@GSA: Teaching SfM and GNSS/GPS Methods to Undergraduates in the Field

October 7-8, 2022
Boulder, CO

UNAVCO Idaho State University USGS science for a changing world

Short Course Materials

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Table of Contents

Skip to Main ContentSkip to Navigation

Instructor Materials: Overview of the *High Precision Positioning* module

Module Goals

Students will be able to:

1. **Design** and **conduct** static and/or kinematic GPS/GNSS surveys to **address** a geologic research question.
2. **Apply** the findings of GPS/GNSS surveys to issues important to society
3. **Justify** why different high-precision positioning techniques are appropriate in different situations.

Supports Earth Science Big Ideas ESBI-1: Earth scientists use repeatable observations and testable ideas to understand and explain our planet; ESBI-4: Earth is continuously changing; ESBI-7: Humans depend on Earth for resources; and ESBI-8: Natural hazards pose risks to humans.

Summative Assessment

The overarching Summative Assessment for the module is a series of critical thinking questions that ask students to synthesize learning across the different units. Instructors may elect to use some of these questions for final exams or other final assessments. In addition, each unit includes important summative assessment questions for topics and concepts specific to that unit. These are also critical because there is a high probability that most teachers will only teach a subset of the units. The assessment questions are broad because each instructor will use a different field setting. Remote field teaching ideas and prepared data sets are available for those courses who are unable to collect their own field data. Pre-existing data sets are available to help locate interesting change detection options. Learn more about assessing student learning in this module.

Outline

This module is composed of three core components. The first is an introduction to satellite positioning fundamentals and provides students with the terminology and basic physics to understand how the system works (Unit 1: GPS/GNSS Fundamentals). The second focuses on how kinematic systems work as well as how to create a topographic data set and detect change in monumented positions (Unit 2: Kinematic GPS/GNSS Methods). Unit 2 contains subunits that introduce students to specific applications for using kinematic GPS/GNSS: topographic surveys and change detection. Unit 3 is an exploration of static systems, which provide the highest precision necessary for detecting extremely small changes (Unit 3: Static GPS/GNSS Methods).

The module introduces material in an order of increasing complexity and precision, but the units (after Unit 1) can often be taught as stand-alone lessons. For instructors who do not wish to use the module in its entirety, suggested pairings are included in the "Context for Use" section on each unit's page. Instructors can request support for some types of equipment and technical support from UNAVCO, which runs the NSF's Geodetic Facility.

Note: Although the term GPS (Global Positioning System) is more commonly used in everyday language, it officially refers only to the USA's constellation of satellites. GNSS (Global Navigation Satellite System) is a universal term that refers to all satellite navigation systems including those from the USA (GPS), Russia (GLONASS), European Union (Galileo), China (BeiDou), and others. In this module, we use the term GNSS to refer generically to the use of one or more satellite constellations to determine position.

Unit 1GPS/GNSS Fundamentals

This unit introduces students to how global navigation satellite systems work, a comparison of their accuracy and a first field opportunity to set up an antenna and receiver.

The constellations of satellites orbiting our planet enable high-precision positioning not just for consumer or survey applications but also for geoscience research such as detecting plate motions, landslide movement, or other changes on the Earth's surface. This unit introduces students to the fundamentals of these global navigation satellite systems (GNSS), the reference frames used for positioning and the different acquisition techniques, including their merits and accuracy. Through classroom and field activities, students develop a familiarity with the variety of instrumentation and applications available with GNSS. This unit provides a broad conceptual understanding of GNSS applicable to all acquisition techniques. Subsequent units focus on kinematic and static methods and the different products generated using those GNSS methods.

Unit 2Kinematic GPS/GNSS Methods

This unit focuses on teaching the techniques necessary to run a kinematic survey. It is explicitly hands-on, giving students the opportunity to set up, operate, and post-process their data. Though they are less precise, kinematic surveys require more equipment and design considerations than static systems. Kinematic systems have the advantage of rapidly acquiring numerous positions with an accuracy of several cm. They are effective for a variety of applications including measuring rapidly deforming landforms, surveying topography, or other applications that are time sensitive and do not require precision greater than 2–3 cm.

The application of Global Navigation Satellite Systems (GNSS) in the earth sciences has become commonplace. GNSS data can be collected rapidly and compared in common reference frames. Real-time kinematic (RTK) GNSS methods enable the rapid delivery of high-precision, high-accuracy positioning information to field scientists. This unit focuses on the design and execution of kinematic surveys, emphasizing the benefits and limitations of the technique. Students will learn which questions the technique is most applicable for as well as the standard data-processing techniques. Students advance their understanding of GNSS through a technical knowledge of kinematic GNSS surveys. This unit prepares students to design and implement a survey of their own through hands-on instruction and demonstration of real-time kinematic (RTK) or post-processed kinematic (PPK) techniques in a field setting.

Unit 2.1Measuring Topography with Kinematic GPS/GNSS

This unit focuses on an application of kinematic techniques to rapidly and efficiently collect topographic points and process them to create a continuous surface.

Kinematic GNSS surveys can provide a rapid means of collecting widely distributed, high-precision topographic data. The advantages of this technique over optical instruments such as a total station are that it only requires one person to operate and it does not rely on maintaining a direct line of site. Once points are collected, students will learn to interpolate them using ArcMap to create a continuous model of elevations. Students must think carefully about where they collect their points and evaluate the merits of different interpolation techniques including TIN and Kriging. Through a field-based application of kinematic GNSS, students will design and conduct a topographic survey and interpolate collected points to create a continuous elevation field. This builds upon skills learned in Unit 2 and prepares students for future techniques such as surface differencing and topographic change detection (Unit 2.2).

Unit 2.2Change Detection with Kinematic GPS/GNSS

This unit focuses on the application of kinematic techniques to detect change in monumented objects such as benchmarks or boulders moving down a hillslope.

Though it may be difficult to perceive, landscapes are constantly changing form and position. High-precision GNSS is one of a handful of techniques capable of quantifying these changes and is a key component of many modern geologic, biologic, and engineering studies. In this unit, students will learn how to approach a study in change detection in the context of a geomorphic or structural problem, then design and implement a GNSS survey that effectively explores the problem. Through field-based application of kinematic GNSS techniques, students will design, execute, and analyze data from a survey to detect change. Students design the survey based on a question of scientific or societal interest and are asked to defend their design and implementation. This is the final unit focused on kinematic GNSS and is aimed at solidifying students' knowledge and technical skill in this technique.

Unit 3Static GPS/GNSS Methods

This unit focuses on teaching the tools and techniques necessary to run a static survey. It is explicitly hands-on, giving students the opportunity to set up, operate, and post-process their data. Static surveys take more time to collect points than a kinematic system, but they can be significantly more precise, able to resolve movements of several millimeters, including hill slope creep, slow-moving landforms, and tectonic motion. Static systems vary depending on application, but are often used for time-series analysis of slow-moving monuments.

The application of Global Navigation Satellite Systems (GNSS) in the earth sciences has become commonplace. GNSS data can produce high-accuracy, high-resolution measurements in common reference frames. Static GNSS methods take advantage of long occupation times to resolve fine measurement and time-series data to capture events such as tectonic deformation, earthquakes, groundwater depletion, and slow-moving landforms. This unit focuses on design and field execution of simple static surveys, emphasizing the benefits and limitations of the technique. Students will learn which applications the technique is most applicable for as well as the standard data-processing techniques. Additionally, students advance their understanding of GNSS systems through interpretation of field data from static surveys and public data sets of continuous-operation stations. This unit prepares students to design and implement a survey of their own through hands-on instruction and demonstration of rapid-static or static techniques in a field setting.

Summative Assessment

There is no single summative assessment for this module. This is because kinematic and static GNSS require different equipment and different interpretative tools. Instead, we offer a suite of questions that may added into the summative exercise of different units. Alternatively, these questions may be asked as part of a final exam.

Making the Module Work

To adapt all or part of the module for your classroom you will also want to read through

- Instructor Stories, which detail how the module was adapted for use at different institutions, as well as our guide to
- Using GETSI Modules for Your Course, which outlines how to effectively use GETSI modules.

The module authors provided additional information about teaching this module. If interested, click on the blue text below to display these notes.

Requesting technical support: UNAVCO, which runs NSF's Geodetic Facility, can offer some forms of technical support for the educational use of GNSS equipment. Learn more about the support available from UNAVCO and make a support request at UNAVCO's Field Geodesy Learning page.

Keeping students engaged: The course materials contain significant supporting material written into the assignments so that students have ample explanation for why and how they are to complete each step. Much of this material is or should be covered by lectures. If you plan to lecture on much of the written material in the assignments, consider streamlining the assignments so that students do not get lost in reading the accompanying material.

Keeping students occupied: One of the challenges of integrating these techniques into a course with more than a few students is making sure that students stay engaged and mentally challenged even while they are waiting for their instrument time. While they wait to work with geodetic equipment, there are a series of possible tasks that instructors can assign to help students better understand the components of survey design AND keep them occupied and engaged. These include:

- Multiple rovers can operate concurrently from the same base station. Groups of 4 or 5 per rover are a maximum. Alternatively, one set of students can be keeping field notes and filling equipment sheets while the other part of the group is physically navigating the unit.
- During surveying, split tasks between individuals in a group, rotating between taking notes, operating the equipment, and/or finding the next point to measure.
- On the first day, students should be encouraged to review their geodetic method field manual(s) during any downtime they may have.
- Students can complete equipment sheets from their assignment packet for surveys during downtime.
- Survey maps and accompanying notes are very important. Remind students to periodically update maps and field notes.
- Consider having the students take traditional observations and measurements: strike/dip, rock type, and other observations, which can inform their write-ups later.

More about data exploration:

- One limitation of this unit for field courses is the reliance on computers for interpretation and analysis. Computers with necessary programs (ArcMap and post-processing software) should be loaded prior to the course and tested.
- An internet connection is necessary for post-processing through systems such as OPUS. Kinematic post-processing can often be done without a connection if using an established benchmark.
- Consider surveying points and processing a stable data set ahead of the course if you expect any trouble or are new to the process! Download a prepared dataset (such as provided in several units) in case your survey fails for any reason.
- Allow time to post-process! There is a typical 24-hour lag time between when a survey finishes and when OPUS will have stable corrections for that time period. Allow time in the schedule for this to take place or use a pre-processed base station or monument.

Additional tips:

- GNSS surveys are equipment-heavy, so plan accordingly for getting it into the field.
- Four or five students is the maximum per rover unit in kinematic surveys. However, you can have as many rovers connected to a base station as you like.
- GNSS does not work well in heavy vegetation or urban areas where a significant portion of the sky is obstructed.
- Anticipate the survey process moving slowly initially as students become familiar with instrumentation setup and the data-collection workflow.
- Visit the site prior to taking students there to survey—to assess access, site size, features and vegetation that may obstruct or complicate the survey, and to obtain landowner permission (if required).

Metacognition (reflection) is built into all student exercises in this module. Metacognition, or "thinking about thinking," encourages students to examine what and how they learned, to help them monitor and then alter their learning techniques to ensure best learning practices. Each unit's final write-up includes a reflection question for students to answer about their learning experience. In addition, ask students questions such as: What was rewarding about this exercise? What was challenging? How have your ideas about fieldwork changed because of your experience with geodetic techniques? What other applications would you suggest applying geodetic techniques to in future research you might do? More information on metacognition is at InTeGrate Project's Metacognition page and Teaching Metacognition by the Cutting Edge Project.

Societal importance: For each of the units, students are also asked to apply findings from the different types of surveys to societally important applications. Research shows that students are more engaged in subject matter they see as relevant and important. By tying what might appear to be dry geophysics methods to the underlying reasons we want to conduct such research, students see the relevance and importance of geoscience in everyday life. Geodetic surveys can be used to answer research questions on disparate topics from earthquake, volcano, and landslide hazards to climate change (ex. glacial study).

Adapting the module to non-field courses: This module can be adapted for non-field courses. We have prepared data sets for each unit that can be used in substitution for new field acquisitions. Additional GNSS data can also be acquired through distributors such as UNAVCO or the National Geodetic Survey.

Skip to Main ContentSkip to Navigation

Instructor Materials: Overview of *Analyzing High Resolution Topography* Module

Module Goals

Students will be able to:

1. **Design** and **conduct** a complex TLS and/or SfM survey to **address** a geologic research question.
2. **Articulate** the societal impetus for answering a given research question.
3. **Justify** why TLS and/or SfM is the appropriate method in some circumstances (if both methods are used).

> Supports Earth Science Big Ideas ESBI-1: Earth scientists use repeatable observations and testable ideas to understand and explain our planet; ESBI-4: Earth is continuously changing; ESBI-7: Humans depend on Earth for resources; and ESBI-8: Natural hazards pose risks to humans and Climate Literacy Principles CLP-4: Climate varies over space and time through both natural and man-made processes. (links open in new window)

Summative Assessment

The Summative Assessment, Unit 5, is the final unit of the module. The exercise evaluates students' skills in survey design, survey execution, and simple data exploration. As this is not designed to test any specific geologic context, we include a number of potential study topics with associated questions and prepared data sets for courses not able to collect data in the field. Learn more about assessing student learning in this module.

Outline

The module covers material sequentially, but the units can also often be taught as stand-alone lessons. For instructors who do not wish to use the module in its entirety, suggested pairings are included in the "Context for Use" section on each unit's page. Instructors can request support for some types of technical assistance from UNAVCO, which runs NSF's Geodetic Facility.

Unit 1-TLS: Introduction to TLS

This unit introduces students to the technical aspects of terrestrial laser scanning (TLS) survey design and execution. TLS requires a range of equipment, careful planning, and many hours of scanning in order to complete a successful survey, but it yields a high resolution topographic model valuable for addressing a range of geologic research questions. This unit is designed to be used as an alternative to or concurrently with Unit 1-SfM.

Unit 1-SfM: Introduction to SfM Photogrammetry

This unit introduces students to the technical aspects of Structure from Motion (SfM) photogrammetry survey design and execution. SfM requires less expensive equipment and less field time but more processing time than TLS. In low-vegetation field areas, it can yield a similarly valuable high resolution topographic model applicable to a variety of geologic research questions. Software for SfM varies; the unit was written to work with Agisoft Photoscan Pro but suggestions for open-source alternatives are given in the instructor overview. This unit is designed to be used as an alternative to or concurrently with Unit 1-TLS.

Unit 2: Geodetic survey of an outcrop for stratigraphic analysis

Geodetic surveying techniques have many applications in sedimentology research, including lithological identification and analysis, sediment surface topography, and sequence stratigraphy. In this unit, students will design a survey of a geologic outcrop to conduct a sequence stratigraphy analysis. The goal is to calculate deposition duration and sedimentation rate based on thicknesses extracted from the data. Students tie these analyses back to societally important issues such as climatic change and energy extraction.

Unit 2.1: Geodetic survey of an outcrop for road cut design

This unit offers an alternative application for high-resolution topographic data from an outcrop. Using engineering geology methods and data collection from TLS and/or SfM, students design safe "road cuts" with low probability of failure for a proposed fictitious roadway along the side of a hill. Cut slopes or "road cuts" are constructed slopes along roadways in mountainous regions. The design of such slopes requires a safe slope angle, rockfall catchment ditch, and drainage provision. The decision of the slope angle is based on kinematic analysis for slope failures due to the orientation of discontinuities (bedding planes, joints, etc.) with respect to that of the proposed slope. Traditionally, discontinuity orientation data are collected from measurements directly on the outcrop. This can be dangerous and the accessible sites may not be fully representative of the cut as a whole. Remote methods such as TLS and SfM generate 3D models from which discontinuity data can be collected safely. In this unit students learn the workflow for designing safe cut slopes using discontinuity data collected from direct field observations and TLS or SfM and compare the methods and results.

Unit 3: Geodetic Survey of a Fault Scarp

Fault scarps are the topographic evidence of earthquakes large and shallow enough to break the ground surface, and are evidence of Quaternary fault activity. In this unit, students will design a survey of a fault scarp. The goal is to create a brief report summarizing the methods used and Quaternary history of displacements on the fault and thus its potential earthquake hazard. This unit also includes an additional optional exercise in data processing. Students will transform a point cloud into a DEM. Then students will be able to extract profiles of the scarp using ArcGIS and import these profiles into MATLAB to conduct hillslope diffusion analysis.

Unit 4: Geodetic Survey for Geomorphic Change Detection

One major application of geodetic surveying techniques in geoscience research is quantifying change in geomorphological settings, such as a fluvial system, forest fire, landslide, or any other erosional features. This is done by finding the difference between georeferenced repeat data sets. Students will learn to clean up the data, remove vegetation, transform the point cloud to a DEM, and then compare that DEM to a previously collected data set to quantify change.

Unit 5: Analyzing High Resolution Topography Summative Assessment

Unit 5 is a final exercise and evaluates students' skills in survey design, survey execution, and simple data exploration and analysis. Unit 5 is the summative assessment for the module. As this is not designed to test any specific geologic context, we include a number of potential study topics with associated questions and prepared data sets for courses not able to collect data in the field.

Making the Module Work

To adapt all or part of the *Analyzing High Resolution Topography* module for your course you will also want to read through

- Instructor Stories, which detail how the module was adapted for use at three different institutions, as well as our guide to
- Using GETSI Modules for Your Course, which outlines how to effectively use GETSI modules

The module authors provided additional information about the teaching this module. If interested, click on the blue text below to display these notes.

Requesting technical support: UNAVCO, which runs NSF's Geodetic Facility, can offer some forms of technical support for the educational use of TLS and SfM. Learn more about the support available from UNAVCO and make a support request at UNAVCO's Field Geodesy Learning page.

Keeping students occupied: One of the challenges of integrating these techniques into a course with more than a few students is making sure that students stay engaged and mentally challenged even while they are waiting for their instrument time. While they wait to work with geodetic equipment, there are a series of possible tasks that instructors can assign to help students better understand the components of survey design and parameter calculation AND keep them occupied and engaged. These include:

- Concurrently using the SfM and TLS methods: When students are not actively working on the TLS survey, they can design and implement an SfM survey of the same feature. Note: care must be taken to avoid obstructing the scanner.
- On the first day, students should be encouraged to review their geodetic method field manual(s).
- (TLS only) Completing the TLS Scan Resolution Parameter Worksheet from their assignment packet for all scans, including those they did not run themselves.
- (TLS only) Compiling the equipment list in their TLS Field Manual (if not done as a part of a previous unit).
- (SfM only) Completing the SfM Photogrammetry Calculations Worksheet
- Traditional observations and measurements: strike/dip, rock type, sketch map of whole feature (not just the scan and target positions).
- Students may start on portions of their final write-up for the unit.
- Observations that would inform analysis later such as:
    - Presence of water (as the scanner cannot scan water and photographs will only represent the surface of the water)
    - Surface texture, color, and condition (for TLS intensity measurements or for reference when examining the SfM point cloud): for example, students can use the Riegl spec sheet on reflectance from their TLS Field Manual to sketch the outcrop with reflectance considered.

More about data exploration:

- One limitation of this unit for field courses is the reliance on computers for interpretation and analysis. If using individual student laptops, the necessary programs (software for scanner or photogrammetric analysis, point cloud manipulation, and vector drawing) should be loaded prior to departure for camp, as internet connections may be slow to nonexistent and programs may not be able to be shared due to licensing issues.
- Allow time in the schedule to transfer the field data to the lab or student computers; it is not uncommon to collect several gigabytes of data during a day of surveying, so having external hard drives to pass the data around is essential.
- Also allow time to prepare the data for student use. If a UNAVCO field engineer is present, she will likely need a few hours to georeference the data if students will not be asked to do it themselves. Take this into account when planning the schedule for the module.

Additional tips:

- TLS requires a large amount of equipment. Choose small sites with relatively easy access.
- SfM does not work in areas of significant vegetation. Choose open sites with little to no vegetation. SfM equipment is easier to transport than TLS, but large field areas will result in considerable processing time, so small areas are still desirable,

particularly for initial learning.
- Anticipate the survey process moving slowly initially as students become familiar with instrumentation setup and the data collection workflow (particularly for TLS).
- Visit the site prior to taking students there to survey-—-to assess access, site size, features and vegetation that may obstruct or complicate the survey, and to obtain landowner permission (if required).
- It is helpful to have several range finders for the TLS method (at a cost of about $250 for one that does 1000 m; UNAVCO TLS kits include one or two). That way more teams can be filling out Scan Resolution Parameter worksheets at the same time.

Metacognition (reflection) is built into all student exercises in this module. Metacognition, or "thinking about thinking," encourages students to examine what and how they learned, to help them monitor and then alter their learning techniques to ensure best learning practices. Each unit's final write-up includes a reflection question for students to answer about their learning experience. In addition, ask students questions such as: What was rewarding about this exercise? What was challenging? How have your ideas about fieldwork changed because of your experience with geodetic techniques? What other applications would you suggest applying geodetic techniques to in future research you might do? More information on metacognition is at InTeGrate Project's Metacognition page and Teaching Metacognition by the Cutting Edge Project.

Societal importance: For each of the units students are also asked to articulate the societal importance of different types of surveys. Research shows that students are more engaged in subject matter they see as relevant and important. By tying what might appear to be dry geophysics methods to the underlying reasons we want to conduct such research, students see the relevance and importance of geoscience in everyday life. Geodetic surveys can be used to answer research questions on disparate topics, from energy and paleoclimate studies (basin analysis) to earthquake hazard (fault scarps) and landslide hazards (hillslope change), and more.

Adapting module to non-field courses: This module may be adapted to non-field courses. We have provided data sets from the full range of "high resolution topography" applications as featured throughout the module. TLS data are provided in point cloud and DEM formats with associated metadata; SfM data are photo sets and DEMs with associated metadata. In addition, all the same data analyses could be done with TLS data that have been collected by others. Check the UNAVCO TLS archive, OpenTopography, or other lidar sharing websites for community-contributed TLS or ALS (airborne lidar scanning) data sets. Research has been done on using aerial photography for SfM applications as well; some of these data sets may be on the OpenTopography website as well.

Using both TLS and SfM: If using both techniques, students can compare and contrast the challenges as well as the benefits of the two methodologies in their write-ups and create a guide for when TLS or SfM is preferable.

The main difference in using SfM and TLS is the allocation in time. SfM generally takes less field time but considerably more processing time. SfM topographic models take hours or even days to be generated, depending on processing power and field area size. Ideally, you could have students collect photographs in the morning and then process them during the day while doing other fieldwork or collecting TLS data. The other difference is the software: both TLS and SfM require specific programs for data processing and exploration.

Structure from Motion Guide for Instructors and Investigators

Katherine Shervais (UNAVCO)

This guide is intended as a resource for using Structure from Motion in teaching and research applications. It does not detail the algorithms or mathematical background of the methodology but rather how to use it in practice. This guide overlaps in content with the provided SfM manuals for students but includes more information about platform selection and other technical aspects necessary for an instructor or investigator to know. (All images not otherwise credited were created by the author.)

Table of Contents

Introduction

Structure from Motion or SfM is a photogrammetric method for creating three-dimensional models of a feature or topography from overlapping two-dimensional photographs taken from many locations and orientations to reconstruct the photographed scene. This technology has existed in various forms since 1979 (Ullman, 1979), but applications were uncommon until the early 2000s (Snavely et al., 2008). The applications of SfM are wide-ranging, from many sub-fields of geoscience (geomorphology, tectonics, structural geology, geodesy, mining) to archaeology, architecture, and agriculture. In addition to ortho-rectified imagery, SfM produces a dense point cloud data set that is similar in many ways to that produced by airborne or terrestrial LiDAR (Figure 1).

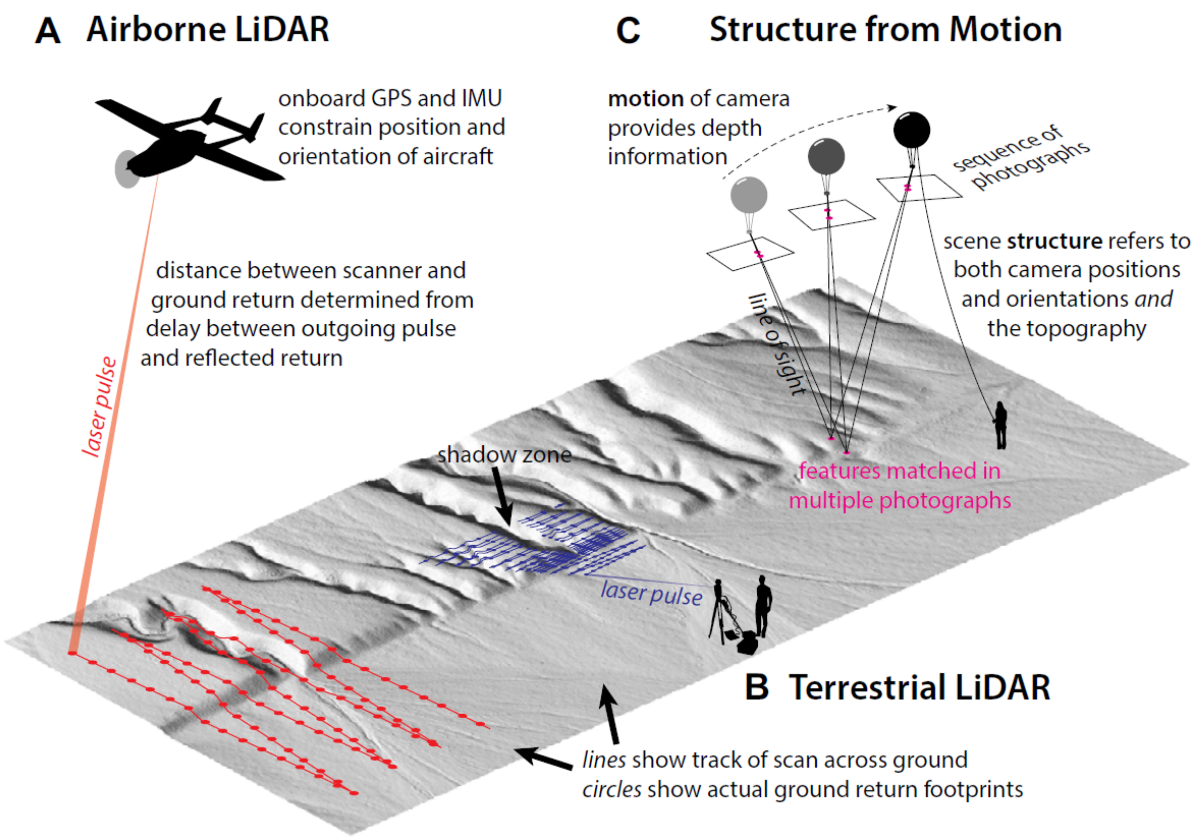

Figure 1. Comparison of SfM to airborne and terrestrial LiDAR methods. Source: Johnson et al., (2014); considered fair use by GSA Publications http://www.geosociety.org/pubs/copyrt.htm

The advantages of SfM are its lower cost relative to LiDAR, as well as its ease of use. The only equipment required is a camera. A computer and software are needed for data processing. Additionally, an aerial platform like a balloon or drone can also be useful for topographic mapping applications. A major limitation is the processing time for software to align the images to generate a model, which ranges from ten minutes for a few photographs to days for hundreds to thousands of photographs. Because SfM relies on optical imagery, it is not able to generate the "bare earth" topographic products that are typical derivatives of LiDAR-based technologies—thus, SfM is usually best suited to areas with limited vegetation.

2. Platforms

Depending on the application and survey objective, a camera can be mounted in numerous configurations to capture imagery for SfM processing (Figure 2). This section provides an introduction to various platforms that can be used to acquire imagery (Table 1).

