Locating and Mobile Mapping Techniques for Forestry Applications

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Abstract
Forest management activities include locating and mapping management boundaries, transportation networks, streams, landscape topography, forest resources, and special management areas. Locating and mapping tasks associated with forest management have traditionally been performed using manual measurement techniques with varying degrees of precision, accuracy, and efficiency. This paper examines the use and capabilities of contemporary digital measurement tools including laser range finders, global positioning systems (GPS), and total stations, in combination with geographic information systems (GIS), to digitally capture and map data associated with forestry activities. The potential contributions of these digital approaches over traditional data collection techniques are discussed. In addition, digital location-based technology advancements that might benefit forest management and planning are identified.
Keywords
forest measurements, GPS, total station, GIS, and range finder

I. INTRODUCTION

Traditional forest management techniques include locating and mapping significant forest resources including stand boundaries, transportation networks, streams, landscape topography, forest resources, special management areas, and other features. Forest resource measurement and mapping tasks have been typically performed through manual survey techniques with variable precision, accuracy, and efficiency (Kellogg, et al., 1998; Wing, Kellogg, 2001). Inaccuracies in location and mapping activities often result in adding to forest management costs, and in some cases may lead to safety concerns. The tasks that are associated with forestry in the U. S. have become more demanding as the focus of forest management has shifted to accommodate multiple goals in addition to timber production (Committee of Scientists, 1999). Forest managers have turned to uneven aged techniques such as patch cutting, selective thinning, and multiple entries in order to accommodate multiple forest goals (Kellogg, et al., 1996). The consideration of multiple goals in forest management places greater demands on the accuracy and reliability of forest data that must be collected to support management decisions. Employing technologies that can collect and analyze forest data more efficiently and accurately than through traditional or manual means is a way to address heightened data requirements. Examples of technological tools include, but are not limited to, laser range finders, global position systems (GPS), total stations, and geographic information systems (GIS). These tools are designed to capture, manipulate, and/or analyze spatial data.

This paper describes the current use, capabilities, and limitations of laser range finders, GPS, total stations, and GIS to digitally capture and map data associated with forested resources, and identifies advancements that could promote digital applications in forestry. These digital tools currently comprise the basis of field-based approaches to measure, locate, and analyze forest features. A laser range finder can measure distances to objects up to 200 meters away to within several centimeters of their actual locations. A GPS can provide coordinate locations of objects to within meters of their actual location but are often limited in forested settings due to canopy cover and topographic conditions. Digital total stations can, with careful use, record the locations of objects to less than a centimeter of actual location. A GIS can verify, analyze, measure, and map data that have been collected by these digital measurement tools. Each of these precision measurement tools is within the budgets and operating capabilities of most organizations that manage forests and many organizations already own GIS, GPS, and other digital equipment, although the actual use of these technologies varies between organizations. A strong need currently exists to identify and apply digital technologies that can increase the effectiveness of forest management so that the multiple resources and values expected from forests can be better provided. The demonstration and comparison of the potential uses and benefits of precision digital tools over manual techniques may help forest management organizations identify opportunities to improve spatial data collection and analysis tasks.

II. HANDHELD RANGE FINDERS

Handheld digital range finders can calculate distances and, in some cases, vertical angles between an instrument operator and an object (Figure 1). Wing and Kellogg (2001) examined laser range finder use for collecting skyline corridor and harvest boundary measurements. In general, the range finder was found to be faster and more accurate than manual measurement techniques but brush and other understory conditions often resulted in difficulties in attaining a line-of-sight between the

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Figure 1. Handheld digital range finder

operator and potential targets. Other studies have examined laser range finder use in traversing stand boundaries (Liu, 1995) and estimating wood pile volumes (Turcotte, 1999) and have found the distance measuring capabilities to be beneficial and faster than those provided by manual measurement tools. In addition, collected data could be stored through digital means, leading to increased efficiencies in database creation. Moll (1992) used a digital laser range finder equipped with a digital compass for low-volume road surveys and noted a 60% time savings in comparison to manual techniques involving a handheld tape, compass, and clinometer. Accuracy assessments, however, for this study revealed that the azimuth (horizontal angle) measurements did not meet the survey requirements; difficulties with azimuth measurements were judged to be a function of the vertical angle at which the operator held the digital compass and instrument reliability. Typically, achievable accuracies in digital compass use is between 1–5 degrees () and vertical tilting of a compass in excess of 10–15 degrees will lead to errors in direction (Grejner-Brzezinska, 2004). Consequently, laser range finder operators should always verify angular measurements as they are being collected since the accuracy and reliability of these measurements has proven suspect.

