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Using High-Performance Global Navigation Satellite System Technology to Improve Forest Inventory and Analysis Plot Coordinates in the Pacific Region

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Abstract

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There is growing recognition that more accurate Forest Inventory and Analysis (FIA) field plot coordinates are required to enable direct comparison of field-measured inventory attributes and high-resolution remotely sensed measurements. After extensive testing and a successful pilot project, in 2014 the U.S. Department of Agriculture Forest Service Pacific Northwest Forest Inventory and Analysis Program (PNW-FIA) implemented a high-performance global navigation satellite system (HPGNSS) initiative to provide high-quality coordinates at the subplot level for all FIA plots in the inventory domain (Alaska, Washington, Oregon, California, Hawai'i, and the U.S.-Affiliated Pacific Islands). In this report, we describe the main components of the HPGNSS initiative as currently implemented by PNW-FIA in the inventory domain, including a brief history of the initiative's use of global navigation satellite system (GNSS) technology, background on GNSS, data collection procedures in the field, postprocessing, accuracy assessment, and database considerations.

Keywords: GPS, GNSS, FIA, forest, inventory, remote sensing, coordinates.

Contents

Introduction

Plot Positioning in the U.S. Forest Inventory and Analysis Program

The Forest Inventory and Analysis program (FIA) of the U.S. Department of Agriculture Forest Service is congressionally mandated to establish and remeasure an immense network of field plots (approximately 116,000 forested plots with about 20,000 measured each year) distributed across all forested lands of the United States (Vogt and Smith 2016). The result of this effort is a massive database representing a spatially balanced sample of field measurements that collectively provide a comprehensive picture of the status and trends for the forest resources of the entire country.

Given that the FIA plot sample is an inherently spatially explicit dataset, maintaining a reliable record for the location of FIA plots has been an important component of the FIA inventory since its inception. Prior to the availability of satellite-based geopositioning technologies (emerging in the 1980s), plot locations were recorded as pin-pricks on aerial photos, then manually transferred to maps to obtain location coordinates that allowed FIA field crews to navigate to and relocate (and remeasure) each plot. Robust protocols were developed to use imagery and reference points to reestablish the location of the plot center in the field, with less emphasis on recording precise coordinates for the plot.

Satellite-based geopositioning technology, global navigation satellite systems (GNSS), emerged in the 1990s with the development of the global positioning system (GPS) within the U.S. Department of Defense. Once GPS technology was made available for civilian use, FIA crews began using the technology to aid navigation and, for the first time, to directly record spatial coordinates for plots in the field. However, initial GPS positions were not averaged or differentially corrected (adjusted for atmospheric bias) and could be off by several tens or even hundreds of meters in a forested environment. Initially, many FIA crews used the Rockwell Precision Lightweight GPS Receiver[1] that, given its military design, used a GPS signal that provided a more accurate[2] autonomous position than would be

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[1] The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

[2] In this document, we use the terms accurate and accuracy as typically used in the field of surveying, where accuracy is defined relative to known positions and represents a combination of both systematic error (bias) and spread (variance), and is typically quantified via the horizontal root-mean-squared-error metric. Furthermore, we use the label “high-performance global navigation satellite system” (HPGNSS) to capture the PNW-FIA enhanced technical specifications (differential postprocessing, dual-frequency GNSS signal reception, higher quality receiver characteristics, >15-minute occupations, etc.) required to consistently provide accurate FIA plot coordinates across highly variable forest conditions. HPGNSS quality assessment methods are provided in later sections of this report.

USDA Forest Service

Figure 1—Use of recreational-grade global navigation satellite system receiver for plot navigation in the Pacific Islands.

possible with consumer-grade products (although still not as accurate as differentially corrected positions). FIA replaced GPS-only receivers with recreational-grade GNSS receivers in the early 2000s when field crews primarily used the GNSS receivers to aid in navigation and plot relocation (fig. 1), not for precise alignment of plots with auxiliary information such as high-resolution remote sensing.

Improved Plot Positioning to Support Forest Inventory and Analysis

By the early 2000s, there was interest in leveraging high-performance geopositioning capabilities provided by (1) differential correction, (2) additional satellite constellations, and (3) more sophisticated GNSS receivers to support the FIA inventory. Forested environments present a notoriously challenging engineering problem for GNSS positioning; GNSS signals travelling through dense forest canopy are subject to blockage and attenuation (reducing the number or quality of signals available) and reflection off woody tree boles and large branches (leading to multipath and non-line-of-sight signals). Rugged terrain poses additional problems related to the number of satellites visible from some locations. While not a problem specific to forested environments, atmospheric conditions affect the propagation of GNSS signals from satellites and the accuracy of calculated positions. Differential correction—a process where GNSS observations collected on a base station GNSS receiver (survey monument with known coordinates) are used to correct rover GNSS receiver positions—can significantly reduce geopositioning errors owing to atmospheric conditions. Mapping- and survey-grade receivers collect information needed to correct for atmospheric conditions, provide more robust GNSS signal filtering, and track more satellites to improve the measurement geometry and reliability of the solution.

Beyond its practical utility to facilitate navigation to FIA plots, more accurate GNSS plot coordinates also enable the direct comparison of conditions observed in the field with auxiliary information such as remotely sensed imagery. The FIA program historically relied on remote sensing data collected from satellites and aircraft to supplement field plot samples and provide additional information describing forest conditions across a broader swath of the landscape, supporting the development of maps as well as more efficient inventory estimates (Lister et al. 2020). The efficiency of standard two-phase, post-stratified estimation procedures used in the annual FIA inventory (Bechtold and Patterson 2005) is dependent upon grouping field plots into homogeneous strata based on physiographic, structural, and spectral characteristics. Plot geopositioning errors in the range of tens of meters can significantly affect the precision of inventory estimates (Strunk et al. 2019) especially in highly fragmented forests, and affect the quality of maps based on models that use FIA plot data. Given the increased availability of high-resolution remote sensing data—including National Agriculture Imagery Program digital orthophotos and photogrammetrically derived 3D surface models (USDA 2017), hyperspectral imaging (Pattison et al. 2018), radar imagery (Alaska Satellite Facility 2019), and airborne light detection and ranging (LiDAR) 3D point clouds (USDI GS 2017 Geological Survey 2017)—there is ever-increasing interest in the development of multilevel inventory techniques that can leverage this information. The national FIA is particularly focused on utilizing remote sensing to improve the quality and timeliness of FIA estimates for carbon monitoring (Woodall et al. 2015), small areas (e.g. counties), and remote regions such as interior Alaska (Vogt and Smith 2016). Plot location errors can have deleterious effects on the strength of (regression) correlations between inventory attributes and remote sensing measurements, which directly affect the statistical efficiency of these multilevel sampling designs (Andersen et al. 2009a, 2011a). As these remote sensing measurements approach decimetric-level resolutions on a consistent basis, the potential for remote monitoring and measurement at the scale of individual (overstory) tree crowns is increasingly feasible (fig. 2). Given the desire to conduct more detailed analyses at higher spatial resolutions, the ability to accurately match remote sensing measurements to forest conditions at specific plot locations has become an important requirement of the FIA inventory.

Researchers at the USDA Forest Service Pacific Northwest Research Station and the University of Washington began testing survey-grade GNSS receivers (dual frequency, multiple constellation) in conifer forests of western Washington state in the mid-2000s (Clarkin 2007) to support analyses of LiDAR data. Additional testing across a range of operational settings and conditions was carried out in 2007 near Fairbanks and Delta Junction, Alaska (Andersen et al. 2009b), and from 2013 to 2015 at the Capitol State Forest in Washington state (McGaughey et al. 2017).

Figure 2—Example of LiDAR-based individual tree detection and measurement and high-resolution airborne orthoimagery on a plot in interior Alaska. Red circles indicate subplots, green polygons represent tree crown segments, and blue dots are predicted stem locations (lighter blue represents higher crown heights).

The results from these tests indicated that precise positions could be obtained for FIA plots in forested settings using survey-grade receivers, postprocessing, and standardized protocols. Based on the results of this early testing, PNW-FIA began using survey-grade GNSS receivers for FIA plots on the western Kenai Peninsula of Alaska, upper Tanana Valley of interior Alaska, and experimental forests in Alaska and Hawai'i to support analysis of high-resolution airborne LiDAR collected over these plots (Andersen et al. 2009a, 2011b; Strunk et al. 2014). Results from these LiDAR studies indicated that the more precise positions obtained using survey-grade GNSS receivers can significantly improve the precision of LiDAR-based biomass estimation. In 2014, PNW-FIA began the high-performance GNSS (hereafter HPGNSS) initiative in response to increasing demand for precise FIA plot positions to support integration of FIA plot measurements with high-resolution auxiliary data sources (especially remote sensing) in the Pacific Northwest region. The HPGNSS protocols are based on results from pilot studies carried out across a wide range of conditions in Alaska, Washington, Oregon, and California.

The purpose of this publication is to provide an overview of GNSS technology and to document each component of the HPGNSS initiative as currently implemented by PNW-FIA.

GNSS Technology

The first operational GNSS technology was the global positioning system (GPS) developed by the U.S. Department of Defense, with the first satellites placed in orbit in 1978. Initially available only for military applications, GPS satellites provided rapid, autonomous, and relatively accurate determination of geographic position anywhere on the globe. The technology was subsequently made available to the civilian sector (although the accuracy of GPS signals received by civilians was intentionally degraded through selective availability until 2000). Following the deployment of GPS by the United States, other nations deployed GNSS constellations and use of GNSS technology is ubiquitous throughout the world (as a majority of mobile phones are equipped with a built-in GPS receiver).

Basic Principles of GNSS

The original GPS constellation consisted of 24 satellites (plus several spares), each orbiting at an elevation of 20 000 km and placed in orbits such that at least five satellites would always be visible from any point on Earth. Each GPS satellite was equipped with four atomic clocks, and continuously transmitted signals at two carrier frequencies, L1 (1.5754 GHz) and L2 (1.2276 GHz), including a precise timestamp indicating when the signal was emitted from the satellite and the position of the satellite. More recently an additional signal was added, L5 (broadcast at 1.176 GHz), which provides higher resolution and stronger signal power (Van Sickle 2015).

The timestamp is used by a GNSS receiver to estimate how long it takes for a signal emitted by the satellite to reach the GNSS receiver. The time difference, multiplied by the speed of light, is used to approximate the distance between the receiver and the satellite (termed "pseudorange").

