# GNSS Basics for the Drone Mapper

Walter Volkmann, Micro Aerial Projects, Gainesville, Florida, USA

Micro Aerial Projects

**Foreword**

I think it is fair to assume that a significant number of drone owners have very little grasp of the importance of, and the role that Global Navigation Satellite Systems (GNSS) are playing in assisted flight and automated navigation. The reliability of orientation sensors, GNSS, powerful computers and software make it just so easy to launch and fly that one can understand why drone enthusiasm is thriving despite often very superficial knowledge levels of what it takes technically to enjoy the ease and power of switches and joysticks.

Add to this drone technology the availability of extremely sophisticated, yet user-friendly and affordable software employing the structure from motion (SfM) modeling technique and one can understand the rapidly growing confidence of novice “drone mappers” – amateurs and professionals alike – who are aggressively entering a market that was until less than a decade ago the exclusive domain of well capitalized, highly skilled enterprises.  Hence the relentless progress in technology and automation is indeed democratizing and disrupting what used to be a highly specialized field: making accurate maps from aerial images.

The raw ingredients in SfM mapping are firstly areal images and secondly, coordinates of Ground Control Points (GCPs) and/or Camera Exposure Positions (CEPs).  While the SfM technique produces high resolution and high-quality models from images, spatial inputs in the form of GCP and/or CEP coordinates are needed to correctly place, orient and scale – i.e. geo-reference - the model before we can call it a map. And since GNSS is the most efficient and convenient resource to provide this spatial input it seems useful, if not advisable, to understand the practical and theoretical characteristics of GNSS applications in drone mapping. The practice of determining accurate coordinates of GCPs and CEPs relies on the use of differential GNSS – a GNSS positioning technique that distinctly differs from navigational GNSS such as that employed in car navigation and automatic drone flights.

Correctly applying the technique of differential GNSS to SfM mapping is not as straight forward as entering an address into the “GPS navigator” of your car and pressing GO!, or waiting until your drone flashes the green light before arming motors and flicking the take-off switch.  For one, the friendly and reassuring voice guiding you from turn to turn or reporting telemetric data from waypoint to waypoint is not available as you plan and execute a mapping project with the SfM technique.

We often get asked to explain "in simple language" why and how we use differential GNSS in our drone mapping work. Considering the many options and the aggressive, often confusing marketing language around GNSS topics, it is hoped that these notes will help the prospective drone mapper to make informed decisions on the use and appropriateness of GNSS technology in drone surveying and mapping operations. This is not meant to be an academic treatise of the topic but rather a collegial sharing of insights from one practitioner to another.

## 1. Typical survey tasks encountered in unmanned aerial vehicle (UAV) / structure from motion (SfM) mapping projects.

In the context of GNSS surveying with drones there are two distinct tasks to complete, each of them utilizing a different, mutually exclusive feature of GNSS surveying:

### a. Surveying of a local control point on the national spatial reference frame as shown in Figure 1 below.

This step is needed to facilitate the spatial registration of the map you are producing with other spatial data that may have been generated in the past and/or by other means and third parties. It is generally referred to as ***geo-referencing***. To ensure that all survey and mapping work is referenced to the ***national spatial reference frame***, governments provide the necessary ***geodetic control networks*** (geodetic infrastructure) to which geo-spatial practitioners can connect their measurements. Geodetic networks provide practical definition of national, regional or international spatial reference frames. They can be passive or active. Passive geodetic networks consist of permanently marked ***geodetic control points*** for which the government publishes ***official coordinates***, while active networks consist of a distribution of ***continuously operating reference stations (CORS)*** which are connected via the internet to stream ***raw GNSS observations*** to a processing center where the observations are archived and processed for various geo-spatial service purposes. Active networks can be used for on-demand dissemination of official coordinates of CORS and their raw GNSS observations plus they can provide via the internet ***differential corrections*** in real time to subscribing rovers. The spacing of geodetic control points or CORS depends primarily on economic considerations. Passive geodetic control points are typically spaced 10 to 25km apart. CORS stations on the other hand can be spaced apart by as much as hundreds of kilometers. Hence the lengths of the red lines in Figure 1 connecting the Local Control Point to the nearest available geodetic points can vary from tens to hundreds of kilometers. We will see later that a specific GNSS technique will be needed to determine the precise position of a Local Control Point from the lengths and orientation of these long connecting lines.

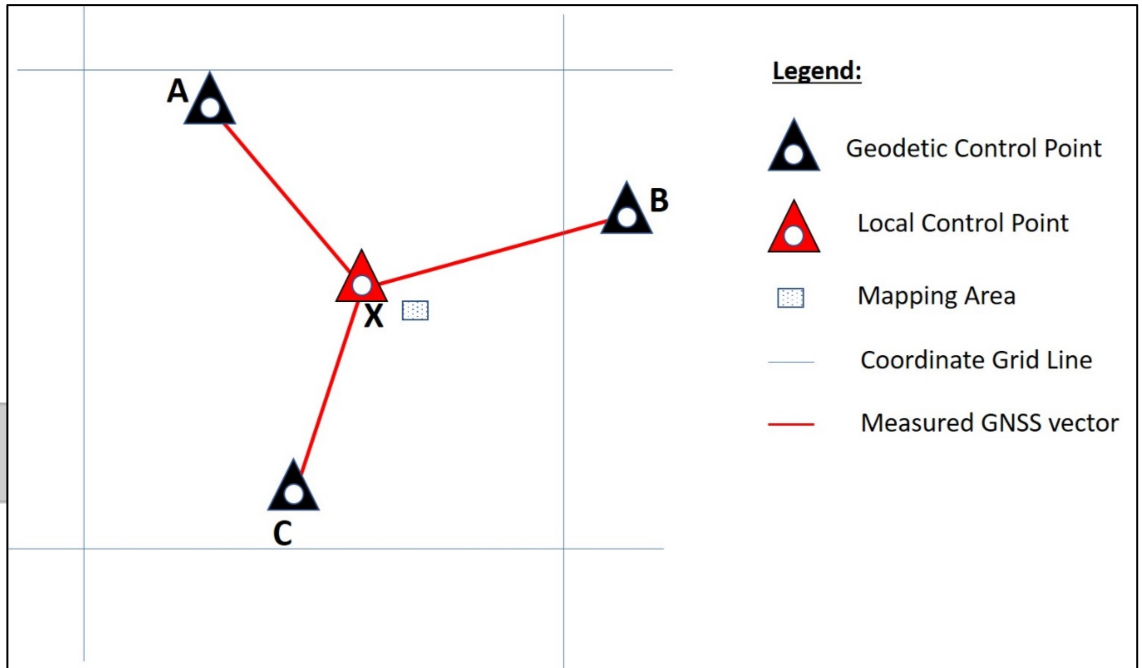


*Figure 1: Using a passive geodetic network and GNSS measurements to survey a local control point for a UAV mapping project.*

Sometimes the UAV mapping practitioner may be asked by his client to reference his geo-spatial products to a ***local coordinate system***. In this case the client should provide the coordinates for at least three local points. In this scenario the need for determining the coordinates of a local control point is obviated. The technique of referencing UAV/SfM derived geo-spatial products to a given local reference system is left for another article.

**b. Surveying of Ground Control Points (GCPs) or Camera Exposure Positions (CEPs) as shown in Figure 2 below.**

This step is needed to determine coordinates of either GCPs or CEPs for input to the structure from motion (SfM) workflow. Note that GCPs and CEPs are linked to the local control point by means of red lines also. The significant difference is that the location of geodetic control points and CORS are a given fact over which the practitioner has no control. The practitioner can however choose the location of the local control point in such a way that the separation between local control point and GCPs or CEPs are significantly shorter, thereby enabling the use of a different, much more effective GNSS method for the measurements of length and orientation of the connecting red lines.

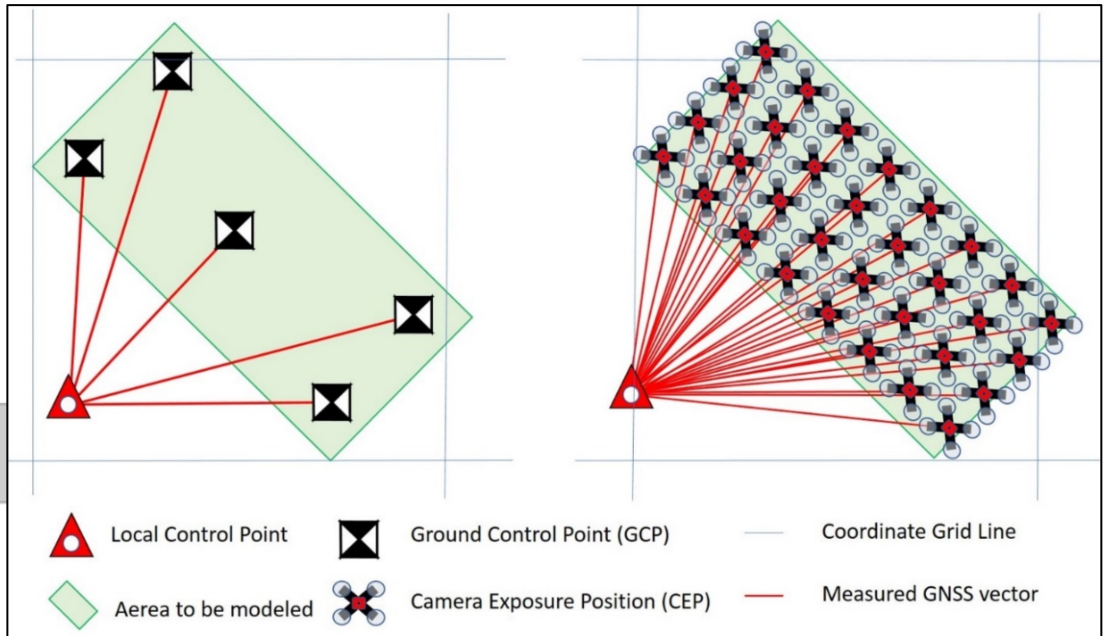


*Figure 2: Using a local control point and GNSS measurements to survey ground control points (GCPs) or camera exposure positions (CEPs) for a structure from motion (SfM) mapping project.*

(Note spelling of area in the figure above!!)

## 2. Measurement techniques with GNSS

In GNSS supported UAV/SfM surveying there are two distinct GNSS measurement techniques:

### a. Direct, single point positioning based on code measurements.

This method is employed by most drones for general navigation. It entails the use of a single receiver which performs measurements of a **code signal with a wavelength of 30m**. The 30m code signal is transmitted from the GNSS satellites on a **carrier signal** of much shorter wavelength (about 20cm). The code measurements are used to derive so-called **pseudoranges** (approximate distances between receiver and GNSS satellites) which in turn are used to determine the position of the receiver by means of a method called **trilateration**. At least four GNSS satellites are needed for this type of positioning. The direct result of trilateration with **pseudoranges** is an **absolute position** (latitude, longitude and height) on ***the WGS84 spatial reference system***. Most smart phones and drones are equipped with GNSS receivers for this positioning technique.

