally, the start waypoint should be located up wind of the UAV launch location and the landing approach sector should be aligned so that the UAV is flying directly into the wind when landing. However, these locations are highly dependent on ground conditions and will require adjustment in the field.



6. Mission Planning

- Select mission area shape [A] and adjust rectangle or polygon to fit area of interest with mouse.
- Adjust desired ground resolution [B], ensuring the target height is below the 400ft (121m) FAA flight ceiling. Suggested values are between 3.0-4.0 cm/pixel.
- Specify lateral and longitudinal overlap [C]. General guidelines are 65-70% lateral and 70% longitudinal for parallel flight lines, or 60-65% lateral and 70% longitudinal for perpendicular flight lines. **Note:** When flying with the RTK, it is recommended to set the lateral and longitudinal to 85%.
- Generate perpendicular flight lines when increased image overlap is desired by selecting the radio box [D]. **Note:** This will approximately double the expected flight time.
- When complete, create the flight plan by selecting 'Upload' [E]. The software will automatically create waypoints and flight lines according to the parameters specified.
- To save the mission plans, select the gear icon, save mission to file, and save to the selected location.

eMotion 2

Microsoft Satellite

WARNING START MISSION RESUME MISSION GO TO START WPT GO TO HOME WPT GO LAND HOLD POSITION **LAND NOW** Click 3x ABOBT LANDING

7.2 ha / 0.07 km²
177°
44.3895702°N 73.2722260°W
Altitudes ATO

Mapping and mission parameters

Difficult terrain Easy terrain

Mission area **A** Polygonal

Ground resolution: 5.1 cm/px

Target height (over take-off): **B** 117.0 m

Use elevation data to set absolute waypoint altitudes

Lateral overlap: **C** 70%

Longitudinal overlap: 70%

D Generate perpendicular flight lines

Reversed flight direction

Save parameters as default

Advanced parameters **E** Upload

Resulting flight characteristics

Number of flights: 1

Flight time: 00:07:53

Total flight distance: 5.1 km

Total ground coverage: 7.2 ha

Number of flight lines: 8+8

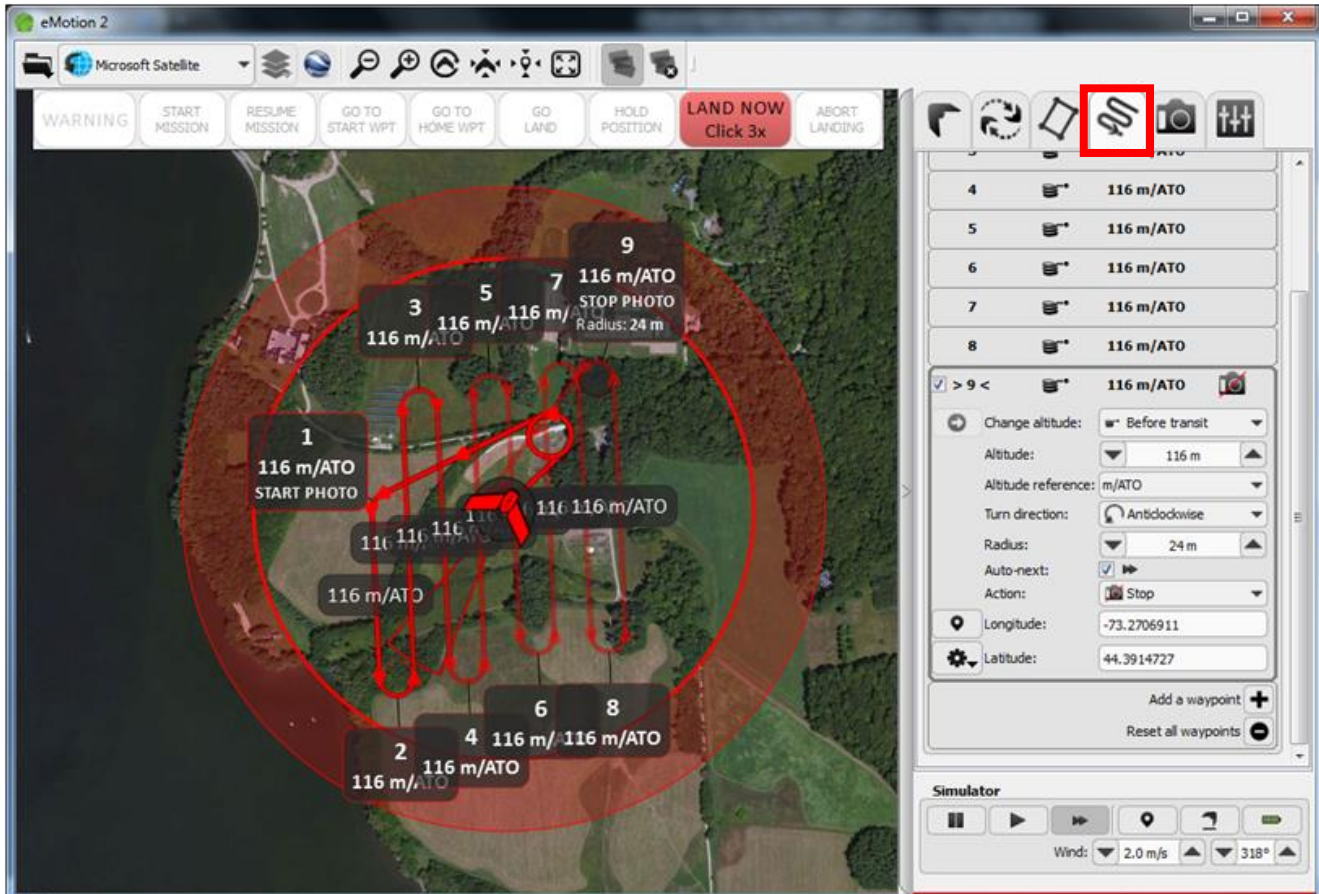
Flight lines spacing: 49.8 m

Simulator

Wind: 2.0 m/s 318°

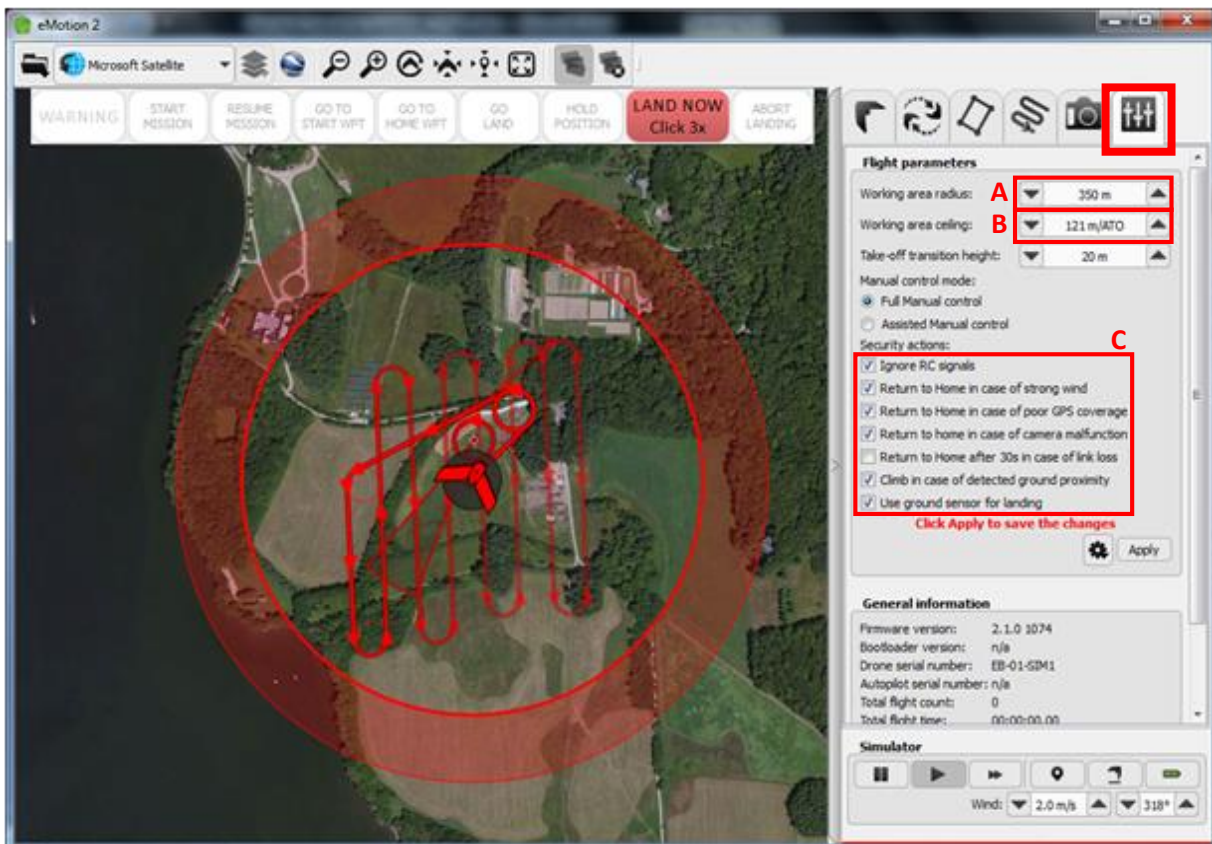
7. Mission Waypoints

If desired, a number of parameters can be adjusted for each of the mission waypoints either by selecting the waypoint on the map or by clicking the corresponding tab. In the majority of cases, no changes to waypoint attributes are necessary. This functionality is most useful for manual creation of flight plans, especially where a number of parallel flight lines mirroring a complex road corridor or stream are desired. Refer to the *eBee* manual for additional information.



