AGRICULTURAL SCIENCE IN FINLAND

Position Dependent Control (PDC) of plant production

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ACADEMIC DISSERTATION
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Preface

As the work is now done it is my pleasure to thank all the people who have made it possible and, moreover, pleasant for me to study the subject. The years of research and reporting have brought me much joy and many moments of satisfaction to be remembered.

The financial support of the Academy of Finland has been essential for this work. Without it this project would never have seen the sunlight. As a junior fellow of the Academy I sincerely thank them for the opportunity offered. I hope that the results will speak for themselves and that the investment will be found worthwhile! In the beginning the Board of Agriculture and Forestry was also financing the research, and I express my gratitude for that, too. The English manuscript was revised by Ms. Viola Frilund, DK, and edited by Ms. Sari Torkko, M.Sc.; I greatly appreciate their collaboration. I would also like to thank the Board of Agricultural Science in Finland for including this work in their journal.

The people at my Department at the University of Helsinki have provided me with an inspiring scientific society to work in. During the years the Department has changed its name and given proof of its ability to make dynamic changes within research. The current Department of Agricultural Engineering and Household Technology is a growing center of multidisciplinary knowledge and know-how. The agricultural and household sectors work together with different emphasis of the activity but utilize the same basic sciences. The much talked-about synergy effect is operating in practise. The nicest thing is that the spirit of the Department is fine. Prof. Aarne Pehkonen has given me valuable advice during my work. The technical staff and my researcher colleagues have helped me in many turns. Thank you all very much for your support!

My research group of Position Dependent Control, the "Star Group" in everyday speech at the Department, has established a new culture at the Department. We are a true multidisciplinary research team, with special responsibilities for everyone involved. I thank you all - Antti, Kalle, Liisa, Markku, Tero, and the short-time workers as well - for a remarkable co-operation. I have really had a good time carrying out this project with you. I wish you all the best for the future, both in research and in "real" life. This study is concentrated on positioning and therefore my special thanks go to Mr. Markku Hirvenoja, M.Sc., who has conducted many of the practical positioning tests, and to Mr. Kalle Lindell, student in engineering, who has been working on the GPS technology. Thank you for a first-class job!

My family - Kaarina, Liinamaija, Sinihannele and Annieveliina have supported me in this stressing phase of life. Your loving patience has been tried many times. I could not express my feelings better than to say, "I love you". This phase is now over and maybe we will find more time for each other in the future. My parents Arvo and Sirkku have always emphasized the value of good work. May this work be a gift to you to show how much I appreciate the agricultural background I have there in Kiikoinen.

Viikki, April 15th, 1995 *Hannu E. S. Haapala*

List of important acronyms

(in the order of appearance)

* Defined in this study

*PDC *Postition Dependent Control.* A control system in which all the used information is position-fixed. The position-fixed information is used to manipulate the inputs to the target position. The target position is called the Production Location (PL). PDC can be utilized in all position-fixed operations. In this study the target PL is an areally limited location in an agricultural field.

*PL *Production Location.* The target position of Position Dependent Control (PDC). The size of a PL is application-specific. The production process and the output required determine the largest area that can be treated as an individual PL. In practise, the incomplete adjustability of machines sets the smallest achievable PL size.

*EC *Effect Curve.* A graphical representation of the effect of a production task, usually performed by an implement. In plant production the production task is a production operation such as fertilising, plant protection, tillage, etc. Thus the EC describes the evenness of spread or tillage in both cross and length direction. The cross EC is scaled so that the target effect level will be 1.0. There are some basic cross EC types some of which are used in this study.

*ES *Effect Sum.* A graphical representation of the sum of Effect Curves (ECs). As production locations are treated there will always be some overlapping if optimum working widths (Wopts) are used. Thus the ECs are allways summed to the Production Locations (PLs). An ES curve shows the effect in the target PLs when ECs are summed. Positioning errors in PDC cause inaccurate targeting of the ECs and degrade the quality of resulting ES.

*Wopt *Optimum working width.* The working width of an implement that produces the best available Effect Sum (ES) of parallell ECs. Wopt can be calculated if the Effect Curve (EC) of the implement is known. In practical work the Wopt changes dynamically. The typical (tested) ES of the implement is used when Wopt is determined.

*CVmax *Maximum Coefficient of Variation allowed.* A limit value for the CV of the Effect Sum (ES) curve. The CVmax sets a quality limit for the implement´s work. The suitable CVmax for each position dependent task must be separately derived from the actual production process. Therefore an alternative definition includes the transfer functions from the ES curve to the production output. The CVmax is calculated for the production output instead of the ES. The last option is more valid because it includes the actual production process.

*Werr *Cross targeting error.* The deviation of the location of the implement from the required location in cross direction of travel.

*Werrmax *Maximum cross targeting error.* The maximum allowed deviation of the location of the implement from the required location in cross direction of travel. Werrmax is calculated by setting a maximum Coefficient of Variation (CVmax) for the Effect Sum (ES) curve.

*Lerr *Length targeting error.* The deviation of the location of the implement from the required location in direction of travel.

*Lerrmax *Maximum length targeting error.* The maximum allowed deviation of the location of the implement from the required location in direction of travel. Lerrmax can be calculated by setting a maximum Coefficient of Variation (CVmax) for the Effect Sum (ES) curve. In this study Lerrmax was set by the reaction of the production process to nitrogen input. Lodging was set as the trigger for poor length targeting.

DR *Dead Reckoning.* A vector navigation system that uses distance and heading information to calculate positions. Different sensors can be used to get the required parameters. The system is sensitive to accumulated error because each new position is based on the previous ones. The best devices can achieve an accuracy of 1..3% of the distance travelled. DR is frequently used as a backup for other methods, i.e. GPS. (Hakala 1992, Krakiwsky 1994)

GPS *Global Positioning System.* A satellite navigation system that gives positioning information 24 hours a day all over the world. The GPS system that is based on a network of 24 geosynchronised satellites is managed by the U.S. Department of Defence (DoD) and in the future by the Department of Transport (DoT) as well. Positioning accuracy levels available range from the standard Coarse/Acquisition (C/A) to Precise (P) service level. The best accuracy is not available for civilian users and the signals are intentionally degraded (S/A, Selective Availability in C/A, and encryption of the P-code). The standard GPS gives an accuracy level of ±100 meters (95%, typical values are c. ±20..30 m). The most accurate systems for geodetic measurements are accurate down to below one centimeter (95%). There are receivers that use the digital codes transmitted by the satellites (Code Receivers) and those that use the carrier wave instead (Codeless Receivers). The C/A service can be enhanced to the level of approx. one meter by differential corrections (DGPS). The differential corrections can be achieved by purchasing extra equipment or they can be received from commercial sources. The standard positioning service is free of charge. (Toft 1987, Tyler 1993, Van Dierendonck 1995)

DGPS *Differential Global Positioning System.* The GPS system with a correction system that includes a fixed reference station the coordinates of which are accurately known. The differential corrections are calculated in three basic ways. The first option is to calculate the position of the fixed receiver and correct the moving receiver´s position with the calculated error. The second way is to correct the satellite ranges. The third option is to send the needed raw data to the receiver that calculates the corrections locally. The corrections can be done by postprocessing or in (near) real time. The real-time corrections require a data link between the receivers. The reference station can be in quite a high distance (200..300 km) from the moving receiver without considerable degradation of the accuracy. It must, however, see all the same satellites than the moving receiver to be able to make the corrections accurately. (Toft 1987, Bäckström 1990, Tyler 1993, Van Dierendonck 1995)

RTKGPS *Real-Time Kinematic Global Positioning System.* The GPS system that uses the carrier phase and On-The-Fly ambiquity resolution (OTF) technics. An RTKGPS. also called RTS- (Real-Time Survey) GPS calculates the number of carrier cycles between the receiver and the satellites and keeps track of the phase continuously. In case of carrier slip the OTF technique ensures a rapid solution of the unknown number of cycles (the ambiquites). The OTF can be assisted with code receiving to limit the probable search space of the lost cycle. The RTKGPS requires a nearby (<10..20 km) reference station. (Tyler 1993, Abidin 1994, Van Dierendonck 1995)

Contents

Abstract

Citations in the text are made according to the technical system. This system is not normally used in Agricultural Science in Finland.

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The aims of this work were to get answers to the following three questions: (1) What are the potentialities of coordinate-based field crop production? (2) What are the requirements for the method of attaching field crop information to a coordinate system? (3) What are the possible solutions?

The work was focused on the effects of positioning quality. In PDC (Position Dependent Control) positioning is needed to target the inputs and to relate inputs and outputs accurately to each other. Systems analysis was used to accomplish a mathematical model of the position dependent control system. The model developed describes a system which consists of models for the positioning method and the target. An accuracy requirement of ±5 meters for N-fertilization was set with the developed model.

The results from Keimola gave information on the variability of soil and wheat yield. Regressions for individual input variables and multiple regressions calculated for whole sample lines (á 50 m) were low ($r^2<0.11$ and $r^2<0.15$). Attachment of the variation information to coordinate gave regression estimates with r^2´s up to 0.99. Positioning tests in Viikki show adequate accuracy (uncertainty ellipse $<25\ m^2$ @95%) of DGPS (Differential Global Positioning System) satellite positioning. DGPS was tested both in an accurately measured test route and field tests during drilling. Road tests in covered locations were also made.

PDC of plant production gives accurate control over the position fixed production process. The enhanced controllability can be used to adjust the production to meet environmental or economical criteria. The variable requirements for positioning can be set with simulation. The simulations need valid models for the production in the target area. GPS satellite navigation together with a GIS (Geographical Information System) database is a potential technics for the realization of this local control.

Key words: site-specific control, spatially variable field operations, GPS, GIS, simulation

1 Introduction

1.1 Sustainable agricultural engineering and the need for accurate control of field operations

Sustainability is a widely used term but it also has variable meanings. Sustainability can be defined by various criteria of production, economy or environment. In engineering, sustainability is commonly accepted to include environmentally and economically sound technologies which utilize their inputs efficiently. This means, in other words, technologies which use renewable resources and have high efficiency coefficients. In other contexts, sustainability is considered to be a philosophy or a set of rules used to select production methods. Furthermore, it can be a synonyme for organic production or economically maximized production. It is widely agreed that nonrenewable resources should not be used. The time span of sustainability is subject of constant argument. Current practises can be sustainable for us but not for the future generations. (Francis and Youngberg 1990, Heinonen 1993, Azelvandre 1994)

As a result of a large literature review Francis and Youngberg (1990) conclude:"Sustainable agriculture is a philosophy based on human goals and on understanding the long-term impact of our activities on the environment and on other species. Use of this philosophy guides our application of prior experience and the latest scientific advances to create integrated, resource-conserving, equitable farming systems. These systems reduce environmental degradation, maintain agricultural productivity, promote economic viability in both the short and long term, and maintain stable rural communities and quality of life."

Azelvandre (1994) summarizes sustainability criteria as follows:

1. Does a technology cause environmental damage and/or resource depletion in its creation or manufacture?
2. Does a technology cause environmental damage in its use or implementation?
3. Does the technology promote and encourage direct democracy when feasible?
4. Does it foster community self-reliance on a local, regional, national level?
5. Does it encourage human growth and fulfillment?
6. Does it encourage equitable distribution of material wealth? (Does the community which utilizes and benefits from a technology own it?)
7. Does it contribute to community stability?
8. Does it adequately reflect human values and aesthetics?
9. Does it not have negative effects on human health? (Closely related to criteria 1 and 2 above.)

Two additional criteria:

10. Technical efficacy: Does it do the required task efficiently on top of all the above criteria?
11. Context dependency: The Appropriateness of a technology will depend on the particular context. There is no universally correct technology.

