Development of a GIS Based Imagery Database for Groundwater Recharge Areas and Key Reaches of Streams on Guam

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ABSTRACT

Proper management of a region's water resources requires that water managers and water resources researchers have accurate baseline information on the geomorphological and ecological health of surface water streams in a region. It is also vital to have a detailed baseline knowledge of potential pollution sources in groundwater recharge areas. Along with this baseline information, there is also a need for periodic sampling of water quality indicators to identify changes in the environmental health of streams and groundwater recharge areas. Studies such as those for surface and ground water supplies, depend on this kind of long-term variable information to develop the best management practices for a region's water resources.

In the past the only means of visual monitoring of stream and groundwater recharge area health was either with direct on-ground monitoring or the use of high-altitude satellite imagery or LIDAR (Light Imaging, Detection, and Ranging) data. This imagery and data were typically accurate to less than 0.5-meter resolution. Because of the expense of data gathering, these resources were not available at intervals that could be used for the continued monitoring of the environmental health of Guam's streams and recharge areas.

Recent advances in commercially available sUAS (Small Unmanned Aerial Systems) technology have made lower cost highly accurate, sub- meter resolution aerial imagery available. Commercial sUAS drones fly at elevations less than 400 ft. and can gather data used for the development of georeferenced imagery on these low elevation flights. The photographs can be used as detailed high-resolution individual photos of streams or groundwater recharge areas or can be composited into highly accurate georeferenced photos of various areas of study. Photogrammetric procedures are also available to remove foliage cover from the data to develop high resolution composite ground surface (bare earth) digital elevation models of areas of interest.

The first phase of this project involved evaluating and choosing which sUAS drones and cameras would be most appropriate for the stream and groundwater recharge study areas on Guam. The second phase of the project involved evaluating available photo mission pre-planning software. The pre-planning software helps to deal with issues such as Federal Aviation Agency (FAA) no-fly zones, military restrictions and site accessibility and land ownership. The final phase of the project involved evaluating the available imagery analysis software. Commercial software such as LiMapper, DroneDeploy, Drone2Map, and Microsoft Image Composite Editor (ICE) were explored as a means of developing georeferenced imagery and digital elevation models of the areas of interest. The detailed georeferenced aerial data provide baseline knowledge of the location, size, and potential pollution sources in groundwater recharge areas in North Guam. In South Guam, we can accurately plot stream cross sections, determine erosion potential and possible sediment loading, and other sources of environmental contamination.

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INTRODUCTION

Proper management of a region's water resources requires that water managers and water resources researchers have accurate baseline information on the geomorphological and ecological health of surface water streams in a region. It is also vital to have a detailed baseline knowledge of potential pollution sources in groundwater recharge areas. Along with this baseline information, there is also a need for periodic sampling of water quality indicators to identify changes in the environmental health of streams and groundwater recharge areas. Studies such as those for surface and ground water supplies, depend on this kind of long-term variable information to develop the best management practices for a region's water resources.

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STUDY AREA

This project developed strategies for carrying out sUAS missions over both the surface water resources of Southern Guam and groundwater recharge areas of Northern Guam. As shown in Figure 1, the Island of Guam is located in the Western Pacific approximately 2,600 miles southeast of Japan. Guam is a territory of the United States, and as of 2017, the population of the island was approximately 164,000. The land area of the island is approximately 212 square miles. Average annual rainfall on the island ranges from 80 to 120 inches per year. The topography of the South Guam study area is mountainous intersected with many streams. The more detailed map of Southern Guam in Figure 2 shows the many streams located on the south half of the island. Figure 3 shows the North Guam study area. The area shown lies over the Northern Guam aquifer. The sinkholes shown on the map are topographic sinks that serve as catchments for surface recharge that is quickly routed directly to the aquifer.

Figure 1. Guam study area and location map.

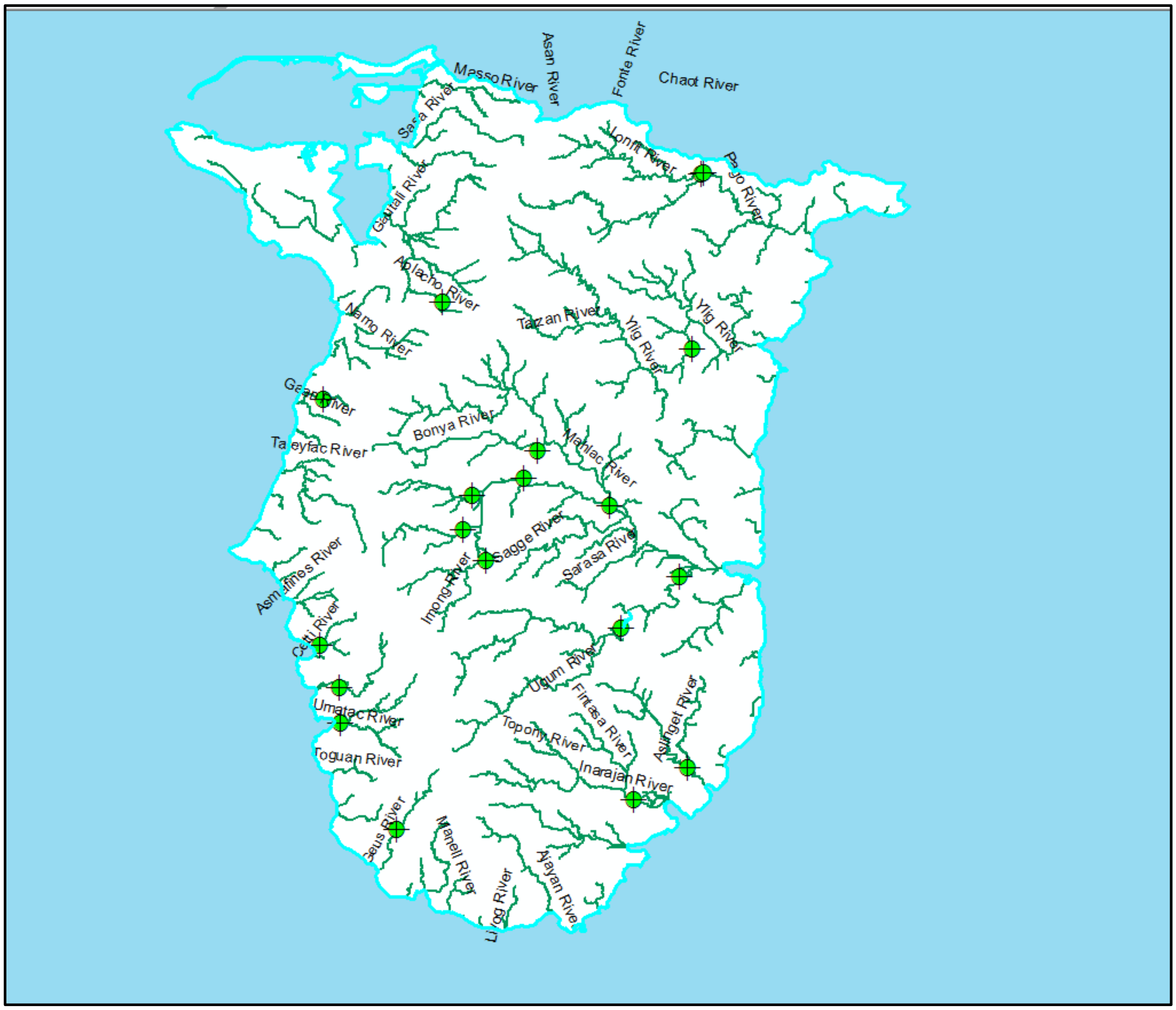


Figure 2. Potential stream study sites in South Guam

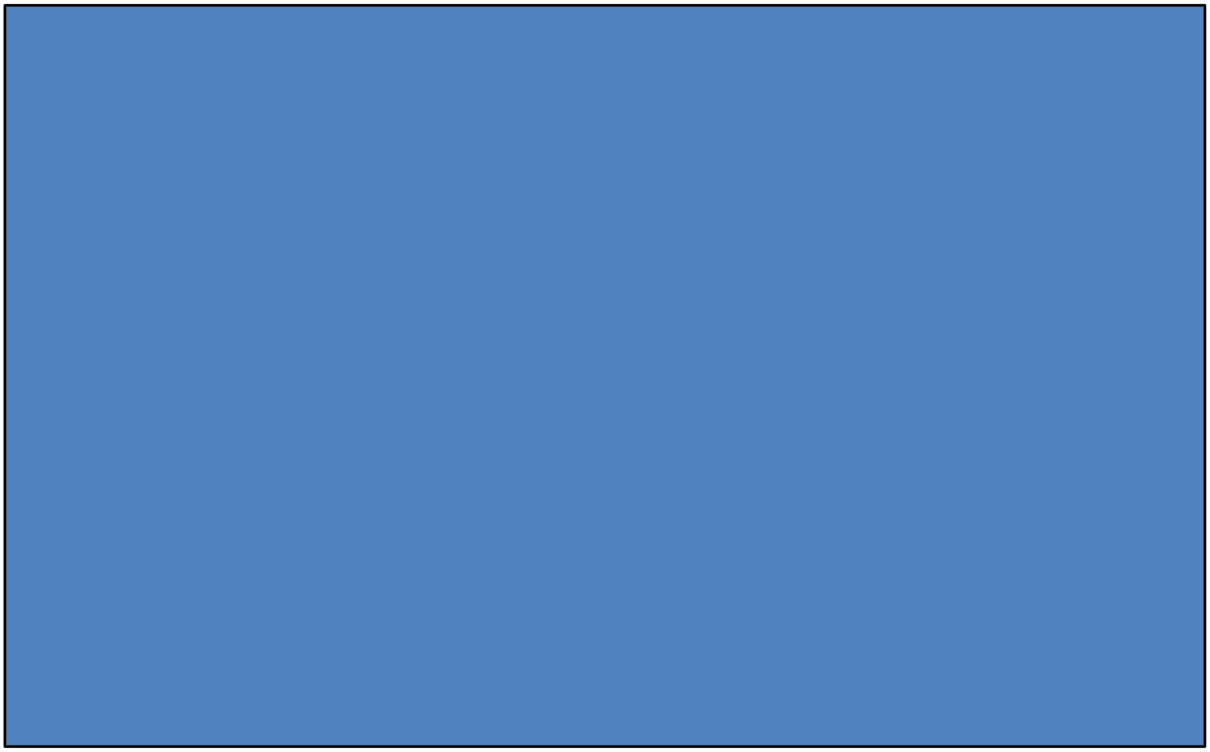


Figure 3. Potential study sites in Northern Guam showing major sink holes.

OBJECTIVES

This project developed strategies for carrying out sUAS missions over both the surface water resources of Southern Guam and groundwater recharge areas of Northern Guam. The sUAS cameras used gathered detailed orthophoto data that was processed into mosaiced digital orthographic models and digital elevations models. This data will be maintained in WERI's Geographical Information System (GIS) data base.

The specific objectives of the research were to:

1. Evaluate and choose which sUAS aircraft and sensors would be most appropriate for the stream and groundwater recharge study areas on Guam.
2. Test and evaluate various available software products capable of pre-planning aerial data gathering mission.
3. Test and evaluate various available software products capable of processing gathered digital images into georeferenced composited imagery and digital elevation models capable of being used by and stored in WERI's Geographic Information system.

METHODS AND PROCEDURES

This project was divided into three phases. Each of these phases is described below.

PHASE I: EVALUATION OF SMALL UNMANNED AIRCRAFT SYSTEMS AVAILABLE

The first phase of this project involved evaluating and choosing which sUAS aircraft, cameras and planning and analysis software would be most appropriate for the stream and groundwater recharge study areas on Guam. Figure 4 shows the sUAS aircraft that were evaluated. Parameters such as flight time, flight speed, load carrying capacity, stability of the sensor platform and software and hardware compatibility issues were evaluated. Figure 5 shows the takeoff of the DJI Inspire 2 on a photo gathering mission in South Guam.