Global navigation satellite system positioning uses the distances between multiple satellites (with known positions) and a receiver to solve for the XYZ coordinates of the receiver using a process called trilateration (fig. 3). The concept of trilateration is demonstrated in figure 3 where the distances between the satellites and receiver are represented as circles. The position of the receiver then is the single point at which the circles intersect. The concept of trilateration is readily extended

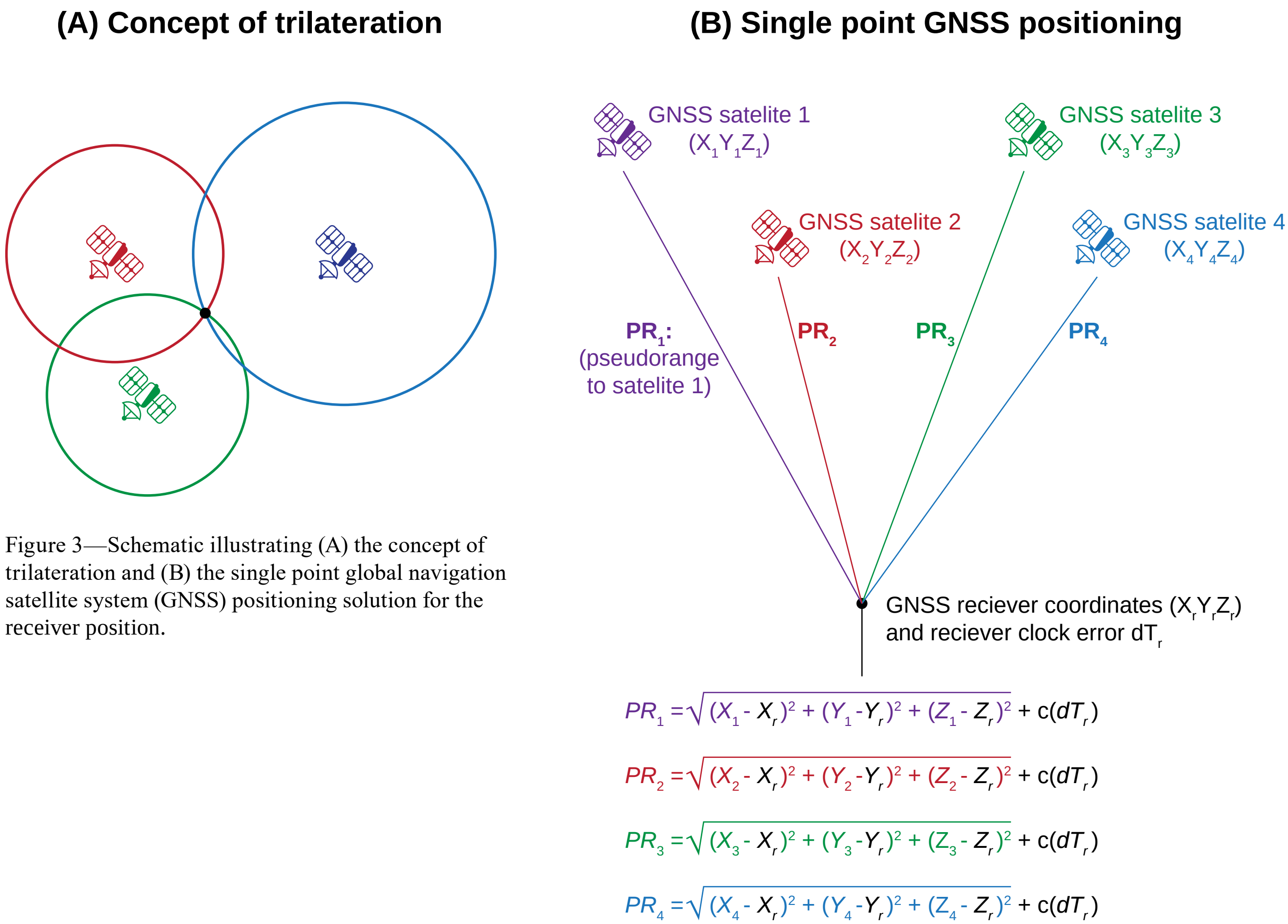

Figure 3—Schematic illustrating (A) the concept of trilateration and (B) the single point global navigation satellite system (GNSS) positioning solution for the receiver position.

to a three-dimensional context where the two-dimensional circles become three-dimensional spheres. While the intersection of three spheres appears sufficient to calculate an XYZ coordinate for the receiver position, a fourth satellite is needed to estimate the time differences between satellite signals needed to obtain an accurate solution for the receiver position. Because it is impossible to precisely synchronize the (highly precise) satellite clock and the (less precise) receiver clock, there is an unknown receiver clock error that must be solved along with the receiver XYZ coordinates. Even a time offset of one millionth of a second can lead to several hundred meters of error in ranging (Bidikar 2014). Therefore, the time offset (dT) along with the XYZ coordinates of the unknown position creates a system of four equations (or more, if more satellites are available) with four unknowns that are used to solve for receiver position (fig. 3). Signals received from additional satellites provide redundancy to the solution and further decrease the error in the position obtained via trilateration.

Depending on the type of receiver used and the quality of the observed GNSS signals, there are two types of solutions in GNSS positioning—code-phase and carrier-phase. A solution that uses pseudoranges based on the timestamps transmitted with GNSS signals is termed a "code-phase" solution, whereas a solution based on the precise measurement of the number of wavelengths in the satellite signal carrier frequency between receiver and satellite is termed a "carrier-phase" solution. While carrier-phase solutions can be much more precise than code-phase solutions, estimating the "cycle ambiguity" (unobserved number of whole cycles or wavelengths between satellite and receiver) typically requires longer occupations than code-phase solutions and can be infeasible in scenarios with a low signal-to-noise ratio (e.g., beneath the forest canopy). There are several approaches to estimate the cycle ambiguity, depending on the quality of the observed carrier-phase data. When possible, it is preferred to constrain the solution of cycle ambiguity to integer values (plus the observed fractional wavelength, or phase), termed a "fixed" solution. With lower quality observations, the cycle ambiguity cannot be constrained to fixed integer values and a "float" solution is used. When using differentially corrected survey-grade receivers with an open view of the sky, code-phase solutions are typically of metric accuracy (0 to 10 m), carrier-phase float solutions are of centimetric accuracy (0 to 10 cm), and carrier-phase fixed solutions can approach millimetric accuracy (0 to 10 mm). In practice, the GNSS postprocessing solution type can either be manually specified or the software can automatically select the appropriate type of differential processing based on the quality of the observed signals.

Sources of Error in GNSS Positioning

Several sources of error contribute to overall error in positions. The speed of radio signals through the ionosphere is a function of wavelength and the number of free electrons in the path of the signal. Significant delays can occur in the time it takes for the signal to travel from the satellite to the receiver because levels of free electrons in the ionosphere can vary significantly over time, depending on ionization of gases, levels of solar activity and geomagnetic disturbances. Because the ionospheric delay is wavelength dependent, a receiver that receives both L1 and L2 signals can use the differential delay between these wavelengths to directly estimate the ionospheric delay and remove a significant portion of the error in the GNSS position (see "Differential Processing" below). In addition, water vapor in the troposphere also causes a delay in the GNSS signal and is not wavelength dependent. This delay has less temporal variation than ionospheric delay so the associated error is typically estimated through modeling.

Another significant source of error, especially in urban and forested environments, is related to interaction of the GNSS signal with reflective structures, such as buildings, cliffs, and trees. These reflected signals can produce either a multipath or a non-line-of-sight (NLOS) error (Petovello and Groves 2013) (fig. 4).

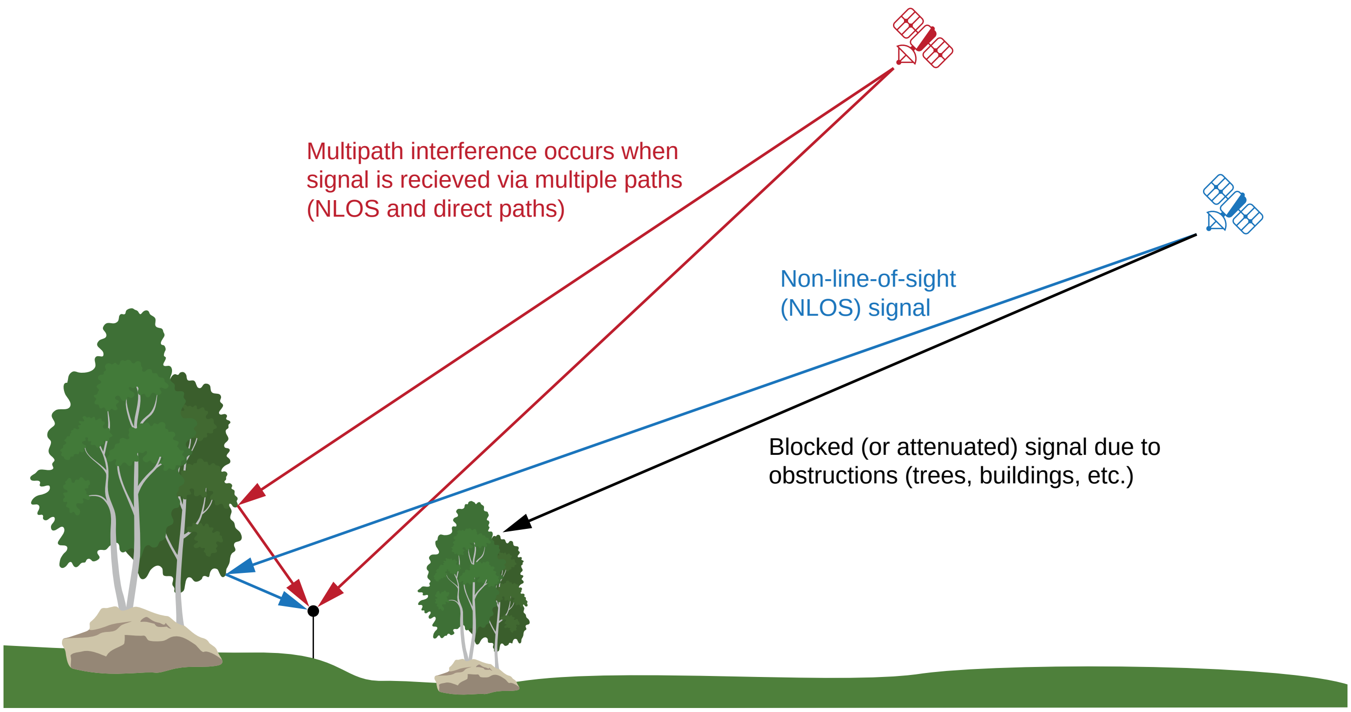

Figure 4—Sources of error in global navigation satellite system receiver positioning include signal blockage or attenuation, multipath interference, and non-line-of-sight effects (adapted from Petovello and Groves 2013).

Quick Look: Primary Sources of Error in Global Navigation Satellite System Positioning

- Ionospheric delay
- Tropospheric delay
- Interaction with reflectors (signal blockage or attenuation, multipath interference, and non-line-of-sight effects)
- Satellite geometry (positional dilution of precision)
- Receiver noise

Multipath error occurs when the receiver records a direct-line-of-sight signal and one or more NLOS signals from a given satellite, resulting in one or more versions of the same signal. A NLOS error occurs when the line-of-sight signal from a given satellite is completely blocked by a structure and one or more reflected satellite signals are received. Both situations can produce errors in GNSS positioning, especially in forested or urban settings. In many cases, the effects of multipath interference can be mitigated through antenna design (polarization-sensitive, choke ring antennas, etc.) and sophisticated filtering algorithms, but NLOS signals are much more difficult to filter (Breßler and Obst 2017). Note that in areas with rugged terrain (steep slopes, deep valleys, or canyons), terrain surfaces can act as reflectors in the same way that buildings and tree boles act as reflectors in urban and forested settings.