As shown in the examples above, sustainability criteria are many. International attempts have been made to decide which criteria should be used. Sustainable development has been viewed in e.g. the so called Brundtland Comission (Harris 1988, EC 1992). Regional authorities have made their own decisions. In Finland the Academy of Finland has a Research Program for Sustainable Development (Väyrynen et al. 1990) and a Research Program for Sustainable Agricultural Engineering (Elonen et al. 1991). In the latter program sustainable agricultural engineering is defined as the technology that operates with a high efficiency coefficient and that does not cause environmental degradation. (comp. Francis and Youngberg 1990 and

Azelvandre 1994 above)

Plant production is very important in the determinination of sustainability because it is a primary part of production. Thus plant production technology plays an important role in the efficiency of the whole agricultural production system. It determines to what extent we get primary products and byproducts that can not be used or that have negative effects on the environment. (Elonen et al. 1991, Fig. 1)

The Research Program for Sustainable Agricultural Engineering focuses on the following (Elonen et al. 1991):

1. Development of calculation methods and information systems.
2. Development of adaptive control technology.
3. Development of operating principles and construction of agricultural machinery.
4. Development of cropping systems that keep the soil covered as much of the time as possible.
5. Future research in agricultural engineering.
6. Improvement of soil structure and the use of minimized tillage to maintain soil health, to get low production costs and to minimize soil and nutrient losses.
7. Better utilization of machine capacity and reducing energy consumption.
8. Possibilities of renewable energy use in agriculture.
9. Developing methods for keeping the setaside easily accessible for continued food production.
10. Developing systems for mutual management of water, gas, temperature and nutrient balance in the soil and plants.
11. Technology of alternative plant protection.

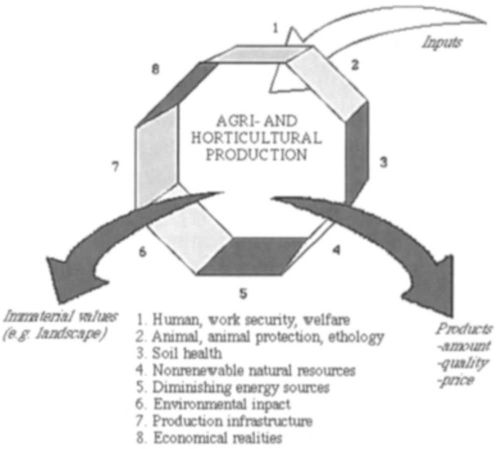


Fig. 1. Restricting factors of agri- and horticultural production (Elonen et al. 1991).

The program states that multidisciplinary knowledge is needed in the development of sustainable technics. This kind of knowledge is scattered, so that we need information systems such as knowledge based systems to manage it. We also need sophisticated methods to identify technologies that stress the environment. Adaptive control is needed in almost all of the listed tasks, i.e. we need technology that adapts its performance to animal and crop variation. To achieve this, it is inevitable to develop agricultural machines and implements to meet more accurate control requirements. Future research is needed because particularly strategic but also operative decision making needs knowledge of future trends. Improvement of soil structure is possible with light-weight transport technics and production methods that do not compact the soil. We should use more integrated solutions that take into account all factors of the plant´s surroundings. (Elonen et al. 1991)

Technology Assessment (TA) is nowadays a central part of major decision making in many countries and international organizations. This is because it is generally accepted that technics can have negative effects on the environment, social structures and other surrounding systems. TA can be divided into formal and informal types. The formal TA is defining its target systems in terms of mathematical models and calculations, whereas the informal one is based on the researcher´s own comprehension and estimations. The formal TA resembles systems analysis, the informal one a learning process. (Larsson 1990, OTA 1993)

Larsson (1990) concludes in his informal TA method study that agricultural TA can not only be based on a money scale. He draws his conclusions on criteria of environment, biology, work environment, technics, energy and economy. He judges these components and concludes that the most important research and development goals in plant production are as follows:

1. Development of methods and technology to measure the efficiency of various plant production tasks.
2. Development of automatic and manual measurement methods of soil parameters.
3. Development of calculation methods which enable automatic measurement and control.
4. Development of control technics for manual and automatic control.
5. Development of technics needed in plant production management
6. Development of alternative technical systems and sub-systems needed in future plant production.

Position Dependent Control, as it is defined in this work, is dealing with a major part of the above mentioned tasks. It is a tool that enables sustainable production, if correctly used. The correct use is only possible if the target system is adequately known. This emphasizes the need for accurate local information. In turn, the quality of positioning information is a central issue for proper operation of the control system.

1.2 Production Location and Position Dependent Control

In traditional crop production we do not follow in-field variation of production potential or environment pollution risks. The whole field is treated with constant settings. This is not, however, optimal because the field consists of individual locations. These locations need variable amounts of inputs and they give different responses. The production process is vulnerable to several disturbances and errors. Widely speaking, these negative factors have an effect on the planning process, the inputs, the location itself and the outputs. To enable generalizing, the target is here named the Production Location (PL). (Fig. 2)

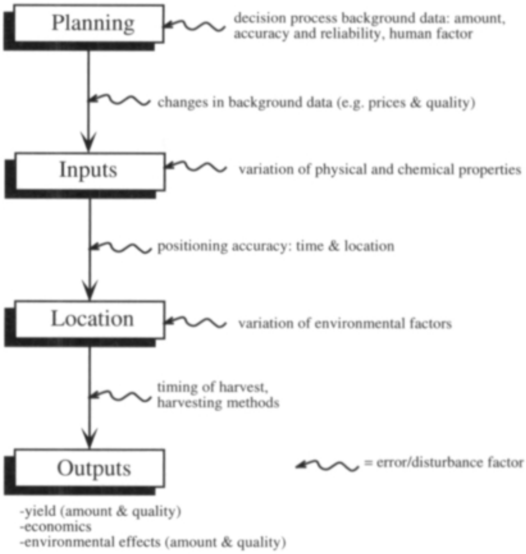


Fig. 2. Error and disturbance factors connected to the Production Location (PL). The term PL is universal: agricultural terms are used as an example.

Control engineering, in general, is used to decrease the effects of disturbances and thus to reach the goal wanted with a reasonable accuracy. The goal can be e.g. maintaining quality, economy or safety or minimizing environmental stress. Feedback control is frequently the only technical solution when the target is a complicated process. (Haugen 1990)

Geographical information describes the data and its location. The location can be expressed in coordinates or by a locating property, such as land register number. GIS (Geographical Information System) is an information system that uses geographical information. A narrowed def-

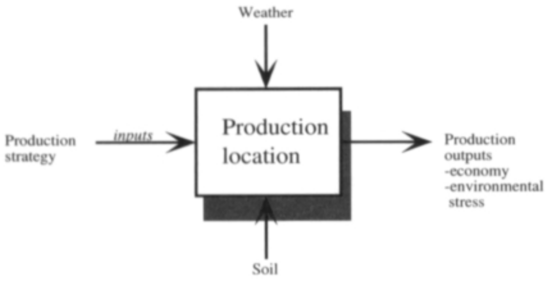


Fig. 3. Production Location (PL) in the field.

inition includes a configuration of computer hardware and software specially designed for acquisition, maintenance and use of cartographic data (Tomlin 1990).

The GIS has widened its application area. Nowadays it is widely used in administrative tasks: in 1988 there were over 30 state organizations and several municipal and private organizations in Finland that provided information for joint use. There were over 200 registers, in public administration only, including local information. (Rainio 1988) Lateron there have been much more providers, and much is invested in GIS-technic (Kosonen 1993, Rainio 1994). The technical applications of GIS include management of local information in different scales from local to global applications (Tomlin 1990, Rainio 1992, Ruutiainen 1994, Taipale 1994, Ahonen 1993b).

Position Dependent Control (PDC) is here defined as a control system that integrates control engineering and the GIS to a new concept. PDC uses local setpoints to achieve locally wanted control. The location which the setpoints are fixed to is named the Production Location. Agricultural PL is e.g. an areally limited location in the field. (Fig. 3)

Attaching information to Production Locations has several positive effects on the controllability of production. Production Locations tie all local information to manageable units where it is quite easy to distinguish responses of given inputs and thus to get accurate feedback. The feedback from the PLs can be used in planning the inputs (choosing their quality and setting the application rate, working depth, effect, etc.).

PDC is an adaptive control method. In adaptive control the controller parameters are continuously changed to meet the requirements of the controlled process (Haugen 1990). This is just what PDC is aiming at: to adjust the control system to local needs.

1.3 Position Dependent Control in crop production

The information of the Production Locations in crop production is currently not located, i.e. there is no local information available. In Position Dependent Control, information on the need of inputs, the amount of given inputs and received outputs (production, environmental stress) is connected to the PL. Therefore all the information needed should be localized.

PDC also needs local real-time setpoints. Part of the setpoints can be calculated on the basis of direct measurements, but the majority of them must be stored in a GIS. This is because direct measurement methods are not available or they are so slow that measurements can not be made in real time. There are also measurements that are to be made in a certain phase of the production, which is not the current one. In crop production, it is common that the system has considerable time delay: the PL integrates inputs for a variable time and then produces its output. This also requires the data to be put in a GIS.

PDC needs good models for the local production process so that the outputs can be predicted. In crop production this sets the need for good weather knowledge. Forecasts can be used in some cases where the effects are quite instant. Other cases may need simulation models which use different possible weathers to illustrate the risk of giving alternative treatments. The overall system for position dependent control could consist of planning, realizing and feedback parts

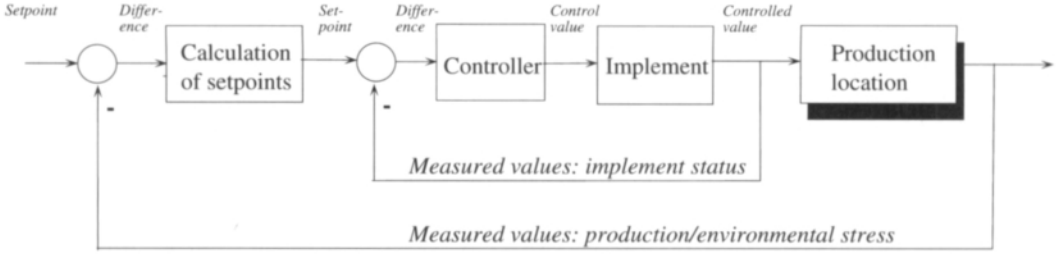


Fig. 4. Control loops of Position Dependent Control (PDC).

(Fig 4). In the figure (Fig. 4) the box ´calculation of setpoints´ uses production outputs as feedback of the production outputs of previous years. This stage is an adaptive controller because it changes its parameters according to changes in PL. The inner control loop is taking care of the implement. It checks if the implement is following the setpoints of the outer loop or not. The adaptive control loop uses the implement to realize its goals. Furthermore there could be additional loops which represent external legislative, social, ethological, etc. restrictions (Fig. 1 above, comp. Larsson 1990).

1.4 Earlier work on locational control

Positioning of agricultural machines is not a completely new idea. Positioning is used in traditional methods to distinguish between parallel passes and to enable driving accuracy. Driving accuracy aids, other than actual positioning systems, have been developed for a long time. These include traditional markers and row sensing devices (Schueller et al. 1994). Later these have been followed by more developed radio beacon (AGNAV 1988, Palmer 1991), laser (Shmulevich et al. 1988) and other low distance sensor systems (Yoshida et al. 1988, Vuopala 1990, Mäkelä et al. 1991).

Nowadays positioning systems have developed to a state that allows accurate positioning in virtually unlimited areas on the Earth (Auernhammer et al. 1994b). Specially the satellite navigation system GPS (Global Positioning System) gains more markets. This development enables even the use of small robot tractors in agriculture (e.g. Palmer et al. 1988, Nieminen and Sampo 1993).

Position Dependent Control is a new application for positioning. When this study began in the late 1980´s, there were no ready-made systems suitable for agricultural PDC. Currently there are several reported systems (e.g. Auernhammer et al. 1994a, Colvin et al. 1994, Stafford et al. 1994).

1.4.1 Off-line and on-line measurements

Most suggestions for the realization of locational control in crop production have been based on the idea that setpoints could be produced separately from control: setpoints that are calculated in office are brought to the implement with some memory media and realized. (Clark et al. 1987 ref. Møller 1990, Petersen 1991, Auernhammer 1990). (Fig. 5)

On the other hand, on-line measurement technologies for the measurement of yield and soil parameters have been developed. Larsson (1990, 79) thinks that sensor development is crucial for the development of crop production systems. This is a common conclusion of several researchers (Auernhammer 1990, Stafford 1993, Colvin et al. 1994). The development areas of these measurement technics can be divided into soil and plant/yield measurements. Multiple examples of these technologies are found in literature.

