The Italian National Forest Inventory: Geographical and Positioning Aspects in Relation to the Different Phases of the Project

Giacomo Colle[1], Antonio Floris[2], Gianfranco Scrinzi[3], Giovanni Tabacchi[4], and Lorenzo Cavini[5]

Abstract.—In this article, we describe in depth the analysis and solutions to manage the multiple coordinates of the sampling objects coming from the three different phases of the second Italian national forest inventory (Inventario Nazionale delle Foreste e dei serbatoi forestali di Carbonio [INFC]). In particular, this article describes the criteria used to determine the sample point coordinates of the first phase, the Global Positioning System (GPS) positioning procedure of the second phase, and the GPS-aided retrieval procedure of sample points during the third phase of the INFC. Because about two-thirds of the Italian territory is hilly or mountainous, with rough orography or with tree coverage, this article also provides a nationwide analysis and survey on the use of GPS technology in forest and natural environments.

Introduction

The Inventario Nazionale delle Foreste e dei serbatoi forestali di Carbonio (INFC) is aimed at updating the data on Italian forests in a way consistent with the current international definitions and commitments detailed in the statements of the Ministerial Conference on the Protection of Forests in Europe (FAO 2000, MCPFE 2003) in relation to the Kyoto Protocol to the United Nations Framework Convention on Climate Change (UNFCCC 1997, 2002). The INFC pays particular attention to the quality of the collected data to obtain a good accuracy and a high precision of results at both the national level and the regional level. This goal was achieved with three-phase sampling for stratification (Fattorini *et al.* 2006), which allowed us to apply a high sampling intensity in the first two phases of the inventory and with the continuous assistance of the surveyors and a careful control of the collected data. In addition, various information sources were used to collect data regarding many aspects of the forest ecosystems (Tabacchi *et al.* 2005, 2007).

This particular sampling design required significant attention to geographical and positioning aspects, due to the necessity to reach twice the ground sample points, during the second and third phases, ensuring that the plot center was in the very same position, to refer the data collected in these two different surveys to the same area.

At the same time, every effort was made to avoid a navigation and positioning procedure too heavy with respect to the time and human resources needed for the whole survey (data collecting and processing).

[1] Research Assistant, Istituto Sperimentale per l'Assestamento Forestale e per l'Alpicoltura, ISAFA-CRA, Piazza Nicolini 6, 38050 Villazzano (Trento), Italy. Phone: +39 0461 381117; fax: +39 0461 381131. E-mail: giacomo.colle@isafa.it.

[2] Forest Technician, Istituto Sperimentale per l'Assestamento Forestale e per l'Alpicoltura, ISAFA-CRA, Piazza Nicolini 6, 38050 Villazzano (Trento), Italy. Phone: +39 0461 381113; fax: +39 0461 381131. E-mail: scrinzi@isafa.it.

[3] Head of Forest Management Department, Istituto Sperimentale per l'Assestamento Forestale e per l'Alpicoltura, ISAFA-CRA, Piazza Nicolini 6, 38050 Villazzano (Trento), Italy. Phone: +39 0461 381117; fax: +39 0461 381131. E-mail: floris@isafa.it.

[4] Head of Forest Biometrics Department/INFC Project Leader, Istituto Sperimentale per l'Assestamento Forestale e per l'Alpicoltura, ISAFA-CRA, Piazza Nicolini 6, 38050 Villazzano (Trento), Italy. Phone: +39 0461 381112; fax: +39 0461 381131. E-mail: giovanni.tabacchi@entecra.it.

[5] Independent Cartographer. E-mail: lorenzocavini@katamail.com.

