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

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WERI

WATER AND ENVIRONMENTAL RESEARCH INSTITUTE
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UNIVERSITY OF GUAM

Technical Report 171
January 2020

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Technical Report No. 171

February 2020

ABSTRACT

Proper management of a region's water resources requires water managers and water resources researchers to 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 dealing with surface and ground water supply depend on this kind of long-term variable information to develop the best management practices for a region's water resources.

Recent advances in commercially available mall Unmanned Aerial Systems (sUAS) technology have made lower cost, highly accurate, sub-meter resolution aerial imagery available. Commercial sUAS, or drones, fly at elevations less than 400 ft. and can gather high resolution 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 allow foliage cover removal from the data. This facilitates the development of high-resolution composite ground surface Digital Elevation Models (DEMs) of areas of interest. These sUAS flights can be made at intervals that could be used for the continued monitoring of the environmental health of Guam's streams and recharge areas.

This report covers Part II of a continuing project on drone imagery gathering and use on Guam. Phase I of the project is described in a University of Guam (UOG) Water and Environmental Research Institute (WERI) Technical Completion Report (Habana, Heitz, and Ziobro, 2019). The first phase of this project involved the completion of the installation and calibration a Global Navigation Satellite System (GNSS) Real Time Kinematic (RTK) base station at WERI. The base station consists of an EOS Arrow Gold GNSS unit connected to a survey quality antenna placed on the roof of the WERI building located at the lower UOG campus.

The second phase of this project involved extensive testing to be certain that rover coordinates gathered using Real Time Kinematic (RTK) corrections from the base station match locational coordinates and elevations used on base maps in WERI's Geographic Information System (GIS). Our goal was to be able to provide 3 to 6-centimeter accurate composited aerial images and DEMs. We evaluated the accuracy of the elevations gathered for the Ground Control Points (GCPs) required to developed accurate geo-reference composited sUAS images. Secondly, we did a complete composited imagery project for an area in South Guam. This allowed us to evaluate how well composited imagery using the WERI base station established GCPs fit our existing WERI satellite imagery. Finally, we carried out a project in a particularly problematic area in South Guam. This area was isolated and required the use of a portable base station and a Low Power Radio (LoRa) base to rover connection.

For the most part we found that the latitude, longitude and elevation coordinates provided by RTK correction techniques provided the accuracy and precision required for our environmental studies on Guam.

TABLE OF CONTENTS

Page

LIST OF FIGURES

LIST OF FIGURES (CONT.)

LIST OF TABLES

INTRODUCTION

Proper management of a region's water resources requires water managers and water resources researchers to 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 dealing with surface and ground water supply 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 the health of stream and groundwater recharge areas was either with direct on-ground monitoring or the use of high-altitude satellite imagery or LIDAR (Light Imaging, Detection, and Ranging) data. Available satellite imagery was accurate to 0.3-meter resolution. The LIDAR data was accurate to1.0-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 Small Unmanned Aerial Systems (sUAS) technology have made lower cost, highly accurate, sub- meter resolution aerial imagery available. Commercial sUAS, or drones, fly at elevations less than 400 ft. and can gathering high resolution 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 allow foliage cover removal from the data. This facilitates the development of high-resolution composite ground surface Digital Elevation Models (DEMs) of areas of interest.

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The second phase of this project involved extensive testing to be certain that rover coordinates gathered using Real Time Kinematic (RTK) corrections from the base station match locational coordinates and elevations used on base maps in WERI's Geographic Information System (GIS). Our goal was to be able to provide 3 to 6-centimeter accurate composited aerial images and DEMs. We evaluated the accuracy of the elevations gathered for the Ground Control Points (GCPs) required to developed accurate geo-reference composited sUAS images. Secondly, we did a complete composited imagery project for an area in South Guam. This allowed us to evaluate how well composited imagery using WERI base station established GCPs fit our existing WERI satellite

imagery. Finally, we carried out a project in a particularly problematic area in South Guam. This area was isolated and required the use of a portable base station and a Low Power Radio (LoRa) base to rover connection.

STUDY AREA

This project continued the development of strategies for carrying out aerial photo gathering using 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 in the Western Pacific approximately 2,600 miles south east 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 a portion of 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
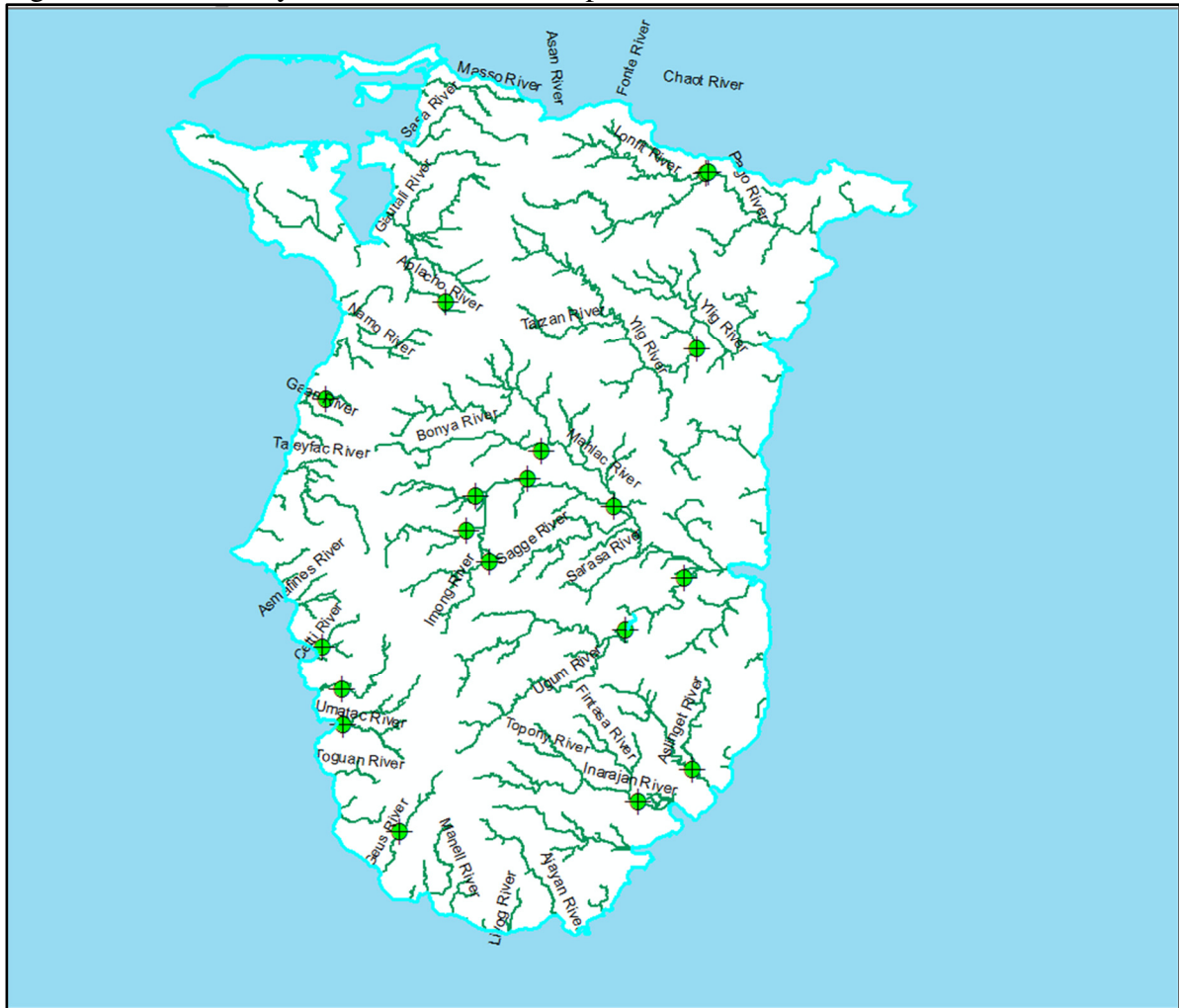
Figure 2. Potential Stream Study Sites in South Guam
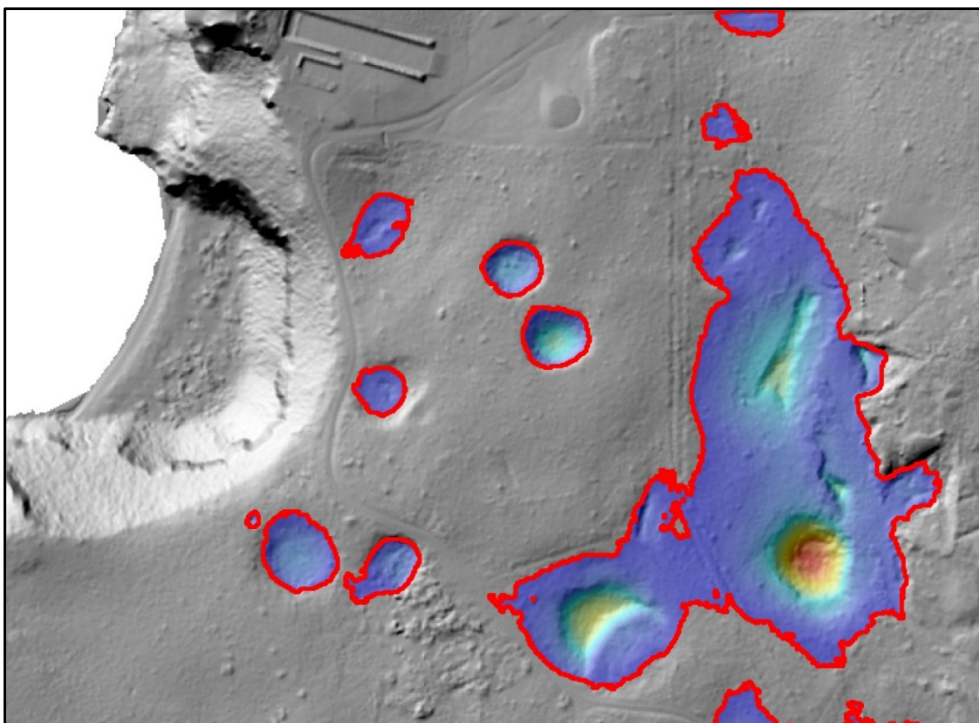
Figure 3. Potential Study Sites in Northern Guam Showing Major Sink Holes

OBJECTIVES

This project continued the development of 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 composited digital orthographic models and digital elevations models. Particular emphasis was applied to developing GNSS techniques for the correction of location and elevation data used in developing composited ortho-photos and DEMs from imagery gathered by sUAS missions.

The specific objectives of the research were to to:

1. Complete the Installation and calibration of the EOS Arrow Gold RTK base station and antenna system at WERI.
2. Provide extensive testing to be certain corrected rover coordinates gathered for GCPs used in orthoimage compositing match locational coordinates and elevations used in the base maps available in WERI's GIS system.
3. Provide testing to be sure that locations shown on developed composited ortho images correspond accurately to those shown on WERI's GIS based Satellite imagery.

METHODS AND PROCEDURES

This project was divided into two phases. These two phases are described below.

PHASE I

Complete the Installation of the WERI base station and evaluate techniques of getting centimeter accurate control points for our composited ortho-photos and DEMs

In order to develop accurate composited images and DEMs, requires that a set of GCPs be in place before makings sUAS image gathering missions. Figure 4 shows a typical GCP panel. The GCP panels should be visible on various images that are gathered on the sUAS mission. These GCPs act as latitude, longitude and elevation control references. In order to be compatible with existing WERI satellite imagery and LIDAR DEMs, the corrected coordinates of the GCPs must be precise and match the coordinate systems used by the existing imagery. Our goal was to achieve 3 to 6-centimeter accuracy for latitude, longitude and elevation values. The corrected coordinates and elevations are incorporated during the image compositing process. The compositing software can then provide accurate geo-referencing of the final composited images and DEMs.