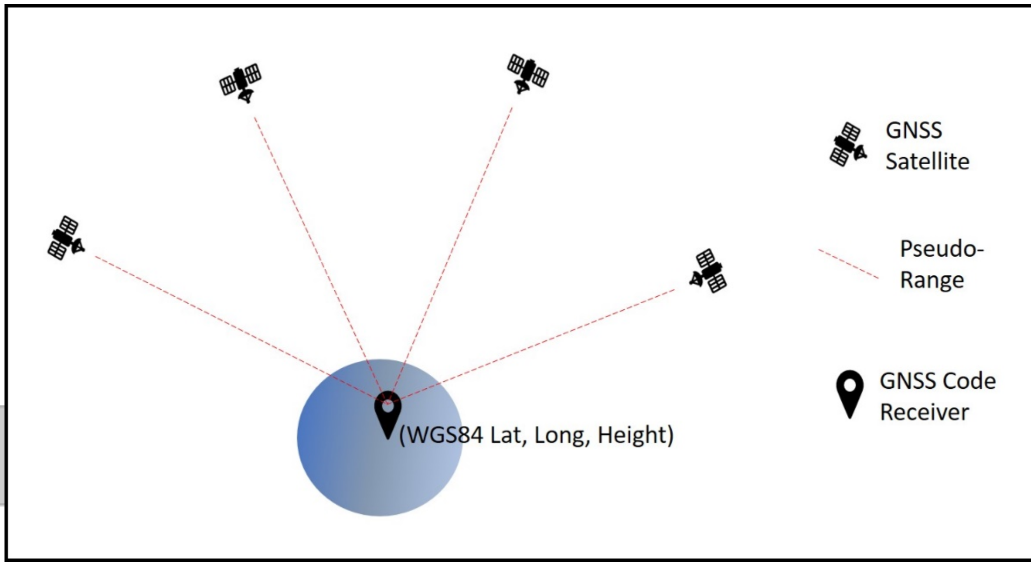


*Figure 3: Absolute positioning by means of pseudoranging*

The accuracy of stand-alone single point GNSS solution depends significantly on the geometry of the current satellite configuration. As measure of goodness in the geometry the GNSS receiver computes a ***dilution of precision (DOP)*** factor. It is derived from the volume enclosed in the surface defined by the satellite and the user positions. The more widely distributed the satellites are the more volume they enclose, thus yielding a low DOP value. A closely bundled distribution on the other hand encloses small volume and yields a high DOP value. DOP values are thus lowest for conditions of small errors and highest for conditions of large errors. Various DOP values are presented. ***H-DOP*** is a measure of ***horizontal***, ***V-DOP*** a measure of ***vertical accuracy***. Since most flight controllers use barometric pressure as primary input for altitude sensing, the threshold for acceptable GNSS navigation is most often defined by a maximum H-DOP value.

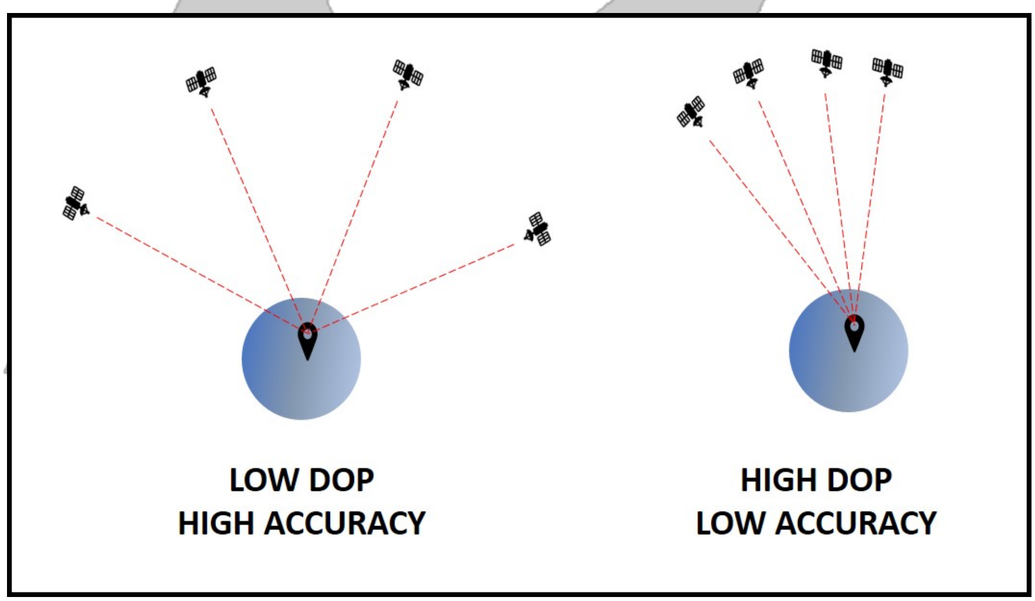


*Figure 4: The effects of geometry on accuracy in single point GNSS positioning.*

As mentioned, the wavelength of the code signal is 30m. The code signal can be used like a ruler with 30m tick marks to measure the pseudorange. The accuracy of the pseudoranges is significantly affected by continuously changing tropospheric and ionospheric effects. It can be improved by using corrections from so called ***Satellite Based Augmentation Services (SBAS)***. These corrections, transmitted via geo-stationary satellites, are applied by GNSS receivers to improve the direct absolute positioning accuracy from about 30m to the 2 to 5m range. Note that the geo-stationary satellites are located on the plane of the earth's equator. Any obstructions in the path between GNSS receiver and the geo-stationary communication satellite will result in a loss of the SBAS corrections.

Examples of SBAS are the Wide Area Augmentation System (WAAS) covering the North American continent and the European Geostationary Navigation Overlay Service (EGNOS). As can be seen in Figure 5 below, large areas on the earth, such as the entire continents of South America, Africa and Australia do not have SBAS and thus do not have the benefit of improved pseudoranging.

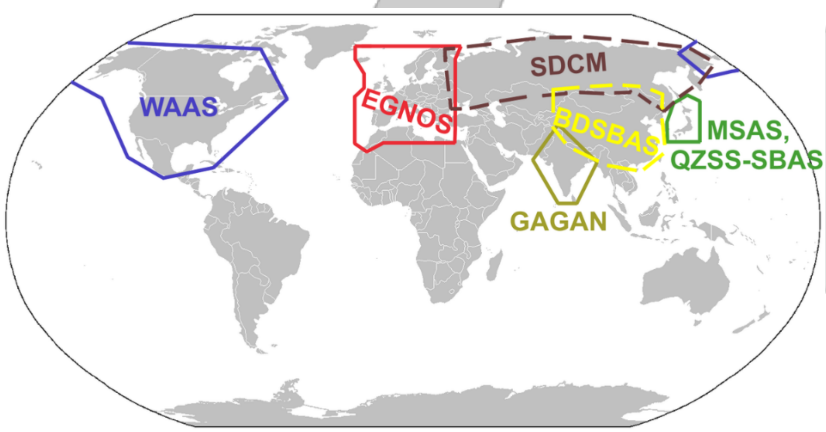


*Figure 5: SBAS coverage as of 2018. Source: Persimplex - Own Work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=18957671*

It is worth noting that UAVs capable of automatic navigation also use the single point GNSS method to control sensor payload such as the triggering of cameras. Assuming zero latency between trigger command and actual exposure, actual camera exposure positions can thus at best be achieved only as accurately as the single point GNSS method allows. Hence the coordinates of images which were geo-tagged by the single point GNSS drone navigation system must be presumed to have an accuracy of a few meters and thus are **not adequate for precise geo-referencing** of SfM geo-spatial products.

### b. Differentially corrected carrier phase GNSS positioning.

While pseudoranging is very affordable and very efficient at low accuracy levels, precise positioning requires the use of more expensive carrier phase capable GNSS receivers. The current GPS carrier signals L1 and L2 have, for comparison to the code wavelength of 30m, wavelengths of a mere 19 and 25 cm respectively. In other words, some 120 L2 wavelengths fit into a single code wavelength. Carrier signals thus provide for much finer graduations on the imaginary ruler referred to above and thus allow for more accurate ranging between receiver and satellite.

At this significantly higher level of basic measurement accuracy, the effects of the ionosphere and the troposphere on the GNSS signals become even more significant. To eliminate these (and other lesser) effects, the GNSS measurements must be ***differentially corrected***. In contrast to the direct determination of an absolute position by means of pseudoranging, ***differential GNSS*** is used for the determination of the ***precise position*** of a point with unknown coordinates ***relative to*** another ***point with known coordinates***. We refer to this relative position as a ***GNSS vector*** or a ***GNSS baseline***. It is derived from ***simultaneously measured carrier phases*** (commonly referred to as ***raw observations***) at both ends of the vector. If accurate coordinates of the vector origin (commonly referred to as the ***reference station***) are known, then accurate coordinates of the vector terminal (commonly referred to as the ***rover*** position) can be computed by applying the GNSS vector components to the reference station coordinates.

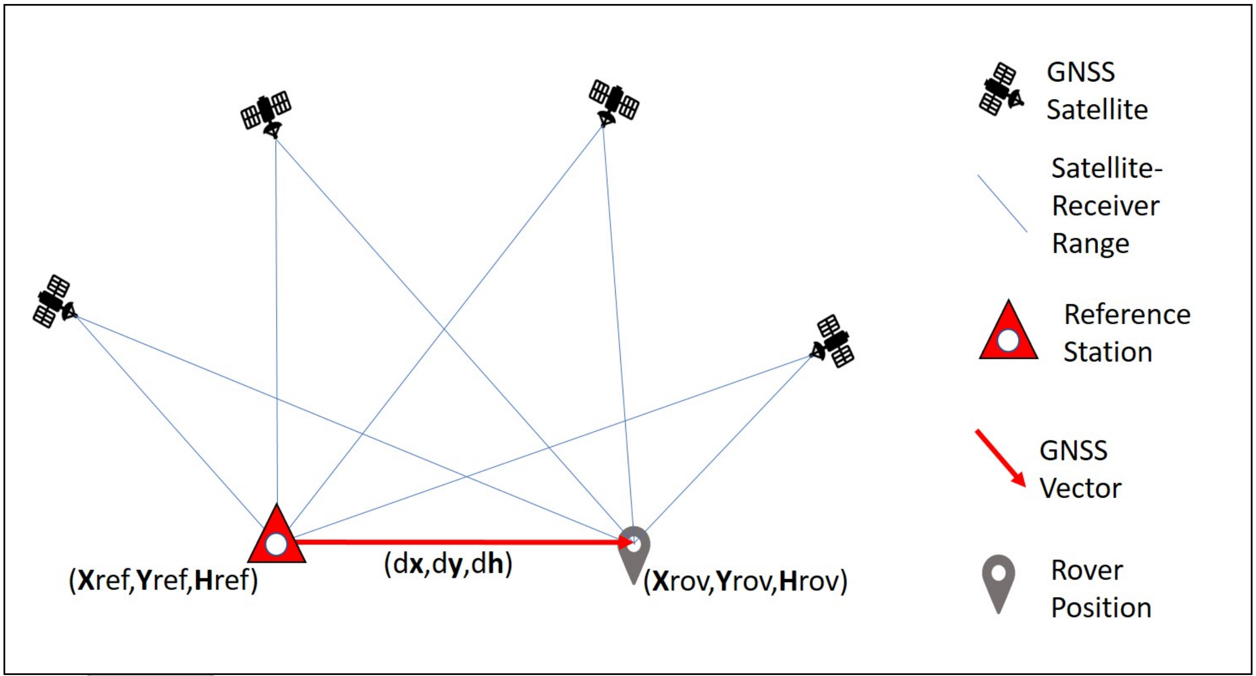


*Figure 6: Carrier phase differential GNSS*

In simple mathematics

Xrov = Xref + dx

Yrov= Yref + dy and

Hrov = Href + dh

Where

Xref, Yref, Href are accurate, known coordinates of the reference station,

dx, dy, dh is the precisely measured GNSS vector between reference station and rover and

Xrov, Yrov, Hrov are the coordinates of the rover.