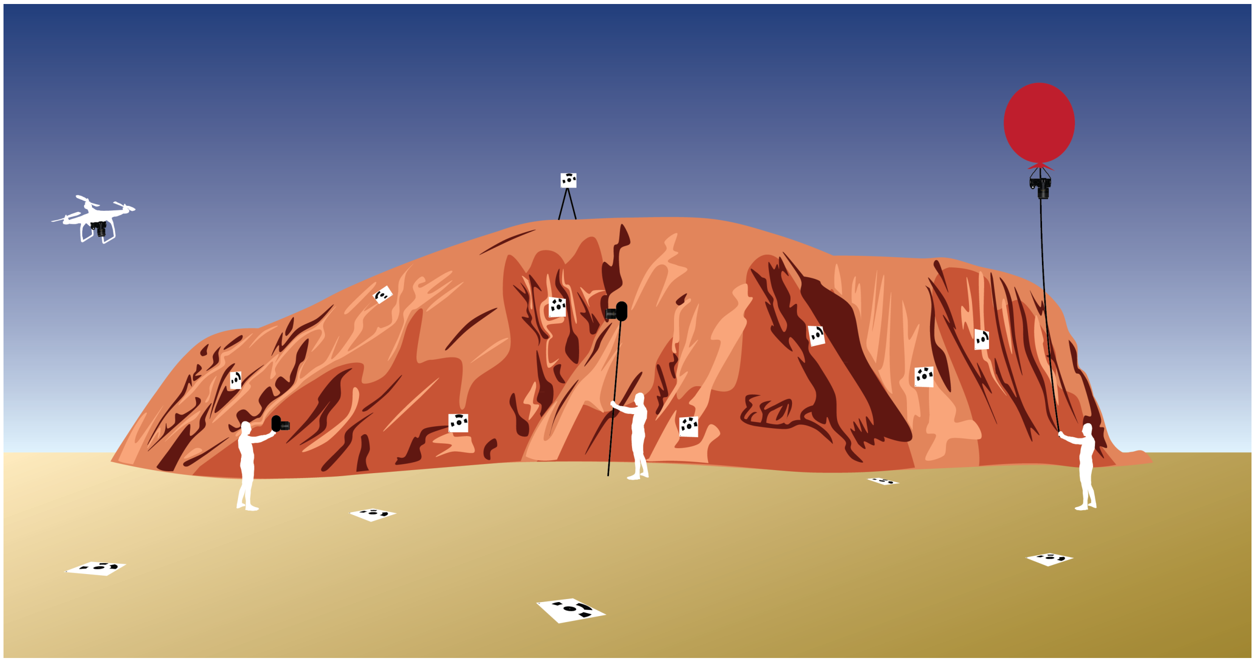

Figure 2. Various platforms for Structure from Motion *(from left to right)*: UAS (uncrewed aerial system), handheld camera, pole, balloon. The white squares with black patterns are targets to georeference the survey.

Some things to consider:

- Many of the platform descriptions include a reference to a picavet: picavets are simply a camera mount designed to keep a camera vertical, even if the line the camera is suspended on is not. Picavets are available to purchase, but there are guides on the Internet for those who wish to build their own.
- These platforms are highly customizable. The limiting factor is typically weight, but if one has a kite or balloon with enough lift, the system could include a remote control camera mount to change the orientation of the photos during the survey. Other additions include a radio controller to regulate when photographs are taken if your camera does not have a time-lapse, and a GPS tagger on the camera to georeference photographs if the camera does not have an internal GPS. UASs (uncrewed aerial systems) can now be purchased with GNSS receivers, expediting the process of aligning photographs in the software.
- To conduct an Internet search for the equipment related to one of these platforms, try searching for “<platform> aerial photography” (ex. kite aerial photograph). This should yield platform-specific equipment designed to accommodate a camera.

Table 1. Cost, advantages, and disadvantages of common SfM platforms.

Platform	Cost	Advantages	Disadvantages
Person (hand-held)	$0	Cost, good for detail work (characterize specific, small-scale features), potentially more efficient for outcrop scale work	Limited applications; not useful for areas larger than 100–200 square meters
Pole (Figure 3)	~$50–250, depending on pole height. Can purchase kits online, but building your own is often more economical.	Cost, ease of setup and use, good for certain kinds of features (slope underneath an overhang, for example)	Must build mount for camera, limitation for maximum pole height, inefficient in comparison to UAS
Balloon (Figure 4,5)	~$300–5000. Building your own system is inexpensive, but systems on the market can cost much more because they may have video systems to show what the camera is viewing. A weather balloon is ~$100, the picavet mount is ~$50, kite line ~$20, and helium ~$180, for an appropriately sized tank	Cost (unless you purchase a commercial version), simplicity, camera orientation (can shoot straight down, unlike many pole setups), height. Balloons are a good option for topographic mapping applications. Tether line line removes legal complications associated with UASs	Easier with two people rather than one, affected by the wind, requires picavet mount (build or purchase), requires helium (a limited resource)
Kite (Figure 6)	Cost depends on the weight of the camera mount system. Kites can be used with v. lightweight cameras and cost around $50; kites made for aerial photography can cost $100–400. For both options, you will need to purchase or build a picavet for $50.	Cost, height, camera orientation (can shoot straight down, unlike many pole setups), similar range to a balloon but no helium! Well suited to topographic mapping applications. Tether line removes legal complications associated with UASs	Dependent on weather, must build/purchase picavet for camera, kite line can get in the way of photographs, kite must be large/have good “lift”

UAS – motorized glider, multi-rotor copter (quad-, hexa- or octa-) **(Figure 7)**	Cost is highly variable; a motorized glider is around $200–300 + cost of picavet; quadcopters can range from $400–$5000 or more depending on their capabilities.	Height, camera position may be controlled and survey flightlines can be pre-planned and automated, GNSS integration for efficiency	Cost, requires a skilled operator, length of survey depends on the charge of the battery, may require light camera setup. Potentially dangerous if improperly operated. Legal landscape for use of UASs can be complex; users should consult institutional rules and/or legal counsel before operation.

Lift

Kite lift is more difficult to determine in a simple chart, as it is highly dependent on the kite and the wind at any given time.

Balloon lift is simpler because it is dependent on the helium (Table 2). Use this chart (minus the weight of the balloon) to determine the size of balloon needed to lift your camera setup.

Table 2. Balloon size relationship with lift in pounds or grams. Source: University of Hawaii, Manoa, Department of Chemistry (http://www.chem.hawaii.edu/uham/lift.html)

Diameter (ft)	Diameter (m)	Volume (liters)	Lift (grams)	Lift (lbs)
1	0.3048	14.8	15.2	0.03
2	0.6096	118.6	121.7	0.27
3	0.9144	400.3	410.9	0.91
4	1.2192	949.0	973.9	2.15
5	1.524	1853.4	1902.2	4.19
6	1.8288	3202.8	3287.0	7.25
7	2.1336	5085.9	5219.7	11.51
8	2.4384	7591.7	7791.5	17.18
9	2.7432	10809.3	11094	24.46
10	3.048	14827.6	15218	33.55
11	3.353	19735.5	20255	44.65
12	3.6576	25622.1	26296	57.97
13	3.9624	32576.2	33433	73.71
14	4.2672	40686.9	41757	92.06
15	4.572	50043.1	51360	112.23
16	4.8768	60733.8	62332	137.42
17	5.1816	72847.9	74765	164.83
18	5.4864	86474.4	88750	195.66
19	5.7912	101702.3	104378	230.12
20	6.096	118620.6	121741	268.4
21	6.4008	137318.2	140931	310.7
22	6.7056	157884.0	162038	357.24
23	7.0104	180407.1	185154	408.2
24	7.3152	204976.4	210369	463.79

Examples of possible platforms

Figure 3. Pole aerial photography (PAP) platform. This platform requires a long, telescopic pole to elevate your camera for the purpose of shooting down on the area of interest or to reach higher on an outcrop. The camera will need to take photographs at certain intervals and can be accomplished through time-lapse, continuous, or remote-controlled shooting. Many cameras (particularly newer DSLR have apps available that allow the camera to be controlled by a smart phone). These researchers are photographing a series of small, melt-bearing strike slip faults within the nearly horizontal outcrops. Photo: Katherine Shervais.

Figure 4. Balloon platform. The photo on the left shows the position of the camera while the balloon is in flight. The center photo shows the position of the balloon relative to the pilot while in flight; the photo on the right shows the more detail of the camera setup. Because of the picavet setup, the camera is oriented directly at the ground. See Figure 5 for a schematic of how this works. Photos: 2014 UNAVCO Science Workshop, Beth Bartel and Linda Rowan.

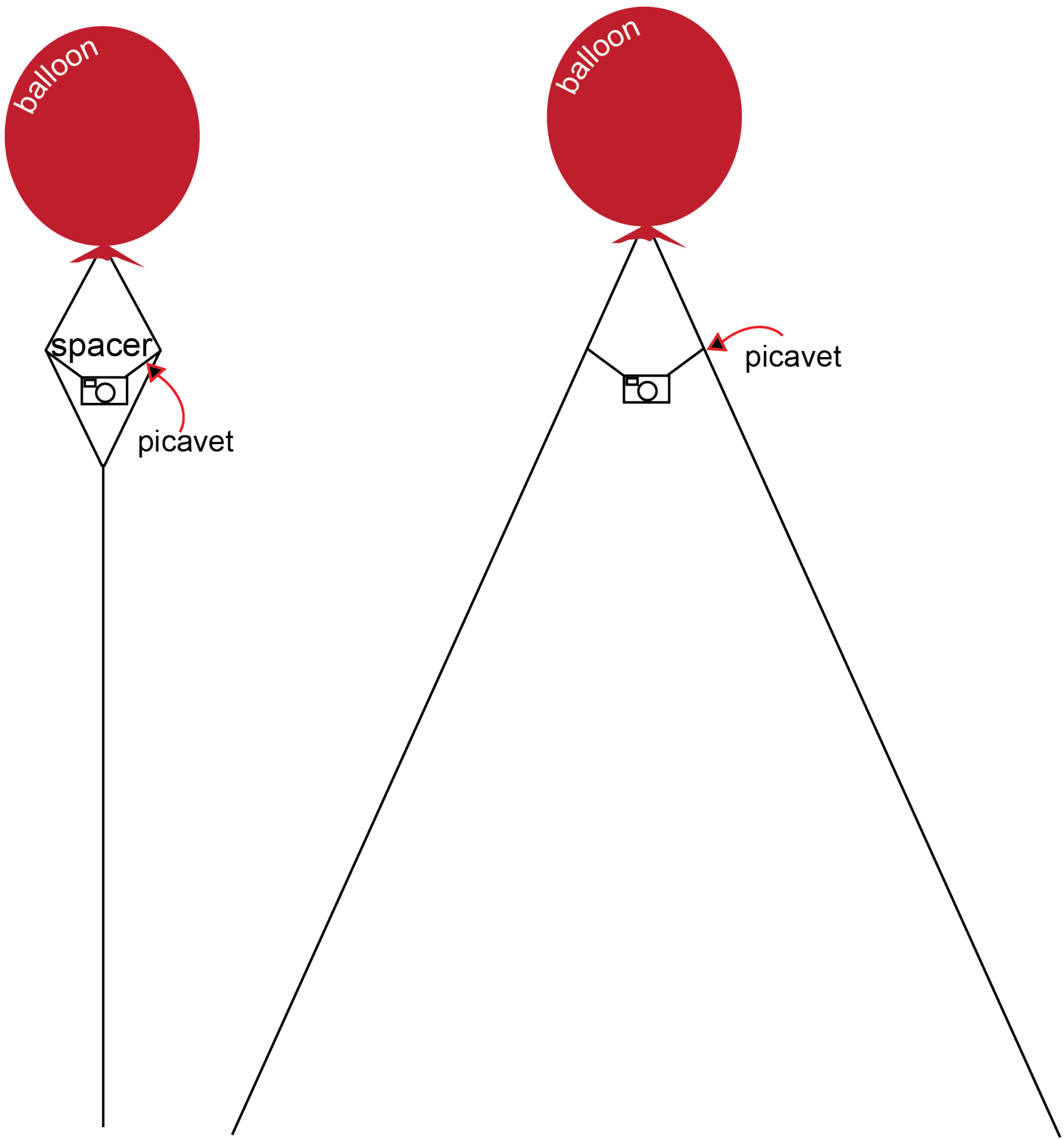

Figure 5. Demonstration of picavet system using a balloon platform. The left schematic demonstrates an ideal setup with one operator, while the right schematic demonstrates an ideal setup with two operators. You may set the orientation of the camera using the picavet; some also come with a remote control “servo” or rotator system so you can change the camera orientation while in the air.

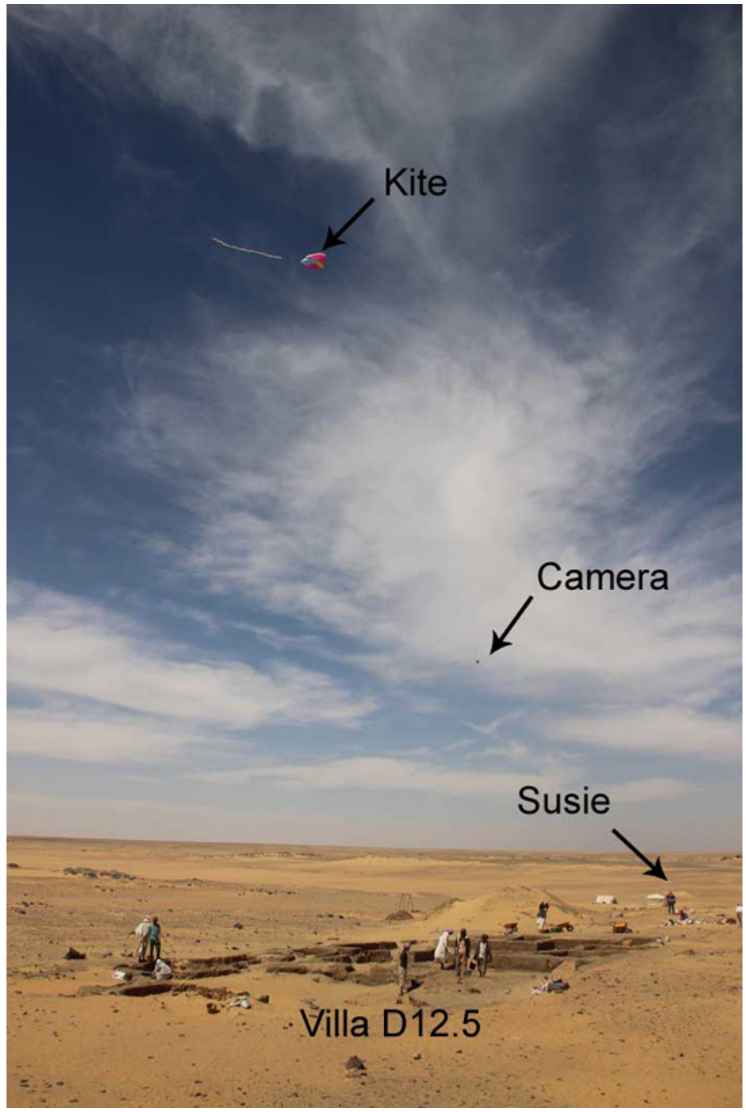

Figure 6. Above is a picavet setup for a kite—note this is basically the same as the setup for the balloon. However, this system is remote controlled with the camera mounted on a gimbal so the pilot can change the orientation of the camera while the kite is in flight. To the right is the location of the pilot (Susie) relative to the camera and the kite while in flight photographing Villa D12.5, the study area of interest. Source: Neal Spencer, British Museum.

Figure 7. Examples of a UAS with cameras – DJI Phantom 4 and Mavic 2. (https://commons.wikimedia.org/w/index.php?curid=58430612; https://commons.wikimedia.org/wiki/File:DJI_Mavic_2_Pro_mit_Hasselblad_Kamera.jpg)

3. Camera choices

Rather than recommend a specific camera, compiled here is a list of general guidelines to follow when picking a camera. This list was synthesized from Johnson et al. (2014), http://www.paulillsley.com/airphoto/systems/Phantom/ (accessed July 1, 2015), Raugust and Olsen (2013), http://adv-geo-research.blogspot.com/2013/10/cameras-for-sfm.html (accessed February 18, 2016) and personal communication with Kendra Johnson (Colorado School of Mines).

1. Consider the weight your platform is capable of carrying. A large balloon may be able to carry a heavier camera setup than a kite, for example.
2. Opinions about the usefulness of DSLR versus point-and-shoot cameras vary. Most recommend using a DSLR (digital single-lens reflex) or a point-and-shoot that has faster ISO levels than average.
3. GPS: built in GPS tagger saves weight and simplifies the photo stitching process in some modeling software. It also produces more accurate georeferenced point clouds. If the camera you select does not have GPS, it is best to buy a GPS tagger in addition to help the data processing.
4. Shooting: the camera will need to take photographs at certain intervals. This can be accomplished one of three ways but cameras with time-lapse or the ability to modify the camera to take time-lapse photographs are recommended.
    a. Time-lapse: the camera has the capability to take photographs at specific time intervals
    b. Continuous shooting: similar to time-lapse but the camera button needs to be pushed (this is simple—use a rubber band!)
    c. Remote controlled shooting: this option is the most complex, as systems may rely on radio, so you will need to limit the height of the camera.
5. Resolution: some recommend staying at or above 12 megapixels, but the need for this has been debated. Cameras should be above 5 megapixels.
6. Picture format:
    a. RAW image files are most useful, so selecting a camera that is capable of this is a good idea. These can be converted to TIFFs after returning from the field.
    b. Do not use JPEGs because they introduce unnecessary noise.
7. If you would like the option of using a First Person View setup to view a live video feed of the camera sees, make sure the camera has a live video-out option.
8. Manual exposure and focus: this ensures the images have a similar exposure. Manual focus helps the camera record images even if the autofocus is not working perfectly.
9. Avoid ultra-wide lenses such as those found on the GoPro! If using a GoPro, make sure that either:
    a. the software program used for the SfM model generation has an option to select a different camera lens type (Agisoft MetaShape Pro can, for example, in the Camera Calibration menu), or

   b. the photos have been processed through a program that corrects for lens distortion (again, Agisoft has a program called "Lens" that does this; many camera companies [like Canon] have their own program to do this).

10. Turn off "shake reduction."
11. Video: Only use a video camera if you know it will work with your SfM software. Not all SfM algorithms work well with images recorded from video because of differences in how the shutter functions. The other issue with video is that video stills are quite low resolution in comparison to photographs, so the resultant model will not be as high resolution.
12. Where is the camera going? Waterproof or dustproof cameras may be needed in some field environments to ensure functionality.

Extras: bring extra batteries and memory cards for every camera.

4. Software

All SfM software completes one of more of the steps in the workflow figure shown below (Figure 8; Table 3).

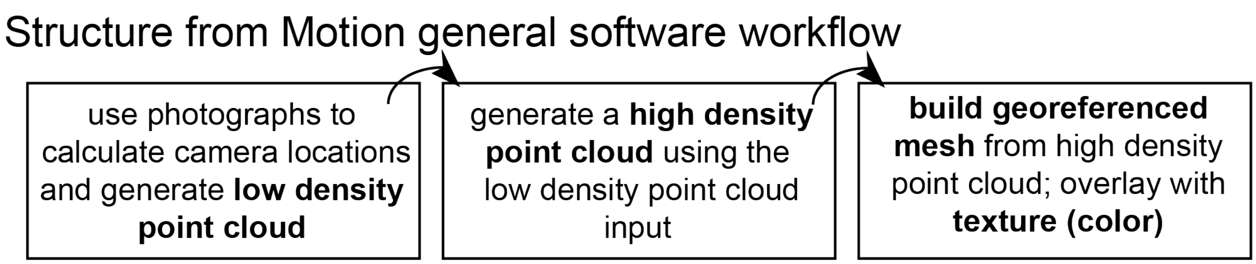

Figure 8. Generalized workflow for SfM software after data has been collected

SfM software typically falls into one of two categories: (1) commercially available software, for which the workflow is more streamlined but the software is a "black box" and (2) open source software, for which the workflow is more complex (several programs may need to be used in sequence, some may not have a graphical user interface [GUI]).

Commercial software

Prices are current as of November 2019.

The primary commercial software used for research in geoscience and archaeology is Agisoft MetaShape. This software is available in Professional ($3499, $549 academic) and Standard ($179, $59 academic) editions. The Professional Edition is best for geologic SfM purposes, as it allows the use of ground control points, measurements, DEM (rather than just point cloud) export, and georeferenced orthomosaic export. Agisoft is a "black-box" but uses the SIFT algorithm used in the open source software (Verhoeven, 2011).

Pix4Dmapper is available for purchase or to rent. This program is $350 for a month-long rental, $3500 for a year, and $4990 for one time purchase (two-computer license). More analysis and data processing can be done in this program rather than exporting the point cloud or DEM to another program such Cloud Compare or ArcGIS.

Another commercial program is PhotoModeler Scanner, which is the PhotoModeler program optimized for UAS mapping. This program is $2495 and does not seem to have an education license. This program has been used less frequently for research applications, so has less peer-reviewed documentation about its capabilities.

Free web-based programs exist, like Microsoft Photosynth. Photosynth builds a sparse point cloud, but the point cloud is not linked to physical coordinates.

Open source software

Many open source software programs exist for SfM or portions of the SfM workflow. These programs range from GUIs to programs run from the command line to programs run through MATLAB (note that MATLAB requires its own, fairly expensive license: $2150, $500 for academic, $49–99 for student edition). An incomplete list is in this Wikipedia article: https://en.wikipedia.org/wiki/Structure_from_motion, which is one of the few sites to aggregate this kind of list.

Papers by Westoby et al. (2012), James and Robson (2012), Fonstad et al. (2013), and Green et al. (2014), go through different workflows using existing open source software. Green (2012) is a master's thesis that outlines the workflow for one method of using open source software and will be a good resource for anyone who prefers the open source option.

Table 3. Comparison of multiple software platforms, both open source and commercial, for Structure from Motion applications. Compiled from Green et al., 2014 and Johnson et al., 2014, as well as websites for the specific platform.

Software	Commercial or open source?	Low density PC	High density PC	Georeference; mesh and texture	Notes and/or extra capabilities
Agisoft MetaShape Pro	Commercial	✓	✓	✓	Primary commercial software used in geoscience and archaeology.
Bundler	Open source	✓			Creates output file of camera locations and low density point cloud; can be input into PMVS2 using "Bundle2PMVS2" script
CloudCompare	Open source			✓	Use for georeferencing output from CMVS + PMVS2
CMVS + PMVS2	Open source		✓		If easier to run from a GUI, use VisualSFM (GUI using same algorithms)

Software	Commercial or open source?	Low density PC	High density PC	Georeference; mesh and texture	Notes and/or extra capabilities
JAG3D	Open source			✓	Add ground control points and apply transformation matrix to georeference; works with MeshLab output
MATLAB	Commercial			✓	Add ground control points and apply transformation matrix to georeference. Also can build mesh.
MeshLab	Open source			✓	Creates and textures meshes; can remove outlier points
PhotoModeler Scanner	Commercial	✓	✓	✓	PhotoModeler software optimized for UAS collection methods
Photosynth + SynthExport	Commercial (free for non-commercial use / open source	✓			Fast, but only produces a relatively low resolution model. SynthExport is needed to export the model.
Pix4Dmapper	Commercial	✓	✓	✓	Specifically for UAS collected data
Points2Grid	Open source			✓	Grid aligned point cloud to DEM
SFMToolkit3	Open source	✓			Uses SIFT algorithm to identify keypoints between photos
VisualSFM	Open source	✓	✓		GUI for CMVS +PMVS2
123D Catch	Open source	✓		✓	Low resolution textured 3D

5. Ground Control Points (Targets)

Ground control points (GCPs) will need to be recorded in the field to link the generated model to the global coordinate system. Ground control points can be recorded on specific points of distinctive features or of targets that are photographed in the field. These points can then be georeferenced after model generation. Survey the targets using a global position system (GPS).

Examples of ground control points:

1. Recognizable natural features
2. Simple Frisbee with an X
3. Coded targets printed from Agisoft (Tools—Markers—Print Markers) on cardstock or other materials.
4. Jacob's staff or scale bar
5. Agisoft coded markers at either end of a scale bar (formal or informal)

Targets should be easily recognizable in photographs, distinct from the surrounding material, be viewable in multiple photographs, not obstruct the feature of interest, and have one specific point that can be used as a differential GPS survey point. The targets must not move over the course of the survey or they will be unusable as GCPs.

Georeferencing falls into two categories: rigorous and less rigorous. In a rigorous survey, you will use GPS to survey clear targets and then integrate these known points into the model. In a less rigorous survey, you may use a georeferenced ALS point cloud to extract the location of recognizable features or use scale bars/Jacob's staffs to scale the model. Rigorous surveys are required to be comparable to TLS and are necessary for any kind of change detection application.

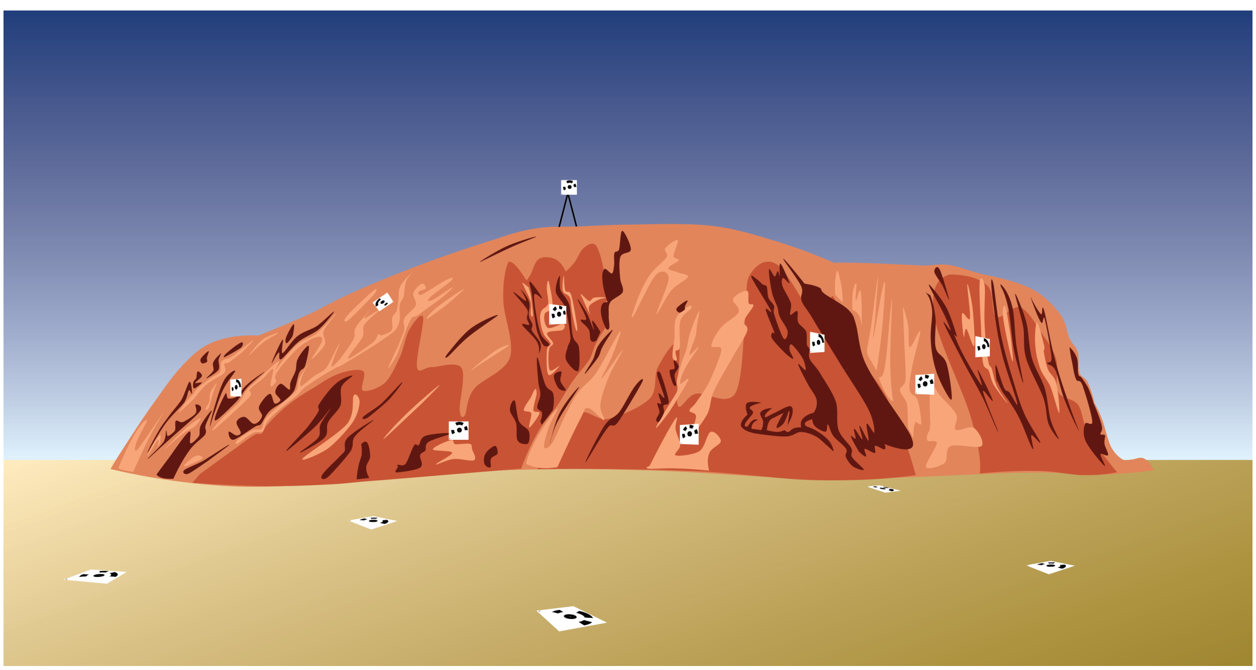

Figure 9. Suggested target placement for a survey of the ground and of the outcrop. Targets should be variable in their horizontal and vertical locations, so they do not appear to be bunched up or in a line.

Recognizable natural features may be used as targets with or without a GPS. If an ALS survey of the location exists (or a TLS survey) and you can assume little change has occurred, the recognizable features can be selected within the ALS point cloud and the location used as the GCP location in the SfM point cloud. These also may be used as targets for a GPS if the resolution of the model is high enough to recognize a specific part of the natural feature used as a survey point.

A Frisbee with an X can be used as a target; survey the centerpoint of the X.

Agisoft recommends using its provided coded targets as they can be automatically recognized by the software and input into the model; however, the auto recognition is often not successful, so expect some manual input of target locations into Agisoft (Figure 10).

If a high-precision GPS system is unavailable to use, targets may still be used. Measure between specific targets and record the distances; these can be input into Agisoft MetaShape Pro to roughly scale the model. More measurements of distance will increase the accuracy of the model.