To get accurate GCP locational information requires the use of GNSS correction techniques. A more thorough description of the various correction techniques is shown starting on page 39 of the Phase I technical completion report (Habana, Heitz, and Ziobro, 2019). An excellent resource on obtaining highly accurate GNSS locations can be found in the Book "GPS for Land Surveyors".(Van Sickle, 2015) Figure 5 below shows a summary of the expected accuracy of the different technique available versus the distance from the base station to the remote location where coordinates are desired (baseline distance). In the case of Guam, a centrally located base station can provide baseline distances of less than 25 km anywhere on the island. Figure 5 shows that RTK techniques can easily provide levels of accuracy of 3 to 6 cm on Guam. (https://www.novatel.com/an-introduction-to-gnss/chapter-5-resolving-errors/gnss-data-post-processing/ (chapter 5 figure 45)). This is well within the accuracy range required for our studies. Figure 5 shows that Precise Point Positioning (PPP) techniques can provide level of accuracy of 5 to 11 cm. This technique has the advantage that no base station is required. Its disadvantages include lower accuracy than RTK, the technique requires long occupation times for each point (greater than 15 minutes), and post processing is required. Because of these limitations, the RTK technique remained the only viable error correction option to use on this project.

Figure 4. Sample Ground Control Point Used for Correcting Orthographic and DEMs Produced by the Processing Applications
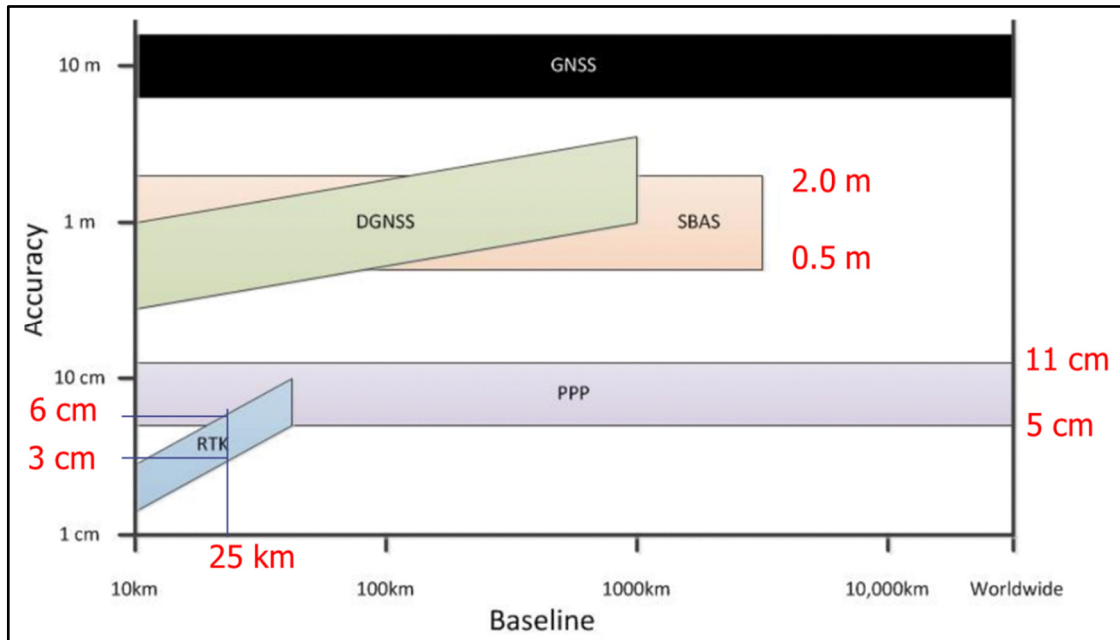
Figure 5. Accuracy of Various GNSS Correction Techniques

RTK requires that the carrier-based phase correction data be available at the time that the GNSS location data is collected. One common method of providing the required corrections during GNSS data gathering is called NTRIP. This stands for Network Transport of RTCM via Internet Protocol. RTCM is an internet protocol for sending GNSS data. The base station serving as the NTRIP server must be located at a precisely located position. It must also be equipped with a high accuracy GNSS unit and have access to the internet. Quite often in the United States, the NTRIP servers are located at US National Oceanic and Atmospheric Administration (NOAA) National Geodetic Survey (NGS) operated Continuously Operating Reference Stations (CORS) sites. A computer program called a caster takes in corrections from various base station sites. Each site in the caster is assigned a name called its mountpoint. The rover unit connects to the caster and requests the correction data from the desired mountpoint. The rover unit then combines the received correction with the known rover location data to compute the RTK corrected position of the rover station.

Currently the two CORS sites operated on Guam, named GUUG and GUAM, do not transmit NTRIP data. We are working with NGS personnel to equip the University of Guam CORS site, (GUUG) with NTRIP capability. A third site is operational at the Guam Memorial Hospital. This site is operated by The Guam Department of Land Management. That site sometimes operates on an intermittent basis and transmits an older format of RCTM correction messages (RCTM 2.3). Currently, we are not able to receive correction data from this site. In light of the above considerations, we decided to establish our own base station and NTRIP caster at the WERI building on the lower University of Guam (UOG) campus. The locations of all four of the GNSS reference sites are shown in Figure 6.
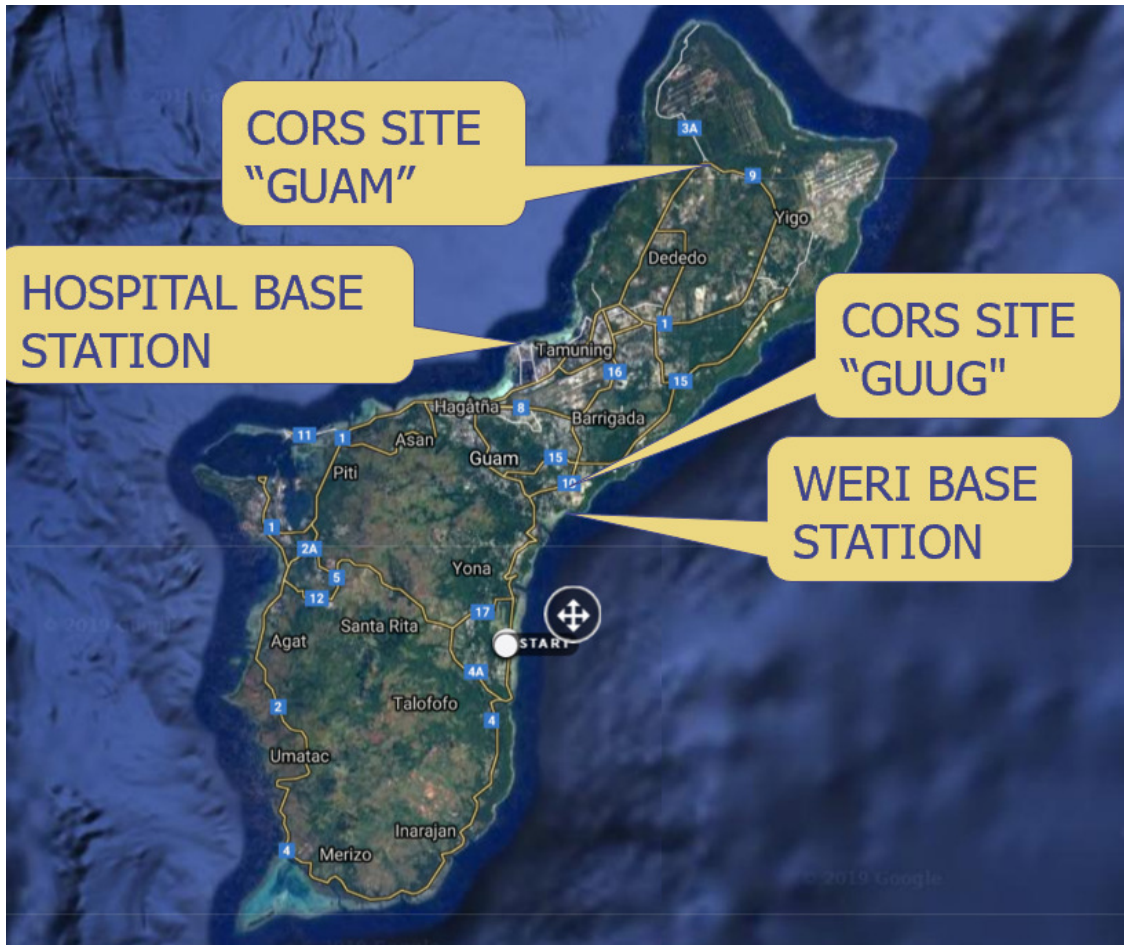
Figure 6. Location Map for Guam GNSS Reference Stations

The maximum baseline distance from any point on Guam to the GUUG and WERI base sites is 25 kilometers. The maximum base line distance from the Hospital site is 30 kilometers. From Figure 5, we can see that RTK techniques these baselines can provide our required accuracy of 3-6 centimeters. The maximum baseline distance from the GUAM CORS site is 42 kilometers. This baseline distance is at the high end for good RTK practice.

We installed an EOS Arrow Gold differential correction (RTK) base station at WERI. We also installed a survey grade GNSS antenna on the roof of the WERI building. The Antenna mount and antenna located at WERI are shown in Figure 7.

Figure 7. WERI GNSS Base Station Antenna

The EOS Arrow Gold (RTK) base station shown in Figure 8 is located in the WERI building. Connection to the roof mounted antenna is provided by coaxial cable.   The EOS Gold GNSS unit is connected through a serial connection to a P.C. running the EOS Server and EOS utility programs.   The EOS utility program is used for making changes and updates to the EOS Gold GNSS Unit. The EOS server program acts as the NTRIP Caster for providing corrections to the outside world via NTRIP.

Figure 8. WERI EOS Arrow Gold Base Station.

After making all the appropriate electrical connections between the EOS Gold Server and the NTRIP Caster computer, the next step was to be sure the NTRIP Caster was available to the outside world. This was accomplished with the help of the UOG Computer Center staff. They provided a pass-through port connection and an Internet Protocol (IP) address that allowed connection to the Caster from the outside world. This IP Address and PORT number along with a USER ID and PASSWORD are required to access the caster. The caster provides the MOUNT POINT list to the user. Once all the credentials are provided, the caster will deliver the correction data from the EOS Gold server directly to the remote GNSS unit via the Internet. The required credentials are issued to researchers desiring to access the WERI base station.

Extensive operations were carried out to establish an accurate location for the new WERI base antenna. Our goal was to obtain final GCP accuracies of 3 to 6-centimeters.   We used a technique called Post Processed Kinematic (PPK) to establish the WERI Base Antenna position. An excellent source for information on PPK and RTK is contained in the publication GPS for Land Surveyors ((Van Sickle, J, 2015), Chapter 7, page 241.

This technique uses the concept of a base station and rover working together. The base station is established at a point where the position and elevation are known very accurately. When the base station is activated, it examines the incoming GNSS signals and determines what corrections must be applied to these signals so that the computed position of the base station matches the known base station position within very high

accuracy limits. The base station makes these correction values available to any rover stations operating nearby through the NTRIP caster described previously. The rover then computes its position based on the corrections provided by the base station. This is a very simplified explanation of RTK. For more details one should look at the software manual for the computer program RTKLIB, (Takasu, Kubo, and Yasuda, (2013)).

We used the PPK option of the program called RTKLIB mentioned above to determine the accurate position of the WERI base station antenna. This program uses the base rover concept mentioned earlier to establish the accurate location of the rover station. We gathered output from the uncorrected WERI base station (as the rover station) for 24 hours. We also downloaded correction data from the GUUG CORS site (as the base station) for the same time period. The two data files served as input to the RTKLIB program. This program uses Kinematic computation procedures applied to the input files to establish very accurately the location of the WERI Base Station antenna. Luckily the WERI Base Station is located very close (0.7 km) from the CORS station GUUG located at UOG. The shorter the distance from the base to the rover (called the baseline) the more accurate the PPK computed position of the rover will be.

The RTKLIB program requires base station coordinates in the WGS 84 geographic coordinate system. We used the NGS Horizontal Time-Dependent Positioning program (HTDP) available on line (https://www.ngs.noaa.gov/TOOLS/Htdp/Htdp.shtml) to transform the published coordinates (NAD83 MA 11 2010) of the GUUG antenna L1 Phase center to the required WGS 84 Transit coordinates. These coordinates are shown in Table 1 below. We used the same program to adjust the epoch (satellite date) of our GUUG antenna coordinates to 1986. This coordinate system and epoch match the maps currently serving as base maps for WERI studies. The completely transformed coordinates are shown at the bottom of Table 1 below.