Note that carrier phase differential GNSS can be carried out with single or multiple frequencies.

## 3. Glossary of GNSS terms encountered in typical GNSS survey operations

The first is ***static*** versus ***kinematic*** surveying. ***Static surveying*** implies that all receivers simultaneously observing and recording raw phase measurements remain stationary for the entire observation session. Static surveying yields the highest degree of accuracy achievable with carrier phase GNSS surveying. ***Kinematic surveying*** implies that the simultaneously observing receivers may be moving during the observation session. Note that the receivers may also be temporarily stationary during a kinematic session, but they don't have to be stationery. Note also that one of the receivers must be designated the ***reference receiver*** (***with known position***) while the other, with unknown position, is designated as the roving receiver, or more simply, the ***rover***.

Although not relevant to the applications being discussed here, note also that the reference receiver itself may be moving. In the scenarios discussed here we will assume that the reference receiver is stationary and that it occupies a position with known coordinates throughout an observation session. In other words, only the rover is assumed to be kinematic. The direct result of a kinematic GNSS session is a series of ***GNSS vectors*** between reference receiver and rover.

Static surveying is typically applied when a single or a few points located a long distance from the nearest available geodetic control points must be surveyed accurately. The GNSS vectors between these points and the nearest surrounding geodetic control points or CORS are classified as ***long baselines*** when their length exceeds 20km. The scenario depicted in Figure 1 is a typical case of such surveys.

Kinematic surveying on the other hand is applied when many points in close proximity must be surveyed to an accuracy of a few centimeters, such as depicted in Figure 2 above. In such cases the GNSS vectors are shorter than 10km and we speak of ***short baselines***.

In countries with modernized geodetic infrastructure you may find that a ***GNSS positioning service*** is available. Subscribers to such a service have the benefit of receiving real time differential corrections from a ***Virtual Reference Station (VRS)*** over the internet, hence they do not need to provide for their own reference station. Since the GNSS positioning service will place the Virtual Reference Station in close proximity of the subscribing rover position, and, unless extremely high precision is required, the subscriber can enjoy the operational efficiencies of kinematic surveying.

The period between successive satellite signal observations by GNSS receivers is referred to as the ***epoch***. A receiver recording raw observations at a rate of 1Hz is said to record at 1s epochs. A ***recording frequency*** of 5Hz is equivalent to an epoch of a fifth of a second or 0.2s. Most receivers can be configured to record at a specific frequency for the entire duration of a session (a variable recording rate during a session is not generally available). For reliable kinematic surveying the frequency at both receivers should be at least 1Hz. Note that the reference receiver recording frequency may be lower than that of the rover by divisible factors. This epoch discrepancy is overcome by interpolation of the reference receiver observations and does not have significant impact on the GNSS vector accuracy. Note however that the reference receiver epoch must be an integer multiple of the rover epoch. Rover epochs of 0.1, 0.2 and 0.5 seconds will work with reference receiver epoch of 1 second while rover epochs of 0.3, 0.4, 0.6 to 0.9 seconds will not. Modern receivers are capable of 20Hz (0.05s epoch) recording rates. A few manage to record at rates as fast as 100Hz!

As explained above, GNSS vectors produced by a kinematic GNSS session are applied to the reference receiver coordinates to yield rover coordinates. A GNSS vector is computed for each rover epoch, hence rover coordinates are computed for each epoch of a session. The series of chronologically ordered rover positions is known as the ***approximated rover trajectory***. Figure 7 below illustrates the relation between actual and approximated rover trajectory.

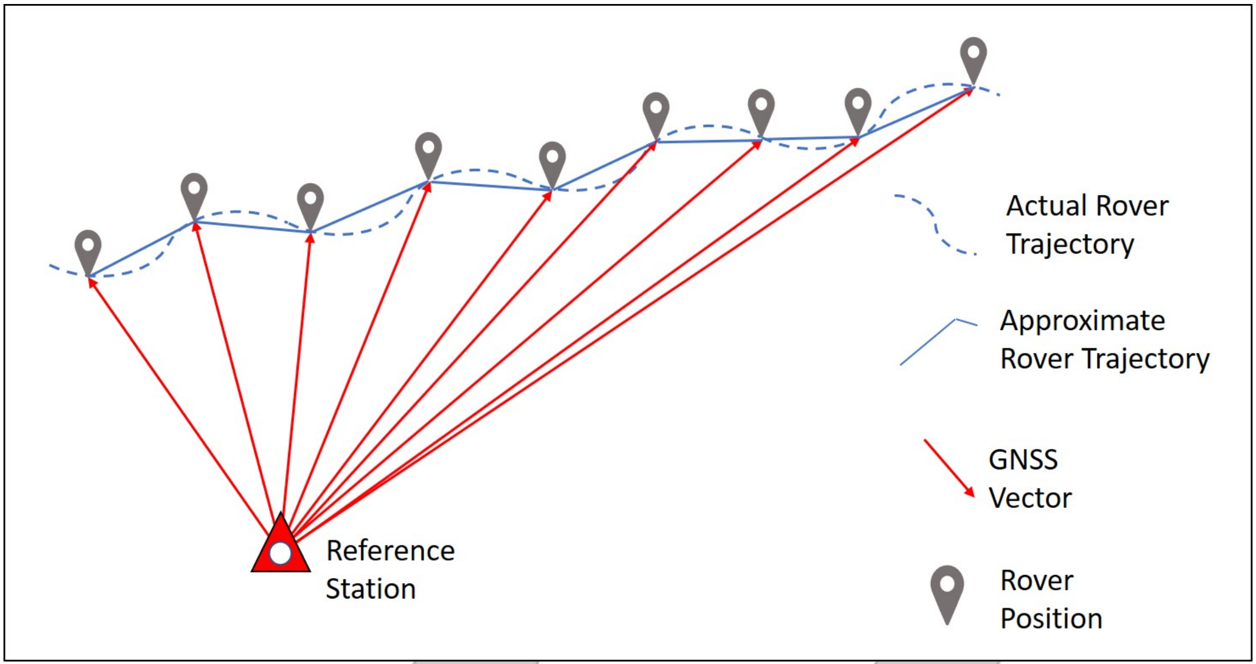


*Figure 7: Actual and Approximate Rover Trajectory*

Looking at Figure 7 it is obvious that the approximation of the actual rover trajectory improves with densification of the distinct trajectory points.

If s is the distance traveled by the rover during one epoch, then

s = v x Δt where v = velocity of the rover and Δt is the epoch.

For example, for a platform ground speed of 10m/s a 20 Hz rover recording rate will yield a trajectory point every 10m/20 = 0.5m. The practical implication of the relationship between frequency and rover velocity is that to maintain the same level of accuracy, an increase in velocity will require an increase in recording frequency. Conversely, decreasing the velocity will result in shorter distances between consecutive trajectory points.

The computations in carrier phase differential GNSS require access to both reference receiver as well as rover observations. The observations may be recorded by the receivers in the field and downloaded to the processing computer after retrieval from the receiver storage devices or they may be wirelessly streamed to the processing computer while the observations are underway. The first scenario is referred to as ***post processed***, the second as ***real time***. Both arrangements can be applied to static and kinematic surveying. When in kinematic surveying the raw observations are downloaded and processed after the observation session has been performed we speak of **post processed kinematic (PPK)** GNSS surveying. When the raw observations are streamed and processed in real time, we speak of **real time kinematic (RTK)** surveying. It is important to note that the algorithms used in PPK and RTK surveying are identical. Note also that in most RTK settings, the processor performing the differential correction computations is located at the rover – either physically in the housing of the receiver or in a processor linked to the rover by means of cable or wireless connection. However, RTK computations can also be performed on a computer that is receiving simultaneously the raw observations from reference station as well as from the rover.

In RTK operations the reference receiver typically transmits via radio telecommunication link correction messages to the RTK processing computer. The Radio Technical Commission for Maritime Services (RTCM) has devised a standard format for these correction messages. This standard makes it possible to use combinations of receivers from various GNSS equipment vendors in RTK surveying. For example, the reference receiver may be from vendor A while the rover may be from vendor B. Often the correction messages are referred to as the ***RTCM*** messages.

In PPK operations it is also possible to use the raw observations from a combination of receivers from different vendors. To overcome data format conflicts, vendors supply software for re-formatting of the highly compressed proprietary raw observation files to a standardized, open ASCII format called ***Receiver Independent Exchange format (RINEX).*** The text below shows the header of a RINEX file.

```
  2.11        OBSERVATION DATA    MIXED           RINEX VERSION / TYPE
TPS2RIN 1.0.24.1481 TPS-USER         08-SEP-18 13:08    PGM / RUN BY / DATE
win32 build Jul 27, 2017 (c) Topcon Positioning Systems     COMMENT
VmapB0908q.tps                                   COMMENT
Observer          Agency                         OBSERVER / AGENCY
O1QKDQR3RQW       TPS B111         5.1 Jun,15,2017 p3  REC # / TYPE / VERS
000             -Unknown-                        ANT # / TYPE
      0.0000       0.0000       0.0000           ANTENNA: DELTA H/E/N
VmapB0908q                                       MARKER NAME
  729902.7117 -5497461.0929  3140005.7464             APPROX POSITION XYZ
   1    1                              WAVELENGTH FACT L1/2
 2018    9    8   16   42   49.9500000    GPS        TIME OF FIRST OBS
 2018    9    8   16   52   34.4000000    GPS        TIME OF LAST OBS
   0.050                               INTERVAL
   7   C1    L1    D1    P1    P2    L2    D2          # / TYPES OF OBSERV
  11                                   # OF SATELLITES
  G02 11613 11613 11613 11570 11570 11570 11570          PRN / # OF OBS
  G05 11690 11690 11690 11689 11690 11690 11690          PRN / # OF OBS
  G06 11690 11690 11690 11690 11690 11690 11690          PRN / # OF OBS
  G09 10242 10242 10242 10124 10124 10124 10124          PRN / # OF OBS
  G12 11690 11690 11690 11571 11570 11570 11570          PRN / # OF OBS
  G17 11690 11690 11690 11690 11687 11687 11687          PRN / # OF OBS
  G19 11690 11690 11690 11689 11688 11688 11688          PRN / # OF OBS
  G25 11689 11689 11689 11677 11679 11679 11679          PRN / # OF OBS
  S31 11601 11601 11601    0     0     0     0        PRN / # OF OBS
  S33 11340 11340 11340    0     0     0     0        PRN / # OF OBS
  S38 11661 11661 11661    0     0     0     0        PRN / # OF OBS
  18                                   LEAP SECONDS
SE TPS AAF92A62                                  COMMENT
                                      END OF HEADER
 18  9  8 16 42 49.9500000  0  6G12G05G19G06G17G25
  21756341.357   114330344.93946     1533.130
  22027718.768   115756442.72746     3969.957              22027718.496
  90199824.41744      3093.473
  22307581.425   117227131.27446     -113.638
  22611562.022   118824559.89446     -327.761    22611561.064
22611563.360
  92590572.16144      -255.399
  23897127.338   125580250.83446     -697.598    23897126.122
```

Once raw observations are in the open RINEX format they can be opened by ASCII editors such as Notepad ++ and subsequently inspected, analyzed and manipulated in several ways. The RINEX standard provides for a standardized file header which contains important meta data such as receiver identification and begin and end times of recording sessions. To reduce file size or to accelerate processing it is often desirable to ***decimate*** the observations to effectively lower recording frequency (or provide for longer epochs).