Non-line-of-sight and low signal-to-noise ratio can increase errors in GNSS positioning data collected under forest canopy, as is evidenced in figure 5 where simultaneous data collections under canopy and in the open demonstrate different

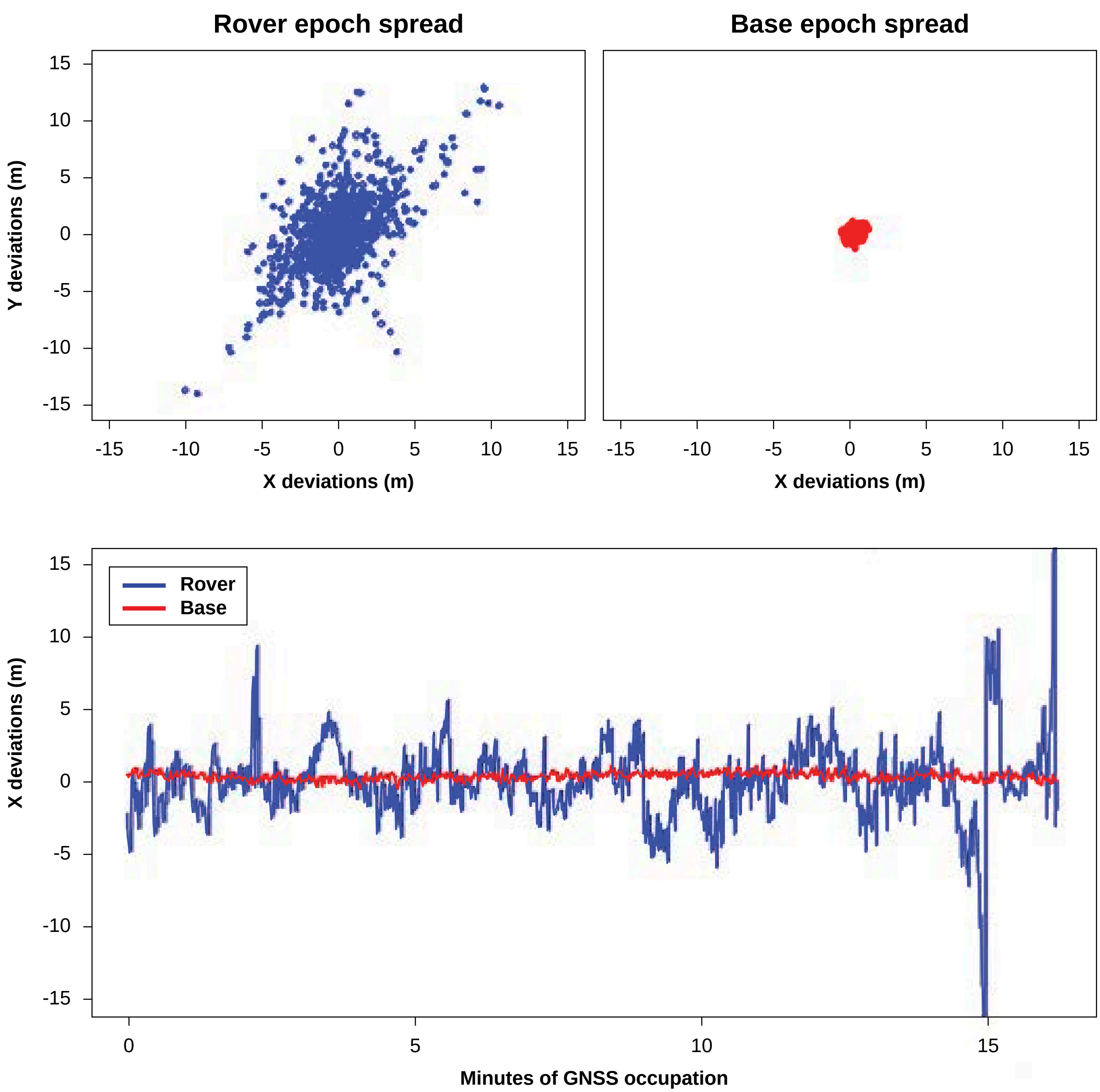

Figure 5—A comparison of coordinate point spreads from simultaneous 1-second epoch data collection using under-canopy rover receiver (blue) and open-sky base station receiver (red), demonstrates increased errors in global navigation satellite system (GNSS) positioning data collected under forest canopy.

point spreads. The GNSS measurements collected under canopy can also have systematic linear patterns, likely caused by NLOS or multipath signals.

The geometry of the satellite constellation used in the GNSS solution can affect the quality of the solution obtained via trilateration. For example, when satellites are clustered in one corner of the sky, uncertainty in the position increases. This type of error is termed "positional dilution of precision," and although it can be mitigated through filtering for long occupations, it can significantly affect the quality of autonomous, real-time GNSS solutions. Another relatively minor source of error is receiver noise (resulting from thermal noise, dynamic stress, etc.), which tends to be more of a factor in code-phase solutions than carrier-phase solutions (Van Sickle 2015).

Differential Processing

The principle of differential processing (or differential correction) is based on the fact that ionospheric and tropospheric delays will be very similar in the signals received at locations that are relatively close together (i.e., tens of kilometers). Furthermore, if we know the XYZ location of one of these receivers (the base), then we can determine the correction needed to remove the effect of the atmospheric delay on the pseudorange at the base receiver and this same correction can be applied to the pseudorange at the unknown location (the rover receiver) (see fig. 6). In operation, these pseudorange corrections are produced for each satellite "seen" by the base and rover so it is critical that the base and rover receivers "see" the same GNSS constellations.

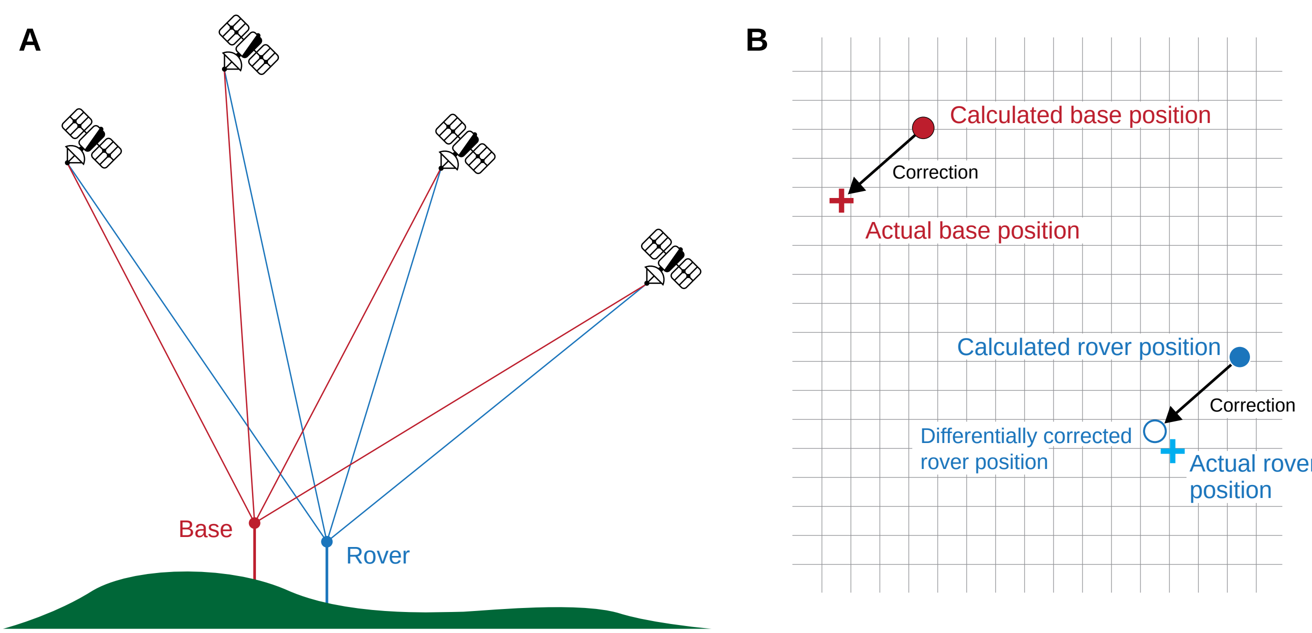

Figure 6—Principle of differential correction: (A) base and rover receivers receive signals from the same global navigation satellite system satellites, where coordinates of base station are known; and (B) known correction for base (difference between calculated base position and actual base position) is applied to the uncorrected rover position to obtain the differentially corrected position for rover.

Differential processing is required for carrier-phase processing and will reduce the errors in code-phase solutions from tens of meters to meters or decimeters. While the coordinate accuracy obtained in differential processing is a function of the distance between rover and base stations, even the use of base stations more than 100 km away from a rover receiver can significantly improve the accuracy of GNSS positions (Andersen et al. 2009b). For FIA work, data available from a network of continuously operating reference stations operated by the National Geodetic Service can be used to differentially correct GNSS data collected on FIA plots. A dedicated receiver positioned over a known geodetic control point can serve as a base station for projects within a small area; however, this is not practical for the FIA inventory where field plots are widely distributed over a large region.

A type of real-time differential correction is also available through satellite-based augmentation systems, such as the Wide Area Augmentation System (WAAS) in the United States. These systems consist of a widely distributed network of ground stations at known locations. The correction information from each of these stations is transmitted to communication satellites, which then broadcast corrections that can be used, in real time, by WAAS-enabled GNSS receivers. Satellite augmentation systems are also available in other parts of the world, including the European Geostationary Navigation System and the Japanese Multifunction Transport Satellite system. Although these augmentation systems, originally developed to support precision navigation for aviation, can significantly improve the positions of recreational grade GNSS receivers in open-sky conditions, the availability and quality of WAAS signals in many forest settings is inconsistent, and therefore this system is of limited or no use in the context of the PNW-FIA HPGNSS initiative.

Another type of real-time differential correction approach is real-time kinematic GNSS positioning. Real-time kinematic GNSS, like static postprocessing, relies upon observation of the same satellite signals by rover (moving) and base station (stationary) receivers. The correction obtained at the base station is used to correct the position of the rover. However, in real-time kinematic GNSS positioning instead of the correction being applied in a postprocessing stage, it is relayed in real-time via a continuous data link between the base station and rover. Because the data link provides continuous correction information, real-time kinematic can be used to obtain carrier-phase solutions in real time and is therefore a primary mode for data collection in land surveying applications. The data link may operate using radio signals, cellular data, or satellite data. A weakness of the real-time kinematic GNSS method is that if the data link between rover and base receivers is disrupted, the ability to correct the rover position is lost. The data link is problematic for many forestry operations where lack of cellular signal and blockage of satellite signals by local terrain relief and trees prevent differential correction.

Types of GNSS Receivers and Applicability to the HPGNSS Initiative

Three main classes of GNSS receivers are in use for navigation and surveying applications: recreational-, mapping-, and survey-grade receivers (fig. 7). With few exceptions, recreational grade GNSS receivers are relatively low cost and single frequency (L1), and have limited options for configuring the data collection, such as signal-to-noise ratio, epoch rate, mask angle, positional dilution of precision, etc. These receivers typically do not collect the carrier-phase data, and therefore are only capable of code-phase positioning. In addition, they use relatively inexpensive receiver hardware and simple antenna designs that can further limit the quality of the observed signals and the expected accuracy of positions. Recreational grade receivers typically have very accessible user interfaces and are designed for ease of use, including clear display of maps, navigation information, and collection of waypoints. While recreational grade GNSS receivers are often used in forest inventory applications for navigating to the plot, they are prone to large errors and not appropriate for use in the HPGNSS initiative.

Jacob Strunk

Figure 7—Three types of global navigation satellite system receivers.

Mapping-grade receivers occupy the middle ground in receiver quality, and typically have many more options for configuring the data collection, including signal-to-noise ratio, mask angle, epoch rate, and positional dilution of precision. Mapping-grade receivers, as the name implies, are designed to collect positions at a quality that is appropriate for mapping applications (feature and boundary mapping or map updates) and are widely used in forestry. They typically use a single frequency but can often collect carrier-phase data, and many can collect signals from multiple GNSS constellations (especially GPS and GLONASS). Higher quality, dual-frequency mapping-grade GNSS receivers can consistently obtain postprocessed positions in forested settings with an accuracy of 1 to 5 m and may be appropriate for forest inventory applications, depending on the required accuracy.