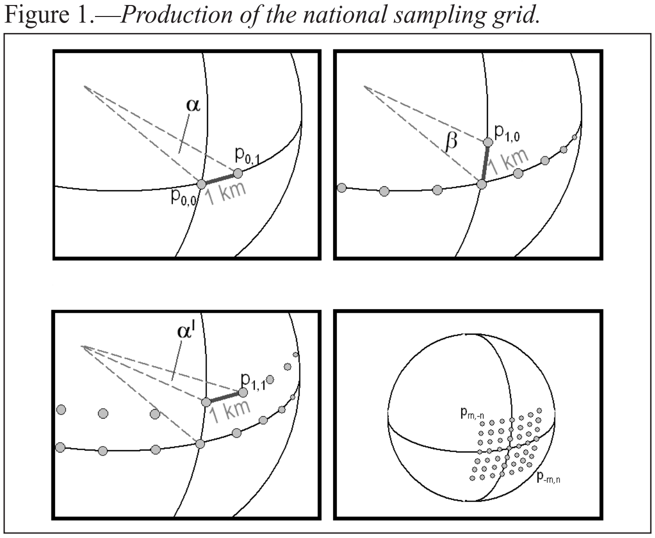
Methods

Production of the National Sampling Point Set

The three-phase INFC sampling inventory is established on a set of sampling points covering the whole Italian territory (30,132,845 ha), each of which represents 1 square km of the land. The proposed method achieves this result using a regular grid covering the whole Italian territory; unlike usual methods, the grid is drawn on the World Geodetic System 1984 (WGS-84) ellipsoid and each sample point is randomly chosen within one of the 1-x-1-km "elliptic" grid squares (Cavini *et al.* 2003).

The first step of the grid production sets the starting point $p_{0,0}$ in Monte Mario in Rome, Italy. The point $p_{0,0}$ is the first point of the sampling grid and determines its central meridian and parallel. The next point of the grid, $p_{0,1}$, is located 1 km east along the parallel passing through $p_{0,0}$. The latitude in degrees of $p_{0,1}$ is the same of $p_{0,0}$; the longitude in degrees of $p_{0,1}$ is the longitude of $p_{0,0}$ plus the central angle α corresponding to the 1-km ellipsoidal arc $p_{0,0}p_{0,1}$, where α is function of the latitude of $p_{0,0}$. In the same way, all the points $p_{0,2},...,p_{0,n}$, and similarly $p_{0,-1},...,p_{0,-n}$, are located along the parallel passing on $p_{0,0}$ (fig. 1). The second step of the procedure generates a new point $p_{1,0}$ located 1 km north from $p_{0,0}$ along the central meridian. The longitude of $p_{1,0}$ is the same of $p_{0,0}$; the latitude of $p_{1,0}$ is the latitude of $p_{0,0}$ plus the central angle β corresponding to the 1-km ellipsoidal arc $p_{0,0}p_{1,0}$ on the central meridian, where β is function of the latitude. The points $p_{1,1},...,p_{1,n}$ and $p_{1,-1},...,p_{1,-n}$ along the parallel passing from $p_{1,0}$ are generated in the same way described previously, but now the angle α^I, corresponding to this step, is determined with the latitude of $p_{1,0}$. The procedure is repeated moving north and south along the central meridian; the resulting set of points $p_{m,-n},...,p_{-m,n}$ determines a nationwide sampling grid formed by same-size elliptic squares.

Figure 1.—*Production of the national sampling grid.*



The procedure to randomly generate the geographic coordinates of the sample point inside each grid square is strongly related to the choice of the national sampling grid plotted on the WGS84 ellipsoid. In proximity of the central meridian, grid squares have a true square shape; moving away from the central meridian, their shape gradually changes to a parallelogram with horizontal sides and height of 1 km still having an area of 1 square km (fig. 2). This change in shape occurs because the central angle α corresponding to a 1-km ellipsoidal arc on a grid parallel is function of the latitude and so varies parallel by parallel. Also, the central angle β corresponding to a 1-km ellipsoidal arc on a grid meridian is function of the latitude, but it is constant for all the squares of a grid row. Thus, the procedure to randomly extract a geographic coordinate (φ,λ) inside the square with low-left grid node $p_{i,j}$ first calculates the latitude φ by randomly generating an arc length between 0 and 1^- km, converting it in the corresponding central angle, and summing it with the latitude φ_i of $p_{i,j}$ (fig. 3). The procedure then extracts the longitude λ by randomly generating a new arc length between 0 and 1^- km, summing it with the arc distance D_j of $p_{i,j}$ from the central meridian (corresponding to j km), converting the resulting arc in the corresponding central angle using the previously calculated latitude φ, and finally summing this result with the longitude of the central meridian (fig. 4).