Range finders vary in operation depending on the manufacturer; some depend on laser pulses while others utilize sound waves. In both cases, however, it is the length of time that it takes for a laser pulse or sound wave to travel between an instrument and target that determines a distance. Laser-based range finders may offer the option to utilize reflective or non-reflective targets, but users will typically find that distance measurements will occur with greater accuracy and reliability with a reflective target. Sound-based range finders offer an advantage over laser-based range finders in that a line of sight is not required between an instrument and target, and operators are not hindered by overly-bright or dark field conditions. A shortcoming to sound-based range finders is that they may be limited to distances of 50 meters or less, as sound waves diminish over space. In addition, other loud or steady noises, such as those generated by a stream or harvesting machinery, may interfere with sound-based range finder operation.

Vertical angle capability is important for many forestry applications including elevation profile measurements and in the calculation of heights, including trees and equipment. Most digital range finders provide vertical angle measurement capability and in some cases will allow an operator to calculate slope distances, which is a function of vertical angle measurements. In addition, some range finders allow the calculation of vertical heights, but may require a solid target. Locating a solid target may be a challenge when attempting to measure a tree's height, as the upper portions of trees do not always provide suitable targeting areas. If directional information is needed in addition to distance measurements, some range finders have digital compass abilities that can calculate and store direction information in conjunction with distance measurements.

Range finder prices vary from several hundred to several thousand U.S. Dollars depending on features, accuracy, and reliability. Potential purchasers should carefully assess their measurement needs and very specifically, the level of accuracy required for measurements. There are usually reasons for price differences between instruments and potential purchasers should not base decisions on price alone. Wing et al. (2004) examined several commercially available digital range finders through a series of forestry measurement trials and found that while most performed within the accuracy ratings claimed by manufacturers, significant differences existed in instrument capabilities and reliability. These differences included the practical measurement ranges, ability to penetrate understory, and the types of measurements that were possible (e.g. horizontal distance, slope distance). In addition, Wing et al. (2004) found that while some range finders were impervious to weather fluctuations, others tended to be negatively affected by conditions such as rain. Given the range of weather conditions that foresters typically operate within, the ability of a measurement instrument to withstand a variety of conditions is a necessary characteristic. Table 1 provides a summary or range finder and other digital measurement tool characteristics.

III. GPS

GPS hardware continues to become more affordable and conveniently packaged but still faces challenges to effective use in forested settings. Elements than can affect GPS use in

Table 1. Digital measurement tool cost, accuracy, and use summary

Digital Instrument	Cost	Distance Measurement Accuracy	Line of Sight Required	Ruggedness	Ease of Use
Laser Range Finder	\$400 – 2500		Yes	Medium	Easy
Sound-based Range Finder			No	Medium	Easy
Consumer GPS	\$100 – 500	2 – 7 m	No	High	Easy
Mapping GPS	\$2000 – 12000	1 – 5 m	No	Medium	Moderate
Survey GPS	> \$25000	< 1 cm	No	Low	Difficult
Total Station	> \$6000	< 1 cm	Yes	Low	Difficult

a forested setting include canopy closure (Stjernberg, 1997, Karsky, et al., 2000), GPS receiver quality (Darche, 1998), landscape topography (Liu, Brantigan, 1996), and environmental conditions (Forgues, 2001).