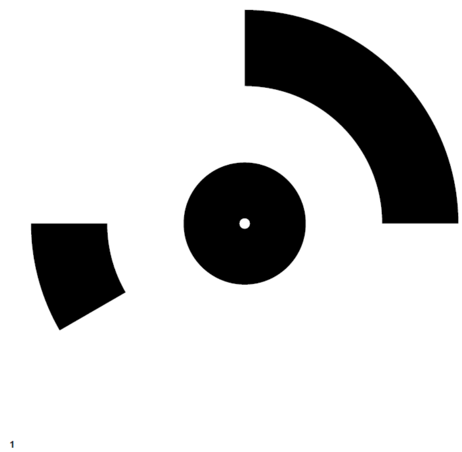

Figure 10. Example of an Agisoft coded target.

Scale bars may also be used in the model to scale it. Scatter scale bars of an appropriate size for the scale of the survey around the survey area without obstructing the feature of interest. Scale bars need to have some sort of texture or color; SfM algorithms have difficulty with items that are glittering, flat, or a homogeneous texture/color (as distinct features are used to link the images for model generation). One way to avoid this is to place the coded targets from Agisoft on the scale bars to add complexity. Follow the link: (http://www.agisoft.com/pdf/tips_and_tricks/CHI_Calibrated_Scale_Bar_Placement_and_Processing.pdf) for an example of scale bars with coded targets.

Another thing to consider with target choice is that SfM software has a difficult time recognizing featureless objects; the keypoints are features that are identifiable because they have a distinct texture. Using a completely flat piece of cardboard that is only one color, for example, may result in a distorted and therefore unusable target. The scale of the targets should match the scale of the survey; do not use small targets if surveying a large area, as the size of the target may be smaller than the model resolution and therefore unusable.

Targets should not be placed in a linear fashion or bunched up, but should be as evenly dispersed as possible around the survey area—both horizontally and vertically, if possible (Figure 9). For a paleoseismic trench survey, twelve targets has been shown to be the ideal number (no significant decreases in error above this number).

6. Field Workflow (and Field Prep)

Based on personal experience and Johnson et al. (2014).

Before leaving for the field

1. Decide on a platform that works best for the data you would like to collect. In selecting a platform, be sure to consider your need for power (to charge batteries) or refill helium (if using a balloon).
2. Select a camera. Remember to use the section above to guide your choice, and ensure that the camera has GPS tagging or can integrate GPS tagging.
3. Select what your targets will be. Make sure they will be visible given the terrain you are surveying and make sense with what you are interested in—if you are mapping the terrain, a flat target (Frisbee, etc.) makes more sense, but if you are photographing an outcrop, a target that attaches to a tripod or a target that attaches to the outcrop makes more sense. Also make sure you have enough targets; Reitman et al. (2015) found twelve targets used as ground control points was an ideal number for a paleoseismic trench survey (more targets did not significantly decrease model error).
4. Have a minimum of two SD cards for your camera that will hold a large number of photos and a way to back up the data. Also have an extra battery (or three).
5. Test your survey setup prior to fieldwork. If using time-lapse or a remote control for the system, ensure these work, as they are key to capturing photographs.
6. Field supply list: platform, camera, camera mount, extra charging supplies, extra SD cards, targets, and GPS (to survey in the targets).

At the field site

1. Make a plan:
    a. What is the furthest extent you would like dense photographs of?
    b. Where should the targets go to not obstruct features of interest?
    c. Is everything of interest visible? If you are mapping an outcrop, you may want to clean it beforehand. SfM algorithms do not work with glittering or homogenous surfaces, so make sure these surfaces are either not included or have been modified in some way to be more algorithm friendly.
    d. If using a UAS, how much flight time do you have and how should that influence your survey design?
    e. What time of day will give you the best lighting to photograph this area? Does that place a limitation on the time you have available and, as a result, the area to survey?
2. Set up and survey the targets as ground control points. Ensure that the targets WILL NOT MOVE; if they change position, they are unusable.
3. Take photographs. Remember the important parts of taking SfM photos: overlap and changing position. Do not stand and take photographs in a circle around yourself, for example. Move the camera locations for best results. If using an aerial platform, set a time (5–10 s) that makes sense with the speed you are moving the platform and the number of photographs you would like to take / the spacing of those photographs.
    a. Go to section 8 for more information on photo acquisition strategies.

4. At the end of the field day (especially if surveying the same location again, or if you have extra days to fix problems) generate an initial model to ensure the photographs you took captured the feature you are interested in (see next section).

7. Agisoft MetaShape Pro

One consideration with Agisoft is the hardware used. Below are the recommendations from Agisoft as of November 2019 (Table 4).

Table 4. Hardware recommendations from Agisoft for optimal use of MetaShape Pro. Source: http://www.agisoft.com/downloads/system-requirements/

	Basic configuration Up to 32 GB RAM	**Advanced configuration** Up to 64 GB RAM	**Extreme configuration** More than 64 GB RAM
CPU	Quad-core Intel Core i7 CPU, Socket LGA 1155 (Sandy Bridge, Ivy Bridge or Haswell)	Six-core Intel Core i& CPU, Socket LGA 2011-v3 or 2011 (Haswell-E, Ivy Bridge-E or Sandy Bridge-E)	For processing of extremely large data sets a dual socket **Intel Xeon Workstation** can be used.
Motherboard	Any LGA 1155 model with 4 DDR3 slots and at least 1 PCI Express x16 slot	Any LGA 2011-v3 or 2011 model with 8 DDR4 or DDR3 slots and at least 1 PCI Express x16 slot	
RAM	DDR3-1600, 4 x 4 GB (16 GB total) or 4 x 8 GB (32 GB total)	DDR4-2133 or DDR3-1600, 8x 4 GB (32 GB total) or 8 x 8 GB (64 GB total)	
GPU	Nvidia GeForce GTX 980 or GeForce GTX 1080 (optional)	Nvidia GeForce GTX 780 Ti, GeForce GTX 980 or GeForce GTX TITAN X	

Table 5. Memory consumption for differing operations with various numbers of photos for Agisoft MetaShape Pro (photo resolution 12 megapixels).

Aligning photos	**100 photos**	**200 photos**	**500 photos**	**1000 photos**	**2000 photos**	**5000 photos**	**10000 photos**
	500 MB	1 GB	2.5 GB	5 GB	10 GB	25 GB	50 GB
Building model – height field							
Lowest quality	25 MB	50 MB	125 MB	250 MB	500 MB	1.25 GB	2.5 GB
Low quality	100 MB	200 MB	500 MB	1 GB	2 GB	5 GB	10 GB

Medium quality	400 MB	800 MB	2 GB	4 GB	8 GB	20 GB	40 GB
High quality	1.6 GB	3.2 GB	8 GB	16 GB	32 GB	80 GB	160 GB
Ultra-high quality	6.4 GB	12.8 GB	32 GB	64 GB	128 GB	320 GB	640 GB

Building model – arbitrary	**20–50 photos**	**100 photos**	**200 photos**	**500 photos**
Lowest quality	100–300 MB	150–450 MB	300 MB–1 GB	1–3 GB
Low quality	500 MB–1.5 GB	750 MB–2.2 GB	1.5–4.5 GB	4–12 GB
Medium quality	2–6 GB	3–9 GB	6–18 GB	15–45 GB
High quality	8–24 GB	12–36 GB	24–72 GB	60–180 GB
Ultra-high quality	32–96 GB	48–144 GB	96–288 GB	240–720 GB

Decimating model (millions of faces)	**1**	**5**	**10**	**20**	**50**	**100**	**200**	**500**
Memory consumption	128 MB	640 MB	1.3 GB	2.5 GB	6.2 GB	12.5 GB	25 GB	63 GB

For a comparison of differing CPU/GPU's: http://www.anandtech.com/show/7648/gigabyte-brix-pro/3

Based on personal experience

Although many SfM software packages exist, this is my preferred workflow for working in Agisoft MetaShape Pro. If you would rather use open source software, see James and Robson, (2012), Westoby et al. (2012), Fonstad et al. (2013), and Green et al. (2014). I would also suggest looking into the blog http://archaeologysfm.blogspot.co.uk/, in which Susie Green (of Green et al., 2014) includes additional details on the open source workflow, as well as a link to her master's thesis on the topic.

Workflow for Agisoft:

1. Take a cursory glance through your photographs to ensure that none are obviously blurry. This will help with the texture overlay later and get rid of errors in the generated point cloud.
   - Agisoft has a function called Estimate Image Quality that will assess image quality automatically. Use images with a quality rating of 0.6 or higher.
2. Load photos, as well as associated GPS information (known as "camera position"). The details of how to do this are in the Agisoft document here: http://www.agisoft.com/index.php?id=31 and are detailed in the *SfM Data Processing and Exploration Manual*.
3. For the Align Photos and Dense Cloud steps in Agisoft, you have the option to set the "quality." If you select "high," the photos will not be downsampled.
4. Go to Align Photos. Keep accuracy at "high"—this helps with later steps. As you will have camera locations from GPS, selecting "high" does not take significantly longer. Choose "reference" for the pair preselection option as you have camera locations. Hit "OK."
5. Now add Ground Control Points. This process is detailed in the *SfM Data Processing and Exploration Manual*.
6. Go to the Workflow menu and select "Batch Process." This way you can set the model up to run without having to constantly check whether a step has finished.
7. Now add the next step: dense cloud. Use high quality to prevent downsampling. The other setting is "depth filtering." If you would like to include small details, use "mild" to avoid filtering these out as outliers. If small details are unimportant, use "aggressive" and for all other situations use "moderate."
   - If there are time constraints or this is a test model to check the photos, build mesh and THEN build dense cloud (swap steps 7 and 8). If using this option, source data from the sparse cloud. Choose the "medium" or "high" option for polygon count. Hit "OK."
8. Build the mesh. Surface type should be "height field" if a planar surface and "arbitrary" if something like a building.
9. The last step is adding texture. Select "arbitrary" if working on something like a building; "adaptive orthophoto" if there is a flat portion and a vertical portion; "orthophoto" if it is flat, "spherical" if it is spherical. Blend a mosaic for slightly higher quality texture. Blending should be modified based on your results, but mosaic works best for a quick model. Hit "OK."
10. Run the batch process. Processing speed is dependent on your hardware and number of photos; processing significantly slows above ~250 photos.
11. Break the model into chunks and perform the above steps to each chunk if working with a large number of photos (500 or more). Then it is possible to merge the chunks after all the processing has occurred, significantly speeding up the process.

8. Photo Acquisition Considerations

Based on personal experience and Raugust and Olsen (2013).

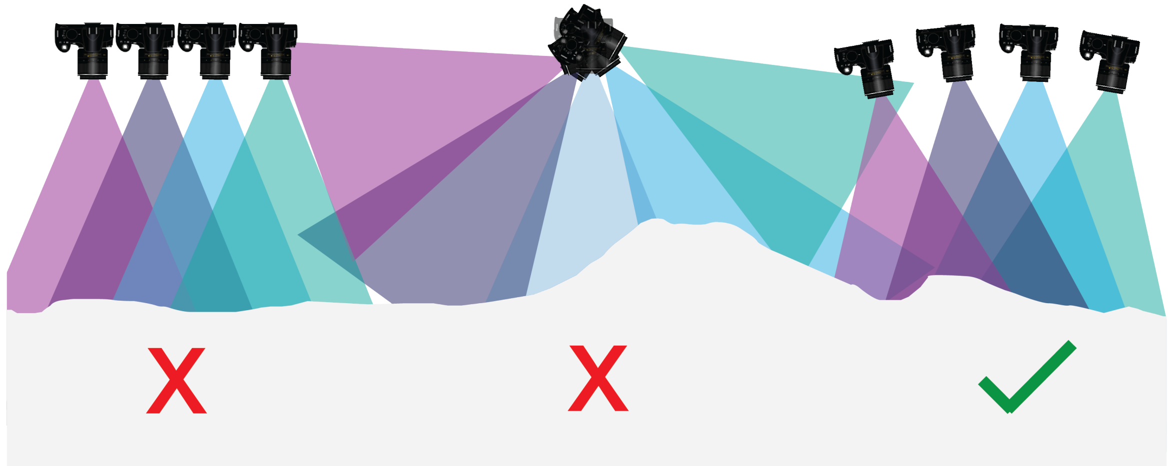

Figure 11. Do not take photos in a planar or divergent fashion (left and center). Take photos in a convergent fashion.

1. Photos should be taken in a convergent fashion (Figure 11). James and Robson (2014) have shown photographs taken in a divergent or planar orientation distort the model.

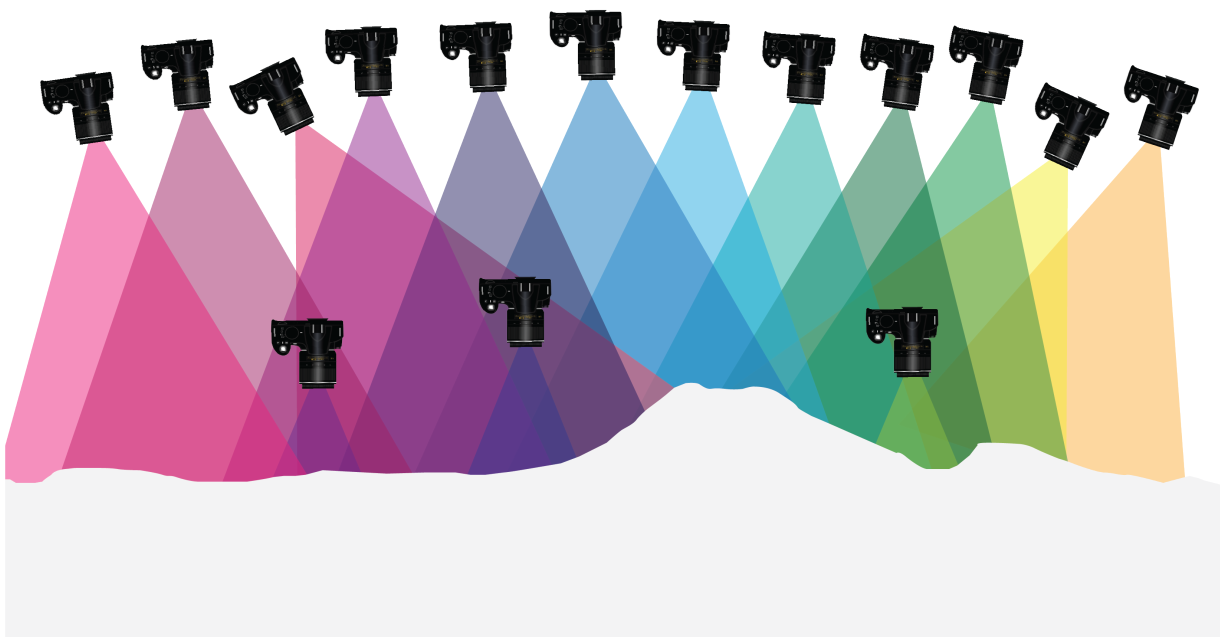

Figure 12. Take photos converging on the feature, at multiple distances and angles.

2. When in the field, consider taking photographs at multiple distances and angles (Figure 12). If using a balloon or UAS, collect a flight path at a single height and then either increase or decrease the height depending on whether you would like more surrounding context or more detail

3. Always photograph a larger region than you anticipate needing. The edges of the area you are surveying will have a lower photo density, so ensure that these are not areas that apply to your research.
4. OVERLAP IS KEY. Overlap your images as much as possible. Different software programs have different guidelines, but it is essential all portions of the area of interest are covered by multiple photographs. Less than 70% overlap will affect the interpreted scene, while more than 90% overlap may significantly increase processing time.
5. When considering overlap, keep in mind the goals of your project. Do you want decimeter resolution? Centimeter resolution? If you are interested in lower resolution models, high overlap percentages are unnecessary.
6. Lighting the photos well is important. If it is too dark, features (especially texture) do not stand out, but if is too bright, these features are washed out. Ideally, if working on smaller-scale features, take photographs when the feature is in shadow or lower lighting but the sun is still out. This usually corresponds to late afternoon or early morning light.
7. Georeferencing targets rather than geologic features is best. If necessary, use parts of the outcrop as ground control points, but some features may be less visible in the model and georeferencing is essential for scale.
8. Surface texture is essential. If there is little variation on the surface, SfM is difficult. Problematic materials: glass, mirror, very smooth dirt, painted surfaces, surfaces that do not vary in color or texture (i.e., a box), many other man-made materials, snow. PRACTICE photographing a similar feature beforehand to ensure that the texture will be represented.
9. Break areas into blocks if there are a large number of photographs (greater than 250) and processing is extremely slow. This is a way to speed up processing time, and with georeferenced data, all blocks can be tied together later.
10. To work with data while in the field, make lower resolution models that require less processing time and computer power to check that the model covers all of your area of interest. In addition, if using Agisoft MetaShape Pro, generating the mesh prior to generating the dense point cloud (after the photos are aligned) will be a quicker way to stitch the photographs together. This method is less reliable—sometimes models generated are just black blobs rather than textured accurate representations—but is useful in a field setting when you are prepping for the next day of work.

9. References for the guide

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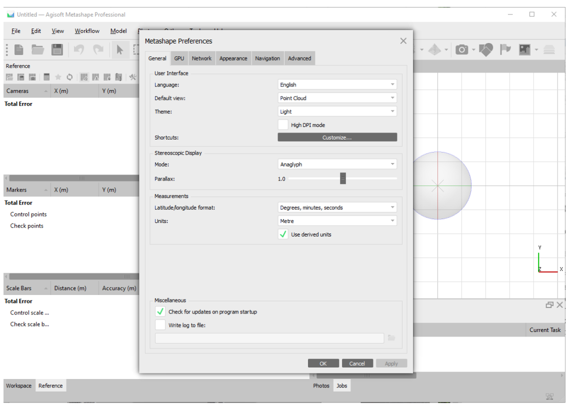
Agisoft MetaShape Quick Guide (local reference frame)

Originally by Yonathan Admassu (James Madison University) with modifications by Beth Pratt-Sitaula (UNAVCO). Updated 6/25/2020 by Sharon Bywater-Reyes (University of Northern Colorado) from Unit 2.1: Geodetic survey of an outcrop for road cut design in GETSI module Analyzing High Resolution Topography with TLS and SfM.

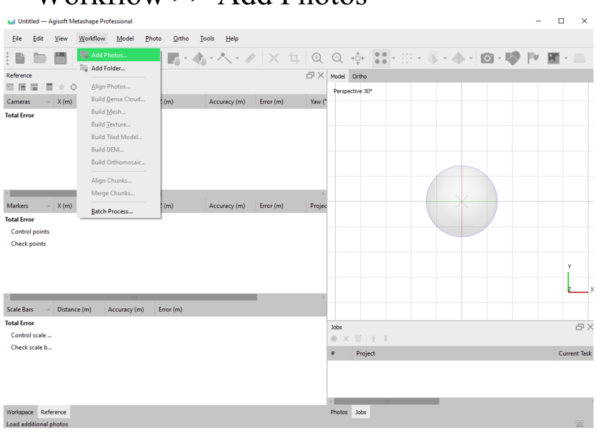
1) Open Agisoft Metashape and change the preferences. Got to Tools >> Preferences

On Mac metashape pro >> Preferences

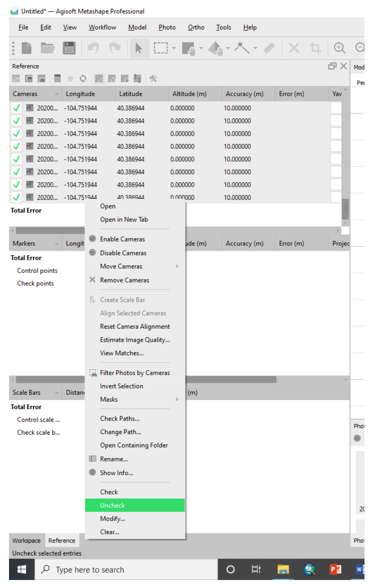
Change Default View to “Point Cloud” and make sure measurement units is “Metre”



2) Add photos
Workflow >> Add Photos

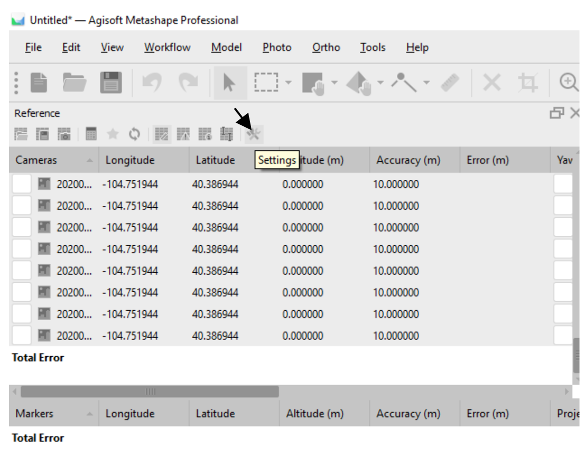


Note: For photos taken with your phone or camera that have inaccurate GPS coordinates, you will want to uncheck the Cameras (photos are referred to as cameras). To uncheck them all at once, click on the reference pane, select all the photos, right click >> Uncheck

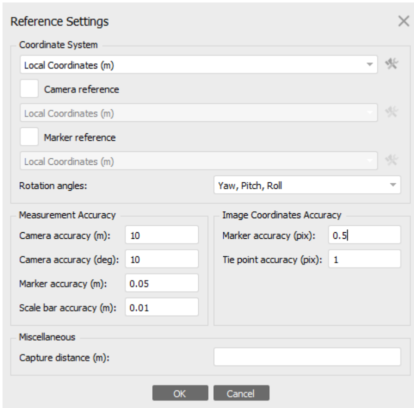


3) Make sure to save your project. File >> Save As

4) In the reference pane, go to Settings

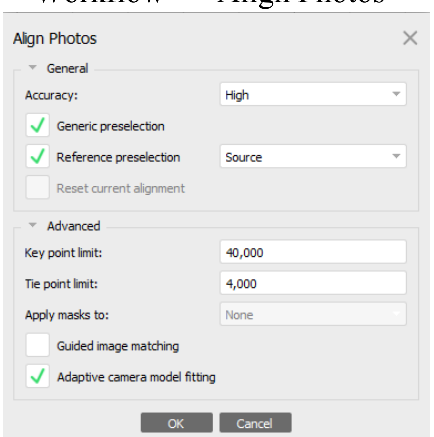


If needed, change the coordinate system you would like to use for your project and specify those of the camera (if applicable) and/or ground control (Marker Reference). In this case, it should just be “Local Coordinates (m)”.



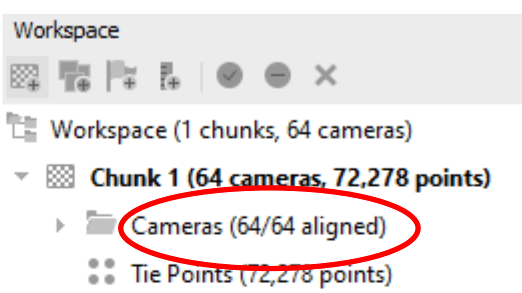
Also specify the accuracy of your camera and marker (ground control points). In the example above, the marker accuracy is about 0.05 m, or 5 cm, because we collected these by hand with a tape!

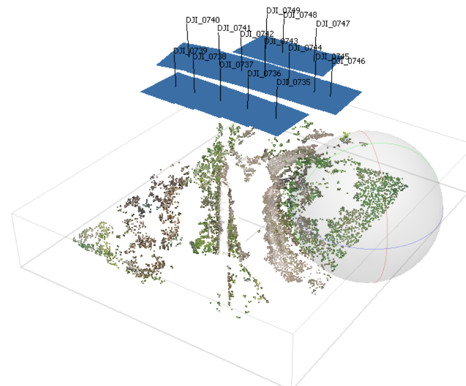
5) Align Photos
Workflow >> Align Photos



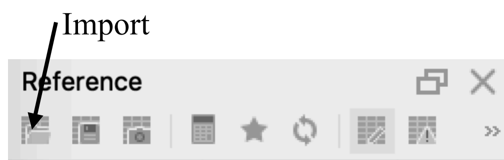
Check alignment by looking in the Workspace.

You may have to check in the camera icon. 

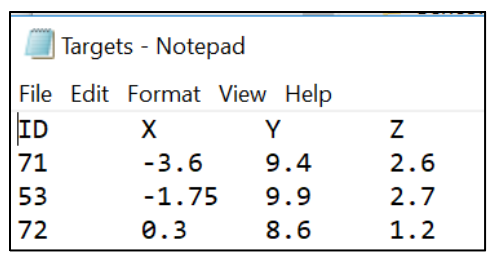




6) In the Reference screen, import the coordinates of the targets (also called ground control points [GCP])



The ground control (GC) coordinates should be in .txt format as shown below (tab delimited). Make sure you choose the appropriate coordinate system at the top. For a local coordinate system, choose "Local Coordinates (m)". Choose the appropriate columns such that the text imports correctly.


Targets - Notepad

File Edit Format View Help

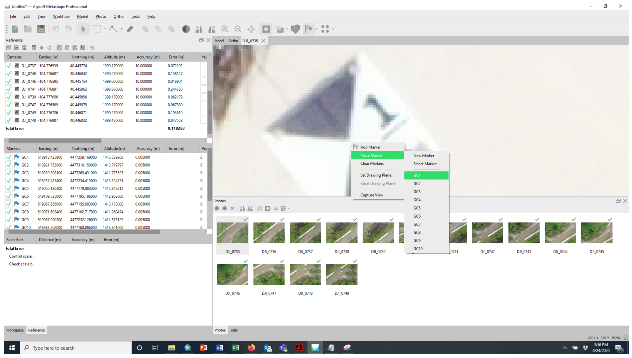
ID	X	Y	Z
71	-3.6	9.4	2.6
53	-1.75	9.9	2.7
72	0.3	8.6	1.2

A dialog box will appear with the message "Can't find match…"—just say "Yes to All"

Cannot find match to "1" and choose "Yes to All"

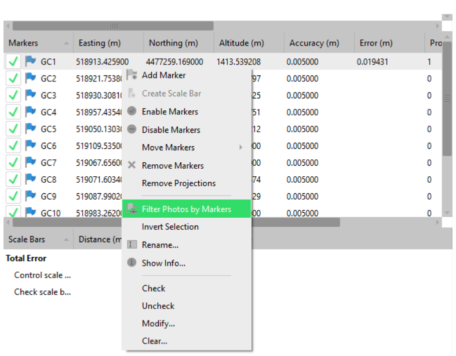
Double-click on each photo with GCP. A new window showing the photo will appear.

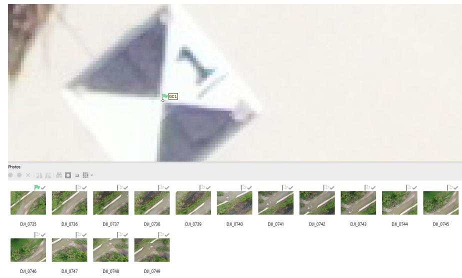
Zoom in on each target/GCP. Assign coordinates by: Right clicking on each target center >> Place Marker >> Choose the corresponding target from the ones that were imported above.



Another alternative is to first place the markers by right clicking on the image and choosing "Add Marker." Choose the correct marker. Then in the Reference Pane, you can rename it by double clicking on the name in the Markers pane and import the text file afterward. Make sure the name matches your text file.

Once you have placed a marker, you can filter the photos by that marker to get Metashape's best guess as to matching photos. In the Reference Pane, right click on the marker and click "Filter Photos by Marker." The associated photos Metashape has found will show up in the photo viewer. You will get white flags for guesses. You will need to go through ALL the photos with the marker and reposition them in the correct location or confirm they are correct by dragging the flag to the correct place. You can always right-click >> Remove Marker if you make a mistake.





Work your way through the photos assigning or correcting the GCP in each photo. Click the Update button in the Reference pane to roughly georeference the model based on these points. This will expedite the process of placing the remaining GCPs.

To optimize the camera alignment and generate a camera calibration based on the GCPs, click the Optimize Cameras button in the Reference pane toolbar. Accept the default settings.

7) Errors

At this point it is worth checking your errors. There are several sources of error to consider.