Survey-grade receivers represent the most precise class of GNSS receivers. Receivers of this type are usually highly configurable and are capable of collecting both code- and carrier-phase data for dual or multiple frequencies (L1, L2, L5), typically for several different GNSS constellations, and at high sampling rates (short epoch intervals). Survey-grade receivers usually have higher quality antenna hardware than mapping-grade receivers and often have more sophisticated built-in signal filtering capabilities. Survey-grade receivers usually can maintain higher accuracies at long baselines than mapping-grade receivers and can provide accuracies of 0.1 cm for postprocessed coordinates. For these reasons, survey-grade receivers offer the most consistent performance in highly challenging forestry settings and are the preferred option in cases where accurate spatial registration with high-resolution remote sensing is the primary objective, such as the PNW-FIA HPGNSS initiative.

Quick Look: Types of Global Navigation Satellite System Receivers and Expected Performance in Open-Sky Conditions

Type	Autonomous horizontal accuracy	Postprocessed horizontal network accuracy
	Meters	
Recreational grade	5 to 15	Not applicable
Mapping grade	2 to 10	0.3 to 15 (L1); 0.02 to 0.9 (L1/L2)
Survey grade	2 to 10	<0.01

Modified from Van Sickle 2015.

There is a relatively new class of receivers that use real-time kinematic with correction data received via a subscription service (free or paid) using a radio or cellular data link. These receivers provide multifrequency and multiconstellation capabilities, tend to be cheaper than survey-grade receivers, and provide subdecimeter accuracy in open conditions. Many also log epoch information to facilitate differential postprocessing or precise point positioning (described below). While these receivers may be suitable for the forest inventory programs, their reliance on a radio or cellular data link is problematic for FIA, and additional testing is needed to assess their horizontal accuracy under forest canopy.

Field Protocols and Postprocessing of GNSS Data Collected Under Forest Canopy

There have been relatively few rigorous, quantitative assessments of the absolute accuracy, optimal field protocols, and postprocessing settings when using mapping-grade and survey-grade GNSS receivers under forest canopy. Multiple tests of GPS-only, mapping-grade receivers under varying conifer forest canopy conditions in the Pacific Northwest (United States) indicated that accuracies were related to both forest density and occupation time and reported errors of 4 to 9 m across a wide range of stand densities (Frank and Wing 2014). Næsset et al. (2000) demonstrated that submeter accuracy could be obtained for plot positions under forest canopy in southeast Norway using survey-grade receivers with observation times of 30 minutes, and accuracies were significantly improved through the use of GPS and GLONASS versus GPS alone. This study also showed that it was often possible to obtain carrier-phase fixed solutions (with <10 cm error) even under forest canopy, and the quality of postprocessed positions was highly dependent on the number of available satellites. The primary importance of the number of satellites available for GNSS solutions obtained with survey-grade receivers under canopy was confirmed by Clarkin (2007). In another study of dual-frequency, survey-grade GNSS receivers in Norway, Næsset (2001) reported mean positional accuracies in the range from 0.08 to 1.35 m, and again indicated that highest accuracies were observed at points where fixed solutions were possible; however, he cautioned that gross errors are possible when solutions are constrained to fixed solutions under dense canopy and therefore recommends the use of float solutions for cases when large errors are unacceptable. Interestingly, these authors also found that the single-most useful predictor of the accuracy for postprocessed GNSS positions was the reported precision of the postprocessed solution (not to be confused with the true accuracy obtained from comparison to actual surveyed coordinate).

In another test of different GNSS receivers and field collection protocols under forest canopy carried out in Spain, Valbuena et al. (2010) reported that the precision computed by the postprocessing software was not a reliable measure of the absolute accuracy of plot positions under canopy. This study also found that handheld receivers were not appropriate for the collection of coordinates in a forest inventory context where comparisons to high-resolution imagery are needed and the occupation time on a plot is constrained. In tests carried out in dense conifer forests in western Washington state, McGaughey et al. (2017) reported that plot positions with average horizontal error of 0.83 m and a maximum error of 1.75 m could be obtained using survey-grade GNSS receivers and a 15-minute occupation time. In this study, no correlation was found between horizontal precision of the postprocessed solution and the true horizontal accuracy, although there was little variation in the range of canopy cover (nearly 100 percent cover for all points). Another important finding from the McGaughey et al. (2017) study was that, in general, positioning accuracy was directly related to the duration of the GNSS occupation (with longer occupations yielding more accurate positions).

Potential Future Improvements to the HPGNSS Initiative

Several additional constellations established by other countries, including GLONASS (Russia), Galileo (European Union), and BeiDou (China), collectively make up the GNSS (global navigation satellite system) (fig. 8). Most receivers can track signals from at least two constellations and use them to obtain an improved solution. However, the utility of the various constellations depends on your location and the time of day as each constellation is optimized to provide coverage for different parts of the globe. In general, the GLONASS constellation is useful for all areas within the PNW-FIA domain. While nearly all receivers used within the HPGNSS initiative can collect data from other GNSS constellations in addition to GPS and GLONASS (as of 2021), at this time, many publicly available base stations do not support other constellations, especially in Alaska where often only GPS is available.

In recent years, a system has been developed, termed precise point positioning (PPP), that uses more precise information on satellite positions and clock offsets (satellite ephemerides) that can significantly reduce the error in single-point positioning, and when used with dual-frequency receivers (to estimate ionospheric delay) can obtain accuracies that compete with differentially corrected positions.

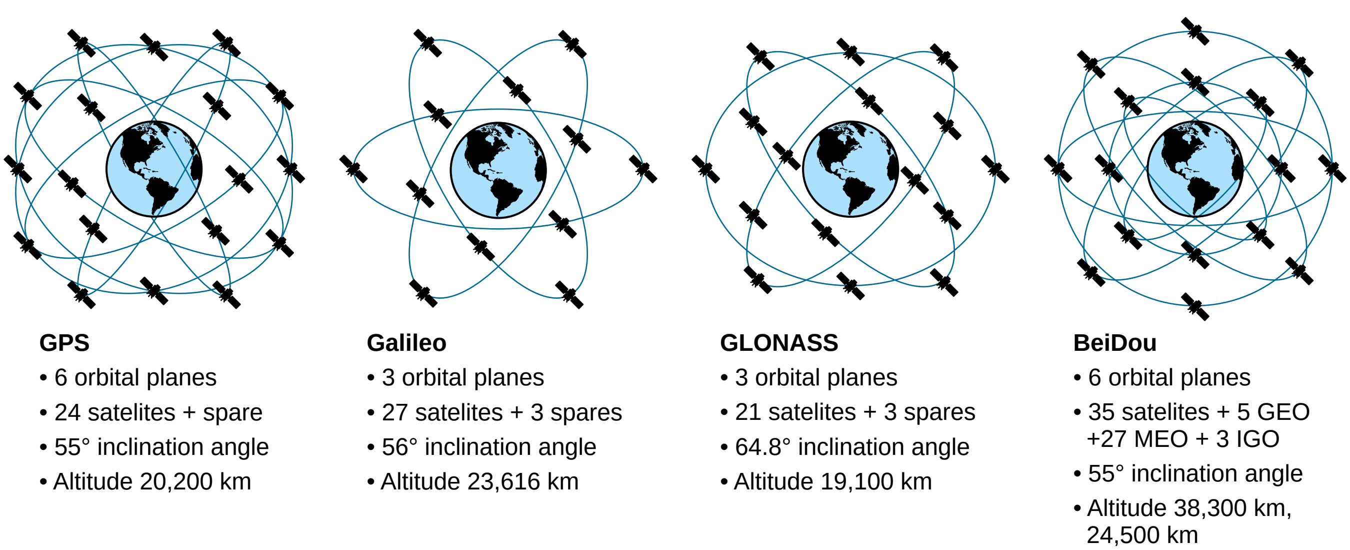

Figure 8—Four global navigation satellite system constellations currently available (adapted from Van Sickle 2015).

Given that this approach obviates the need for base station data, it potentially offers great advantages in the forest inventory context. However, a disadvantage of the current PPP approach is that it can take relatively long occupations (>20 minutes) to adequately resolve the integer ambiguity in carrier-phase positioning, although the inclusion of additional GNSS satellites (GLONASS, etc.) in the PPP solution could address this limitation over time (Van Sickle 2015). Another disadvantage is a delay (about 2 weeks) in the online availability of the precise empherides (Van Sickle 2015). Næsset and Gjevestad (2008) evaluated the accuracy of positions obtained using a dual-frequency, survey-grade GNSS receiver under conifer forest canopy in Norway and processed using PPP, and found that for 15-minute occupations, positions were not found for 8 to 44 percent of the locations, indicating that differential processing with a base station was a more robust option for forest inventory applications. However, this technology is still evolving and PNW-FIA will continue to monitor the utility of PPP for the HPGNSS initiative going forward.

The brief overview of GNSS principles and technology described here is meant to provide enough background and context to understand the various components of the HPGNSS initiative. However, the theoretical and practical effects of various specific GNSS data collection approaches and postprocessing configurations on the accuracy of positions collected under forest canopy are understudied and are not well-represented in the relevant surveying, engineering, or forestry literature. Examples include the effects of receiver height, occupation duration, number of base stations, and type of satellite constellation used for postprocessing. To answer questions related to the use of GNSS in a forest inventory context as they arise, PNW-FIA research scientists continue to carry out investigations using surveyed test courses in the region to inform equipment choices, field protocols, and postprocessing procedures.

The PNW-FIA HPGNSS Initiative

The PNW-FIA HPGNSS initiative, which began in 2014, is operational for all areas covered by PNW-FIA. The implementation workflow for HPGNSS includes GNSS receiver selection; field protocol development; implementation, consisting of data collection, postprocessing, validation, and database integration; followed by an overall accuracy assessment (fig. 9). The following sections describe the workflow in more detail.