A signal originating from a position close to the horizon must penetrate the earth's atmosphere for a much longer distance and is thus much more subject to degradation than a signal originating from the zenith. To exclude these sub-optimal signals from the computation process, GNSS receivers and processing software can be configured to apply an ***elevation mask***. It is defined by an angle above the horizon below which no satellite signals are recorded or used in the calculations. In practice elevation masks are generally set in the range from 5 to 15 degrees.

The quality of a GNSS signal can be expressed in terms of the ***signal to noise ratio***. A strong, un-obstructed signal has a high signal to noise ratio while a weak signal has a low signal to noise ratio. Signal to noise ratios above 40% are considered strong, signal to noise ratios below 20% are considered weak. Weak signal to noise ratios occur due to meteorological interference, obstructions, reflections, electromagnetic interference (EMI) and low altitude paths.

When a signal is reflected by a surface near the GNSS antenna it may be confused with an original, direct signal. This phenomenon is referred to as ***multi-pathing*** and may adversely affect GNSS accuracy. Hence it is good practice to place antennas in environments void of any reflective surfaces within 10m of the antenna.

Electromagnetic waves move through a vacuum at the known speed of light, commonly denoted by the letter c. Apart from highly accurate time keeping and clock synchronizations, the speed of light is a most important element in GNSS positioning. However, GNSS satellite signals pass through extensive layers of matter (the ionosphere, the troposphere and the lower layers of the atmosphere) which reduce their speed and thus delay their arrival at the GNSS receiver. This delay must be accounted for in satellite ranging. To correct for the delay, it is necessary to establish the refractive index of the medium through which the signals travel. The refractive index, N, of a medium is defined as the ratio of the speed of light in a vacuum to the speed of an electromagnetic signal in a medium. Mathematically expressed the refractive index N of a medium is defined as follows:

$N=c/v$ where c is the speed of light in a vacuum and v is the speed of light in the medium.

If the value of the refractive index is known, the speed of the signal in the medium $v=c/N$. If the time it takes a signal to travel from satellite to receiver is t, then the distance travelled by the signal, i.e. the range $r=v*t$ or $r=(c/N)*t$.

The ionosphere, the troposphere and the atmosphere all contribute to the refractive index to which GNSS signals from space are subjected. Without knowing the value of the refractive index experienced by each of the GNSS satellite signals used in a solution, one cannot correctly calculate the satellite ranges. Note that the refractive index does not depend on the wavelength (and thus the frequency) of the signal. It is the same for all frequencies.

The reason for classifying baselines as short or long rests on the validated assumption that the refractive index is the same at both ends of a short baseline and thus will have no effect on the value of the GNSS vector. This assumption does not hold for long baselines and hence a method of correcting for the difference of the refractive indexes at either end of a long baseline must be applied.

To be useful for accurate geo-referencing of SfM outputs, a PPK equipped drone should allow for the accurate survey of camera exposure positions. For this purpose, the external flash hot shoe connector of the camera is connected to an on-board carrier phase GNSS rover. Every time the camera exposes, it sends a pulse through the external flash hot-shoe connector to the GNSS receiver which records the exact time that it received the pulse. This recording of the exact time of the exposure is called ***event marking***. A hardware configuration of this kind is shown in Figure 8 below.

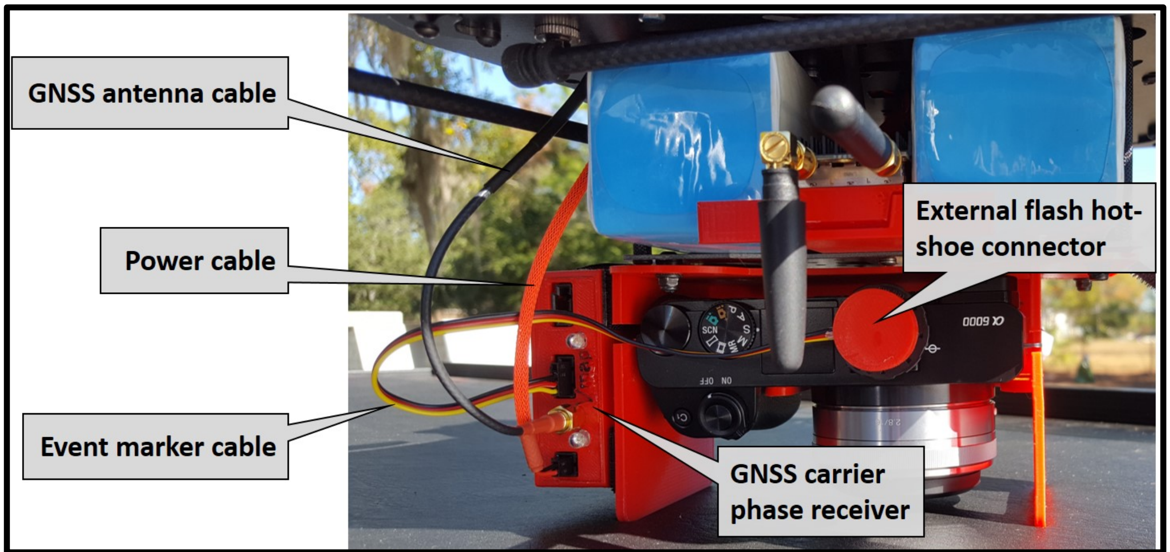


*Figure 8: Multirotor platform payload: Camera and dual frequency GNSS receiver capable of event marking.*

Figure 9 below illustrates a method called ***linear interpolation*** in which the marked event, $t_c$ and the rover trajectory points at times $t_n$ and $t_{n+1}$ are used to determine the ***camera exposure position (CEP)***.

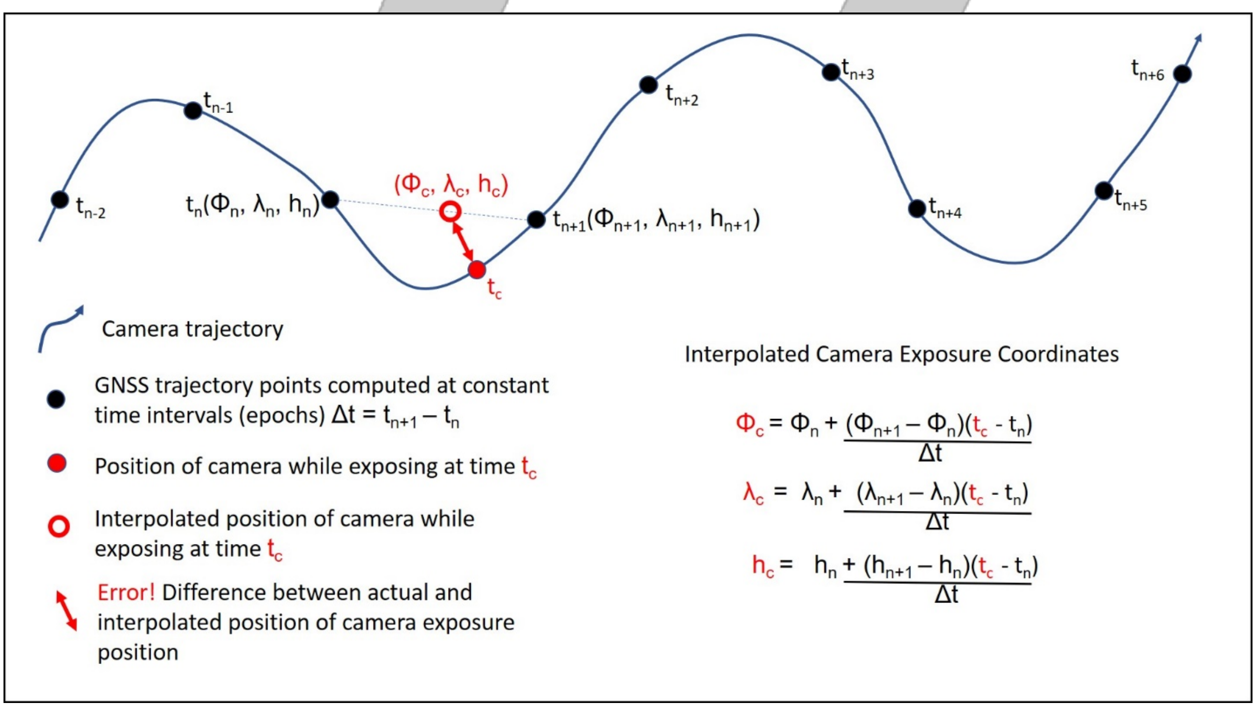


*Figure 9: Linear interpolation of camera exposure events.*

This method assumes that the velocity of the camera (i.e. speed and direction) remains constant from epoch to epoch. In practice that condition can never be established exactly and hence the interpolation error is inevitable. The interpolation error can however be minimized by

- Keeping the velocity and course as constant as possible;
- Increasing the measurement rate of the rover and/or
- Reducing the speed.

In carrier phase differential GNSS computations the range between receiver and satellite is expressed as the sum of an integer (i.e. a whole) number of wavelengths plus a fraction of a wavelength or, in mathematical notation, ***Range = (n + f)λ where n is the integer number of wavelengths, f is a fraction and λ is the length of the wave***. Figure 10 below illustrates the concept schematically.