Your control points show Error (m) and Error (pix).

1. Error (m) - residual error per coordinate or in 3D space. That is distance between the input (source) and estimated positions of the marker.

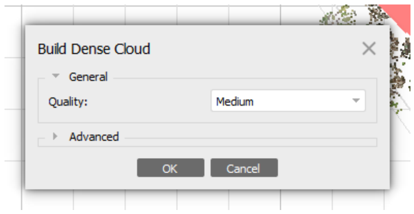
2. Error (pix) - root mean square reprojection error for the marker calculated over all photos where marker is visible.

Save your project (.psx) periodocially just to make sure you do not lose work.

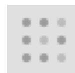
8) Build dense cloud

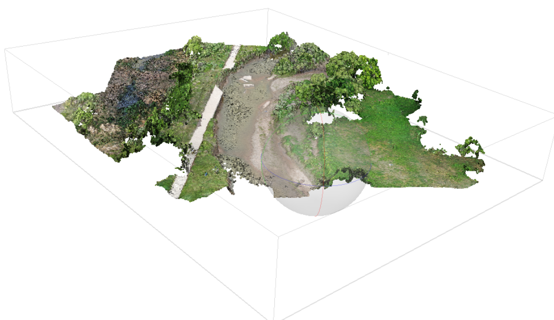
Workflow >> Build Dense Cloud

Choose "Medium"



9) View dense cloud
Model >> View Mode >> Dense Cloud
OR click the dense cloud icon





10) After the dense cloud is created, the points may need to be edited. Some portions of the model may be inaccurate, or just outside of the region of interest. This is an appropriate time to remove these points. Select points to delete by using one of the selection tools.

11) Save your project again and then export. To export point cloud:
File >> Export >> Export Points >> use XYZ Point Cloud (.txt) format for this project. Accept the default options and click Ok.

Processing Coastal Imagery With Agisoft Metashape Professional Edition, Version 1.6—Structure From Motion Workflow Documentation

By Jin-Si R. Over, Andrew C. Ritchie, Christine J. Kranenburg, Jenna A. Brown, Daniel Buscombe, Tom Noble, Christopher R. Sherwood, Jonathan A. Warrick, and Phillipe A. Wernette

Open-File Report 2021–1039

U.S. Department of the Interior
U.S. Geological Survey

Table 1. Quick start guide for the structure from motion workflow used to aid hurricane relief and recovery efforts by the U.S. Geological Survey.

[GPS, Global Positioning System; INS, inertial navigation system; m, meter; RMSE, root mean square reprojection error value (reported in pixels); NAD83(2011), North American Datum of 1983 with 2011 adjustment; UTM, Universal Transverse Mercator; NAVD88, North American Vertical Datum of 1988; GCP, ground control point; DEM, digital elevation model; 3D, three-dimensional; 4D, four-dimensional; >, greater than; <, less than; ≤, less than or equal to; %, percent; —, no specification]

Step	Menu	Function	Action	As used in this workflow
			Image setup and alignment	
1	Main Menu >> Workflow	Add imagery	Navigate to directory with imagery and select all imagery associated with the project	.jpg file format
2	Workspace pane >> Cameras	Add camera group	Put images from same collection into a new camera group	For example, separate images from 2018-10-06 and 2018-10-07 into camera groups
3	Main Menu >> Tools	Camera calibration	Import precalibration (optional)	—
			Set GPS or INS offset for lever arm	0.1/−0.15/1.25 (0.05) (in meters)
			Create camera calibration groups	Make for each 4D or 3D collection
	Reference panel >> Import	Add camera positions (optional)	Import file of coordinates and altitude for each image	.txt file of latitude, longitude, and height above ellipsoid
4	Reference panel >> Settings	Set camera accuracy	Under Measurement Accuracy, set Camera accuracy	0.1/0.15 (in meters)
		Set tie point accuracy	Under Image Coordinates Accuracy, set “Tie point accuracy”	1 (default; in pixels)
		Set camera coordinate reference system	Select from “Coordinate System” dropdown	NAD83(2011)
5	Main menu >> Workflow	Align imagery	Change settings to: high, generic, reference-source, 60000, 0	—
			Add ground control points (optional)	
6	Reference panel >> Import	Add GCPs	Import or detect	Load from .csv file
7	Reference panel >> Settings	Set GCP accuracy	Under “Measurement Accuracy”, set “Marker accuracy”	0.02/0.03 (in meters)
			Under “Image Coordinates Accuracy”, set “Marker accuracy”	0.5 (in pixels)
		Set GCP coordinate reference system	Make sure dropdown “Coordinate System” matches cameras in step 5	NAD83(2011)
8	Reference panel >> Markers	Filter by marker	Manually adjust GCPs on individual images	—
			Error reduction and bundle adjustment	
9	Workspace panel >> Chunk	Duplicate	Before optimization, duplicate chunk and rename	Uncheck “Keep key points”
10	Reference panel >> Optimize	Initial optimization	Check on: f, cx, cy, k1, k2, k3, p1, p2, tie point covariance	—

Table 1. Quick start guide for the structure from motion workflow used to aid hurricane relief and recovery efforts by the U.S. Geological Survey.—Continued

[GPS, Global Positioning System; INS, inertial navigation system; m, meter; RMSE, root mean square reprojection error value (reported in pixels); NAD83(2011), North American Datum of 1983 with 2011 adjustment; UTM, Universal Transverse Mercator; NAVD88, North American Vertical Datum of 1988; GCP, ground control point; DEM, digital elevation model; 3D, three-dimensional; 4D, four-dimensional; >, greater than; <, less than; ≤, less than or equal to; %, percent; —, no specification]

Step	Menu	Function	Action	As used in this workflow
			Error reduction and bundle adjustment—Continued	
11	Main Menu >> Model >> Gradual Selection	Reconstruction uncertainty (geometry)	Set level: 10 (if >50% points are selected, increase until <50% points are selected)	—
			Delete points and optimize (optional)	—
			Check on: f, cx, cy, k1, k2, k3, p1, p2, tie point covariance	—
			Monitor: projections goal >100, RMSE (in pixels) ≤0.3	—
12	Main Menu >> Model >> Gradual Selection	Projection accuracy (pixel matching errors)	Set level: 2 (if >50% points are selected, increase until <50% points are selected)	Projection accuracy set to level 3
			Delete points and optimize	—
			Check on: f, cx, cy, k1, k2, k3, p1, p2, tie point covariance	—
			Monitor: projections goal >100, RMSE (in pixels) ≤0.3	—
13	Main Menu >> Model >> Gradual Selection	Reprojection error (pixel residual errors)	Set level: 0.3 or the level when about 10% of points are selected	—
			Delete points and optimize	—
			Check on: f, cx, cy, k1, k2, k3, p1, p2, tie point covariance	—
			Repeat until level 0.3 selects no points or <10% of original tie points remain	—
			Monitor: projections goal >100, RMSE (in pixels) ≤0.3	Stop if <10% original number of tie points remain, the Errors column exceeds Accuracy column in the Reference panel, or the Errors column starts to increase
14	Reference panel >> Optimize	Optimization (optional)	Check on: f, cx, cy, k1, k2, k3, p1, p2, additional coefficients, tie point covariance, and fit additional corrections	Coefficients b1, b2, and k4 are inappropriate to model or enable with most consumer grade cameras.

Table 1. Quick start guide for the structure from motion workflow used to aid hurricane relief and recovery efforts by the U.S. Geological Survey.—Continued

[GPS, Global Positioning System; INS, inertial navigation system; m, meter; RMSE, root mean square reprojection error value (reported in pixels); NAD83(2011), North American Datum of 1983 with 2011 adjustment; UTM, Universal Transverse Mercator; NAVD88, North American Vertical Datum of 1988; GCP, ground control point; DEM, digital elevation model; 3D, three-dimensional; 4D, four-dimensional; >, greater than; <, less than; ≤, less than or equal to; %, percent; —, no specification]

Step	Menu	Function	Action	As used in this workflow
			Error reduction and bundle adjustment—Continued	
15	Reference panel >> Settings	Tighten tie point accuracy and continue Reprojection error gradual selection (optional)	Change tie point accuracy (in pixels) from 1 to 0.1–0.3	—
			Optimize	—
			Check on f, cx, cy, k1, k2, k3, p1, p2, additional coefficients, tie point covariance, fit additional corrections	—
			Monitor: projections goal >100, RMSE (in pixels) ≤0.18	—
			Stop if RMSE ≤0.18, <10% original number of tie points remain, or the Errors column exceeds the Accuracy column in the Reference panel or RMSE begins to increase	
			Repeat step 14 using 10% of points per gradual selection. Stop if RMSE (in pixels) ≤0.18 or begins to increase	—
			Build dense point clouds, DEMs, and orthomosaics	
16	Main Menu >> Region	Resize output region	Use resize and rotate region tools to redefine output area	—
17	Workspace panel >> Chunk	Duplicate	Create duplicate chunk for each 4D flight chunk and rename	Not necessary in 3D
		Disable or delete	Disable or delete cameras not related to product being produced	Repeat for each flight chunk
18	Main Menu >> Workflow	Build dense cloud	Set Quality: high; depth filtering: mild; check all	—
	Main Menu >> Tools or Main Menu >> Model	Edit dense cloud	Use filter by confidence or manually select flyers and sinkers	—
19	Main Menu >> Workflow	Build mesh (optional)	Height field, dense cloud, high, enabled	If built from depth maps, the setting is arbitrary
		Build DEM	Select from “Coordinate System” dropdown, dense cloud, interpolation disabled	Build in NAD83(2011)
		Build orthomosaic	Build from DEM, mosaic	Build from a separate interpolated DEM to avoid holes in the orthomosaic
			Export and file naming	
20	Main Menu >> File	Export	Change coordinate reference system to UTM projection and vertical datum (may need to download a geoid)	NAD83(2011) UTM Zone 18N + NAVD 88 (meters)
			Set resolution size	0.25 m
			Set region boundaries to round numbers	Nearest 10s of meters

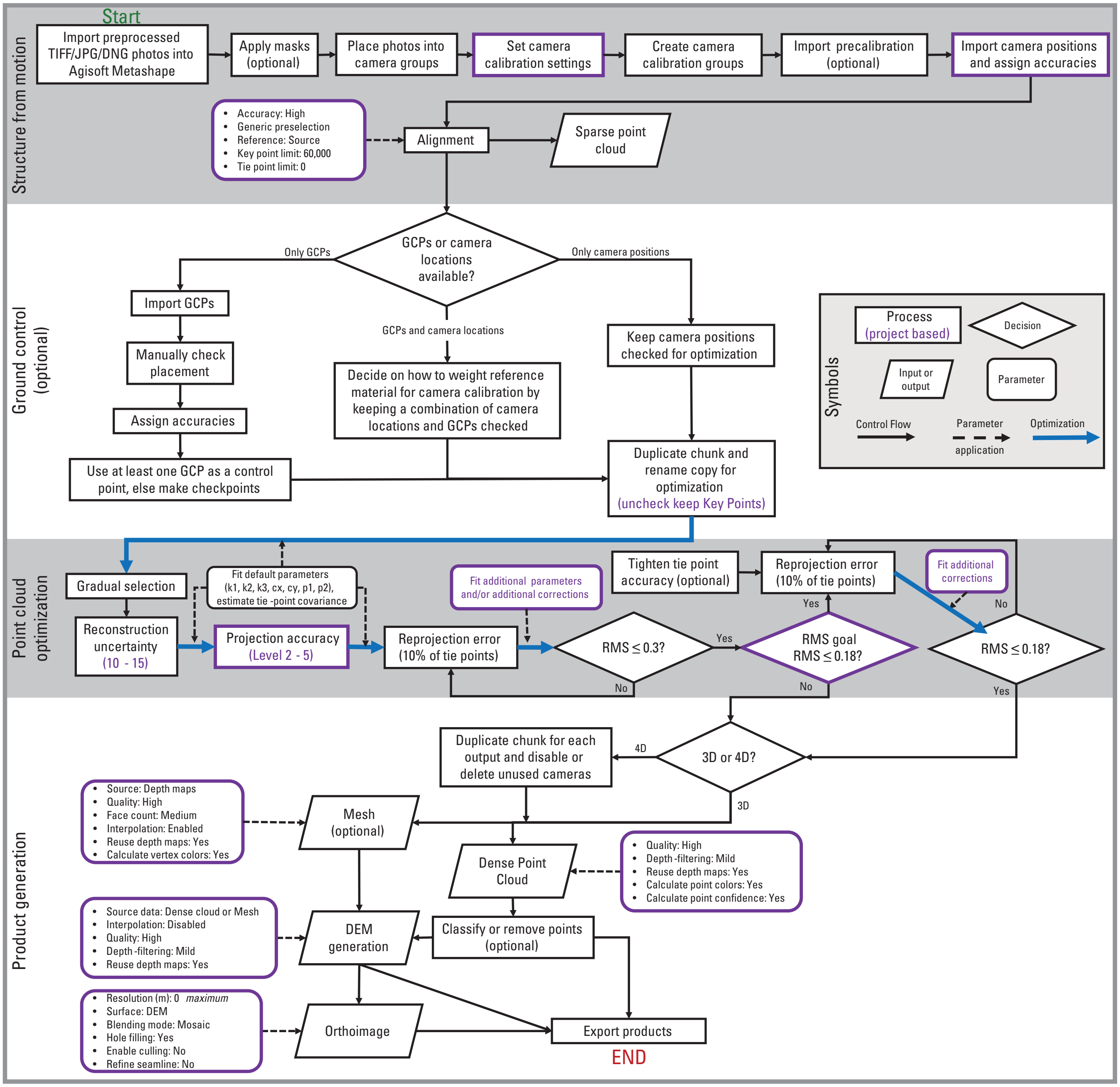


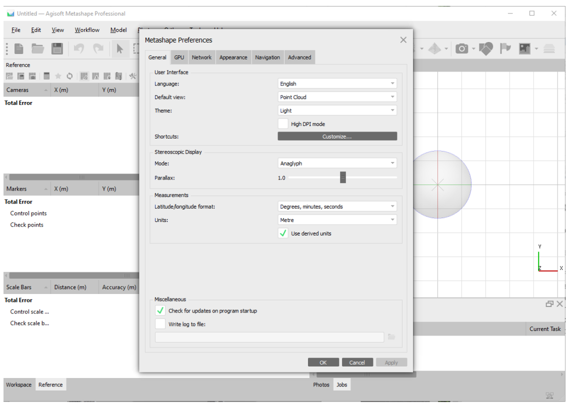
Figure 1. Schematic diagram summarizing a workflow using Agisoft Metashape Professional Edition. The workflow conceptualizes four main stages: structure from motion, ground control, point cloud optimization, and product generation. Each stage contains a series of processes, decisions, inputs, and parameters important for consideration in the software. The workflow can be applied to projects with optional inputs. Steps or inputs that may change based on the requirements of a project are indicated by purple text or a purple outline. GPS, Global Positioning System; INS, inertial navigation system; GCP, ground control point; RMS, root mean square; %, percent; ≤, less than or equal to 3D, three-dimensional; 4D, four-dimensional; DEM, digital elevation model; m, meter.

Agisoft MetaShape Quick Guide for River Characteristics Activity

Originally by Yonathan Admassu (James Madison University) with modifications by Beth Pratt-Sitaula (UNAVCO) – updated 6/24/2020 by Sharon Bywater-Reyes (University of Northern Colorado)

1) Open Agisoft Metashape and change the preferences. Go to Tools >> Preferences

Change Default View to “Point Cloud” and make sure measurement units is “Metre”



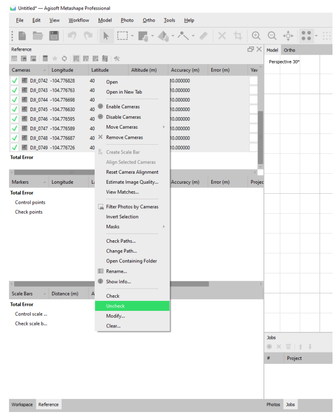
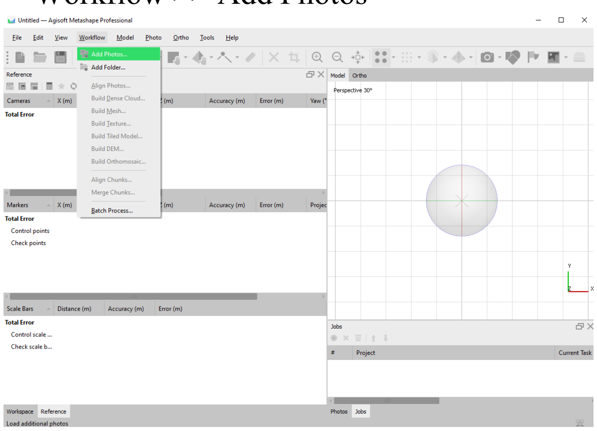


Image quality may be a problem. In the Photos Pane, select all images, right click >> Estimate Image Quality and choose all images. You may want to remove photos below a quality of 0.7. (switch Photo pane to List view to see Quality)

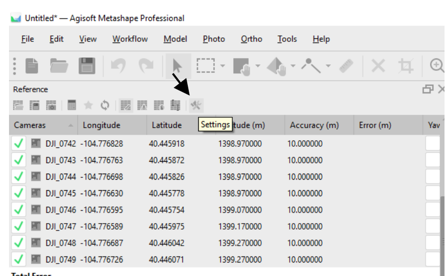
2) Add photos
Workflow >> Add Photos



Note: For photos taken with your phone or camera that have inaccurate GPS coordinates, you will want to uncheck the Cameras (photos are referred to as cameras). For the drone images, keep them checked – these will be good enough locations to help with alignment. To uncheck or check them all at once, click on the reference pane, select all the photos, right click >> Uncheck (or Check)

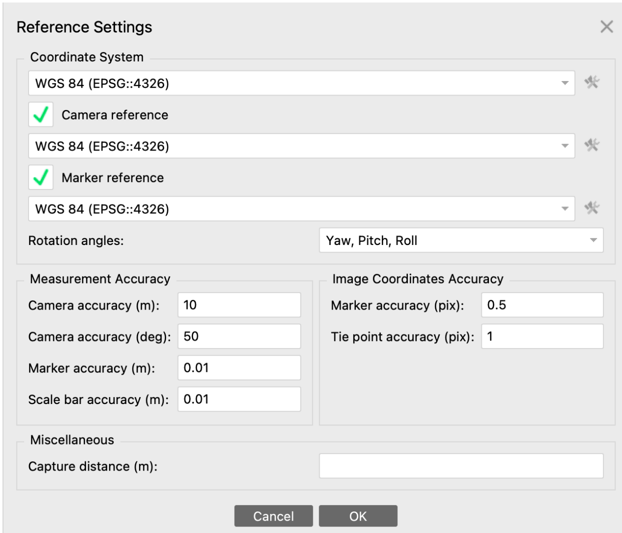
3) Make sure to save your project. File >> Save As

4) In the reference pane, go to Settings



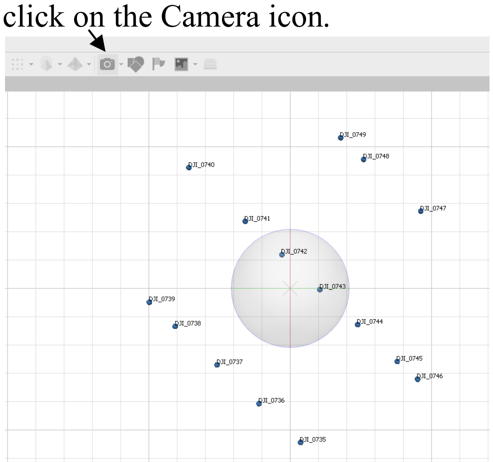
If needed, change the coordinate system you would like to use for your project and specify those of the camera and/or ground control points (Marker Reference).

In our case both DJI Mavic 2 Pro and Emlid GPS use WGS 84. If conducting in a local coordinate system, simply change all to “Local Coordinates (m)”. Or select whatever other coordinate system(s) you may be using.

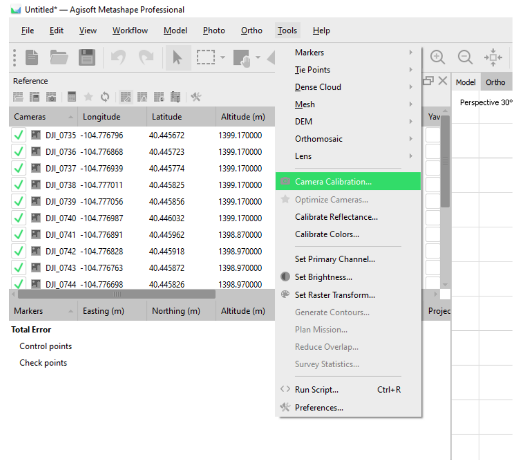


Also specify the accuracy of your camera and marker (ground control points). In the example above, the marker accuracy is about 0.01 m, or 1 cm, because we used RTK GPS.

5) If camera GPS information has been successfully imported, you should see the locations of the images. If you don't see them, click on the Camera icon.

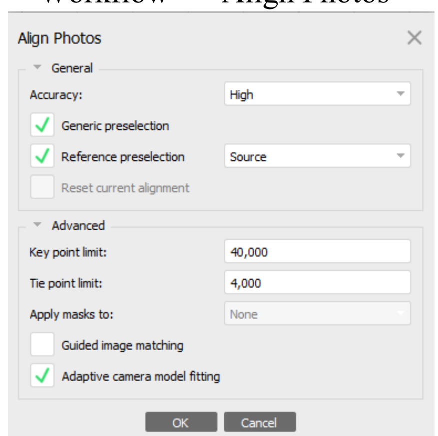


6) Go to Tools >> Camera Calibration



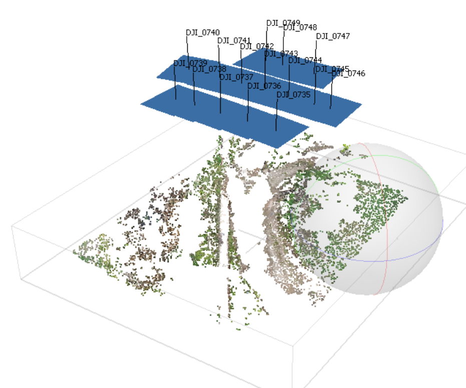
For the DJI Mavic 2, make sure "Enable Rolling Compensation" is checked.

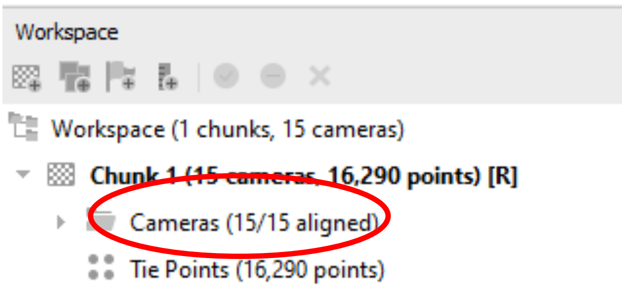
7) Align Photos
Workflow >> Align Photos



Check alignment by looking in the Workspace.

You may have to check in the camera icon. 



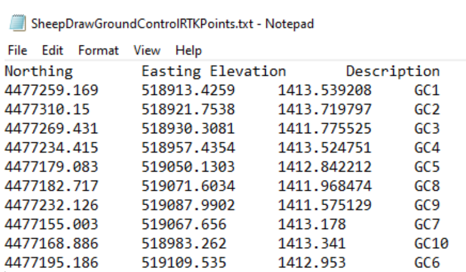


We are now done using the GPS locations of the cameras (if they were checked in Step 2). Select all cameras in the Reference Pane, right click >> uncheck. We will no longer use the drone locations. We will now use our Ground Control Points.

8) In the Reference screen, import the coordinates of the targets (also called ground control points [GCP])

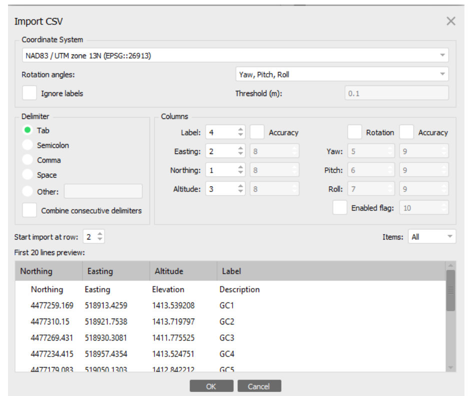
Import

The ground control (GC) coordinates should be in .txt format as shown below (tab delimited). Make sure you choose the appropriate coordinate system at the top. For the DJI Mavic 2 coordinates, UTM zone 13N. For a local coordinate system, choose "Local Coordinates (m)". Choose the appropriate columns such that the text imports correctly.


SheepDrawGroundControlRTKPoints.txt - Notepad

File Edit Format View Help

Northing	Easting	Elevation	Description
4477259.169	518913.4259	1413.539208	GC1
4477310.15	518921.7538	1413.719797	GC2
4477269.431	518930.3081	1411.775525	GC3
4477234.415	518957.4354	1413.524751	GC4
4477179.083	519050.1303	1412.842212	GC5
4477182.717	519071.6034	1411.968474	GC8
4477232.126	519087.9902	1411.575129	GC9
4477155.003	519067.656	1413.178	GC7
4477168.886	518983.262	1413.341	GC10
4477195.186	519109.535	1412.953	GC6

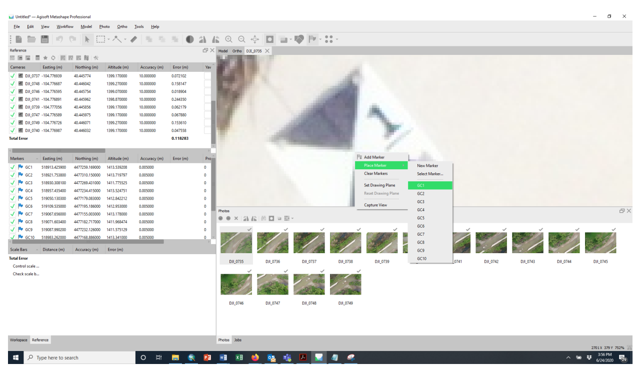


A dialog box will appear with the message "Can't find match…"—just say "Yes to All"

Note, because there are two areas of interest at Sheep Draw, you will not use all the ground control points.

Double-click on each photo with GCP. A new window showing the photo will appear.

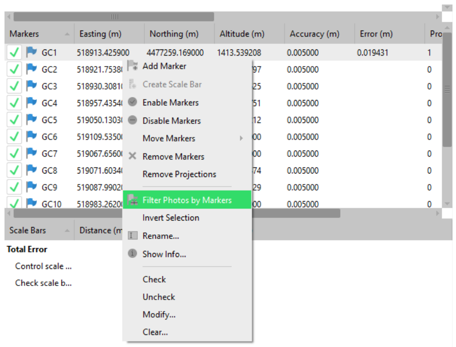
Zoom in on each target/GCP. Assign coordinates by: Right clicking on each target center >> Place Marker >> Choose the corresponding target from the ones that were imported above.

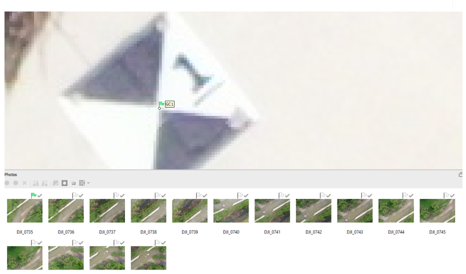


Another alternative is to first place the markers by right clicking on the image and choosing "Add Marker." Choose the correct marker. Then in the Reference Pane, you can rename it by double clicking on the name in the Markers pane and import the text file afterward. Make sure the name matches your text file.

Once you have placed a marker, you can filter the photos by that marker to get Metashape's best guess as to matching photos. In the

Reference Pane, right click on the marker and click "Filter Photos by Marker." The associated photos Metashape has found will show up in the photo viewer. You will get white flags for guesses. You will need to go through ALL the photos with the marker and reposition them in the correct location or confirm they are correct by dragging the flag to the correct place. You can always right-click >> Remove Marker if you make a mistake.