GNSS Receiver Selection

Three types of receivers have been used by the PNW-FIA HPGNSS initiative—the mapping grade Trimble GeoExplorer XH6000 and GeoExplorer 7x receivers

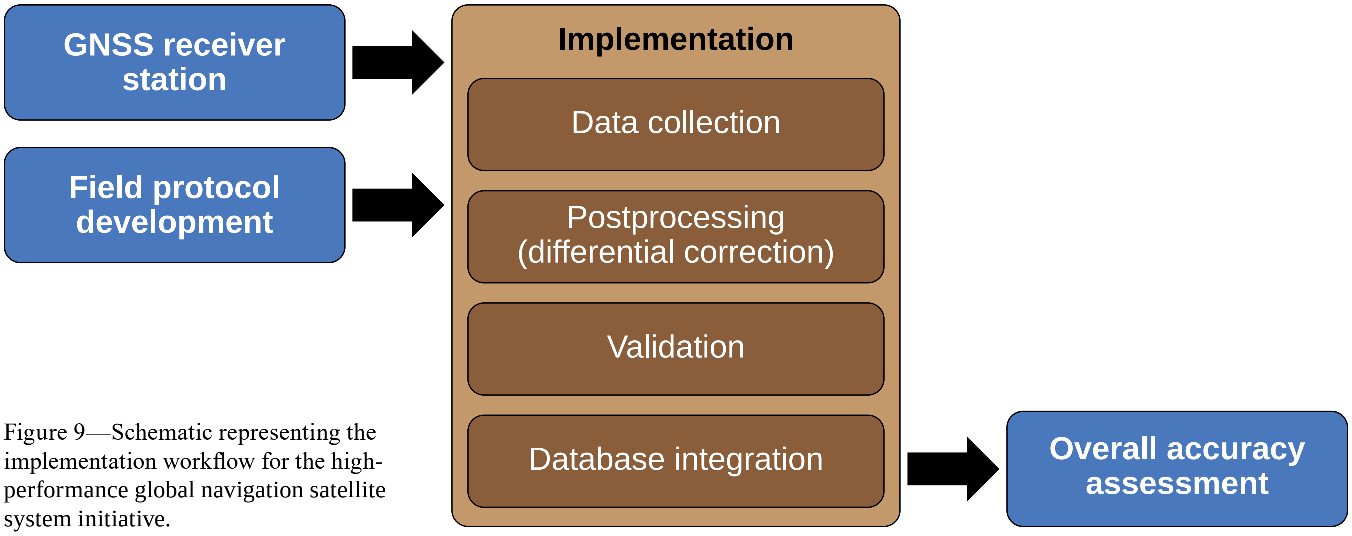

Figure 9—Schematic representing the implementation workflow for the high-performance global navigation satellite system initiative.

and the survey-grade Javad Triumph-2 receiver. When the program started in 2014, Trimble GeoXH6000 units were the most capable receivers that were easily acquired (available on U.S. General Services Administration contract and with technical support available within the U.S. Forest Service). Trimble introduced the Geo7X receivers soon after the program started, and many damaged GeoXH600 units were replaced with the Geo7x units for a short period of time. As the program developed, newer receivers offering improved accuracy became available. As of 2021, aside from a limited number of contract field crews who still use Trimble receivers, all PNW-FIA crews use Javad Triumph-2 receivers.

Field Protocol Development, Testing, and Implementation

The current PNW-FIA HPGNSS field protocol calls for collection of at least 15 minutes of data with one measurement per second (USDA FS 2019). The Trimble receiver is designed as a handheld unit and is not easily used with a tripod; however, crews are advised to keep the patch antenna level, elevate the receiver above ground vegetation, and remain at least 5 ft from large-diameter trees (fig. 10). The Javad Triumph-2 is used with a lightweight tripod that elevates the receiver above most ground vegetation (fig. 11). The Javad receivers can be controlled using a WiFi- or Bluetooth-enabled external device, such as a cell phone or tablet. While not necessary, the use of an external device allows more control of the unit and direct naming of data files. The protocol allows for a horizontal offset (distance, azimuth) if it is impossible to collect data at the subplot center (due to a large tree or hazardous condition). This offset is then applied to obtain a corrected position during postprocessing.

USDA Forest Service

Figure 10—A mapping-grade global navigation satellite system receiver (Trimble GeoXH6000) in use on a burned plot in California.


USDA Forest Service

Figure 11—A survey-grade global navigation satellite system receiver (Javad Triumph-2) in use on a plot in Oregon.

Results from testing and additional considerations—

Research suggests that the longer GNSS data are collected for a survey point, the better the horizontal position of the resulting GNSS surveyed position (Andersen et al. 2009b, McGaughey et al. 2017). The FIA field crews typically spend several hours collecting measurements for a single plot. However, given the need to access each subplot center and move around the plot to conduct tree measurements, it is not practical to collect GNSS positioning data for many hours for each point. Although the PNW-FIA HPGNSS protocol currently requires collecting GNSS data for a minimum of 15 minutes at each subplot center with one measurement per second, field crews are encouraged to collect data for as long as possible, including while taking other measurements at subplot center. From a GNSS accuracy standpoint, collecting more data at the subplot center is preferred but not always practical.

A surprising result of some initial tests comparing rover to reference position coordinates is that dramatic differences (1 m versus 2 m horizontal root-mean-square error [HRMSE]) are achieved as a function of the GNSS receiver brand and model, which would not be evident from receiver specifications (McGaughey et al. 2017). In 2013, Pacific Northwest Research Station scientists compared two GNSS receivers currently used by PNW-FIA (Trimble GeoXH6000 and Javad Triumph-2); both receivers were dual frequency (L1 and L2) and dual constellation (GPS and GLONASS) configurations. The more expensive mapping-grade Trimble GeoXH 6000 receiver (costing about $9,000 USD) was found to have approximately 1 m poorer positioning accuracy under forest canopy than the smaller, less expensive, survey-grade Javad Triumph-2 receiver (costing about $3,500 USD). Survey-grade GNSS receivers (HRMSE ≤1 cm under open skies) conceivably also perform well under forest canopy; however, none were available for testing. The improved positioning accuracy and the ability to mount the Javad Triumph-2 on a tripod are factors that motivated PNW-FIA to transition from the Trimble mapping-grade receivers to the Javad survey-grade receivers. One desirable feature of the Trimble mapping-grade receivers was their integrated touch screens that simplified file naming—a feature not present on many survey-grade receivers, including the Javad Triumph-2.

Another initial finding arising from the first 2 years of PNW-FIA HPGNSS initiative implementation was that using horizontal offsets for data collection (positioning the GNSS receiver away from plot center and recording the distance and azimuth to plot center) was the largest source of error. As a result, the HPGNSS field protocol now prohibits horizontal offsets unless there is a safety concern (e.g., hazard tree, poison oak, wasp nest, or cliff) or something on the subplot center physically prevents its occupation. Prior to our operational experiences with offsets, the practice of offsetting the GNSS receiver was encouraged to facilitate plot measurements; however, we found that the azimuth was often recorded incorrectly (e.g., south instead of north and wrong declination settings).[3] In addition, the positioning quality is degraded with distance from subplot center.

[3] Electronics can interfere with magnetic compass readings. It is important to test your equipment and see whether the GNNS receiver affects your compass readings. Our experiments with Javad Triumph-2 receivers indicate there is no noticeable effect when the compass and the receiver are separated by 61 cm or more. However, this may vary by receiver, receiver type, and compass type.

Quick Look: Data Collection Procedures in High-Performance Global Navigation Satellite System (GNSS) Initiative

- Collect GNSS data for each subplot
- Collect data using 1-second epochs
- Collect data for ≥15 minutes (when feasible)
- Make sure the antenna is level (e.g., mount receiver on a mini-tripod)
- Do not offset, except for safety or impediment
- Use survey-grade receiver (Javad Triumph-2 receivers currently adopted)
- Keep compasses ≥61 cm from the GNSS receiver (may affect compass readings)

Postprocessing Procedures

Postprocessing or differential correction of GNSS data involves a number of considerations, including choice of base station (which vary in distance and configuration) and processing modes (fixed or float carrier phase and code-phase solutions). The HPGNSS postprocessing protocol uses free, publicly distributed National Oceanic and Atmospheric Administration (NOAA) Continuously Operating Reference Station (CORS) (https://geodesy.noaa.gov/CORS/data.shtml) and UNAVCO (https://www.unavco.org/data/gps-gnss/gps-gnss.html) base station data; field crews do not set up their own temporary, dedicated base stations, even in interior Alaska and remote Pacific islands. Generally speaking, when we process rover data, we use the default processing engine (which automatically chooses the type of solution based on the quality of the data) and also let the postprocessing software automatically import data from the nearest base stations to the rover locations. However, a better solution can sometimes be obtained by manually selecting slightly farther away base stations with both GPS and GLONASS constellations (GPS-only base stations are common in Alaska) or with higher epoch rates. As noted earlier, in our experience, base stations at distances of up to 160 km in western Washington, or 320 km in interior Alaska, can be used without significant impact on the quality of postprocessed coordinates (Andersen et al. 2009b).

Data Validation Procedures

With high-quality, survey-grade GNSS receivers, data collection even in highly variable forest conditions is generally straight forward and robust. However, some rover datasets may not process when using default postprocessing settings. For these cases, some additional troubleshooting and adjustment of postprocessing settings may be necessary. The specific troubleshooting steps will depend on software and data (Trimble versus Javad); however, there are some general guidelines to follow in cleaning the input data, or modifying settings, to enable solutions. Processing should be attempted with step 1, then continue with steps 2 and 3 if necessary.

Step 1. Verify that there is temporal overlap for base station and rover data—it is not uncommon for base stations to have periods when no data are collected and archived, even though the base station appears to be active.

Step 2. Visualize the scatter of individual epoch data and omit observations that are clearly erroneous (e.g., epochs tens of feet to miles from rover median position).

Step 3. Attempt different processing configurations, especially code-phase processing.

Several additional items should be considered when using publicly available base station data. First, base station epoch rates archived on continuously operating reference stations and other public storage locations are frequently down-sampled after some period of time, and the period is not consistent (e.g., 1 week, 1 month, or 1 year). The result of the down-sampling is that data collected at a rate of one

Quick Look: Postprocessing Configuration Used in High-Performance Global Navigation Satellite System (HPGNSS) Program

- Auto processing mode (automatically chooses carrier- or code-phase processing depending on data quality)
- Static solution—constrains solution to a single point/coordinate (note: Trimble Pathfinder Office does not allow static solutions)
- Software automatically downloads GNSS data from nearest base stations
    - GPS and GLONASS base station preferred—if needed, manually select data from more distant base station to obtain multiple constellation data
- Latitude and longitude NAD83 (2011)
- Troubleshoot processing issues:
    - Verify temporal overlap
    - Remove outlier epochs (may appear miles away from rover)
    - Attempt code-phase processing

point per second is only available at a much lower frequency (one point every 30 seconds). Data collection programs using GNSS may consider processing protocols that include rapid (within 3 weeks) download of base station data. For example, PNW-FIA only processes data collected for the HPGNSS initiative once per year, typically starting in January for the previous field season. In some instances, this means that we are processing with down-sampled base station data.

Second, the base stations visible on maps for public archives (e.g., NOAA CORS and UNAVCO) are not always active and their configuration may not be precise. The best way to verify that sites are active when planning a GNSS campaign is to download example data from the target base station sites. This is especially relevant in remote areas where base data are few and far between, such as interior Alaska.

Database Integration

Once GNSS data have been postprocessed to achieve final coordinates, the data are ready to be incorporated into the FIA data repository. While the process outlined below is specific to PNW-FIA, similar processes are recommended for anyone collecting GNSS data to ensure quality data. The GNSS data are collected using stand-alone receivers that produce data files that are either automatically or manually named, so there are opportunities to mis-identify location data as it relates to other field measurements. In addition, final locations need to be compared with existing plot and subplot location information to verify data integrity. If any anomalies are found, they should be corrected before the data are released for use. These final data checks ensure that any analyses that rely on the plot locations are conducted using locations that have been quality checked and, thus, are unlikely to change.

For PNW-FIA, the postprocessed data are reformatted using scripts to achieve a consistent format (name, longitude, latitude, duration). The reformatted coordinate data are then loaded into a staging table in an Oracle database. Coordinates in the database are compared with the repository of field measurements for the same year. Any observations with incorrect names, duplications, or which are more than 100 m from the nominal plot position are flagged for further inspection. Observations with potential errors are either corrected or marked as invalid in the database. Finally, the coordinates provided via HPGNSS collection and processing procedures become the official plot coordinates. PNW-FIA plots have HPGNSS-based coordinates for each subplot, while other FIA regions typically only retain coordinates for the central subplot (subplot 1).