GUUG L1 CENTER ANTENNA LOCATION

COORDINATE SYSTEM	LATITUDE (DEG MIN SEC)	LONGITUDE (DEG MIN SEC)	ELLIPSOIDAL ELEVATION (METERS)
NAD 83 MA11 EPOCH 2010	13 25 59.51969	144 48 09.79382	132.823
WGS 84 T (7/1/1986)	13 25 59.51611 13.433198919 *	144 48 09.78972 144.4802719367 *	132.868
• Decimal Degrees			

Table 1. CORS Station GUUG GNSS Coordinate Transformations

Once the required input files and base station antenna coordinates are provided to the RTKLIB program, we can compute the rover position.   In our case the rover position is the location and elevation of our new WERI base station antenna. Those coordinates in WGS 84 T 1986 units are shown in Table 2 below.

WERI L1 CENTER ANTENNA LOCATION

COORDINATE SYSTEM	LATITUDE (DEG MIN SEC)	LONGITUDE (DEG MIN SEC)	ELLIPSOIDAL ELEVATION (METERS)
WGS 84 T (7/1/1986)	13 25 42.64320 13.428511999 *	144 47 57.52689 144.799313025*	75.7639
• Decimal Degrees			

Table 2. Weri Base Station L1 Center Antenna Coordinates

The required RTK correction information can be provided by the base station to the rover station by either an internet link called NTRIP, a radio Link or through file downloads using post processing. Figure 9 Illustrates these three processes. The process we applied to get the WERI base station antenna location is called PPK. Certain GNSS receivers can accomplish a similar process called RTK in real time mode in the field. Our WERI base station will provide the corrections to a rover unit which we are using to get our GCP positions. No post processing will be required. We will know the coordinates of our GCPs immediately.

The corrections between the base and rover units are provided through an internet or direct radio link. Luckily internet connection can be provided in most locations on Guam by using a cell phone or GNSS unit internal hot spot. We plan to use real time processing for the data we will be gathering for GCPs on Guam. If no internet connection is available, we will either use a remote base station or we will use post processing like what was used to establish the location of the WERI base station antenna. All three of these methods were tested successfully during this phase of the project using the WERI base station or remote base station.
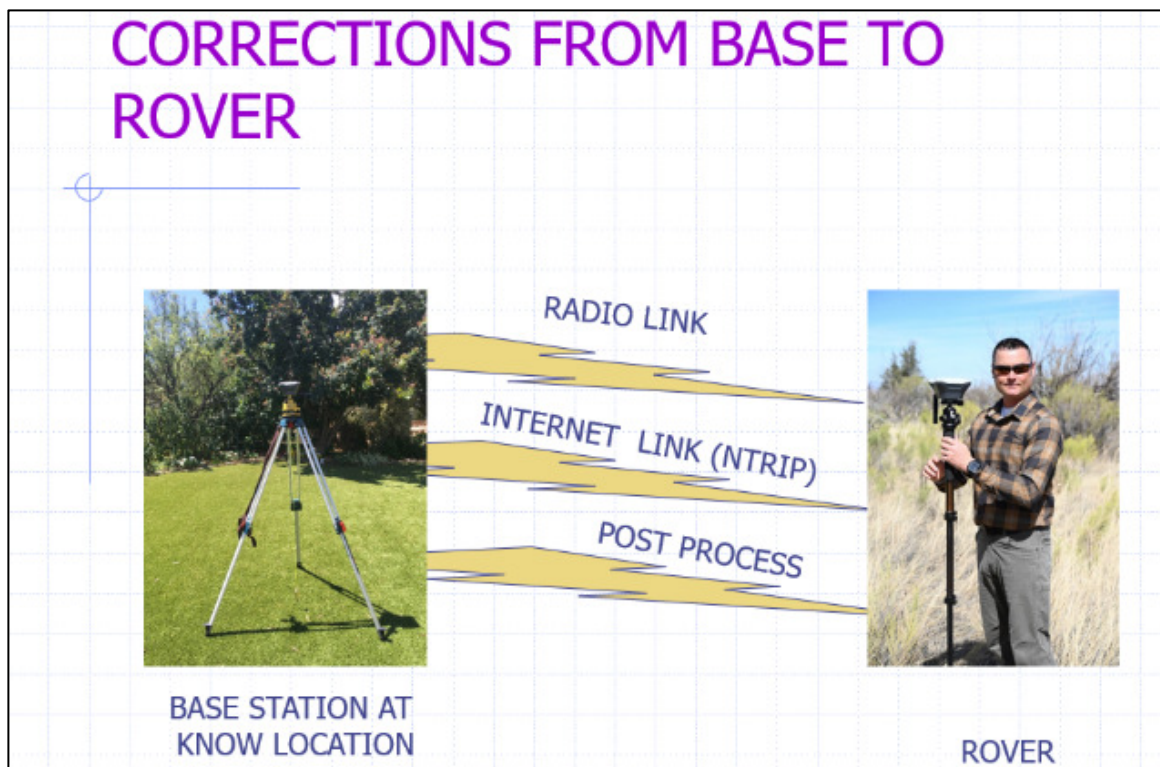
Figure 9. Providing Correction Data to the Rover Station

The radio link correction method was particularly useful in a project we carried out at Jeff's Pirate Cove near Yona, Guam. While we were working in this project area, the internet link to the WERI base station was severed by construction activities. This could have caused several days delay in our project activities. Instead we established a temporary base station shown in Figure 10 at the Jeff's Pirate Cove site. We established the coordinates of the remote base using PPK techniques discussed earlier. The base station was then set up to broadcast corrections by radio link to the rover station. We were easily able to gather the required GCP data for our sUAS drone imagery flights. Figure 11 shows the GCP locations that were gathered at this project site.

Figure 10. Jeff's Pirate Cove Remote Base Station Site

Figure11. Jeff's Pirate Cove GCPs Plotted in ArcMap

PHASE II

Provide extensive testing to be certain that base corrected rover coordinates gathered for GCPs match coordinates used in base maps available in WERI's GIS system.

GUAM NGS MONUMENTS

The first step in this phase was to gather the coordinates for all the NGS monuments on Guam. These monuments are the survey control for Guam and also have been used in the past to provide control for the Guam LIDAR maps used extensively by WERI. We used the NGS program available on line named
HTDP (https://www.ngs.noaa.gov/TOOLS/Htdp/Htdp.shtml) to transform the published coordinates which were in NAD83 MA 11 2010 coordinates to WGS 84 Transit 1986 coordinates. The WGS 84 1986 coordinates match those used by the WERI Base map satellite imagery and the WERI LIDAR DEMs. These coordinates can now be used as an accurately known location if it is desired to set up a temporary base stations over any of these monuments. The monument name and locational coordinates are shown in in Table 3 below.

We computed coordinates derived for Monument GGN 1215 using the WERI base station with our RTK GNSS rover units. We compared the derived coordinates to the published results. A plot of the monuments location and the location computed using RTK by our GNSS Rover unit is shown in Figure 12. Note that the difference in location between the published and measured is approximately 9 cm.   The ellipsoidal elevation difference was approximately 3 cm. During the course of the project field work the WERI optical Fiber high speed internet cable was severed by construction activities. Because of this disruption we were unable to compare the coordinates of any other of the other monuments against those computed using the WERI Base Station. Hopefully locational checks of other monuments can be carried out in the future.

GUAM NGS SURVEY MONUMENTS

NAME	WGS 84 LONGITUDE	WGS 84 LATITUDE	ELLIPSOIDAL ELEVATION	GEOIDAL ELEVATION
LOOK	144.7496981	13.42014469	192.0830	137.876
GGN 1217	144.8024896	13.43017781	120.0460	66.109
GGN 1215	144.801261	13.42892049	89.4080	35.472
GGN 1218	144.8019142	13.43469457	127.9920	74.014
CRUSHER	144.8164177	13.44935234	141.4620	87.475
HAWAIIAN	144.8360297	13.46349165	0.0290	-53.923
GGN 0012	144.8771306	13.49982176	0.0290	-53.906
VILLAGE GG	144.8137091	13.53871941	146.2360	91.675
TAMUNING	144.7904132	13.4924702	88.2410	33.838
AGANA MON	144.751166	13.47389288	57.3210	2.884
LIBERTY	144.753331	13.48111597	56.3000	1.853
GGN 1453	144.7430408	13.47724599	56.8940	2.439
GGN 0001	144.7300328	13.48030943	65.2090	10.743
ASAN 3	144.7135541	13.47260873	57.5620	3.104
163 0000 TIDAL 4	144.6554171	13.44184691	56.4780	2.262
NAMO 1	144.664097	13.40072983	56.9640	2.77
GGN 2235	144.6524315	13.37799944	56.9100	2.846
BEACH	144.650229	13.36455414	55.7730	1.766
GGN 2242	144.650478	13.35706752	68.2260	14.252
GGN 2256	144.6592146	13.33723731	183.5900	129.705
SOLEDAD	144.6600149	13.29508442	97.6830	44.192
GGN 2583	144.7235714	13.24981234	62.3370	9.455
GGN 2205	144.7632967	13.30997674	158.1770	104.954
SABLAN CASTRO	144.7673829	13.33936855	97.3870	43.932
NUTZ	144.7712721	13.34242768	57.7390	4.295
GGN 2456	144.7682506	13.36634361	58.9690	5.288
GGN 1962	144.7627335	13.38180626	154.1380	100.285
CUB	144.6875976	13.39865915	164.5850	110.339
GGN 1952	144.7739505	13.39698522	78.5820	24.694
MACAJNA	144.7376263	13.45479539	270.4080	215.99
GGN 1969	144.7451922	13.41900139	184.6180	130.397

Table 3. Guam NGS Survey Monuments in WGS 84 1986 format
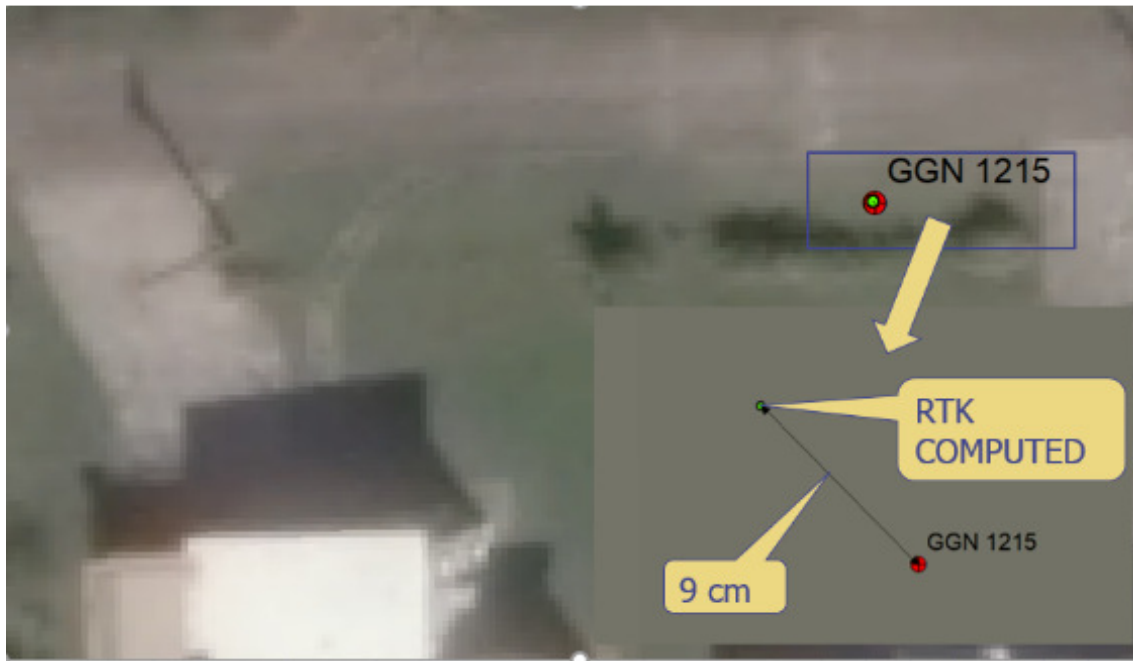
Figure 12. Guam NGS Monument Location plotted Against Monument Coordinates Found Using an RTK GNSS Unit

ASAN PARK PROJECT

Next, we checked the elevation accuracy of the coordinates gathered using RTK techniques applied to WERI base station coordinates. We chose to carry out this phase of the project at The War in the Pacific Memorial Park in Asan, Guam. The location of this site is shown in Figure 13. We used an Emlid RS2 RTK GNSS unit connected to the WERI Base Station through NTRP to collect data for 10 GCPs scattered around the park area. Figure 14 shows researchers gathering the GNSS data. Figure 15 is a GIS map of the Park area showing the location of the GCPs.