Figure 2.—*Differences in elliptic squares shapes.*

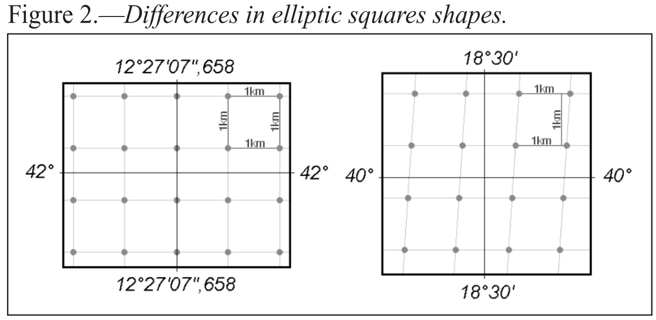


Figure 3.—*Random extraction of sample point latitude (grid squares distortion is exaggerated).*

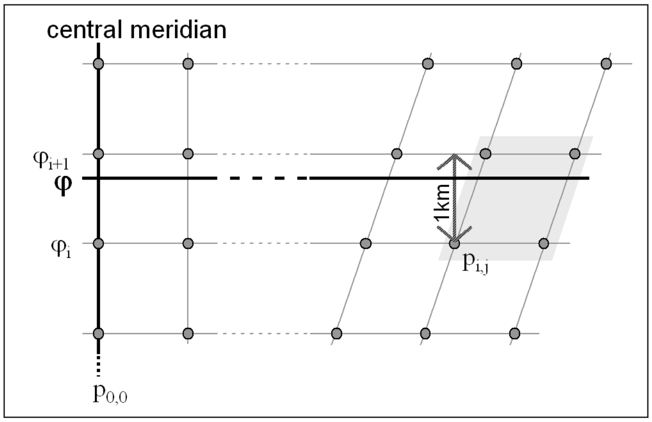
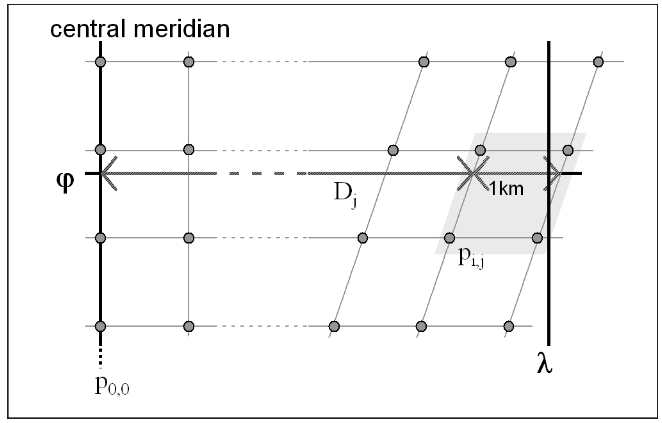


Figure 4.—*Random extraction of sample point longitude (grid squares distortion is exaggerated).*



At the end of the procedure, only sample points inside Italian boundaries were kept, forming the whole sampling set of 301,329 points. Thereafter, the geographic WGS84 coordinates were transformed in the other systems involved in INFC, with the following priority to avoid loss of precision in the various steps: from geodetic system WGS84 to cartographic system UTM-WGS84, with a precision on the order of 10^{-3} m; from geodetic system WGS84 to the geodetic national systems Roma40 and ED50; and from cartographic system UTM-WGS84 to the cartographic national systems Gauss-Boaga and UTM-ED50.[6]