8. Flight Parameters

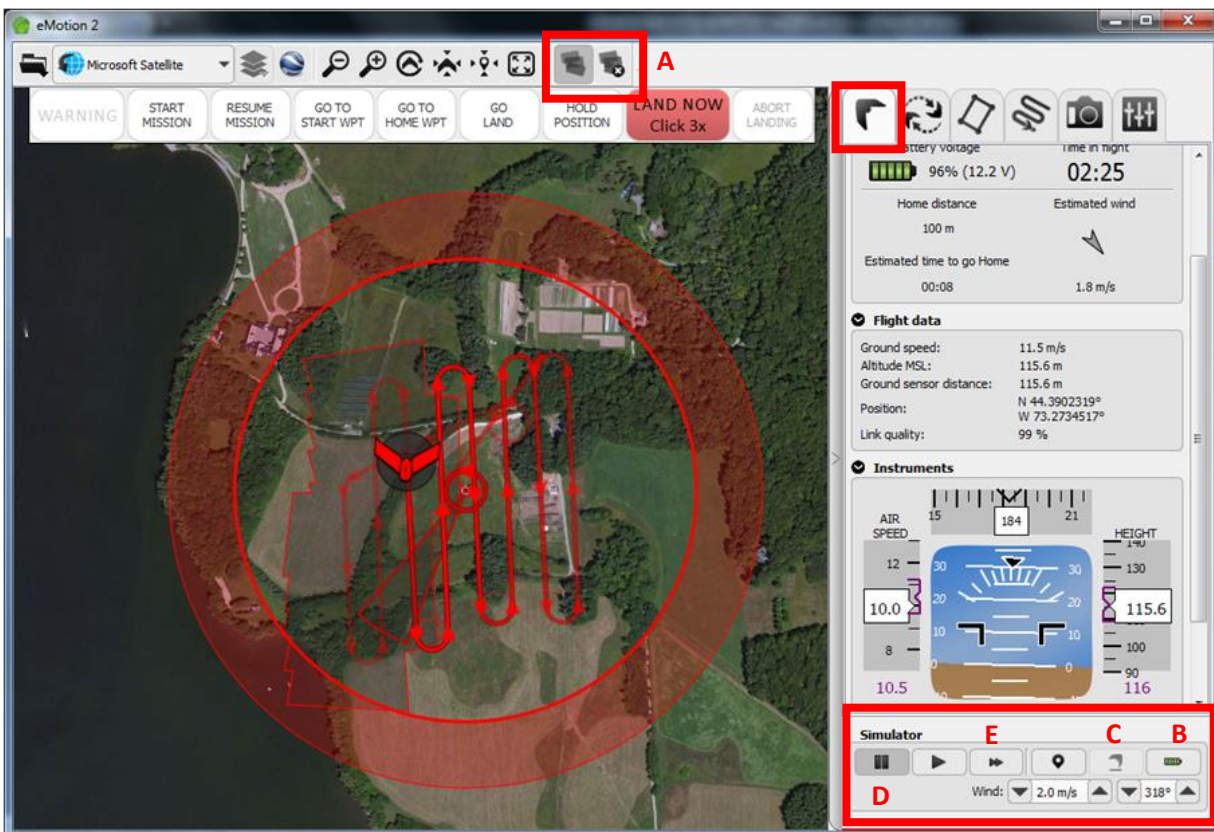
- Adjust working area radius (A) so that the flight path of the *eBee* is fully within the circle. This represents the maximum distance away from the launch location that the *eBee* will fly before returning to the Home waypoint.
- Adjust working area ceiling (B). This is the maximum elevation AGL that the *eBee* can achieve during flight. To comply with FAA regulations, the flight ceiling must be set to 400ft (121m) or less.
- Specify security actions (C) as shown.
- Click 'Apply' to save changes.



9. Simulate flight

It is recommended that the flight plan be simulated as a check of the proposed route and to ensure full photo coverage of the area of interest. Photography is simulated and coverage is displayed by an image footprint on the map. The footprint can be toggled on/off or reset [A].

- Recharge simulated battery [B]
- Simulate take off [C]
- If desired, pause [D] or speed up [E] simulation
- Simulated wind speed and direction can be also be adjusted

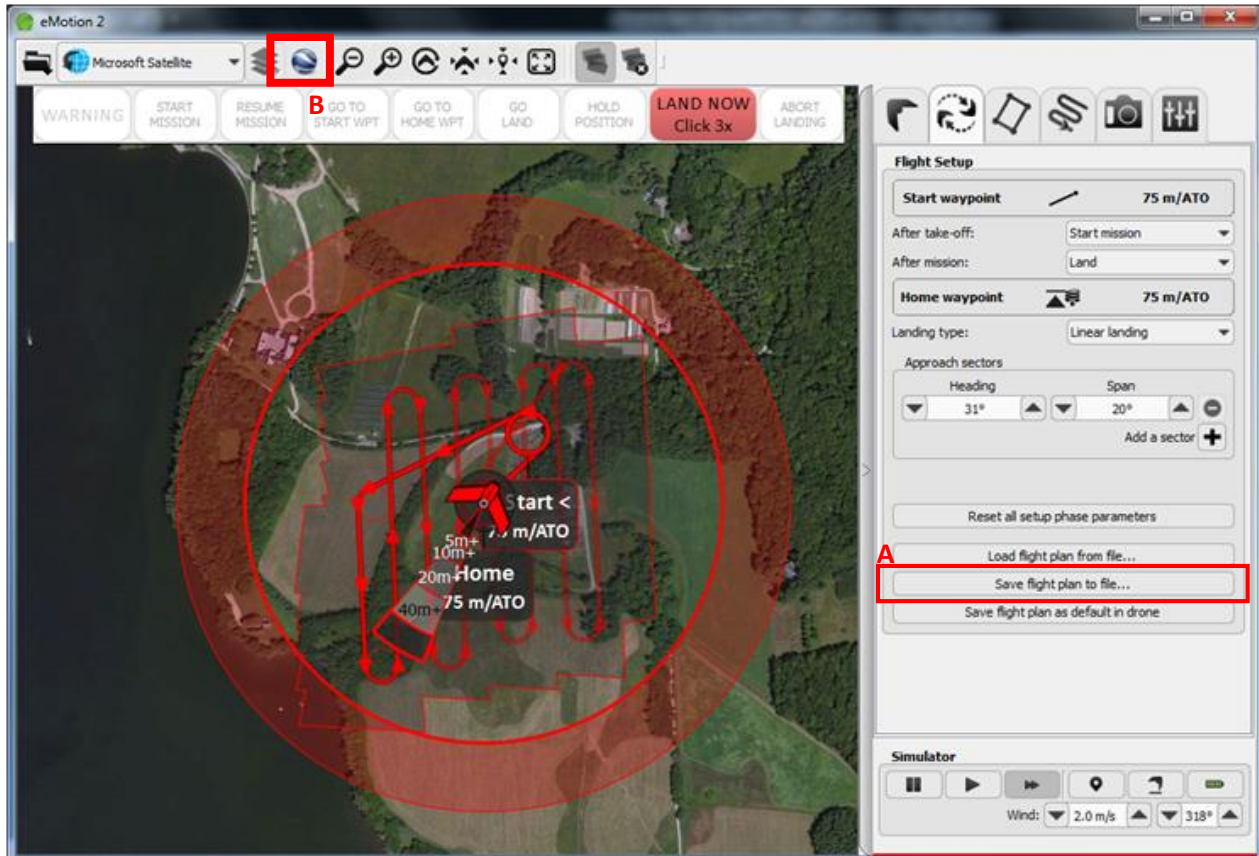


10. Save finished flight plan

When flight plan has been finalized:

- Return to the Setup Phase tab (refer to Step 4 above)
- Select 'Save flight plan to file...' [A]
- Save output XML file according to location and naming convention previously discussed in 'Data Management' portion of document.

- Take a screenshot of flight plan and save according to location and naming convention previously discussed in 'Data Management' portion of document.
- Open flight plan in Google Earth [B] and save KML file according to location and naming convention previously discussed in 'Data Management' portion of document.
- Save the mission area to the same folder where your XML file is saved.