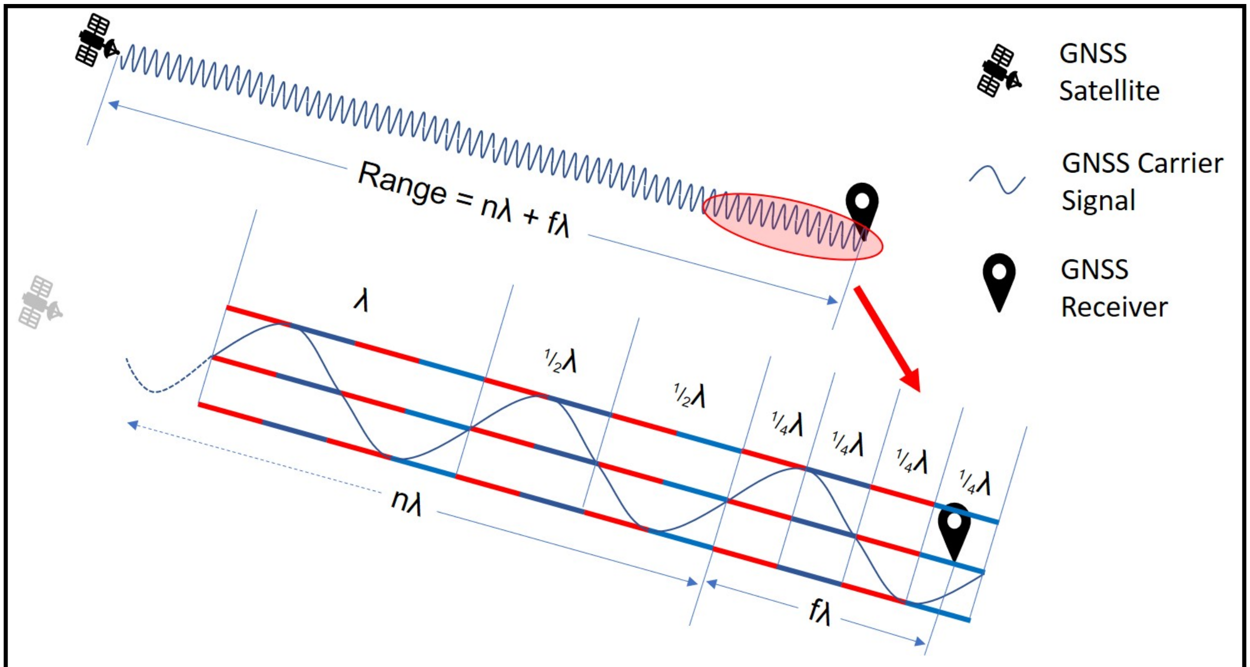


*Figure 10: The satellite range expressed in units of wavelengths of the carrier signal.*

The GNSS receiver can only measure the fraction (f) of the wavelength (also referred to as the ***phase of the signal***). The challenge in phase differential GNSS is to computationally determine the correct integer number of wavelengths (n) that make up the range. This is done in an iterative process that starts with an intelligent estimate of the number n (seed values are derived from the pseudoranges). Utilizing the redundancy of data (i.e. combining the observations of more satellites than are necessary) it is possible to rank the results of a range of estimates and combinations of the numbers n for each satellite in terms of residual error sizes. A solution is accepted as accurate only if it is significantly better than the second-best solution. In such a case the ***integer ambiguity*** is said to have been ***resolved*** and the best result is called a ***fixed solution***. If there is no significant difference in the result between the best and the next best solution, i.e. if the integer ambiguity could not be resolved, the constraint that n must be an integer is (unrealistically) relaxed and a real number (with a “floating point”) is used instead. In such cases the integer ambiguity is said not to have been resolved and the best solution with a non-integer value of n is presented as a ***float solution***.

The fixed or float attribution of a solution in carrier phase differential GNSS is a most useful and powerful byproduct of the result because it is a direct measure of accuracy of the GNSS vector.

The ***estimated error of a GNSS vector*** is expressed in this form:

**Error = c + x** where c is a constant error in units of length and x indicates an additional error component measured in millionths of the length of the vector, so-called ***parts per million (ppm).***

For example, for a vector of length 1 000m, a value c of 0.01m and an additional error of 10 ppm the error would be 0.01 + (10/1 000 000)*1000 = 0.01+0.01=0.02m. Note that this expression implies that the ***absolute error in a GNSS vector increases with length of the vector***. For a vector of 10 000m length the same values for c (0.01) and x (10) will have an error of 0.01+ (10/1 000 000)*10 000 = 0.01 + 0.1 = 0.11m. Readers who are unfamiliar with metric units may find it useful to note that there happen to be 1 million millimeters in one kilometer; in the metric system, the ppm term is equivalent to “millimeter per kilometer”.

A **fixed solution** (i.e. one for which the integer ambiguity has been resolved) can with at least 99.5% confidence be assumed to have an accuracy of c + **1**ppm. **For float solutions there are no reliable estimates for the ppm part of the error.** Furthermore, for static surveying the value c generally is specified as 0.005m; for kinematic surveying as 0.010m. It is thus possible to rigorously assess the quality of differential carrier phase GNSS results and to make reliable estimates of errors in fixed solutions before committing them as inputs for further computations.

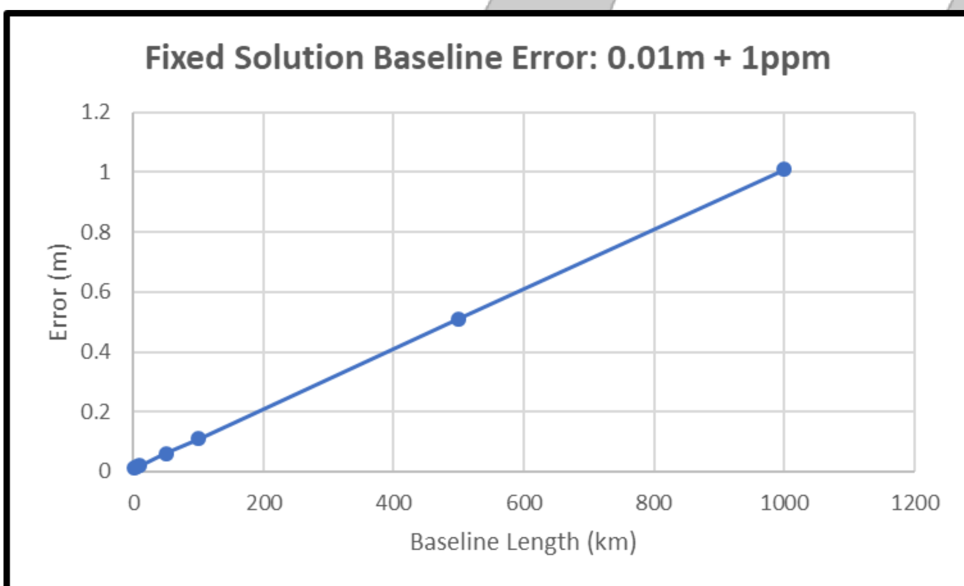


*Figure 11: The error of a fixed solution baseline depends mostly on the length of the baseline.*

It should be noted that the errors described above refer to the vector between the ***antenna phase centers (APC)*** of the reference receiver and the rover. The antenna phase center is the position in the antenna housing ***at which carrier phases are measured***. It hardly ever falls on the geometric center of an antenna housing. For this reason the concept of an ***antenna reference point (ARP)*** was introduced. The ARP is normally located at the center of the bottom surface of the antenna housing. To specify the location of the antenna phase center of a particular antenna, the manufacturer of the antenna provides the distance between ARP and APC.

In practice the reference station and rover receiver antennae are mounted on a survey rod so that it can be centered above a physical marker or feature to be surveyed or on a drone above the camera. To reduce the phase center to phase center vector to their corresponding physical features (peg at ground level or optical center of camera), it is necessary to compensate for the offset between APC and marker, hence it is necessary to measure the ***antenna height***. It is the ***vertical distance between the physical***

***marker or feature (such as, for example, an iron peg) and the antenna reference point***. Figure 12 below illustrates the vertical offsets to be considered in carrier phase differential GNSS surveying.

In addition to the vertical offset one may in certain instances also have to consider horizontal offsets. For example, if the antenna of an airborne GNSS receiver is used to determine the camera exposure positions one would have to specify the offsets in the horizontal plane and use the platform orientation parameters (yaw, roll and pitch) at the moment of the exposure to orient the offset vector correctly.

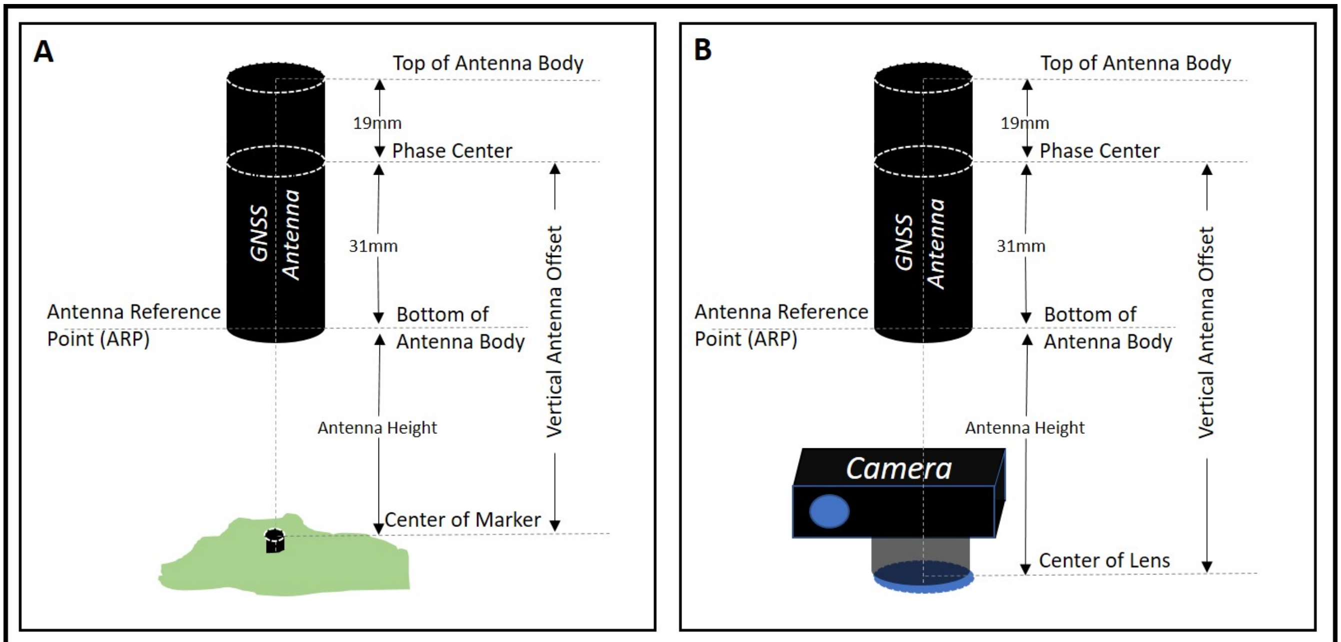


*Figure 12: Illustration of Antenna Reference Point (ARP), Phase Center and Antenna Height for occupation of physical marker (A) or when used to survey camera exposure positions (B)*

Note that the Antenna Phase Offset may be ignored if identical antennas are used at reference station and rover. When different antennas are used the corresponding antenna phase centers must be applied. Offsets for most antennas on the market can be found here: https://www.ngs.noaa.gov/ANTCAL/

Perhaps the most often ignored source of error in differential carrier phase GNSS surveying is the effect that a mal-adjusted rod or tribrach bubble has on the overall error of a reduced GNSS vector. It is critically important to make sure that all bubbles used for the proper centering of GNSS antennas are in proper adjustment.