Automatic soil sampling and sensing technics are developed (Gaultney et al. 1988, Di et al. 1989, Schmidt 1991, Diaz et al. 1992, Thompson 1992, Auernhammer and Muhr 1993). New sensor types, e.g. ion-selective sensors (ISFETs, Ion Selective Field Effect Transistors), are developed for the measurement of soil nutrient content to be used in the determination of need of fertilizers. Research is very active in the area of continuous measurement of nutrients, but the sensors are still on prototype level or sensitive to mechanical stress or impurities in the sample. Such sensors are not suitable for field use (Holmberg 1987, Birrell and Hummel 1992, van den Vlekkert 1992). Seedbed assessment can be done by image processing (Stafford1988a). Soil density can be measured with a radar (Doolittle 1987, Stafford 1988b). Soil mechanical impedance is measured with a horizontal penetrometer (Alihamsyah and Humphries 1991). Soil moisture content is measured with e.g. dielectric (Arnold et al. 1992) or thermal (Altendorf et al. 1992) properties, microwaves (Jackson et al. 1987, Whalley 1991, Borgelt 1992) and Near-Infra-Red (NIR) sensors (Price and Gaultney 1993).

Plant parameters can be assessed on-line by image processing (Han 1988, Blazquez 1991, Fouche 1992), light reflectance measurement (Gaultney et al. 1989) or using portable radiometers (Nilsson 1991, Rao et al. 1992, Richardson and Everitt 1992, Wiegand et al. 1992). Image processing is also used for measurement of crop cover (Han et al. 1988) and crop residue cover (Meyer 1988, Endrerud 1994). Yield measurement systems are being developed in many research groups. Various methods that use either volumetric or mass flow principles are reported (Searcy et al. 1987, Roberts 1991, Borgelt and Sudduth 1992, Demmel et al. 1992, Stafford and Ambler 1992, Auernhammer et al. 1994a, Colvin et al. 1994, Stafford et al. 1994). Impact type sensors are also developed (Vansichen and De Baerdemaeker 1992).

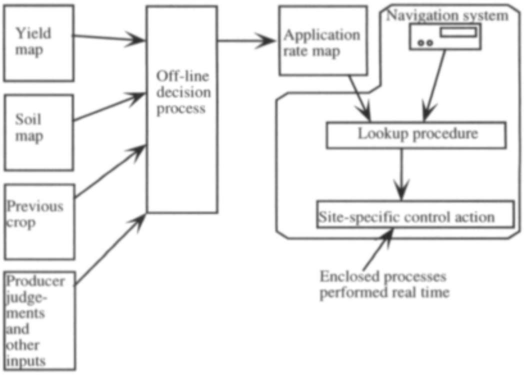


Fig. 5. Configuration of local control based on off-line measurement (Clark et al. 1987 ref. Møller 1990).

Field conditions do not allow some of the above mentioned examples of current research or prototype methods to be used. In practise it is not possible to use sensors that need extra care or constant calibration. The sensors should be rugged and fit to many soil types. There are also some difficulties with the frequency response, and speed of the analyzing, particularly. The measurement of soil nutrient content should work at least in the time that the tractor-implement combination passes the soil. This means a reaction time of c. 1–4 seconds (5 m combination length, 1.25–5 m/s forward speed). The same requirement is also found for other measurements that use sensors mounted to the tractor and where the measurement result is used for local control.

The restrictions of real-time measurements in connection with the spatial nature of field parameters makes GISs very attractive in the search of efficient technologies for better control of field operations. GIS is made for storage and analysis of local information. A combination of GIS- and control technology would serve the needs of precise plant production if economical and environmental benefits cover the costs of investments needed. The ease of operation should also be one of the leading goals of "Farm-GIS" development.

1.4.2 Earlier international work on locational control

Currently there are a few total solutions of locational control with variable names like Site-Specific Farming, Spatial Control of Field Operations, Spatially Selective Field Operations and Site or Soil Specific Crop Management reported. Maybe the most complete system is reported by Buschmeier (1990) and Schnug et al. (1990).

At the University of Kiel a concept of Computer Aided Farming (CAF) has been developed. A positioning method is used to attach chemical doze (herbicide and fertilizer) to the corresponding yield. The system includes data acquisition, data management and realization. The data acquisition part uses data acquisition units such as soil sampling and a yield meter installed in a combine. There is also a method for mapping. The data acquisition units are positioned so that the results can be attached to coordinates. The data are classified to once measured constant basic data (e.g. geography, soil clay content), medium term data (usable P or K) and fast changing data (usable N or S). The basic data are either constant or very slowly changing. Medium term data are measured in 2–4 year intervals, whereas fast changing data are measured many times a year. The data management part consists of a data management program, LORIS (Local Resource Information System). The data are saved in a standard raster format, where the raster size is 100–200 m^2. The program has tools for data interpolation and conversion. In the data management part the data are classified in areas that are equally treated. Classifications are combined to raster setpoints that are given to the realization part. The realization has a positioning method (GPS satellite navigation), a tractor computer and connection to implements. The setpoints are transferred in memory cards to the tractor computer. The setpoints are given to sprayers and fertilizers. Yield is acquired with the yield meter of the combine. The system development has been going on since 1988. (Schnug et al. 1990)

In the U.S.A. there are corresponding projects that use a multidiscliplinary approach. Sophisticated technics such as remote sensing and image analysis are widely used to get the huge amount of data needed in large scale natural resource management. Measurement methods for in-field variability are widely used. Satellite-(GPS)-based positioning is initiated in the U.S. DoD (Department of Defence) so most PDC-related projects use it. (Schueller et al. 1992a, b, Colvin et al. 1994)

In the U.K. there are numerous projects on subjects related to PDC. PDC of fertilizer and herbicide application, control of cultivation, seedbed preparation and yield mapping are central points of these research projects. (Møller 1990, Stafford and Miller 1993, Stafford 1993, Stafford et al. 1994)

The Nordic countries conduct their research activities with slightly different focuses. Sweden has carried out projects on methods for precision farming, such as positioning systems (Ekfäldt 1994), remote sensing (Nilsson 1992) and precision of machines (Svensson 1992). There has also been technology assessment of local control (Holstmark and Nilsson 1989, Larsson 1990). Danish projects have concentrated on yield mapping (Christensen 1991a) and tramline positioning (controlled traffic agriculture) (Wejfeldt 1990). There are also projects on machine guidance (Emgardsson 1991).

Besides these above mentioned there are many related researches concerning individual parts of realizing the PDC. Measurement systems, as mentioned above (Ch. 1.4.1), belong to the integrated technologies needed. Software for planning and management is being developed (Oliver 1987, Petersen 1991, Colvin et al. 1994). Control strategies and economy (Forcella 1992, Jahns and Kögl 1992, McBratney 1992) are considered. Data formats for communication (ISO 1994d) are researched. There are several R/D-projects to achieve flexible equipment (e.g. Auernhammer 1990, Møller 1990, Auernhammer and Rottmeier 1992). Vehicle data buses are developed in Germany, Denmark, France, the U.S.A. and the U.K. (Schueller 1988, Siirtola and

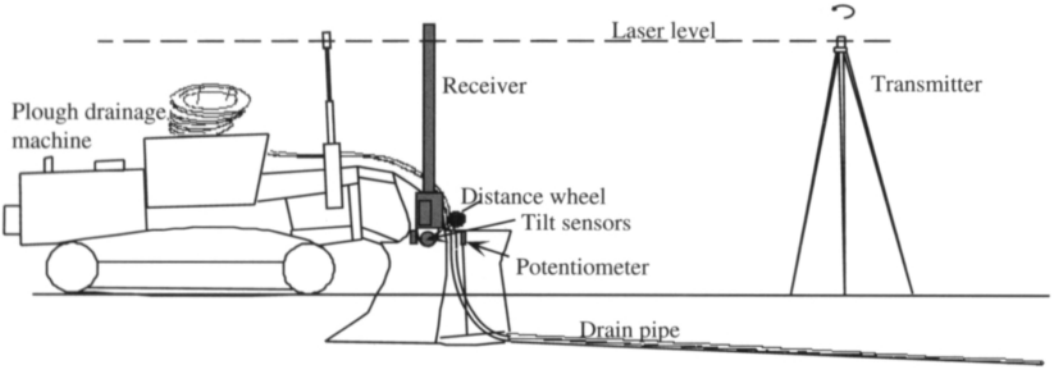


Fig. 6. The measurement system of installation precision on a plough drainage machine (Haapala 1992).

Alanen 1990, Stafford and Ambler 1993, Auernhammer 1991, Auernhammer 1993, KTBL 1993, ISO 1994). An agricultural bus system is to be standardized (ISO 11783-1–11783-5). Positioning trials are done in most countries involved in PDC (Auernhammer et al. 1994, Christensen 1991a, Colvin et al. 1994, Ekfäldt 1994, Stafford and Ambler 1994).

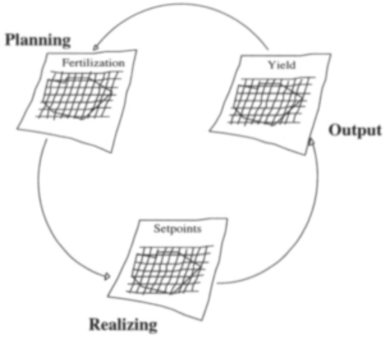


Fig. 7. Position dependent management of production (Haapala 1990).

1.4.3 Earlier work at the Department of Agricultural Engineering and Household Technology

In 1987-89 the author developed an on-line method for the measurement of digging depth and pipe location variation in underdrainage installation (Haapala 1992). On-line measurement required that the system would operate at sufficient speed and provide accurate enough (±5 mm, 95%) results. The developed system consisted of a laser level transmitter (revolving laser beam), a laser receiver (laser photodiodes in a movable grid), a potentiometric sensor, two tilt sensors (damped inclinometers), a DAQ-unit based on a single-chip microcomputer (MC68HC11) and a master laptop computer for control of the measurement cycle. The software controlled the measurement, displayed the results graphically and saved them for further use. Printouts were available on request.

In laboratory tests the system had an accuracy of ±2,9 mm (95%). For field tests the system was installed to a plough drainage machine (Fig. 6). The tests showed that the system was able to fulfill the set requirement of ±5 mm (95%). Problems ocurred when there were gusts of wind that made the transmitter oscillate. This lead to a degradation of the installation accuracy. A recommendation was given not to install drains in stormy weather and to keep the transmitter at a moderate distance in windy conditions. (Haapala 1992) The conclusion was made that the system could be used as a general method to measure the vertical coordinate accurately. If positioning was added to this accurate height measurement, a very accurate 3D-positioning system for limited area (Ø 300 m) use could be accomplished. This would make it possible to have underdrainage without marking drain locations

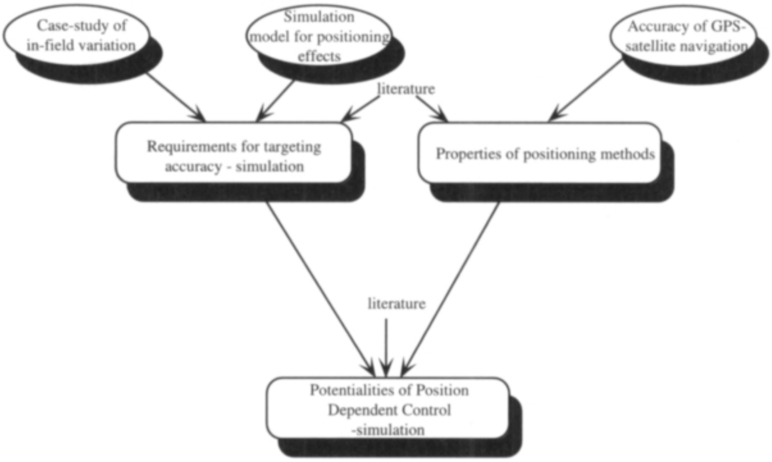


Fig. 8. The study consists of literature surveys, modeling and experiments. Simulations for getting the requirement for targeting accuracy use both empiric and simulated components.