Land Navigation and GPS Positioning in Phase 2 and in Phase 3

Positioning and Data Collection Instruments

Trimble GPS Pathfinder® ProXR and Trimble GeoExplorer® GeoXT receivers were chosen after a comparative test among five Global Positioning System (GPS) receivers of Geographic Information System-mapping class that were eligible to be used in the INFC surveys (Scrinzi *et al.* 2003). The test outcome also provided the expected values of positioning uncertainty (table 1) considering stationary positioning with an average of 170 to 200 single fixings (1 position per second). The uncertainty values under the stand-alone positioning, in particular, were considered sufficient to localize on the ground the phase 3 sample points surveyed in phase 2, by means of a standard GPS navigation procedure (aided by description notes, drafts, and photos taken in phase 2). Therefore, all positioning during the ground surveys of INFC was performed by collecting

Table 1.—*Estimated performance (uncertainty positioning in meters) of the two Global Positioning System receivers chosen.*

Positioning probability (%)	Stand-alone positioning		Postprocessed DGPS	
	Pro XR receiver (meters)	GeoXT receiver (meters)	Pro XR receiver (meters)	GeoXT receiver (meters)
50.0	1.4	3.1	0.9	2.0
66.6	2.0	4.5	1.3	2.8
90.0	3.5	7.7	2.2	4.8

DGPS = Differential Global Positioning System.

[6] All these elaborations were carried out using the software program Cartlab2® (Cima 2002).

and averaging at least 170 to 200 positions and registering a Trimble Standard Storage Format (SSF) file for postprocessed differential correction.

The Pro XR receiver was equipped with an Intermec 700 data logger and its L1 external antenna; the GeoXT receiver was equipped with its external patch antenna. Three possible settings of GPS filter values were chosen: best accuracy, standard, and best performance.[7] The surveyors were suggested to use the highest quality configuration when possible and to perform the GPS calendar planning periodically during the sampling campaign.

Two software applications, INFOR2 and NAV3/RAS3, were expressly developed for phases 2 and 3 of INFC. Each application runs on Microsoft® Windows CE Pocket PC handhelds and provides several ad hoc navigation and positioning functions integrated with the Trimble GPS technology. INFOR2 and NAV3/RAS3 also provide data processing and database storage functionalities for qualitative classifications and quantitative measurements specific for their own inventory phase.

Procedure for Land Navigation and GPS Positioning in Phase 2

During the second phase of INFC, 30,000 sample points were surveyed to discriminate forests from other wooded lands, identify different forest types, and collect information about other qualitative attributes of forest stands (Gasparini and Tosi 2004). More than 100 crews made up of national and local Forest Service personnel were involved in the data collection. The effort needed for this phase required the definition of a detailed procedure to locate on the ground the sample area center, called C, with the best accuracy and collect the necessary positioning data for its retrieval in the following phase of the inventory (Scrinzi and Floris 2004). The procedure was designed to achieve the utmost objectivity in the localization of C and it consists of two subsequent steps depending on the distance of the surveyor to C. This method was inspired by the ground sampling procedures adopted by the British Columbia Resource Inventory Committee for the vegetation resources inventories. (BCRIC 2001, 2002).