When doing a kinematic survey with the use of a rod, bubble errors can be minimized by observing every point twice and making sure that for the second occupation the rod is turned by 180 degrees. In other words, if the bubble was on the northern side of the rod for the first occupation the rod should be turned such that the bubble is located on the southern side of the rod for the second occupation. As illustrated in Figure 13 below the mean of the two corresponding positions is free of the bubble error effects. A short video clip of the field procedure is located here: https://www.youtube.com/watch?v=K2az1K8jxRs

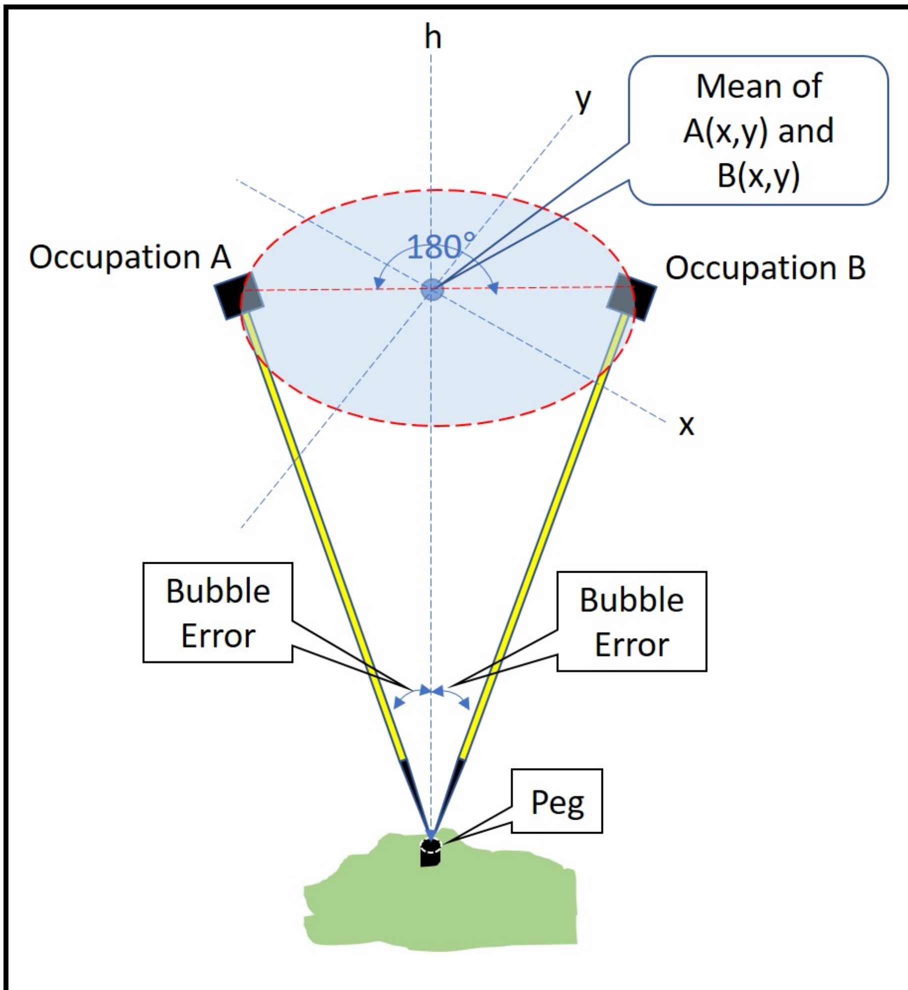


*Figure 13: The 180 ° double occupation to eliminate rod bubble error.*

The resolution of the integer ambiguity requires a certain number of observations which, depending on the observation epoch will require a certain time, called the ***initialization period***. This is the ***time it takes the algorithm to converge from a float solution to a fixed solution***. The minimum requirement for initialization to occur is that carrier phases of the same four satellites are simultaneously and continuously being observed by both reference station and rover. Anytime this condition is disrupted the initialization period re-commences. The length of the initialization period depends on the following factors:

- The length of the GNSS vector
- The number of carrier phase frequencies observed
- The number of common satellites being observed by both reference station and rover
- The quality of the GNSS phase observations

## 4. Operational aspects of carrier phase differential GNSS in drone/SfM mapping.

The most important decisions a prospective user of carrier phase differential GNSS in the SfM mapping business can make are:

**Whether accurate camera exposure positions (CEPs) are needed;**

**Whether to acquire dual frequency or single frequency GNSS receivers;**

**Whether RTK is necessary.**

### a. Geo-referencing by means of accurate camera exposure positions

The practice of accurately surveying CEPs has established itself firmly in GNSS-supported classical photogrammetry as a major cost saving approach. It reduces the number of necessary ***Ground Control Points*** from hundreds to as few as three or four, thereby significantly reducing the time and cost to produce a map from aerial imagery. Can camera exposure positions in SfM mapping similarly reduce the number of GCPs or replace them altogether? Although this question is still under debate, the popularity of accurate CEPs is steadily increasing, not so much as a means of improving accuracy but rather to reduce costs and time taken to make a high- resolution, high-accuracy map. There are several white papers on this topic. In most of them it is recommended to provide independent validation using a few validation points. An interesting point to consider when analyzing validation points is the coincidental fact that kinematic GNSS yields accuracy of the same order as high resolution SfM products. And since the overwhelming majority of conventionally produced high accuracy geo-spatial products are derived from kinematic GNSS, the use of SfM as an additional survey tool is very plausible. In fact, high confidence level validation of SfM products should preferably be conducted with more accurate techniques than kinematic GNSS.

The hardware requirements for accurate camera exposure positioning are:

i. A **carrier phase GNSS receiver** that is
   - Small and light enough to be added to the sensor payload of the drone to be used
   - Capable of observing and recording rates of at least 5Hz but preferably 20Hz
   - Capable of recording events to an accuracy of 30 ns (nano seconds – 1s = 1 000 000 000 ns)
   - Capable of using power from the drone power system
   - Optionally, if on board RTK is required, capable of receiving differential corrections and streaming results to an on-board transmitter
   - Optionally, is removable so that it can be installed on other drones.

ii. A **camera** that issues a well-defined analogue pulse during the exposure period (with no or constant latency)

iii. A **drone** that can
   - Supply power to the GNSS receiver
   - Can accommodate the carrier phase GNSS antenna in an unobstructed position
   - Does not emit electromagnetic noise at levels which spoof the GNSS satellite signals.

- Has sufficient payload capacity to carry the additional weight of GNSS receiver and antenna and related cables.

Refer to Figure 8 above for a PPK GNSS event marking capable payload. Figures 14 and 15 below show examples of PPK GNSS event marking enabled drones that are equipped for PPK GNSS exposure event marking.

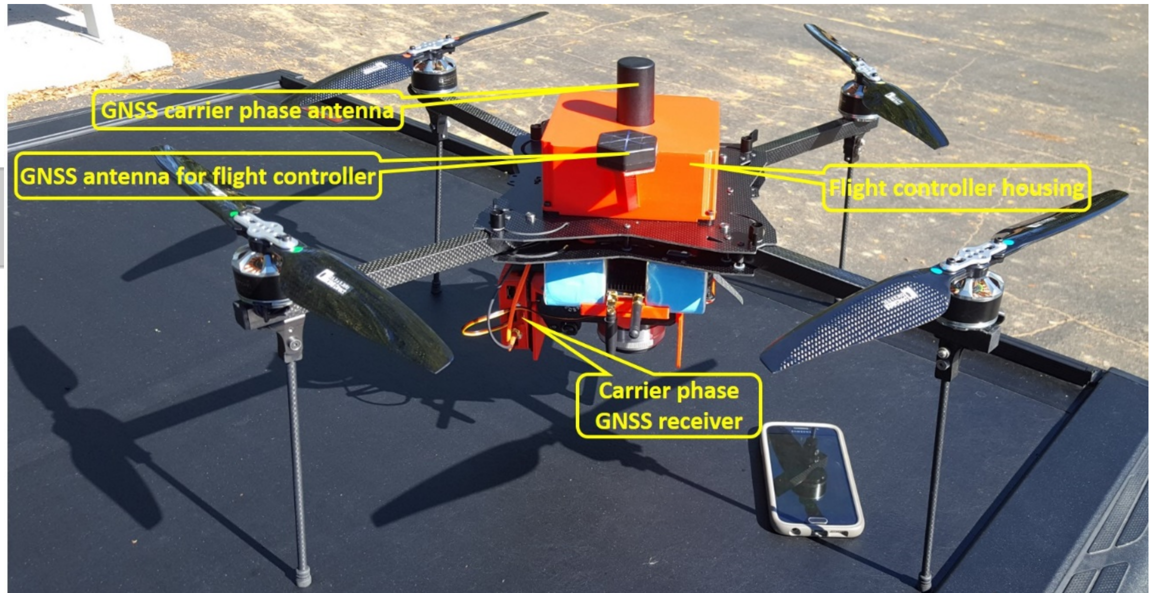


*Figure 14: Quad Copter equipped with PPK GNSS for camera exposure event marking.*

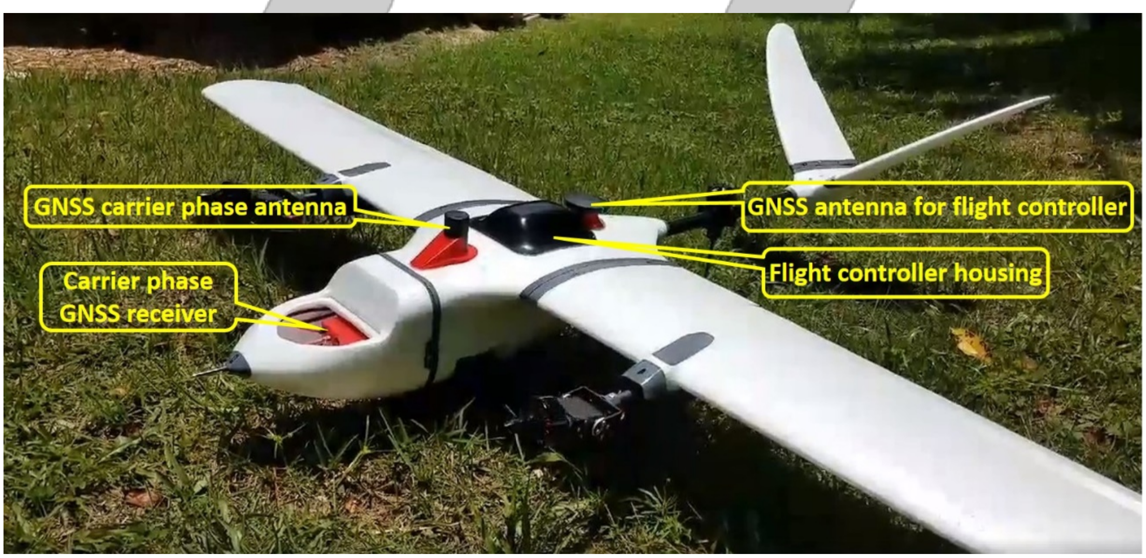


*Figure 15: Hybrid VTOL/Fixed Wing platform equipped with PPK GNSS for camera exposure event marking.*

iv. The typical workflow in camera exposure positioning with PPK GNSS event marking requires the following software elements:
  - Downloading of raw observations in compressed proprietary format
  - Conversion of proprietary formatted raw observations to RINEX
  - Carrier phase differential PPK GNSS computation of trajectory
  - Extraction of event times from rover RINEX file
  - Linear interpolation of exposure event positions