(staking-out) on the field. Furthermore, a position-based crop production system (Fig. 7) could be established. Coordinates could be used to link production outputs, planning and realization. (Haapala 1990, Haapala 1991, Fig. 7)

The currently involved research projects at University of Helsinki, Department of Agricultural Engineering and Household Technology are concentrating on developing detailed models for planning and realizing position dependent control of selected field works, such as fertilization and crop protection. Field tests are conducted in order to get information on the technical realization. R/D-projects are going on to get the machinery needed (more controllable drills and sprayers, aerial photography, mapping systems) and software (Farm-GIS, production models, control software) for position dependent applications. (Haapala 1994b)

1.5 Contents of this study

This study concentrates on in-field-level precision of plant production. The research uses systems analytical methodology (Gustafsson et al. 1982). Plant production in a field is thought to consist of the by-position-and-area-defined units, the Production Locations. The methodology deals with these restricted areas, systems. The PL-system is represented in application-specific detail. It is mathematically modelled and simulated. The results are validated with early results and collected empiric data. Thereafter the research problems are solved by means of the models. Results are discussed and criticized. (Gustafsson et al. 1982, App. 1)

The models use either modeled or measured positioning accuracy and parameter data of the target Production Location. There are submodels both for the targeting and for the PLs. The modeled targeting error is fed to the PL-model with transfer function from the input to production output.

A general system model that is divided into two separate models for targeting errors in crosswise and lengthwise direction is constructed. These models are used to give solutions for some inputs and transfer functions. Besides these a semi-empiric case-study is simulated. Actual soil parameters and DGPS- (Differential Global Positioning System) positioning data from positioning tests are used together with modeled transfer functions to get the accuracy requirement for targeting of site-specific nitrogen fertilization. In this case-study the target-PL is a simple nitrogen application–yield model. (Fig. 8)

2 Position dependent adaptive crop production

King (1990) defines sustainable soil fertility as a state in which nutrients are available forever. This is achieved by a closed nutrient cycle, where the nutrients taken up by the plants return to the soil for further use. In a practical soil-plant system this is not, however, possible. In practise nutrients are added to and lost from the cycle. For practical farming King (1990) suggests that we should add only the necessary amount of nutrients and that losses should be minimized. This is exactly what the position dependent plant production is aiming at: to give site-specific inputs.

2.1 Need for Position Dependent Control

Position Dependent Control integrates production processes to better manageable units, the Production Locations. These can give much more detailed information on the health of the production process and its outputs than traditional production methods. Local information is used to adjust the production to local, regional or global requirements.

Differences in soils cause great variation of grain yield and quality with same fertilization in Finland (e.g. Heikkilä 1980, Mukula and Rantanen 1989a, b). Economic results vary for the same reasons because further uses of grain, e.g. industrial use for milling, starch or malt production, set strict quality standards for grain. The variation is due to the fact that Production Locations (PLs, Ch. 1.2) have varying properties. The existence of variation has been known for a long time (e.g. Kivinen 1935, Peck and Melsted 1973, Jokinen 1983, Diaz et al. 1992, Catt 1993, Delcourt and De Baerdemaeker 1994, Puustinen et al. 1994) and various measurement methods are being developed for its assessment (Nash et al. 1990, Bhatti et al. 1991a, b, McBratney 1992, Lesch et al. 1992, Wendroth et al. 1992). Variations cause noise in measurements that use large test plots, and must be accounted for if clear results are wanted (Bhatti et al. 1991b, Wendroth et al. 1992, Finke 1993). This instability of soil properties in time and space is also seen as discrepancies when validating simulation results with empiric field data (Johnsson et al. 1987, Moxey et al. 1995).

Production Locations are dynamic (McBratney 1992). The structure is changing rather slowly whereas soil temperature, gases, humidity and water soluble ions have a periodical variation. These variations indicate soil structure changes and they follow changes in the environment. The soil also acts as an inhibitor or filter for these changes, smoothing them. Soil processes can be classified according to their dynamic behaviour (Table 1, Richter 1986). The processes get less complicated from the left to the right. On the left there are slow processes that are involved with soil formation. To the right there are mainly dynamic plant growth processes. Applications are more interested in the upper level prosesses of the rightmost column (Table 1).

Clark et al. (1987, ref. Møller 1990) say that the most stable soil parameters are texture, humus content, hardness, suitability for artificial raining and fertility. ´Semistable´ ones are things that form the history of soil use: previous crops, plant protection, soil tillage and the current plant disease and pest situation. Unstable (dynamic) processes are such as soil humidity and need for artificial raining. Soil nutrients can be divided in more detailed stability groups where water soluble nutrients are most instable. Nutrient storages and their mineralization stabilize plant uptake. Weather conditions affect the uptake. The soil water and gas exchange systems by far determine the availability of nutrients. Thus they also determine with a great impact the actual effect of the fertilizer given. (Cooke 1982, Richter 1986, Peltonen 1992)

Table 1. Soil processes classified according to their dynamics (Richter 1986).

less complicated processes with increasing dynamics
→

Humification Humus decomposition Podsolization Gleying Laterization Solodization	Mobilization of Fe Clay formation Clay destruction Clay transformation Pseudogleying Erosion Salinization Mineralization Loosening Compaction Desalinization	Infiltration Evaporation Heat transport Leaching of carbonate Gas diffusion Ion exchange Immobilization

The nutrient cycle can be viewed on several levels. In nature plant residues return to the soil. The cycle has losses and nutrient addition. Nitrogen is added through biological fixation and precipitation; and it is reduced by soil erosion, leaching, denitrification and volatilization of ammonia. The nutrients are in constant movement between soil solution and organic matter or clay. Micro organisms take up nutrients from the solution as they decompose organic matter. This nutrient returns to the solution as micro organisms die. The weathering of minerals brings nutrients to the solution Plant roots act as a sink that integrates the nutrients. (King 1990)

In an agricultural nutrient cycle some of the nutrients are taken away in the yield (Auernhammer 1990). If we want this system to work continuously we must replace the harvested amount. (Fig. 9, King 1990)

The cycle can be expanded to comprise an entire region. On a farm that produces both crops and animals, the nutrients first leave the field in the harvest and then the farm in grain, hay or animal products. A large fraction of nutrients consumed by animals return in manure. The net loss is compensated by buying fertilizers and feed. Products leave the farm and are processed and consumed. A fraction of the nutrients is deposited in surface water or landfills. Part of these nutrients could be returned to the farm in the form of food processing by-products, effluent or sewage sludge. This is not true recycling because the processing industry gets its input from several farmers. The effect is the same though because nutrients are returned to the cycle. (Fig. 10, King 1990)

As PLs vary it is natural that inputs to them must vary, too: if we do not vary our production methods and their effect we do not get optimum outputs. Production methods have considerable effect to fast changing components of soil processes (Richter 1986). Lack of control of these processes gives a diminished efficiency coefficient in comparison with individually optimized inputs. Adaptive Position Dependent Control makes it possible to get simultaneuosly both better economy and less environmental stress (Finke 1993, Nielsen and Bouma 1993). This kind of production is based on the ideas of sustainable agriculture. The current methods which do not vary the inputs can not be optimal and are thus not sustainable (comp. Elonen et al. 1991, Stafford 1993). The plant and variety given, varying the inputs is the only way to affect the production output. Input is here seen as efficiency (or level) of the site-specific crop production works (fertilizer doze, tilth effect, ploughing depth, etc.). Production strategy of PDC is reflected by the given inputs (Jahns and Kögl 1992). Alternative production methods (e.g. incorporation/surface spreading, autumn ploughing or ploughless production) are groups of different inputs.

Some inputs need to be variated both in time and space. Seedbed preparation is very sensitive for right timing in certain clay soils, some other soil types are not so sensitive to the timing. In economic terms, there is a big timeliness effect in clays, requiring correct dimensioning of machine capacity. Insufficient capacity causes increased costs as it leads to inaccurate timing. Variations in nutrient uptake in different years can cause a need for supplementary fertilizing. The timing of this additional treatment is crucial (Esala 1991, Peltonen 1992). Evidently the need

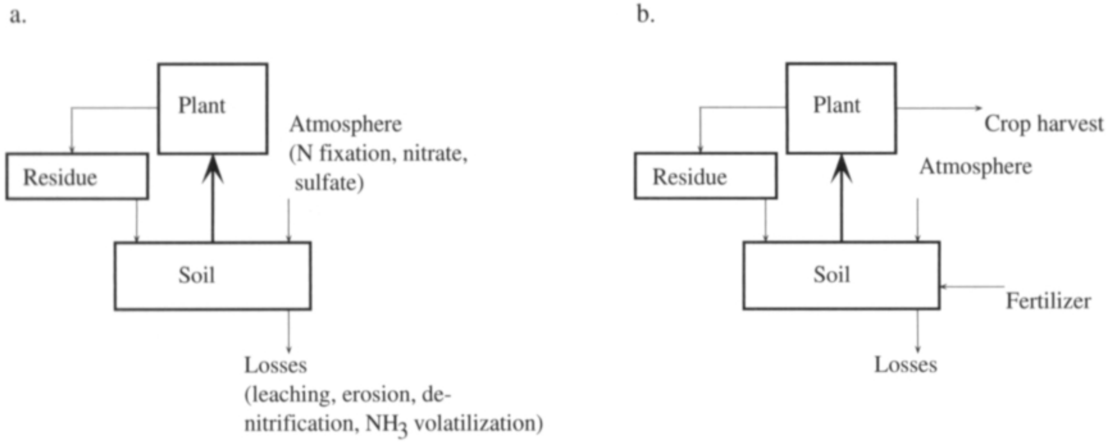


Fig. 9. Nutrient flow (a) in nature and (b) in agricultural systems (King 1990).

of seedbed preparation and adjusted fertilization varies in space as well. The same variability is true with weeds (Erviö and Salonen 1987).

2.2 Size of the Production Location

This study concentrates on components that directly affect the Production Location. The maximum size of PL that can be treated with constant treatment is defined. To be able to do this, we have to know what are the consequences of giving the inputs to variable areas. This in turn needs to be considered against the variation of the true requirement of inputs in the field.

When a location and its data are connected to a coordinate, the size of the area which is considered as the same location is a primary question. Choosing a certain size leads to several other decisions. A large area is much easier to locate than a small one. A small target area leads to positioning and control problems since the target has to be detected in order to perform the related task. According to Richter (1986) soil, apart from being a connection point, is a growing place for the plant. This is the smallest separate unit in the field. This unit has its own energy and materia flow and transport systems and produces as much as local conditions and the plant itself admit. The environmental impact is also dependent on these restrictions. The target location of Position Dependent Control, the PL, may consist of several of these units. Choosing the appropriate size of the PL can be expressed in form of a few questions as follows (Fig. 11).

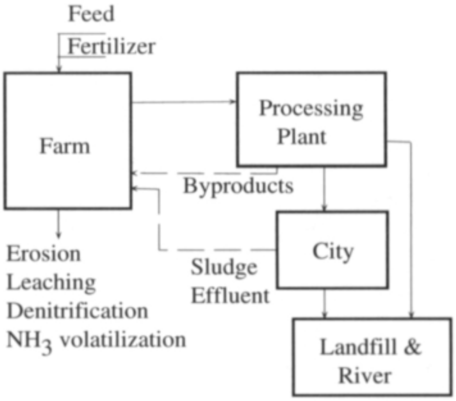


Fig. 10. Nutrient flow in a region (King 1990).

The first question (Fig. 11) has to be asked because we want to know if the target area has to be divided in different subareas or not (comp.

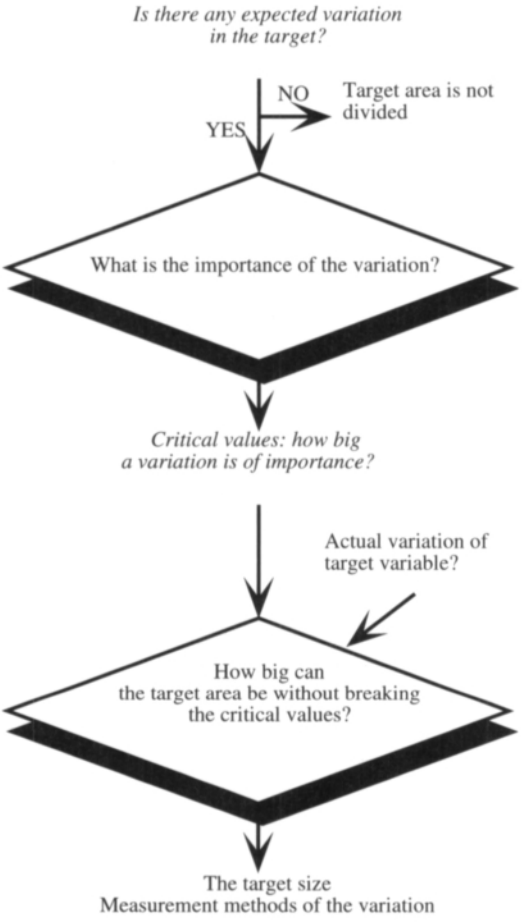


Fig. 11. Choosing the size of the target and measurement methods according to the variation of the local information.