There is a wide variety of GPS equipment currently available to consumers and numerous new products appear every year. At the most basic level, a GPS consists of a variety of components that must work in tandem for successful measurement including an operator, receiver, antenna, data collector, satellite system, and satellite monitoring station(s). The operator's major input is with the receiver, antenna, and data collector. There are several GPS satellite systems orbiting the earth at present but only the U.S. operated NAVSTAR system freely provides consistent worldwide coverage to GPS users. The Russian Glonass system has been unreliable and a European-based Galileo system is expected to be fully operational in 2008. Regardless of the satellite system, a GPS antenna must receive at least four satellite signals simultaneously to compute a reliable position on the earth's surface. Positions are calculated based on the amount of time it takes a satellite signal to reach a GPS antenna. Successfully recorded positions can be stored in a data collector and can be later transferred to a computer for display and analysis. Perhaps the greatest challenge to using GPS within a forested setting is that presented by forest canopy. GPS receivers must be able to continuously detect and process satellite signals in order for coordinate locations to be calculated. Forest canopy can degrade the signal strength or prevent the signals altogether from reaching a receiver. In addition, canopy can result in signal multipathing, a situation in which a signal reflects off of a surface before reaching a GPS antenna. Multipathing can also result from other solid objects, including vehicles and structures, and will vary based on satellite geometry as well as GPS receiver hardware. Regardless of the source, multipathing results in excess time being attributed to the travel path of a satellite signal and can lead to incorrect position calculations. Multipath errors are often unpredictable in magnitude and direction but can reach 20m depending on the type of satellite signal being captured and processed by a GPS receiver (Hofman-Wellenhof, et al., 2001).

Liu and Brantigan (1996) directly compared the ability of a differential GPS with a chain and compass for measuring land areas. Differential GPS involves using a roving, or mobile, GPS unit in coordination with a fixed base GPS station at a known location. The location that the GPS base station calculates from satellite signals is compared to its known location.

Location differences are used to correct potential measurement inaccuracies from the roving GPS unit. Although Liu and Brantigan(1996) found that variations in GPS measurements were affected by canopy closure and topography, forest stand area measurements derived from GPS were superior to those produced by chain and compass manual measurement techniques.

Sigrist et al. (1999) found that as forest canopy increased, GPS measurement ability and accuracy decreased. The relationship between canopy closure was determined to be exponential in character; small increases in canopy cover often resulted in very large increases in location error. Holden et al. (2001) also investigated the influence of canopy cover on differential GPS and determined that open canopy conditions led to a 2–3 fold decrease in measurement ability whereas closed canopy resulted in a 4–5 fold degradation of measurement ability.

There are three broad grades of GPS hardware available: survey, mapping, and consumer grade. Survey grade GPS will typically cost users in excess of \$25000 but can provide measurement accuracies within one cm of true position when used properly (Rizos, 2002). Proper application and use of survey grade GPS requires advanced knowledge of GPS principles (Van Sickle, 2001). Unfortunately, survey grade GPS require satellite signal consistency and quality that is often unachievable under forest canopy, or only available for brief periods. Survey grade GPS is therefore presently of very limited use in forestry applications although this may change in future years as satellites that are capable of transmitting more powerful electromagnetic signals are launched.

Mapping grade GPS cost approximately \$2000–12000 and are capable of accuracies within several meters of true position. Within a forestry context, these systems are also limited by interference of satellite signals resulting from canopy cover (Karsky, et al., 2000). Users can identify the best periods for data collection through mission planning software. Mission planning software can enable users to identify periods when satellite availability is high and measures of optimum satellite reception (e.g. Position Dilution of Precision- PDOP) indicate the best times for field data collection. Mission planning software for GPS can be accessed free of charge on the WWW but may sometimes prove unreliable. Potential users may want to purchase mission planning software from a reputable GPS manufacturer to maximize mission planning effectiveness. Regardless, the influence of forest canopy can only be estimated and it may be that even under ideal data collection periods, as identified by mission planning, that sufficient satellite coverage is not available to consistently collect location data in a forested setting.

