Science

Sense and Non-sense of Satellite Navigation for Precision Agriculture in the Tropics

By Egbert Spaans, EARTH University, Costa Rica and Leonidas Estrada,
Ingenio San Carlos, Ecuador, e-mail: espaans@earth.ac.cr

The article describes experiences of precision agriculture in Latin America. Due to several local conditions it is not effective to gather field information based on pin point GPS data, but rather per management units, which are homogeneous areas defined by natural or man made boundaries. K-GPS proved, however, to be an excellent alternative to survey the management units, because it is much faster and more accurate than the theodolite.

1 Introduction to Precision Agriculture

The technical and scientific advances in agriculture over the last century have made it possible to meet today's demands of society for food and fibre. Mechanisation, breeding of better varieties, fertilisation and pest management are just a few of the areas that have contributed to higher, and more reliable yields. In order to synthesise our improved understanding of these areas and their relation to crop growth in useful terms for the farmer, technological packages were developed; a recipe type of approach that stipulates, crop for crop, what to do, how and when, in order to obtain a successful harvest.

These packages have been very useful to the farmer, as an orientation particularly when starting with a new crop where the farmer didn't have any prior experience. However, farmers noticed that crop response to a technological package was not uniform throughout the field. In certain parts of the field the crop was higher, or greener or less infested with pests, than in other. It was obvious that there was variability in growth conditions to which a uniform management could not respond to.

And so precision agriculture was born, as a farm management strategy that takes into account this variability and intends to do what is right according to the specific needs of different parts in the field, therefore also called site-specific management. It allows for making the most out of every part of the field, maximising the profit of the agricultural enterprise on a detailed scale.

Since precision agriculture demands lots of information, it stimulated the technological sector to develop sensors and technology to acquire this information, such as accurate satellite positioning in seemingly endless corn and wheat fields.

Typical application of satellite navigation in precision agriculture is machine guidance and real time positioning for yield monitoring and site specific fertilisation. Real time positioning is used to produce high-resolution harvest maps on-the-go, which are consecutively converted to income maps. Fertiliser applications are calculated according to soil condition and potential, and executed with GPS and GIS-equipped tractors, to apply the exact fertiliser amount and mixture as the tractor advances through the field (this is called VRT, variable rate technology). Fertiliser and other field-operation costs are accounted for and presented in production-cost maps that show how much money was spent at different parts in the field. The difference between the income map and the production map yields a profit map, a visualisation of the spatial variation of the profit made from the agricultural enterprise. This spatially-detailed monitoring of all variables involved in the production of a crop or livestock, allows for precise and correct decision taking of what needs to be done when and where, in order to optimise available resources, thereby optimising profit and minimising environmental impact.

This profit optimisation, however, is also highly relevant for agriculture in tropical countries, particularly in Latin America where mainly primary products are produced. Primary products are in a rather raw state, with little value added, such as processing, packing or marketing. Unfortunately, the reality is that most money is made by adding value to products, and not by producing them. For instance, planting, fertilising, weeding, pruning, harvesting, fermenting, and drying coffee pays $1.56 per kilo of raw coffee beans (Herald International Tribune, 14 may, 2004). Shipping, roasting, packing, and putting

Figure 1 - Field worker hanging the banana bunch on the rail. Notice the coloured ring on the gate

them on the shelf of the supermarket raise that price from $1.56 to about $5.00 per kilo. A box of bananas leaves the farm for around $3-4, in the supermarket that same box costs around $30.

Thus producing primary products requires efficiency because profit margins are narrow and competition is strong. Therefore, precision agriculture is an excellent strategy for Latin American agriculture, but rather than "copy-paste" current technology, we should go back to the basics of precision agriculture and evaluate how it can best be implemented considering the identity of the agricultural production system at stake.

2 Implementing Precision Agriculture in the Tropics

The first step towards implementing precision agriculture is dividing the farm into smaller units, called management units, which can be considered uniform in growing conditions so that the farmer can do the same thing throughout the management unit and expect a uniform crop response. In order to know what needs to be done (weeding, fertilising), measurements are done on the soil and the crop within each unit, and these data are interpreted so that the best management decision can be taken for every unit individually. This requires intensive data collection and management.

To examine the profit of every management unit, we must know their income and cost, where the former is derived from the harvested product, so yield monitoring is crucial in precision agriculture. In cereal and soybean production in the Western world, where precision agriculture originally started, fields are rather large and field operations completely mechanised. Sensors were developed to monitor harvest on-the-go, and GPS provided the geographical information of every harvest datum. As satellite positioning became more accurate with the introduction of RTK-GPS and faster in response, the pixel size of measurement reduced.