Forcella 1992). This leads to the need of *a basic survey* that finds out the variation type. The survey should be conducted with a resolution that is at least twice higher than all predictable future applications of the data (sampling theorem, Haugen 1990, Franklin et al. 1994). The second phase is to determine the trigger value of variation: how high deviations are of importance. These critical values have to be defined in terms of accepted range, frequency and local concentration of the variation. The size of the target is derived out of the critical values and actual variation. This also leads the selection of variation measurement technics. (Fig. 11 above)

The estimation of Production Location size resembles the problems found in geostatistics (App. 2): we have to find the most rational way to collect information (Clark 1984). Geostatistics is based on Matheron´s (1971 ref. Clark 1984) Theory of Regionalized Variables. Geostatistical procedures are extensions to classical statistics with the assumption of sample independence removed (Upchurch and Edmonds 1989). Geostatistics can be used in various applications where the location of the estimation target is known and surrounding targets are both located and measured (Oliver and Webster 1991). Geostatistics is most utilized in mining (Clark 1984). Agricultural applications of geostatistics are in the areas of sampling design (Di et al. 1989, Webster and Oliver 1990, Thompson 1992, Delcourt and De Baerdemaeker 1994), interpolation (Bhatti et al. 1991a, Delcourt et al. 1992) and modeling (Flaig et al. 1986, Oliver 1987, Nielsen and Alemi 1989, Goovaerts and Chiang 1992, Bouma and Finke 1993, Mulla 1993)

2.3 Possibilities of realizing adaptive Position Dependent Control

PDC can be viewed on several levels of tasks and in time domain. The task level consists of the creation of control strategy and its coding to setpoint values and, on the other hand, realization of these setpoints. The latter task, realization, is Position Dependent Control of the implements. Adaptivity is maintained through feedback and the control strategy (see Ch. 1, Fig. 4).

In time domain short and long term effects must be discriminated. (Fig. 12) The strategic level concentrates on long term effects of production whereas realizing is dominated by short term thinking. Control strategy creation operates with global concepts such as sustainability: are

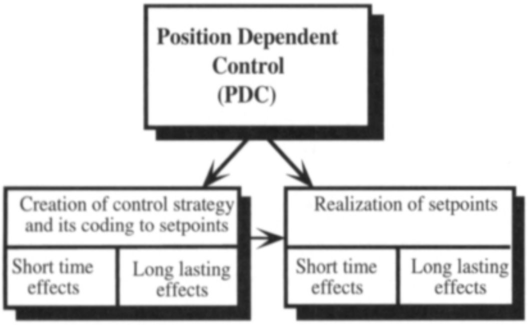


Fig. 12. Levels of viewing Position Dependent Control.

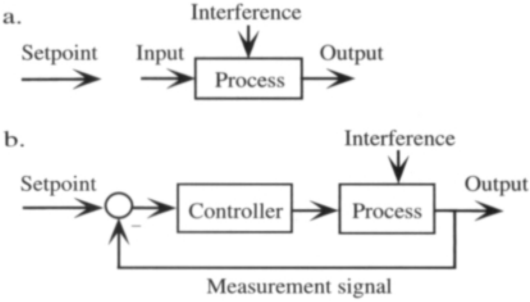


Fig. 13. (a) Control task. The system output is expected to follow the setpoint. (b) Solution through feedback control (Haugen 1990).

we doing the right things? Setpoint realization/ implement control finds technological solutions: doing the right things as well as possible. (comp. Elonen et al. 1991)

This study is concentrated mainly on the realization (right branch in Fig. 12). Current projects at the Department of Agricultural Engineering and Household Technology deal with the strategic level as well (Haapala et al. 1994).

The required state of the controlled system is achieved through changing the inputs of the system. This in its turn needs setting the reference values, i.e. the setpoints. The setpoints are given to a controller that passes them on to the system. The system itself, its inner properties and external disturbances, decides how these inputs show up in system state and output variables. (Gustafsson et al. 1982, Haugen 1990, Fig. 13).

The setpoint is set to the level desired. This level can either be constant or dynamically variable. The dynamics can be based on e.g. time, location or distance traveled. Setpoints are set in such a resolution that the reference is achieved with a reasonable accuracy. The most usual control method is feedback control. It is based on the measurement of the output (Fig. 4 above). Other generally used methods are feed forward control (from reference and/or disturbance) and gain scheduling (parametric control). Adaptive control, in which controller parameters change realtime as a function of measured values, is getting to general use.

The realization of control, in general, requires that (Gustafsson et al. 1982, Haugen 1990, Franklin et al. 1994):

1. The system controlled is adequately known
2. The system is controllable
3. The control is technically possible
4. The control is economically justified

2.3.1 System knowledge

If the system is not known it is not possible to identify components that affect system behaviour. It is, though, possible to act to a certain extent with so called ´black box´ knowledge: we know how the system reacts to known inputs and choose the most effective inputs to be controlled. If the system model is known we can achieve good tracking and control ratios even with feed forward (open loop) control. On the other hand, feedback (closed loop) control often operates well although the system model is not known. In practise system knowledge is something between the black box and complete knowledge. (Gustafsson et al. 1982, Haugen 1990, Tuomivaara 1994, Franklin 1993).

Literature describes the basic performance of soil and plant systems (e.g. Jaakkola and Turtola 1985, Richter 1987, Johnsson et al. 1987, Peltonen 1992, Karvonen and Varis 1992). When system knowledge is not perfect, specially with complex target systems, control realization includes testing of the system. Another option which is often used parallel to testing is simulation. Simulation is done with a mathematical model of the target system. (Gustafsson et al. 1982, Haugen 1990, Karvonen and Varis 1992, App. 1) PDC is a hypothetic system that is not fully testable. Therefore, systems analysis (App. 1) is used to describe the system in application-dependent detail (Ch. 1.5, 2.4). Testing shall be used in the realization phase in design and adjustment of the PDC-controllers for individual field machines. This is, however, done later in continuing research (Haapala 1994b , c).

2.3.2 Controllability of the crop production system

The controllability of a system is dependent on which of the factors that have considerable effect on the output can be adjusted and how accurately it can be done. (Gustafsson et al. 1982, Haugen 1990, Franklin et al. 1994) The controllability in a system like crop production is always incomplete because:

1. Part of the factors that have considerable effect on the output (e.g. weather) are not controllable or they are partly controllable (e.g. pests and diseases, soil structure). In practical farming, one can not manipulate the weather; therefore, from the system point of view, it is classified as a disturbance factor.
2. There are several tasks in crop production that must be carried out once at a certain time, and can not be fine-adjusted later on. Tilth and seeding are this kind of tasks. Fertilizing, on the other hand, can be completed with surface or leaf application as weather conditions and resulting plant growth rate change (e.g. Peltonen 1992).
3. Realizing an optimal setpoint can be technically difficult. The control system reaction speed, accuracy and resolution may restrict the result. Targeting the setpoint may be inaccurate.
4. The controlled implement itself limits the control: the implement is not controllable enough for optimal realization of adaptive control.
5. Properties of the material applied or the target Production Location vary in such a way that it is not possible to give the doze or treatment needed. The inhomogeneity of cattle manure limits its use in accurate control of nutrients, and some soil types have very varying tilth properties which makes it difficult to have even tilth with once-over operation (comp. Fig. 2 in Introduction).
6. There are compensation mechanisms in the Production Location (e.g. tillering) and interactions (e.g. alternative uptake of nutrients with changing pH). They show up as buffer effect for some treatments and dual sensitivity of the system.
7. Reaction time varies. Some responses are immediate (e.g. tilth quality), some take a few hours (pest control), a few days (weed control), a few months (yield), a year (leaching) or several years (production methods cause gradual compaction, acidification or soil erosion)

Technological measures can make the plant production system more controllable (the numbering refers to the points above):

1. Weather forecasting, predictions of pest or disease infections.
2. Development of cultivation methods that are less sensible to condition changes in the growing season. Use of estimates and forecasts of the production result and its environmental impact to fine-adjust dozes and treatments that are given just once. Split application technic.
3. Automatization of control and better targeting. Accurate targeting is realized with additional sensors and measurements (image processing, sensing, positioning).
4. Better implements are developed. Controllability is set as a primary goal.

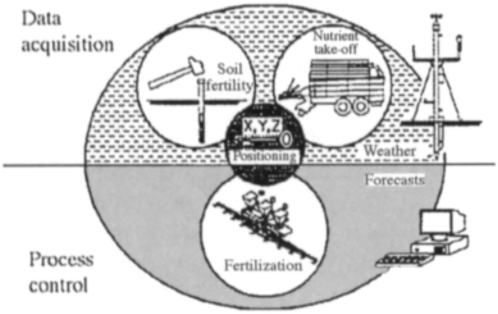


Fig. 14. Components of a fertilization system that is environmentally sound and the rate of which is in accordance with the yield (Auernhammer 1990).

5. Processing of material (drying or composting of manure, use of land betterment or change-over to ploughless production).
6. System reactions are tested. Achieved knowledge is used in calculation of the setpoint. Mathematical models are used.
7. Attachment of the information to something else than time, e.g. position coordinate. Management with GIS-software.

2.3.3 Technical possibilities

It would be most rational to get all system knowledge from real time measurements. There are not, however, practical real time measurement methods for many important parameters, such as soil nutrient content (Ch. 1.4.1). In spite of this, the setpoints must be available in real time as the implement passes the Production Location.

A huge amount of local information is collected in PDC. A natural solution is therefore to attach the information to position coordinates. This attachment enables adaptive control to be realized as Position Dependent Control. The setpoints can be produced either beforehand or in real time. The system consists of a GIS, where there is information on local production potential, environmental risks and setpoints for implements. The GIS also contains feedback from successes of the operations, production results and environmental impact. (Ch. 1.4, Fig. 7) GIS systems are based on positioned information. Auernhammer (1990) has presented positioning as a key component for environmentally sound and neccessity-based fertilizing (Fig. 14). This is the common conclusion of many other researchers as well (e.g. Palmer and Matheson 1988, Tyler 1993, Searcy et al. 1994, Stafford et al. 1994)

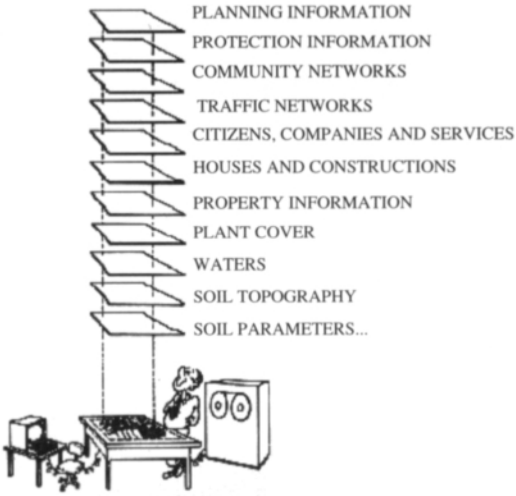


Fig. 15. Central components of geographic information (Rainio 1988).

The Geographical Information System is an effective way to combine site specific data. GISs are used more and more frequently in various applications that have localized material. A pioneer project in new uses of the GIS was the GIS of the gas network in Tokyo (Ueno et al. 1989). The longest history of local information management is in cartography. Statistical, forestal and transport applications are also areas where GIS-technologies have been used for a quite long time. (Rainio 1992). In Finland, the use of GISs has been encouraged because of their rationalizing effect in data management. The use of geographic information is subject to constant research and development (Rainio 1988, Fig. 15).

Positioned measurement data that are to be transferred to a GIS can be called local information. Local information comprises at least coordinate data or positioning properties (like land register codes) and describing properties (Rainio 1988). Local information is a logical combination of localizing and descriptive knowledge of the target. The localizing knowledge includes coordinates, the relative order and connections of which are called topological and geometric data. The descriptive knowledge consists of identification codes, possibly a positioning property, timing data and the actual property. (Fig. 16, Rainio 1988)

Location of the local information is given in coordinates or with a positioning property. When the latter one is used, coordinate information is situated separately, e.g. in Finland land register and coordinate data are stored in separate information systems and interconnection is achieved through the use of a standardized number code. (Rainio 1988) In position dependent plant production the positioning property is naturally the code of Production Location.