A typical mapping grade GPS will include an antenna, receiver, and data collector that work in tandem to collect, process, and store location data (Figure 2). This instrument setup results in several pieces of equipment, accompanied by communication cabling, that can present physical challenges in efficiently collecting forest data. Recently, some manufacturers have created mapping-grade GPS that are contained within a single handheld unit but measurement accuracy in these units is typically less than other mapping grade GPS that feature multiple components (antenna, data collector, and receiver) packaged separately. Data collectors for GPS have traditionally been a significant cost ($2000–5000) but some GPS users have turned to using hand-held PDAs (Personal Digital Assistants) that offer more affordable and versatile alternative to traditional data collectors. PDAs and other digital data collectors may also be used with range finders or other digital measurement equipment to capture, store, and display spatial data.

Figure 2. Mapping grade GPS

A PDA costs about $500, typically features a color display, and can run handheld-based mapping software while allowing users the flexibility to store other digital files, such as digital orthophotograph and topographic map images, that can enhance the data collection process (Figure 3). One disadvantage of the PDA is its fragility. Continued exposure to rain or rough handling can result in a PDA becoming unusable and the operator may lose any data that were collected. While costing more, field data collectors (Figure 4) may provide more reliability for forestry applications than the

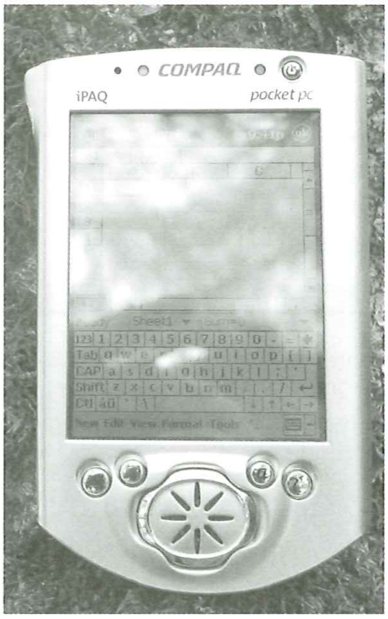

Figure 3. Personal digital assistant (PDA)

Figure 4. Field data collector

lesser priced PDA.

Digital data collectors have many advantages for GPS and laser range finder operators. Users can view their position, and the location of features from which they have gathered location information, in reference to other digital files and thus gain confidence in their field data collection process. Digital images may also enhance field data collection safety by identifying proximity to potentially hazardous locations, such as ongoing forest operations or steep topography, and reduce the probability of becoming lost. Some PDAs can accommodate Bluetooth wireless communication technology (Krishnamurthy, Pahlavan, 2004). Bluetooth technology enables a personal networking environment, limited to about 10m around supporting hardware, through which digital devices can be connected This technology removes the need for physical cabling between hardware devices, reduces the amount of equipment that must be taken to the field and allows GPS data collection personnel to operate more freely. A GPS has recently become available, the SXBlue GPS, that is designed to operate specifically with Bluetooth technology. In addition, the SXBlue reportedly can gather location information under a forested canopy for up to 45 minutes once a solid GPS signal has been attained. A peer-reviewed assessment of SXBlue accuracy and reliability has yet to be published.

Consumer grade GPS are usually handheld units (Figure 5) that are contained within a single device; the GPS antenna, receiver, and data collector are all integrated into one unit. Prices range from approximately $100–500 for a consumer grade GPS. With the disabling of Selective Availability by the U.S. Government in 2001, manufacturer estimates of accuracy typically claim that consumer grade GPS positions should fall within 15–20 meters of actual location. A recent development in terms of potential satellite availability and signal quality is the Wide Area Augmentation System (WAAS). WAAS is currently available only for GPS operations in North America and presently features two operational WAAS satellites although more are expected in the future. Designed to aid to airborne navigation, WAAS signals are only intermittently available to on-the-ground GPS users due to obstructions between GPS receivers and satellite positions. At present, consumer grade GPS manufacturers in the U.S. claim that WAAS signals will increase the accuracy of consumer GPS units to within three meters of actual location. While there is a future potential for GPS that utilize WAAS technology to consistently attain these accuracies, it is premature for users to expect such performance at present due to the limited number of available satellites.