Work your way through the photos assigning or correcting the GCP in each photo. Click the Update button in the Reference pane to roughly georeference the model based on these points. This will expedite the process of placing the remaining GCPs.

To optimize the camera alignment and generate a camera calibration based on the GCPs, click the Optimize Cameras button in the Reference pane toolbar. Accept the default settings and make sure "Adaptive camera model fitting" is selected.

9) Errors

At this point it is worth checking your errors. There are several sources of error to consider.

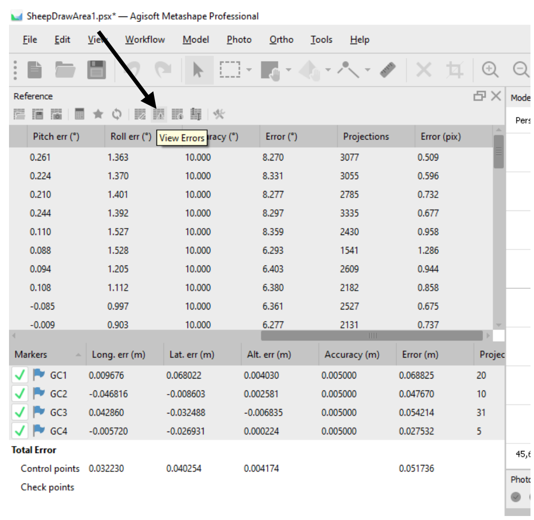
Scroll all the way to the right in the Markers pane, hopefully your errors will be under a meter. You can remove cameras with large errors, but we won't for our purposes.

Your control points show Error (m) and Error (pix).

1. Error (m) - residual error per coordinate or in 3D space. That is distance between the input (source) and estimated positions of the marker.

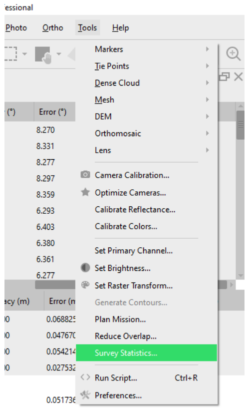
2. Error (pix) - root mean square reprojection error for the marker calculated over all photos where marker is visible.

To view more errors, click on the very tiny View Errors icon.



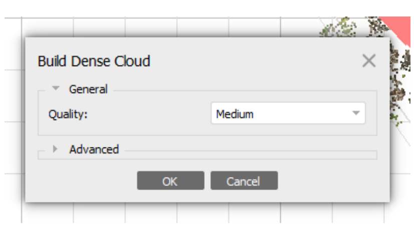
This will show the X, Y, and Z errors.

Lastly, you can build a report, Tools >> Survey Statistics. You can see how many images overlap in different regions (and more) and error of ground control points visually.

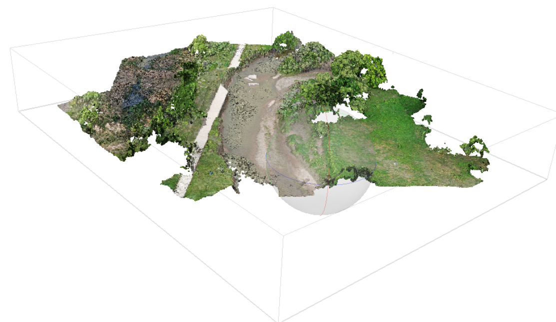


Save your project (.psx) periodocially just to make sure you do not lose work.

10) Build dense cloud
   Workflow >> Build Dense Cloud
Choose "Medium"



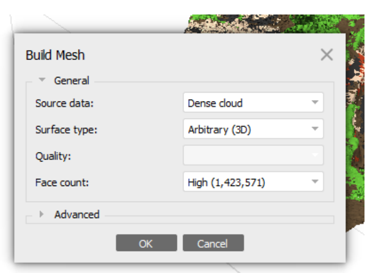
11) View dense cloud
   Model >> View Mode >> Dense Cloud
OR click the dense cloud icon

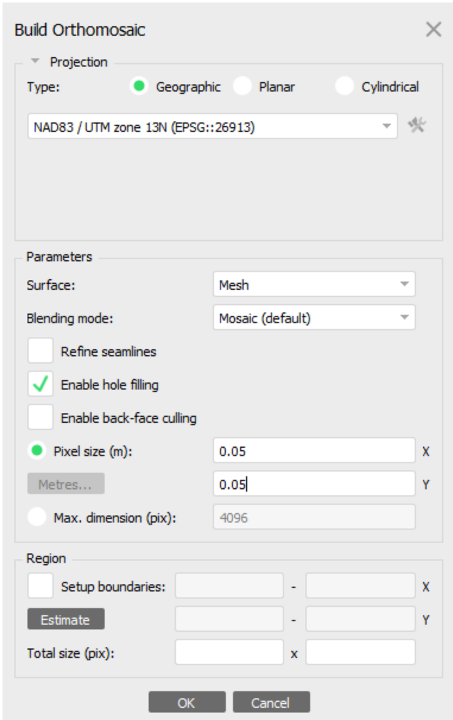


12) After the dense cloud is created, the points may need to be edited. Some portions of the model may be inaccurate, or just outside of the region of interest. This is an appropriate time to remove these points. Select points to delete by using one of the selection tools.

13) Save your project again and then export. To export point cloud:
   File >> Export >> Export Points >> use XYZ Point Cloud (.txt) format for this project. Accept the default options and click Ok.

14) We will also want to create and export an orthophoto (high-resolution aerial image). For this, we will need a mesh. From the Workflow menu >> Build Mesh and choose Dense cloud. When this is complete, Workflow >> Build Orthomosaic.



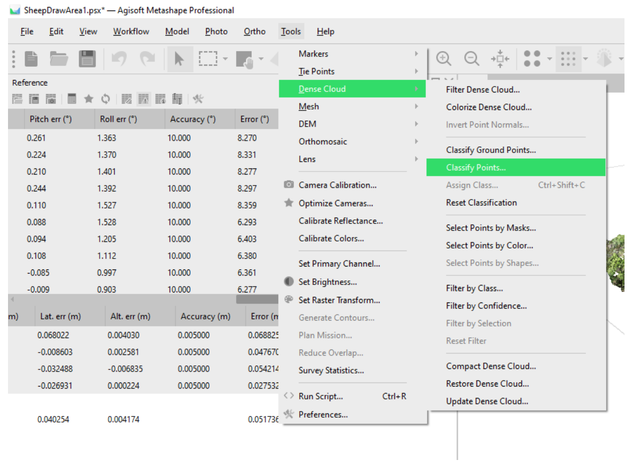


Choose a pixel size that isn't rounded, e.g. 0.05 m. Export as as .tiff or .kmz. Notice you can view the orthoimage on the "Ortho" tab of the viewer.

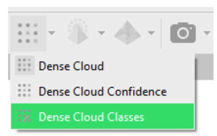
15) Classification and Ground Model

Now you have a large point cloud in text format. Now what? There other features in MetaShape that might be appropriate in some cases. For example, you can create a textured mesh or a digital elevation model (raster). Because most scans have vegetation present, a raster of the entire cloud would average each raster cell and represent the average of anything captured in the scan. Hopefully, some ground points exist, despite dense vegetation. Alternatively, you may be interested in capturing the vegetation. As such, we want to CLASSIFY the cloud into ground and vegetation points (and maybe other things like buildings, etc.). MetaShape has a classification tool and there are other open source tools. We will use both, with the ultimate goal of separating ground points to create a digital elevation model that could be used for geomorphic analyses.

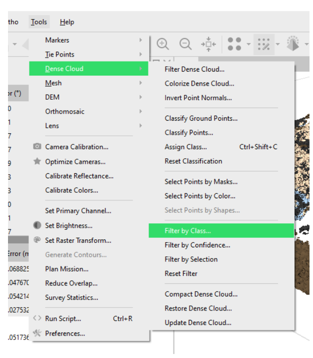
In MetaShape, click on the Tools menu >> Dense Cloud >> Classify Points.



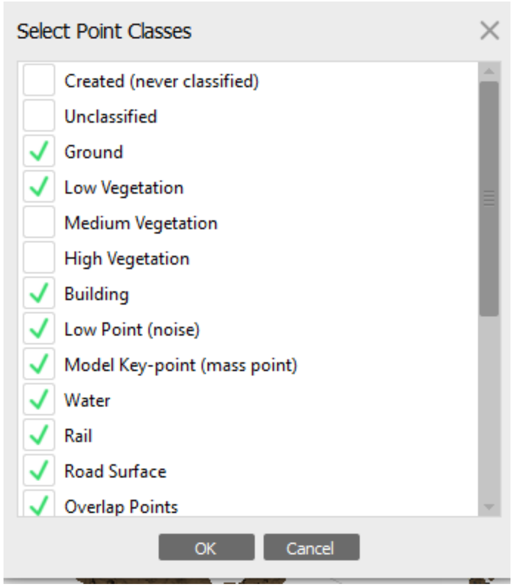
To view the results, click on dense cloud icon >> Dense Cloud Classes



You can filter by class by Tools >> Dense Cloud >> Filter by Class



You can unselect vegetation classes and remove vegetation (play with different options and compare visually).



[More about the classification tool https://agisoft.freshdesk.com/support/solutions/articles/31000148866-dense-cloud-classification]

Now, you could choose to re-export the point cloud with just the classes you are interested in using.

16) CloudCompare is an open-source point cloud viewer and has many cool plugins. We will use several, including CANUPO classification. We will practice this plugin as well as revisiting a point cloud differencing tool in the second unit of the course. http://nicolas.brodu.net/en/recherche/canupo/

Kinematic GPS/GNSS Methods Manual

Ian Lauer (Idaho State University); additional edits by Diana Krupnik and Beth Pratt-Sitaula (UNAVCO)

This document is intended as a practical guide to field methods for kinematic positioning systems. It does not cover positioning computation or theory, but is focused on field-based use of kinematic survey systems. This guide is intended for both instructors and students in its current form and includes asides of technical or theoretical material targeted toward advanced users.

Table of Contents

Note: Although the term GPS (Global Positioning System) is more commonly used in everyday language, it officially refers only to the USA's constellation of satellites. GNSS (Global Navigation Satellite System) is a universal term that refers to all satellite navigation systems including those from the USA (GPS), Russia (GLONASS), European Union (Galileo), China (BeiDou), and others. In this module, we use the term GNSS to refer generically to the use of one or more satellite constellations to determine position.

1. Introduction to Kinematic GPS/GNSS

Kinematic GNSS surveys are used to rapidly collect large numbers of high-precision survey positions, which are post-processed against a static base station. The system is composed of a base station, a rover, and potentially a radio system. The base station may be a combination of a temporary local base station or a permanently installed GNSS station, such as a Network of the Americas (NOTA; https://www.unavco.org/instrumentation/networks/status/all) or Continuously Operating Reference Station (CORS; https://geodesy.noaa.gov/CORS/) site, which is located close to the study area. A rover is an antenna and receiver combination, which can be mounted to a range pole or backpack and is carried to each site for measurements.

The basis of the kinematic system is a mobile rover, which takes initial positions, and a base station, which allows for corrections of the rover's position. The rover is carried to each measurement site and is stabilized during a short occupation, typically 5–30 seconds, to acquire an initial position. The rover's position is processed against the static base station's position to remove several types of error including integer ambiguity and atmospheric delays. This results in a high-precision position for the rover on the order of a couple centimeters. This correction may take place either during post-processing or in real time if the rover receives correction information via radio or cellular connection. Whether processed after or during the survey, these methods produce the same results.

1.1 Real-Time Kinematic (RTK) Survey

Real-time kinematic surveys take advantage of constant radio communication between a static base station and the roving antenna to provide signal correction for increased positioning accuracy of the rover in the field (Figure 1). The real-time correction has the advantage of processing and viewing corrected, centimeter-accuracy measurements in real time while in the field. Additionally, RTK allows positions to be located within a georeferenced coordinate system and enables real-time measures of angles, distances, area, and navigation while in the field. However, to obtain these advantages the base station must either be established over a known position such as a previously installed benchmark or monument or run for a sufficiently long time to be corrected using independent software (e.g., OPUS [Online Positioning User Service]). RTK systems also provide an enhanced level of quality assurance that equipment is functional and positions are approximately correct before leaving the field area, potentially preventing loss of time. With post-processed systems (discussed in the next section), you must wait to see your corrected results.

An RTK setup consists of the base and rover antennas, receivers, a controller, and the addition of a radio at both the base and rover for positional corrections (Figures 1, 5, 6). The base station is typically set up over a monument or other position with a known coordinate. This can be assigned to a local coordinate system, but reduces many of the system's advantages. The base antenna receives positioning code from satellites and delivers it to the base receiver for processing. The base receiver then saves the base antenna's position and communicates the carrier code correction and base position to the roving antenna and receiver unit via radio. The rover receiver combines the base station data and a GNSS positioning signal from satellites. The receiver compares the variations and noise in the base station's code with its own, which allows it to eliminate several sources of error including atmospheric and tropospheric delays, integer ambiguity guesses, and clock errors. The correction of these errors increases the accuracy of the rover's position from tens of centimeters to 1–2 cm precision. Although RTK systems have many advantages, some systems require more equipment in the form of two radios, batteries, and supporting equipment. You must also maintain radio communication between base and rover.

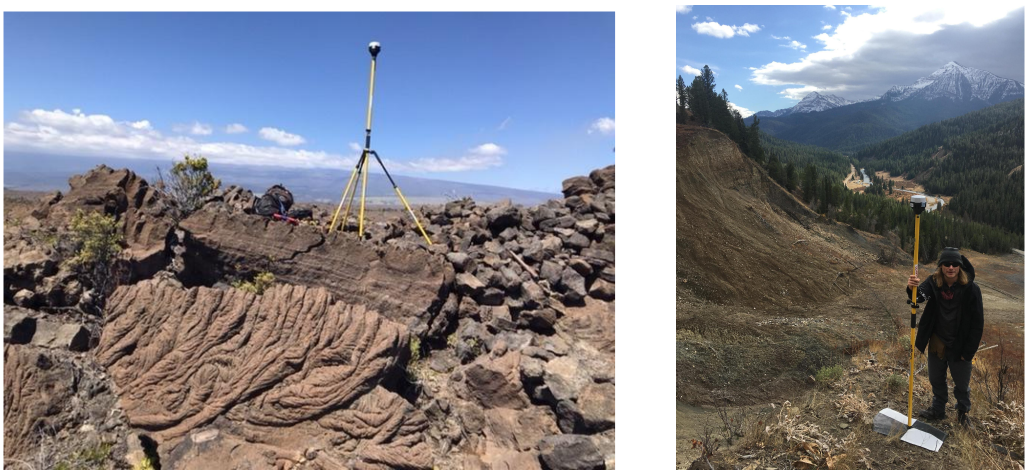


Figure 1. An example of a Real-Time Kinematic (RTK) base station (left) and rover (right). Many options are available for rover mounts including poles, bipods, and backpacks (shown). A PPK setup is essentially the same, minus the radio link. (Source: Steve Lundblad and Benjamin Crosby)

1.2 Post-Processed Kinematic (PPK) Survey

Post-processed kinematic (PPK) survey benefit from lower equipment and technical logistics, but with positions equally precise as RTK setups and do not require a known base station. Instead PPK requires downloading and then processing signals on a computer connected to the Internet in order to calculate and apply the correction. Post-processing is advantageous whenever terrain or logistics limit the ability to carry additional equipment to the field, when it is not necessary to have corrected data immediately, or when a monument or benchmark is unavailable. Most topographic and geologic surveys do not need real-time processing unless they involve engineering-style work where distances or other geometries need to be calculated in the field. PPK equipment consists of a base station and rover, each with an antenna and receiver. The rover additionally has a controller for data collection and inputs. PPK surveys collect continuous, static signals at the base station and short, 5–30 second occupation signals with the rover. The data is then downloaded and backed up after fieldwork and processed against other continuously operating stations. This can be done in Trimble Business Center, in the case of Trimble hardware, or other proprietary and free software as necessitated by equipment. The base station data must be processed in RINEX and corrected against other static, permanent stations in the region in order to correct for its position and then apply baseline corrections to the rover's data. Emlid Studio (https://docs.emlid.com/emlid-studio/) is available for PPK with Emlid receivers (see https://serc.carleton.edu/getsi/teaching_materials/high-precision/equipment.html#emlid; Instructor Guide for Emlid ReachRS2). One can also utilize the open source RTKLIB (http://www.rtklib.com/) software to apply PPK corrections but it takes some time to learn to use it effectively.

Scan Type	Advantages	Disadvantages
RTK	Real-time corrected positions in a known coordinate plane. Able to navigate to and compute geometries of data points in the field	Potentially more equipment needed. Must have radio connection between base and rover. Must set up base on a known position to utilize advantages
PPK	Reduced logistics, cost, and complications. Sufficient for most non-engineering surveys	Corrected data is typically not available until processed. Necessary to set up base at benchmark or fix its location later. Challenging workflow for more affordable receivers such as Emlids.
RTX	Base station not required, centimeter-level positions in real time, no base station is required, available in remote locations.	Can take 5-30 minutes to initialize RTX correction service, adding the RTX option to Trimble receiver introduces more cost

2. Equipment

Various types and combinations of antennas, receivers, and controllers are available in the modern market and are constantly evolving. For the most part, it is easiest to work with antennas and receivers from the same manufacturer unless other compatibility is specifically mentioned, although the data is completely interchangeable once retrieved and processed. Generally, UNAVCO-supported education projects receive Emlid brand units. However, because processing software and workflow is manufacturer dependent, instructions provided here are manufacturer independent. The general workflow should apply to most manufactures, but see manufacturer literature or the UNAVCO Knowledge Base (http://kb.unavco.org/kb/) for specific instructions. Emlid-specific guides are available in the GETSI GPS/GNSS Equipment page (https://serc.carleton.edu/getsi/teaching_materials/high-precision/equipment.html#emlid)

2.1 Antennas

Antennas are the physical equipment that receives the carrier frequency and positioning code from the satellites and transmits it to the receiver for processing (Figure 2). Antennas may consist of just an antenna or include one or more signal-modifying or blocking apparatus, which are aimed at reducing or enhancing multipath signals and atmospheric distortion. Some modern antennas, such as the Emlid ReachRS2 (Figure 2, *left*), have a combined antenna and receiver unit in one package, sometimes referred to as a smart antenna.

Figure 2: (Left) Emlid Reach RS2 antenna/receiver combination (Photo: Andy Moore). It contains a LoRa radio and is designed to be self-contained. (Right) Trimble Zephyr geodetic antenna mounted on a tribrach and connected to an external receiver via a port on the bottom of the saucer. (Photo: Ian Lauer)

2.2 Receivers

Receivers are the central processing units of the GNSS system (Figure 2 left, 5, 6). They connect the various other hardware including antennas, radios, and often power. They receive signals from the antenna and compare the satellite and receiver time codes to calculate distance between them. This time differential is fed into a complex code for determining position based on at least four satellite signals. Positional data may be stored in various formats, most of which are proprietary for each manufacturer. The receiver is responsible for sending the position data to the controller computer for user viewing and for taking user input and executing the commands. On an RTK setup the receiver will also connect to and receive or transmit carrier phase correction data from base station to rover. Certain models, such as the Emlid Reach RS2 and Septentrio Altus APS3 are a receiver and antenna combination, allowing for the use of a cell phone, laptop, or tablet for configuration and data access.

2.3 Radios

Radios are only used on RTK setups where a correction signal is needed for real-time processing. The radios typically use a high-frequency band near 0.5–1.5Mhz. They receive carrier phase signals from the base station receiver and transmit them to the radio and receiver on the rover unit for use in correcting and increasing precision in the rover's position calculation.

2.4 Power and Batteries

Receivers, antennas, and controllers use both internal and external batteries for power. Average running time for batteries depends on manufacturer design but typically last 4–10 hours for internal setups, with external setups limited only by ability to transport larger batteries to the site (Table 1). Battery technology will depend on environmental conditions. Gel cell and LiPo batteries have the advantage of being environmentally stable and spill proof. Battery estimates need to be made based on equipment. A simple formula for estimating battery consumption is

Total Amperage (Volt*Watts) * Total Operational Time (hours) = Battery Capacity (Amp/Hrs)

Capacity should be overestimated to account for logistical oversight or complications, keeping in mind that battery capacity ages over time and with use. Power can also be supplemented by many means including solar, wind, or other power sources as demanded by the site.

Table 1: UNAVCO Campaign GPS GNSS Handbook, Receiver Power Consumption

Receiver	**Power draw (approximate)***	**Lifetime w/ a 12 V, 18 Ah battery***
Trimble NetRS	3.5 W	2.25 days
Trimble 5700 or R7	3–4 W	2–2.5 days
Topcon GB1000	4 W	1.9 days
Septentrio APS3G	4 W	~1.5–2 days
Emlid Reach RS2	0.1 W	16 hours as 3.5G rover with 6.3 Ah internal battery

*For information on power options available from and testing performed by UNAVCO, see http://kb.unavco.org/kb/category/gnss-and-related-equipment/power/93/.

2.5 Data Management, Storage, and Initial Settings

Data management is a small but critical step in the survey design. It is ineffective to have a well-designed survey only to find out you have run out of storage space, lost the data, or collected improper occupation lengths for the precision needed. Each unit has a unique set of capabilities and limitations (Table 2). Consider the following:

- **File length** – do you want the receiver to bin the data into files of a fixed time window?
- **Sample rate** – how often do you want the receiver to collect data? The base station (fast static and kinematic surveys) must collect data at least as often as the rover(s). A kinematic rover will typically collect 1 sample/second for a total occupation at each site of 5–15 seconds.
- **Elevation cutoff angle** – data coming from low-elevation satellites is often noisy because of the atmosphere; below what elevation do you want the receiver to discard, rather than store, the data? Note that this data can also be discarded during processing. A typical value is 5–10°
- **Storage Capacity** - There must be enough free memory in the receiver for the desired survey. Whereas memory is an issue with older receivers, the later generation receivers have large amounts of data storage. File size is dependent on manufacturer file formatting. Note the Topcon collects half as much data at a 30-second sample rate (versus 15-second on Trimble) but produces a larger file. Upgraded storage space is relatively cheap and easy to acquire.

Table 2: Typical parameters for different survey styles (file lengths, sample rates, and elevation cutoffs)

Survey style	File length	Sample rate	Occupation time	Elevation cutoff angle
Continuous	24 hr	30 seconds	Continuous	10 degrees
Static	2+ hr	30 seconds	2+ hours	10 degrees
Rapid Static	none	15 seconds	5+ minutes	10 degrees
Kinematic	none	1–15 seconds	5+ seconds	10 degrees

2.6 Tripods, Benchmarking, and Distance Measurement

Details on this equipment can be found in the *GETSI GPS/GNSS Antenna Mounts Guide*. Basic equipment could include a bipod, tripod, or spike mount for static or rapid-static surveys. For repeatable surveys, some kind of permanent benchmark or monument will need to be located or established such as a NGS survey marker, pin, or threaded rod mounted in an appropriately stable surface. A collapsing measuring stick, engineer's tape, or other measuring device appropriate for your setup is necessary for metadata collection, especially for establishing antenna height. See the *GETSI GPS/GNSS Antenna Mounts Guide* for more information.

3. Field Workflow: General

3.1 Site Analysis

Initial site analysis is integral to good survey design and subsequent successful data collection (Figure 3). Anticipating and compensating for good sky coverage, line of sight, and multi-pathing issues as described in Unit 1 will significantly increase your success. The largest inhibitors to good surveys are overhead or high standing structures such as trees, buildings, canyon walls, etc., which limit sky view, obstruct signals, and create multi-path signal error. Strategies for overcoming these obstructions include placing base stations away from the study area in a position that best limits obstructions to the sky. A base station ideally may be placed within several kilometers of the area to be measured, although baseline distances up to 10 km may still yield high-accuracy, high-precision measurements for PPK surveys. RTK surveys must maintain radio contact for real-time corrections to work and are typically limited to baselines of several km with good to moderate line of sight. In areas where complicated topography obstructs communication with the base station, two or more base stations may be operated to provide saturation of baselines throughout the area.

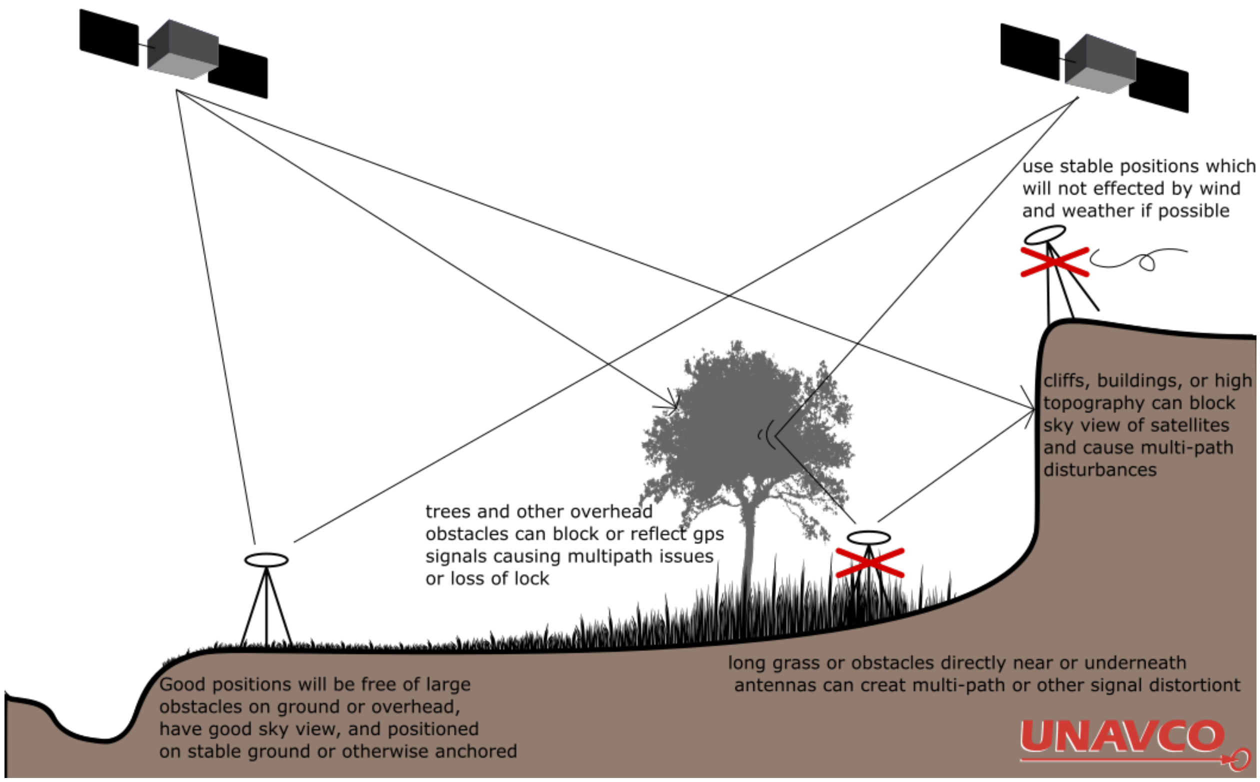


Figure 3. Base locations considerations to maximize safety and function.

3.2 Preparation and Logistics

1. Calculate power needs for equipment. Charge and test batteries.
2. Locate memory devices (typically SD cards) and verify sufficient storage is available.
3. If unfamiliar with equipment, do a complete test setup and verify connectivity between equipment before leaving for the field or be prepared to troubleshoot later
4. Do reconnaissance of the field area. Topographic maps, Google Earth Imagery, or a pre-trip to the area can significantly improve success on your field day.

5. With reconnaissance knowledge, plan the base sites, data points, and paths to navigate the field site. A good plan will reduce time spent in the field later. Anticipate the number of points to be collected and time associated with the plan.
6. Pack all equipment using a checklist.
7. **Note:** It is necessary to know which type of kinematic system (RTK or PPK) you will use before continuing. Workflow processes (diverge depending on whether processing is done in real time or after in a lab (Figure 4).