In Position Dependent Control the local information comprises Production Location specific parameters, measurement data and knowledge of the control realized. As a conclusion, the following are the most important ones:

1. Local production potential and environmental risk
2. Local implement control (expressed as the setpoints)
3. Local feedback on success of treatments (actual control values)
4. Local production results and other resulting outputs such as environmental stress caused by the production

In PDC the local setpoints compensate for model and parameter changes of the Production Location (comp. adaptive control, Haugen 1990) The control technic is chosen according to the demands of the specific control task. Specifications of the technic (e.g. control speed and accuracy) must be such that the required variation of inputs may be realized. The setpoints of the outer loop (Fig. 4 in Ch. 1.3.) are based on the perceived production strategy of the user. That is why an additional strategy loop can be thought to be added to the figure. This loop (or group of loops) is related to the values and knowledge of the user in general. It has background variables like education, personal properties, society demands, values, etc. things that guide and explain the actual decisions. These can be called internal and external frames (Larsson 1990) or limiting borders (see Ch. 1.2, Fig. 1, Elonen et al. 1991).

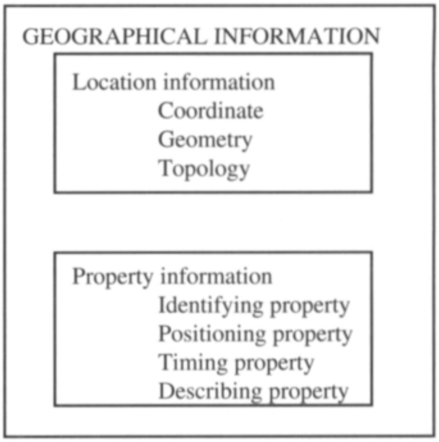


Fig. 16. Concepts of geographical ingformation (Rainio 1988).

This study mainly concentrates on possibilities to realize the setpoints (the inner loop in Ch. 1.3, Fig. 4). The site-specific setpoints that are stored in the GIS are realized when the implement is at the Production Location. In addition to this, there are setpoints that are calculated in real time. Setpoints that are in the GIS are based on measurements and calculations that are made before the control time. Of course, both types of measurement and calculation can be used. The calculation of setpoints is not fully automatic but it is also affected by the knowledge and values of the user. (Fig. 17)

Off-line (before control time) measurements include e.g. soil conditions and the calibration of the equipment. On-line (at control time) measurements are divided into measurements of local (mainly soil and yield) conditions and feedbacks of implement operation. Off-line measurements begin again after the control time with assessment of growth and quality. In all phases positioning is a very important measurement.

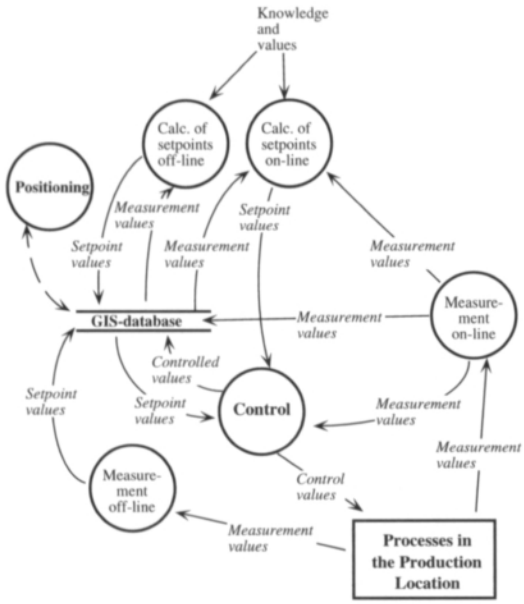


Fig. 17. Data flow in the realization of adaptive Position Dependent Control.

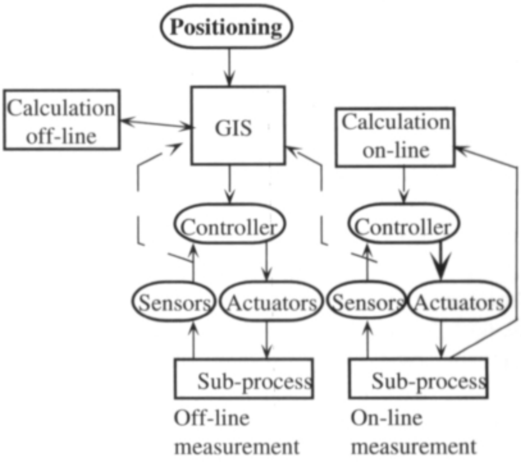


Fig. 18. Measurements in Position Dependent Control. The technical realization includes both off -line and on-line measurements.

The technical realization of PDC includes a computing unit, a positioning device, a GIS, implement controllers and sensors. The computing unit selects the right setpoint from the GIS according to position information or calculates it on basis of on-line measurements and/or the information stored in the GIS. The setpoints are realized with the controllers. Controllers need information on the operation of the implement, which is given by the sensors. Actuators complete the operation. Most of the measurements are carried out off-line. On-line measurements (Ch. 1.4.1) also belong to position dependent production as an integrated part. As they develop they can be selected instead of off-line measurements. This does not, however, diminish the need of a GIS. Data management gets complicated and needs GISs for the organization of the data. The GIS is a very important and efficient tool in managing huge amounts of spatial data (Rainio 1988). (Fig. 18)

It is common in crop production that direct measurement is not possible. The measurement target is actually a physical variable that is in well-known relation to the variable required (e.g. soil conductivity - moisture content, ripeness of grain - satellite image). The result is converted with this relation to a value of the variable required. If the relation is of the form y=ax+b, then the actual measurement result is as shown in following equation (eq. 1, Hari 1991):

$$\boxed{1}\ \hat{y} = y + \varepsilon_y + \upsilon_y = a(x + \varepsilon_x + \upsilon_x)(1 + \varepsilon_t) + b$$

where $\hat{y}$ = estimate of the value, measurement result
y = actual value
ε_y = random error (noise) in value determination
υ_y = systematic error in value determination
a, b = constants
x = true value of the measured variable
ε_x = random error (noise) in variable measurement
υ_x = systematic error in variable measurement
ε_t = interference caused by the measurement

It can be concluded that it is preferable to have few measurements and direct ones instead of indirect, if possible. If the result consists of several measurements, each measurement brings its own uncertainty to the result. (Dally et al. 1984). The sum of all errors connected to one measurement result is called error budget (Toft 1987, App. 9). In individual measurement applications the error budget is adjusted, with the selection of instruments and methods, so that the final result is accurate enough.

The range and the importance of variation in the target variable are important criteria in the selection of measurement targets and methods (Clark 1984, comp. Fig. 8). The measurement targets of Production Location are selected so that the system is controllable enough for the application. The inner control loop of PDC needs measurements on the success of implement adjustment (see Ch. 1.3, Fig. 4 above). If the control strategy is either economical or environmental, it needs measurements that describe the production and the environment of the Production Location, respectively. Production rate and quality and input/output ratio are the most important required measures of economy (Pehkonen 1987).

There is no way to have control without setpoints (Haugen 1990). The setpoints of PDC need exact criteria. For this study it is not important how the setpoints are achieved. There is a necessity of money or a value scale or another scale that is at least of ordinal level. The best solution would be to have a relative scale in order to judge different strategies and technical choices. For this reason, environmental impact of production is converted to environmental costs. There are several ways to do this, e.g. willingness to pay or the costs of correcting the negative impact. The environmental cost is subject to live discussion, because it is not clear which costs should be included and what is the price of immaterial or non-commercial things, such as clear water or air, a rare species, etc. If the criteria is ´sustainability´, a concept or philosophy that has many meanings, it is also a very complicated issue to be handled (see Introduction, Heinonen 1993).

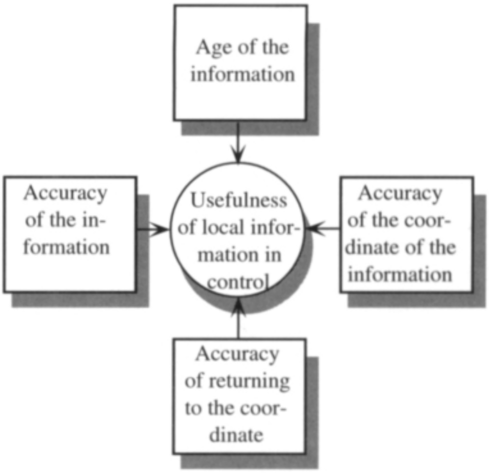


Fig. 19. Usefulness of local information in Position Dependent Control.

Natural systems are dynamic: the difference between measurement data and ´reality´ is changing as a funtion of time (Ch. 2.1). So the age of measurement data affects its accuracy and usability in control. (Gustafsson et al. 1982) Slowly varying variables can be measured before control time. Setpoints can then be calculated and realized when we are at the right Production Location. Instable phenomena are difficult to handle. If they are known well enough we can use prediction models (e.g. Karvonen et al. 1989, Peltonen 1992, O´Callaghan 1995). Prediction models in PDC enable measurement of dynamic things some time before control time. The measurement interval can also be increased if good predictions are available. The adaptive control can manage a system, the parameters of which change. This requires measurement of system parameters. (Haugen 1990)

As a conclusion, the usefulness of local data is dependent on its validity, age, accuracy and accuracy of its position. Position accuracy is further divided into positioning during the measurement and positioning during returning to the point. (Fig. 19) The accuracy of the data consists of numerical accuracy and e.g. accuracy of possible classification.

2.3.4 Economy and markets of Position Dependent Control

In PDC, different economical goals show up only as variable setpoints, their level and range of variation. Strategic goals are also built in the manipulation required, represented by the setpoints. (Ch. 1.3, Fig. 4)

Sustainable production needs to be economical. To be economical the production has to be profitable and give maximum benefits. The benefits are normally expressed in monetary values. Generally the best total outcome is available when marginal costs equal marginal selling price. The economical optimum is located in this point. Recently economical thinking has been widened to include environmental influence of the production (Francis et al. 1990). Often this moves the optimum point. Environmental impacts of crop production are the sum of soil, air and water pollution of the technic used. Besides environmental effects there are also social, political and other such effects that are difficult to value in terms of money. The transfer function of an input to the environment should be known for each Production Location. For social and political effects this is very complicated. (Francis et al. 1990)

High efficiency of inputs in the production system (measured e.g. as product units per input unit) is an important indicator of system health (Pehkonen 1987, Elonen et al. 1991, Jahns and Kögl 1992, 1993, Azelvandre 1994). This efficiency and the amount of production units per Production Location determine how much of the inputs are given in vain or lost outside the individual Production Location. The effect of this loss depends on the ability of neighboring Production Locations to utilize excess treatments and on the response of the environment to the amount eventually lost from the field. In some cases the environmental impact is very negative and sometimes the extra input changes over to a non-hazardous form. (Auernhammer 1990, Elonen et al. 1991, Francis et al. 1990)

Position dependent plant production is expected to have good economical effects. Palmer and Matheson (1988, Table 2) forecast that as much as half of the present production costs can be saved. The result is based on a typical Saskatchewan farm in Canada (a farm of c. 800 ha 1/3 of which setaside). The situation requires that well-operating positioning systems are available. The table shows the economical result with a step-by-step increase in the use of positioning in crop production. First driving accuracy is improved, which reduces overlapping and non-treated area in fertilizing and plant protection. Reduced overlapping reduces costs and gives more outcome by avoiding negative effects (soil compaction, over/under dozes). The next step is to start night spraying that gives a higher effectivity in herbicide use (reduced wind drift and evaporation, higher relative humidity). This leads to reduced herbicide use and cost savings. The following steps, need-dependent fertilization and tillage, reduce costs because inputs are diminished in some cases. Up till this the table is based on test results. Further steps include prospects of effects of a very individual treatment of field parts. Small robot implements are used to achieve optimal tilth. This would eliminate the need for setaside. Lightweight robots do not cause much soil compaction and they are very flexible in use. The robots are expensive but they do not need driver instruments (cabins or ventilation). Full realization of the system would give savings of c. 66% in fertilizer, pesticide and fuel costs. (Table 2, Palmer and Matheson 1988)

The scenario (Table 2) is somewhat optimistic. The thought model assumes that test results are transformed to management practises. This is not easily done because local situations must be reliably identified. Identification procedures that have the necessary resolution are expensive. There are also different views on the priorities of the above mentioned technics. Many authors think that driving accuracy is not the first one to give positive effects. Position Dependent Control (Site-Specific Farming, Farming by Location, Farming by Soils, Computer Aided Farming or equal term) is thought to give more po-

Table 2. Economical effect of using a positioning system (Palmer and Matheson 1988). The figures are in dollars.