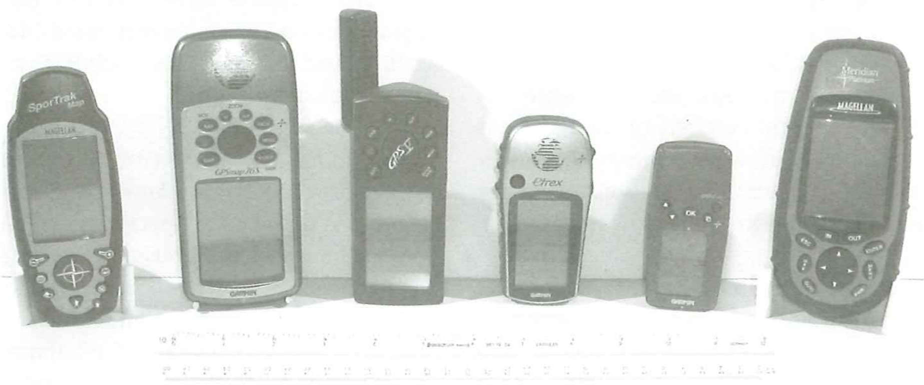

Figure 5. Consumer grade GPS

Given their inexpensive cost, consumer grade GPS may yield accuracies that are acceptable for some forestry mapping activities. Shannon et al. (2001) found that consumer grade GPS had an average accuracy of 2.4 m in precision agriculture applications. Wilson (2000) found that a consumer grade GPS receiver had a horizontal error distance of 7.1m. In an examination of mapping and consumer grade GPS, Karsky et al. (2000) determined that with good satellite geometry (PDOP) under a moderate forest canopy, consumer grade GPS receivers are capable of providing accuracies suitable for forestry applications. Nonetheless, a rigorous appraisal of consumer grade GPS accuracy and reliability for forestry applications has yet to be published.

In general, GPS consumers should expect continued advancements in GPS applicability during the future. In addition to more satellite systems becoming available, several communication frequencies are expected to become available, hardware quality should improve and reduce in size, and resistance to multipath errors should become more robust (Grejner-Brzezinska, 2004). Also, the prevalence of GPS basestations, from which users can make locational corrections should increase.

IV. TOTAL STATION

A digital total station (Figure 6) can calculate highly accurate and precise measurements of forested features to less than a cm from actual locations (Kavanagh, Bird, 2000). Available measurements include distances and angles in both horizontal and vertical dimensions. For accurate and reliable measurements in a forested setting, the total station still has few equals. The total station operates very similarly to a handheld laser range finder in that a beam of light is emitted from the instrument, reflects off of a target, and is sensed by a receiving lens (Wolf, Ghilani, 2002). Distances are computed as a function of the time that elapses during the light beam's travel. Typically, a reflective prism is used as a target. Although digital total stations can also operate with reflector-less targets, measurements will typically be more reliable with a reflector, such as a prism. Digital total stations

Figure 6. Digital total station

cost approximately $6000–12000 for manually operated instruments, and robotic versions are available for approximately $30000. Robotic versions of total stations greatly increase the efficiency of measurements when only one operator is available. Robotic total stations allow for remote control of targeting and measurement operations.

Considerable care must be taken in the operation of a total station including instrument leveling, registration of instrument position to a known or assumed location, and proper recording of instrument and target heights. These procedures typically require an additional investment of time for total station users that is greater than that required by handheld laser range finders or GPS. In addition, whereas handheld range finders and GPS are somewhat forgiving and user-friendly, proper total station use requires that operators be well-versed in instrument use and data collection, transfer, and processing procedures. Total stations also require that a line-of-sight exists between the instrument and target, and that great care be taken in instrument leveling and handling. Despite its limitations, a total station remains the most reliable instrument for gathering accurate and precise locational measurement data in forested settings.