The investment in all this equipment is substantial and often technical support and customer service is inadequate in Latin America where the market is small. Training and technical assistance is required in order to install and operate the system and manage the rather large data sets. In addition, there are some important differences with tropical production systems on the operational level that have to be considered. Many of the crops are perennial, which hampers the use of mechanised field operations, and labour is relatively inexpensive, so many field operations including harvesting, are performed manually. These circumstances call for adjustments to be made in the current precision agriculture applications, if widespread implementation of precision agriculture in Latin America is desired.

We found that the profit optimisation of current precision agriculture applications is not limited by the spatial resolution (pixel size) of the data acquisition. Rather, it is limited by knowledge of how to interpret the data and what the best action is to be taken in the field, given a set of conditions. So in our precision agriculture initiatives we have chosen to augment the pixel size, and create management units ideally by soil type, topography of the terrain, and crop type and variety, and by doing so, management units can be considered uniform. However, soil information is not always available, in which case existing infrastructure, such as roads, drainage and irrigation canals can be used to divide the farm. In that case we can't assure uniformity, but reducing the size of the management unit by itself increases the probability of uniformity. Once defined, the management units are identified in the field with a code, which are displayed on posts, signs, or ribbons. The unit identification serves as a geographic reference in communication with field workers or in data acquisition. Decisions are taken per management unit, so for instance fertiliser rate is variable between units, instead of from one GPS reading to the other. Specific positioning within the unit is not necessary because the unit is considered uniform. Hence, there is no need for satellite positioning to know where we are within the unit, neither to geographically pin point data acquired in the field. With our approach, field observations will be spatially less detailed (less *precise*), but the logistics are simpler and the system easier to implement.

2.1 Case one: Bananas in Costa Rica

The first case concerns a banana plantation of the Commercial Farm of EARTH University, located in the tropical lowlands of Costa Rica (Guácimo county). The farm has four banana plantations, and we selected the least productive one, which was also the most heterogeneous one in terms of soil types. It has an extension of about 110 ha (hectares) and is a rather old (approximately 40 years) plantation.

Banana plantations have a dense network of rails used to transport the bananas from the field to the packing plant. The rails are parallel and spaced 100 m apart, to assure that field workers don't have to walk more than 50 m with the harvested bunch on their shoulder, to the nearest rail. The overhead rail is supported by gates, which are spaced 10 m apart. This network of rails and gates serves as a suitable, local navigation system, so we numbered the rails and colour-coded the gates, to define our management units of 4 ha (hectares) each. As the field workers hang the bunches on the rail, they attach a ribbon to the bunch which matches the colour of the nearest gate (Figure 1), and a plastic plate with the code of the rail. Once 40 to 60 bunches have been harvested, they are transported to the packing plant. In the packing plant, a scale, which is integrated with the rail, determines the weight of every bunch as it passes. One person registers the weight, together with the colour of the ribbon and the code on the plate on a form which is later entered into a data base. We are now automating the registration of the harvest data, so the data go automatically into the data base, to increase data quality and reduce labour. Harvest data for 2002 are presented in Table 1.

Number of management units:	31	
Average production:	1538	= - $1245
Maximum production:	3040	= + $2316
Minimum production:	943	= - $2655
Standard deviation:	563	

Table 1 - Production statistics for the year 2002. Production expressed in boxes/ha/year, the corresponding profits in USD/ha/year

From the production statistics we learned that on the average, the plantation produced 1538 boxes of bananas/ha/year. This is the conventional way of expressing production numbers since detailed information is usually not available. With the precise monitoring of the yield, however, we found that in reality the productivity within the plantation ranged from 943 to 3040 boxes, a variation of more than 300%, and that 67% of the units produced between 975 and 2101 boxes.