- Quality control – filtering of float and uncorrected from fixed solutions
- GIS or Google Earth for 3D-visualization to assist in allocation of image files to exposure positions
- Optionally: Writing exposure positions to EXIF headers of aerial images

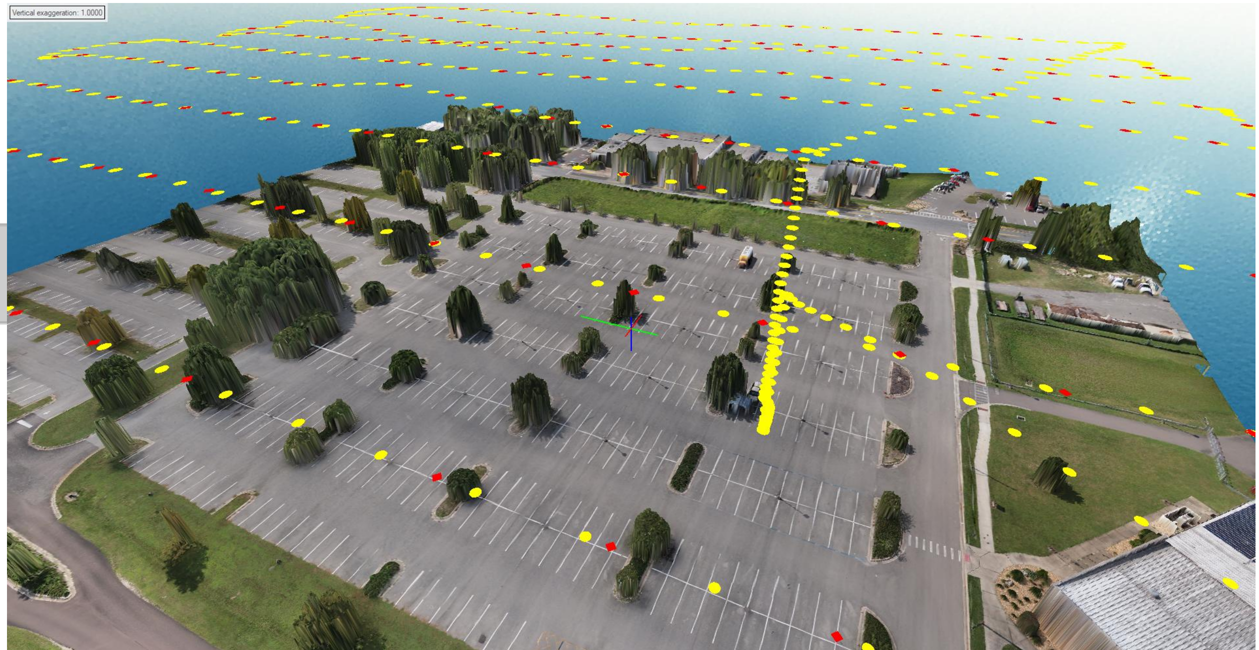

*Figure 16: 3D visualization of trajectory points (yellow and interpolated camera exposure positions (red).*

**b. Single or Dual Frequency?**

This is probably the most critical choice you can make in setting up differential carrier phase GNSS capacities in your operation. The second frequency can be utilized to perform at any one time **ONLY ONE** of the following two functions:

Elimination of meteorological effects over long baselines

**OR**

Acceleration of the carrier phase ambiguity resolution (i.e. shortening of initialization period).

Note that the second frequency cannot be used for both functions at the same time. In other words, if it is used in the processing of static long baseline observations (to eliminate metereological effects) it cannot be used at the same time to speed up the resolution of the carrier phase integer ambiguity.

**i. Dual frequency advantages in static surveying of long baselines.**

As described in 1.1 above, and depending on the density of available geodetic control points or CORS, it may be necessary to survey long baselines to reference your map to a specified spatial reference frame. These long baselines can only be surveyed reliably accurately with the use of dual frequency static carrier phase differential GNSS. In the static GNSS approach the second frequency is used to mitigate meteorological effects. Whether the gains in accuracy are significant or not depends on the meteorological conditions during which the GNSS observations were taken. When volatile, the ionosphere alone can cause changes in the satellite range at a rate of more than 19cm per second! Figure 17 below is a plot showing an example of the distribution of single frequency and dual frequency baseline results. Note that the shorter the baseline, the smaller the differences between single and dual frequency results.

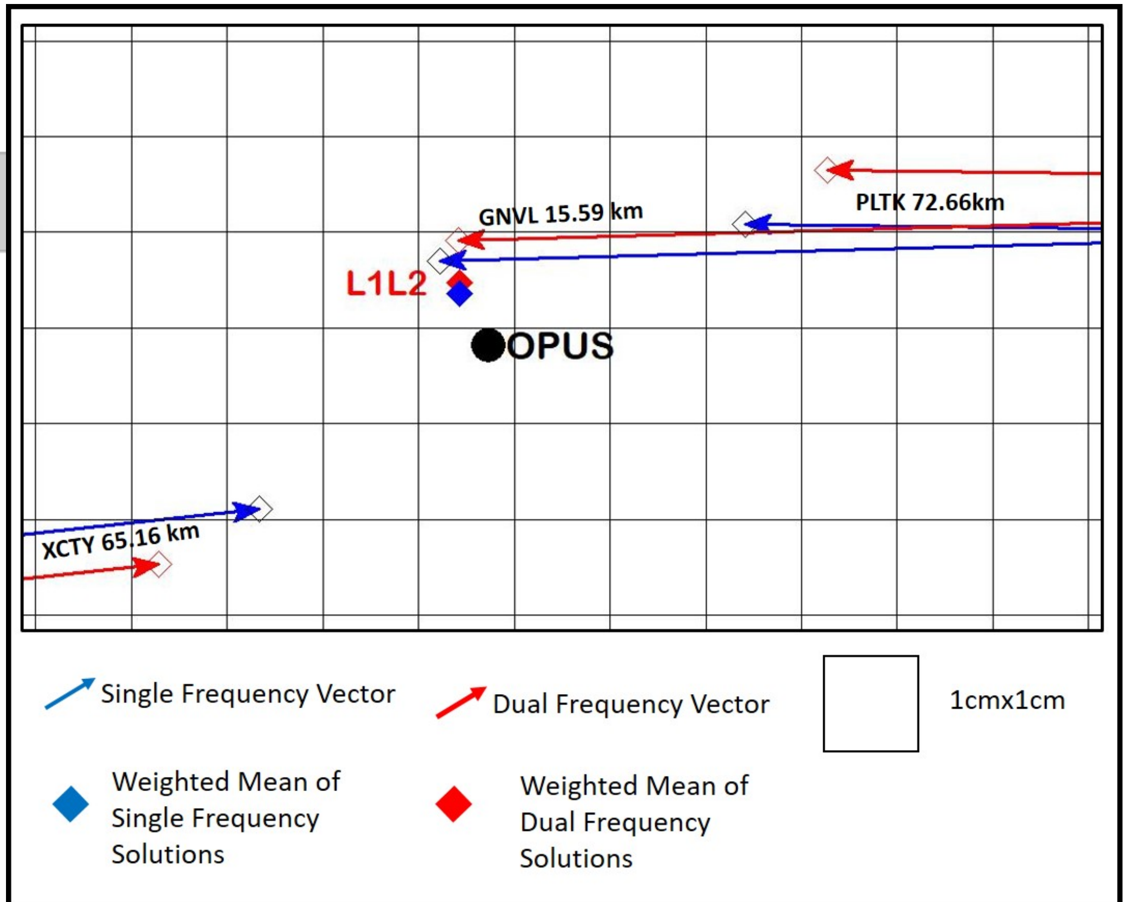


*Figure 17: Example of the distribution of single frequency and dual frequency baseline solutions.*

There are several on-line services which will accept static raw observations and return an absolute set of coordinates of the location at which the observations were made. One such example is NOAA's On-Line Position User Service, (OPUS) (https://www.ngs.noaa.gov/OPUS/) which has a rapid version accepting a minimum of 15 minutes of raw dual frequency observations and a regular version which will accept a minimum of 2 hrs of raw dual frequency observations. The OPUS position plotted in Figure 14 above was obtained from 72 minutes of continuous dual frequency raw observations. An extract of the OPUS service return is shown in Figure 15 below. Note that baselines of longer than 200km were used to produce the result.

Note that instead of connecting a local control point to a geodetic network with long baselines, use can be made of so-called positioning services which can deliver differential corrections from a virtual reference station placed in close proximity to the rover. Most of these services are delivered commercially, requiring monthly or annual subscription fees. Although some of them may accept single frequency raw observations, the initialization period is not predictable. Unless one uses these services in RTK mode there is never a foolproof guess as to how long a point should be occupied to resolve the integer ambiguity.

```
REF FRAME: NAD_83(2011)(EPOCH:2010.0000)          IGS08 (EPOCH:2018.27894)

       X:     729806.705(m)   0.010(m)          729805.887(m)   0.010(m)
       Y:   -5497408.757(m)   0.020(m)        -5497407.218(m)   0.020(m)
       Z:    3140132.739(m)   0.010(m)         3140132.584(m)   0.010(m)

     LAT:   29 41  7.18922      0.009(m)       29 41  7.21111      0.009(m)
   E LON:  277 33 43.43494      0.009(m)      277 33 43.41233      0.009(m)
   W LON:   82 26 16.56506      0.009(m)       82 26 16.58767      0.009(m)
  EL HGT:          29.550(m)   0.021(m)              28.054(m)   0.021(m)
 ORTHO HGT:         57.434(m)   0.025(m) [NAVD88 (Computed using GEOID12B)]

                                BASE STATIONS USED
PID       DESIGNATION                     LATITUDE    LONGITUDE DISTANCE(m)
DQ0907 FLCB CARABELLE CORS ARP           N295033.361 W0844142.532  218984.5
DF5773 ORMD ORMOND BEACH CORS ARP        N291753.469 W0810632.013  135835.5
DE9140 PRRY PERRY CORS ARP               N300440.119 W0833428.609  118106.6
DE6012 PLTK PALATKA CORS ARP             N293948.148 W0814115.861   72659.1
DF7990 ZEFR ZEPHYRHILLS CORS ARP         N281339.322 W0820952.671  163746.2
DE6016 TALH TALLAHASSEE CORS ARP         N302347.483 W0842121.035  201063.7
DG9757 DLND DELAND CORS ARP              N290322.897 W0811547.480  133671.1
DI4159 MCD5 MAC DILL AFB 5 CORS ARP      N275059.338 W0823156.335  203633.9
```

*Figure 18: Extract of an OPUS solution.*

### ii. Dual frequency advantages in kinematic surveying of short baselines.

Short baselines are most efficiently surveyed with kinematic carrier phase differential GNSS. The addition of a second carrier frequency drastically reduces the initialization period. This means that not only can a survey proceed much sooner after reference station and rover are set up, but also not much time is needed to recover from an interruption in the observations to regain initialization. Using only single frequency observations requires an unpredictably long re-initialization period whenever interruptions have been caused by, for example, insufficient GNSS satellite reception under trees or bridges. Given a sufficient number of satellites, the second frequency can reduce initialization or re-initialization periods to as short as a second of time.