Table 4 shows the comparison of elevations observed during GNSS surveys and the elevation shown on the bare earth Lidar map used by WERI. Note that the GNSS survey provided elevations in WGS84 ellipsoidal elevations. The Lidar map used by WERI defines elevations in Geoidal elevations. An explanation of the difference between these two elevation systems can be found in the publication GPS for Land Surveyors (Van Sickle, 2015) (chapter 5 page 172). Guam uses the Geoid defined as Geoid 12B. We used the NGS program called Geoid 12 b calculator (https://www.ngs.noaa.gov/GEOID/GEOID12B/computation.html) to change the GNSS gathered ellipsoidal heights to the Geoid 12 B heights shown in Table 4.

Figure 13. Location Map for Asan Park Project Area

Figure 14. Researchers Gathering GCP Coordinate Data at Asan Park

Figure15. Asan Park GCPs Plotted in ArcMap

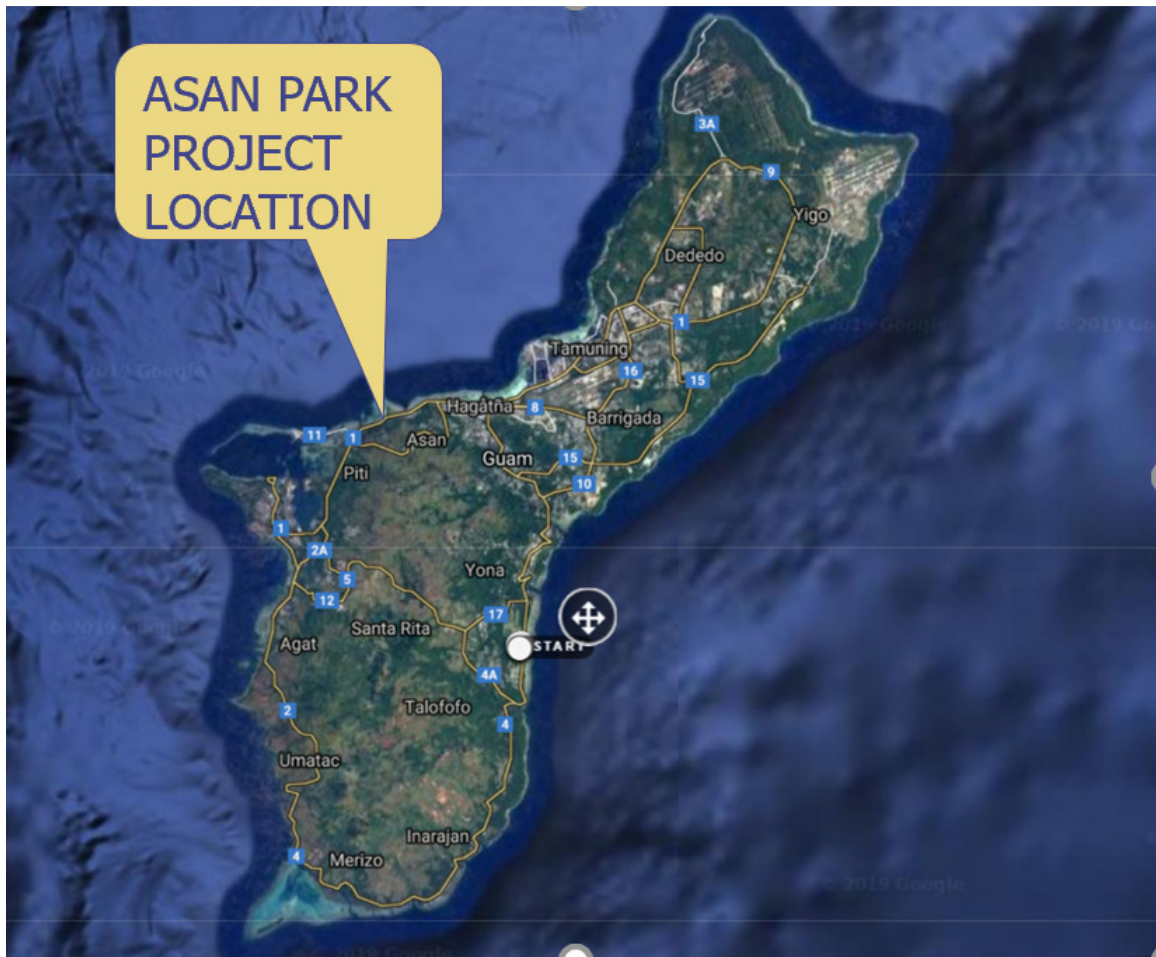| NAME	GCP GEOID ELEVATION (METERS)	LIDAR GEOID ELEVATION (METERS)	DIFFERENCE IN ELEVATION (METERS)	DIFFERENCE IN ELEVATION (FEET)
Asan 1	2.512	2.438	-0.074	-0.24
Asan 2	1.809	1.614	-0.195	-0.64
Asan 3	1.866	1.646	-0.220	-0.72
Point 4	3.551	3.439	-0.112	-0.37
Asan 5	3.141	2.998	-0.143	-0.47
Asan 6	3.434	3.431	-0.003	-0.01
Asan 7	2.925	2.930	0.005	0.02
Asan 8	2.806	2.661	-0.145	-0.48
Asan 9	2.843	2.656	-0.187	-0.61
Asan 10	3.193	3.084	-0.109	-0.36

Table 4 Asan Park Comparison of GCP Elevations to Lidar Data Elevations

The average difference between the LIDAR map and the GCP elevations was 0.12 meters. The accuracy of the LIDAR map is shown in the Metadata as being between 0.25 and 0.35 meters. The average of the difference between the GNSS measured elevations and LIDAR elevations is well within the published accuracy of the LIDAR data.

JEFF'S PIRATE COVE PROJECT

Next, we wanted to test how well the processed sUAS gathered imagery would match the existing satellite imagery available at WERI. To accomplish this, we did a complete photomosaic development of the imagery gathered during a sUAS flight over a project area located at Jeff's Pirate Cove near Yona, Guam. Figure 16 shows the location of the site. We chose this area because it contained a stream reach, was located near the WERI building and the owner (Jeff Pleadwell) granted us full access to the sight. The first step in this process was to lay out our proposed drone flight using the DroneDeploy web site (https://www.dronedeploy.com).

Figure 16. Location Map for Jeff's Pirate Cove Project Area

This web site was used to develop the flight parameters and to layout the flight routes. The companion DroneDeploy iPad App was used to control the drone during the imagery flights. Flight parameters such as flight direction and elevation and photo overlap were input to the web site program and the program developed the flight lines required. The flight was designed for our DJI Inspire 2 drone. The flight elevation was 100 ft which resulted in pixel resolution of .4 in or 1 cm. The flight lines superimposed on the project area are shown in Figure 17.

Figure 17. Jeffs Pirate Cove Project Flight Lines Superimposed on the Project Area
(From DroneDeploy App)

Using the DroneDeploy flight lines, we chose the desired locations to place the GCP
panels. Our goal was to get good aerial coverage of nine panels across the project area of
interest. Figure 18 shows the GCP locations that were chosen.

Figure18. Jeff's Pirate Cove Project GCP Locations Shown in ESRI ArcMap

We place GCP panels, as shown in Figure 4, at each of the selected GCP locations.
These panels were designed to be visible in the aerial imagery that would be gathered.
Next, we used an Emlid RS2 RTK GNSS unit to collect data for the nine GCPs scattered
around the project area. The GNSS techniques were the same as described above for the
Asan park area. As was mentioned earlier, because of internet difficulties we set up
another Emlid RS2 GNSS to act as the base station for our GCP surveys at this site. We
used the PPK option of the RTKLIB program to establish the coordinates for the portable
base station.

We used the DroneDeploy App on an iPad as the flight controller for a DJI Inspire 2
drone for the aerial imagery gathering. We carried out two image gathering missions.
One at 100 feet and one at 210 feet. We will be providing illustrations here from the 100-
foot flight. We captured 498 images during the 100-foot flight. Figure 19 shows one of
the images that was gathered during the flight. All images for the 100-foot flight were
gathered at 1 cm/pixel resolution.   Note the GCP panel is visible on the image.

Figure 19. Jeff's Pirate Cove Project Raw Imagery from sUAS Imagery Gathering Mission

The next step in the process was to merge the digital imagery captured during the flights into what is called a digital orthomosaic. The goal of this process is not only to stitch the aerial imagery together, but to have the resulting products be correct in scale and matching the WGS 84 T 1986 geographic coordinate system of the GCPs. Additionally, two DEMs were developed with the same geographic reference system as the orthomosaic. The elevations used matched the geoidal elevation coordinates of the GCPs. The two DEMs developed are called Digital Surface Models (DSM) and Digital Terrain Models (DTM). The DSM model represents the elevation tops of all surface vegetation in the area. The DTM model represents elevation of the bare earth surface in the area.

The program used to develop the Orthomosaics and DEMs was Drone to Map (D2M) developed by Environmental Systems Research Institute (ESRI). This program is designed to interact easily with the ESRI ArcMap products used by WERI.

The first step in using D2M is to bring the aerial imagery from the drone flights and the coordinate data for the GCPs together into the D2M interface. After loading the imagery and GCP data, the program overlays the data on to a map window. Figure 20 shows the D2m interface with the map locations of the centers of all images that were imported for the Jeff's Pirate Cove project. Figure 21 shows the GCPs plotted over a portion of the flight lines.
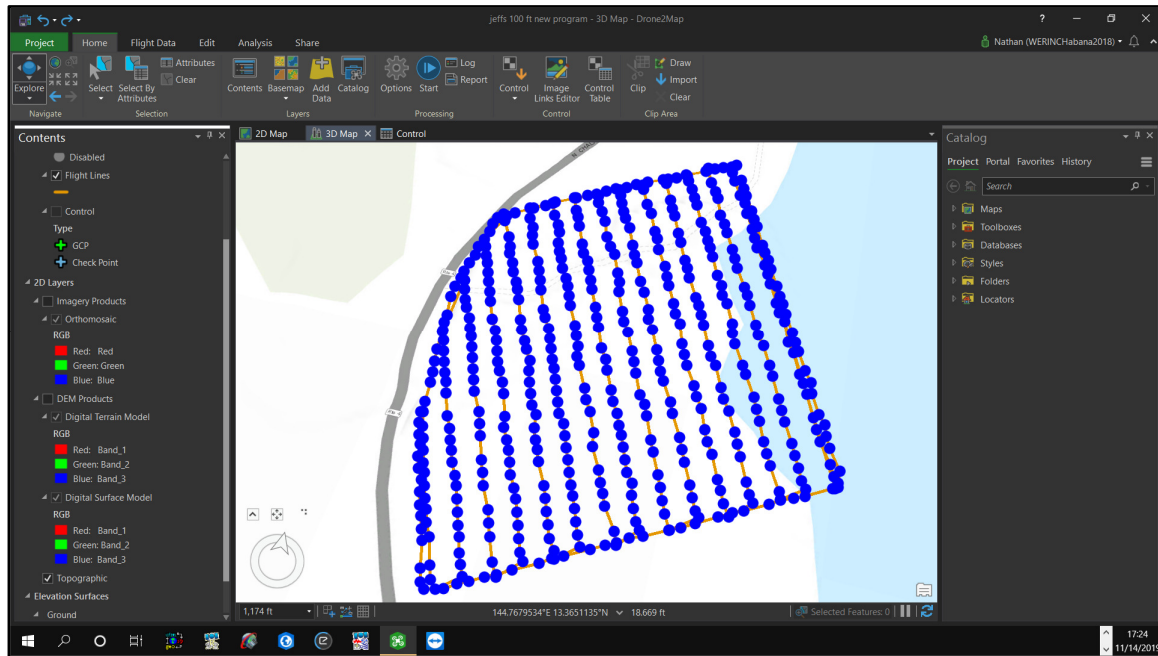
Figure 20. Jeff's Pirate Cove Project Showing Image Centers for all Images Used
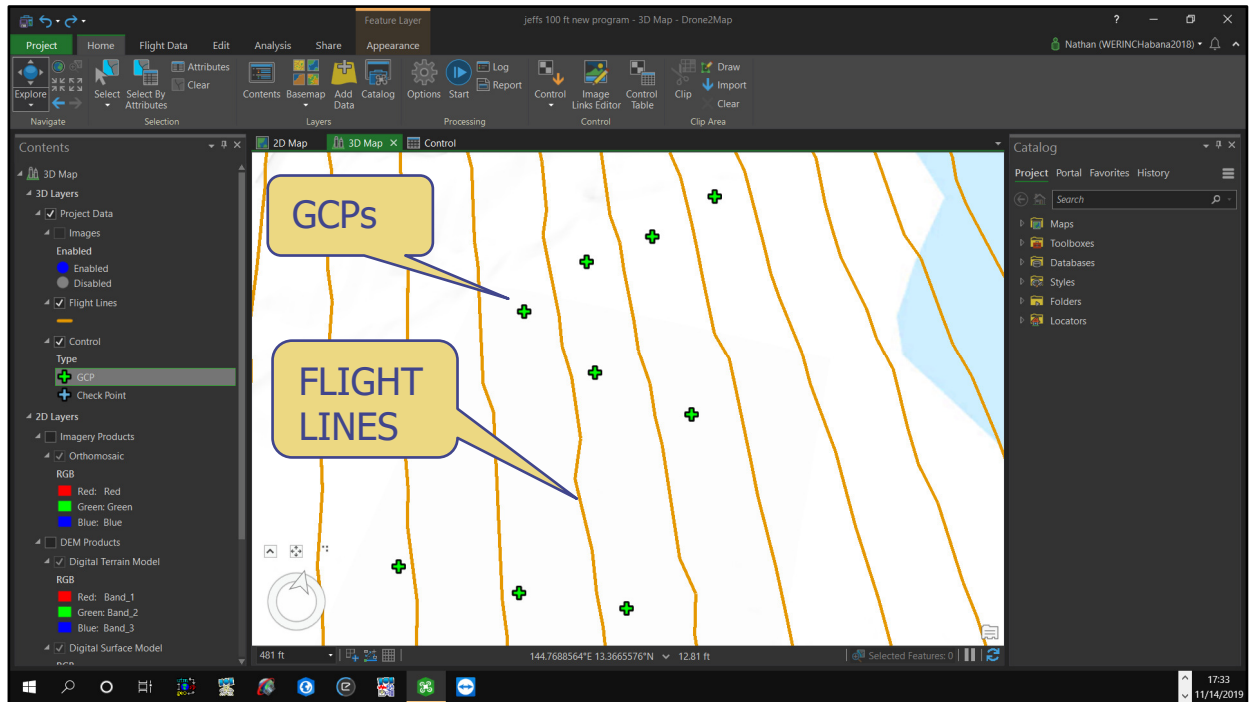
Figure 21. Jeff's Pirate Cove Project Showing GCPs and Flight Lines