V. GIS

GIS use has become a staple for many natural resource organizations and provides an avenue for organizing, viewing, analyzing, and mapping data collected by range finders, GPS, and total stations (Wing, Bettinger, 2003; Bettinger, Wing, 2004). Many forestry organizations that are interested in hiring view GIS skills or familiarity as a desired skill (Wing, 2001) and GIS coursework is now often a requirement for forestry students (Wing, Bettinger, 2003). GIS use spans a wide range of activities in forestry organizations from merely serving as a mapping tool to providing the basis for spatial modeling in scheduling forest operations over decades or centuries of time. Through its adoption as standard tool for most forestry organizations, GIS has emerged to become one of the most profound developments in forestry to ever occur.

There are multiple GIS software manufacturers worldwide but the majority of GIS users use software by Environmental Systems Research Institute(ESRI) or Intergraph Corporation. Both manufacturers produce a suite of GIS software products that allow organizations to select the software functionality they need for their specific GIS activities. In general, organizations can choose from among lesser-featured "desktop" or full-featured "workstation" software and can expect to pay between $1000–15000 depending on the version(Bettinger, Wing, 2004). There are often other costs that should be considered in choosing a GIS including software maintenance, operator training, and necessary peripherals such as plotters and data storage. Organizations should also consider whether their GIS needs to be Internet-based or have Internet capability. Increasingly, organizations are using Internet-based GIS to make spatial data available and to extend GIS capabilities to organizational users and clients(Karimi, 2004).

A GIS product that has recently begun to receive wide use for forestry data collection is ArcPad GIS software by ESRI. This software is designed to operate on a PDA and sells for about $500. Given the broad use of ESRI software by forestry organizations, ArcPad has become a preferred field-based GIS software that allows the seamless use of data structures on both PDA and workstation GIS platforms. A similar product, TerraSync, is produced by Trimble and provides many of the same features as ArcPad. TerraSync was specifically created to operate in tandem with Trimble GPS products but can also used with equipment from other manufacturers. Both ArcPad and TerraSync allow users to synchronize PDA operations with a GPS receiver and has user-intuitive tools for viewing available satellites and monitoring the potential strength of satellite signal reception. Users can configure GPS collection defaults so that only signals that meet minimum quality standards can be used to calculate positions. Users can immediately view their position, and GPS-collected data points, and background data layers, such as transportation networks and digital orthophotographs. Users can also attribute data points they collect, so that descriptive information can be added to the digital files during the field collection process.

VI. INTEGRATION OF DIGITAL TECHNOLOGIES

It is unlikely that a single digital measurement tool will completely fulfill an organization's measurement requirements. Increasingly, forestry organizations are integrating multiple digital data collection technologies to meet management goals. An example of such an approach might be establishing the location of a forested road system and associated culverts that facilitate hydrological drainage and potential fish passage.

The length and number of features to be measured, accuracy requirements for road and culvert features, time and personnel available would dictate whether GPS, or some combination of digital instruments will meet measurement objectives. If a road system is of any appreciable size (>10km), it is unlikely that a total station could efficiently be used for this process due to the time required for instrument setup and the need for a sighting target. Additionally, the need for a sighting target would likely also rule out use of a laser range finder as a tool for efficiently traversing the road system.

One solution would be to drive a truck-mounted GPS along the road system, capturing location points at selected time or distance intervals, or at every significant change in direction in the road system. Satellite reception would likely be worst at the margins along the roads, which would contain many of the culverts. The GPS logging process could be paused at culvert locations and field personnel could use a laser range finder and digital compass combination to record culvert locations relative to the current location of the truck-mounted GPS. If highly accurate measurements were required for culvert location relative to the road, or for culvert dimensions (diameter, inclination), a total station could also be used to record this information. The range finder or total station could also be used to measure road distances when satellite availability was poor or heavy canopy prevented sections of the road from being measured by a GPS.

The road and culvert locations could be viewed within a GIS to check for consistency and multipath errors. Viewing other spatial databases, such as streams, digital elevation models, or forest stand boundaries simultaneously with the roads and culverts in a GIS may help detect errors. Field crews could revisit any locations where data collection or multipath errors are detected and recollect data to fix the errors. Any corrected data could be entered into to create final road and culvert spatial databases. In addition, as changes to the road system and culverts are made over subsequent years, the measurement tools can be used to collect measurements of the changes, and GIS can be used to integrate changes into the final spatial databases.

