The Status of Accurately Locating Forest Inventory and Analysis Plots Using the Global Positioning System

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Abstract.—Historically, field crews used Global Positioning System (GPS) coordinates to establish and relocate plots, as well as document their general location. During the past 5 years, the increase in Geographic Information System (GIS) capabilities and in customer requests to use the spatial relationships between Forest Inventory and Analysis (FIA) plot data and other GIS layers has increased the value of and requirements on measurements of plot locations. To meet current FIA business requirements, it is essential that GPS locations be accurate. The Northeast FIA program (NE-FIA) used Rockwell Precision Lightweight GPS Receivers (PLGRs) in the late 1990s. This moderately priced unit enables accurate navigation and reasonably accurate locations under a canopy without the requirement of differential correction. NE-FIA tested the PLGR on 12 surveyed points (2 nonforested and 10 forested) and determined the average deviation of GPS coordinates from the known point to be 8.0 m with a standard deviation of 2.0 m. On a set of Maine plots measured in 1999 and again in 2004 using the PLGRs, 85 percent of the paired GPS positions were within 12.5 m of each other. Six percent of the paired plots were separated by more than 20 m. These indications of location accuracy are reasonable; however, 15 percent of the plots still have questionable locations. This inaccuracy is a concern for those doing GIS analysis and modeling. In a few cases, gross errors were encountered due to GPS unit malfunction or user error. Furthermore, significant problems with reprojections of plot locations from different datums were identified by additional tests with two different GPS brands on a survey course. Solutions to these problems and proposed FIA GPS protocol recommendations are discussed.

Introduction

During the 1990s, the U.S. Department of Agriculture Forest Service Forest Inventory and Analysis (FIA) program began collecting Global Positioning System (GPS) coordinates for its field plots. Before the use of GPS, plot locations were recorded in the field by pin-pricking an aerial photograph at the image of the center of the plot position. The pinprick on the photo was then transferred to a U.S. Geological Survey map to determine the geographic coordinates. Plot position coordinates provided by GPS should be more accurate and much more efficient to collect and record.

The GPS receiver most used by the FIA program was the Rockwell Precision Lightweight GPS Receiver (PLGR). Its selection as the primary unit by FIA was justified for field work under forest tree canopies. It is relatively lightweight and inexpensive. It uses standard inexpensive batteries. It has five channels, can average multiple position calculations, has a flexible setup menu for customizing position collection and presentation, and provides reasonable accuracies most of the time for both plot location and field navigation under a forest tree canopy. When it was purchased, it had one other advantage over all other GPS units available. Because it was built for the military to be used in battle, the PLGR did not have any position degradation due to *Selective Availability* (SA). SA is an artificial signal degradation that causes location errors of 100 meters or more. Except for the PLGR, GPS equipment required post processing of the field-recorded data, or the errors would routinely exceed 100 meters. Post processing of the many

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GPS positions collected over very large areas required more expensive hardware and software, plus time-consuming efforts to acquire the differential correction files needed to reduce errors. The Federal Government disabled SA on May 1, 2000.

The obvious disadvantage of the PLGR GPS unit is that the positions could not be differentially corrected for errors from atmospheric and ionospheric effects or clock errors. Furthermore, the plot positions had to be manually entered into a data logger (or written on paper), which makes them vulnerable to transcription errors.

FIA plots in some States and public lands were located using GPS equipment that provided differentially corrected results. Differential correction was the exception. The PLGR units now are being replaced by new equipment. Nearly all plots have at least one location provided by GPS. All newly acquired plots will use GPS positioning. Hundreds of FIA data users are relying on accurate locations. How accurate are these locations? Should we collect additional GPS locations on plots that already have a GPS position? What GPS collection methods and GPS equipment purchase decisions might help ensure accurate plot locations?