When using GNSS for the survey of Ground Control Points, single frequency GNSS will work efficiently only in environments where no obstructions to the GNSS satellites occur. Adding a second frequency allows for efficiency in a much larger variety of terrain scenarios because crews do not have to constantly be mindful of loss of initialization.

Figures 19 and 20 illustrate the relative efficiencies between single and dual frequency kinematic GPS surveying. The trajectory shown in Figure 19 was produced with L1 GPS raw observations only. The trajectory in Figure 20 was produced from dual frequency data. Note that for both trajectories the same L1 observations were used. The trajectories were produced by mounting a dual frequency receiver on a vehicle and driving it across the terrain at speeds in the region of 15km/hr.

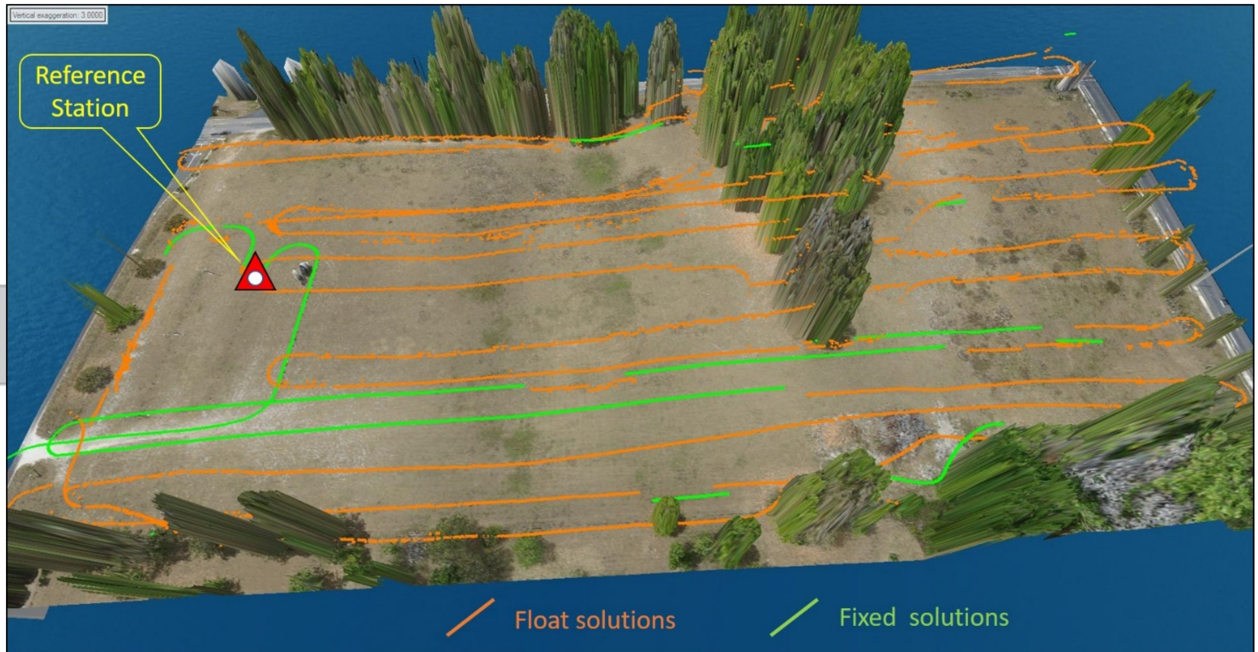


*Figure 19: Single frequency PPK GPS results at rover speed of approximately 4m/s. (Approximate field dimensions are 200m x 400 m)*

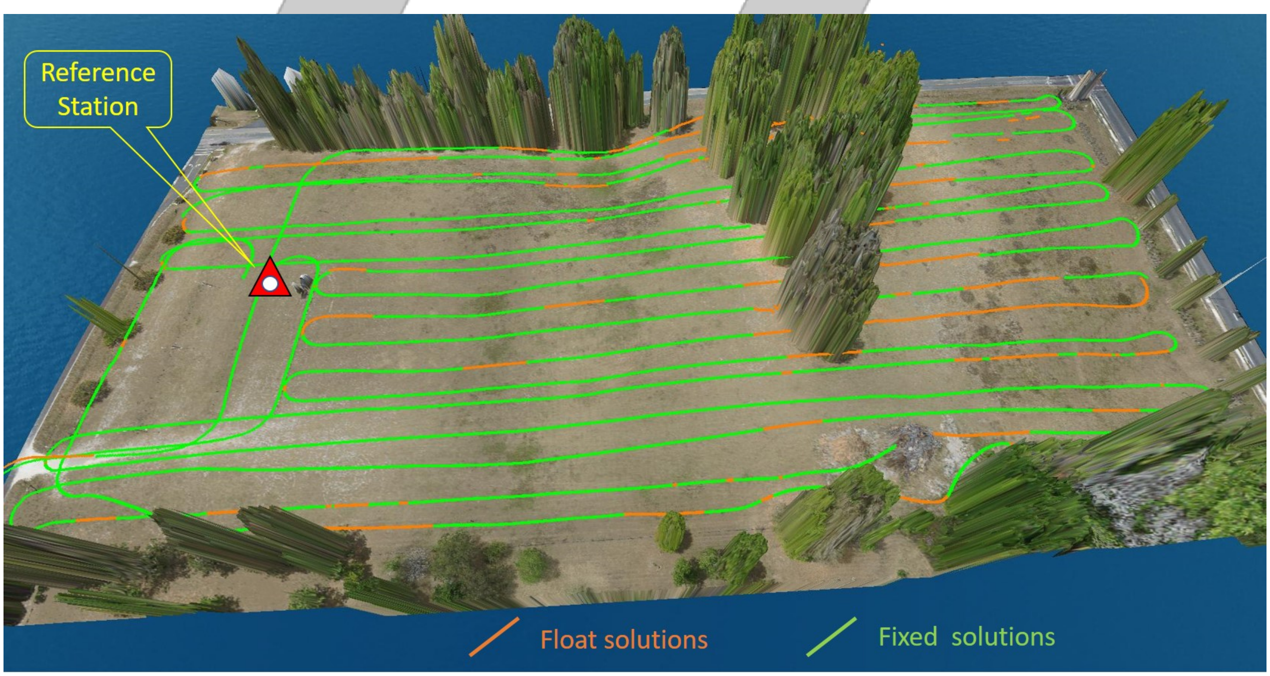


*Figure 20: Dual frequency PPK GPS results at rover speed of approximately 4m/s. (Approximate field dimensions are 200m x 400 m)*

Note that in Figure 19 large sections of the trajectory appear to be missing altogether. Those sections are comprised of single frequency float solutions that are so bad?another word that they fall below the terrain surface and are thus obscured. (The antenna was mounted about

1.5m above ground level.) Note also that the float solutions in the L1 trajectory are much worse than the float solutions in the dual frequency trajectory.

The above example shows how critical the initialization recovery period may be in kinematic surveying. In aerial applications the most likely occurrence of a loss of initialization is expected when the drone banks at the end of a flight line. Typical multi rotor flights last for about 30 minutes at 5 to 10m/s, thus for every minute of lost initialization there will be a 300 to 600 m section of float solutions in the trajectory. In fixed wing applications the ground speeds typically vary from 15m/s to 25m/s. Losing initialization at these speeds results in float solutions over distances of 900 to 1500 m per minute.

In terrestrial applications initialization will be lost every time the rover is moved under or near a tree or other tall object, forcing the crew to provide for a sufficient recovery period before work can proceed.

The initialization period for single frequency carrier phase differential GNSS is highly unpredictable and may take up to 15 minutes over short baselines. Production outages of such duration completely diminish the efficiency of kinematic surveying and may in most terrestrial applications indeed render kinematic GNSS completely unfeasible. The initialization period in short baseline dual frequency kinematic GNSS on the other hand is almost instantaneous and seldom lasts longer than a few seconds, hence the major cost factor in kinematic GNSS surveying is a matter of whether single or dual frequency equipment is being used. When analyzing overall operational costs the higher acquisition costs of dual frequency equipment are by far outweighed by the relative gains in dual frequency kinematic GNSS efficiencies.

### c. RTK or PPK?

The primary advantage of RTK GNSS is the instantaneous availability of not only the current rover position but also the information about the quality of the current solution. Knowing in real time whether you are in fixed or float mode means that you make fully informed decisions during the field operation. Not knowing the quality status whilst performing field work means you must make intelligent guesses and thus risk either too much time spent on estimated initialization periods or discovering too late that only float solutions were gained. Since initialization periods are particularly unpredictable in single frequency operations, real time knowledge about the ambiguity status is especially helpful in single frequency operations. This is of relevance especially in terrestrial applications where GNSS signal obstructions are much more prevalent than on top of an airborne platform.

Note also that unless you are using RTK for precise navigation control of the platform the real time availability of the CEP coordinates does not really save any time since the aerial imagery has to be downloaded before they can be meaningfully applied in the SfM workflow.

The other advantage of RTK is that no time needs to be spent on performing calculations after the field work. Depending on the recording frequency and duration of the session the time saved as a result of using RTK for GCPs as well as CEPs may range from 30 minutes to an hour for typical multirotor operations and not more than an hour for longer fixed wing flights.

RTK requires the setting up of a live radio link between reference station and rover. The extra equipment and time to set up **and maintain** the link are cost factors that do not apply to PPK operations. Furthermore, the extra radio equipment that must be added to the payload of the drone adds to the complexity of the equipment and related logistics, and unless reference station and rover are recording raw observations, any loss of radio link between reference station and rover will result in total loss of differentially corrected rover positions.

Apart from operational simplicity, PPK has the advantage that the raw observations can be processed "forward" and "backward". This means that in PPK any loss of initialization can theoretically be reduced to durations of a very few epochs. Figures 21 and 22 illustrate the difference in fixed solution yields.


*Figure 21: Dual frequency PPK forward GPS results (as in RTK) at rover speed of approximately 4m/s. (Approximate field dimensions are 200m x 400 m)*


*Figure 22: Dual frequency PPK forward **and** backward GPS results (as in RTK) at rover speed of approximately 4m/s. (Approximate field dimensions are 200m x 400 m)*

Note how much longer the float solution sections are in the forward (RTK simulated) PPK solutions. By comparison, the forward and backward combined solution set yields significantly more fixed solutions.