VII. DISCUSSION / CONCLUSION

As with many disciplines that place an emphasis on collecting and using locational data, spatial accuracy requirements for forestry applications are shifting to place greater importance on correctly and reliably locating features of interest. This emphasis may be greater for forestry organizations in comparison to other disciplines given the increased value and expectations that society expects from forested resources today.

Foresters have relied for many years on analog measurement tools including tapes, clinometers, string boxes, and compasses to supply data required for forest management purposes. These analog devices are gradually being replaced by contemporary precision digital measurement tools. Digital precision instrument use in forestry has tremendous potential advantages over manual methods of data collection including the speed at which measurements, particularly over long distances, can be taken. In addition, the accuracy and precision of measurements taken by digital instruments can be superior to those captured by manual tools. With digital data collection, databases can be created rapidly and can be transferred to a GIS for inspection, analysis, and mapping. This digital database creation process can reduce the opportunity for error as data no longer needs to be transcribed in a field notebook and then entered manually into a digital database.

Despite these potential advantages, there remain challenges to digital precision instrument that must be surmounted for these tools to become ubiquitous in forestry applications, including expense, ease of use, and reliability. Digital equipment often involves an expense that exceeds those of manual measurement tools, and includes instrument components that may be much less robust to use impacts and adverse weather conditions. Some users are also hesitant to adopt digital technology as it involves additional knowledge and skills beyond those required by manual instruments. Digital equipment often requires multiple components that must be linked by cabling and that rely on one or more energy sources to operate. Should cables or energy sources fail, users may have to abandon data collection and return at a later date once the difficulties are solved. There is also an uncertainty with digital data collection that is unresolved until the data are downloaded and examined in an office setting. These uncertainties revolve around whether all data of interest have actually been saved to the database and whether the data can be successfully extracted.

Although a variety of range finders, GPS, and total stations are available to forestry organizations, there is no single instrument today that can serve a majority of measurement requirements. A need currently exists for an affordable yet rugged measurement instrument that can reliably collect distance and directional information between points or other objects. If this instrument did not depend on an reflective target, it could be operated efficiently by one person for many measurement applications. The preferred instrument should be housed in a single unit, or should make use of reliable wireless technology if multiple units exist, so that cables do not hinder field activities.

A GPS-based system will probably have the greatest likelihood of meeting these qualities but some years, perhaps decades, will be needed before the combination of satellite availability and signal strength are capable of providing consistently reliable reception through canopy and in mountainous terrain.

Another need for forestry-based digital applications would be the strengthening of wireless technology so that field-based personnel could communicate and exchange data with a centralized office over long distances. This communication would allow databases, that were not taken to the field but became necessary in support of field operations, to be uploaded and accessed by field personnel. In addition, field personnel could potentially immediately upload databases that they had collected to the centralized office so that the databases could be examined and, if necessary, clarifications or corrections be directed toward field personnel. This capability might reduce the number of field visits required and increase the likelihood that the appropriate data were collected.

Forestry organizations may also benefit from more robust field-based GIS software designed to operate on a handheld computer. Although several field-based GIS packages exist (eg. ArcPad, TerraSync), they are limited in capability, including the ability to edit spatial databases and to integrate multiple databases into a cursory analysis. In addition, the number and size of databases that can be taken to the field is often restricted. These limitations are in part due to the hardware and operating system capabilities of PDAs and handheld computers that are typically used for data collection in the field and also partly due to a lack of software sophistication. Field personnel may benefit from having field based GIS available that allow greater versatility in accessing and analyzing spatial databases. In particular, being able to view high resolution imagery, such as that produced by digital aerial photographs or digital elevation models may lead to greater efficiency and safety in field operations.

Regardless of the current challenges to digital precision instrument use in forestry, technological advancements will continue to lead to new instruments that can benefit forestry. Advancements will result in digital instruments and software that are more accurate and reliable, easier to operate, and more flexible in the types of measurements that can be collected.

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