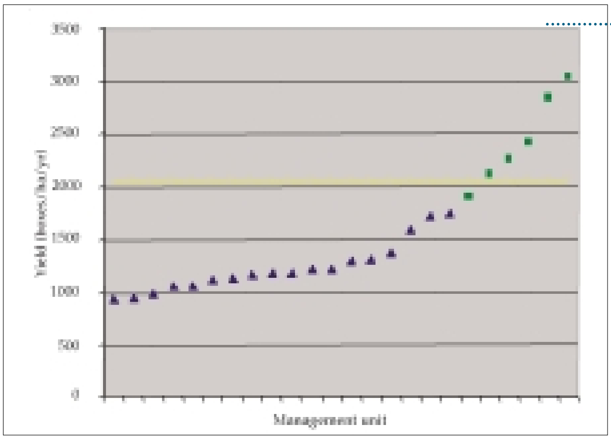

Figure 2 - Production of the management units, in order of productivity. The triangular data points refer to units with old plantation, the square data points are those of the renovated plantation. The horizontal line represents the productivity level where costs match income (zero profit)

In terms of profit, this meant that although this plantation was loosing money in 2002, the good-producing units were generating high profits, while the poor-producing areas were loosing money.

The next step, obviously, is to investigate what is, or is not, happening in the good-producing areas in comparison to the poor-producing ones. In every unit we measured soil fertility, plant nutritional status, and infestations of root and leaf diseases, however, none of these parameters showed a significant correlation with production. It turned out that all good-producing areas were those that had recently been renovated, and all poor-producing areas were still old plan-

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tation (Figure 2). The conclusion of the analysis was that in order to improve the profit of this particular farm, applying more fertiliser or more chemicals to control diseases will not have much effect as long as the plantation is not being renovated (replanted).

There are 31 units in the 110 ha, since the rail might not have an integer number of sets of 40 gates (the length of the management unit); units at the end of the rail are usually a bit smaller in size. It should be mentioned that the fixed costs, such as maintenance of drainage ditches and weed control, were not available with precision, so those costs were divided equally amongst the units according to their area. Since farm management and analysis is usually done considering the entire farm as one single unit, data are often general, averaged over the entire farm, which makes spatially-precise analysis difficult.

However, once the farmers see the variability within the farm and become convinced of the limitations of the "one size fits all" approach of conventional farm management, they are enticed to change data acquisition (economic data) in order to be able to improve the precise analysis of the farm. Therefore, we see the implementation of precision agriculture as a gradual, participatory process of improving data acquisition and decision taking, accompanied by training and exchange of experiences.

Figure 3 - Obtaining satellite signals with K-GPS receivers to determine the position of corner points of the management units. Note the post with the 6-digit code (091502) of the management unit

In other regions like Colombia for instance, GPS has recently been used to map disease-infested areas, which are subsequently controlled by chemical spraying with airplanes or helicopters. This allows for more precise spraying and eliminates the man in the field that holds a large bamboo pole with a red flag on the top, to indicate to the pilot the next flight strip of the airplane. This precise, GPS-referenced spraying, reduces the health risk of field workers, and reduces costs and environmental impact.

2.2 Case two: Sugar cane in Ecuador

The Ingenio San Carlos [1] is a 16,500 ha plantation of sugar cane in the coastal plains of Ecuador, near Guayaquil (2°13'14.61" S and 79°24'32.23" W). It produces approximately 150,000 tons of sugar per year and provides for thousands of jobs. World prices of sugar fluctuate and competition is strong, so profit optimisation is a key issue. In 2003 we started implementing precision agriculture at the Ingenio San Carlos. The plantation used to be divided into about 347 management units, which were rather large in size and therefore likely to be heterogeneous in growing conditions. Hence, we subdivided these existing management units into 1309 smaller units, reducing the average size from 48 to 13 ha. A soil map was not available (a common situation) and the topography was rather level, so logistically the most sensible division was using existing infrastructure such as roads and drainage and irrigation canals as limits between the units. As a result, the units are of different shape and size, ranging from 2 to 20 ha. The infrastructure clearly divides the units, and every unit has a 6 digit code which is painted on posts placed in the corners of the unit (Figure 3).

For the purpose of analysis and comparison, data have to be expressed per unit area, so accurate area measurement was needed for every unit. Due to the large number of data collected, and the size of the farm, it was necessary to manage the information in a Geographic Information System (GIS). Over the years, the entire plantation had been surveyed piecewise by means of theodolite, but the different pieces didn't join well and the map was not georeferenced. A preliminary survey measuring some checkpoints with GPS, showed that offset within the plantation was anywhere between 20 and 300 m. In order to fully exploit the power of the GIS, the plantation had to be surveyed again.

We studied the different techniques for executing this survey, and it became clear that optical devices were not ideal. They are cumbersome, labour intensive because you need various people walking with the graded pole through the field, paths have to be cleared if vegetation limits the sight, while sighting in open field is limited to distances of approximately 300-500 m, depending on atmospheric conditions. Moreover, measurement errors are cumulative, since every measurement depends on its previous one.