FIA Plot Accuracy

The Need

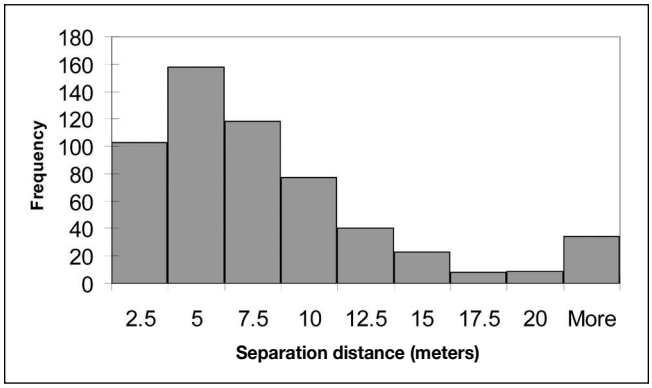
The demand for using FIA plots as a valuable data layer in Geographic Information Systems (GIS) and remote sensing analyses and mapping has increased dramatically since the program started using GPS for more accurate locations. The increase in GIS capabilities and in customer requests to use the spatial relationships between FIA plot data and other GIS layers has increased the value of and requirements on measurements of plot location accuracy. To meet current FIA business requirements, it is essential that GPS locations be accurate. For example, FIA sample stratification requires that plots be as close as possible to true locations to accurately exploit the imagery-plot link. In Connecticut, one-third of the forested plots are within 60 m of the forest edge. An evaluation of the effect of FIA plot and satellite pixel location error indicated that when the combined errors reached 50 m, the resulting forest/nonforest map classification error ranged from 4 to 10 percent (McRoberts and Holden 2006). Recent direction from the national FIA management has charged us with increasing our geospatial product output, a process that also requires the best possible GPS data. The FIA program created a Spatial Data Services Center so customers outside of the FIA program can use the data spatially without compromising plot confidentiality. More than 145 requests for service were received in 2005. As GIS data and imagery (e.g., large scale imagery; State forest land, protected areas and other boundary files) become more accurate, it is absolutely critical that our spatial reference information be as accurate as possible. With accurate spatial locations, not only can we exploit these advances, but also confidently stand behind the data we supply to customers who will be using them.

PLGR Accuracy

FIA plot location accuracy is expected to be as good as that provided by typical resource mapping grade GPS units used by the National Forest System. In general, the PLGR often does not provide the same level of accuracy as the differentially corrected positions of the GPS units used by the rest of the USDA Forest Service. Historically, FIA plot GPS coordinates were intended to assist field crews in establishing and relocating the plots, as well as to document general location. The current edition of the FIA Field Manual requires that the quality (accuracy) of 99 percent of GPS positions be within 42.7 m. The average error of most GPS receivers, including the PLGR, is much lower than 42.7 m, but positions are not that accurate 99 percent of the time. This FIA measurement quality objective cannot be used to indicate the current quality of GPS positioning and is rarely checked or reported.

In field tests of PLGR accuracy conducted by Richard McCullough of the Northeast FIA program (NE-FIA), surveyed markers scattered under a dense 80-ft-tall deciduous forest canopy were located with an average error of 8 m (standard deviation = 2.0 m). By comparison, a set of Maine FIA plots measured in 1999 and again in 2004 using the PLGR reveals similar distance offsets between the measurements in time 1 and those in time 2, with some notable differences (fig. 1). Half

Figure 1.—*Frequency distribution of the separation distance between pairs of Precision Lightweight GPS Receiver positions of 570 remeasured FIA plots (1999–2004).*



FIA = Forest Inventory and Analysis; GPS = Global Positioning System.

the separation distances were less than 5.5 m. Only 20 percent of the distances exceeded 10 m; however, 4 percent exceeded 20 m and 2 percent of the separation distances were greater than 1 km. Small separation distances do not verify accuracy, but rather suggests precision, from which we can infer accuracy. It is unlikely that two GPS units used 5 years apart would give locations of the same ground plot so close together by chance. The most likely reason for this phenomenon is that the units were close to measuring "true" location. Because all of these plots were forested, the PLGR seems to be remarkably accurate on average. The essential field procedure required to determine which plot locations are accurate is to remeasure. Remeasurement identifies a potential inaccuracy with one or both of the GPS coordinates. Users can flag suspect plots and remove them from GIS and remote sensing analyses.