Unfortunately, HPGNSS-based coordinates are not available on all plots measured in the field for various reasons that include equipment malfunction, user error, and data corruption. The current plan for coordinates in the PNW-FIA HPGNSS initiative is to provide two opportunities to acquire HPGNSS-based coordinates, with a target completion rate of 99.5 percent by year and state. Using the final HPGNSS-based coordinates, data are summarized by year and state to evaluate completion rates, or proportion of measured plots and subplots with associated HPGNSS coordinates.

Overall Accuracy Assessment for the PNW-FIA HPGNSS Initiative

Objectives of the PNW-FIA HPGNSS initiative include obtaining GNSS coordinates on all subplots (99.5 percent completion) with less than 1 m HRMSE and less than 2 m horizontal error for 95 percent of remeasured subplot locations. Although the positioning accuracy is only evaluated for a sample of plots, this calculated accuracy can be used to infer accuracy—and adherence to data quality standards—for the overall HPGNSS initiative across broader inventory domains, for example, at the state or regional scale. Coordinate quality for HPGNSS-based subplot coordinates (defined as the proportion of remeasured subplot coordinates with less than 2 m error) is estimated using the rover-to-rover approach described in the next section.

PNW-FIA HPGNSS accuracy assessment methods—
To estimate positioning accuracy, HPGNSS-based subplot coordinates collected by standard FIA field crews are compared with HPGNSS-based coordinates collected by quality assurance (QA) crews on the same subplots. The accuracy assessment methods have been tested in a 2019 pilot study carried out in interior Alaska, and the methods are now being implemented throughout the PNW-FIA inventory domain, with a target of 30 remeasured plots (about 120 subplots) in each Pacific state (Alaska, Washington, Oregon, California, and Hawai'i) and Pacific Islands group.[4] The pilot study indicated that with current protocols, the estimated HRMSE for interior Alaska is 0.23 m and 95 percent of sample positions have horizontal errors <0.59 m, which is well within target tolerances. However, these results cannot be extrapolated to other regions with different environmental conditions.

Our assumption is that the distribution of independent GNSS positions collected on a given point are unbiased. In other words, if we collect 1,000 GNSS coordinates on 1,000 different reference points, we expect the average error in X and Y coordinates (relative to the true coordinates) to be very close to zero. That is to say that some of the errors in the X coordinates will be positive, and some will be

[4] PNW-FIA conducts inventories on six U.S.-Affiliated island groups in the Pacific: American Samoa, Commonwealth of the Northern Mariana Islands, Guam, Federated States of Micronesia, Republic of the Marshall Islands, and Republic of Palau.

negative, but the average of the positive and negative errors will trend toward zero. This means that while the coordinates are "unbiased," we still need to understand the distribution of horizontal errors in assessing the quality of GNSS coordinates. We are interested then in characterizing the spread of errors, or the "variance" of GNSS positions.

Note that the discussion of GNSS coordinate accuracy should not be confused with the spread of single-epoch positions that are used to compute a single GNSS position. When we collect data in the field on a single position, a receiver will sometimes show the spread of raw epoch data or provide a real-time HRMSE value. This data can often also be viewed in postprocessing software. However, the user should never infer accuracy from the HRMSE reported for a single position by a receiver or postprocessing software. The data is temporally correlated and highly biased and cannot be used as a surrogate for positioning errors. The user must follow special procedures to be able to estimate positioning precision.

Rover-to-reference accuracy assessment approach—
The most reliable approach to evaluate positioning accuracy for a GNSS position is to compare the GNSS position to a reference position with known coordinates. This generally requires creation of a survey traverse under forest canopy, which ties into survey hubs placed in the open. The GNSS positions taken in the open with survey-grade receivers can achieve better than 1 cm accuracy. The horizontal error of a survey traverse in a forest setting is likely a few centimeters, or much more accurate than would reasonably be expected from GNSS receivers under dense forest canopy. Survey traverses provide highly accurate measurements of positioning errors for every rover position as well as a general assessment of multiple rover positions for the entire traverse (e.g., HRMSE). However, survey traverses are expensive to implement (typically requiring 1 to 2 days per site for a two-person surveying crew) and they are difficult to establish across a wide variety of representative forest conditions for a region.

The PNW Vegetation Monitoring and Remote Sensing team has set up survey traverses under forest canopy in both Washington and Alaska to enable rover-to-reference assessments of GNSS positioning accuracy (fig. 12). These include two semipermanent traverses (survey points monumented with stakes and tags) near Olympia, Washington (McGaughey et al. 2017), and several traverses distributed across different forest conditions in the Tanana Valley of interior Alaska (Andersen et al. 2009b), although wildlife and vegetation tend to render anything but concrete or steel monumentation temporary.

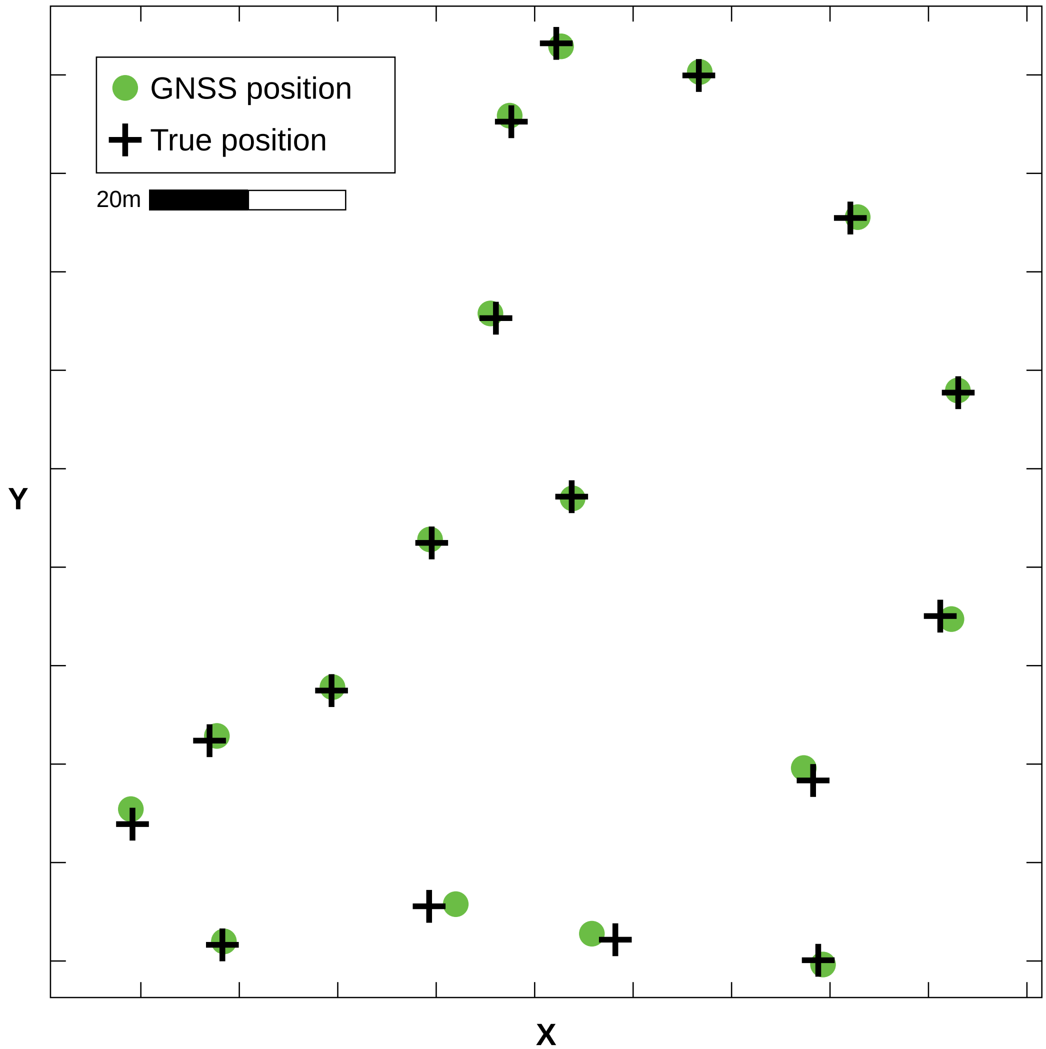

Figure 12—Example of dataset for rover-to-reference accuracy assessment. Survey traverse near Olympia, Washington, overlaid with example global navigation satellite system (GNSS) rover receiver positions.

Horizontal positioning error for a GNSS position (e_{xy}) is defined as the distance between the reference point (x_0, y_0) and the GNSS position (x_{GNSS}, y_{GNSS}):

$$e_{xy} = \sqrt{(x_{GNSS} - x_0)^2 + (y_{GNSS} - y_0)^2}$$

Usually, a single point is of limited value, and we wish to summarize the distribution of positioning errors. When we want to compare two datasets (e.g., different tripod height or processing configuration), it is easiest if we have a single measure of accuracy such as horizontal root-mean-squared error (HRMSE):

$$HRMSE = \sqrt{\frac{\sum_1^n e_{xy_i}^2}{n}}$$

In figure 13 we see the HRMSE and 95th percentile horizontal error overlaid on the distribution of horizontal errors for an example dataset. If another approach provides us with a lower HRMSE, it suggests the accuracy of that approach is better.

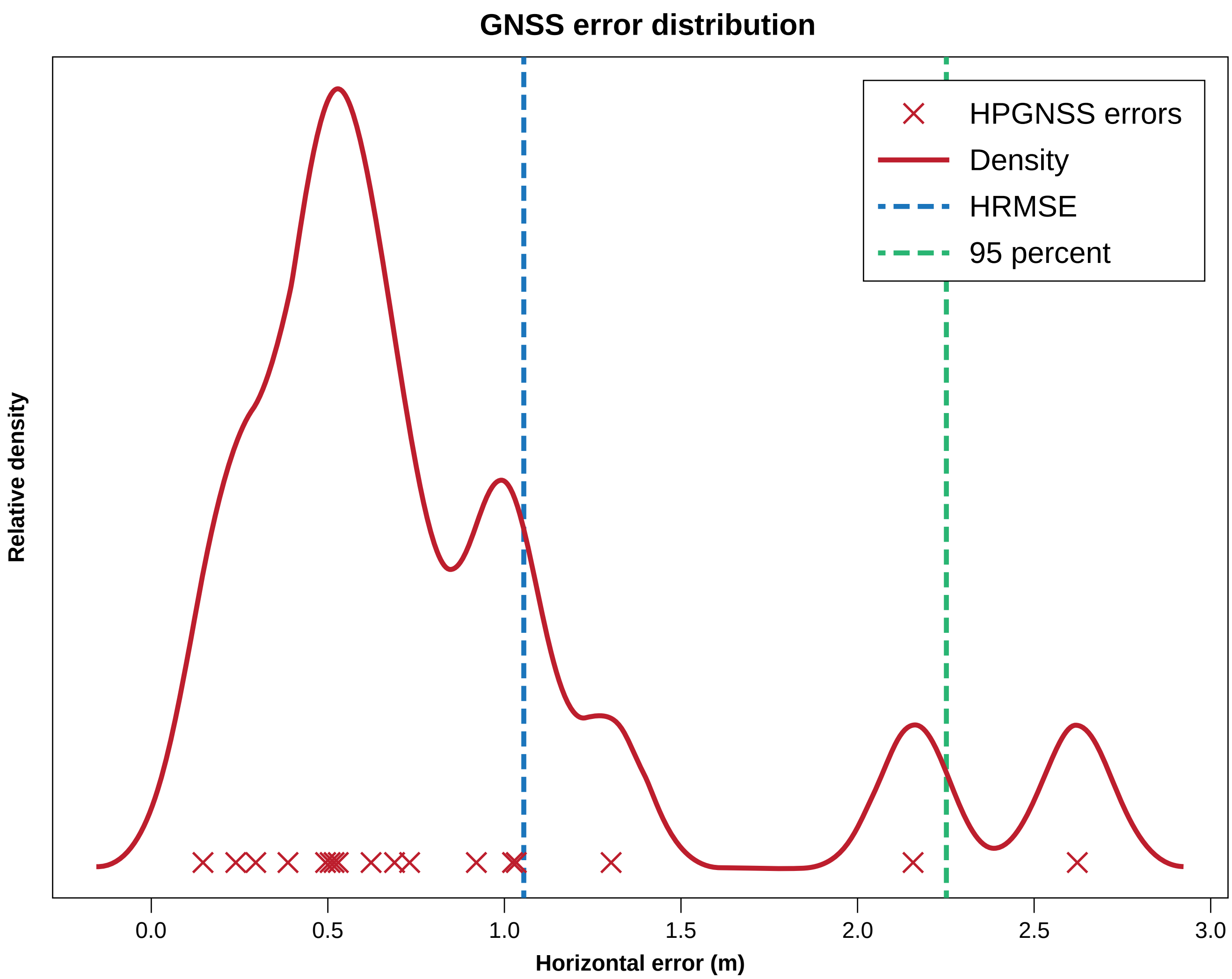

Figure 13—Example distribution of global navigation satellite system positioning errors relative to reference traverse. HPGNSS = high-performance global navigation satellite system, HRMSE = horizontal root-mean-squared error.