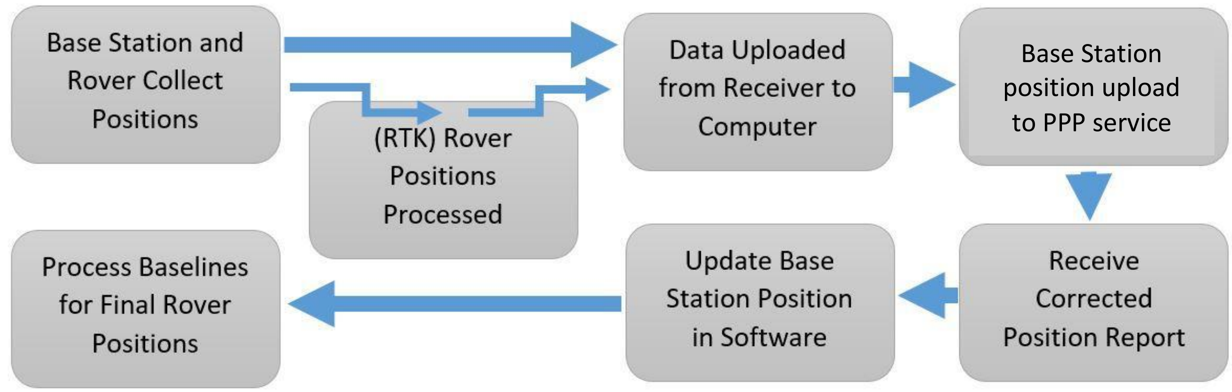


Figure 4. RTK and PPK workflow.

4.1 Base Station Preparation

Base stations need to be programmed with a specified sampling rate, measurement length, and (RTK) radio communication protocol and baud rate. Typically, this is preprogrammed by UNAVCO or the user in the office prior to deployment. Setting the configuration file to load on power-up is common. Changes can be made in the field with a controller or a laptop with the necessary software. Additionally, starting parameters for the survey, including the known or assumed positions of the benchmark or monument, will need to be entered before data collection.

General Pre-field Workflow:

1. Connect the receiver to a controller or computer and power up.
2. Connect to the receiver through a program (ex. Trimble Configuration Tool) or controller.
3. Download the current configuration and back up for posterity.
4. Set the antenna model and (RTK) radio type as necessary. If using an external RTK radio, establish the Baud rate and communication protocol. This must match with rover radio.
5. Set the elevation mask and output reference and coordinate system.
6. Set the configuration file to load on power-up or boot and transmit the file to the receiver.
7. Reboot the receiver, then connect and download the configuration file to verify settings were saved.
8. Connect the GNSS antenna (and controller, if used) to the receiver. Verify connectivity either in the controller or using indicator lights/screen on the receiver. (RTK) Test connection with the rover radio when complete.
9. Once verified, remove all cables, install protective caps, and pack equipment.

4.2 Base Station Field Setup

1. Locate the benchmark, monument, or landmark to be measured. Alternatively, establish a new monument, using best practices in UNAVCO Resources: GNSS Station Monumentation (http://kb.unavco.org/kb/article/unavco-resources-gnss-station-monumentation-104.html) and recording a monument log (http://kb.unavco.org/kb/article/campaign-monument-log-sheet-62.html).
2. Set up the tripod, spike mount, or another mount on top of the benchmark. See the *GETSI GPS/GNSS Antenna Mounts Guide* or for the "UNAVCO" method of leveling tripods and spike mounts, see the UNAVCO GNSS Antenna Mounts (http://kb.unavco.org/kb/category/gnss-and-related-equipment/gnss-antenna-mounts/23/).
3. Center tripod or spike mount over the benchmark and level the antenna mount
4. Anchor legs so they will not move throughout the survey.
5. Attach antenna to the top of the mounting system.
6. Attach antenna to the tripod or other antenna mount (http://kb.unavco.org/kb/article/unavco-resources-gnss-antenna-mounts-394.html) and hang the receiver and radio on one of the legs if available or in a protective case if necessary or convenient.
7. Connect all appropriate cables. The GNSS and (RTK) radio antenna will connect to the receiver, with the battery being connected last. This will avoid errors in receivers not detecting ancillary equipment.
8. Measure and record slant height or antenna height to phase center as appropriate. To measure slant height, place measuring stick or tape on center of benchmark and measure to the outer edge of the antenna where phase center is located (as found in manuals). Measure in at least three locations around antenna. Measurements should be equal if the tripod is level, +/- 0.5cm. If not, re-level system before recording data. Do not move the tripod after leveling is completed or while data is being collected. Doing so will affect the precision of positioning.
9. Record general site observations, location, times, and configurations in a field book (ex. http://kb.unavco.org/kb/article/logsheets-and-field-notes-72.html).
10. Power up receiver and verify connection to antenna and radio.
11. Some receivers automatically begin logging on power up, others require a prompt. If necessary, start data collection.

4.3 Rover Setup and Preparation

Generally, the rover receiver will need to be pre-programmed much like the base station. In some cases, the setup will be entirely done through the controller, in which case this may be done in the field. It is still wise to verify connectivity with a base station prior to fieldwork.

1. Connect the receiver to a controller or computer and power up.
2. Connect to the receiver through a program (ex. Trimble Configuration Tool) or controller.
3. Download the current configuration and back up for posterity.
4. Set the antenna model and (RTK) radio type as necessary. If using an external radio antenna, establish the Baud rate and communication protocol. This must match with the base station radio.
5. Set the elevation mask and output reference and coordinate system.
6. Set the configuration file to load on power-up or boot and transmit the file to the receiver.
7. Reboot the receiver, then connect and download the configuration file to verify settings were saved.
8. Connect the GNSS antenna (and controller if used) to the receiver. Verify connectivity either in the controller or using indicator lights/screen on the receiver.
9. (RTK) Test connection with the base station radio when complete.
10. Once verified, remove all cables, install protective caps, and pack equipment.

4.4 Rover Field Setup

1. Attach antenna, receiver, and controller to monopod, bipod, or alternative mounting setup
2. Connect antenna, radio, and receiver cables. Install batteries and power up.
3. Measure and record antenna phase center height for software setup
4. With the controller, set and verify the occupation time, sampling rate, antenna height, elevation mask, and (RTK) radio communication protocols.

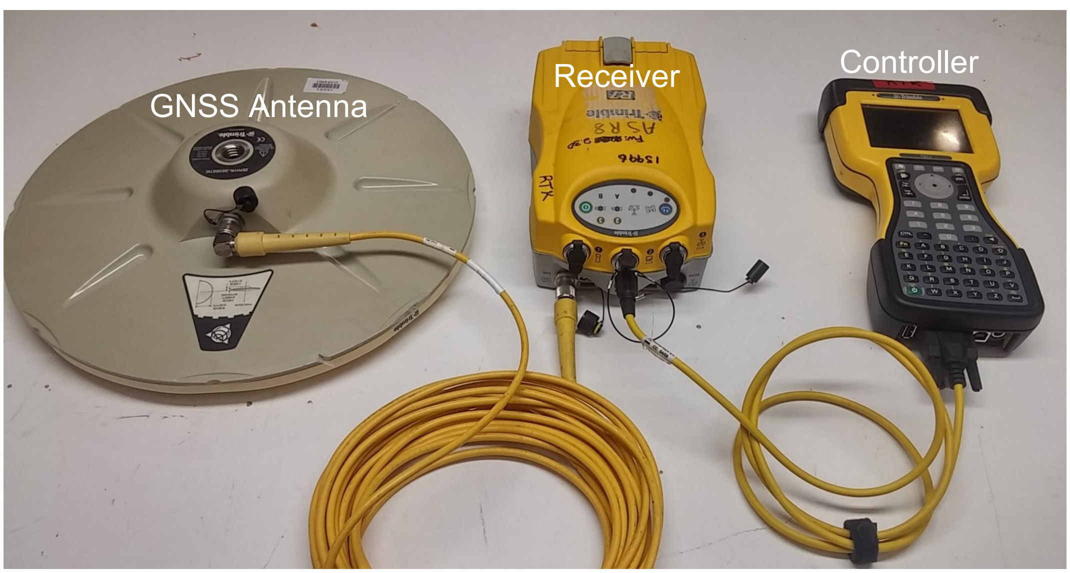


Figure 5. An example of the main components on a PPK or RTK rover. Trimble Zephyr antenna, R7 receiver, and controller. The RTK set up would also include a radio antenna attached to the R7. (Source: Ian Lauer)

Figure 6. An example of the main components on Emlid Reach RS2 PPK or RTK rover. GNSS antenna, receiver, and LoRa antenna are together. The controller is a phone/tablet app. (Source: Beth Pratt-Sitaula)

4.5 Conducting a Survey

Once the base station and rover are functional, it is time to begin surveying! Before starting, review and optimize your plan of attack. It may be beneficial to take a quick measurement within a known distance of the base in order to provide QA later. On the controller, begin a new project or job (this term varies with manufacturer). Verify the survey settings are correct, satellites signals are available, and (RTK) radio communications are working. In general, 4+ satellites are required to obtain a position but 6 or more is really much better. You must maintain satellite communication for 5–10 minutes to receive an initialization fix before proceeding. If you lose initialization during the survey, stop, and begin survey again at this step. It will not harm previous measurements that were taken.

To collect a data point:

1. Move to the location you wish to measure. Check for potential obstructions or multi-path inducing objects in the immediate vicinity.
2. Name the point on the controller. Verify satellite availability and reasonable PDOP. A PDOP of less than 4 and ideally less than 2–3 is required for precise measurements.
3. Place the range pole's tip directly on the surface to be measured or in the dimple if a monument is present.
4. Level the pole using the manual bubble level or electronic level on controller. Bracing your body in a tripod stance with feet shoulder width and ranger pole braced in front is a stable position. If using a bipod, do not leave it alone. You must watch it to prevent falls.
5. Begin collecting data. Maintain a steady, level orientation for the antenna for the duration of the occupation time.
6. After point is collected, move to the next location.
7. Continue steps 1–6 until complete. You can pause a survey if there is need for a break. If so, make sure to initialize the antenna's position before continuing the survey.
8. It is advisable to reoccupy the starting point (the location next to the base station) for QA.
9. When complete, stop the survey. Check to verify the data file is complete and of appropriate size. Some will allow you to check individual positions.

10. Once verified, you may power down the receiver and controller.
11. Before disassembling, measure the antenna's height again and record on your data sheet. There should not be a change in height. If so, you must be aware of this when processing results.
12. Disassemble and pack the unit using the checklist.

4.6 Base Station: Finalize Survey

Disassembly of the base station is the last step. The station must record its location for the entire duration of the survey in order to correct the rover's baseline. Two hours of data or more is best.

1. Stop data collection on the receiver or controller.
2. Verify there is a saved file with the correct date, time, and duration of your survey.
3. Before moving anything on the base station, check the slant height of the antenna and record it in your field book. It should not have moved.
4. Verify that the tripod is still level and centered over the benchmark or landmark. If not, record this with any observations or measurements as to how it moved.
5. If a field laptop is available, remove the memory card from both rover and base station receivers and back up data files to an external device for redundancy.
6. Pack all equipment using the checklist.

5. Data Processing

5.1. Data Downloading and Backup

(Adapted from the UNAVCO GPS/GNSS Survey Guide)

Data collected with geodetic GNSS receivers must be downloaded as soon after data collection as possible to free up receiver memory (if needed) and to back up the data. As a field precaution, a duplicate copy of the data should be made as soon as it is downloaded from the receiver. Data are typically downloaded to a laptop computer. To download a receiver, manufacturer-specific download software and procedures are usually required.

Downloading instructions depend on the equipment (receiver and/or survey controller) being used; see http://kb.unavco.org/kb/category/gnss-and-related-equipment/2/.

Considerable expense goes into collecting geodetic quality GNSS data, and the data should always be backed up as soon as possible to safeguard against loss, destruction, or corrupted media. While the particular data backup strategy may vary with logistics and personal preferences, there should always be three independent copies of all GNSS data until it is confirmed that the data have been safeguarded in a data archive such as UNAVCO's. Options for data storage prior to final archiving include DVDs, PC memory cards, USB drives, computer hard drives, and the GNSS receiver memory. Before deleting any files from a GNSS receiver, make sure they are adequately backed up elsewhere! A good practice is to keep copies of the data in separate locations and with different people.

5.2. Data Formats

GNSS receivers generally collect and store the raw GNSS data in a proprietary format, which may need to be translated into a different format for data processing or data sharing. Later generation Trimble GNSS receivers (5700, R7, NetRS) collect data in .T01 files, a format that must be translated to be read into Trimble's processing software, Trimble Geomatics Office (TGO). These data are automatically translated to .DAT files, a Trimble format that can be read by TGO, when downloaded via the Trimble Data Transfer Utility. The Topcon GB-1000 collects data in a .tps file.

RINEX (Receiver Independent Exchange Format) is the ubiquitously accepted data format for raw GNSS data. Reference site data is generally provided in RINEX. RINEX is read by most processing software, including Trimble Geomatics Office and Topcon Tools, and also more sophisticated processing software such as Bernese, GAMIT, and GIPSY. Almost any raw high-precision GNSS data can be converted to RINEX using TEQC. **TEQC** (pronounced "tek") is a simple yet powerful and unified approach to solving many pre-processing problems with GNSS, GLONASS, and SBAS data. The three main functions from which TECQ gets its name—**t**ranslation, **e**diting, and **q**uality **c**heck—can be performed altogether, in pairs, or separately. You can download TECQ for free at: https://www.unavco.org/software/data-processing/teqc/teqc.html., although TEQC is no longer being updated as of 02/2019.

While most raw data are stored as binary files, RINEX is in an ascii format and can therefore be viewed in a text editor. An example of a RINEX file is given below (Figure 7) and illustrates the information contained in raw GNSS data files.

5.3 Data Processing

GNSS data collected for high-precision applications (excluding data collected using RTK methods) must be post-processed to provide millimeter- to meter-level precision. Typically, the post-processing involves differential processing relative to a fixed base location. For certain survey types, such as stop-and-go kinematic, it is essential to process the data while still in the field as a data quality check. This allows for a re-survey if there are problems with the data.

Post-processing the data accomplishes several things. First, there are numerous error sources in GNSS positioning, the most significant of which are:

- Receiver and satellite clock errors,
- delay of the GNSS signal through the Earth's atmosphere (most significantly, the ionosphere and the troposphere),
- use of imprecise satellite orbits, and
- multi-path (multiple signal arrivals resulting from the signal bouncing off nearby objects or the ground).

Many of these errors can be greatly minimized or eliminated in post-processing by using data from at least two receivers with at least four satellites in common (>6 is preferable).

Data Processing Workflow:

1. Import data from receivers and open base station and rover positions into your hardware-specific processing program (ex. Trimble Business Center for Trimble receivers). Set the antenna heights, equipment models, etc. during importing if this was not done in the field. Double-check these values.
1. Export the data for your base station as a RINEX file. Can be done in TEQC (https://www.unavco.org/software/data-processing/teqc/teqc.html) or a proprietary software.
2. Upload the RINEX file for your base stations through an appropriate precision processing program (such as OPUS for surveys in the U.S.) You will receive a file with the corrected base position from OPUS.
3. Correct your base and rover positions in your hardware-specific processing software (i.e. Trimble Business Center or Emlid Studio). Detailed tutorials for Trimble Business Center and RTKLIB can be accessed at https://geospatial.trimble.com/trimble-business-center-tutorials and https://docs.emlid.com/emlid-studio/ respectively.
4. Enter the corrected base station coordinates. Skip this step if you are processing in the field for a quality assurance check (not as precise, but okay for QA).
5. Create baselines from base station to rover positions. Visually inspect reasonable distances and spatial relationships from rover to base station.
6. Process baselines to correct for sources of error and receive new positions.
7. Transform and project data if necessary.
8. Export your data in the appropriate format for further analysis and processing.

A variety of portals provide precise point positioning (PPP) post-processing. The following summarizes some of the options. Most require RINEX data format. A data file of at least two hours is recommended. More than four hours is preferable. These services will provide final solutions to within a couple cm for a static point. The very highest precision (mm-scale) requires

much more involved and complicated processing and is beyond the scope of this document (ex. GAMIT/GLOBK processing).
Several online services are available:

a. **OPUS –** http://www.ngs.noaa.gov/OPUS/
   - Online Positioning User Service by the US National Geodetic Survey. This service is supposed to be optimized for North America locations.

b. **CSRS-PPP** – https://webapp.geod.nrcan.gc.ca/geod/tools-outils/ppp.php
   - Canadian Spatial Reference System – Precise Point Positioning (CSRS-PPP) is a flexible service that offers both static and kinematic data processing that is offered by Natural Resources Canada (NRCAN). Access to the database is free but requires a username and password.

c. **Trimble CenterPoint RTX Post-Processing** - https://www.trimblertx.com/Home.aspx
   - Trimble PPP service. Takes Trimble and RINEX formats.

d. **AusPos** - https://www.ga.gov.au/scientific-topics/positioning-navigation/geodesy/auspos
   - Australian service.

e. **APPS** - https://apps.gdgps.net/
   - A JPL service that replaces AutoGIPSY.

These services can provide increasingly better solutions in the two weeks after the data collection as more errors are accounted for. The different types of solutions are:

- Ultra Rapid solution is available 1.5 hours after the GPS data are collected
- Rapid solution is available the next day
- Final solution is available ~2 weeks later

Read more about it (https://docs.emlid.com/reachrs/common/tutorials/ppp-introduction/#nrcan-csrs-ppp-service-overview).

For cm-level static or kinematic surveys with short (ideally < 10 km) baselines, commercially available software (e.g., Trimble Geomatics Office [TGO], Topcon Tools) is often adequate. See http://kb.unavco.org/kb/article/trimble-geomatics-office-how-to-process-fast-static-and-post-processing-kinematic-surveys-using-tgo-613.html for a how-to on TGO.

Additional helpful processing resources include the following:

Several organizations provide precise satellite orbital information, which is calculated daily and available with a two-week delay. The application of this information (rather than the orbital information broadcast by the satellites) can improve precision of ground coordinate solutions. Examples of places to find precise orbital information, generally available in files appended .SP3

- **SOPAC** - http://sopac-csrc.ucsd.edu/
- **IGS** - http://www.igs.org/
- **NIMA EGM96 Geoid Calculator**, to calculate the geoid-ellipsoid separation at any given point: https://earth-info.nga.mil/index.php?dir=wgs84&action=egm96-geoid-calc
- **NGS Reference Frame Transformation**, to translate coordinates from one reference frame to another: http://www.ngs.noaa.gov/cgi-bin/HTDP/htdp.prl?f1=4&f2=1
  Also, see the section on Reference Stations for links to data from continuous GNSS sites.

5.4. Data Archiving and Data Access

As a service to the geodetic community, the UNAVCO Boulder Facility Archive manages, stores, and provides access to high-precision GNSS geodetic data. The archive will also accept non-geodetic GNSS data projects (e.g., mapping). The data stored are primarily collected on research projects sponsored by the National Science Foundation (NSF) and National Aeronautics and Space Administration (NASA). Please contribute to the Boulder Facility Archive immediately after campaign completion to best preserve time-sensitive information. Most data must be archived within six months of data collection. See the UNAVCO GPS/GNSS Data Policy for more information: https://www.unavco.org/community/policies_forms/data-policy/data-policy.html.

To archive project data, fill out a project support request form if you have not already done so for your project: https://bsportal.unavco.org/newproject/supportform.aspx

Prepare legible copies of site descriptions and log sheets (e.g., Monument Record forms [http://kb.unavco.org/kb/assets/63/monument.pdf] and Site Visit Log sheets [http://kb.unavco.org/kb/article/campaign-monument-log-sheet-62.html]) and any other pertinent material (photos etc.) to accompany data. At the very least, the archive needs the site name, antenna height, antenna height measurement method (e.g., slant), antenna mount type, and antenna and receiver models and serial numbers; this is the minimum information needed to meaningfully process the GNSS data.

Data should be submitted in raw format, if possible. Data may additionally be submitted in a translated format.

Coordinate submissions with the UNAVCO Data Management and Archiving Group: archive@unavco.org. Submissions can be mailed/shipped or dropped off via ftp (preferred) for the archive. For more details, look up Submissions on the UNAVCO GSP/GNSS Data Archive page: http://www.unavco.org/data/data-help/submission/submission.html.

UNAVCO Data Management and Archiving Group mail/shipping address:

Attn: GPS/GNSS Data Archive
UNAVCO
6350 Nautilus Drive
Suite B/C
Boulder, CO 80301

If submitting data and metadata (accompanying information) via ftp, a directory will be assigned to you.

To access both campaign and permanent station data, check out our interactive Data Archive Interface, the DAI (Figure 7): https://www.unavco.org/data/dai/.

Search for data by data type, date collected, and/or geographical region. For a brief tutorial, see the Help feature at the top right corner of the page.

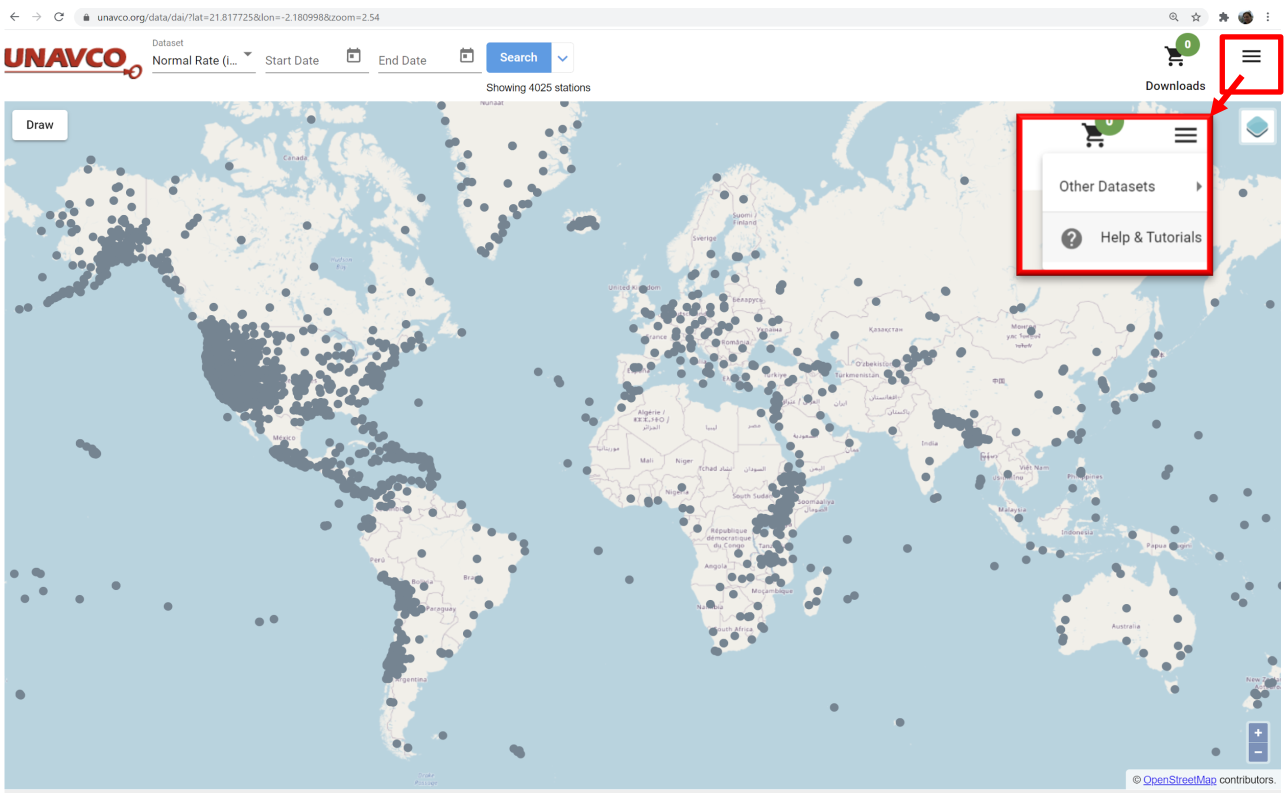


Figure 7. UNAVCO Data Archive map interface.

QuickStart Guide for the Emlid ReachRS2

Beth Pratt-Sitaula and John Galetzka (UNAVCO)

Quick Start

Emlid provides many good resources for getting started with Reach RS2 GPS/GNSS receivers https://docs.emlid.com/reachrs2/. This guide is designed to augment the online resources for easy access in the field.

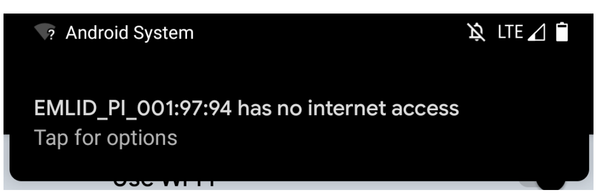
Figure 1. Image of the Emlid Reach RS2 receiver. (1) power button, (2) battery status, (3) Wi-Fi status (4) RTK status

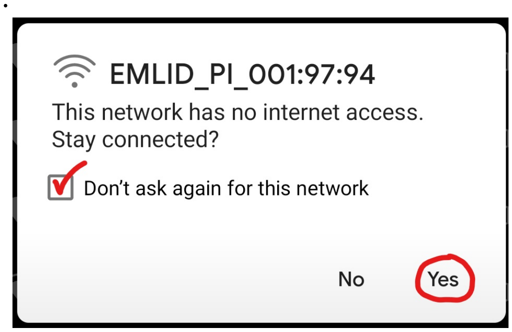
This QuickStart Guide assumes:

- Students have learned the basic overview of how Realtime Kinematic (RTK) GPS/GNSS surveys work with both base station and rover/s.
- The supplied Reach RS2 base and rover are preconfigured and fully charged so that you may rapidly carryout an RTK survey of points you desire to know at centimeter precision and accuracy.
- You are provided a benchmark for the base station with accurate known coordinates.
- You are provided a pole-tripod for the Reach RS2 base and survey poles for the Reach RS2 rovers.
- Minimal solar activity—check NOAA website (https://www.swpc.noaa.gov/)
- You already downloaded the **ReachView3** app from your phone/tablet's app store (do not get any of the earlier apps). Apple and Android are both supported. Do this before you leave cellular or WiFi range if you are headed to a remote field site.

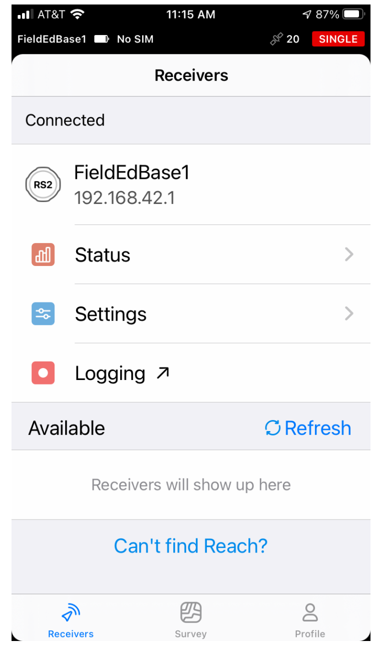
Turning on and connecting with a Reach RS2 receiver

1. Turn on the receiver by pushing the round button for 3 seconds until all LEDs light up. Wait until the WiFi LED turns white (about 60 seconds) – the receiver is now in hotspot mode and broadcasting WiFi. (if the WiFi LED stays blue, see trouble shooting section below)
2. Go to your phone/tablet's Settings and select the WiFi network from the receiver you want to connect to (it will take it a little while to show up after the receiver turns on).
   Password for all Emlid Reach RS2 is "emlidreach"
   NOTE: After selecting the receiver's network on your list of available WiFi connections, make sure you are truly connected. On some Android and Apple phones, a pop-up notification may say that the newly selected network 'has no internet connection' and will default to immediately disconnect unless you specify otherwise. See images below. The name of your receiver's connection may not be the same as shown below.