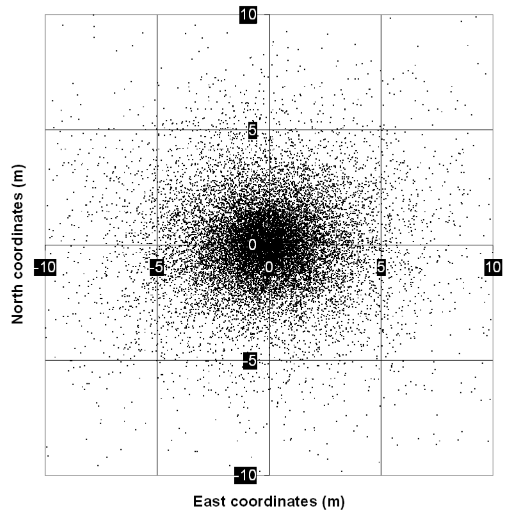
In the first step, when the surveyor is far from C, a standard navigation procedure is used: distance and bearing to C are obtained from an instantaneous GPS position and printed digital orthophotos and cartographic maps help the surveyor to navigate toward C. If the GPS signal is obstructed by the orography of the terrain or by a high canopy density, the procedure allows the surveyor to perform a traditional *open traverse* starting from a known coordinate location: the surveyor works with a compass and a laser rangefinder and clinometer, and a special functionality of the INFOR2 software calculates the coordinates of each traverse station and the distance and bearing to C.

The second step starts when the surveyor is about 15 to 25 m from C; here, the location of C involves a second point, F, chosen subjectively near C where the forest crowns allow the best transparency to the GPS signal and characterized by a nearby existing object (like a tree or a stone). Point F is marked with a temporary stake hidden under the ground and its coordinates are obtained with an averaged GPS positioning. With the surveyor standing at point F, C is located on the ground by calculating the distance d and the azimuth α from the GPS (average) coordinates of F to the theoretical coordinates of C (fig. 5).

Afterwards, a temporary stake is placed at C and its coordinates are collected with GPS positioning as well. These coordinates differ from the theoretical coordinates of C due to the instrumental positioning error of GPS and the error in measuring distance d and azimuth α from F to C; this new point is called C_{GPS} and becomes the true sample plot center for phase 2 surveys. Additional markers like metal plaques are placed near C and F to assist in the phase 3 retrieval of the stakes.

[7] Best accuracy—maximum Position Dilution of Precision (PDOP) of 4, minimum elevation of 15 degrees, and minimum Signal-to-Noise Ratio (SNR) of 6 Amplitude Measurement Units (AMUs). Standard—maximum PDOP of 8, minimum elevation of 12 degrees, and minimum SNR of 4 AMUs. Best performance—maximum PDOP of 12, minimum elevation of 12 degrees, and minimum SNR of 3 AMUs.

Figure 5.—*Scatterplot of C_{GPS} around C.*



Procedure for Sample Point Retrieval in Phase 3

The third phase of INFC, carried out during 2006, implied a further national ground survey to collect dendrometric measurements. The phase 3 points were chosen inside the second phase sample set and stratified by administrative region and forest type (Tabacchi *et al.* 2007). The result of the selection was a sample subset of 6,865 points, each of which still had the sample plot center in C_{GPS}. A retrieval procedure was set up to relocate on the ground the stake placed in C_{GPS} at the end of the previous phase. To perform the retrieval procedure, the surveyor first navigates toward the object of point F using the GPS receiver and locates the F stake; the surveyor then may locate C_{GPS} stake using the distance d and the azimuth α from point F to C. Other quick procedures using the marks placed on the ground were set up to find C_{GPS} stake in different ways. Moreover, if the surveyor misses point F, he or she could perform near C a new average GPS positioning to get accurate values of distance and bearing to C and then retrieve the C_{GPS} stake. All retrieval procedures are supported by a metal detector.

If none of the procedures for C_{GPS} stake retrieval succeeds, the procedure used in phase 2 to locate C from point F must be executed again in phase 3. The new located point C_{GPS} will need new average GPS positioning and becomes the new center of the sample plot. This positioning procedure was also repeated if the Trimble SSF file was missing or corrupted or if the average coordinates of C_{GPS} did not satisfy some given quality requirements (at least 170 positions and a maximum distance between C_{GPS} and C of 20 m). At the end of the procedure, a permanent stake is placed in C_{GPS} to enable the retrieval of the sample point in the future.