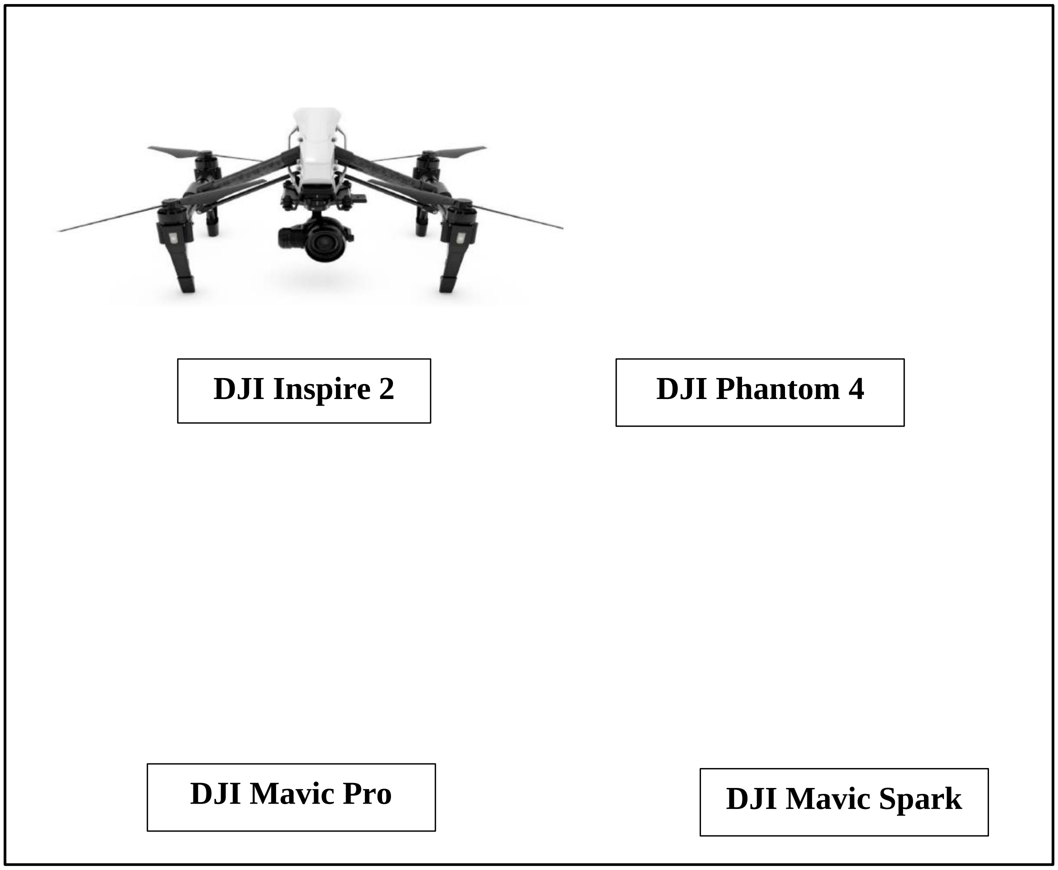


Figure 4. Unmanned aerial systems aircraft that were evaluated for use in the project

Figure 5 Inspire 2 on takeoff for photo mission in North Guam

Each of the aircraft tested has its own set of strengths and weakness. Table 1 below shows a comparison of the aircraft tested. The Inspire 2 was the most expensive of the aircraft tested. Its speed and stability characteristics were the best of all drones tested. The Inspire camera mount is such that it is very easy to interchange various cameras for upgrading or adding future capabilities without having to buy a new aircraft. On the downside the Inspire 2 is big and heavy. It is marginal when one is planning a mission that requires transporting the aircraft system (plane, controller and accessories) to a location not accessible by motor vehicle. The Mavic pro had good flight times and great picture quality. Its real advantage is in its small size and portability. The airframe folds into a compact shape which can be easily backpacked to remote sites. It is somewhat less stable than the larger aircraft tested. This limits orthophoto missions in windy conditions. The Spark is simply too small for good orthophoto gathering. On the other hand, because of its small lightweight size it is great to bring along for "selfie" type photos of field operations. The Phantom 4 Pro sets between the Inspire 2 and Mavic Pro in stability. Its high-resolution (20 mega pixel) camera takes stunning orthophoto shots considering the price of the aircraft and camera system.

All the aircraft tested take excellent still pictures. The resolution and quality are such that the images can be easily composited into excellent images with 1 inch per pixel resolution.

AIRCRAFT	CAMERA/ LENS SENSOR (mega pixel resolution)	FLIGHT TIME (minutes)	STABILITY	PORTABILITY
Inspire 2	20.8 mp /Interchangeable camera	30	Very stable	Hard to transport in field.
MAVIC PRO	12 mp	27	stable	Easy to transport in field
SPARK	12 mp	16	Wind effects flight stability	Very easy to transport can carry in pocket
PHANTOM 4 PRO	20 mp (1in. sensor)	30	stable	Back packable in field

- See the DJI web site for more information on these aircraft. (https://www.dji.com/

Table 1. Comparison of sUAS Aircraft Tested

PHASE II EVALUATION OF FLIGHT PLANNING SOFTWARE

Two applications were evaluated for use in planning and carrying out optimal aerial imagery acquisition. These two were DroneDeploy (https://www.dronedeploy.com/) and Maps Made Easy Drone Map (https://www.mapsmadeeasy.com/). The first step in applying these applications is to input the flight parameters for the mission to be flown. These include things such as aerial extent and altitude of flight. The flight altitude determines the resolution of the raw orthophotos. A third important parameter is photo overlap. Both front and side overlap are input. These parameters determine the accuracy of the triangulation that is used to produce the composite imagery. A sample screen shot from the DroneDeploy application applied to the planning of a composite photo mission on the Tongan River near Umatac, Guam is shown in Figure 6. We used the second application, Maps Made Easy Drone Map to plan missions where we wanted to fly a single flight line while taking photos. This was exclusively used for simple maps of steam segments. A screen shot from a planning exercise used on the Toguan River is shown in Figure 7.

Figure 6. DroneDeploy application screen for planning a composite photo mission for the Toguan River near Umatac, Guam

Figure 7. Maps Made Easy Drone Map screen for planning a single line photo mission for the Tongan River near Umatac, Guam

Another iPad application called UAV Forecast was used to evaluate weather conditions and Global Navigation Satellite System (GNSS) satellite availability for the proposed time of the UAV orthophoto missions. GNSS satellites include those operated by the U.S. (GPS), Russia (GLONASS), Japan (QZSS), China (BeiDou), European Union (Galileo), India (IRNSS)

The application provides weather conditions such as average and gusting wind speeds, likelihood of precipitation and visibility. GNSS satellite information such as number of visible satellites, likely signal strength of the satellites and number of satellites likely to be locked. The application also proves information on any flight restrictions in the proposed flight area. All these parameters are useful in determining ahead of time whether or not it is worthwhile to go to the field to fly an orthophoto mission. Screen shots from the application are shown in Figure 8.

Figure 8. Sample screen shots from UAV Forecast application

The Island of Guam has numerous airports, military installations and special designation areas identified by federal and local governments. Each of these areas present a different set of challenges when flying sUAS missions. Luckily there are several applications available that help identify where restricted sUAS flying areas are located. In some cases, the applications can help with obtaining Federal Aviation Agency (FAA) permission to fly in the restricted areas. Figure 9 shows the web based AirMap application (https://app.airmap.io/geo?13.449779,144.730049,12.335411z) with Guam Airspace Part 107 restrictions. The restrictions for the area outlined in yellow are shown in the center message box. In most cases, at U.S. airports, you can immediately apply for FAA Part 107 automatic authorization to fly in that airspace. A Part 107 mission must be flown under the supervision of a FAA certified Pilot in Command. Currently, Auto Authorization for missions is not available on Guam. Hopefully, Auto Authorization will be available for Guam airspace soon. Figure 10 shows details of the airspace over North Guam. The area shown as “no restriction” is the only area where sUAS mission can be flown without previous FAA permission at this time. This is the only area overlying the Northern Guam aquifer available for investigation by sUAS missions. Figure 11 shows the AirMap application showing details of restricted airspace for South Guam. As with the North, much of the area south of the International airport is still waiting for Automatic Authorization. A large portion of the center of South Guam is restricted do to the military restrictions. Several of the watershed areas in South Guam are open to unrestricted flights. When Automatic Authorization becomes available a large portion of both South and North Guam will be opened to part 107 flight authorization.

Figure 9. AirMap application showing Part 107 restricted airspace for Guam

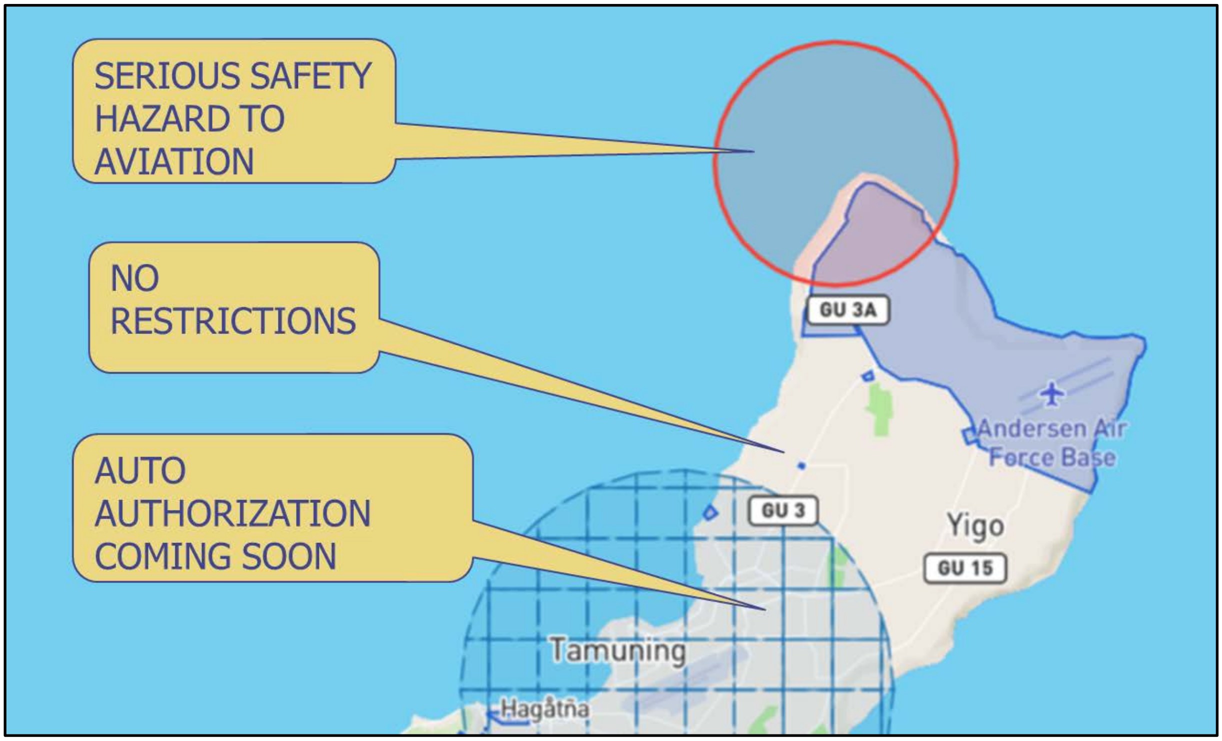


Figure 10. AirMap Application showing details of Part 107 restricted airspace for North Guam

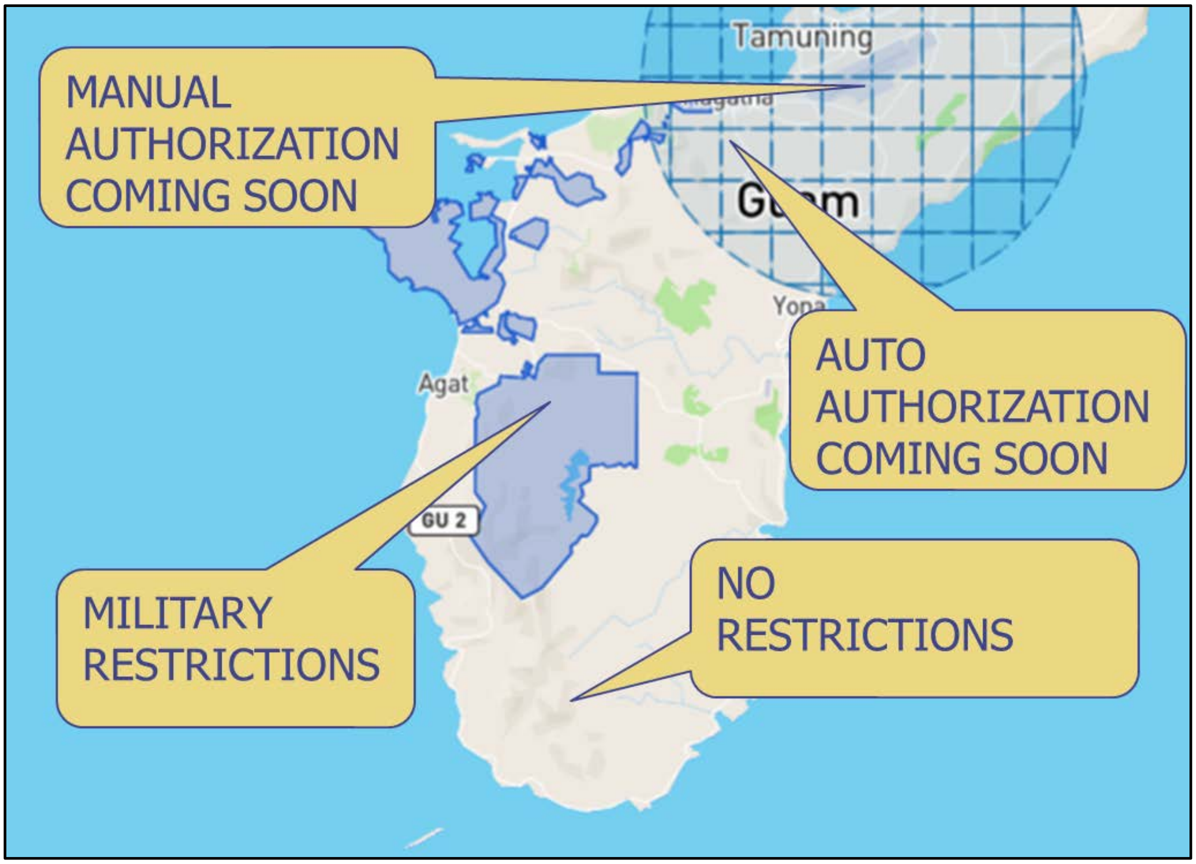


Figure 11. AirMap application showing details of Part 107 restricted airspace for South Guam

Missions flown not under the supervision of a FAA certified Pilot in Command are not available for Part 107 rules and a different set of flight restrictions are applied. These flights are referred to as “Fun Flying”. Figure 12 shows the Fun Fly restricted areas for the entire island. Figures 13 and 14 provide close-up views of North and South Guam respectively. The shaded areas show the areas where flights are restricted. There is almost no unrestricted “Fun fly” flight airspace in North Guam. In South Guam the Part 107 and Fun Fly restrictions are nearly the same. The exception is just South of the International airport where the Fun Fly restricted areas are slightly larger.