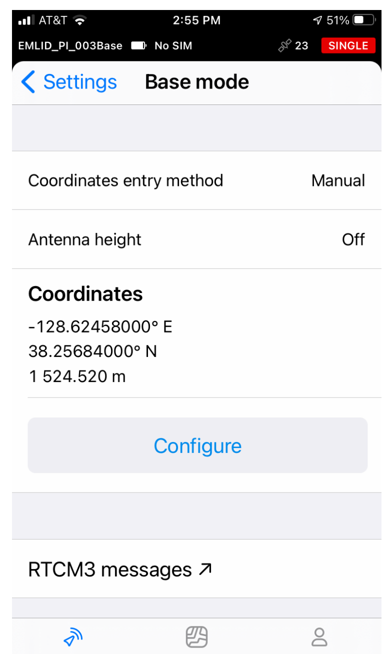


3. Open ReachView app. If it is already open, it might work best to close and reopen. (Generally, if you have any issues with the ReachView app, restarting usually helps.) Once the dot-lights on the receiver become solidly on, the receiver will show up in the ReachView app and you can select it. This will take you to the Receivers page and show you the one you are connected to.



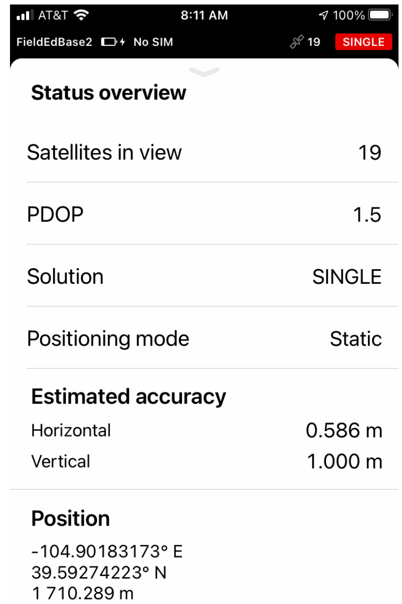
Starting the base

1. Attach the LoRa antenna and mount the Reach RS2 base on the tripod and accurately level over the benchmark.
2. Turn on and connect with the receiver as described above.
3. Select **Settings** and page down to **Base mode**.
4. In the **Base coordinates** section select Configure > Coordinate entry method > **Manual** and enter in the coordinates for the base station that you have been given. Antenna Height: Measure from the ground to the base of the Reach RS2 device to determine the **Measured height**. For example, if you are using a 2-meter pole and quick-tripod setup, your **Measured height** will be 2 meters. The actual phase center of the antenna is 0.134 m higher but the receiver will include that automatically.



5. OR if the survey you are doing does not require a highly accurate base location and there is no known benchmark, your instructor might tell you to just collect a quick location. To do this, select **Average single** instead of **Manual**. Then select a duration of time to average the position over. Five minutes can work if your instructor does not tell you otherwise.
6. Select **Status** on the main receiver page and check that there are plenty of Satellites in view. Technically 4 is enough but these receivers are set to require 7 or more; more than 10 is really best and these days >15 is pretty common. PDOP (position dilution of precision): describes the error caused by the relative position of the GPS/GNSS satellites. Basically, you want the

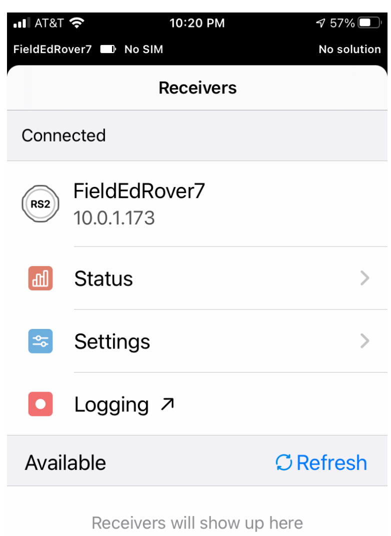
satellites as spread out across the sky as possible and not only in one area – say overhead. Low PDOP values, in the range of 4.0 or less, indicate good satellite geometry, whereas a PDOP greater than 7.0 indicates that satellite geometry is weak. Solution will be **Single** because the base is not receiving any corrections from another receiver. Positioning mode should be **Static** if the base is set up correctly. Estimated accuracy will likely be in the meter-range for the base.

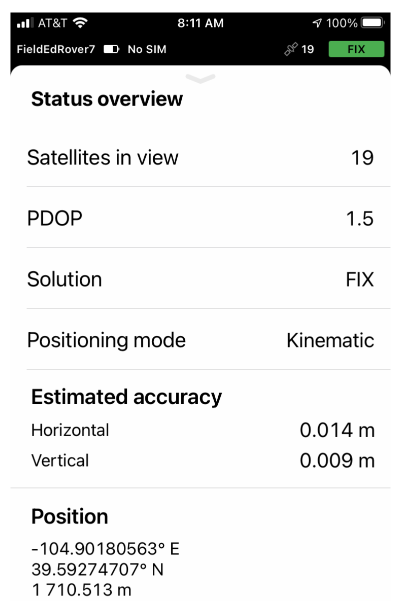


7. Check **Logging** tab. Start recording Raw data (RINEX 3.03) and Position (LLH or XYZ). If the data are already recording, it means the previous user did not stop the logging before turning off the receiver, so the logging automatically restarted when the receiver was turned back on. This is ok, but less reccomended. If you turned on the base station after the receiver was in place on the tripod, you can just let the logging continue. If the base station receiver was moving around while on, then you should stop the logging and then restart it. This will ensure that all the data in the file was collected after the receiver was in place. (Base correction is not needed for the base receiver so this can stay off.)
8. When the survey time is complete, stop the Logging and export the Raw and Position files before turning off the receiver (see final step in Rover section below on how to export).

Starting the Rover

1. Attach the LoRa antenna and mount the Reach RS2 a survey pole. Turn on and connect with the receiver as described above in the base section. Select **Status** on the main receiver page and check that there are plenty of Satellites in view. Technically 4 is enough but these receivers are set to require 7 or more; more than 10 is really best and these days >15 is pretty common. PDOP (position dilution of precision): describes the error caused by the relative position of the GPS/GNSS satellites. Basically, you want the satellites as spread out across the sky as possible and not only in one area – say overhead. Low PDOP values, in the range of 4.0 or less, indicate good satellite geometry, whereas a PDOP greater than 7.0 indicates that satellite geometry is weak. Positioning mode should be **Kinematic**. After a few minutes, the Solution should change from **Single** (no base correction) or **Float** (base connection but not full correction) to **Fix**, meaning all ambiguities are resolved and RTK solution is showing centimeter-level Estimated accuracy. Establishment of **Fix** is accompanied by a beep from the receiver. You are now ready to start your surveying. You can close the **Status** page.

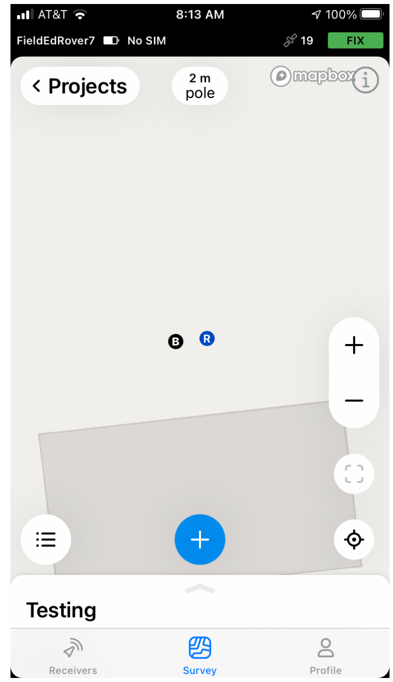




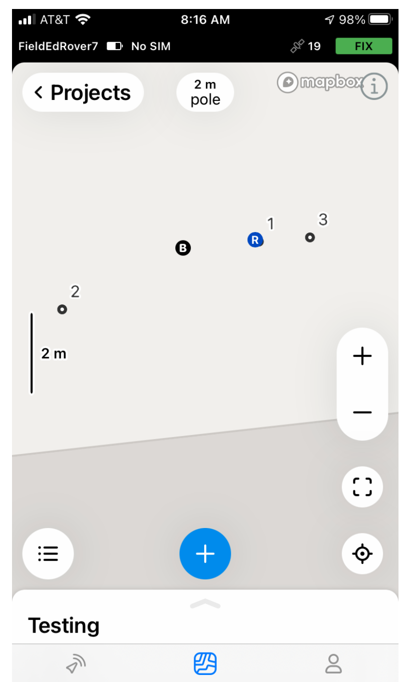
2. Check **Logging** tab. Start recording Raw data (RINEX 3.03), Position (LLH or XYZ), and

Base correction (RTCM3). If the data are already recording, it means the previous user did not stop the logging before turning off the receiver, so the logging automatically restarted when the receiver was turned back on. This is ok, but less recommended.

3. Go to the **Survey** icon on the bottom of them main receiver page. This feature allows you to make project-based point collection with auto-save rules or manually and then export the data into different formats. It is perfect for surveying and ground control point collection.



4. Click the + in the upper right corner to start a new project (or click on a project name to open an existing one). Give the new project a name, put down the people involved in the survey as Authors, and add a description if it will be helpful. The typical coordinate system default will appear as “Global CS” (which is the Emlid term for WGS 84, EPSG:4326) with vertical datum of “ellipsoidal height”. There is no reason to change this unless your instructor tells you to. Then click **Save**.
5. On the map view page, press [2 m pole] the button to open the pole height menu. In most cases you will be using a 2-meter pole so no changes will be needed, but if your pole is a different height, enter that value instead. Click **Save**.
6. The survey map shows the base (**B)** and rover (**R**) on it.
7. Press [+] to go to the point collection window. You can select “Edit” if you wish to change the point’s name or add a description. If you do not change it, the default point name will increment through “1”, “2”, etc. If you want the data collection to average over a certain time period, select **Averaging** > **Timer** > select the duration you want. 10 seconds can work fine if your instructor does not give you another protocol. To ensure highest quality results, it is a good idea to activate **FIX only** option. You will not be able to collect a point unless the rover has a **Fix** solution. When you are ready to collect a point and the pole is being carefully held over the survey point with the level bubble leveled, select the blue “measure” button at the bottom of the screen to start collecting.



8. If you are having trouble maintaining **Fix**, there are suggestions in the Troubleshooting section below. If that still does not solve the issue, your instructor may decide to switch to a PPK workflow. In that case, turn off **FIX** only and each collection point should be done for 30 seconds.
9. Point options: To open the list of all points, press [list icon]. You can open point details, edit the point info, find it on the map or stake out the point. You can work with each point separately by choosing it on the map. Read more about Point Stake Out function (finding a point of known coordinates) in the Emlid guide (https://docs.emlid.com/reachrs2/common/reachview/survey/#point-stakeout). When you are done, press **<Projects** to close and save. The project will be available in the **Survey** menu.

10. Exporting Data: When you finish collecting points, you can export your project. Press ••• and **Export**. Generally, the default format is CVS. You will be prompted to decide how you wish to send the file. Then go to the Logging tab and turn off logging for Raw, Position, and Base correction data and export those as well. *If you choose to email files to yourself and you are currently connected to the receiver hotspot, after you "send" the email, disconnect from the receiver hotspot so that the email can actually can go out via cellular or another WiFi network.*

Troubleshooting and some good things to know

This is not a comprehensive troubleshooting guide but provides some potentially more common things.

1. If the ReachView app does not seem to be finding the receiver or is taking a really long time to move from the selection pane to showing you the status of the receiver, try restarting the app. Restarting the app seems to help with many things.
2. If the WiFi LED light to the left of the power button is showing blue, then the receiver is joined to a local WiFi network rather than serving as hotspot itself. Join the same local WiFi network so you can connect to the receiver through it. Go to **Settings** > **WiFi**. Then switch the Hotspot on. If you wish to prevent this in the future, you can "forget" the known WiFi network.
3. Some phones are set to not-connect to hotspots/WiFi networks that are not connected to the internet. If you appear to be joined to the receiver's hot spot but are then are not actually able to connect in the app open your phone's settings. Select the receiver's WiFi network and require it to "join anyway" (even though it is not connected to the internet)
4. If the ReachView app is saying "sorry ReachView is not responding" try forgetting the receiver's WiFi network and then rejoining it again. Rebooting your phone/tablet can also work.
5. The reference frame used by Emlids is WGS84.
6. Getting **Fix** status with the rover: Usually the rover shows **Fix** after a few minutes (accompanied by a beep). However, sometimes, it can take longer – even more than 10 minutes – for reasons that can be hard to determine. Here are some things to check:
   a. Make sure the LoRa antenna on both the base and rover are screwed all the way on. You often need to hold the little rubber flap back with one hand in order to get a completely perpendicular angle to screw in the antenna with the other hand.
   b. If your rover is still not getting a **Fix** status, trying waiting longer. If it still does not work, try restarting the rover. Moving slightly different distance from the base can help sometimes (perhaps there is interference at a particular distance?).
   c. Make sure that your base has a fairly accurate known location. If the base location is off by >10 meters from its actual location, it can take longer to get and keep **Fix** with the rover. If the base location is off by 100 meters, it is unlikely **Fix** for the rover will be achieved. If you used a **Manual** location in **Base coordinates**, check that you entered it correctly. If you used an **Average single**, try collecting again for a longer period of time.
   d. Check solar activity (NOAA Space Weather https://www.swpc.noaa.gov/). It can affect the signal from the satellites as they pass through the ionosphere. If either the base or the rover is not getting consistent "lock" on at least seven satellites, the rover will not get **Fix**.

e. Consider whether there could be radio interference in your area from other sources or a significant multipath reflector (nearby buildings, vehicles, or trees reflecting the GPS/GNSS signal along a path longer than the direct signal).

f. If you lose **Fix** after having it, try coming back closer to the base. You may have lost line-of-sight between the two receivers and need to reestablish **Fix** from a closer point. You may need to experiment for a particular location on conditions for how far away you are able to get away from the base or what LoRa settings (above) are optimum.

g. Make sure you have the same LoRa settings in the *Correction output* tab on the base unit and in *Correction Input* on the rover. The base should be at full Output power of 20 dBm. You could also try adjusting the LoRa settings, such as lowering the air data rate (this typically allows the LoRa signal to have a longer baseline although fewer corrections will be sent per unit time, so you would likely need to select just the GPS constellation to limit the amount of data). You could also try adjusting the frequency. Although generally higher frequency will penetrate further, you may have local interference and certain frequencies. Try stepping down 1-2 MHz at a time (of course you need to make the same changes on both base and rover/s). More information is available from https://docs.emlid.com/reachrs2/tutorials/basics/tuning-lora/.

h. If you still have troubles establishing **Fix** and would like to discuss it with a technician, please take multiple pictures of the site and contact education@unavco.org.

i. In the meantime, if a survey needs to be completed that day, it may make sense to switch to a PPK (post processing kinematic) survey. That workflow is described in the Instructor Guide for Emlid Reach RS2 (https://serc.carleton.edu/getsi/teaching_materials/high-precision/equipment.html#emlid). Be sure to increase survey point collection time to at least 30 seconds and hold that pole as still as possible even for this longer time.

Instructor Guide for Emlid Reach RS2

Beth Pratt-Sitaula, Sam Beane, Diana Krupnik (UNAVCO) and Brigid Lynch (Indiana University)

This document provides a guide on the setup of Emlid Reach RS2 receivers and other functions that may be needed by instructors or field engineers. This manual includes:

1. *Updating receiver firmware using mobile device*
2. *Initial settings for both the base and rover receivers for an RTK survey*
3. *Good Base locations*
4. *Determining a known point for Base Position with Precise Point Positioning (PPP)*
5. *Base shift (moving the base during a survey)*
6. *PPK – Post processing kinematic*
7. *Using NTRIP over cellular to access a permanent GNSS station instead of a local base*
8. *Downloading a system report*
9. *Connecting to receiver using computer (Windows or Mac)*

1. Updating receiver firmware

*If you borrow equipment from the GETSI Field Project (UNAVCO) you will most likely **NOT** need to do the steps in Section 1). The receivers should arrive to you with updated firmware and base/rover setting. However, these are provided for your reference or in case an update is released while the survey kit is in your possession.*

Figure 1. Image of the Emlid Reach RS2 receiver. (1) power button, (2) battery status, (3) Wi-Fi status (4) RTK status

Charge receivers to full power

Check battery status of the receivers. Press the power button once to display the current power level (Fig. 1). If device needs to be charged, plug it in using the included USB charger.

Update firmware using phone or tablet

You will need the Reach RS2 receivers, a 2.4 GHz WiFi connection, and a smartphone or tablet with the ReachView3 companion app installed (alternatively you can connect using a computer as described in the last section below). If you have issues with ReachView app, restarting it and it will typically solve the problem. For additional help with firmware updates: https://docs.emlid.com/reachrs2/reference/troubleshooting/updater/

Note: somewhat confusingly, the mobile app is called ReachView AND the firmware on the receiver is called ReachView. In this case you are updating the **firmware** ReachView, not the app. App updates come through your device's app store.

1. Connect to the receiver as described in the Emlid Quick Guide with your phone/tablet using the ReachView app (the receiver in hotspot mode and you connecting to its WiFi network).
2. Next you need to change the configuration so that both the devices are on a **2.4 GHz** (not 5 GHz) internet-connect WiFi network, rather than having the receiver serve as a hotspot. **Settings** > **WiFi** > **Available**. Select the WiFi network that you wish to use. The receiver will then switch to that WiFi network and stop being a hotspot to

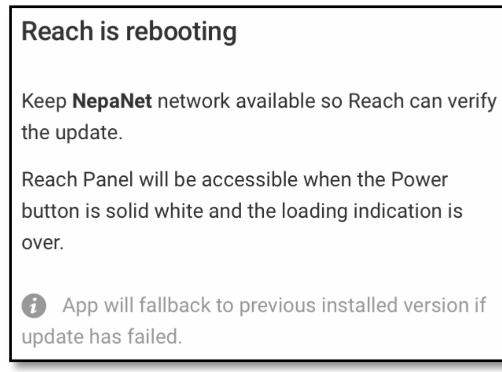
1. Connect to the same network as Reach

2. Access Reach Panel again

Mobile app: Go to the list of devices and refresh it.
Browser: Scan the network and find the new IP address of Reach, then type it into your browser's address bar.

your phone/tablet. You will see a notice that says "Connect to the same network as Reach." When both devices are on the same WiFi network, the phone/tablet can function again as a controller.

3. **Settings** (will have a red dot if a firmware update is available) > **New Reach Firmware is available** > **Update Reach** > **Update Reach**
4. It will take a few minutes for the update. It often helps to keep the phone screen active in order to maintain the connection between devices (i.e. do not let your phone screen turn off). When it is done, select "Reboot and go to the app".
5. Backtrack through the ReachView menus to get to the Receivers page. After a couple minutes, **Refresh** to find the receiver again. If needed, restart the app. When the receiver is done turning on again, both the receiver and your phone/tablet will still be on the same local WiFi network. Select the receiver in the ReachView app.



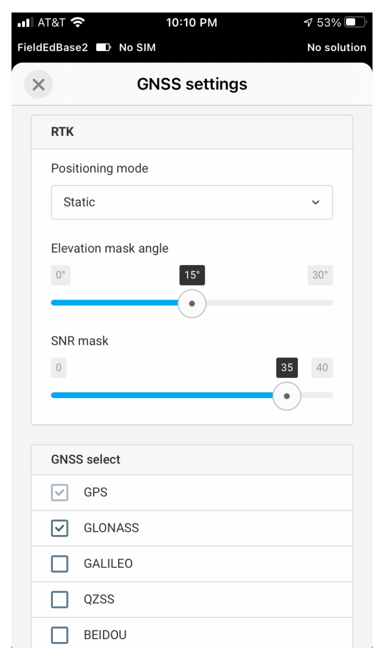
6. If you wish to have the receiver stop reverting back to the local WiFi network whenever it reboots, you can "forget" the local network. Go to **Settings** > **Wi-Fi** > **Networks**. Turn the hotspot ON. Go to your phone/tablet's Settings and choose the receiver as your WiFi network again. Refresh or restart ReachView app > choose the receiver. Go to WiFi page again and forget the local network that you had the receiver connected to.

2. Initial settings on base and rover for RTK

<u>Base settings for RTK survey</u>

*This section provides a list of the initial settings that this receiver should arrive with from UNAVCO if it is designated as the base. Starting from the initial **Receiver** page once you are connected to the receiver (see Quick Guide for getting the app started).*

- **Settings** (scroll down to the ones lowest on the page)
  - GNSS Settings
    - Positioning Mode: Static
    - Elevation Mask Angle: 15°
    - SNR (Signal Noise Radio) Mask: 35°
    - If you are going to process a PPP survey in CSRS only select GPS and GLONASS. If you have other processing plans or if the base location is already known, then it may be fine to select GALILEO, QZSS, BEIDOU as well.
    - Update Rate: 1 Hz
      - 3 or 5 Hz will also work if you are doing more continuous surveys and want smaller data files.
  - Correction Input:
    - Off
      - Unless you are connected to a real time permanent station for corrections.



- Correction Output:
  - Select **LoRa**
  - Frequency: 902.0 MHz
  - Output Power: 20 dBm
  - Air data rate: 9.11 kb/s
- Position Streaming:
  - Output 1: Off
  - Output 2: Off
- Base mode
  - Base Coordinates (see QuickStart Guide for more detail): Configure > Coordinate entry method:
    - Average Single (If you want to collect a quick location)
      a. Coordinate Accumulation Time: options for up to 30 min but 5 minutes can work fine. It is fine to set it to "Average Single" if you are just collecting a longer occupation for PPP processing (see below PPP section).
    - Manual (If you are using a known benchmark location)
      a. Antenna Height: Measure from the ground to the base of the Reach RS2 device to determine the **Measured height**. The actual phase center of the antenna is 0.134 m higher but the receiver will include that automatically.
      b. Enter in the Latitude, Longitude, and Ellipsoid height of the benchmark
  - ARTCM3 messages:
    - ARP station coordinates: 0.1 Hz
    - GPS MSM4: 1 Hz
    - GLONASS MSM4: 1 Hz
    - uncheck Galileo MSM4, BeiDou MSM4, and GLONASS code-phase biases

- **Logging** – If someone stopped the logging before turning off the receiver last time, then you will need to restart the logging. If the receiver was turned off with logging still going, it will automatically restart when you turn the receiver on. You can turn off logging to save memory or pick the exact time that surveying begins. In general, the base should be logging **Raw data** and **Position**. The Base correction file is not really relevant to the receiver being used as the Base so that is typically left off.
  - Raw Data: Start Recording: On - RINEX3.03, GLONASS, GPS
  - Position: Start Recording: On - LLH or XYZ (lat-lon-height or X-Y-Z from Earth's center)
  - Base correction: Off
- **Status** – there are no settings on this page but it can be helpful to think about some of the info displayed
  - Satellites in view: just what is sounds like; 6 is really a minimum that you would want to use and more than 10 is better and these days more than 15 is very normal, although technically 4 is enough for a basic solution
  - PDOP (position dilution of precision): describes the error caused by the relative position of the GPS satellites. Basically, you want the satellites as spread out

across the sky as possible and not only in one area – say overhead. Low PDOP values, in the range of 4.0 or less, indicate good satellite geometry, whereas a PDOP greater than 7.0 indicates that satellite geometry is weak.
  - Solution: **Single**
  - Positioning mode: this should be **Static** if your **Base Mode** is set up correctly.

<u>*Rover settings for RTK survey*</u>

*This section provides a list of the initial settings that this receiver should arrive with from UNAVCO if it is designated as a rover. Starting from the initial **Receiver** page once you are connected to the receiver (see Quick Guide for getting the app started).*

- **Settings** (scroll down to the ones lowest on the page)
  - GNSS Settings
    - i. Positioning Mode: Kinematic
    - ii. Elevation Mask Angle: 15°
    - iii. SNR (Signal Noise Radio) Mask: 35°
    - iv. Generally, the base is only set to collect GPS and GLONASS because those are the systems that can be used with the CSRS PPP portal. The rover is also generally set to just be GPS and GLONASS but it is fine to select GALILEO, QZSS, BEIDOU as well if you wish.
    - v. Update Rate: 1 Hz
      1. Generally, it is good to have this be the same as the base.
  - Correction Input: should match the base's Correction Output
    - **i.** Select **LoRa**
    - ii. Frequency: 902.0 MHz
    - iii. Air data rate: 9.11 kb/s
  - Correction Output: Off
  - Position Streaming 1: Off
  - Position Streaming 2: Off
  - Base mode: not relevant to a receiver set up as a rover
- **Logging** - If someone stopped the logging before turning off the receiver last time, then you will need to restart the logging. If the receiver was turned off with logging still going, it will automatically restart when you turn the receiver on. You can turn off logging to save memory or pick the exact time that surveying begins. In general, the rover should be logging **Raw data** and **Position** and **Base correction**.
  - Raw Data: Start Recording: On - RINEX3.03, GLONASS, GPS
  - Position: Start Recording: On - LLH or XYZ
  - Base correction: On - RTCM3
- **Status** – same as above for the base except
  - Solution: Fixed (or Float) but fixed is needed for the full RTK solution
  - Positioning mode: Kinematic

3. Good Base locations

When you choose a base location, you need to think about both the sky view for good satellite coverage, but also the base-rover communication. RTK surveys depend on a radio link between the base and rover. The goal is to have the base location and rover survey plan such that the rover is always able to achieve **Fix** between the devices. Some things to keep in mind:

- Open sky view, free from large nearby objects as much as possible, and stable ground. (see also the Kinematic GPS/GNSS Survey Methods Manual - https://serc.carleton.edu/details/files/108023.html; https://serc.carleton.edu/getsi/teaching_materials/high-precision/unit1.html - manuals)
- Line-of-sight between the base and rover is best for being able to do longer distances but over shorter distances may not be essential.
  - We have been able to get up to 8 km with full line-of-sight when base was on a building, the rover was used in various places that had a view of that building, and the air data rate was slowed from 9.11kb/s to 4.56 kb/s (this also meant only the GPS constellation was being used due to slower data transfer rate).
- High ground for the base seems to particularly help.
  - We have been able to get ~5 km distance between the Emlid base and rover when the base was on a hill and the rover was out in the plains below. Line-of-sight largely available but not completely perfect.
  - Even without line-of-sight, having the base up on a hill allowed 1-1.5 km distance through trees and bamboo.
- Base placement can be a bit of an art. As an instructor, if you have time, you may choose to scope and test an ideal base location well before going out with students. That would also allow you to get the best solution using PPP (see next section). However, if you are not able to test the base location before going out with students, you can include the students in that part of the survey design and decision making, which is also a super valuable learning outcome, even if it reduces the time spent on addressing a geoscience research question.
- Troubleshooting suggestions for getting good **Fix** with the rover are given in the *Quick Guide*.
- If you still have troubles establishing **Fix** and would like to discuss it with a technician, please take multiple pictures of the site and contact education@unavco.org.

4. Determining a known point for Base Position with Precise Point Positioning (PPP)

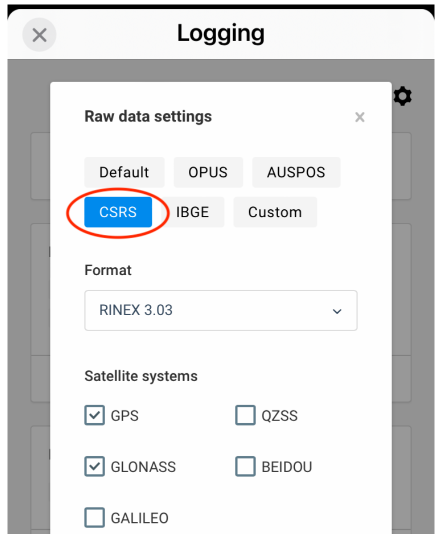
If you will be working at a location that does not have a known benchmark, you will typically want to get a known point for your base station. This section will describe setting up the base receiver for PPP and uploading the results to the Natural Resources Canada (NRCAN) Canadian Spatial Reference System website (CSRS-PPP). It is ideal to do this workflow the day before, several days, or even two weeks before you want the known point for an RTK survey. If you prefer to use the NOAA's OPUS (Online Positioning User Service), Emlid describes that workflow https://docs.emlid.com/reachrs2/tutorials/post-processing-workflow/opus-workflow/.