The next step in the process involved linking the location of the GCP panels on the images with the data set of the coordinates of the GCPs measured during our RTK GCP surveys. This is accomplished by the user in the image link editor. Figure 22 Shows the image link editor window. The user identifies the precise GCP location on between 3 to eight images showing that GCP panel. The process is repeated for each of the GCP locations. This is tedious and somewhat time consuming, but essential to developing composite imagery and DEMs that match actual geographic coordinates and elevations of our GIS maps.
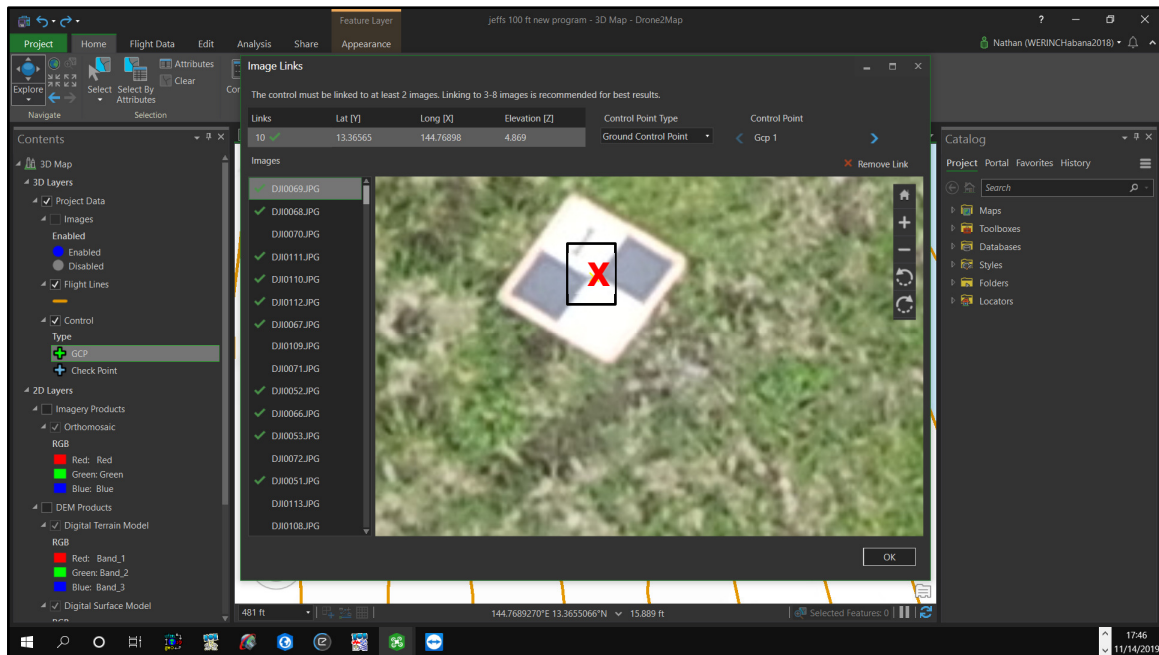
Figure 22. Done to Map Image Link Editor Window

After the images and GCPs are linked, it is time to do the actual image processing. The program uses photogrammetric processing to mosaic the input images. The processing also includes development of DSMs, DTMs, and surface contours. Figures 23 shows the entire digital orthomosaic developed in the D2M program. Figures 24 shows an enlargement of part of the same area. Figure 25 shows the same enlarged area as seen on the WERI satellite imagery. This shows the greater picture fidelity from going from the 0.3-meter resolution satellite image to the 1-cm resolution using the drone imagery.
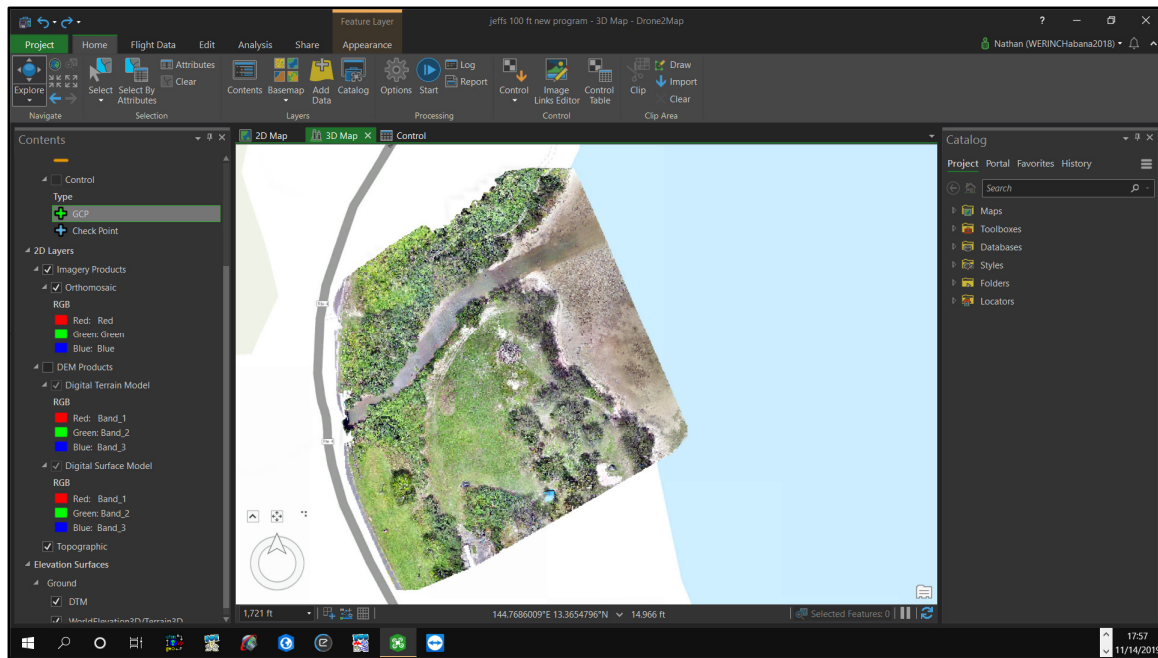
Figure 23. Orthomosaic of Jeff's Pirate Cove Project

Figure 24. Enlargement of Orthomosaic of Jeff's Pirate Cove Project

Figure 25. Enlarged Portion of Jeff's Pirate Cove Project Showing the WERI Satellite Imagery

It is very important that the final composited orthophoto coordinates match the GCP coordinates that were gathered at the project site. Figure 26 shows an enlargement of the composited orthophoto showing GCP 1. The distance between the actual coordinates measured using RTK techniques and the coordinates of the center of the GCP on the orthophoto was approximately 2.4 cm or just less than 1 in. The distance was measured using our ArcView GIS program. This accuracy is well within the bounds required for our environmentally oriented studies.
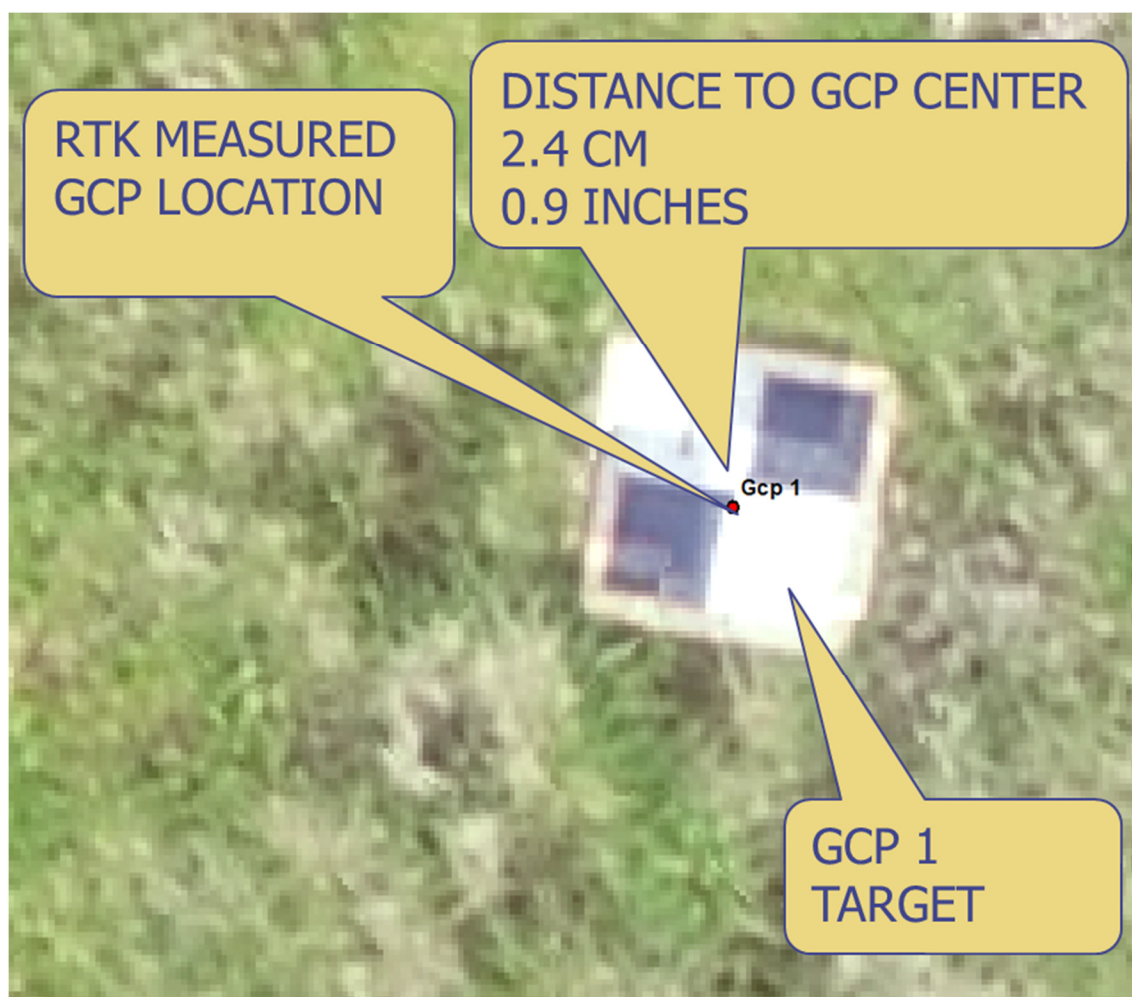
Figure 26. GCP Measured Location Versus GCP Location on the Composited Orthophoto

Another important factor is how well does the composited orthophoto fit WERI's satellite base map imagery. To investigate this fit parameter, we picked a physical feature that could be seen on both our satellite imagery and the composited orthophoto. We chose to use the base of an entrance sign that could be seen in both the satellite imagery and the composited orthophoto. Figure 27 shows this sign in the satellite imagery. The South East corner of the sign based is marked with a red marker. Figure 28 shows an enlargement of the satellite image again showing the estimated sign base corner. Figure 29 shows the Enlarged Composited Orthophoto showing the entrance sign base along with the base corner marker. There was approximately 2 cm difference between the corner shown in the composited imagery and that shown in the satellite imagery. This degree of accuracy is well within the limits required for our environmentally oriented studies.