11. Cache background map data

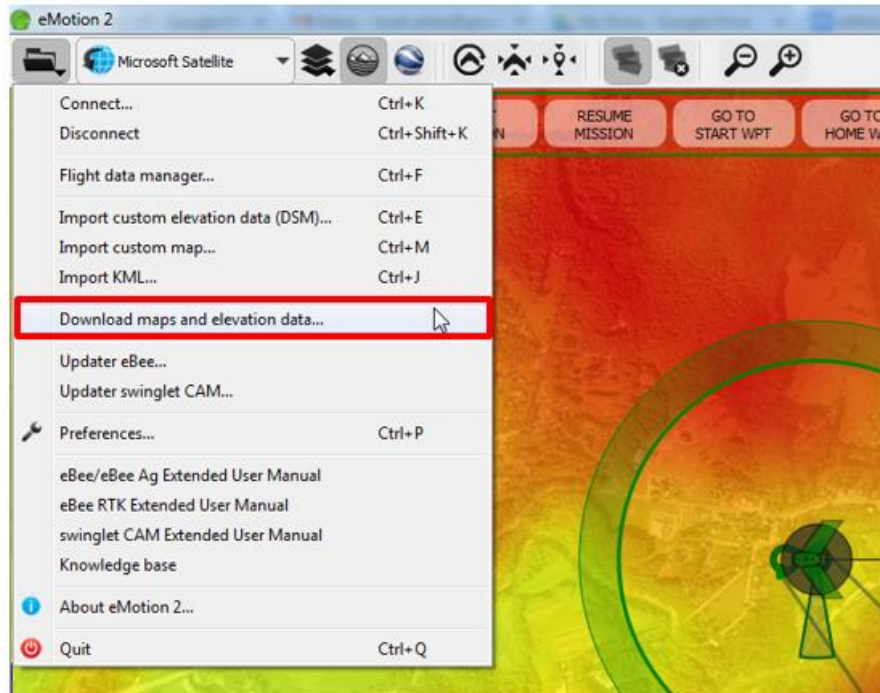
At different levels of zoom, cache tiles of the desired background map data for the extent of the area to be flown by scrolling around the area until each imagery tile is displayed. This cache will be saved in the software even after the computer is shutdown. This is an important step in regards to in-flight monitoring and proper placement of the start and home waypoints when in the field. This step can be accomplished for multiple background map layers.

12. Download maps and elevation data

Elevation data (DEM) can be used to more accurately plan a mission and its waypoints. Map and elevation data can be downloaded for an area of interest from the dropdown menu in the upper left of the *eMotion* interface. This will create a bounding box over the imagery, which caches the imagery and SRTM data (Shuttle Radar Topography Mission, the default *eMotion*

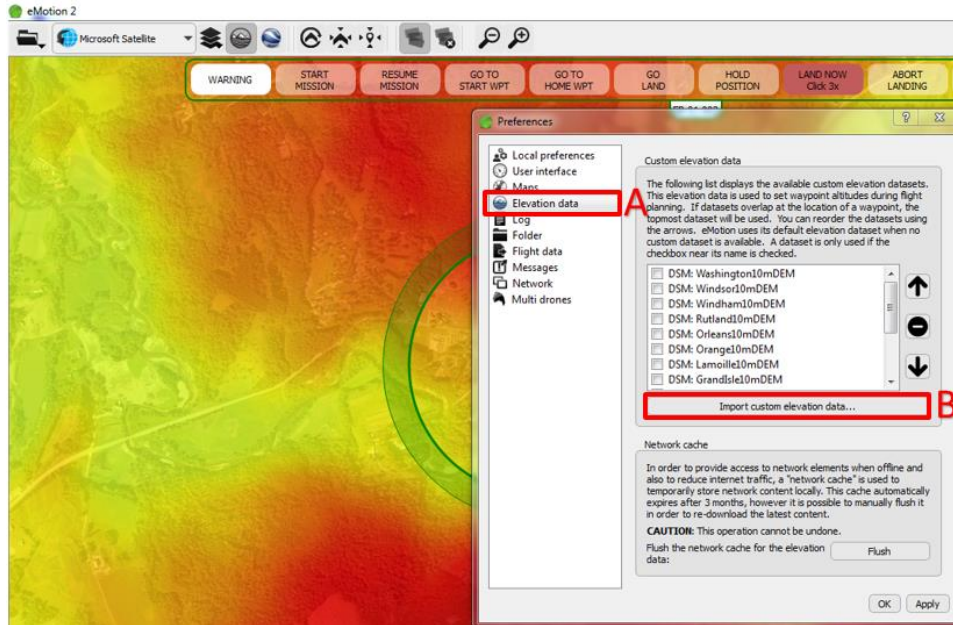
elevation dataset). The SRTM is relatively low resolution so it may be best to use a DEM provided by the state/county of interest. *eMotion* may not handle large mosaics of DEM's, so it may be necessary to load the DEM by county. There are two measurements of altitude provided by *eMotion*: ATO (above take-off) and AMSL (above mean sea level).

NOTE: It is recommended to cache data by scrolling over the imagery in addition to this step.

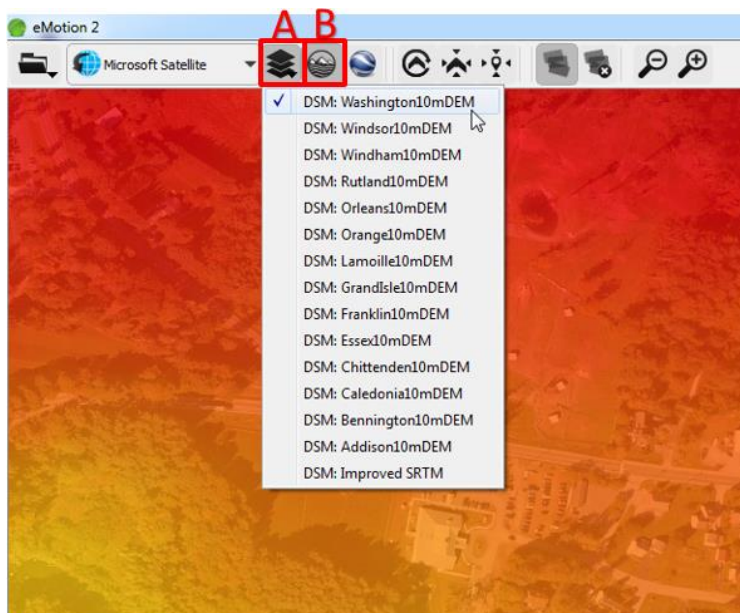


DEM's can be added by opening preferences (located in the upper left dropdown menu, Ctrl+P) and choosing the "Elevation data" tab [A] and "Import custom elevation data..." button [B].

NOTE: *eMotion* labels these as DSM's e.g. DSM:Washington10mDEM. Ignore the DSM label as they are actually DEM's.

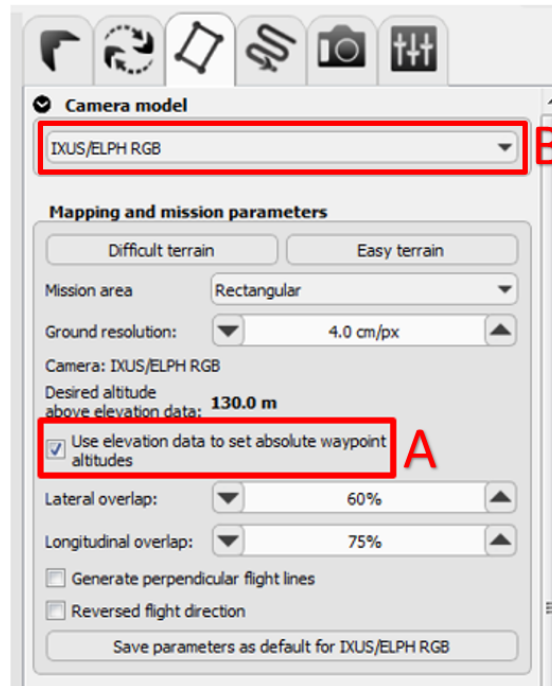


Elevation data can be selected using the set elevation data layer dropdown menu [A] and toggled on and off with the “Display elevation data layer” button [B]. The topmost DEM will be used to calculate waypoint altitudes, however, it is advised to only have one DEM checked at a time when creating a flight plan.

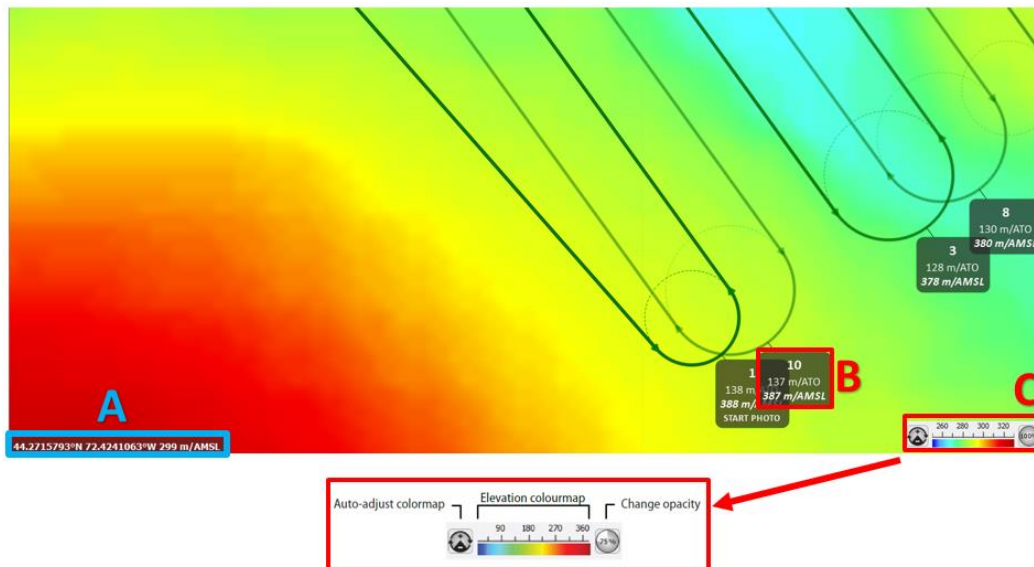


Check the radio button in the “Mission Planning” tab, “Use elevation data to set absolute waypoint altitudes” [A] before uploading waypoints to incorporate the DEM. Make sure to specify what camera will be used for the flight [B].

Note: Waypoint and flight line altitudes, overlap and resolution will vary depending on the camera type (S110 RGB or S110 NIR). It is imperative to create each flight plan knowing which camera will be used for the flight.