Rover-to-rover accuracy assessment approach—
A second approach to estimate the performance of GNSS positioning uses repeated measurements (rover-to-rover) on the same locations, for example, FIA subplot center monumentation (fig. 14). Rover-to-rover data may be obtained when a standard FIA field crew visits and collects GNSS data on all four subplots of an FIA plot followed by a second set of measurements during the same field season when a second field crew performs a QA check of the first field crew's data (a so-called

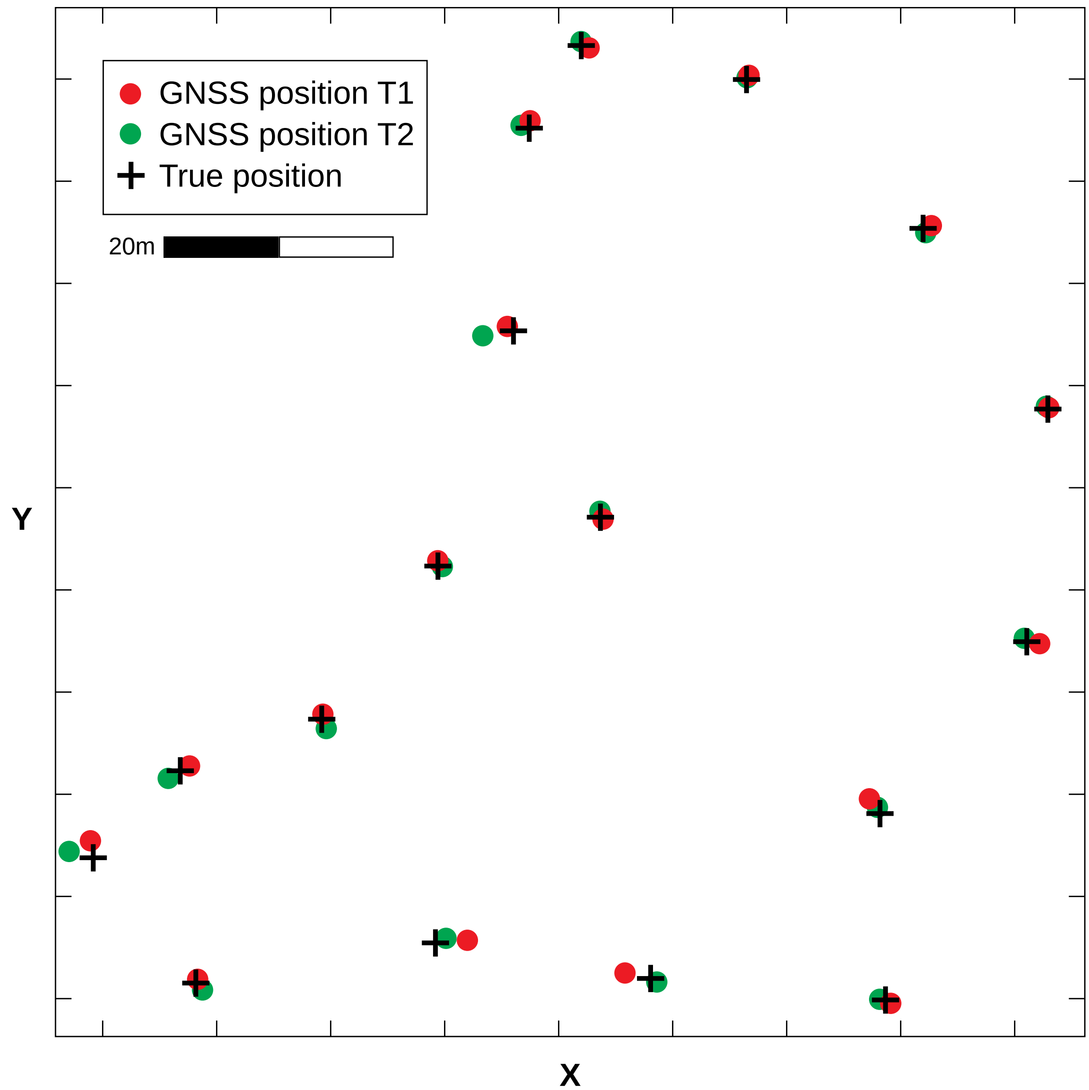

Figure 14—Rover-to-rover scenario in which we compute errors from repeated global navigation satellite system (GNSS) receiver positions. True positions are not known using this technique, but are shown here to better illustrate the difference between precision of repeat position measurements and actual accuracy of individual rover postprocessed locations.

"cold check" quality control visit). As long as there is not a systematic bias in the collection of GNSS data for a single monument, the difference between GNSS subplot coordinates obtained by the standard field crews and QA crews can be used to estimate positioning errors. This approach does not provide a reliable measure of positioning error for a single point (unlike the rover-to-reference approach), but can be used to characterize the distribution of errors across an area and under certain assumptions (explained below) can be used to estimate HRMSE and horizontal error quantiles. This approach is less expensive and easier to implement than the rover-to-reference approach and can be implemented across an entire county, biome, or state.

The rover-to-rover approach is easier to implement than the rover-to-reference approach as it does not require a survey traverse, but there is an important assumption of independence between rover datasets. For example, if two field crews were to visit the same plot at the same time and collect GNSS data simultaneously, the rover GNSS data from the first crew would be highly correlated with the GNSS data of the second crew. This is because the satellite and atmospheric conditions would be identical for the two crews and the positioning errors could be quite similar between the two datasets. This would result in a negative (too small) bias in estimates of positioning errors. To obtain reliable estimates of accuracy, the two crews need to visit the same points far apart enough in time that the GNSS satellite constellations and atmospheric conditions are sufficiently different that the positioning errors are no longer correlated. We currently do not have a good estimate of how long this takes, and our current recommendation is that the two rover GNSS positions which are compared should be taken at least 24 hours apart.

One possible confounding factor in error estimation using the rover-to-rover approach is that environmental factors may cause a systematic trend in positioning errors, resulting in a negative bias or underestimation of horizontal positioning errors. The idea is that environmental factors such as slope, aspect, or large tree boles may result in rover positions which are systematically grouped in a specific direction (e.g., downhill or away from the bole), which violates the assumption of independence between rover positioning errors. If repeated rover positions are both shifted in the same direction, this will result in an underestimate of positioning errors. While this topic is worthy of future investigation, we feel that the assumption of unbiasedness for repeated observations taken on different days is reasonable for most situations encountered in the field.

Computing positioning errors with the rover-to-rover approach is slightly different than from the rover-to-reference approach. As with the rover-to-reference approach, we difference the two sets of coordinates, but in this case we divide the sum of squared errors (x and y) by two. This is because both the coordinate at time one ($x_{GNSS-T1}$, $y_{GNSS-T1}$) and the coordinate at time two ($x_{GNSS-T2}$, $y_{GNSS-T2}$) contribute variance to the positioning uncertainty resulting in twice the expected error:

$$e_{xy} = \sqrt{\frac{(x_{GNSS,\ T1} - x_{GNSS,\ T2})^2 + (y_{GNSS,\ T1} - y_{GNSS,\ T2})^2}{2}}$$

This approach can be used to estimate accuracy for groups of observations such as those that fall into a county, bio-region, or state since accuracy (HRMSE) is equivalent to variance when bias is zero. Breaking the HRMSE estimates apart by region is helpful in assessments, as the performance in different regions is expected to vary as a function of vegetation and topographic conditions. For example, we would expect lower accuracy in regions with steep terrain and large, tightly spaced trees that block more GNSS signals, when compared to flat areas with smaller or widely spaced trees. Accuracy may also be affected by latitude (e.g., Alaska versus Washington, Oregon, and California) owing to the configuration of GNSS constellations. The GLONASS satellite constellation covers greater latitudes (north or south), and GPS is more centered on middle latitudes (Springer and Dach 2010).

PNW-FIA implemented a rover-to-rover accuracy assessment protocol to evaluate quality of HPGNSS-based coordinates by state. The protocol involves collecting a minimum of 30 observations in each location—Oregon, Washington, Alaska, Hawai'i, and the Pacific Islands. This protocol is complete from a design perspective but has only been implemented for a pilot study area in interior Alaska for the 2019 field season. The accuracy assessment protocol uses GNSS rover positions collected separately by standard field crews and QA field crews at least 24 hours apart. The positioning differences for the same subplots are then compared using the rover-to-rover accuracy assessment approach.

Using the accuracy assessment protocol for the HPGNSS pilot study during the 2019 field season, we were able to determine that interior Alaska positions achieved approximately 23 cm HRMSE using the nearest base station to each rover (mixed epoch rates, and most base receivers only had GPS signals) and approximately 20 cm HRMSE when using a slightly farther away (270 km maximum, 30-second epochs) base station with both GPS and GNSS signals. This suggests that for interior Alaska, the slightly greater base distance and longer 30-second epoch rate was less important than having a base station that receives from both GPS and GLONASS constellations.

Although boreal forests of interior Alaska are less dense (in terms of biomass and volume) than forests elsewhere in the Pacific Northwest, key findings from the Alaska HPGNSS pilot study can inform processing protocols in other Pacific states. For example, while we expect HPGNSS-based coordinates in denser forests will be less accurate than coordinates obtained in interior Alaska, we also expect another key result from the pilot—that using multiconstellation GNSS data (i.e., more satellites) should be a higher priority than maintaining shorter distances to base-stations—will be even more applicable in regions where timber cover and terrain conditions are more challenging. Also, note that compared to interior Alaska, the conterminous U.S. has a denser network of base stations with higher epoch rates that use predominantly dual constellation receivers (GPS and GLONASS).