In any of the areas where FAA Authorization is required without Automatic Authorization the application procedure is quite arduous. This procedure requires application far in advance of when the mission is to be flown.

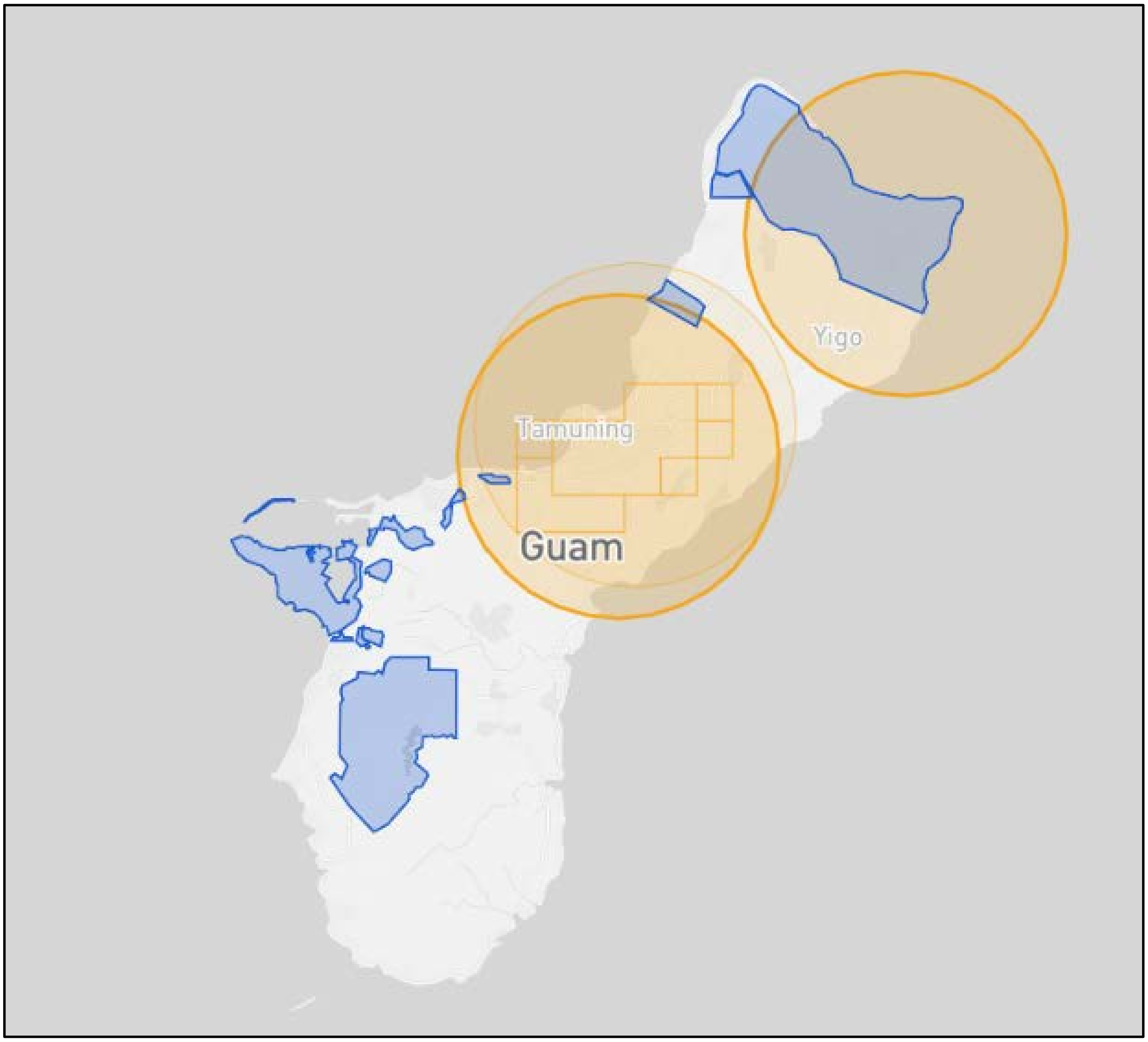


Figure 12. Fun Fly restricted areas designated in AirMap application

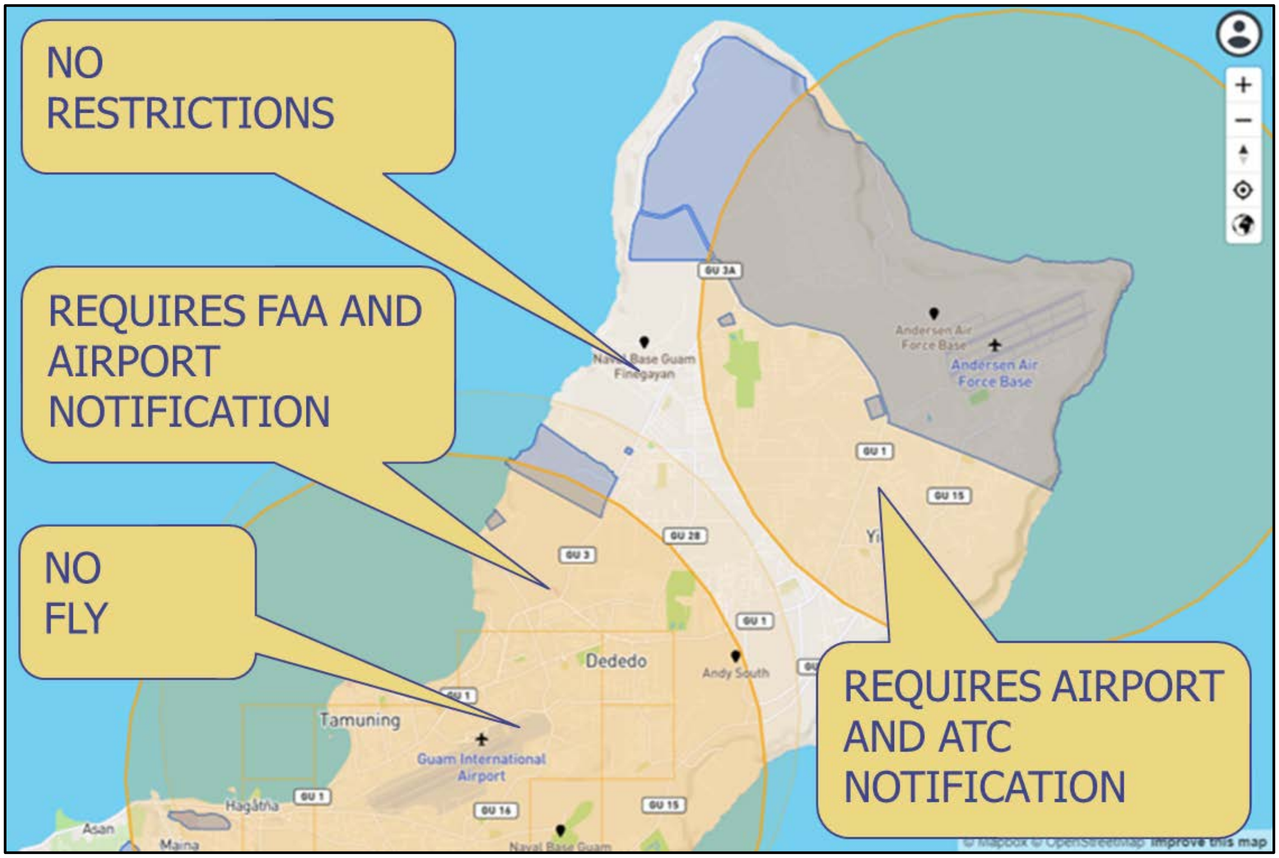


Figure 13. Fun Fly restricted areas in North Guam as designated in AirMap application

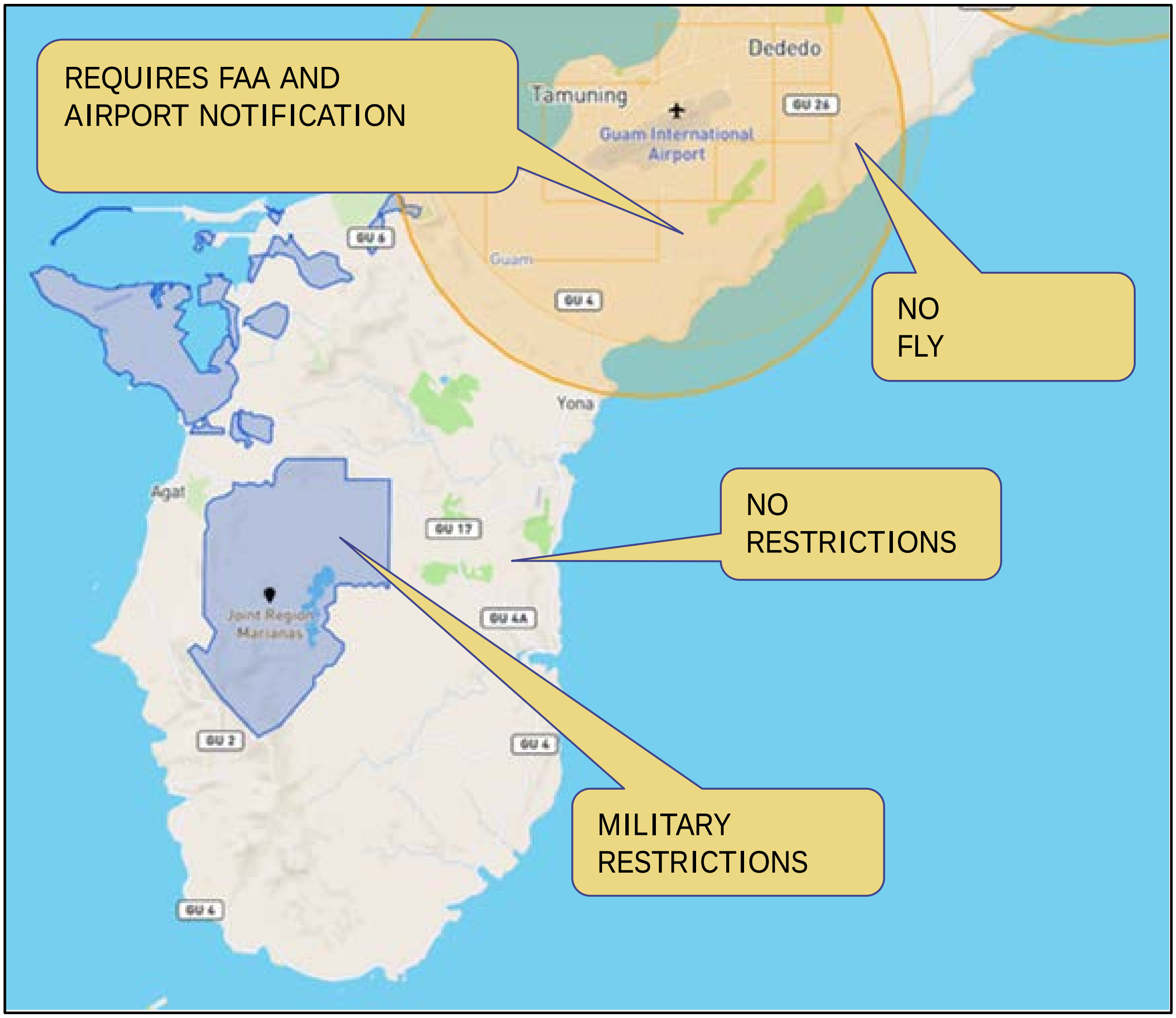


Figure 14. Fun Fly areas in South Guam as designated in AirMap application

PHASE III EVALUATION OF IMAGERY ANALYSIS SOFTWARE

OVERVIEW OF ANALYSIS PROGRAMS

Four different software packages were evaluated for the development of composited images and digital elevation models from the orthophotos that were gathered on our sUAS photo missions. These packages included LiMapper (https://greenvalleyintl.com/software/limapper/), Drone2Map (https://www.esri.com/en-us/arcgis/products/drone2map/overview), DroneDeploy (https://www.dronedeploy.com/), and Microsoft Image Composite Editor (ICE) (https://www.microsoft.com/en-us/research/product/computational-photography-applications/image-composite-editor/). The processing steps are similar for all the software packages.

We will use the LiMapper application to illustrate the processing steps. The first step, shown in Figure 15, involves choosing which previously gathered images will be used in the composite. The next step, which is shown in Figure 16, involves setting up how the images will be blended to form the composite. Information will be provided on how the photos will be aligned and how the Digital Orthographic Model and Digital Elevation Models will be developed. Figure 17 shows the input parameters for the photo alignment procedure. Figure 18 shows the parameters that are input for the development of the Digital Elevation Models. LiMapper, DroneDeploy, and Drone2Map have a means to develop a digital elevation model of the study area with vegetation and building features removed. The screen shown in Figure 18 shows the parameters for the coordinate system and resolution of the resulting elevation models. These will be determined by what coordinate systems are locally used and the resolution required for the studies being made. Higher resolutions provide more details but require larger file sizes. and longer processing times. The Digital Elevation Model stripped of buildings and vegetation is sometimes referred to as a bare earth digital elevation model. LiMapper calls the bare earth model a DEM.

There is a similar setup procedure for the development of the composited image called a Digital Orthographic Model that will be produced. Figure 19 shows the resulting orthographic model developed for the Toguan River near Umatac, Guam. Details of this orthographic model will be discussed later in the report. Figure 20 shows the Digital Surface Model of the Toguan River Study area. This model includes all ground features. Figure 21 shows the Bare earth model where vegetation and building features have been removed. Comparisons of these types of elevation models will be provided later in this report.