As indicated above, plot location errors of about 20 m can result in map classification errors of 10 percent when combined with common image pixel position errors. Investigators in the North Central FIA unit found the average separation distance of 1,145 remeasured plots was 13.6 m (standard deviation = 46.2 m).

Datum Errors

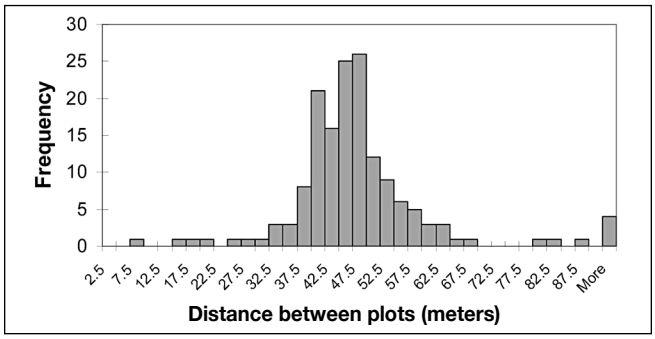
Another source of error with the PLGR, which we have also found to occur in other types of GPS units used by FIA, is an inaccurate datum conversion formula used to convert coordinates of positions from World Geodetic System 1984 (WGS 84) to North American Datum 1927 (NAD 27). Datums define a set of constants specifying the coordinate system used for geodetic control. GPS software calculates coordinates in the datum WGS 84 and coverts them within the unit to display coordinates for other datums selected by the user. Most FIA plots were collected using NAD 27 because most available maps were based on that datum. The conversion formula used in the PLGR causes location errors of about 12 m in the Northeast and other regions. The solution is to collect data in NAD 83, which is nearly identical to WGS 84 and is currently mandated by the Forest Service Handbook 6609.15, Standards for Data and Data Structures. The standard use of NAD 83 will provide more integrated and accurate data, reduce errors in GPS data, and align FIA with the current Agency and Federal standards.

Starting immediately, all FIA GPS coordinates should be collected using NAD 83, and all of the previous collected GPS coordinates acquired using NAD 27 must be converted to NAD 83. To correctly change a coordinate collected in a non-WGS84 datum (e.g., NAD 27) back to WGS 84, and then subsequently to NAD 83, the operator needs to first use the reverse of the transformation method that the GPS unit applied. For example, the NAD 27 coordinates collected by the PLGR can be converted in ArcGIS using the transformation method called "NAD_1927_TO_WGS_1984_4." The GPS unit's documentation or technical support staff can supply the transformation parameters needed. To choose a datum transformation method to apply in ArcGIS, consult http://support.esri.com/index.cfm?fa=knowledgebase.whitepapers.viewPaper&PID=43&MetaID=302. This Internet site lists the transformation method name and the parameters used by ArcGIS to perform the transformation. Conventional wisdom in the GPS community is that it is always appropriate to use North American Datum Conversion (NADCON) to transform any NAD 27 GPS coordinate to NAD 83. This assumption is generally correct, unless your GPS does not use NADCON to convert from WGS 84 to NAD 27. If NADCON is used with PLGR data, the location errors are retained.