Satellite positioning was found to be ideal for the task. It is a one person operation, thereby greatly re-

[1] *"Ingenio" is the Spanish word for a farm that grows sugar cane and mills it, to produces sugar.*

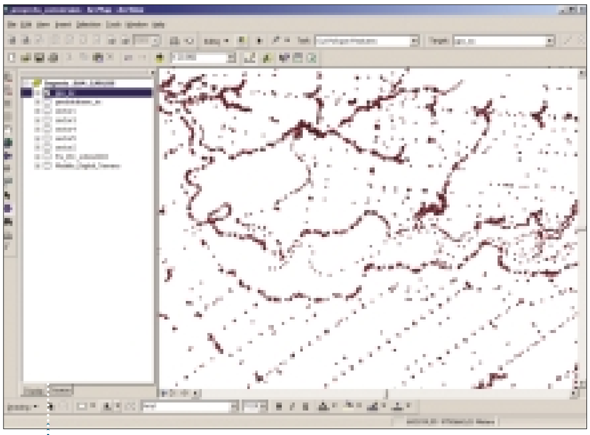

Figure 4 - GPS-determined points in the field imported into GIS software

ducing labour cost. The positioning of every point in the field is independent, and latitude-longitude information provides georeference. Altitude information of every point is crucial and should be accurate to within approximately 10 cm, because irrigation water is applied by gravity. Thus the accuracy requirements in altitude are far stricter than for latitude and longitude, where meter-accuracy probably would be sufficient, and that while errors in altitude are typically twice the error of latitude-longitude. Neither GPS nor DGPS meet these specifications, but kinematic GPS does. However, RTK-GPS equipment is expensive, ranging from $25,000 to $30,000 per set. Considering our application, we don't really need the geographic information in real time, since we are constructing maps to feed the GIS. So we opted for kinematic, post-processing GPS which is less expensive. For around $10,000, we purchased three GPS receivers (Ashtech Promark 2; one base and two rovers), post-processing software and a four-day, on-site training course.

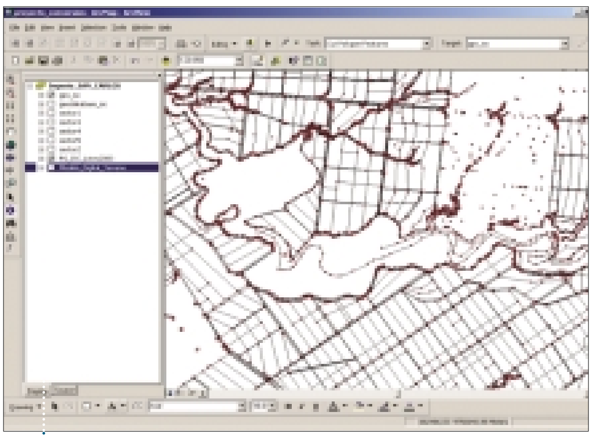

Figure 5 - Points are connected to create polygons, which can be management units, roads, irrigation canals, or other features in the field

It is generally recommended that rover and base should not be separated by more than 20 km. In addition, in order to reduce data-acquisition time in kinematic mode and obtain highly accurate data, that maximum distance should be more in the order of 5-8 km. The nearest benchmark from the Military Geographical Institute (IGM) of Ecuador was located in Jujan, about 40 km away, so that location was chosen as the reference to establish a local network of 24, regularly-spaced benchmarks within the plantation. Every benchmark was cemented into the ground and identified with a four digit code, and its location determined in static, differential mode (about 1 hour readings).

Rapid data acquisition is accomplished in the "Stop&Go" mode of the GPS receiver. In this mode, rover and base are first initialised (the two units together for 5 minutes), and then the rover is moved from one field point to the other. Daily work plans were established to collect data only during hours of sufficient satellite coverage and in recently harvested management units, to improve reception of satellite signals and facilitate access in the field. Signals were clear; we typically had a PDOP between 3.5 and 4, receiving signals from 8 to 10 satellites. At every point, data were collected for 20 seconds (static mode) and a two digit code was entered to identify the point, before moving to the next point. While moving, data are still collected (kinematic mode). If data collection is, for some reason, interrupted, one should go back to a point measured before the interruption. However, that point might be difficult to find back within centimetres, so it was more practical to go back to the base and initialise again. The field crew consisted of five man; one at the base (basically guarding the equipment), and for every rover one topographer taking the data and a driver operating the vehicle.