Figure 15. LiMapper setup screen for choosing images Toguan River near Umatac, Guam

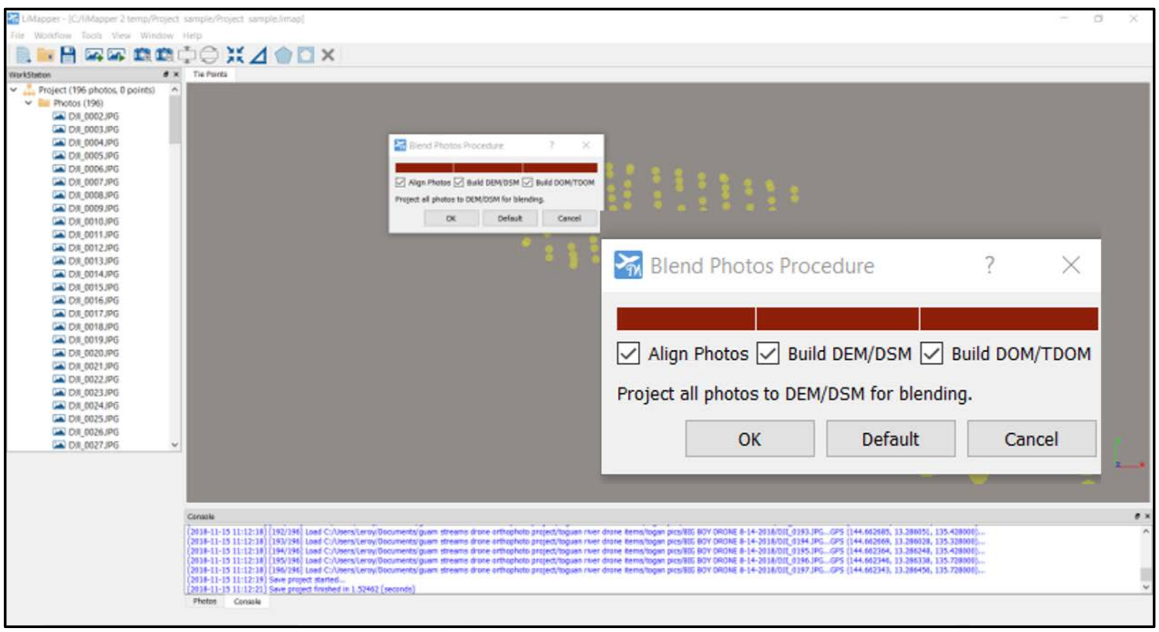


Figure 16. LiMapper Blend Photos setup procedure

Figure 17. LiMapper Blend Photos setup

Figure 18. LiMapper DEM/DSM setup procedure

Figure 19. LiMapper resulting orthographic model of Toguan River near Umatac, Guam

Figure 20. LiMapper resulting Digital Surface Model (DSM) of Toguan River near Umatac, Guam

Figure 21. LiMapper resulting Digital Elevation Model (DEM) of Toguan River near Umatac, Guam

Next, we will take a tour of the remaining compositing software packages that were evaluated. We will begin with the Drone2Map Application. Figure 22 shows the basic setup Screen. Project name and file structures are input on this screen. The source imagery is also selected on this screen. Figure 23 shows the location of the flight path and image locations for the selected drone imagery. Figure 24 shows the processing options input area. This is where the parameters are input for the composited orthographic model, Digital Surface Model and the bare earth elevation model called a Digital Terrain Model (DTM) in this software. Figure 25 shows a partial view of the Orthographic Model of the Toguan River near Umatac, Guam developed by the Drone2Map software. Figure 26 shows a partial view of the Drone2Map Digital Surface Model (DSM) of the Toguan River near Umatac, Guam. This model includes details of all surface features. Note the building and vehicles shown on the DSM. Figure 27 shows a partial view of the Drone2Map Digital Terrain Model (DTM) of the Toguan River near Umatac, Guam. The DTM has surface features stripped away to create a bare earth elevation model. By Comparing Figures 26 and 27 one can see how the software strips away the surface features. The vehicles and building shown in the DSM are missing from the DTM.

Figure 22. Drone2Map setup screen Toguan River near Umatac, Guam

Figure 23. Drone2Map photo locations Toguan River near Umatac, Guam

Figure 24. Drone2Map processing options Toguan River near Umatac, Guam

Figure 25. Partial view of the Drone2Map resulting orthographic model of Toguan River near Umatac, Guam

Figure 26. Partial view of the Drone2Map Digital Surface Model (DSM) Toguan River near Umatac, Guam

Figure 27. Partial view of the Drone2Map Digital Terrain Model (DTM) Toguan River near Umatac, Guam

The LiMapper and Drone2Map software applications run on a Windows 10 based P.C. The next software application that will be discussed, DroneDeploy, is a completely web-based application. All aspects of the project from planning the flight mission, submitting the drone gathered photos, inputting analysis parameters and outputting results are handled through the DroneDeploy web site. Figure 28 shows a partial View of the DroneDeploy resulting orthographic model of Toguan River near Umatac, Guam. Figure 29 shows a partial view of the DroneDeploy resulting Digital Surface Model (DSM) Model of the Toguan River near Umatac, Guam. Please note that the resolution of the DroneDeploy DSM was not as fine as that shown for the other applications. We were unable to rerun the DroneDeploy Toguan project at a finer resolution due to software licensing issues. These issues will be covered in a later discussion.

The last software application we evaluated was the Microsoft Image Composite Editor or Microsoft ICE. This application is free and runs on a Windows 10 PC. Figure 30 shows the first step in the photo stitching process where the desired images are imported for the Toguan River near Umatac, Guam. Figure 31 shows the stitched photo composite develop by Microsoft ICE for the Toguan River near Umatac, Guam. The Microsoft ICE software provides high quality stitched images from the sUAS gathered orthophotos. The drawback to these stitched images is that they are not georeferenced at all. Further processing is required in a program such as ARCMAP in order to provide georeferencing if required.

Figure 28. Partial view of the DroneDeploy resulting orthographic model of the Toguan River near Umatac, Guam

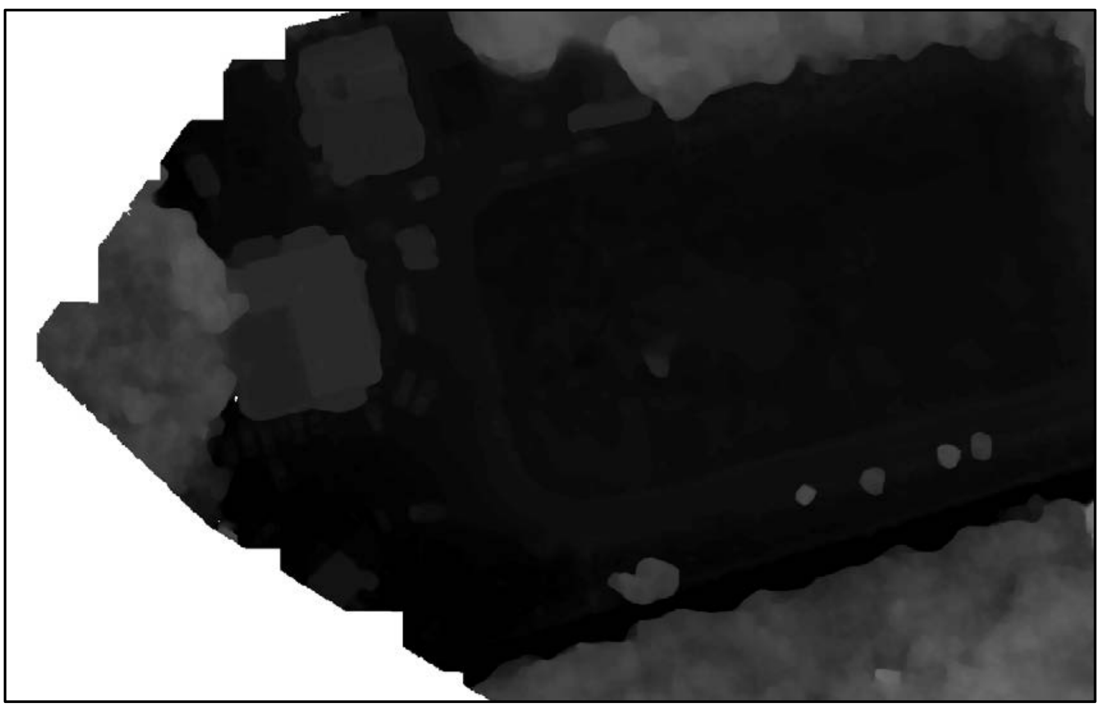


Figure 29. Partial view of the DroneDeploy resulting Digital Surface Model (DSM) of the Toguan River near Umatac, Guam

Figure 30. MICROSOFT ICE showing imported photos Toguan River near Umatac, Guam

Figure 31. MICROSOFT ICE showing stitched photos Toguan River near Umatac, Guam

COMPARISON OF ANALYSIS PROGRAMS

As can be seen from the previous sections, the Li Mapper, Drone2Map and DroneDeploy applications provide similar analysis products. These products all start from a set of drone-gathered orthophotos. The applications can develop composited georeferenced orthographic, and digital elevation and digital surface models of the areas that were flown. The resolution and quality of the original drone gathered imagery is key to the quality and resolution of the composited orthographic imagery and elevation models developed by the analysis programs.

The resolution and imagery of the drone imagery is affected by the aircraft height when the images are taken and by the limitations of the on-board cameras. The DJI Inspire 2 drone with the Zenmuse X5 camera, DJI Mavic Pro and the DJI Phantom 4 Pro evaluated in this study were all capable of providing excellent quality imagery as long as flight altitudes and camera setting are carefully selected before each flight.

Comparison of features for the various imagery analysis software packages that were evaluated is shown in Table 2 below. The first column of the table “EASE OF USE” represents the authors’ impressions of how difficult it was to go from the digital orthophotos taken by the drone to the finished orthographic and elevation models. The LiMapper application proved to be the most complex to set up. This complexity seems to stem from the application developers desire to add as much analysis flexibility as possible. This complexity is not bad. It just means it takes a longer time to learn the ins and outs of the analysis setup menus.

The Drone2Map application proved to be relatively easy to setup but capable of applying a wide range of analysis parameters. This application is designed specifically to interface with the ARCMAP GIS program. Anyone who plans to use their composited images and elevation models with the ARCMAP” program should strongly consider the Drone2Map application.

The DroneDeploy application proved very easy to use. The programs include the capability to plan flights along with analysis capabilities. One drawback of the analysis phase of the application is that it is done through the internet. The drone gathered photos and analysis parameters are down loaded to the DroneDeploy server through a web site. Depending on the nature of your license, the analysis job is put into a que on the DroneDeploy server. The wait times can prove to be annoying when multiple runs are required to home in on the desired analysis results. That being said, the DroneDeploy application loaded on the tablet being used as the drone controller proved excellent for setting up and flying the photo gathering missions. After setting up the desired image overlap, flight paths and altitude, flying the mission is very easy. Using only the application one merely tells the drone to take off. The application flies the mission taking the photos at proper intervals along the flight path. When finished the drone returns to the start point and lands. The gathered images are stored on the onboard storage card.

The Microsoft ICE program proved to be the easiest to set up and run. One must realize that this application is not a comprehensive analysis program cable of producing georeferenced orthoimages and digital elevation models. Additional georeferencing of the stitched images will be required if the stitched image is to be used in a GIS system. No elevation information is available from this application. If all that is desired is a high-quality stitched image of an area, then this application should be considered. It is free and runs on the users P.C.

All the comprehensive analysis applications evaluated required some experimentation with various analysis parameters to get the results required. These applications are not like using Microsoft Word where you can sit down and almost immediately get a usable product. One must be willing to put in the time trying different techniques and parameters to take advantages of the strengths of the applications.

Table 2 columns three and four "PLATFORM AND SPEED" are somewhat tied together. All of the applications have some component that run on the users P.C. LiMapper, Drone2Map and Microsoft Ice run exclusively on the users P.C. Li Mapper requires a Graphical Processing Unit "GPU". This application will not run without a GPU. The GPU provides for much faster analysis than with the other applications. The DroneDeploy application runs on a website accessed on the users P.C. A tablet application is also available for controlling the drone during the photo gathering missions. After the mission is flown the user submits the gathered images to the DroneDeploy server through the DroneDeploy web site. Depending on the number of drone images and how busy the DroneDeploy server is, processing can be very quick to extraordinarily long. As was stated before, the wait times can prove to be problematic when multiple runs are required to home in on the desired analysis results.

Column five "TWO DIMENSION FEATURES" shows the output features available that were important for our studies. The first three applications listed on the table all produced Digital Orthographic Models (DOM). These applications have a means of producing Digital Elevation Models including Bare earth models and elevation models including plant cover and other surface features such as buildings. The Microsoft ICE application provides for only the development of a stitched photo of the drone gathered images. No elevation data is extracted from the images and georeferencing is not provided.

The final column "COST" reveals the pricing structure for the various applications. The Li Mapper software requires a first-time fee for the software plus and annual maintenance fee. The Drone2Map application was purchased as part of our ARCVIEW license. DroneDeploy has a very complex pricing structure which starts at free for just flight planning and minimal analysis. Adding features raise the price of the software. Another factor in the price structure is that fees are charged for each user. The final price for the option we explored (three users plus Ground Control Points) was $6,997 per year. If students and co-researchers are involved in a project, then the price of the license can easily escalate out of control. Because of these cost limitations we are planning to use the DroneDeploy application only for planning and flying the image gathering missions.