Another datum error common with the PLGR is the unexpected (and unknown to field crews) reversion of the unit to its default datum, WGS 84, without the user selecting it. In several

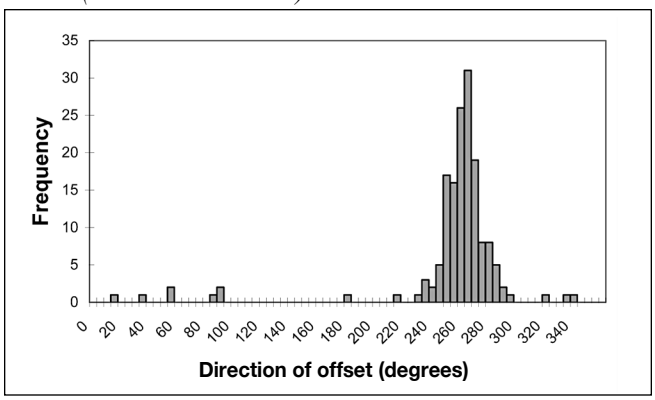
regions in the northeast, all the FIA plot locations were found to have been collected in WGS 84 instead of the "selected" NAD 27. The reason for this uncommanded reversion is unknown, although battery power interruption is suspected. The discovery was made when many of the plots in the region were remeasured. Had this not been the case, there would be no way to tell that the separation distances of the coordinates were averaging 50 or so m in one general direction of 260 degrees. Normally the separation distances would be expected to be less than 10 m and bearing randomly in all directions. If the distance separation between remeasured plot locations are all about the same distance and bearing as a map coordinate varies between NAD 27 and NAD 83, it is likely to be caused by collecting the plots in WGS 84 instead of the assumed NAD 27 datum (figs. 2 and 3). The lesson is clear: collect FIA plots in NAD 83 (coordinates are within 1 m of WGS84) and remeasure all plots until the accuracy is confirmed.

Figure 2.—*Frequency distribution of the separation distance between pairs of Precision Lightweight GPS Receiver positions of 157 remeasured FIA plots (1997–2003) where it is highly likely that all or most of the measured pairs are acquired using different datums (NAD 27 and NAD 83).*



FIA = Forest Inventory and Analysis; GPS = Global Positioning System; NAD = North American Datum.

Figure 3.—*Frequency distribution of the direction between pairs of Precision Lightweight GPS Receiver positions of 157 remeasured FIA plots (1997–2003) where it is highly likely that all or most of the measured pairs are acquired using different datums (NAD 27 and NAD 83).*



FIA = Forest Inventory and Analysis; GPS = Global Positioning System; NAD = North American Datum.

GPS Replacements for the PLGR

During the past few years, FIA has replaced the PLGR with no fewer than six other brands of GPS hardware with various combinations of software and system configurations. This replacement is due mainly to increased hardware problems with the PLGR because of extended field service. Choice of replacement units is still very much influenced by a combination of capability and cost. NE-FIA required 60 replacement units, so cost was a big issue. Several units were tested on a surveyed field course with markers both under a heavy forest canopy and in the open. The GPS unit finally selected has 12 channels, a built in real-time differential correction system called Wide Area Augmentation System (WAAS), and the ability to radio the position to a field datalogger for electronic storage using Bluetooth technology. NE-FIA helped in the design of the software that resides in the field datalogger, which has a detailed setup menu allowing the selection of datum, PDOP limits (PDOP is a measure of accuracy based on the geometry of well-spaced GPS satellites), and the ability to average multiple positions. Multiple field tests of this system over several months show an error of 5.5 m (standard deviation = 3.2 m) under a dense 80 ft deciduous canopy. In the open, the root mean square error (RMSE) was 2.2 m (standard deviation = 0.9 m).

Multiple studies of how well a dozen currently available resource mapping and consumer-grade GPS systems function under forest canopies have been recently published (Bolstad *et al.* 2005, Piedallu and Gegout 2005, Sigrist *et al.* 1999, Tucek and Ligos 2002, Wing *et al.* 2005). These studies indicate that the sophistication of GPS equipment has a significant affect on position accuracy. Furthermore, accuracies are much better in the open than in forested areas. What is surprising is that the average error of all of the units, except one, was less

than 7 m under a closed forest canopy. Another useful fact was that differential correction has much less effect on the accuracy of forested plots. Apparently, errors caused by multipath signals due to signal reflections off trees are much greater than the errors that differential corrections can reduce (Piedallu and Gegout 2005). In one study, no significant differences were found between GPS units using WAAS-corrected, differentially corrected, and uncorrected positions (Bolstad *et al.* 2005). WAAS requires the GPS unit to receive a position correcting signal from a satellite. The signal can be blocked by trees and other obstructions. Within a mature forest, the signal may be available less than 50 percent of the time (Bolstad *et al.* 2005). Artificially introduced errors from a SA signal could change the value of differential corrections in the future.