At the end of the day, data were downloaded on a computer, and with software (Ashtech Solutions) processed to yield latitude, longitude and altitude, already converted to UTM coordinates (region 17). The software allows for rejecting data that don't meet a specified accuracy; in our case we used 2 cm as a maximum error, and only few data points did not meet that criteria. These GPS determined points were imported into the GIS software (ArcView 8.2, ESRI), and connected to create the management units, as is shown in Figures 4, 5, and 6. Since harvest is scattered throughout the plantation, so was the surveying. At the conclusion of the project, all management units did fit perfectly as a puzzle, which was another check of the quality of the data.

In this manner, 16,500 ha were mapped measuring about 70,000 points in the field in about 8 months of time, including two months down time due to

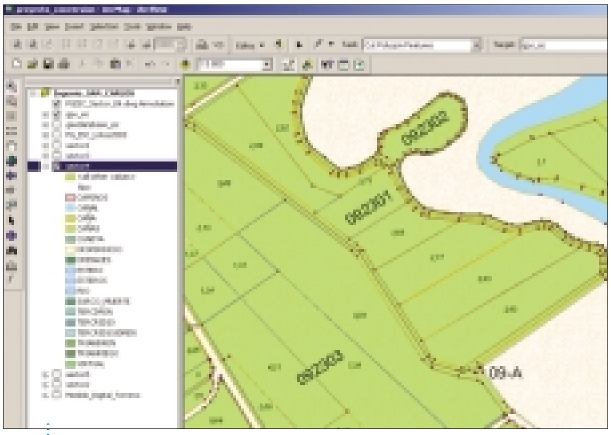

Figure 6 - All features are classified and identified with a code, and the GIS calculates the area of every polygon. The code of every management unit serves as the relation between the GIS and the database that contains all the agronomic and economic information of every unit

repair of the plug on the GPS receiver that had worn out. This is a great achievement and would have been impossible using the theodolites. It greatly reduced surveying costs, mainly in labour. With the same crew of 5, data collection in the field with theodolites took 2.9 times longer. In the office, data processing was reduced to one fifth of the time, mainly because with the theodolite data were registered in the field on paper, and had to be typed into a spreadsheet to do the calculations. Overall, the cost of surveying using post-processing, kinematic GPS was $0.49 per ha, compared to $1.45 using the theodolite method, while initial investments for both equipment is similar.

Every year about 10-20% of the plantation is renovated, and that is when topography is being checked and corrected, or fields are being redesigned where necessary. Thus, the GPS equipment and benchmark infrastructure will continuously serve its purpose.

Harvest was monitored per small management unit in 2003 and we found that 80% of the old, large management units had variability in harvest of more than 10%. Also, doing an inventory on the type of soils in every management unit based on knowledge of field workers, we found that about one half of the original large management units are heterogeneous with respect to soil type. We expect that decisions taken over the smaller, new management units, will be more certain and the outcome more predictable.

Conclusion

Precision agriculture is a promising alternative for tropical agriculture, because it focuses on profit optimisation on a detailed scale. For successful implementation of precision agriculture, practical and logistically simple systems need to be developed. One of the key issues is how to subdivide the farm into small management units, and their size has to be carefully considered. Too small a size will produce overwhelming amounts of data and not necessarily make decision taking more certain.

GPS is a valuable, but not indispensable tool for precision agriculture in tropical production systems. Its usefulness is not as much as a real-time positioning and machine guidance technique as we know it from conventional precision agriculture application, but rather as a tool to rapidly, economically and accurately survey fields.

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Biography of the Authors

Egbert Spaans has been a faculty member at EARTH University in Costa Rica since 1997. His degrees in soils science are from the Agricultural University in Wageningen, Holland, (MSc, 1988), and subsequently from the University of Minnesota, USA (PhD, 1994).
Aware of the inefficiency of certain agricultural production systems, and its environmental and social consequences, Egbert started to investigate how precision agriculture can be applied to improve the sustainability of these systems. In 2003 he spent his sabbatical year at the San Carlos Sugar Mill, Ecuador, leading the application of precision agriculture at the 16,500 ha sugarcane plantation.

Leonidas Estrada is from Ecuador and graduated from EARTH University in 1997, and has since worked in several agricultural enterprises. Since 2001, he has been working at the San Carlos Sugar Mill, where he was one of the key figures to start the precision agriculture initiative. In 2003 he worked closely with Egbert Spaans in the precision agriculture project at San Carlos, which he is now heading. Leonidas is currently pursuing his MSc in GIS and its application to precision agriculture.●