Figure 27. Jeff's Pirate Cove Entrance Sign Showing the South East Corner Location
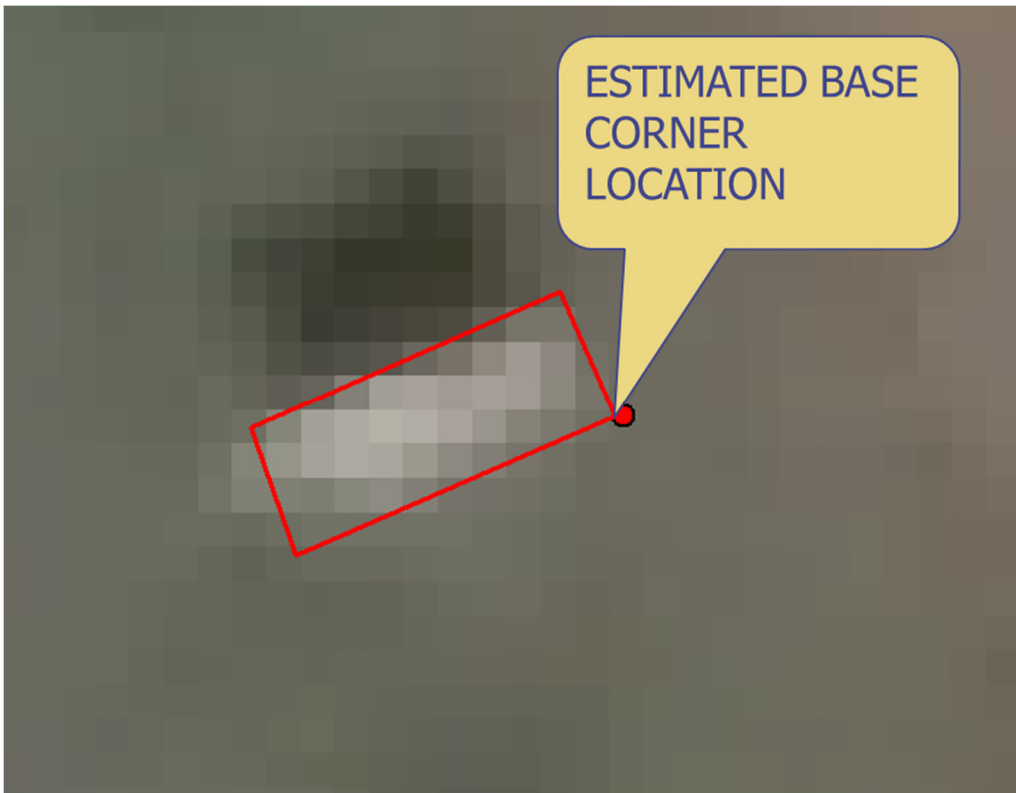
Figure 28. Enlargement of Entrance Sign Location Showing the South East Corner Location

Figure 29. Composited Orthophoto Enlargement of Entrance Sign Location Showing the South East Corner Location

Figure 30 shows and enlarged portion of the DTM that was developed. Note this model represents the bare earth elevations as computed by the D2M program. Figure 31 shows the same area as seen in the DSM which represents the tops of vegetation in the area. Hopefully by having the DTM and DSM views we will be able for the first time to see the vegetated areas stripped of vegetation in detail.   We should then be able to compare the hydrologic and environmental effects of vegetation on an area.

Figure 32 shows a profile line drawn through the project area. Figure 33 show the cross section for the profile line shown in Figure 32. It easy to see the effect of removing the vegetation that occurs when going from the DSM to the DTM. Figure 34. shows elevation contours for the project area. These contours were drawn at 0.2-meter intervals computed from the DTM data. The detailed profiles and elevation contour maps that can be developed from the DTM and DSM data will be invaluable for carrying out various hydraulic engineering and environmental studies.

Figure 30. Digital Terrain Model (Bare Earth) of Jeff's Pirate Cove Project

Figure 31. Digital Surface Model (Top of Vegetation) of Jeff's Pirate Cove Project

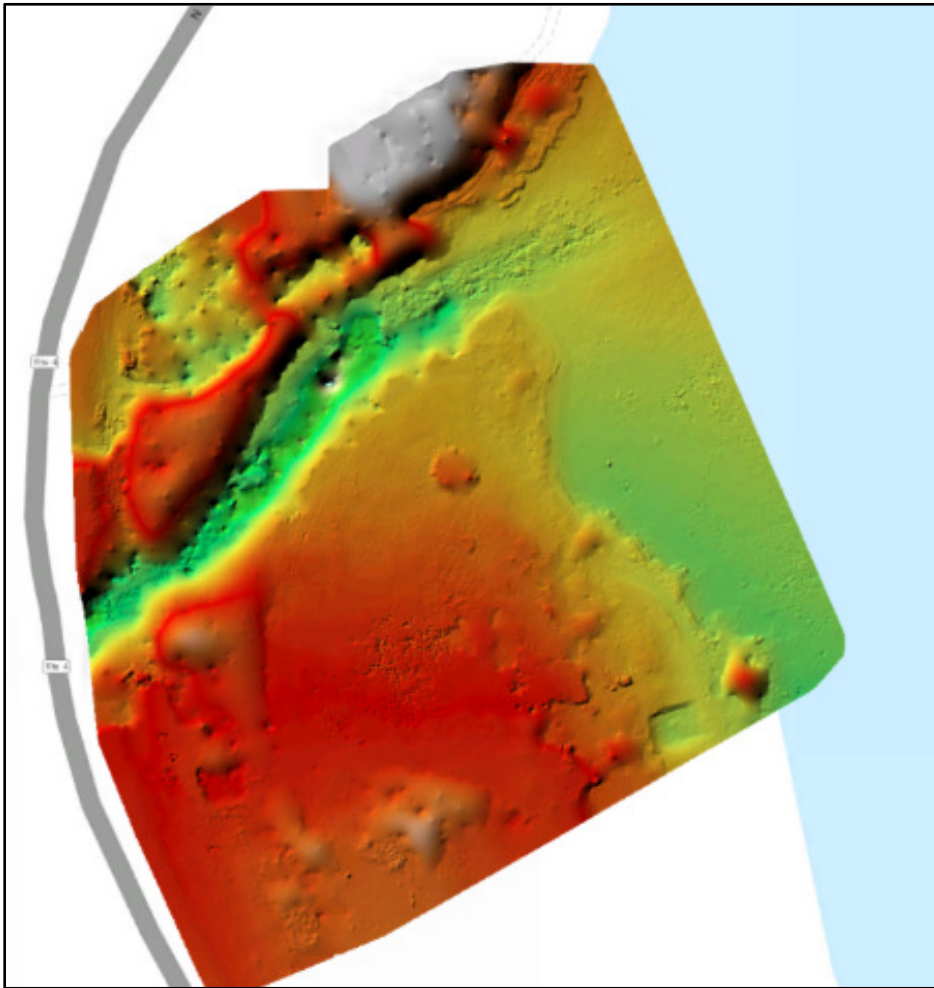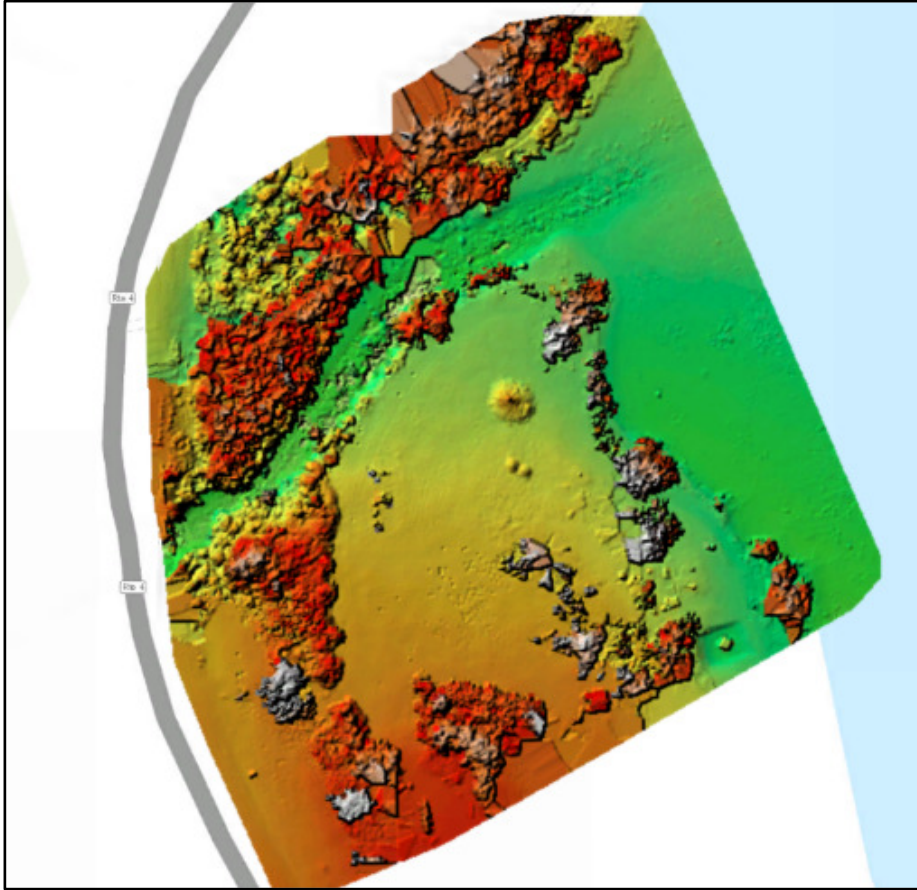Figure 32. Profile Line Drawn Through the Area of Jeff's Pirate Cove Project
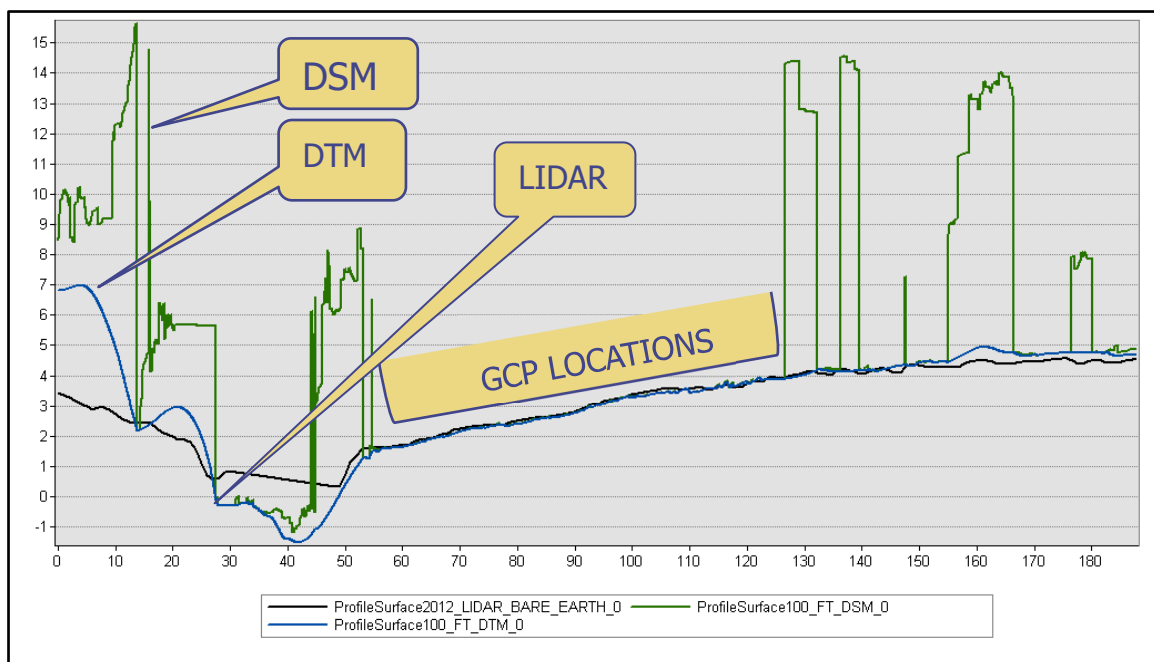
Figure 33. Cross Section Along the Profile Shown in Figure 32
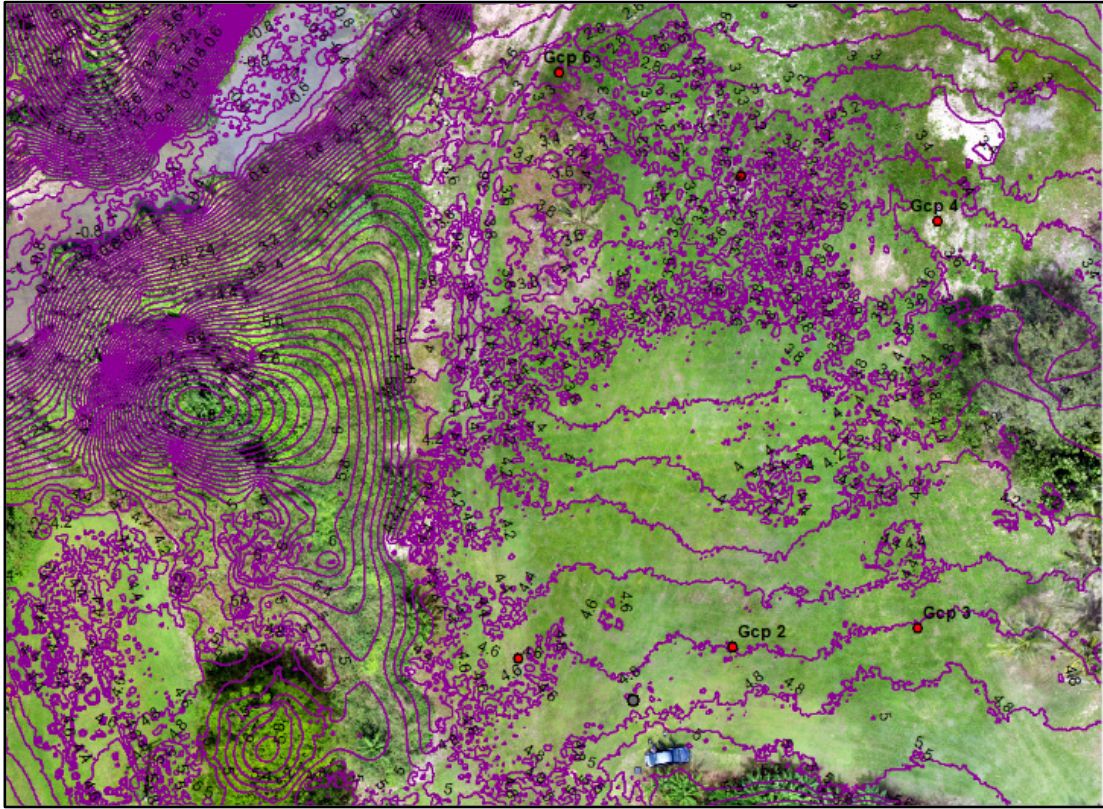
Figure 34. Elevation Contours at 0.2-meter intervals drawn from the DTM