SOFTWARE	EASE OF USE	PLATFORM	SPEED	TWO DIMENSION FEATURES *	COST
LIMAPPER	complex	pc with GPU	very fast	DOM, DEM, DSM, Contours	Perpetual License $100 One Year tech support and upgrades $100
DRONE2MAP	easy to use	pc	very slow	DOM, DEM, DSM, Contours	$1451
DRONEDEPLOY	easy to use	pc and tablet	very slow computations on-line only	DOM, DEM, DSM, Contours	Business license $2900 per year Unlimited GCPs $2000 per year Additional user $999 per user Student discount available
MICROSOFT ICE	very easy to use	pc	fast	Stitched image not georeferenced	FREE

*DOM Digital Orthographic Model
*DEM Digital Elevation Model
*DSM Digital Surface Model

Table 2. Comparison of features for the various Imagery analysis software packages that were evaluated

DIGITAL ELEVATION MODEL COMPARISONS

LiMapper, DroneDeploy, and Drone2Map have the means to develop a digital elevation model of a study area with vegetation and building features removed. This is sometimes referred to as a bare earth digital elevation model. LiMapper calls the bare earth model a DEM. Drone2Map and DroneDeploy call the bare earth model a Digital Terrain Model (DTM). All three of the applications call the elevation model showing all features a Digital Surface Model (DSM).

The bare earth elevation model is particularly valuable in Guam because many of the features which require investigation are blocked from view by dense vegetation. An example of this problem is when it is desired to develop a cross section view of a stream for hydraulic analysis purposes. Figure 32 shows a comparison of cross sections developed from a DSM and a DTM for the Toguan River near Umatac, Guam. The Digital Orthographic Model, DSM and DTM used were developed using Drone2Map as shown previously in Figures 25 through 27. The black line shown in the blue box on figure 32 is the location of the desired hydraulic cross sections for the stream. Note that the area under the black line is covered with very dense vegetation including tall trees. The lower right cross section (X-SECTION FROM DSM) is a profile along the black line and shows the tops of the vegetation. The upper right cross section (X-SECTION FROM DTM) is a profile along the black line and shows the bare earth with vegetation removed. The profiles to the left show the DTM (Bare Earth) profile plotted in red and the DSM (Surface) profile plotted in black. If a flood plain water surface profile were being developed for the stream the red profile would be used to develop channel hydraulic properties. The black surface profile would be used to determines areas of the profile blocked by vegetation. We will also be using the bare earth model in North Guam to identify surface sink hole structures hidden by overlying vegetal cover.

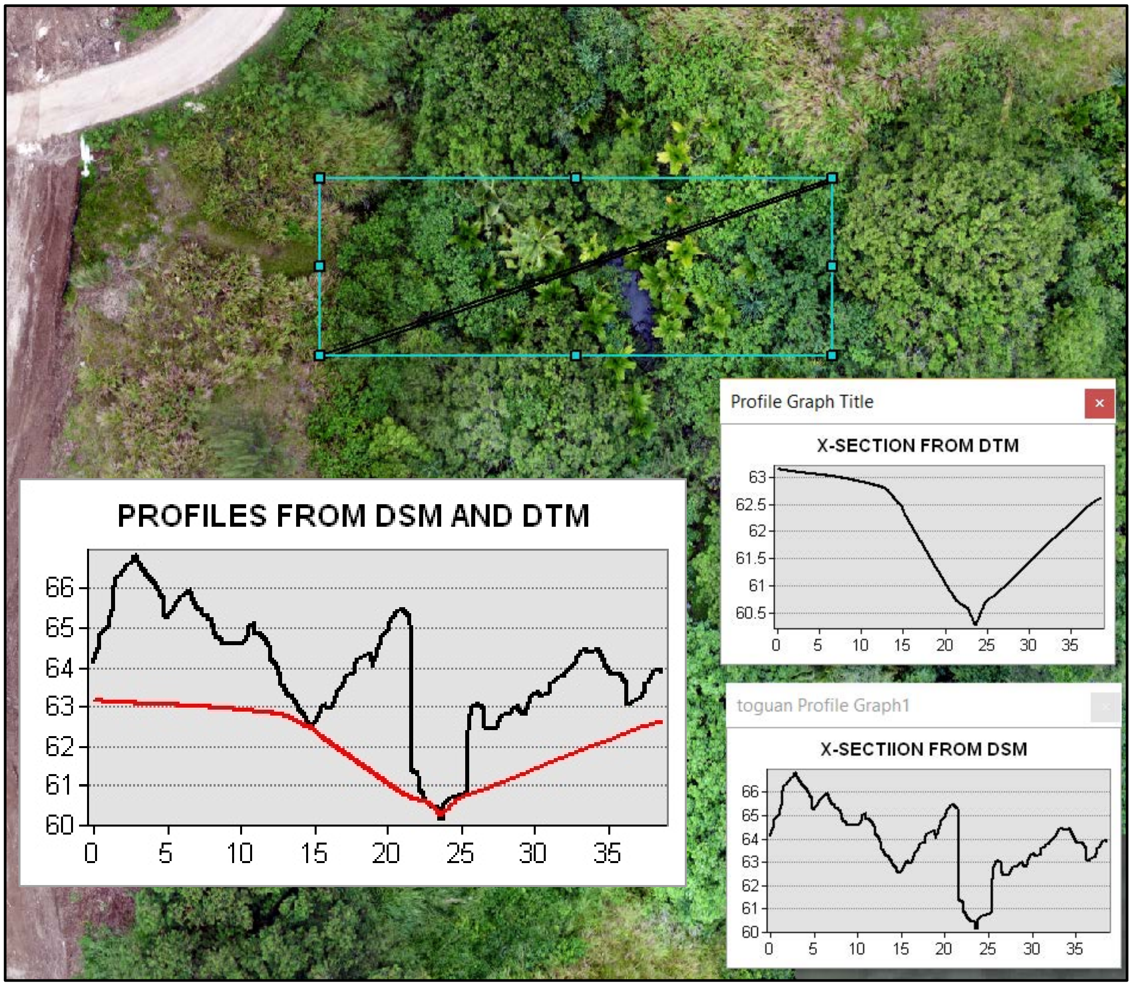


Figure 32. Comparison of cross sections developed from a DSM and a DTM for the Toguan River near Umatac, Guam

NEED FOR GROUND CONTROL POINTS

All the analysis applications discussed earlier depend on the quality of the drone gathered raw GNSS data acquired for each image. These applications use the GNSS location along with various alignment and photogrammetric procedures to generate the composited orthographic and elevation models. If we attempt to overlay the orthographic and elevation models on existing GIS maps, we find that the new maps do not fit well. The reason for these errors is primarily because the raw uncorrected GNSS data is not of sufficient quality so that the maps developed from this data will match maps developed using controlled survey points.

In order to correct this shortcoming, we will apply a procedure that uses Ground Control Points (GCPs) to correct our end-product models. Figure 33 shows a sample of a GCP. The characteristics of a good GCP include: 1.) It must be readily seen in the drone images that will be gathered for the project, and 2). a center point on its surface must be easily identified. It also very useful if there is an identifying number located on or nearby the GCP so that each GCP can be identified during the GCP processing procedures. The GCPs should be spread evenly across the project area before the photo gathering mission is flown. A minimum of four GCPs are required with more being better. Figure 34 shows an image of a GCP on one of orthophotos gathered on a Toguan River, near Umatac, Guam photo mission.

The next step in the GCP procedure will involve collecting latitude, longitude and elevation data for each of the GCPs shown on our drone gathered orthophotos. Figure35 shows a researcher gathering the location and elevation data for a GCP located along the Toguan River near Umatac, Guam using an EOS Arrow Gold GNSS Rover receiver. If the resulting orthographic and elevation models are to be accurately overlaid on existing GIS maps then the GCP locations need to be gathered at least to sub meter accuracy and preferable in the 2 to 4 cm range. This required accuracy is far beyond the capability of recreation grade GNSS units. Survey grade GNSS will be required with the addition of differential corrections to obtain the accuracy and precision desired.

As mentioned previously, all the analysis applications discussed earlier depend on the accuracy and precision of the raw GNSS data gathered for each image by the drone. The raw data is supplemented by correction information obtained from the GCP coordinates.

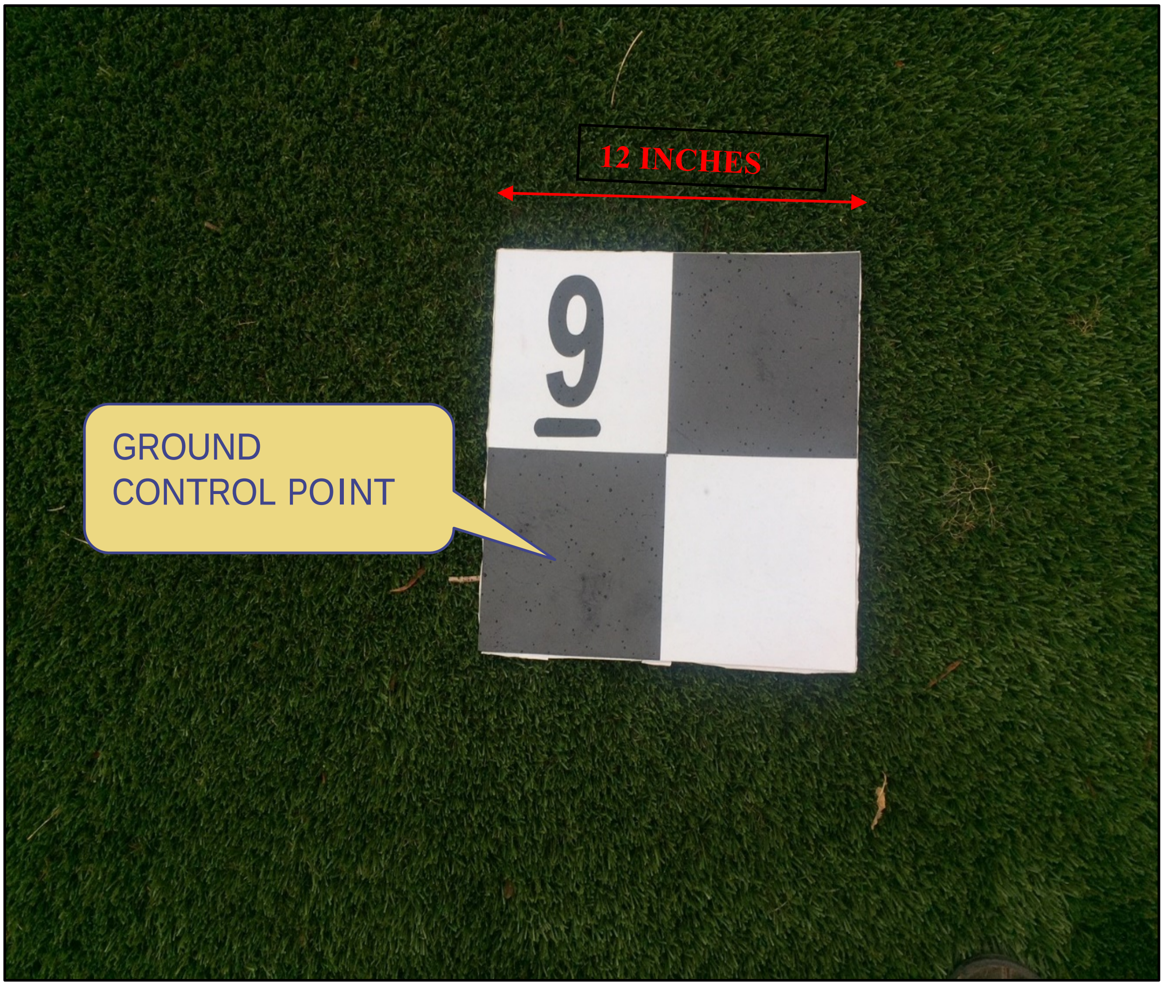


Figure 33. Sample Ground Control Point used for correcting orthographic and elevations models produced by processing applications

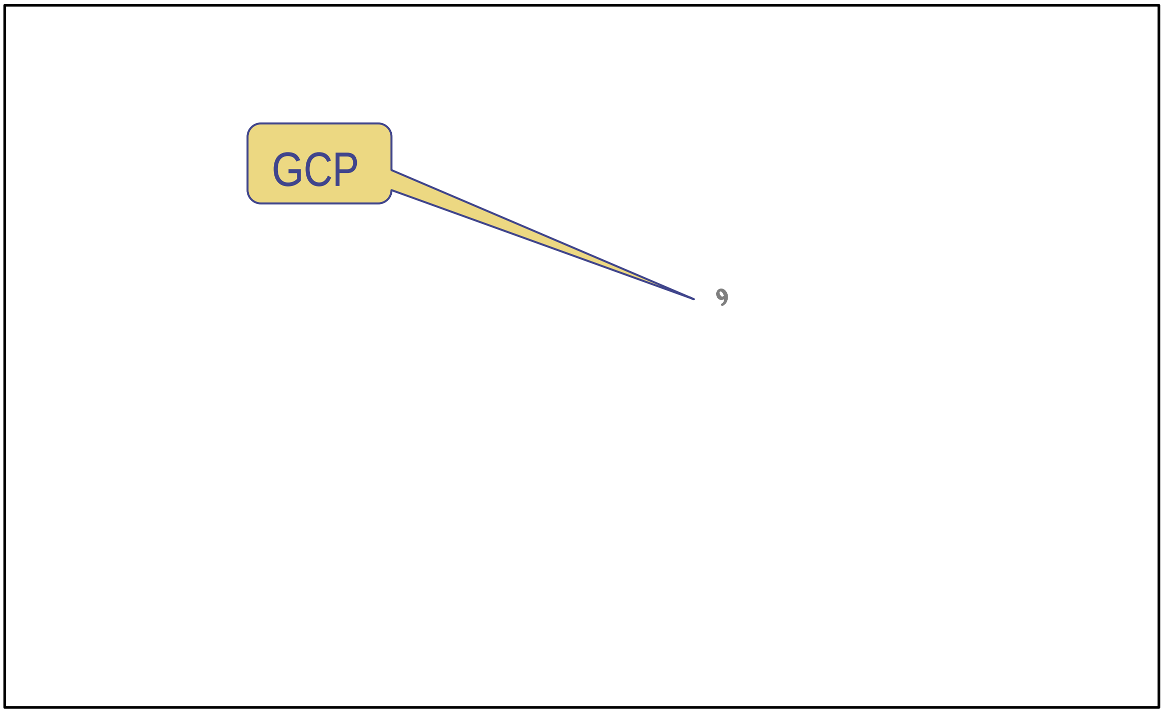


Figure 34. Image of GCP on one of the orthophotos gathered on a Toguan River near Umatac, Guam photo mission

Figure35. A researcher gathering the location and elevation data for a GCP located along the Toguan River near Umatac, Guam using an EOS Arrow Gold GNSS rover receiver

IMPROVING THE ACCURACY AND PRECISIONS OF LOCATIONS AND ELEVATIONS OF GCPs

The term accuracy and precision are very precisely defined when discussing computed GNSS coordinate data. Figure 36 illustrates GNSS Location Accuracy versus Precision. The targets represent the location of a point on the earth's surface. The bullseye represents the actual location of our point in some prescribed coordinate system. We want to have the maps we develop to be aligned to this bullseye location.