GPS Positioning Quality Results

No real-time differential correction procedures were performed during the phase 2 and phase 3 surveys. Real-time Differential GPS procedures, in fact, could not be performed in many Italian forest scenarios due to the weak European Geostationary Navigation Overlay Service[8] signal under tree coverage and in mountainous environments and to the difficulties to receive (for the same reasons) other broadcast signals via radio or cellular phone connections (European Space Agency 2006). On the other hand, positioning accuracy obtained by means of standard mode had already been estimated as sufficient for our main operational purposes (Scrinzi *et al.* 2000), which consisted of finding again in phase 3 the sample points positioned in phase 2. Moreover, this assumption has been confirmed during the third phase field campaign, which is currently in progress: of a total of 6,865 sample points, 6,724 have been surveyed so far and about 98.8 percent of them have been exactly relocated without any particular problem. Therefore, all the following analyses are referred to stand-alone positioning data. By the way, postprocessed differential correction using the European Reference Frame Permanent Network will be performed on phase 3 points, which, at the end of the phase 3 surveys, is supposed to set up a permanent network.

At the end of phase 2, the postprocessing of Trimble SSF files permitted a deep analysis of GPS positioning quality. Approximately 74 percent of phase 2 sample points had SSF C_{GPS} coordinates valid for the analysis. Most of those sample points excluded (21 percent) did not satisfy the 170 positions

[8] European Geostationary Navigation Overlay Service correction data were not fully available until July 2006.

constraint; some of them (5 percent) were provided with a corrupted or missed SSF file, and only few (less than 0.25 percent) were discarded because they had a theoretical outside distance between C_{GPS} and C of more than 20 m.

The first analysis on C_{GPS} coordinates was the measurement of their distance from the C theoretical coordinates; although this analysis is not a real performance test (C is not a tangible object with known and precise coordinates and the surveyors located C using nondifferential corrected GPS positioning in point F), the regular scatterplot of C_{GPS} around C (fig. 6) proves the absence of systematical errors in the phase 2 positioning procedure. In addition, almost 90 percent of C_{GPS} points have a distance from C of less than 5 m (fig. 7), indicating a high proximity of sample area center of phase 2 to the photo interpretation site of phase 1. The analysis on the distance of C_{GPS} from C coordinates showed also that the Pro XR receiver performed better than the GeoXT receiver (fig. 7), albeit the Pro XR was generally assigned to surveys characterized by severe terrain and forest conditions.

The SSF files provided also information about the maximum Horizontal Dilution of Precision (HDOP) of positioning in C_{GPS}: approximately half of the positioning was performed with high horizontal accuracy values (HDOP of less than or equal to 3) and more than 90 percent with fair horizontal accuracy (HDOP of less than or equal to 6) (fig. 8). Moreover, the comparison of the maximum HDOP in C_{GPS} and in F positioning showed that HDOP values registered in F were generally lower than those registered in C_{GPS}, proving a correct procedure for the point F location choice.