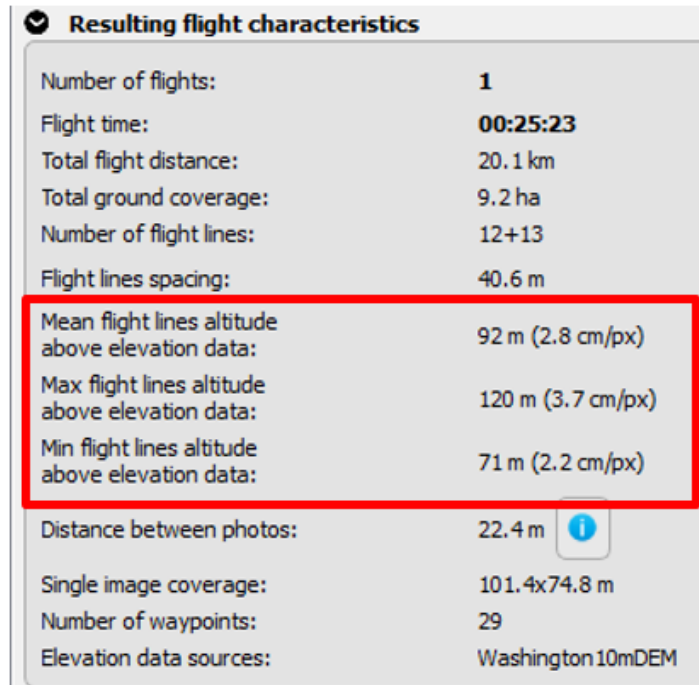


If importing a custom DEM, make sure to cross check it with the SRTM to insure relatively similar results (a difference in altitude is to be expected). This can be done using the altitude measurement at the bottom left corner of the screen [A] while switching between elevation datasets. The altitude of each waypoint will vary when using a DEM [B] and when initially evaluating elevation it is recommended to use 100% opacity [C].




After creating a flight plan, make sure to check that the waypoints won't be above the FAA flight ceiling of 121 meters or below 61 meters as the *eBee* could be too close to trees and other structures. When creating a flight plan, the Mean, Max and Min flight line altitude above elevation data is generated automatically in the "Mission Planning" tab to help stay within this range. It may be necessary to increase the resolution to as high as 2.1 px/cm.

NOTE: The working area ceiling has to be set to above the highest waypoint ATO altitude.



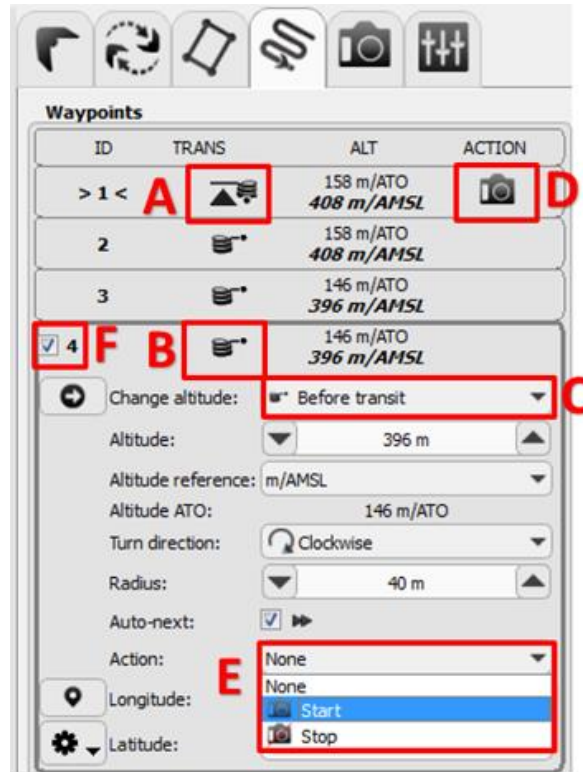
The screenshot shows a panel titled "Resulting flight characteristics" with a list of flight parameters. A red rectangular box highlights the following three rows:

Resulting flight characteristics	
Number of flights:	1
Flight time:	00:25:23
Total flight distance:	20.1 km
Total ground coverage:	9.2 ha
Number of flight lines:	12+13
Flight lines spacing:	40.6 m
Mean flight lines altitude above elevation data:	92 m (2.8 cm/px)
Max flight lines altitude above elevation data:	120 m (3.7 cm/px)
Min flight lines altitude above elevation data:	71 m (2.2 cm/px)
Distance between photos:	22.4 m 
Single image coverage:	101.4x74.8 m
Number of waypoints:	29
Elevation data sources:	Washington 10mDEM

The altitude of the *eBee* will be constant for the duration of a given flight line so it is best to plan the orientation of flight lines parallel to the contours of the terrain. It is helpful to press the "Auto-adjust colormap" button in the lower right corner to see a more detailed color gradient of the terrain.

NOTE: The working area ceiling is measured in m/ATO and needs to be set to above the highest waypoint in the flight plan. This may be above the FAA work ceiling, however, this altitude is from the take-off and does not adjust to the DEM.

Under the mission waypoints tab, the "Change altitude" parameter should be kept at its default settings. The first waypoint will always be "Keep highest" [A], and "Before transit" is highly recommended [B]. More information about the other settings can be found in the manual or by hovering over the settings in the "Change altitude" dropdown box [C]. If there is desired starting waypoint other than the first, uncheck the preceding waypoints and the *eBee* will skip them. The camera icon under the "Action" column [D] will either start the *eBee* taking photos or stop it.



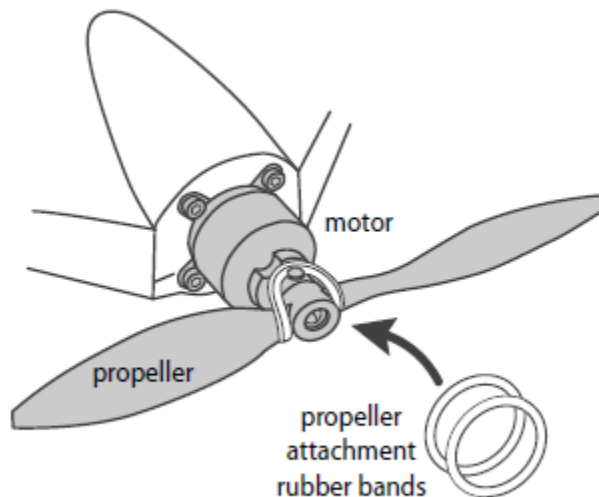
Pre-flight Field Tasks

1. Perform general inspection of eBee

- Check the foam central body and wings for cracks or other damage.
- Verify that the pitot probe is properly attached to the airframe and that the holes in the probe are free of obstructions.
- For the RTK, verify that the RTK antenna is properly attached and in working order.
- Verify that the ground sensor is free of obstructions and that the sensor's lens is clean.
- Verify that the wing struts are not damaged.
- Verify that the engine is clear of obstructions
- Verify that the power cables within the battery compartment are well insulated and not damaged.

2. Install propeller

1. IMPORTANT: the metal ring of the propeller should be on the motor side.
2. Secure the propeller using two attachment rubber bands as illustrated below.
3. Ensure that the propeller is lying flat against the motor mount, and that the rubber bands do not show cracks or other signs of ageing.