SANTA RITA SPRINGS PROJECT

The final project that was carried out as a result of this project was located at Guam Waterworks Authority's (GWA) Santa Rita Springs Water Source Facility. This site is presently planned for renovations and WERI is carrying out various research and planning projects at the site. The location of this facility is shown in Figure 35. Figure 36 shows details of the site as presented on composited sUAS orthoimages of the site. The goal of this project was to gather precision latitude and longitude and elevation coordinates for the survey monument located at the site and to gather the coordinates of test wells that were drilled by WERI at various locations around the site.

Figure 37 shows the location of the survey monument located at the site. The monument is located directly under the intersection point on the GCP. Since the WERI base station was not operating because of technical difficulties with WERI's internet connection, we established a temporary base station over the monument. We gathered 30 minutes of Receiver Independent Exchange Format (RINEX) GNSS data from the base station site. The base station RINEX data was post processed using the previously mentioned PPK option of the RTKLIB program.   We used the GUUG CORS site data as the base station data input to the RTKLIB program. As can be seen on Figure 37, the GNSS elevation data agreed with the Lidar map elevation data to within 5.2 cm. This is well within the accuracy bounds of RTK GNSS data and the Lidar elevation maps.

39

Figure 35. Location of the Santa Rita Springs Project

Figure 36. Santa Rita Spring Site Shown on Composited sUAS Orthoimages
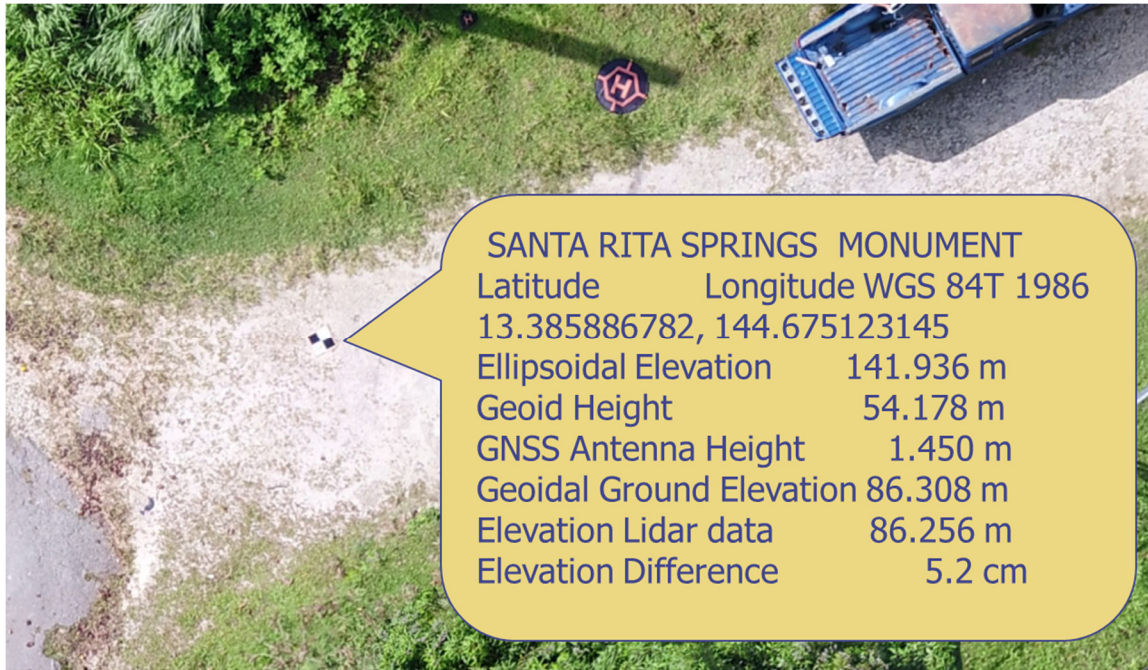
Figure 37. Details of the Santa Rita Springs Monument Position Coordinates

After computing the Santa Rita Monument location coordinates, we returned to the site and gathered locational coordinates for The WERI well locations and for other locations along the perimeter fence. Because of previously described internet problems with the WERI Base station, an Emlid RS2 GNSS unit was set up as a base station over the Santa Rita Springs Monuments. The base station sent correction values to an RS2 Rover through a Long-Range Radio (LoRa) link. Table 5 shows the location data that was collected. Note that a Fix Solution status was obtained for only Point 2. The lateral error for that point was 1.4 cm. A "Fix" solution is required to get centimeter accuracy rms accuracy values. The average lateral rms error values for all points measured was 25 cm. There are two probable reasons for the low accuracy of the measurements. The first being the blocking of the LoRa signal between the units by vegetation and buildings. This blocking increased fix times substantially. Secondly environmental conditions did not allow for long time occupation at the measured points. There were swarms of mosquitoes at the site which kept the researchers on the move to avoid attacks by the mosquitos. We suggest re-measurement at the site. We also suggest using NTRIP data transfer between the GNSS RTK units, and also providing adequate insect protection for those making the measurements.

index	name	longitude	latitude	elevation	collection start	collection end	solution status	lateral rms	sample count	antenna height
1	Point 1	144.6751903	13.38584549	139.953859	2019-10-22 02:04:40 UTC	2019-10-22 02:05:12 UTC	FLOAT	0.1542	161	2.134
2	Point 2	144.6752491	13.38575534	140.1307477	2019-10-22 02:05:58 UTC	2019-10-22 02:06:24 UTC	FIX	0.0139	65	2.134
3	Well 1	144.6753187	13.38574507	139.7845674	2019-10-22 02:07:03 UTC	2019-10-22 02:08:04 UTC	FLOAT	0.0879	304	2.134
4	Point 4	144.6753342	13.3857445	139.6384922	2019-10-22 02:08:20 UTC	2019-10-22 02:09:27 UTC	FLOAT	0.2771	335	2.134
5	Point 5	144.6753922	13.38574695	139.8931194	2019-10-22 02:09:50 UTC	2019-10-22 02:11:17 UTC	FLOAT	0.5615	434	2.134
6	Point 6	144.6754009	13.38578906	139.1932731	2019-10-22 02:11:44 UTC	2019-10-22 02:12:45 UTC	FLOAT	0.2055	305	2.134
7	Point 7	144.6754613	13.38578126	139.013575	2019-10-22 02:13:14 UTC	2019-10-22 02:14:24 UTC	FLOAT	0.3185	12	2.134
8	Well 4	144.6754783	13.38580156	139.0464521	2019-10-22 02:14:51 UTC	2019-10-22 02:15:52 UTC	FLOAT	0.5118	305	2.134
9	Well 5	144.6755244	13.38583043	140.1358367	2019-10-22 02:16:15 UTC	2019-10-22 02:17:17 UTC	FLOAT	0.1431	308	2.134
10	Well 6	144.6755558	13.38587974	141.443568	2019-10-22 02:17:49 UTC	2019-10-22 02:18:50 UTC	FLOAT	0.4589	306	2.134
11	Point 11	144.6755597	13.38587515	139.6422717	2019-10-22 02:19:29 UTC	2019-10-22 02:20:30 UTC	FLOAT	0.2051	304	2.134
12	Point 12	144.6752464	13.38589605	138.2307146	2019-10-22 02:23:20 UTC	2019-10-22 02:24:25 UTC	FLOAT	0.1227	321	2.134
13	Point 13	144.6752671	13.38587897	138.703123	2019-10-22 02:24:33 UTC	2019-10-22 02:25:34 UTC	FLOAT	0.2534	305	2.134
14	Point 14	144.675294	13.38590286	138.7951218	2019-10-22 02:25:54 UTC	2019-10-22 02:26:53 UTC	FLOAT	0.2163	298	2.134
15	Point 15	144.6753544	13.38595132	138.2351597	2019-10-22 02:27:09 UTC	2019-10-22 02:28:13 UTC	FLOAT	0.1672	318	2.134

Table 5. Santa Rita Springs Project Location of WERI Wells and Boundary Fence Corners

COMMENTS ON GNSS
ACCURACY AND PRECISION

The main purpose of this study was to explore just how well WERI's new RTK base station coupled with an RTK GNSS rover could produce both accurate and precise results.