These studies point out the following techniques that could help FIA crews lower errors:

- Raising the antenna height to at least head height or higher increases accuracy (Bolstad *et al.* 2005, Sigrist *et al.* 1999).
- The higher the PDOP, the worse the accuracy. Under a canopy, however, a requirement for a low PDOP may cause very long acquisition times and more error due to multipath signals because the unit is forced to use satellites lower on the horizon that have to send their signal through more trees. PDOP under a forest canopy is 35 percent higher than in the open. Consider using a PDOP limit of eight (the standard is six) under a heavy forest canopy when PDOP stops position collection (Sigrist *et al.* 1999). In general, lower PDOP produce more accurate positions under a forest canopy (Piedallu and Gegout 2005).
- Turn the GPS on in the open and then walk into the forest. It takes five times more signal strength to initially acquire a signal than to keep it (Wilent 2002).
- More expensive GPS units are more accurate under all conditions (Piedallu and Gegout 2005).
- Position errors decrease linearly with the logarithm of the number of position calculations averaged into a final position. Don't limit the number too much.
- The bigger the nearby trees, the worse the accuracy. Offset plots near big trees (Piedallu and Gegout 2005).

FIA GPS Considerations

- Remeasure all GPS plot locations. A single FIA plot location provided by GPS cannot be determined accurate unless it is compared to a reference. Digital ortho quads could be used to evaluate accuracy, but no proven protocol exists. How many times should a plot be remeasured and what should the threshold for separation distance be for acceptable accuracy? Because the current industry average for GPS accuracy under a forest canopy is about 5 m, a reasonable FIA measurement quality objective (MQO) would be three separately calculated GPS locations all within 10 m of each other. At that time, an average of the three positions will be calculated for the final plot location. Keep all GPS locations in the database for users to evaluate. If the program must have an "official" location for each plot, then use the last one collected. After meeting the MQO, the calculated average shall be the best and final position for the plot unless some other evidence indicates an error.
- Begin recording GPS in NAD83, which is currently an Agency requirement. Convert all plot locations previously collected in NAD27 to NAD83 using the correct procedures as described above. This conversion will require careful attention to maintaining records in the database. Always keep a copy of the original record.
- Build into the data recorder a way to flag a measurement that is more than a specified number of meters (e.g., 20 m) from the position that the field crew is directed by the office staff to locate (indicated in the datalogger by "office_lat /long"). This could be done via a mathematical equation and an if/then statement, which would raise the chances of catching gross errors in the field.
- Standard metadata should be developed for all GPS information. These data should include the equipment serial number, date, datum, number of positions averaged, and other parameters required by the FIA program.
- Require that all field crews, including contract crews, receive adequate training for the field collection of GPS positions.
- Create a FIA GPS steering committee to include data collection staff, analysts, and techniques development

members. Require all GPS equipment that is used to provide official plot locations be approved by the committee after evaluating approved field test results.

The GPS coordinate is one of the most important single measurements taken on the plot. It is in no way analogous to measuring aspect or slope (which is measured with basically foolproof, mechanical devices, and which does not contain many numerical values). Rather, it is prone to hardware, software, operator, and random, unexplainable errors. As we have shown, systematic, gross errors exist in the current GPS data. Every GIS analyst in FIA is intensely concerned with this issue, and it is vital that we address it immediately at both a local and national level.

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