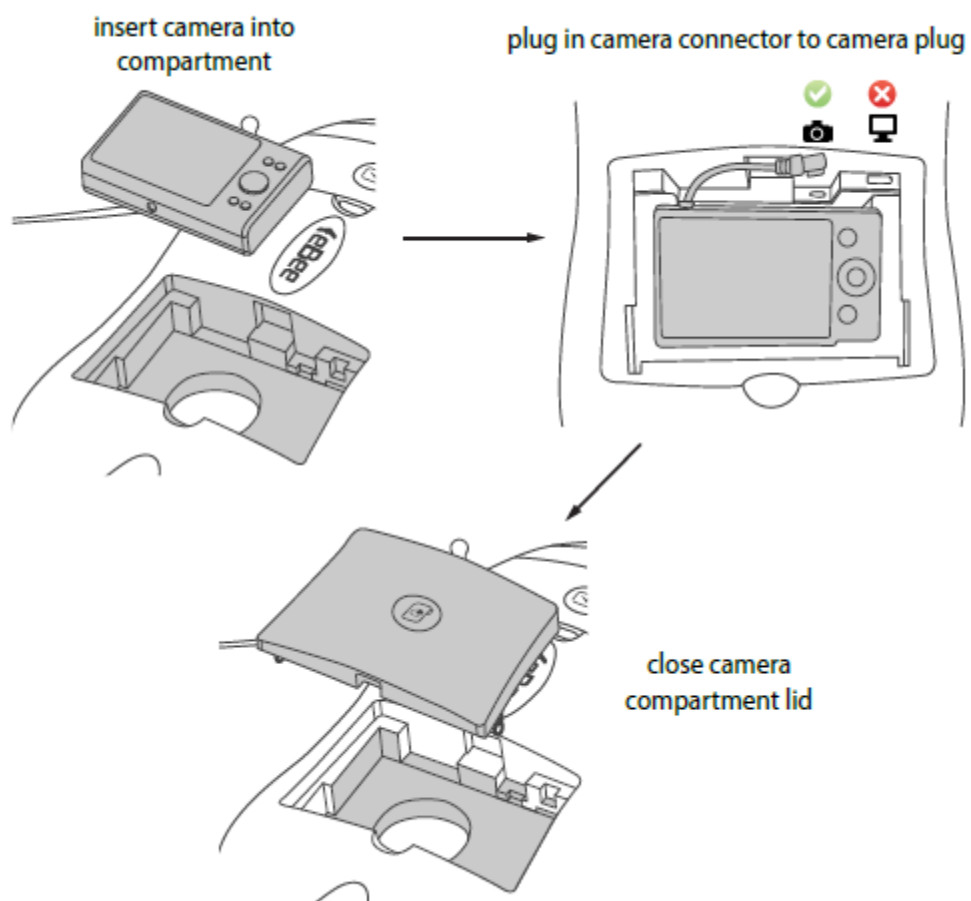


3. Camera check before installation

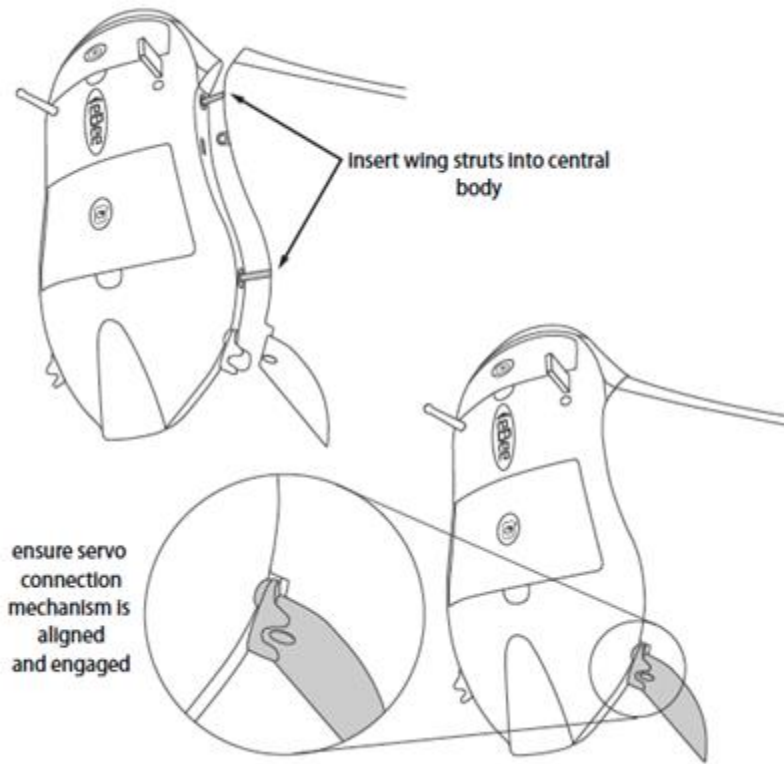
1. Make sure SD cards are empty of data. If not, make sure that data is saved on the computer and the O drive before erasing.
2. Check that the camera's date and time are correct.
3. S110 RGB and NIR are to be set to C (custom) mode. Shutter speed should always be at 1/2000. Factory settings in IXUS are already optimized, but make sure image size is set to L. Factory settings in the WX are already optimized. **NOTE:** The camera check will fail if you have removed the image database from the SD card for the WX camera. If this is the case, when taking a picture an error message will display on the WX screen. To recreate the image database on the SD card, press enter (the button in the center of the camera's control wheel) twice.
4. Install the dial lock (S110).
5. Ensure that the lens is clean.

4. Connect camera

1. Insert battery & SD card (IXUS), Remove battery & insert SD card (S110 NIR, S110 RGB, WX RGB)
2. Remove foam cover for camera cavity
3. Connect camera to the *eBee's* internal port
4. DO NOT TURN ON CAMERA, it will be done automatically during flight
5. **NOTE:** For the WX camera, place the camera into the compartment before putting a battery into the *eBee* or *RTK*
6. Replace foam cover



5. Put the wings together with the body of the *eBee* and ensure that the servo connection mechanism is aligned and engaged (as show below)

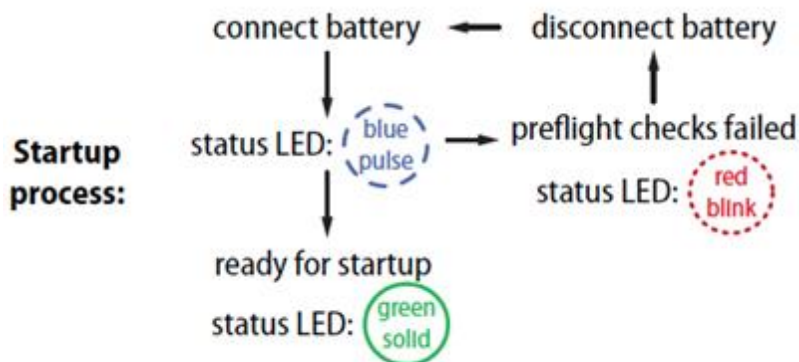


6. Connect the battery (you must hear a “bip”) and close the battery compartment

NOTE: If you are flying the *eBee* with a radio transmitter, install the transmitter into the drone underneath the battery in the battery compartment.

7. Preflight tests

1. Lay *eBee* flat on ground (no more than 10 degree incline), do not move during testing
2. *eBee* will self-check physical functions and acquire GPS signal (refer to step 8)
3. Status of preflight tests will proceed as shown:



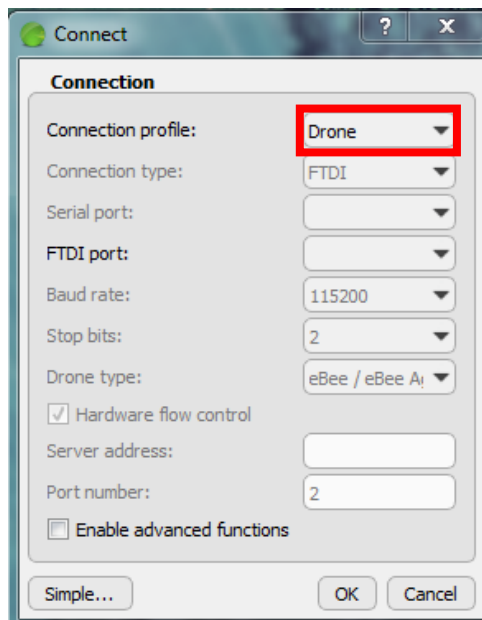
4. For the *RTK*, as soon as the battery is connected the *eBee RTK* will perform an automatic self-check of its sensors and acquire GPS/GLONASS signals. Be sure not to move the drone during these tests. Pre-flight checks may last from a few seconds to several minutes in the case of poor GPS/GLONASS signal reception. As these satellite signals are required for the checks to complete, be sure to place the *eBee RTK* outside with a clear view of the sky.
5. You may already connect the drone to *eMotion* (step 8) before pre-flight checks are complete to get a better idea of the status of the checks.
6. **NOTE:** If there was any problem during the pre-flight checks performed by the drone this will be indicated by a Pre-flight error in *eMotion* as well as by the status LED blinking red.

8. Connect senseFly radio modem to PC via USB

1. Flip power selector toggle switch to USB POWER
2. Ensure 3 red LEDs near antenna light up

9. Launch *eMotion 2* (click on Drone, not on simulator) and select the FTDI port

Note: *eMotion* should automatically select the drone type if a drone is powered on. If more than one drone is powered on (the *eBee RTK* and the *eBee*), select the preferred drone to connect to first. After connecting to the first drone, redo the connection steps with the other selected drone(s) if needed.



10. GPS signal acquisition

Once the GPS position is acquired, an icon of the *eBee* will appear at its location on the map. The *eBee*'s status in *eMotion 2* will be displayed as 'Idle, Ready to take off' and the status LED will be solid green. **NOTE:** The *RTK* has an advanced GNSS antenna, capable of capturing several GNSS signals, which is used for navigation and to increase geo-tagging precision.



11. Load flight plan and upload to UAV

1. Select 'Load flight plan from file...' (Setup Phase tab)
2. Navigate to location of pre-made flight plan
3. Select and load flight plan into *eMotion2*

12. Adjust start waypoint and landing zone/approach (Setup Phase tab)

These locations should be adjusted according to topography and weather conditions. Generally, the start waypoint should be located up-wind from the launch location and the landing approach should be positioned facing the direction of the wind. It is also important to ensure that the landing approach path is clear of obstacles and that the start waypoint is not above the launching position of the drone.

13. Check Flight Parameters

Navigate to Flight Parameters tab and ensure working area radius, flight ceiling, and security actions are correct. If changes are made, select 'Apply.'

14. IMPORTANT: Upload flight plan to UAV (Setup Phase tab)

Select 'Save flight plan as default in drone...' to upload flight plan to *eBee*. A green check mark will appear when successful.

15. UAV is now prepared for launch and to fly the mission. Follow protocol outlined in 'Flight Operations' section of this document.

Flight Operations

Flight Crew:

Prior to or upon arrival at the site, a chain of command should be established and the tasks that are expected of each crew member should be explicitly stated. Vital positions include:

- Flight commander (crew chief) – oversees flight crew and operations. Coordinates between operator and spotters.
- Flight operator – monitor flight from laptop computer. Makes all in-flight changes to flight path, including aborting mission, rolling, fast climb, fast descent (see “Flight Monitoring” section below) or landing and putting UAV into holding pattern if landing zone is not clear
- Spotter(s) – maintain visual line of sight to UAV during flight and relay flight information to commander.
- Launch and Recovery Specialist – ensures safe launch and recovery area. Monitors approach and coordinates with flight operator during landing.
- (Possible) Liaison – Stays with agencies support flight. May be in command post, emergency operations center, or in the field. Coordinates operations with supporting agencies.