Conclusion

PNW-FIA recognizes the growing demand and need for high-quality plot coordinates to support the type of detailed spatial analyses increasingly requested of FIA by Congress, key stakeholders, and cooperators. The PNW-FIA HPGNSS initiative was developed to directly address this need and thereby add significant value to the multitude of measurements already collected on FIA plots. Although it started in 2014 as a pilot project with limited scope and duration, the HPGNSS initiative has grown into a high-priority, long-term component of the PNW-FIA inventory. Under the guidelines for the HPGNSS initiative described in this report, as of 2019 PNW-FIA has acquired high-quality coordinates on 62,500 (54 percent) of the 115,000 forested subplots within the inventory domain. Given the expansion of the PNW-FIA inventory into new regions (interior Alaska) and the intensification of sampling within the existing domain (California), PNW-FIA will be collecting HPGNSS-based coordinates on a significant number of newly installed FIA plots for at least another 12 to 15 years, ensuring that HPGNSS will remain a component of PNW-FIA for the foreseeable future. In this report, we described the background and current implementation workflow for the HPGNSS initiative within PNW-FIA. Because GNSS is a rapidly developing technology, we fully expect the specific receivers and even protocols described here will require periodic evaluation and revision as newer hardware and processing software are used by PNW-FIA field crews in the future. However, the main principles and challenges of satellite geopositioning under forest canopy, and the objectives of the PNW-FIA HPGNSS initiative as described in this report, will remain consistent and provide the basis for implementation of the initiative going forward.

U.S. Equivalents

When you know:	Multiply by:	To find:
Millimeters (mm)	0.0394	Inches
Centimeters (cm)	.394	Inches
Meters (m)	3.28	Feet
Kilometers (km)	.621	Miles

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Glossary

almanac—A file containing the approximate positions (less precise than ephemeris) for all global navigation satellite system (GNSS) satellites for a period of 90 days. All satellites transmit the same almanac. It takes 12.5 minutes for a receiver to download a new almanac. See ephemeris. More information is available at the NovAtel website: https://www.novatel.com/support/known-solutions/gnss-ephemerides-and-almanacs/.

base station—A global navigation satellite system (GNSS) receiver that is placed on a known (surveyed) position. The difference between GNSS positions and the surveyed position for a base station (or reference station) is used to improve rover receiver positioning precision. See differential correction.

BeiDou—Chinese global navigation satellite system (GNSS) constellation. See figure 8.

carrier-phase positioning—global navigation satellite system (GNSS) positioning that uses the position of the receiver relative to peaks and valleys in the code phase sinusoidal GNSS transmission signal to reduce distance ambiguity from GNSS satellites to 20 cm for a single satellite, and 3 to 4 mm for multiple satellite vectors solved together. Types of solutions include fixed (constrained to integer-valued) and float. See code-phase positioning. More information is available at the Trimble website: https://www.trimble.com/gps_tutorial/sub_phases.aspx.

code-phase positioning—global navigation satellite system (GNSS) positioning that relies on time stamps transmitted by GNSS satellites. The satellite time stamps relative to receiver time can be used to solve for the approximate distances between the receiver and satellites. These distances and the approximate satellite locations make it possible to solve for the receiver position. A limitation of this approach is the time that passes between timestamps results in positioning ambiguity on the order of 300 m for each satellite—although by combining satellite vectors the ambiguity can be reduced to 3 to 6 m of error. Higher precision (subcentimeter) can be obtained with carrier-phase positioning. See carrier-phase positioning. More information is available at the Trimble website: https://www.trimble.com/gps_tutorial/sub_phases.aspx.

CORS— Continuous operating reference station; a U.S.-based system of continuously operating reference (or base) stations. See base station.

cycle ambiguity—The (unknown) number of whole wavelength cycles on the path from satellite to receiver that needs to be solved in carrier-phase processing.

differential correction—A process used to improve the quality of global navigation satellite system (GNSS) survey positions. For a rover GNSS receiver, a correction is created from a nearby base station by taking the difference between the surveyed base station position and the position indicated by the GNSS receiver. The correction is then applied to GNSS data that is not on a known position.

dual frequency—A receiver that can accept L1 and L2 global navigation satellite system (GNSS) signal wavelengths. The different wavelengths help to overcome signal ambiguities resulting from atmospheric distortion of GNSS signals.

ephemeris—Files transmitted by global navigation satellite system (GNSS) satellites, which contain the approximate locations and other information about the satellite that transmitted the file. An ephemeride (file from a single satellite) is more precise than the similar information carried by an almanac; ephemerides are valid for 2 hours and take 30 seconds to download. See almanac. More information is available at the NovAtel website: https://www.novatel.com/support/known-solutions/gnss-ephemerides-and-almanacs/.

epoch—A period of data collection; for example, a receiver that records a position every second has a 1-second epoch rate.

fixed solution—Carrier-phase global navigation satellite system (GNSS) solution with cycle ambiguity constrained to integer value; potentially provides the most accurate solution, but requires high-quality GNSS signals.

float solution—Carrier-phase global navigation satellite system (GNSS) solution with cycle ambiguity estimated with a decimal (floating point) value.

Galileo—European Union's global navigation satellite system. See figure 8.

GLONASS—Russia's global navigation satellite system. See figure 8.

GNSS—Global navigation satellite system (e.g., GPS and GLONASS); a constellation of satellites orbiting the Earth, designed for positioning on the Earth. The satellites transmit positioning information, which is used by a GNSS receiver near the surface of the Earth. The GNSS receiver has a series of finely tuned sensors that record transmitted GNSS signals from multiple satellites and use this information to solve for the position of the receiver on the ground. See code phase and carrier phase positioning.

GPS—Global positioning system. United States global navigation satellite system. See figure 8.

high-performance global navigation satellite system (HPGNSS)—Enhanced technical specifications (differential postprocessing, dual-frequency global navigation satellite system signal reception, higher quality receiver characteristics, >15-minute occupations, etc.) used by the USDA Forest Service Pacific Northwest Forest Inventory and Analysis (FIA) program to consistently provide accurate FIA plot coordinates across highly-variable forest conditions.

horizontal root-mean-squared error (HRMSE)—A common quality metric in surveying, based on direct comparison of observed global navigation satellite system positions and reference points with known coordinates (see the "Rover-to-reference accuracy assessment approach" section of this report).

ionospheric delay—Difference in the propagation time for a signal passing through the ionosphere compared with the time for the same signal to pass through a vacuum. The magnitude of the delay is a function of the time of day, latitude, season, solar activity, and observing direction. Ionospheric delay is frequency-dependent and can be corrected by comparing signals that are affected differently by the atmosphere.

L1, L2, and L5—Signals with different wavelengths transmitted at different frequencies by global navigation satellite system satellites.

multipath error—Occurs when multiple GNSS signals (direct and non-line-of-sight) arrive at the GNSS receiver at the same time, causing ambiguity in the pseudorange measurement.

non-line-of-sight (NLOS) signal—When only a reflected signal is received by a global navigation satellite system receiver from a given satellite and a line-of-sight (direct) signal is blocked by surrounding structures, vegetation, or terrain.

occupation—A single instance of a global navigation satellite system receiver collecting data on a point.

positional dilution of precision (PDOP)—A measure of suitability for the configuration of visible global navigation satellite system (GNSS) satellites for positioning. For example, a low or good PDOP would arise from an even scatter of visible GNSS satellites, and a high or poor PDOP would result from a clustered pattern of visible GNSS satellites near the horizon.

reference station (or "base" station)—A global navigation satellite system (GNSS) receiver that is placed on a known (surveyed) position. The difference between GNSS positions and the surveyed position for a reference station are used to improve rover positioning precision. See differential correction.

rover—A global navigation satellite system receiver used to survey locations; for example, a receiver carried to plot center by FIA crew.

signal-to-noise ratio—This ratio affects the ability of the receiver and postprocessing software to use the signal for positioning.

trilateration—The process of solving for the position of a single point by the intersection of three overlapping circles defined by their radii relative to known locations. The extension of this concept is the basis of global navigation satellite system positioning.

Wide Area Augmentation System (WAAS)—Geo-stationary satellite constellation over North America that is designed to augment global navigation system and improve positioning precision.

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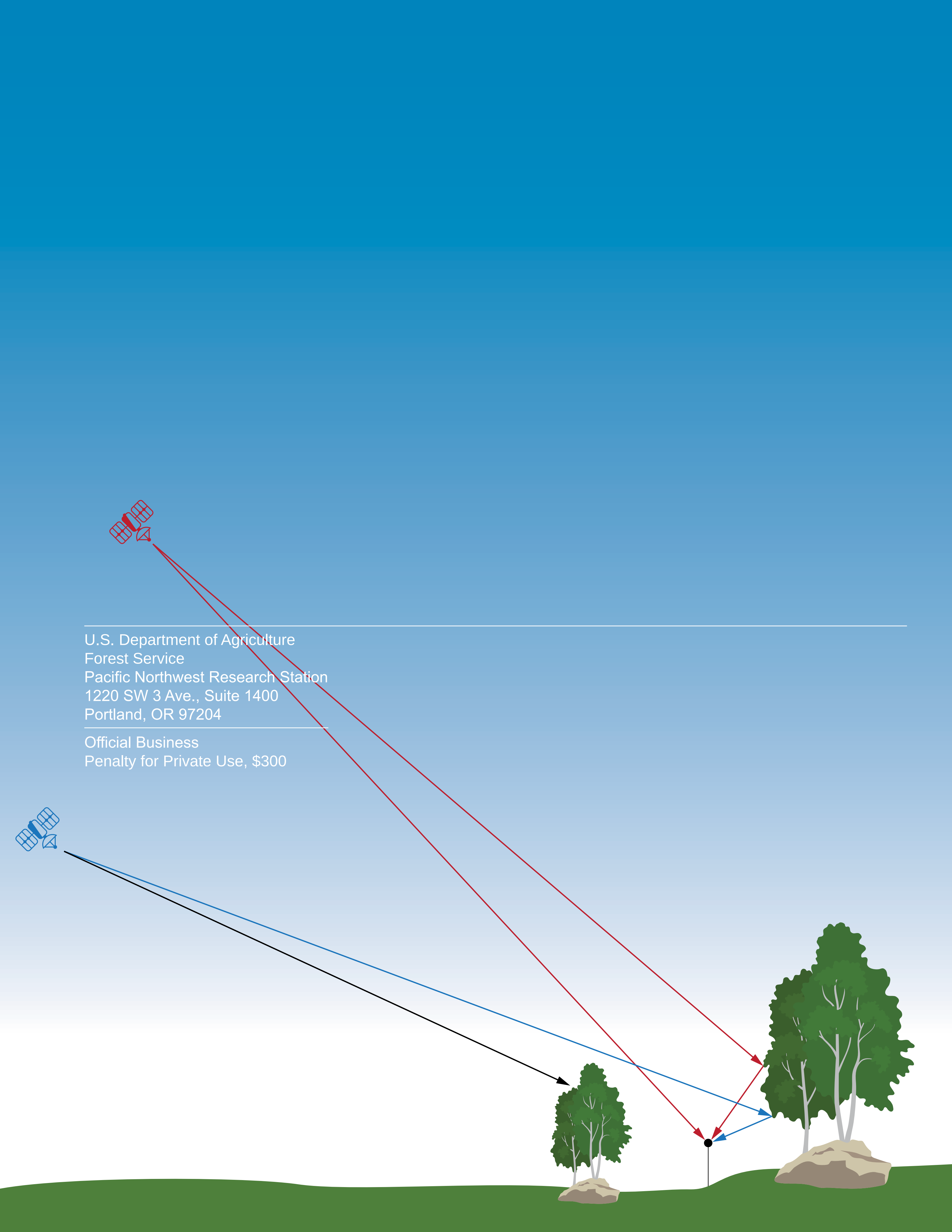

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