	Current situation	Over-lapping in turns	Over-lapping in parallel driving	Night spraying fertiliz.	Need dependent tilth	Position dependent planting	Plot seeding/	Small automatic implem-ents or robots
Fuel	3.61	3.25	2.93	2.93	2.93	2.93	1.95	1.76
Seed	5.00	4.50	4.05	4.05	4.05	3.64	3.27	2.94
Fertilizer	9.23	8.31	7.47	7.47	5.38	5.38	4.84	4.35
Herbicide	7.71	6.94	6.25	4.38	4.38	3.92	0.39	0.35
Pesticide	3.00	2.70	2.43	2.43	2.43	2.43	1.70	1.58
Spare parts	6.15	5.53	4.97	4.97	4.97	4.97	3.31	1.89
Machines	15.30	15.30	15.30	15.30	15.30	15.30	10.20	5.82
Cost	50.00	46.53	43.40	41.53	39.44	38.57	25.66	18.69
Tax	5.76	5.76	5.76	5.76	5.76	5.76	5.76	5.76
Insurance	6.92	6.92	6.92	6.92	6.92	6.92	6.92	6.92
Cost/acre	62.68	59.21	56.08	54.21	52.12	51.25	38.34	31.37
Income/acre	70.00	70.60	71.20	71.20	71.20	71.20	71.91	71.91
Result/acre	7.32	11.39	15.12	16.99	19.08	19.95	33.57	40.54
Prod. area	1333	1333	1333	1333	1333	1333	2000	2000
Total income	9760	15186	20160	22653	25439	26660	67140	81080
Year	1	2	3	4	5	6	7	8

tential (e.g. Auernhammer 1990, Buschmeier 1990, Larsson 1990, Møller 1990, Schnug et al. 1990, Heege 1991, Kloepfer 1991, Stafford and Ambler 1991, Muhr and Auernhammer 1992, Wollenhaupt and Buchholz 1993, Stafford 1994).

Nielsen and Bouma (1993) report good economy of PDC in U.S.A.. Savings in fertilizer use and increased yields met or exceeded the increased costs of PDC - even without inclusion of environmental benefits. Robert et al. (1991) got maximum $517/ha benefits with soil-specific fertilization. Wollenhaupt and Buchholz (1993) conclude based on wide experiments in the U.S.A. that variable rate fertilizer application can give quite different returns inside soil type classes. This is because there is great variability in the need of fertilizers. The situation is very clear wihen only P and K are managed. They also report that the high short distance variation is not easily manageable. Nitrogen management shows the most potential for yield improvement and efficient fertilizer use. They emphasize that even if the variable rate application would be economically as profitable than single fertilizing rate approach, there are undoubtful environmental benefits. They are, though, very difficult to calculate. In a study on P and K management for potato production, Hammond (1993) concludes that the additional cost for the managemment was minor but the effects on crop return could be significant. The increased returns concentrated on the low-yielding spots of the field that would get insufficient nutrient rates with conventional whole-field management. The increase in crop quality through more even grade is also a potential source of better results. A minor increase in yield and a signicficant increase in the uniformity of the grade, give the potato farming returns that exceed the investment costs of variable P and K management Hammond (1993) also concludes that variable fertility management is “a best management practise to ensure environmental conservation and sustainability of resources for production agriculture".

Schueller et al. (1994) say that positioning systems penetrate into the market first via large units, such as cooperatives. Crop protection cooperatives are the most probable users of advanced positioning systems in the U.S.A. In Finland this kind of units are rare for the time being. The accurate positioning systems needed in robot tractors are costly and thus need big field areas. They are more likely used in mass production countries other than Finland. On the other hand some special uses in certain crops (e.g. row crops, valuable crops) are possible in our conditions as well. It can be anticipated that partnership in the European Union will introduce larger scale and/or more specialized farming in Finland. Probably these units will be the first ones to economically utilize Position Dependent Control in Finland.

Prices of technics used in PDC are constantly decreasing. The hardware and software involved find many applications outside agriculture. (Koskelo 1990, Bäckström 1990, Choi and Charr 1994) The benefits of large-scale manufacturing are therefore lowering the costs of agricultural PDC. For the complete realization of PDC, special agricultural software is to be developed. International research projects show that such programs are already available. (Buschmeyer 1990, Petersen 1991) Technology transfer from concepts developed internationally should be used to reduce excess costs of local R/D. Holmes (1993) concludes that the speed and degree of adoption of site specific farming practices is mainly dependent on the success of technology transfer. This must be realized through automated data collection, the development of approppriate equipment for the control needed, user friendliness of the equipment and other systems used, affordable cost of the systems per unit and the sufficient amount and quality of shared data by government agencies, and positive development of the general economic factors affecting agriculture and the economy as a whole.

As a conclusion, the economic effect of Position Dependent Control in plant production is potentially positive. The technology itself is not profitable but needs to be used in such a manner that the best potentialities are found. Potentialities are present in both low and high-yielding parts of the fields. In high-yielding parts the economic returns are achieved when the inputs are effectively utilized, whereas the low-yielding parts are best treated with diminished application rate. The low rates give less potential to negative environmental impacts in these parts not capable to utilize the normally applied excess doze. The control of nitrogen shows the most promising potential that has not yet been utilized very well, mainly because of the difficulties in control. Nitrogen is a most dynamic nutrient that should be applied with extra care because of the risk of leaching. Thus the control system possibly needs a possibility to correct the basic N-doze during the growing season (comp. Peltonen 1992).

2.4 Effect of targeting accuracy - simulation with mathematical models and empirical data

To be efficient, PDC needs special implements. Current agricultural machines are poorly controllable and adjustable because actually no in-field control is carried out. PDC needs continuously controlled machines with large adjustment ranges. Facilities for partial width operation must be developed. Multimodal machines with momentaneous change-over between different modes are needed (e.g. soil tillage machines with adjustable effect, fertilizers and sprayers with multi-chemical capabilities). These devices are hypothetical technological solutions. Justification of all these modifications should be economically evaluated in continued research. This is best done by simulation because corresponding solutions do not exist.

Targeting errors and corresponding accuracy consist of length and cross positioning of the production input compared with the right position. The targeting accuracy required sets standards for the technology used in realizing the required targeting, i.e. for the positioning. A new concept, the Effect Curve (EC) is here defined as a general description of the efficiency of a position dependent task. The EC describes the distribution of the effect of position dependent task in space. The EC can be calculated both along and across the driving direction. The EC is scaled to the required effect level of 1.0, measured in the target. In crop production ECs can be calculated e.g. for fertilization, spraying or tilth. The most important property of an EC is its shape. In fertilizing, the changes in EC in the driving direction are due to changes in feed rate, and in the cross direction they are caused by the variation in the evenness of spread of the machine. Evenness of spread is traditionally expressed as a coefficient of variation (CV) or deviations from the value aimed at (Ndiaye and Yost 1989, Auernhammer 1990, Delcourt and De Baerdemaeker 1994). This does not count for the sensitivity of CV. If the EC is sharp-edged, slight driving errors lead to a drastic degradation of the CV. A big effect is summed outside the required area and total misses are found inside it. Because of the small driving errors there can be effects ranging from zero to double of the effect wanted in the field. Sloping ECs allow more tolerance.

One could imagine that accurate driving is not needed when automatic Position Dependent Control is in use. Implements are not, however, flexible enough to allow for inaccurate driving. The combination of automatic PDC of the implement and inaccurate driving leads to an increased need to adjust the implements in partial widths or to turn them quickly on or off. Furthermore, it is not reasonable to make implements fully adjustable just because of the inaccurate driving. Most probably it is cheaper to control the total effect of the task (e.g. fertilizer or pesticide doze) than partial widths. In some tasks it is even technically difficult to adjust the working width without affecting the result negatively (e.g ploughing, sowing, row crop production). Inaccurate driving would also increase soil compaction and fuel consumption (Palmer et al. 1989, Nieminen and Sampo 1993). In practise, as both the working width and the output of the machine are incompletely adjustable, the production result is always affected both by driving and by positioning accuracy. The driver realizes the route required with the help of positioning information received either from marks in the field or from the positioning system. (Fig. 20)

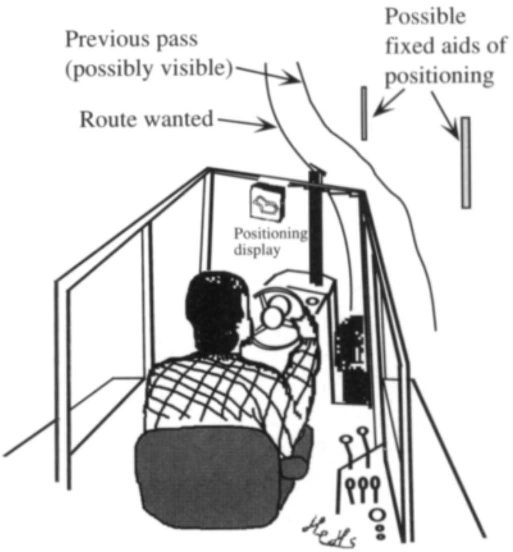


Fig. 20. Practical Position Dependent Control of implements. The most propable system does not include automatic guidance but there will be a driver present.

It is a very straightforward method to fix a CV-limit for a particular position dependent work. Instead of this generalizing, the CV-limits should be fixed to the properties of the production system in the PLs. In this study, the requirements for targeting accuracy are given in terms of the transfer functions of the PLs. CV-limits are set for the output from these functions to indicate the adequacy of the targeting accuracy in these modeled locations.

A general model of targeting and separate simulation models for crosswise and lengthwise targeting were developed. The simulation models were constructed in the Stella® simulation environment (App. 3) in a MacIntosh™ IIcx microcomputer. The platform and simulation programs were selected according to comparative tests of Autti et al. (1989).

The EC is not constant but changes with time. Both the shape and the total effect vary dynamically. The total system of Position Dependent Control with varying driving accuracy, positioning accuracy and EC can be simulated with the following general three- dimensional model. The model (Fig. 21, App. 3) includes converters (circles) that have data tables/equations for implement position (*required_route, position_error* and *driving_error*), machine ECs in cross (*EC_i*, iŒ{1,2,..,n}) and length direction (*effect*), the sum of cross and length effects (*effect_i*, iŒ{1,2,..,n}) and transfer functions (*tf_i*, iŒ{1,2,..,n}) from *effect_i´s* for individual PLs. State variables of the system (rectangulars) are work time (*work_time*), distance (*distance*) and the outputs from the PLs included (*output_i*, iŒ{1,2,..,n}). *Res* is the resolution in cross direction [m]. Model parameters can be input in several ways. Both measured and simulated values are usable. Values of *driving_error*, *positioning_error* and *effect* are functions of simulation time. *Required_route* is a function of *distance. Distance* is a function of simulation time and can be used to alter the driving speed in the route. Values for the parameters above are given graphically, as data values or as equations. The ECs in cross direction (*EC_i´s*) are constant within simulations. The shapes could be variable but they are set constant for the sake of clarity. In the present model they can be given graphically or as data values. (Fig. 21)

The *effect* varies depending on the position dependent task that is modelled. Generally *effect* values are higher than zero (for tasks that can not reduce the effect in PLs). Transfer functions (*tf_i´s*) are task-dependent equations for *effect_i´s* in the *output_i´s*. They can be given independently for each PL and input graphically or in data values. If connection to route was realized, they could also be site-specific in travel direction. For clarity, they are kept equal and constant in simulation. (Fig. 21)

The PL reacts only to the input value (*Effect_i*). The result is given as output units per PL (e.g. yield, environmental impact, economy). The result is given at variable resolutions in cross direction by changing the *res*-parameter [m]. In travel direction the resolution is dependent on the smallest simulation step (dt) used. The general three-dimensional model shows the system components (Fig. 21). There are some serious drawbacks in the model. The model is not very good for setting the requirements for cross targeting: in practise it is not possible to give enough PLs to the model to judge large working widths or entire field widths. The same limitation is found when high crossweis resolution is needed. Effects of parallel driving are difficult to simulate because separate runs and summing of the *output_i´s* is needed. For these reasons separate two-dimensional models for cross and length targeting were developed for further studies of targeting accuracy (Ch. 2.4.1 and 2.4.2).