Safety:

During all phases of flight operation, all crew members should wear high visibility vests. In areas near road corridors, construction sites, or locations where there may be any indication of potential safety issues, construction helmets are an additional safety requirement. The aircraft must be inspected prior to any launch. This should be checked by two separate people to ensure that the aircraft is properly assembled and that no anomalies appear to be present in flight control surfaces or any other part of the aircraft. All members of the flight crew are responsible for the safety of the flight and at any time may scrub a mission if they believe there is a safety concern. Prior to any flight, weather, physical hazards, and the safety of the crew must be evaluated with the final go/no-go decision made by the flight commander. At a minimum, any flight must have a flight commander, flight operator, and spotter. Complex or large scale flights must have at least one spotter and a launch and recovery specialist. Notices to Airman or NOTAMS must be checked prior to flights and can be accessed using <https://pilotweb.nas.faa.gov/PilotWeb/>. These will provide information regarding safety and any flight restrictions for an area.

Communications:

To ensure consistency in communications, guidelines for use of the handheld radios should be established prior to launch. Due to the requirement for visual line of sight at all times during a UAV flight, crew members may have to be positioned along the flight path and maintain communication by radio. These crew members should establish and verify their positions prior to take-off with the flight commander. A ‘sterile cockpit,’ where all communications should cease except those relevant to flight

operation, should be maintained during take-off and landing procedures. (We should come up with standard call signs. Perhaps flight crew names can be the default)

Launch:

The launch area should be inspected to make sure that it is adequate for launch operations. An area of at least 40' by 40' (terrain dependent) must be clear. The launch specialist should check wind speeds and report conditions to the flight operator to come up with a launch plan. Once the flight operator has loaded the launch into the *eBee*, the flight commander will make a final go/no-go decision. Any team member may abort the launch at any time if they believe an unsafe situation has developed.

To launch the aircraft, hold *eBee* with two hands by front of wings. Shake *eBee* parallel to ground 3x to initiate propeller motion. If the *eBee* is not parallel to the ground the green LED light will turn blue, indicating that it is not prepared to take off. Once activated allow the propeller to reach full speed (up to 5-10 secs). Aiming the *eBee* into the wind, gently propel it forward at a 10° angle from the ground in a lunging motion with extended arms. Release *eBee* to launch. Refer to *eBee* manual or trained crew member for further instruction.

Flight Monitoring:

Flights are to be monitored using the *eMotion 2.4.7* software and at least one in-field spotter visually monitoring the *eBee*. Any notifications of in-flight warnings will be displayed in the software interface. In addition, the *eBee*'s mission or landing can be aborted if necessary or, if the landing zone is not clear, the UAV can be put into a circular holding pattern. The UAV can now use evasive action if necessary with the roll, fast climb and fast descent buttons.



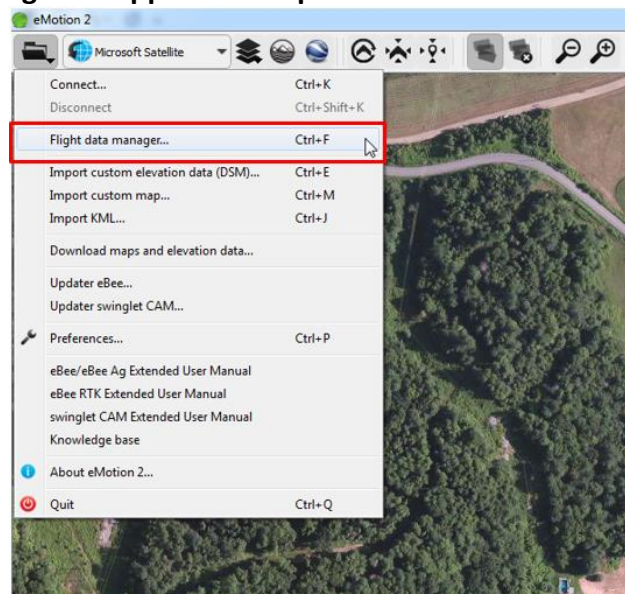
Landing:

The landing zone should be cleared of any obstacles prior to initiation of the landing procedure. The home waypoint radius should be adjusted to greater than its default (30m) if there are high wind speeds. If possible, the landing area should be marked and kept clear throughout the flight so that it's available in an emergency. In most situations it is recommended to program a linear landing pattern. Following the completion of a mission the *eBee* will circle the designated start waypoint twice to determine wind conditions at the landing site. It will then automatically determine the best landing trajectory within the potential landing swath previously specified in the flight plan. During its descent towards the landing zone, the software will provide auditory notifications of the UAV's altitude. The Launch and Recovery Specialist will monitor the landing to ensure the aircraft safely approaches the landing site and to ensure that no hazards enter the landing site during a landing. The mouse should be hovering over the abort landing button once the *eBee* is circling the start waypoint and preparing to land. Landing can be aborted at any time through the *eMotion* software. Following a successful landing, the software can be exited and the *eBee's* battery removed.

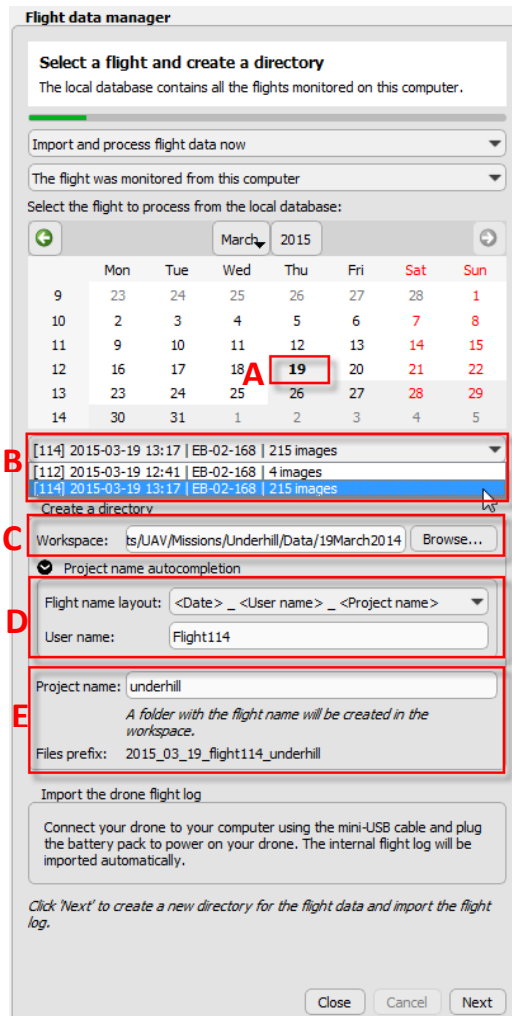
Data Processing

NOTE: Open the UAV Flight Processing Steps sheet under the UAV folder in Google Drive. Indicate which steps have been completed and look for which remain to ensure all processing steps are finished as you go along.

1. Connect *eBee* to computer via USB and connect battery. The UAV will display a white light.
2. Insert camera's SD card into computer (recommended) or connect camera to computer via USB.
3. Open *eMotion 2* software
4. Select 'Flight Data Manager' in upper left dropdown menu



5. Using the calendar choose the date of your flight [A], and select the flight of interest by [flight number], date, and time [B].
 NOTE: If the computer that was used to monitor the mission is not the computer used to process with eMotion, select the ‘... flight was monitored...’ dropdown selection menu and select ‘The flight was monitored from another computer.’ It is important to note that the correct date should still be selected before doing this step in order for the correct date to be used in the project name.
6. In the “Create a directory” section select a work space. Navigate to the mission’s folder in the local drive [C]. Note: if you are working on the Surface tablet, then you must to connect the external (E:) hard drive. If on eBee laptop, “local drive” refers to the D: drive.
7. In the drop-down menu “Flight name layout” below select <Date>_<User name>_<Flight name> [D].
8. For the user name enter “Flight” and its flight number [D].
9. For project name enter the location of the flight in lowercase. eMotion 2 will now format the final name according to the chosen layout and the information you previously entered [E]. NOTE: If it is an RTK flight, the naming convention changes to ‘RTK_[location].’ For convention and location specifics see “Data Management” on pages 8 and 9.
10. Select ‘Next’



11. UAV flight log (.bbx file extension) will be imported automatically. Accept these defaults and select 'Next'. NOTE: if you are using a different computer to process with eMotion than the one used to monitor the flight, the drone log location will be blank and you will need to manually select the location of the flight log.

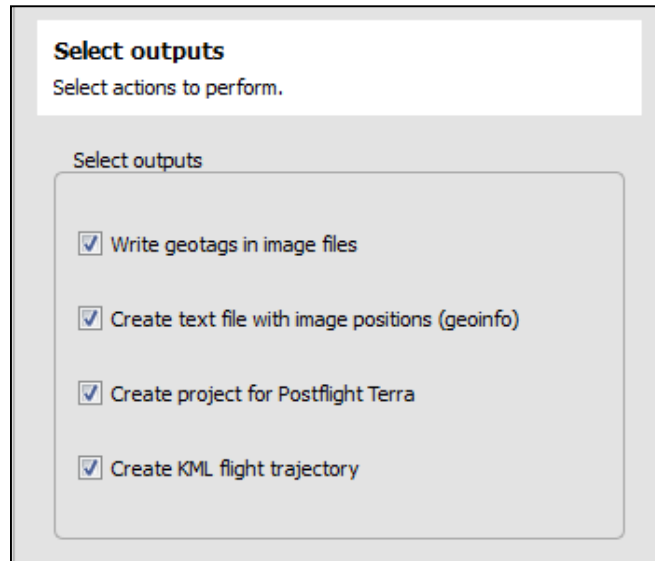
12. Browse to the camera's SD card or temporary folder containing the copied images. Select 'Next'.
13. If NIR camera was used, eMotion will recommend that you import images in RAW format. In such case, import as RAW and they can be converted to JPEG afterwards. If not recommended to import RAW, import as JPEG.