If the GNSS field unit gives us data corresponding to that shown in the upper left target, then the data is highly repeatable (all predicted locations are consistently located). This data is considered to have high precision. In the case of the upper left target the high precision points are all located away from the bullseye and therefore lack accuracy. If the GNSS field unit gives us data corresponding to that shown in the lower right target, the data is consistently located around the bullseye it is said to be to have high accuracy. In the case of the lower right target the high accuracy points are not well grouped with each other so and therefore lack precision. If the GNSS field unit gives us data corresponding to that shown in the lower left target, we see that the computed points are not well grouped nor are they located close to the bullseye location. This data has low accuracy and low precision. The best of all possibilities is shown on the upper right target. The calculated coordinates are well grouped and all fall in the bullseye. This data would be assumed to be highly accurate and highly precise. In a perfect GNSS world all our data would fall in the highly accurate and highly precise category.

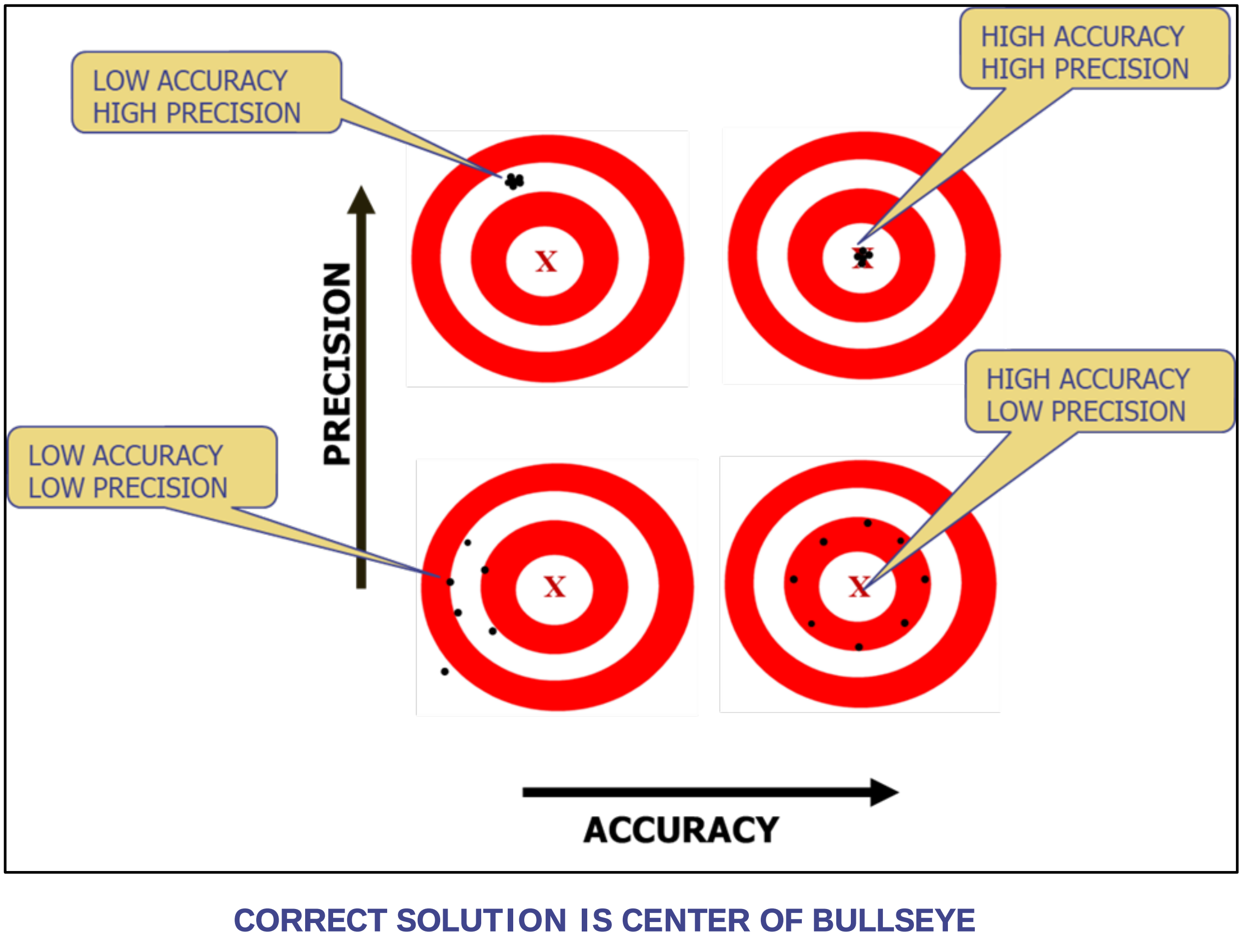


Figure 36. GNSS location accuracy versus precision

The world of Global Navigation Satellite Systems (GNSS) satellites and receivers is very complex. We will try to provide a "brief" explanation of why we have accuracy and precision issues and what we can do to help improve our location and elevation estimates. Later we will discuss how we improve the predicted locations of our processed drone gathered imagery using the GCPs discussed previously. The GNSS product supplier, Novatel, has developed a very complete discussion of GNSS. This discussion can be found at https://www.novatel.com/an-introduction-to-gnss/chapter-1-gnss-overview/).

First, we must realize that the world of GNSS is a very complex game of timing. All GNSS satellites have coordinated time bases (with atomic clock accuracy). The GNSS units we use calculate the time the signal takes to get from the satellite it's observing to the GNSS unit. If we know the speed of the radio wave coming from the GNSS satellite, we can calculate the distance our point is from the satellite. If we know distance from at least four GNSS satellites and where these satellites are located, we can compute the location of the GNSS unit's antenna.

There are several sources of error in the computation of the distance from the GNSS satellites. One important source of error comes when changes in the ionosphere and atmosphere below bend the path of the radio waves passing through it. These changes can vary with time and location. Another consideration is how many satellites are available for use in computing the position. Four is a minimum, but more are desirable. Another consideration is the strength of signals from the satellites. Weaker signals can give less reliable results. The geometry of the satellites used must also be considered. If the satellites used are all located relatively close, the geometric calculations will lead to less reliable results. Another source of error comes when we look at the path taken by the signal from the GNSS satellite to our ground-based GNSS unit. In areas with tall buildings or forest cover we can get what is called "multi-path errors". This means the signal may take different routes when coming to the GNSS unit. This can lead to positional errors. A final consideration is how good are the GNSS unit's electronics and internal software. The range of possibilities here is great. In general, high end (survey grade) GNSS receivers can yield much better results than the less expensive varieties.

The next question is, "How can we improve the precision and accuracy of our GNSS measurements?". The basic methodology of the techniques we used is called applying differential corrections. Environmental Systems Research Institute (ESRI) has a good explanation of differential GNSS correcting on their web site (https://www.esri.com/news/arcuser/0103/differential2of2.html) . The differential correction procedure revolves around the basic assumption that I have a GNSS base station where I know the antenna's location very accurately. This base station must be relatively close to where I want to make my GNSS measurements. Since Guam is relatively small, even one good base station can provide good differential correction data for the whole island.

Using the known locations of an in-view GNSS satellite and the base station antenna, the base station can compute the distance between the two using three-dimensional geometry only. The base station then computes the distance to the satellite from the signal being sent down from the same GNSS satellite. This computed distance value will have some error. This error is because of the path bending of the radio signal due to affects in the ionosphere and lower atmosphere. The GNSS base station then computes the difference between the actual distance and the measured distance which includes error. This is called the differential correction. This procedure is repeated at the base station for all in-view satellites. These differential corrections are broadcast to the nearby rover units. The rover units apply the corrections to the values they compute from the same satellites at the same time. This result in a GNSS rover antenna position down to 1 or 2 cm accuracy depending of GNSS Rover hardware and software.

There are several ways to implement the differential correction technique. The technique that has been around longest is called post processing. In this methodology the rover station is located at the desired site for a period of time and the GNSS satellite data is recorded and saved. GNSS satellite correction data from a known base station are applied to the rover data for the same time period and the final corrected locations of the rover are computed.

In the United States the National Geodetic Survey maintains a network of base stations called Continuous Operation Reference Stations (CORS).
Direct access to the data files for the CORS sites is available at https://www.ngs.noaa.gov/cgi-cors/CorsSidebarSelect.prl?site=guug&option=Standard%20Files/ . Figure 37 shows a screen shot of the CORS internet web site for downloading GNSS differential correction data. Data for the CORS site closest to the rover location is downloaded for the same time segment that the rover data was taken. The files downloaded from the rover and the CORS site are loaded into a differential corrections program and the corrected location of the rover is computed. We used a program called RTKLIB (available at http://www.rtklib.com/) for making post processing corrections. Figure 38 shows a screen shot of RTKLIB application used to apply differential GNSS corrections. Some rover GNSS units have built in post processing capabilities. We used the Trimble post processing software (Trimble TerraSync) to obtain this post processing capability.

Since differential correction post-processing technique are somewhat cumbersome and time consuming, it was desirable to compute differentially corrected positions within the Rover GNSS unit as location data for our GCPs was being gathered. There are several methods available for providing the differential correction data in real time. The first general classification of providing differential corrections is called Satellite Based Augmentation System or SBAS. A good source of information on SBAS is https://en.wikipedia.org/wiki/GNSS_augmentation and (Kee et al, 1991).

We explored the use of three different SBAS systems for this project. The first was the Wide Area Augmentation System (WAAS), operated by the United States Federal Aviation Administration (FAA). The Trimble Company has a good explanation of WAAS at https://www8.garmin.com/aboutGPS/waas.html . This system consists of a system of ground stations that compute differential correction data that is sent to a geosynchronous satellite. These satellites rebroadcast the data stream downward where it is used by the GNSS rover unit to correct the GNSS position and elevations. This system was developed by the US Federal Aviation and Agency and Department of Transportation to provide correction data for precision landing systems for aircraft. The accuracy of GNSS data with WAAS correction is less than 3 meters depending on local conditions. Unfortunately, the footprint of the WAAS ground stations and Geosynchronous satellites does not cover Guam. We were unable to use WASS dependably on Guam.

Fortunately, Japan has developed a SBAS system for use in and around Japan. The system is called The Multi-functional Satellite Augmentation System (MSAS), operated by Japan's Ministry of Land, Infrastructure and Transport Japan Civil Aviation Bureau (JCAB). Figure 39 shows the components of SBAS System using Japanese MSAS. The operation footprint of this system extends just down to Guam. We were able to obtain differential corrections accuracy of less than 3 meters using this system in Guam. These differential corrections for GCPs were not accurate enough to use for correcting our composited orthophotos for use as overlays in our GIS system.