Figure 6.—*Distance of C_{GPS} from C.*

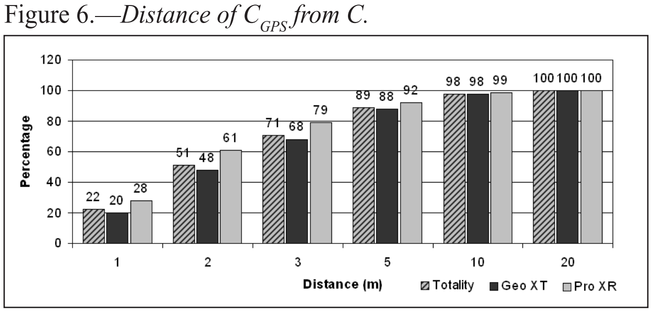


Figure 7.—*Maximum Horizontal Dilution of Precision in C_{GPS}.*

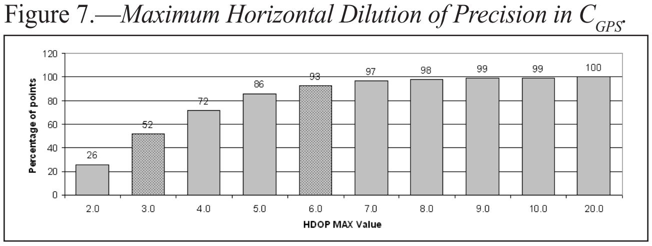
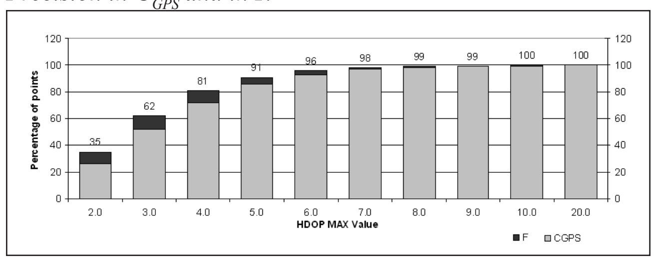


Figure 8.—*Comparison of maximum Horizontal Dilution of Precision in C_{GPS} and in F.*



Discussion

Methods and results previously described suggest some considerations. The production of the national sampling point set was quite hard, but the adopted solution provides two major advantages with respect to standard solutions.[9] First, the appreciable reduction of the area distortion in the eastern regions of Italy (up to 8,000 m^2 per square kilometer) compared to the one obtainable using a unique projected Gauss-Boaga/Roma40 square grid. The "elliptic" grid, in fact, is formed of squares with a constant area of 1 square km on the ellipsoid, each one having the same measurement error. The second advantage is that generating sample point coordinates in the WGS84 geographic system ensures their direct usage in GPS surveys.

Regarding the navigation and positioning procedures adopted in phase 2 and phase 3, the surveys highlighted the almost trouble-free use of GPS receivers in forest environments. Only in very few situations, in fact, the best performance GPS setting had to be used, and the use of the open traverse method in substitution of the GPS-driven one was exceptional (24 cases out of 22,289). The use of point F in the adopted procedures

[9] The two mostly used cartographic systems in Italy are Gauss-Boaga/Roma40 (digital orthophotos and regional maps) and UTM (Universal Transverse Mercator)/ED50 (European Datum of 1950) (national topographic map).

allowed an objective location of point C; moreover, the several markers placed around them guaranteed the invisibility of C_{GPS} position and minimized the time wasted on average GPS positioning during phase 3 surveys.

Regarding the performances of the different GPS receivers used, the Pro XR receiver showed better positioning precision than the GeoXT receiver did. In addition, the Pro XR receiver operated more efficiently under tree coverage, probably because of its specific hardware features and better antenna, and experienced fewer system failures in the field than the GeoXT receiver did. According to our experience, it would be better to use an instrumental configuration with separate devices for the GPS antenna and for the personal digital assistant (PDA) component, although an integrated device like the GeoXT receiver could offer advantages in terms of weight and portability. Moreover, our experience put in evidence that PDAs still show difficulties in working in real multitasking mode. This pitfall was one of the reasons for having two separate software applications in phase 3: one for navigation and positioning and another for collecting attributes.

INFC has been the first Italian experience of using GPS technology in natural environment assessment on a nationwide scale. Data collected during this survey are available for further analyses and can be useful for improving positioning specifications and protocols in future field campaigns. Although a prudential criterion of collecting at least 170 to 200 positions for each point feature was used in INFC, in fact, it is reasonable to assume that this value could be significantly reduced after data distribution analyses.

GPS can be nowadays considered a mature technology in forest assessment applications at a certain scale, such as navigating to a target plot center or positioning stand boundaries. So far, it still is not possible, however, to determine the position of any single tree inside a stand with sufficient accuracy, using only GPS technology.

On this matter, significant improvements are expected in coming years as a result of GALILEO full operational deployment (European Commission 2006) and its integration with other Global Navigation Satellite System services, especially GPS.

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