14. eMotion 2 will attempt to match images to the eBee flight plan. If image matching is successful, select 'Next' to copy images to project directory.

Number of geotags found:	245
Number of potential images found:	343
Images matched:	100%
Average matching offset:	0.24 s

Image matching is successful.

15. Select the following outputs and select 'Next' to create the project files



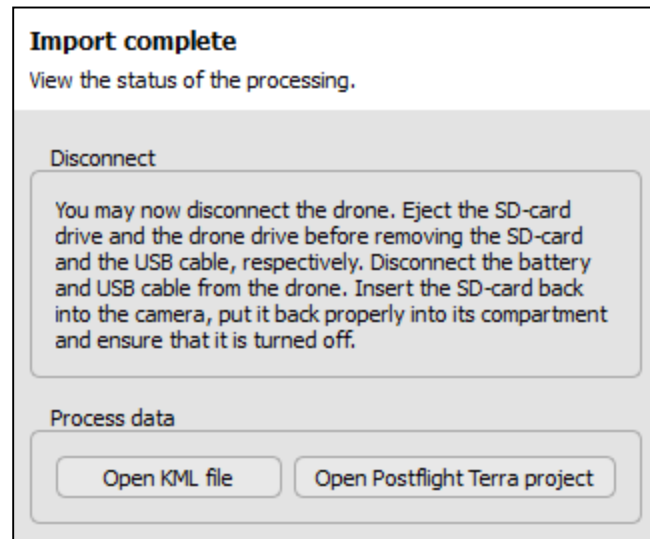
Select outputs
Select actions to perform.

Select outputs

- Write geotags in image files
- Create text file with image positions (geoinfo)
- Create project for Postflight Terra
- Create KML flight trajectory

16. The following dialog will display when the project file has been created. The flight plan and individual images can be viewed in Google Earth by selecting 'Open KML file.'

17. Copy the recently created flight folder and paste into O: drive. Postflight Terra 3D data best processed locally on a desktop computer.



Import complete
View the status of the processing.

Disconnect

You may now disconnect the drone. Eject the SD-card drive and the drone drive before removing the SD-card and the USB cable, respectively. Disconnect the battery and USB cable from the drone. Insert the SD-card back into the camera, put it back properly into its compartment and ensure that it is turned off.

Process data

18. Open Post-Flight Terra 3D. Select New Project.

19. Browse to the parent folder that you wish the mosaic to be placed in [A]. Once selected, name the mosaic with the “dayMonthyear_projectsitename_mosaic” naming convention [B].

New Project

This wizard creates a new project.
Select a name, a directory location, a project type and a processing type for your project.

B

Name:

Create In:

Use As Default Project Location **A**

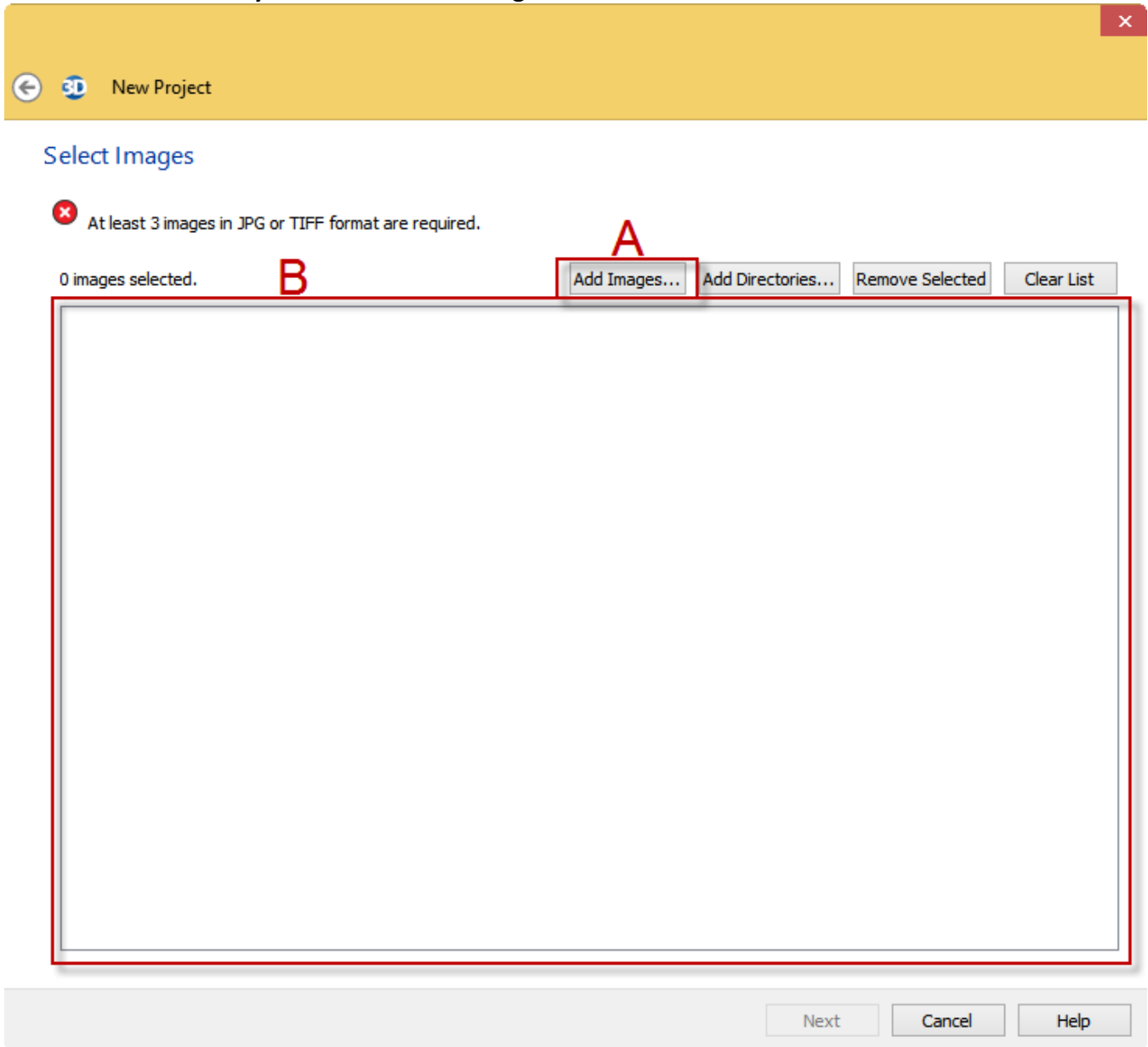
Project Type

New Project
 Project Merged from Existing Projects

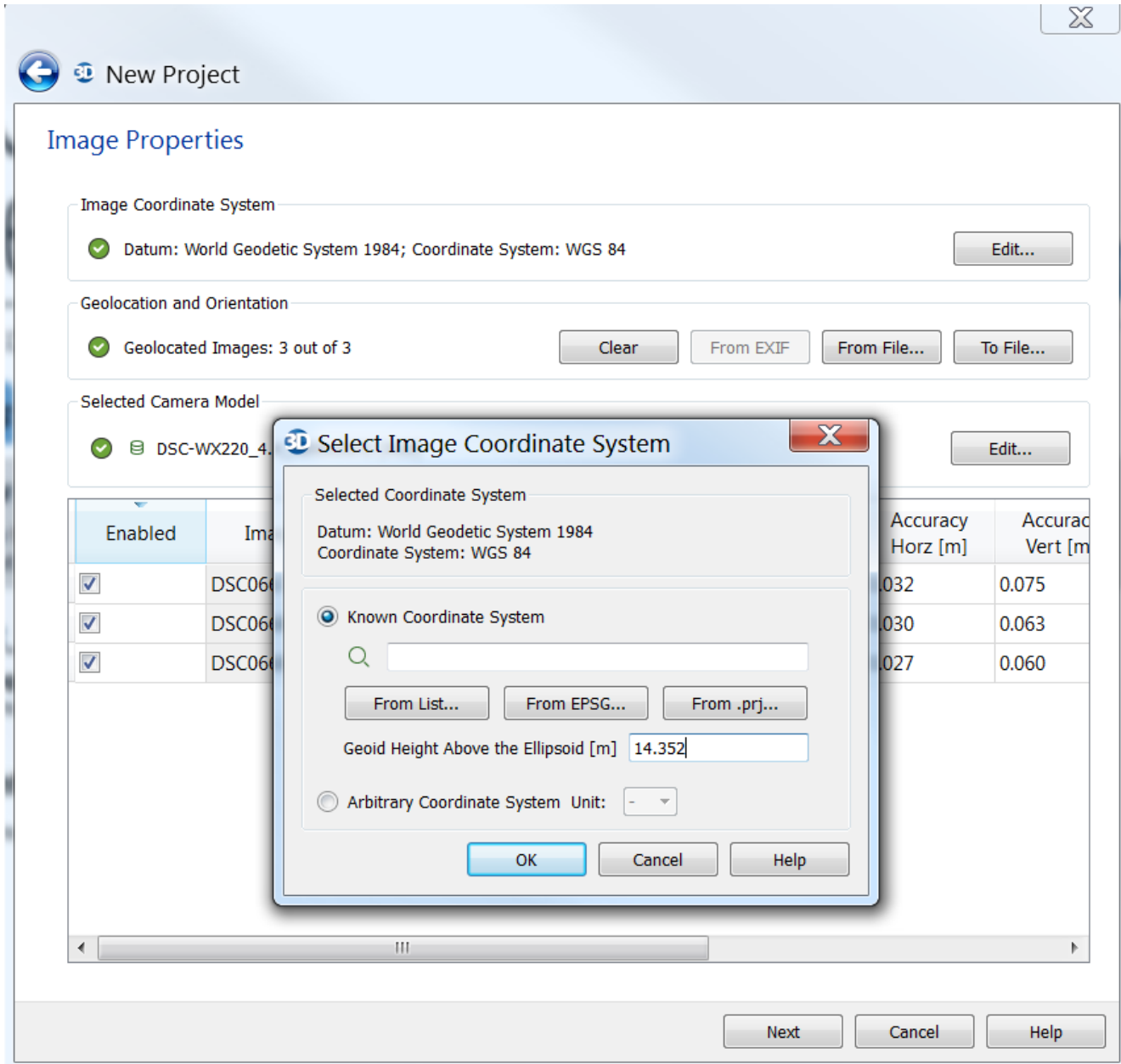
Processing Type

Aerial Nadir (Generate point cloud, DSM, and orthomosaic.)
 Alternative Processing Mode
(For images with low or complex texture and very accurate image geolocation.)
 Aerial Oblique or Terrestrial (Generate point cloud only.)

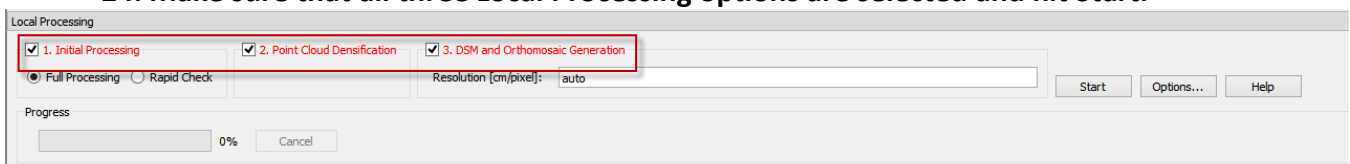
20. From the Select Images dialog box, select the Add Images button [A]. Browse to the image folder location that was created through *eMotion*. Select all images and hit open to add them to the Image Selection display [B]. Repeat this step until all the images from all the flights that need to be combined are selected. Then hit Next.
21. In the Image Properties window, make sure that the Image Coordinate System, the Geolocation and Orientation, and the Selected Camera Model are all properly selected, indicated by a checkmark inside a green circle.




22. Under the “Select Image Coordinate System” window enter the Geoid Height Above the Ellipsoid. To find this number use this website: <http://geographiclib.sourceforge.net/cgi-bin/GeoidEval>
23. After calculating the Geoid Height Above the Ellipsoid, divide that number in half, reverse the sign and enter it into the space provided, hit OK. Then hit Next and Finish.



24. Make sure that all three Local Processing options are selected and hit Start.



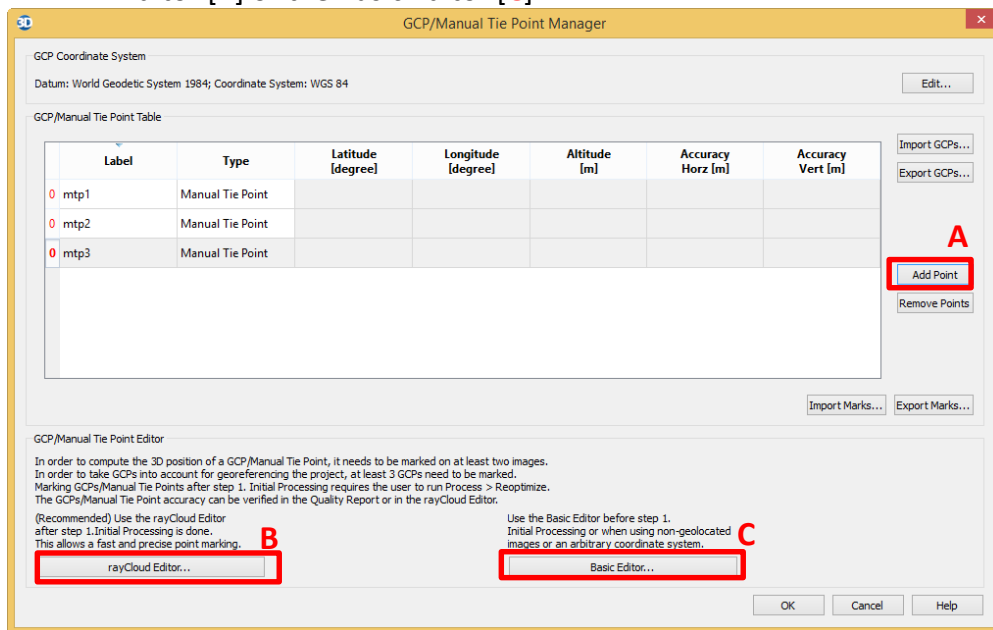
25. If Ground Control Points (GCPs) were utilized in the mission, select the  toolbar icon to open the GCP Editor. If GCP's were not used, skip to step 20.

1. Specify GCP coordinate system. Click the “Edit” button at the top of the GCP / Manual Tie Point Manager window. Generally, the default datum is WGS84. You are also able specify the coordinate system, such as which UTM Zone within this datum.
2. To process GCPs, you need their latitude, longitude in degrees minutes seconds, and their altitude in meters. You can add this information in two different ways:
 - i. Manually select the GCPs in georeferenced imagery
 - ii. Import a file with each GCP and its coordinates and then edit (recommended)

The second option is much easier, faster, and more accurate.

Option i: Manually add GCPs via selection of images

- A. First, in the GCP / Manual Tie Point Manager, add the amount of GCPs to the table by clicking “Add point” [A]
- B. You can select the location of the GCPs in images using either the rayCloud Editor [B] or the Basic Editor [C]



Option ii: Importing GCPs. You can attain these values in either the field with a GPS, or on ArcMap using an accurate DEM to find Z coordinates.

- A. ‘Import GCPs’ and navigate to a text file with the following structure:
[GCP#],[X coordinates],[Y coordinates],[Z coordinates]

For example:

```
GCP1, 43.568841, -72.972022, 174.781
GCP2, 43.569677, -72.971815, 175.796
GCP3, 43.569198, -72.969412, 174.951
GCP4, 43.568567, -72.974274, 172.098
GCP5, 43.569342, -72.979195, 165.713
GCP6, 43.570728, -72.980851, 163.793
GCP7, 43.570599, -72.983179, 162.915
```

- B. Ensure that you select “Longitude, Latitude, Altitude” is selected if you formatted your GCP coordinates in the text file in that way (shown above).
- C. Click “OK” and the GCPs and their coordinates will populate the table. Now you can start editing in the rayCloud editor.

NOTE: This method is preferred because you can locate the GCPs much more easily in the rayCloud, making it faster and easier. It also produces better output, especially in its elevation values. This is because the *eBee* does not collect very accurate DSM values, so it's best to incorporate known and accurate elevation values for processing.


Continue to step 3.

3. Locate and edit GCPs in the rayCloud editor. (ADD LABELLED SCREEN SHOT TO THIS PLEASE!)

A. When rayCloud is open you see your tie points and the calibrated images hovering above.

B. To find a GCP, click your desired GCP on the table of contents at the left. In the rayCloud zoom into the area where your GCP is located, and click a tie point. Lines will draw from that point to the images that capture that point's location. Note that this it is much easier to find a GCP's location if you imported the coordinates text file, as it is indicated by 3D cross hairs in the rayCloud.

C. Geotagged images will show on the right side. Find the GCP in two of the images and then click “Apply”. Continue the process until you've located the GCP in all images. Repeat this step for all GCPs and click “Apply” when complete.

D. When finished locating GCPs, click the “Reoptimize” button .

E. After the reoptimization process has finished, generate a new quality report and see if the GCPs processed correctly.

26. Before opening raster imagery, it is suggested that pyramids and statistics are created in ERDAS Imagine following these steps:

1. Open Imagine.
2. Under manage data tab, select pyramids and statistics.
3. Navigate locally to the tiff file and select OK, beginning the process.
4. Wait for the process to finish and then close the window.
5. Open the tiff in Arcmap to check that the tiff opens without having to create pyramids.
6. Look through the imagery to see if there are errors in the imagery.



27. After processing has completed, the orthomosaic can be edited with the MosaicEditor. This process is ideal for correcting parts of imagery that might have noise or do not realistically represent the feature (i.e. roads and bridges appearing unclear or wavy).

1. Select a tile that appears to have an error [A]
2. On the right side of the screen, under Available Images, select an image that provides a clearer display of the area [B]. You can also manipulate the connecting vertices until images align and or appear correct.
3. When imagery is fixed, click the Blend Mosaic radio button [C]
4. An “apply” window will appear on the right. Confirm the changes by clicking the “Blend Mosaic” button. Give the mosaic time to reprocess your edits.