Figure 37. Screen shot of the CORS internet web site for downloading GNSS differential correction data

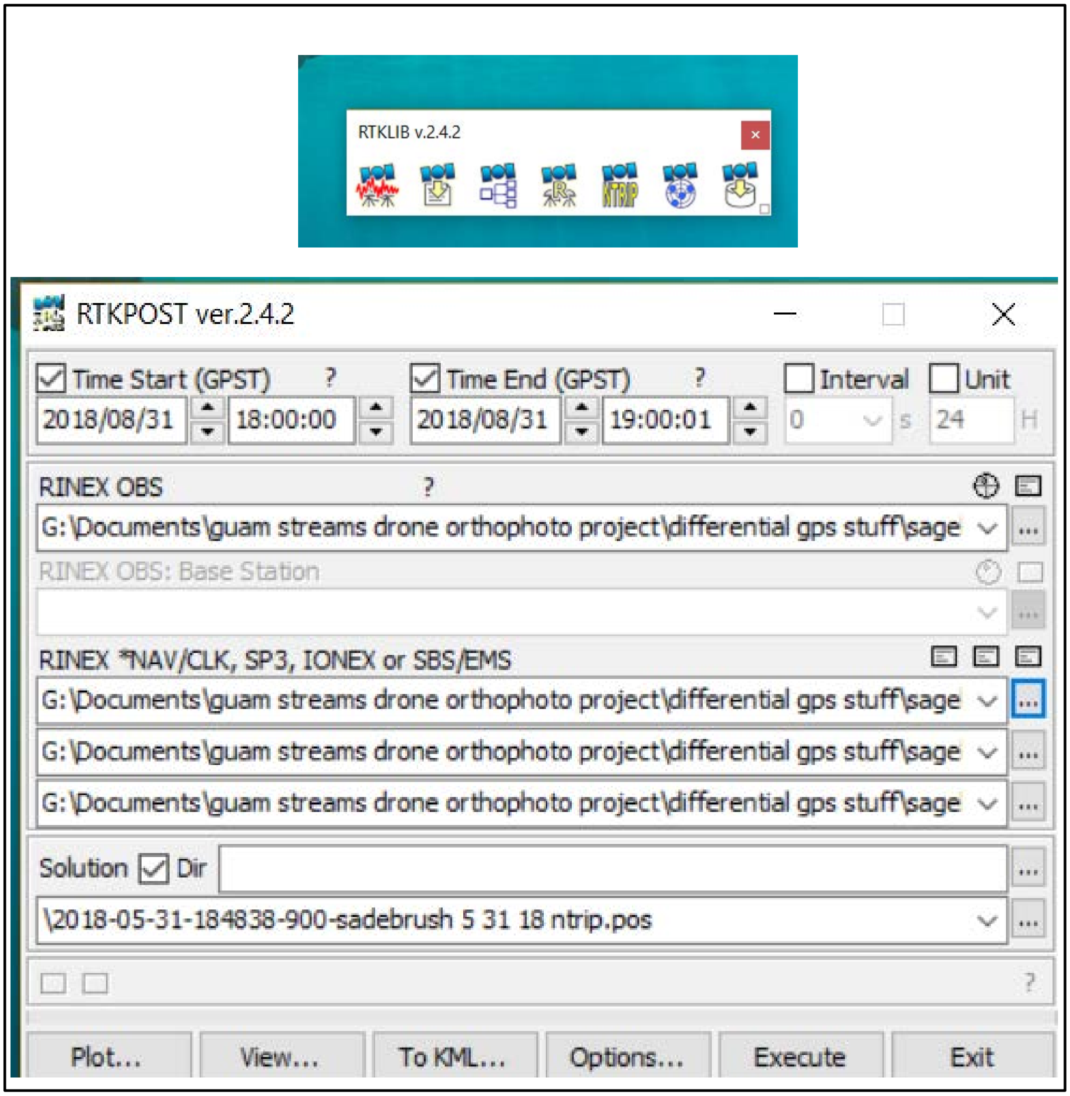


Figure 38. Screen shot of RTKLIB application used to compute differential GNSS corrections

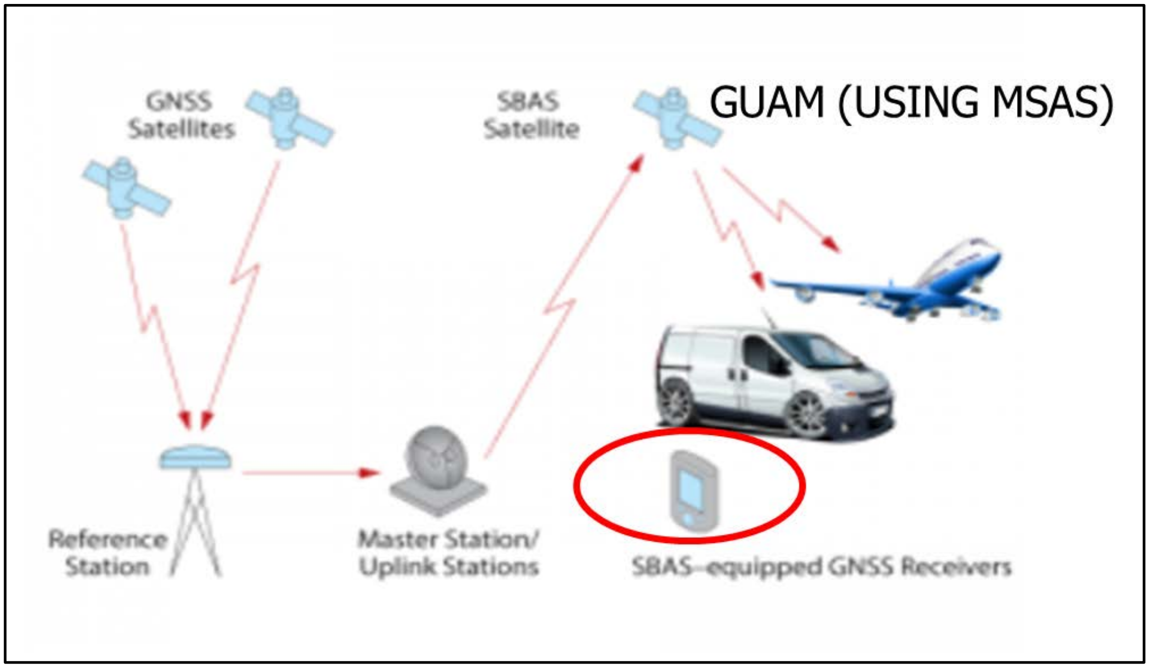


Figure 39. Components of SBAS system using Japanese MSAS

Several commercially available SBAS implementations are available from private vendors. We explored the use of a system called Atlas which is available for our EOS Arrow Gold GNSS receiver. Information on Atlas can be obtained at https://hemispheregnss.com/Atlas/atlas174-gnss-global-correction-service-1227 . This system can give world wide 4 cm accuracy. Initial convergence to an accurate solution can take up to 15 minutes using this system. Also, overhead cover can cause reception problem with signals from the Geo-Synchronous satellites used by Atlas. Another drawback is that the price of the subscription for using the service is $2,500 per year. The high cost of the subscription make it prohibitive for the small amount of user time we need for our projects.

The Third differential corrections method that was explored is called Networked Transport of RTCM via Internet Protocol (NTRIP). In this system corrections from the base station are sent directly to the rover unit through the internet. RTCM is an internet protocol for sending GNSS data. Figure 40 shows the components of NTRIP for real time processing of differential GNSS data. Figure 40 was provided by Anatum GeoMobile Solutions. They have a extensive write up on NTRIP on their web site https://www.anatumfieldsolutions.com/What-is-NTRIP_b_42.html .

Once the correction data is received by the rover, it is immediately processed, and corrected location and elevation coordinates are provided. NTRIP requires that a connection to the internet can be obtained by the rover or rover software (depending on the unit). This is easily obtained in Guam by using a cellular hot spot set up on a cell phone at the rover site. This works well on Guam since much of the Island has cellular coverage. The problem that we were confronted with on Guam is that even though there are two CORS stations on Guam neither of these sites are connected to a working NTRIP system. To solve this problem, we decided to commission our own NTRIP site at WERI. We used our existing EOS Arrow Gold GNSS unit as a base station with a direct internet connection through EOS Server Software. Figure 41 shows the GNSS antenna for the Base station. We will be using our existing Trimble Juno T 41/S as a rover unit.

Figure 40. NTRIP base station components

Figure 41. WERI GNSS base station antenna

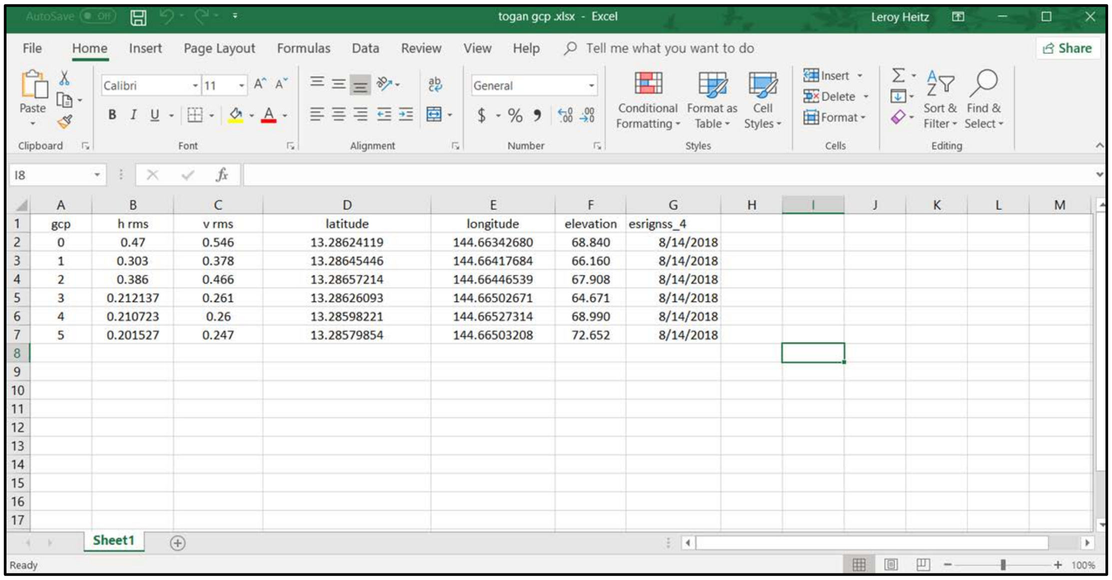
IMPLEMENTING GCPs IN THE ORTHOPHOTO COMPOSITING ANALYSIS APPLICATIONS

Once the orthophoto gathering mission including the GCPs have been flown and the GCP locations have been determined, the next step is to implement the GCP processing components of the compositing analysis programs. LIMapper, Drone2Map and Drone Deploy all have GCP capabilities and the implementation of GCPs is similar in all of the programs. We will use the Drone2Map program implementation of GCPs as an example.

The first step in the GCP implementation is to read the coordinates of the GCPs into the program. Drone2Map requires a ".CSV" format file for the location data. We used the ESRI collector program working with our EOS Arrow Gold Rover unit to gather the locational data. Figure 42 shows the Excel file of locational data for the GCPs that was gathered. This data was exported in ".CSV" format for use by the Drone2Map program.

Once the GCP locations are loaded, they show up both on the map window as a red X and in the Manage GCP window as shown in Figure 43. The next step in the process is to link the coordinates for each GCP with the location of the center of the GCP on the orthophotos gathered during the drone mission. The first step is to select the particular GCP coordinates in the Manage GCPs window. Next, we select the “Links” button. Figure 44 shows and enlarged view of the linking process. An image is selected from the images column, and we zoom in on the GCP located on the image. Next, we click on the center point of the GCP where the corrected GNSS coordinates were gathered. Figure 45 shows an enlarged view of the linking process. This process is repeated for at least 3 to 8 images for each set of coordinates.

The set of images and GCPs are then processed into the desired composited images and elevation models. Figure 46 shows the location of the GCP and its correct coordinates first without GCP correction and next with GCP Corrections. The error in location without corrections is about two meters. With the corrections the error is 2-4 centimeters.



gcp	h rms	v rms	latitude	longitude	elevation	esrignss_4
0	0.47	0.546	13.28624119	144.66342680	68.840	8/14/2018
1	0.303	0.378	13.28645446	144.66417684	66.160	8/14/2018
2	0.386	0.466	13.28657214	144.66446539	67.908	8/14/2018
3	0.212137	0.261	13.28626093	144.66502671	64.671	8/14/2018
4	0.210723	0.26	13.28598221	144.66527314	68.990	8/14/2018
5	0.201527	0.247	13.28579854	144.66503208	72.652	8/14/2018

Figure 42. GCP locational data for the Toguan River study area near Umatac, Guam

Figure 43. GCP locational data for the Toguan River study area near Umatac, Guam shown in the Drone2Map application