The term accuracy and precision are very specifically defined when discussing computed GNSS coordinate data. Accuracy refers to how well computed points match a particular coordinate system of latitude, longitude and elevation. Precision refers to the repeatability of the location and elevation data. Sometimes the two terms are confused and sometimes accuracy is used for either term.

Figure 38 illustrates the concept of GNSS location accuracy versus precision. The "targets" represent the location of a point on the earth's surface which we want to locate in a particular coordinate system. The target bullseyes represent the correct location of our point in that coordinate system. We want to have the plotted RTK measured points 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. Its statistical locational error is very low. 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 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 this highly accurate and highly precise category.

When looking at the output from a GNSS receiver one must keep in mind this concept of precision and accuracy. In uncorrected GNSS output, the accuracy/precision data that is generally provided only really provides a measure of precision. It is merely a statistical measure of the limit of the coordinates calculated usually in statistical terms. These are usually computed as one or two standard deviations plus and minus from the mean of several measurement. Usually the locations and errors are expressed in terms of the latest rendition of the WGS 84 ellipsoidal coordinate system.

LOW ACCURACY
HIGH PRECISION

CORRECT SOLUTION IS
CENTER OF BULLSEYE

HIGH ACCURACY
HIGH PRECISION

X

PRECISION

LOW ACCURACY
LOW PRECISION

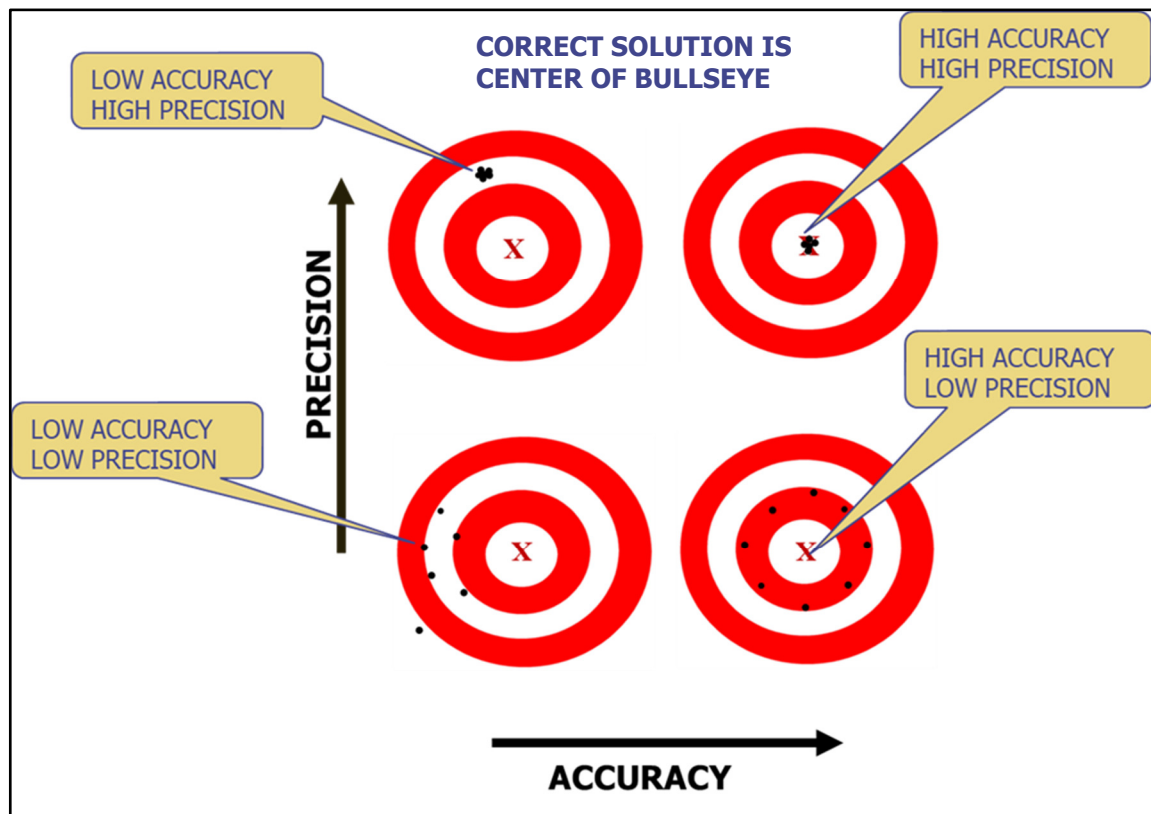HIGH ACCURACY
LOW PRECISION

X

X

ACCURACY

Figure 38. GNSS Location Accuracy Versus Precision

If the GNSS unit applies on the fly corrections or if post processing is used, we must be very cognizant of what coordinate systems are being used during the correction process. Corrected data can use various coordinate systems depending on the correction techniques used. If the correction technique does not use the coordinate system which the users map system is defined, then the accuracy of the data will always be in question.

Satellite Based Augmentation Systems (SBAS) apply corrections derived from a broad area of base stations. One must be sure of the coordinate system (generally some rendition of WGS84) that the corrections are based.

Differential GPS (DGPS) corrections are based on the coordinates system used by the base station. Locational data is provided in the coordinate system of the Base station. Real Time Kinematic (RTK) correction solutions are generally provided in the WGS84 coordinate system. DGPS and RTK corrections improve both the precision and accuracy of the results.

One must keep in mind that the WGS84 ellipsoidal definition is not the only geographic definition of the earth shape that is used by geodesists and surveyors. In fact, the WGS 84 ellipsoid has changed many times since the original was developed. The changes were generally small dealing with the length of major and minor axis of the ellipsoid and

the location of the center of mass of the earth. In the days when GNSS accuracy was in the tens of meters range, the changes in the ellipsoid didn't really change the computed location of a point on the earth surface by a meaningful amount. In today's GNSS world, we can define point locations in terms of centimeters or sub centimeter ranges. In those cases, we must be very careful to know which coordinate system is being provided by the GNSS unit and what coordinate system we are using in our mapping system.

Another consideration is that the GNSS location coordinates are based on distances from the GNSS satellites and not actually tied to any particular real point on the earth's surface. One problem arises because the location of a point on the surface of the earth is not constant with time. This is caused by tectonic plate movement. If we look at the data sheet for the GUUG CORS station on Guam, we see that it is moving at a velocity of 0.21 centimeters laterally per year. While this doesn't seem like much, it can add up over time. If we were working with a map that was made say 30 years ago, a point on that map measured today with an accurate corrected GNSS observation could be different by as much as 6 centimeters. We are confronted with that problem when we use our Guam satellite imagery map which is based on 1986 locational data. Depending on our accuracy requirements, this may or may not be a concern. These days accurate GNSS coordinates should be referenced with the coordinate system used and the satellite time (EPOCH) that applies to when the values were measured.

In some cases, the rover station might have built in transformation capability. In this case the user can request the output to be provided in a coordinate system and epoch other than a particular WGS84 system. If this capability is not available, we can make the required transformation by using the National Geodetic Survey (NGS) Horizontal Time Dependent Positioning (HTDP) program that is available online. This program allows us to easily transfer coordinates between various coordinates system and time epochs. In either case, the accuracy of our final answers will be improved by applying these techniques.

In all cases, we must evaluate with a bit of suspicion, the coordinates that appear on our GNSS unit screens or output by our correction software. These coordinates were derived using some very complex mathematical computations and should always be evaluated carefully for their **Accuracy** and **Precision**.

SUMMARY AND CONCLUSIONS

The primary objectives of this project were to establish that the WERI GNSS base station was providing accurate GNSS RTK correctional data. The goal was that final coordinates derived by rover stations using the WERI base station would have accuracies and precisions in the 3-6 cm range when compared to existing WERI satellite imagery and Lidar data. Because of the accuracy/precision restrictions and the desire to have immediately available coordinates, RTK analysis was chosen as the best correction technique.

The first step in accomplishing these goals was to very accurately establish the latitude and longitude data for the WERI base station antenna. This was accomplished by first transforming the coordinates of the GUUG CORS site to coordinates matching those used by the WERI satellite imagery and LIDAR DEMs (WGS 84 Transit epoch 1986). This transformation was accomplished using the NGS HTDP program. Next the RTKLIB program was applied in post processing mode to compute the coordinates of the WERI base station antenna based on the GUUG coordinates. Because of the short baseline distance between the GUUG CORS station and the WERI base station antenna, the accuracy of the RTK derived WERI base station antenna coordinates fell within our 3-6 cm accuracy goal.

Next, several projects were carried out to evaluate whether applying RTK correction techniques using the WERI base station could provide us with composited ortho images and DEMs meeting our accuracy and geo-referenced fit requirements. The first project was carried out in the War in the Pacific Memorial Park near Asan, Guam. We placed 10 GCPs in the park area and then determined the latitude, longitude, and geoidal elevation coordinates for each GCP. The average difference between the LIDAR map and the GCP elevations was determined to be 0.12 meters. This average is well within the published accuracy of the LIDAR data.

Next, we carried out a project to test how well processed sUAS gathered imagery would match the existing satellite imagery available at WERI. We developed a complete set of composited images, DTMs and DSMs for a site near Yona, Guam. We then chose a physical feature that could be seen on both our satellite imagery and the composited orthophoto. There was approximately 2 cm difference between the feature shown in the composited imagery and that shown in the satellite imagery. This degree of precision is well within the 3 to 6 cm criteria required for our environmentally oriented studies. This project also showcased the advantage of having both DTM (bare earth) and DSM (top of vegetation) models of a study area. The detailed profiles and elevation contour maps that can be developed from the DTM and DSM data will be invaluable for carrying out various hydraulic engineering and environmental studies.

A final project was carried out at Santa Rita Springs near Santa Rita, Guam. The project area is the Site of the GWA Santa Rita Springs water supply project. We established a PPK determined location of the survey monument at the site and explored the use of using a LoRa radio link between a temporary base station located at the monument and an RTK GNSS rover unit.

The overall conclusion for the project is that the WERI base station can provide RTK corrections to rover units around Guam with accuracies and precision in the range from 3 to 6 cm. Ground control point locations determined using the WERI base station and RTK techniques can be used to develop composited orthophotos that can provide locations and elevations information that match existing WERI satellite imagery and LIDAR data.

FUTURE STUDIES

If WERI is serious about continuing with the sUAS drone imagery program, it is recommended that a new RTK capable GNSS unit be purchased to be used with the WERI RTK base station. WERI's exiting Trimble unit has hardware problems which make it very undependable and difficult to use. To replace the existing WERI Trimble unit will require quite a sizable investment if similar capabilities are required and to include RTK capabilities. Trimble is now selling their model GEO7 X for a hardware base price of $6000. To add the required software and extend the units capability to RTK adds and additional $8,000 to the base price. This brings the total price of a Trimble replacement unit to $14,000. Since portability and ease of use are important concerns to WERI faculty, the Trimble GEO 7 all in one handheld looks quite attractive. Currently, if 2-10 cm RTK accuracy is desirable, a survey grade antenna is a must. Adding a survey grade antenna (larger than an internal handheld antenna) requires the use of a range pole to accurately place the antenna over the desired survey point and adjust the antenna orientation to the GNSS satellites. This does place portability and field usability limitations on the unit.

Another option would be to purchase an EOS Arrow Gold similar to that used for the WERI base station. This unit would work well with the existing base station. The cost would be approximately $8,000. The downside again is the EOS Arrow units require a tablet for output and a range pole mount for the antenna. This would limit field portability of the unit.

A third option would be to purchase an Emlid RS2 unit similar to that used in this project. The unit used in this project was the personal property of one of the researchers involved in the study and therefore is no longer available at WERI. The base educational discount price of one RS2 unit is $1451.00. One could by two units and if needed use the extra unit as a remote base unit if the need arises The Emlid RS2 unit also require a tablet or cellphone (iPad or Android) and range pole mount for the antenna. This would again limit field portability of the unit. The Emlid unit is not well suited for the casual user. It uses extended connectivity to wireless networks and hot spots to communicate with the user and the outside world. This make it more problematic for the casual user.

Without the purchase of a new RTK capable GNSS unit, the ability to produce high accuracy sUAS drone imagery will be seriously affected.

If and when a new RTK capable rover unit is purchased, it is suggested that a selection of the Guam NGS Monuments be visited as a check on RTK accuracy at various locations around the island.

ACKNOWLEDGMENT

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