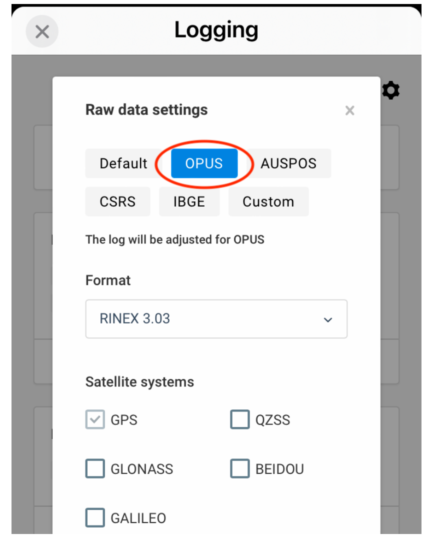
The longer you collect the base location data ahead of time, the better the PPP solution because the satellite locations and correction are better known. There are three options:

- Ultra Rapid solution is available 1.5 hours after the GPS data are collected
- Rapid solution is available the next day
- Final solution is available ~2 weeks later when final satellite location data is included

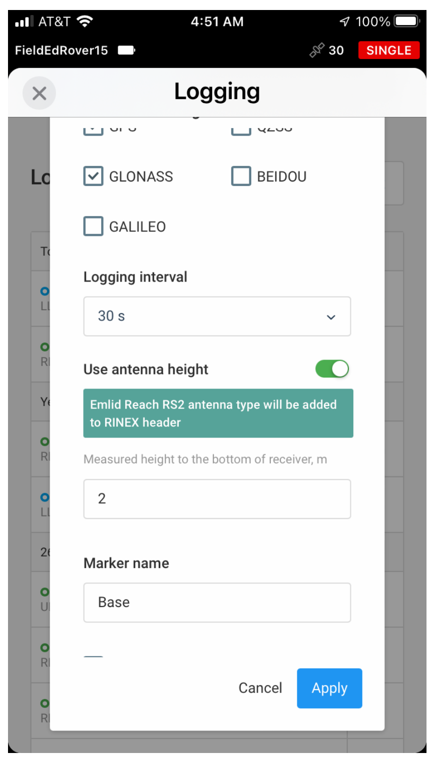
Read more about it (https://docs.emlid.com/reachrs/common/tutorials/ppp-introduction/#nrcan-csrs-ppp-service-overview). The Emlid Community Forum also has a nice example from someone who compared Ultra Rapid and Rapid deviations (https://community.emlid.com/t/study-of-deviation-of-ppp-with-rs2-with-different-observation-times/19185). The published accuracies suggest the Ultra Rapid will have decimeter-scale accuracy, Rapid will have ~½-decimeter accuracy, and Final will be ~2-cm accuracy. In practice we have often found only cm-scale differences between the three solutions. In some cases, Rapid and Final are essentially identical.

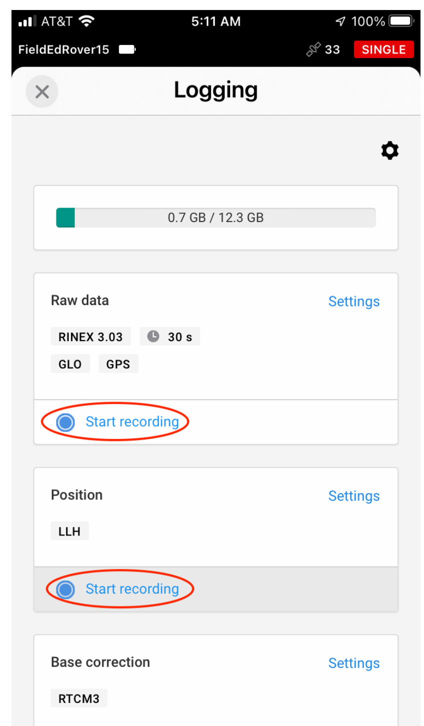
1. Set up the base tripod and receiver over the point for which you want to get a known position and turn the base receiver on.
2. Make sure the base is set up to collect data for the PPP service you plan to use (unless the base location is already a known point). Go to the Receiver page > **Logging** > **Raw data Settings**. Select the service you plan to use. This will probably be CSRS or OPUS. This will ensure that only the satellites that work with a particular service will be included.





3. **Format** > **RINEX 3.03** (unless you have a particular reason to use another format)
4. **Logging interval** > **30 s** is fine if you are only collecting base data at this time. If you are also collecting rover points for post-processing kinematic (see Section 6 PPK), then use **Full rate (as in GNSS settings)**.
5. Toggle **Antenna height** to "on" and enter the height to the bottom of the receiver (in meters). This is 2-meters for a quick tripod and your measured value for a traditional tripod. You can also enter a Marker name. Click **Apply**.



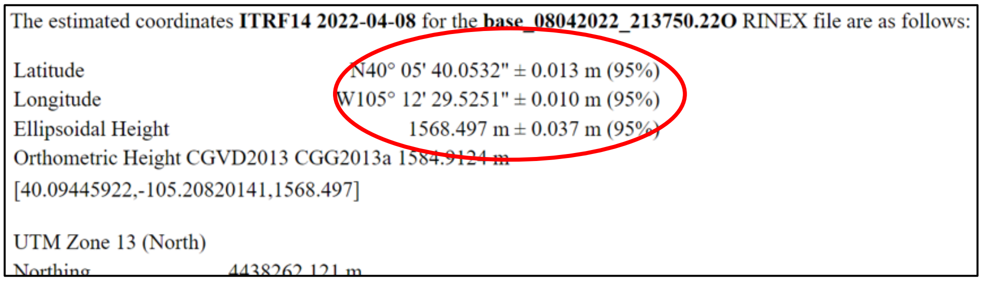


6. Back on the main **Logging** page, **Start recording** the Raw Data and Position. For more on logging within the ReachView app: https://docs.emlid.com/reachrs2/reachview-3/introduction-to-reachview-3/#logging
7. Allow the base receiver to collect data for at least 2 hours, preferably ≥4 hours (really 4 hours or more is much better).
8. Retrieve the raw data that was recorded:

- In the **Logging** tab,
    i. Click the red "stop" button/s to end the logging
    ii. Scroll down lower on the screen; click on the download icon next to the data you want to download. (The data is organized by date, time and type.)

- The data will download as a zip file onto your phone and provide methods to send it to your computer.
    i. Use any method (Airdrop, text message, email) to move the data from your phone to a computer.
    ii. You can either use the receiver's hotspot Wi-Fi to do this or reconnect the receiver and your smartphone to your home Wi-Fi.
- You can also connect a laptop to the Emlid's WiFi hotspot or have both devices on the same local WiFi network. Then go to http://192.168.42.1/#logging in a browser window and downloading the files that way.
- For more on downloading files from the ReachView app: https://docs.emlid.com/reachrs2/common/quickstart/downloading-files/
- Unzip the Raw data file and identify the observation file which will end .xxO (xx denotes the year as in .22O for 2022). It will also be the largest file by size.

9. Now you are ready to submit to CSRS: https://webapp.geod.nrcan.gc.ca/geod/tools-outils/ppp.php?locale=en
    - Create an account with them if you do not have one already.
    - Sign in to your CSRS account, enter the email that you would like the results sent to, then select *Static* and *ITRF*.
        i. For more information on NAD83 vs ITRF and WGS84 see: https://www.e-education.psu.edu/geog862/node/1804#:~:text=It%20is%20important%20to%20note,plate%2C%20and%20moves%20with%20it
    - Upload the .xxO file to CSRS.
10. Record the Latitude, Longitude, and height coordinate, found in the summary link of the CSRS email or in the pdf within the full_output_zip file. *Note: CSRS-PPP only retains saved files for 36 hours, so download them right away.*


The estimated coordinates **ITRF14 2022-04-08** for the **base_08042022_213750.22O** RINEX file are as follows:

Latitude	N40° 05' 40.0532" ± 0.013 m (95%)
Longitude	W105° 12' 29.5251" ± 0.010 m (95%)
Ellipsoidal Height	1568.497 m ± 0.037 m (95%)
Orthometric Height CGVD2013 CGG2013a	1584.9124 m

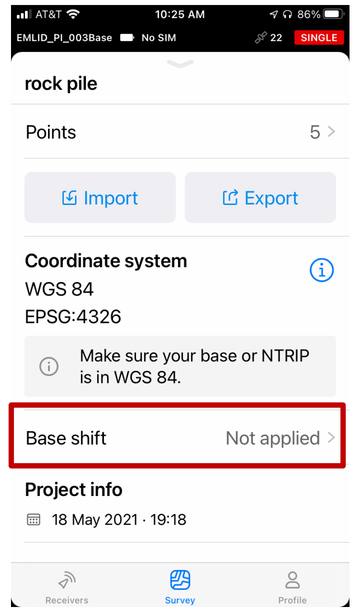
[40.09445922,-105.20820141,1568.497]

UTM Zone 13 (North)

Northing 4438262.121 m

5. Base shift *(moving the base during a survey)*

*There is a feature in the ReachView app (Survey tab) called **Base shift** that will allow you to adjust the base position to a new location and carry on with the survey.*



This can be helpful if you want to move the base to a new location and keep going on the survey (ex. leapfrogging along a survey line that is too long to do from a single base position; you might move the base to the position of a point surveyed by the rover). It does **not** shift the location of the previously collected rover points.

1. Go to **Survey** and then select the **Project** for which you want to shift the base. Scroll down below the map to **Base shift**.
2. Measured point > +Add point > Select the existing survey point that you want to use for the new base position > Apply
   OR
3. Known point > +Add point > Fill in the longitude, latitude, and height. (For instance, this could be a PPP solution from CSRS [see above]).

6. PPK – Post processing kinematic

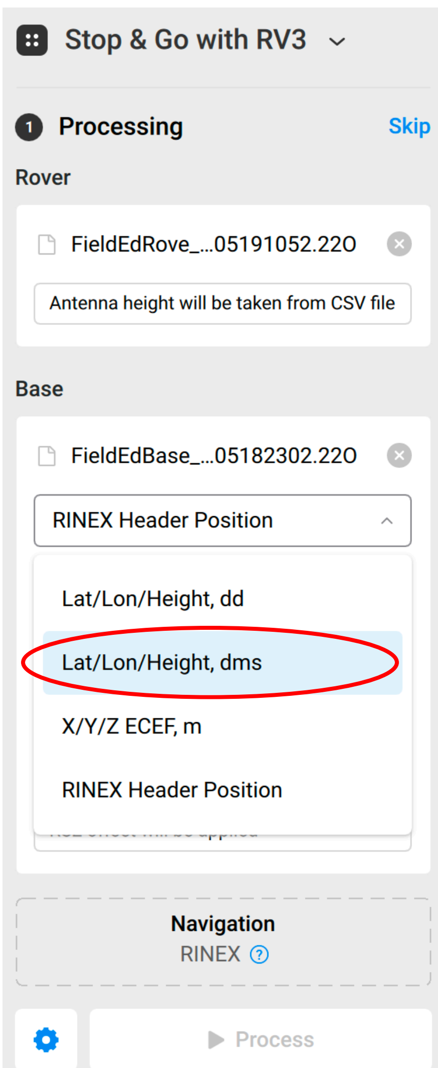
*Post processing kinematic (PPK) allows one to determine corrected rover positions after the survey is completed. The base and rover do not need to have a LoRa radio connection during the survey. This can be a good option if you are having trouble getting **Fix** between the base and rover, if you know ahead of time that line-of-sight will not be possible, or if you will not be able to acquire a known point for your base station prior to the kinematic survey day. At the time of writing, Emlid Studio (https://docs.emlid.com/emlid-studio/#download-emlid-studio; released fall 2021) was still in beta version, but working well.*

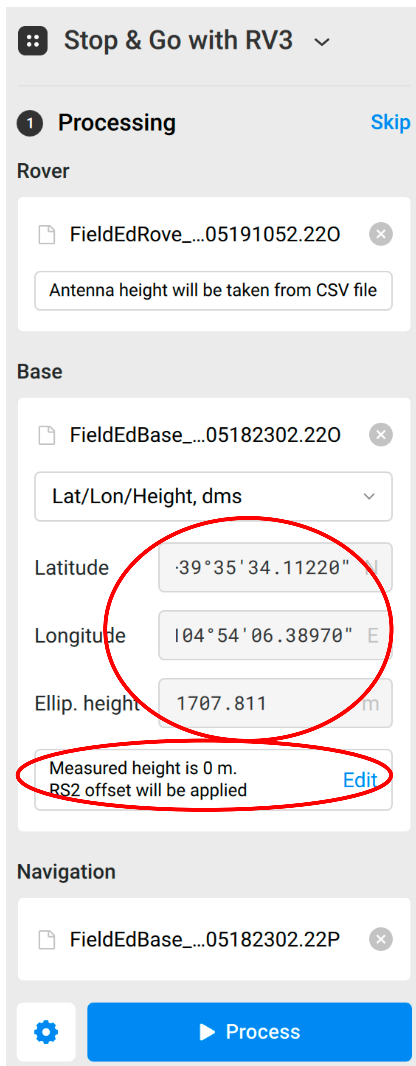
Preparing to collect data

1. Follow the procedures in the PPP section above (Section 4) for details on base station set-up and data recording settings.
2. For both the base and the rover, go into the Receiver page > **Logging**.
   Make sure that raw data is being logged, if it is not, click on the blue circle to start recording. The data should be logged in RINEX 3.03 format.
3. Once the data logging is enabled, collect the survey data as you normally would, except make sure that you collect for at least 30 seconds at each rover point.
4. A base occupation 4-hour, or longer, is best.

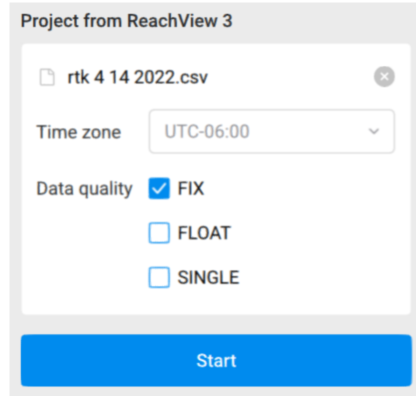
Post-processing

1. Download the RINEX files from both the base and the rover (see instructions in Section 4 PPP).
2. As usual, also download the .csv project file of rover points from the Survey page.
3. Submit the base station data to your PPP service of choice to an online processing service.
4. Open Emlid Studio. In the dropdown menu in the upper left corner, select **Stop & Go with ReachView 3**.
5. Drag the RINEX .xxO file from the Rover into the Rover box.
   Note: the "xx" in the RINEX file's extension indicates the collection year. ".22O" means it was collected in 2022.
6. Drag the RINEX .xxO files from the Base into the Base box. Select **Lat/Lon/Height, dms**. Enter the base coordinates from the PPP service you used.
   Note: if you would like to add a base height, this can be edited in the Base section of Emlid Studio:





7. For the Navigation file, draf in the .xxP file from the base.
8. Click **Process**.
9. For the next step, Generating Corrected CSV, select the project from ReachView3 (.csv file). Select the data quality you would like to keep (Fix, Float, Single)
10. Click **Start**.
11. The output files are located in the same folder on your computer as the input files came from. The resulting csv file will have '_corrected' added to the end of the file name.



7. *Using NTRIP over cellular to access corrections from a permanent GNSS station instead of a local base*

This section will describe how to set up a rover receiver to NTRIP (Networked Transport of RTCM via Internet Protocol). NTRIP allows the rover to receive corrections over the internet and does not require a base receiver. You will need one Reach RS2 receiver that will be the rover station, two smartphones or tablets with the ReachView companion app installed on one, the other will provide a cellular hot spot to the receiver. You can also use a SIM card (not provided) inserted into the receiver if you cannot use your smartphone as a cellular hotspot or do not have two smartphones.

You will also need access to an NTRIP provider in your region. One free option is the Network of the Americas (NOTA) real-time data service. This network has much higher density in the western US. Look for stations near you on the NOTA Real-time Network Monitoring Map. https://www.unavco.org/instrumentation/networks/map/map.html#!/@29.887868204051884,-40.50164876698501,2.000z?network=nota,nota%20affiliated,polar,pi,igs,ggn,sgp,other&type=gps%20realtime&view=horizontal. Request access by emailing rtgps@unavco.org.

Note: The longer the baseline between base (NTRIP station) and rover, the lower the resulting accuracy. Uncertainty increases by ~1 mm per km distance on top of the ~1 cm initial uncertainty. This means that an NTRIP station 30 km away will allow at best 4-cm accuracy. Baselines should be 50 km at most. Less than 20 km is better.

For more information on NTRIP see: https://www.unavco.org/data/gps-gnss/real-time/real-time.html and https://igs.bkg.bund.de/ntrip/index. For Emlid notes on using NTRIP see: https://docs.emlid.com/reachrs2/quickstart/ntrip-workflow.

The rover receiver needs an internet connection to work with NTRIP. There are two ways to connect the Reach RS2 to the internet:

1. Turn on mobile data on your smartphone and share it with the receiver over a Wi-Fi hotspot, the reach will connect to your network and get internet access.
   - The smartphone used as a Wi-Fi hotspot cannot be used to connect to the receiver through the ReachView app. You will need a second smartphone or a SIM card to control the receiver.
2. An active SIM card in the receiver avoids the use of a smartphone hotspot.
   - You will need a Nano SIM card for the Reach RS2,
   - Insert the SIM card into black sealing at the bottom of the receiver.

- Slide the metallic cover to the right, lift it up, insert the SIM card into the cover, close the cover and slide it to the left to lock it in place.

<u>If you will be using two smartphones follow these steps:</u>

1. Prepare your smartphone to provide a mobile hotspot.
    - Typically, you will find this under Settings/Cellular
2. Turn on your receiver and make sure it is in hotspot mode, Wi-Fi symbol (Fig. 1) is white.
    - To turn hotspot mode on, select the menu in the upper right corner (Fig.1), select Wi-Fi and switch **Hotspot** to On
3. On the smartphone you will use to control the rover, connect to the Rover via its Wi-Fi hotspot.
4. Return to the rover's Wi-Fi settings, and connect the rover to the phone's hotspot which should be listed under **Available Networks**.
5. In the **Correction Input** settings, select the *NTRIP* tab, and enter:
    - Address (the IP address of your provider)
    - Port (specified by your provider)
    - Username for your NTRIP provider
    - Password for your NTRIP provider
    - Select your **Mount Point** from the dropdown list.
        - This is your closest GPS station in the network. Scroll through the pull-down list to find the correct station. Be sure to select the closest location with the **RTCM3** option.
    - Format: RTCM3
6. Once these changes are applied and you are connected, the bottom of this page should show that you are *connected* in green text.
    - On the **Status** page:
        - Grey bars next to orange and green bars confirm that you are receiving a correction.
        - **Solution Status** should be **Fix** and the accuracy should be around 0.01m. If not, restart the controller/receiver.
7. At this point, you can leave the smartphone that is acting as the hotspot in your pocket and control the rover with the other smartphone to collect data. No need for a base!

<u>If you are using a SIM card instead of a second smartphone follow these steps:</u>

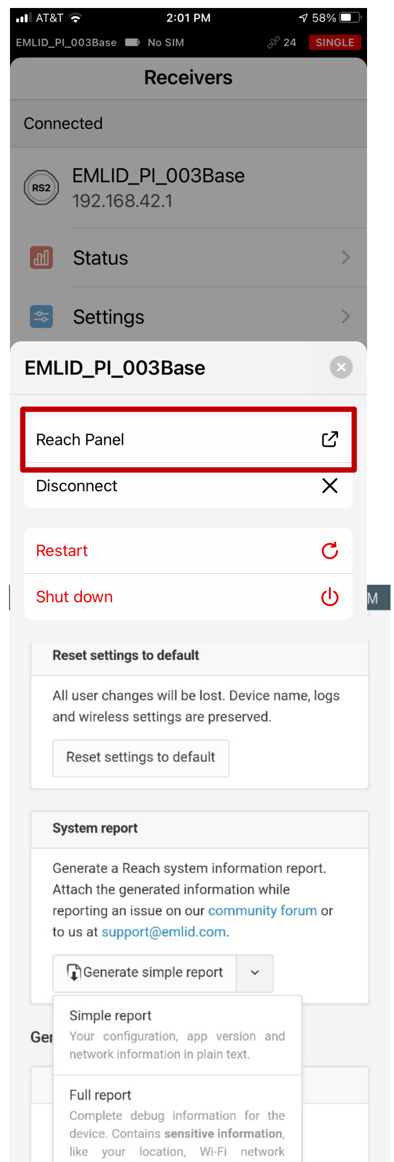
1. Turn on your receiver.
2. Open the ReachView app on your smartphone, click on the rover device and wait for the SIM card to load (it will say *Loading…* at the top of the app).
3. If the SIM card is locked, you will be prompted to enter the PIN for the SIM card. Once connected you should see green bars under Status.
4. Go to the menu and select **Mobile Data** and switch to On. You should now see network bars at the top of the ReachView app next to the battery icon.
5. In the **Correction Input** settings, select the *NTRIP* tab, and enter:
    - Address (the IP address of your provider)
    - Port (specified by your provider)
    - Username for your NTRIP provider
    - Password for your NTRIP provider

- Select your **Mount Point** from the dropdown list.
    - This is your closest GPS station in the network. Scroll through the pull-down list to find the correct station. Be sure to select the closest location with the **RTCM3** option.
- Format: RTCM3
- Once these changes are applied and you are connected, the bottom of this page should show that you are 'connected' in green text.

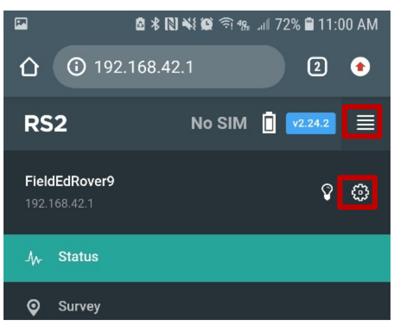
6. On the **Status** page:
    - Grey bars next to orange and green bars confirm that you are receiving a correction.
7. **Solution Status** should be **Fix** and the accuracy should be around 0.01m. If not, restart the controller/receiver.
8. You are now ready to conduct your survey without a base.

8. Downloading a system report

This could be useful in order to retain record of the settings you used. It could also help if a field engineer is trying to diagnose any issue remotely.



1. Connect to the receiver WiFi and open the ReachView3 app. Select the receiver, then select ReachView2
2. The web interface opens, click on the More Options  icon, then click on the Settings icon (gear).



3. Scroll down to the System report section. Under Generate simple report, select the simple or full report.
4. Click on Generate simple report
5. For the simple report, click copy. This will copy the report to the clipboard. Now this can be emailed as text
6. The full report will generate a zipped file, this can be downloaded as well and then emailed or otherwise

transferred, but cannot be copied as text to the clipboard. The simple report does have most settings that we would need to troubleshoot the issue.

9. Connecting to receiver using Windows or Mac computer

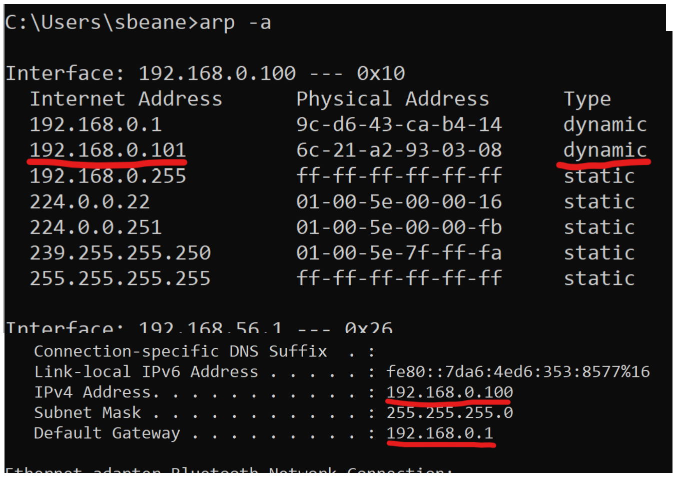
One can also connect to the Emlid Reach RS2 receivers using a computer instead of a mobile device as described in the first section. Instructions for how to connect over WiFi are given here for both Windows and Mac.

Note: You cannot connect Emlid RS2 devices to 5 GHz WiFi networks. If you intend to connect your receiver to a local network, determine its frequency first (listed in network properties) and make sure it is 2.4 GHz. If you accidently connect to a 5 GHz network, see "Troubleshooting".

Connecting Windows computer to receiver over WiFi

Power on the receiver, wait a minute for a steady WiFi indicator.

1. If the WiFi indicator light is **steady white**, the receiver is sending its own signal.
    a. On your computer, connect to the device in your WiFi list (e.g. EMLID_PI_00X:XX:XX)
    b. "Connect using a security key instead". Password: emlidreach
    c. In the command line type "ipconfig/all" to see the IP address of the receiver under "Wireless LAN adapter WiFi: → Default Gateway"
    d. Enter IP address (e.g. 192.168.42.1) into your browser.
2. If the WiFi indicator light is **steady blue**, the receiver is connected to a local network, and you or someone else has configured this receiver to connect to this network in the past.
    a. Connect to this network on your computer.
    b. Option 1: download a program called "Fing" (fing.com) to easily find the IP address of your receiver, and enter it into your web browser to connect to the web interface.
    c. Option 2: Find the IP address of your receiver via command prompt.
        i. In the command prompt, enter "ipconfig".
            1. The IP address of your computer is listed under WiFi next to "IPv4 Address".
        ii. Then, enter "arp -a" to provide a full list of devices on your network. The receiver will likely have an IP address very similar to that of your computer. It will also have a "dynamic" IP address and will be listed as so. (See screenshot below)
        iii. Enter this IP address into a web browser.



```
C:\Users\sbeane>arp -a

Interface: 192.168.0.100 --- 0x10
  Internet Address      Physical Address      Type
  192.168.0.1           9c-d6-43-ca-b4-14     dynamic
  192.168.0.101         6c-21-a2-93-03-08     dynamic
  192.168.0.255         ff-ff-ff-ff-ff-ff     static
  224.0.0.22            01-00-5e-00-00-16     static
  224.0.0.251           01-00-5e-00-00-fb     static
  239.255.255.250       01-00-5e-7f-ff-fa     static
  255.255.255.255       ff-ff-ff-ff-ff-ff     static

Interface: 192.168.56.1 --- 0x26
   Connection-specific DNS Suffix  . :
   Link-local IPv6 Address . . . . . : fe80::7da6:4ed6:353:8577%16
   IPv4 Address. . . . . . . . . . . : 192.168.0.100
   Subnet Mask . . . . . . . . . . . : 255.255.255.0
   Default Gateway . . . . . . . . . : 192.168.0.1
```

"arp -a" showing the router and receiver IP addresses.

"ipconfig" showing the router's IP address as 192.168.0.1 and this computer's IP address as 192.168.0.100

Connecting Mac computer to receiver over WiFi

Power on the receiver, wait a minute for a steady WiFi indicator.

1. If the WiFi indicator light is **steady white**, the receiver is sending its own signal.
   a. On your computer, connect to the device in your WiFi list (e.g. EMLID_PI_00X:XX:XX)
   b. Password: emlidreach
   c. Connect to either IP address: 192.168.42.1 or 192.168.2.15 in a web browser.
2. If the WiFi indicator light is **steady blue**, the receiver is connected to a local network, and you or someone else has configured this receiver to connect to this network in the past.
   a. Connect to this network on your computer.
   b. Option 1: download a program called "Fing" (fing.com) to easily find the IP address of your receiver, and enter it into a web browser.
   c. Option 2: Find the IP address of your receiver via the Terminal by entering "arp -a" and entering that IP address into a web browser.

Connecting Mac computer to receiver using Ethernet over USB

1. Turn on the receiver and connect via USB cable (same one used for battery charging).
2. In System Preferences → Network, you should see "ReachRS2" pop-up with a green light and an IP address 192.168.2.XX. This is the IP address of your computer on this network.
3. Emlid sets an IP address for when the RS2 is connected with a cable to be 192.168.2.15. Enter this in a web browser.

Note: at the time of writing, the method to connect Windows machine using Ethernet over USB was complicated and not reliable.