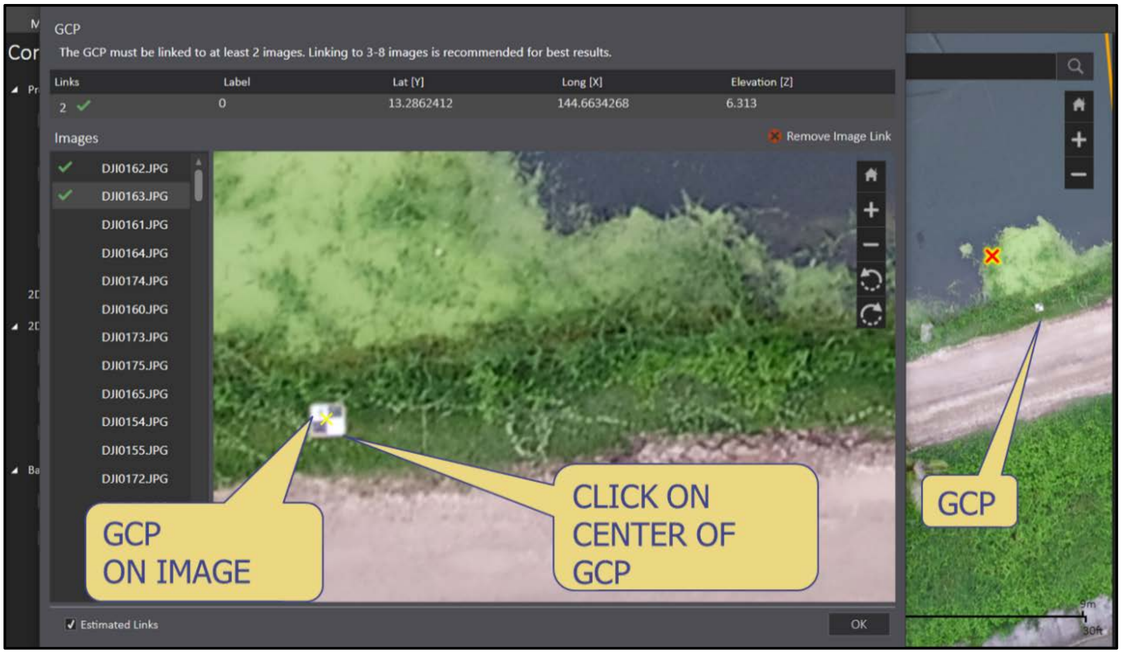


Figure 44. Linking GCP coordinates with GCP on image

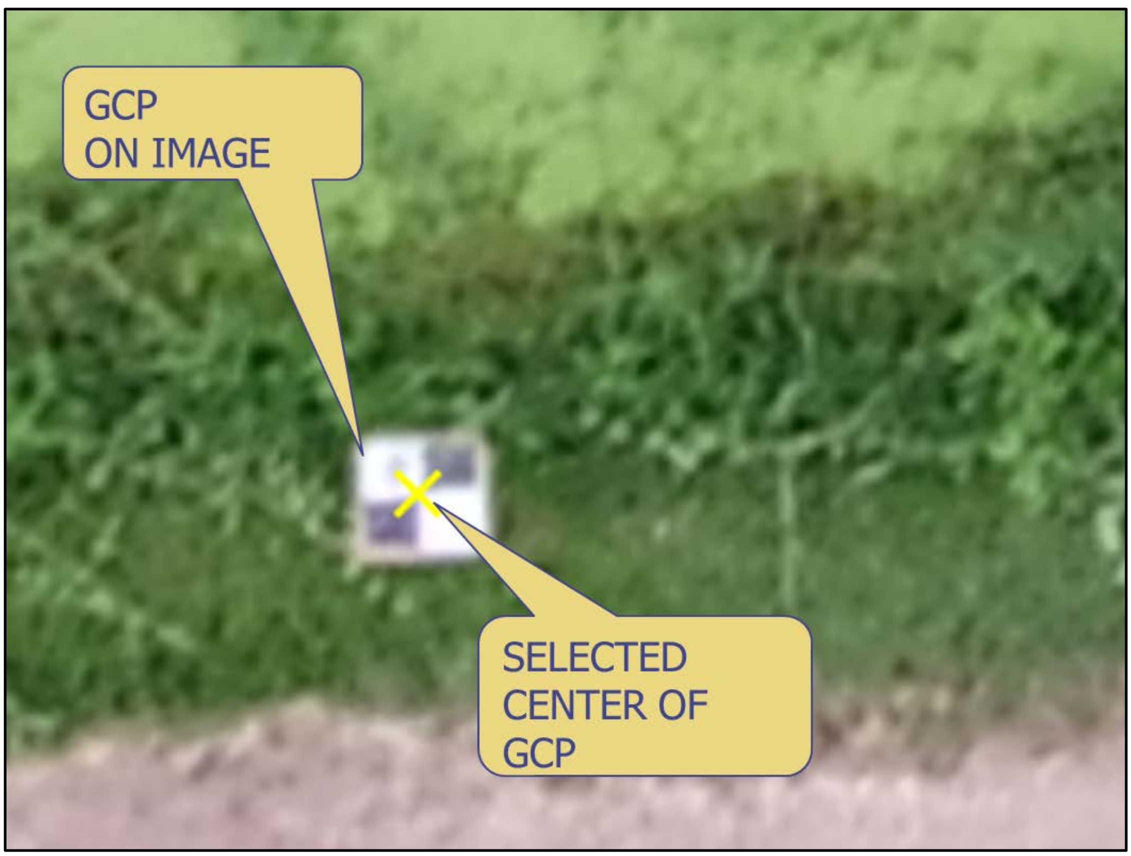


Figure 45. Enlarged view of linking process

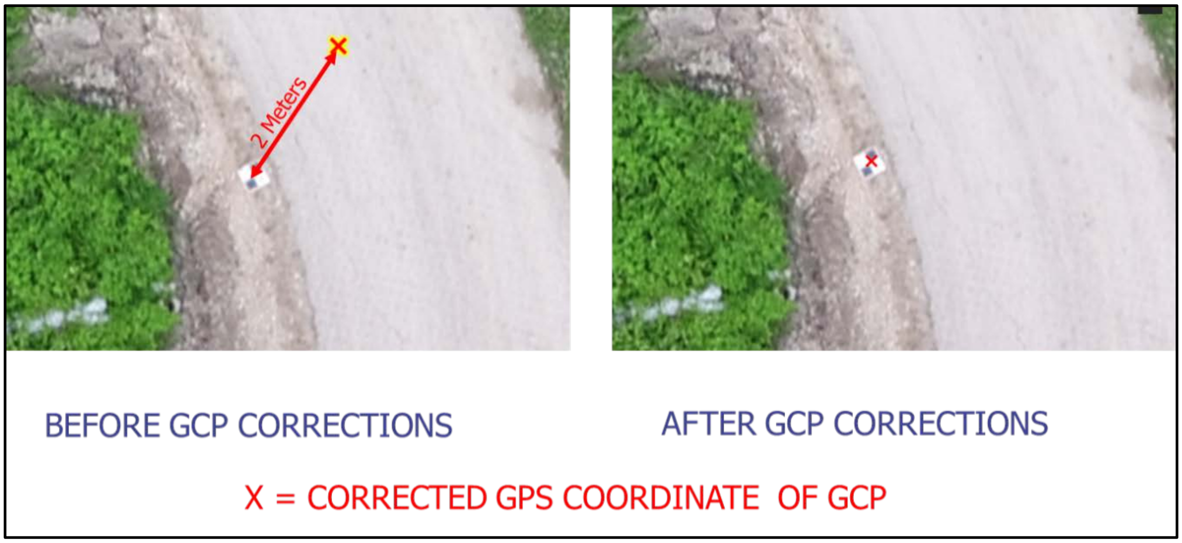


Figure 46. Comparison of GCP location fits

SUMMARY AND CONCLUSIONS

This project evaluated four DJI unmanned aerial system aircraft and camera combinations. Each of the aircraft tested had its own set of strengths and weakness. The Inspire 2 was the most expensive of the aircraft tested. Its speed and stability characteristics were the best of all drones tested. The Inspire camera mount is such that it is very easy to interchange various cameras for upgrading or adding future capabilities without having to buy a new aircraft. On the downside the Inspire 2 is big and heavy. It is marginal when one is planning a mission that requires transporting the aircraft system (plane, controller and accessories) to a location not accessible by motor vehicle. The Mavic pro had good flight times and great picture quality. Its real advantage is in its small size and portability. The airframe folds into a compact shape which can be easily backpacked to remote sites. It is somewhat less stable than the larger aircraft tested. This limits orthophoto missions in windy conditions. The Spark is simply too small for good orthophoto gathering. On the other hand, because of its small lightweight size it is great to bring along for "selfie" type photos of field operations. The Phantom 4 Pro sets between the Inspire 2 and Mavic Pro in stability. Its high-resolution (20 mega pixel) camera takes stunning orthophoto shots considering the price of the aircraft and camera system.

All the aircraft tested take excellent still pictures. The resolution and quality are such that the images can be easily composited into excellent images with 1 inch per pixel resolution.

Two applications were evaluated for use in planning and carrying out optimal aerial imagery acquisition. These two were DroneDeploy and Maps Made Easy Drone Map. The first step in applying these applications is to input flight parameters for the mission to be flown. These parameters include aerial extent and altitude of the flight and photo overlap parameters. Another iPad Application called UAV Forecast was found useful for evaluating weather conditions and Global Navigation Satellite System (GNSS) satellite availability for the proposed time of the UAV orthophoto mission.

The Island of Guam has numerous airports, military installations and special designation areas identified by the federal and local governments. Each of these areas present a different set of challenges when flying sUAS missions. Luckily there are several applications available that help identify where restricted sUAS flying areas are located. We found the "AirMap" application to be very useful in planning flights and determining what kind of FAA flight designations to use. Hopefully automatic authorization of Flights in FAA restricted spaces will soon be available for Guam using this application.

Four different software packages were evaluated for the development of composited images and digital elevation models from the orthophotos that were gathered on our sUAS photo missions. These packages included LiMapper, Drone2Map, DroneDeploy, and Microsoft Image Composite Editor (ICE). The processing steps are similar for all the software packages.

The LiMapper and Drone2Map software applications run on a Windows 10 based P.C. The DroneDeploy application is a completely web-based program. The last software application we evaluated was the Microsoft Image Composite Editor or Microsoft ICE. This application is free and runs on a Windows 10 PC. The Microsoft ICE software provides high quality stitched images from the UAS gathered orthophotos. The drawback to these stitched images is that they are not georeferenced at all. Further processing is required in a program such as ARCMAP in order to provide georeferencing if required.

As can be seen from the previous sections, the Li Mapper, Drone2Map and DroneDeploy applications provide similar analysis products. These products all start from a set of drone-gathered orthophotos. The applications can develop composited georeferenced orthographic, and digital elevation and digital surface models of the areas that were flown. The resolution and quality of the original drone gathered imagery is key to the quality and resolution of the composited orthographic imagery and elevation models developed by the analysis programs.

The LiMapper application proved to be the most complex to set up. The Drone2Map application proved to be relatively easy to setup and capable of applying a wide range of analysis parameters. This application is designed specifically to interface with the ARCMAP GIS program. Anyone who plans to use their composited images and elevation models with the ARCMAP" program should strongly consider the Drone2Map application.

The DroneDeploy application proved very easy to use. The program includes the capability to plan flights along with analysis capabilities. One drawback of the analysis phase of the application is that it is done through the internet. The drone gathered photos and analysis parameters are downloaded to the DroneDeploy server through a web site. Depending on the nature of your software license, the analysis job is put into a que on the DroneDeploy server. The wait times can prove to be annoying when multiple runs are required to home in on the desired analysis results. The DroneDeploy application loaded on the tablet being used as the drone controller proved excellent for setting up and flying the photo gathering missions. After setting up the desired image overlap, flight paths and altitude, flying the mission is very easy. To use the application, one merely tells the drone to take off. The application flies the mission taking the photos at proper intervals along the flight path. When finished the drone returns to the start point and lands. The gathered images are stored on the onboard data storage card.

The Microsoft ICE program proved to be the easiest to set up and run. One must realize that this application is not a comprehensive photogrammetric analysis program cable of producing georeferenced orthoimages and digital elevation models. Additional georeferencing of the provided stitched images will be required if the stitched images are to be used in a GIS system. No elevation information is available from this application. If all that is desired is a high-quality stitched image of an area, then this application should be considered. It is free and runs on the users P.C.

All the comprehensive analysis applications evaluated required some experimentation with various analysis parameters to get the results required. These applications are not like using Microsoft Word where you can set down and almost immediately get a usable product. One must be willing to put in the time trying different techniques and parameters to take advantages of the strengths of the applications.

The final consideration "COST" is an important consideration. The Li Mapper software requires a first-time fee for the software plus and annual maintenance fee. The Drone2Map application was purchased as part of our ARCVIEW license. DroneDeploy has a very complex pricing structure which starts at free for just flight planning and minimal analysis. Adding features all raise the price of the software. Another factor in the price structure is that fees are charged for each user. The final price for the option we explored (three users plus Ground Control Points) was $6,997 per year.   If co-researchers are involved in a project, then the price of the license can easily escalate out of control. Because of these cost limitations we are planning to use the DroneDeploy application only for planning and flying the image gathering missions.

A final consideration when developing composited georeferenced photos or elevation models is the use of Ground Control Points (GCPs). The GNSS accuracy of the raw imagery that was available for our missions was not high enough so that the composited images would match existing maps available in our GIS system. To solve this problems GCPs are used. These points are known locations that can be identified on the ortho-photos gathered by the drone. The Ground control point locations and elevations are determined using high accuracy GNSS methods. The compositing programs we used combined the ground control point data and orthophoto data to provide very accurate composited imagery and elevation maps. The problem in Guam is that, even though there are two GNSS correction (CORS) sites which can provide correction information, this data is not available on a real time basis. We are presently working on setting up a GNSS base station at WERI in order to provide real time access to correction data for measuring location and elevation data for our ground control points.

FUTURE STUDIES

It is recommended that this project be extended for at least one more year to accomplish all the project's initial goals. The first phase of the continuation project should involve the completion of the installation of the EOS Arrow Gold differential correction (RTK) base station and antenna system at WERI. The second phase of the project would involve the calibration of the base station and extensive testing to be certain that rover coordinates gathered using differential corrections from the base station match coordinates used on base maps available in WERI's GIS system. This will assure that the composited images and elevation models developed from the sUAS orthophotos will be compatible with existing GIS data.

The third phase would involve the aerial data gathering and development of georeferenced ortho-maps and digital elevation models of test areas in North and South Guam. The detailed georeferenced aerial data will provide baseline knowledge on the location, size, and potential pollution sources in sinkholes located in the North Guam groundwater recharge areas. In South Guam, we will be able to accurately plot stream cross sections, determine erosion potential and possible sediment loading, and other sources of environmental contamination.

The final phase will involve the development of a data management scheme for the imagery and other digital data gathered by the project. The data management scheme will be compatible with WERI's existing on-line water resources data retrieval system.

Upon completion of this continuation project, WERI will have a robust system for applying sUAS technology to water related environmental issues on Guam.

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