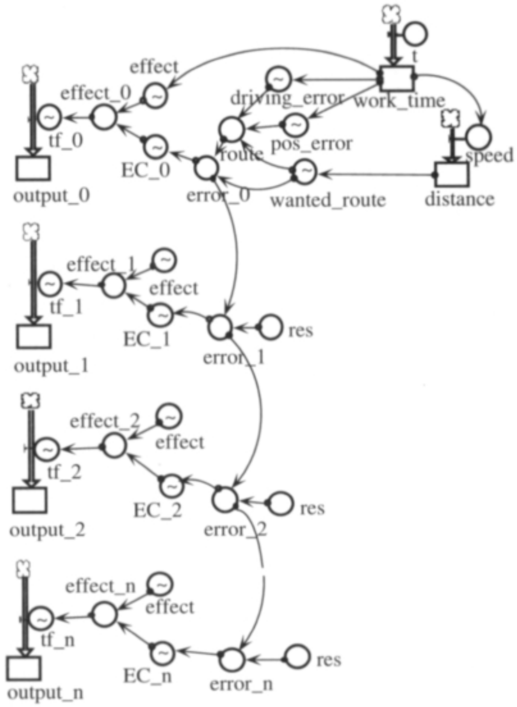


Fig. 21. Stella®-diagram of the general three-dimensional model for Position Dependent Control. EC= Effect Curve.

2.4.1 Accuracy in working width - simulation with the ECs

The effects of poor targeting accuracy in the working width cause variation of treatment. This can be more or less harmful. Basically, overlapping and missing are not required in any rational production strategy. Overlapping is specially harmful in spraying poisonous chemicals. Underdozes lead to wasting the chemical and lower outputs because of a diminished effect. Practical ECs (in both cross and length direction) are dynamic because of the properties of the machine (implement, tractor) itself and external interference. Machines have certain typical ECs. Agricultural chemicals and other applied materials have variable properties that affect the EC. Also the properties of the target PL may modify the EC (e.g. topographic effects).

In individual simulations here the cross EC is set constant for clarity; only different EC-types are separated. Practical ECs are combinations of the types used with some variation. The EC-types used here are

-the triangular (e.g. some centrifugal surface fertilizers),
-the mixed (e.g. chemical sprayer) and
-the rectangular (e.g. harrow, sowing machine) type.

The types are all derived from the basic triangular type. They differ only in the width of the central part and edge angle. (Fig. 22) In simulation, the height of the EC (h) is constantly one unit. Edge angles (α) are 15°, 30°, 45°, 60°, 75° and 90°. In each simulation the right and left edge angles are equal. The optimum working width for an EC is such that CV in parallel driving is at a minimum. This is achieved in the ECs used by "driving" the sloping edge areas halfways overlapped. The target is to get the effect wanted in one pass. That is why the maximum value for each EC is 1.0. (Fig. 23)

The main simulation variable is the working width (W_{opt}). Within it the ECs vary with the edge angle (α). (Fig. 24) As the working width is constant, diminishing the edge angle narrows the even part (Fig. 25). An edge angle of 15° would lead to a negative width of the even part. As this is not possible, usable combinations of W_{opt} and a diminish to 23 (Fig. 26).

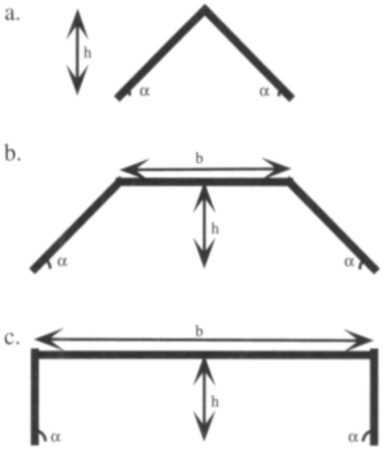


Fig. 22. Basic Effect Curve-types.(a) Triangular, (b) mixed and (c) rectangular type. Variables are edge angle (α) and width of the even part (b). Height (h) is constant (=1).

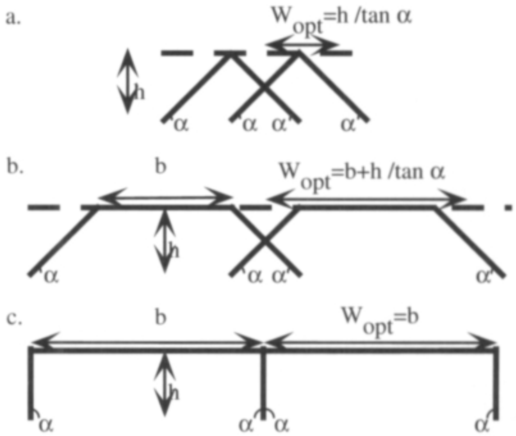


Fig. 23. Optimum working widths (W_{opt}) for basic Effect Curve-types. (a) Triangular, (b) mixed and (c) rectangular Effect Curve. α = edge angle, β = width of the even part and h = height of the Effect Curve.

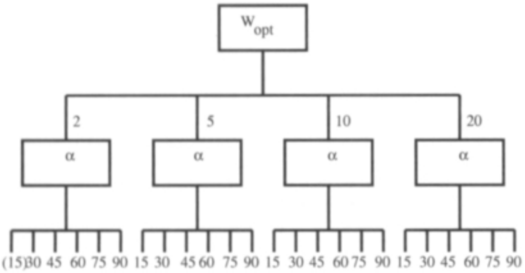


Fig. 24. Edge angles (α) in groups of optimum working widths (W_{opt}) in simulation.

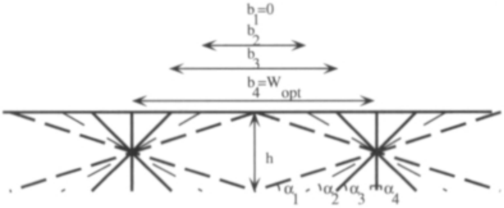


Fig. 25. Effect of the edge angle (α_i) on width of the even part of an Effect Curve (b_i) by constant working width ($W=W_{opt}$) and height of Effect Curve (h). Schematic.

The simulation concentrates on overlapping. The target is to "drive" routes that represent optimum overlap, i.e. to use optimum working widths. Incomplete positioning, however, leads to a location error in the parallel passes. In addition to the combinations above, fixed targeting errors of 0.2–10 meters are used. All combinations are not reasonable. Therefore an error range of c. 10–100% of the optimum working width is used (Fig. 26). In the resulting model (Fig. 27, App. 3) there are three ECs (Eff_curve_1–3) that are situated in positions W1, W2 and W3 in the working width. The simulations for each setup are 128 in total (4 working widths, 4 to 7 targeting errors, 6 edge angles excl. 15° in a 2-meter working width).

There were four steps (A–D) in the simulation model development, each of which used different transfer functions from the effect curves to the output. The basic model was modified for each simulation setup. The setups used include models that calculate the results with no additional transformations and models that imitate filtering or other kind of transformations of the EC. This is done by adding a transfer function block after the Eff sum -block (Fig. 27). The purpose of this iterative process was to show the effects of introducing nature-like transfer functions to the system. The effect curves (ECs) were given in two parameters (Wopt and a). The simulation results were calculated as sums of the ECs (Effect Sums, ESs). The coefficients of variation were determined for the ESs. Furthermore, the requirements for targeting accuracy (Wermax) were calculated for variable CV-limits. (Fig. 28)

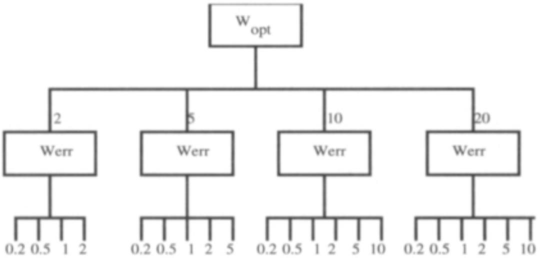


Fig. 26. Cross targeting errors (Werr) in groups of optimum optimum working widths (W_{opt}) in simulation.

In simulations the ECs were functions of the working width. They were shaped so that the result show the ES in the case that only one erroneusly positioned EC would be inserted between two correctly positioned ECs. This situation is the basic element of targeting of an EC. Keeping other error sources (EC variations) constant, only the effect of poor targeting could be evaluated.

Method A is quite straightforward: the effect curves are summed and the CV is calculated for this ES. Sample ES-curves of the simulations are shown in the following figures. The figures show

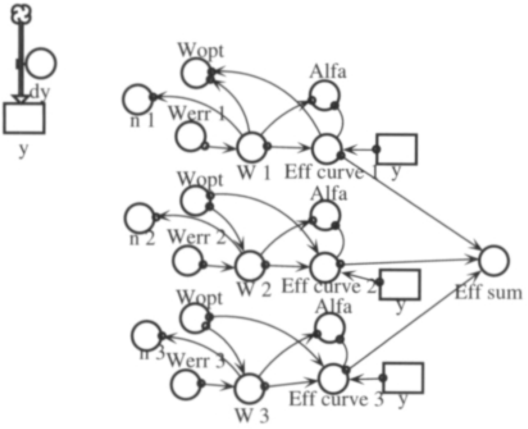


Fig. 27. Diagram of the simulation model for setting the requirements for cross targeting accuracy. Wopt = optimum working width, W1–3 = actual position of the Effect Curve, Werr 1–3 = errors in locations of the adjacent passes, Eff curve 1–3 = shape of the Effect Curves, Alfa = edge angle [rad], Eff sum = sum of the Effect Curves, n1–3 = number of working width (from left), y= cross position in meters, a function of simulation time, dy= simulation step in meters.

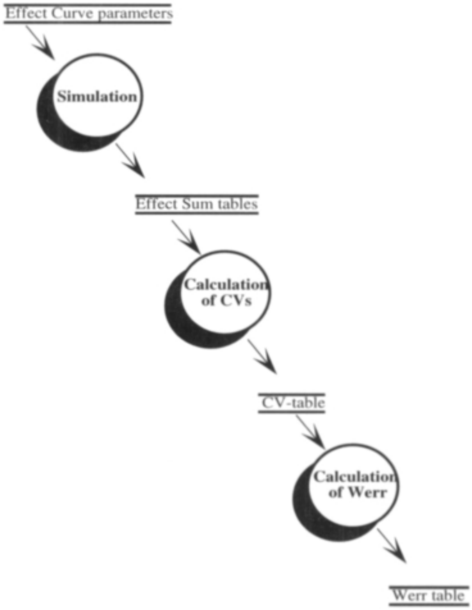


Fig. 28. Data flow in simulations. Simulations are made in the Stella® simulation program and the other phases in Wingz®, a spreadsheet program.

the effect sum curves for optimum working widths of 2 and 10 meters with a targeting error (Werr) of 0.2 meters. The shape parameters of the EC, the edge angle (α) and the optimum working width (Wopt) have a considerable effect on the ES. Sharp edges cause high peaks and sloaping ECs have wide overlapping, even with a little targeting error of 0.2 metres. With changing working width, equal targeting errors can lead to different percentual overlaps. (Comp. Figs 29a and 29b)

Method A does not yet count for the biological transfer function from the input to the output (e.g. yield or environmental stress). The effect of such a transfer is smoothing: plants take their nutrients from a certain area that is typically bigger than the resolution (0.1 m) used in the simulation above (Richter 1986, King 1990) This effect was imitated in method B: smoothing the effect sum curves with a ten-value moving average. The following figures show visible change in effect sum curves (Figs 30a and 30b, comp. Figs 29a and 29b).

In nature, it is common that functions for growth are logistic, “S-shaped”. After a mild starting phase the output begins to grow at an increasing speed. Then there is a phase of more or less constant growth, and finally the speed falls. In the starting phase there is an accumulation of “critical mass” before the growth really begins. The middle phase uses the growth potential until, in the last phase, some restricting factor begins to act against the growth. Sometimes there is an additional phase where the output starts to degrade because of excess input. Mathematically the differential transfer function of growth could be e.g. $dy/dx=ay-by^2$ where y is the yield, x is the input and a and b are constants. The transfer function is first dominated by exponential growth and later by a negative feedback. Negative feedback is the basic element of control in any system (Gustafsson et al. 1982, Haugen 1990, Franklin et al. 1994, O´Callaghan et al. 1994).

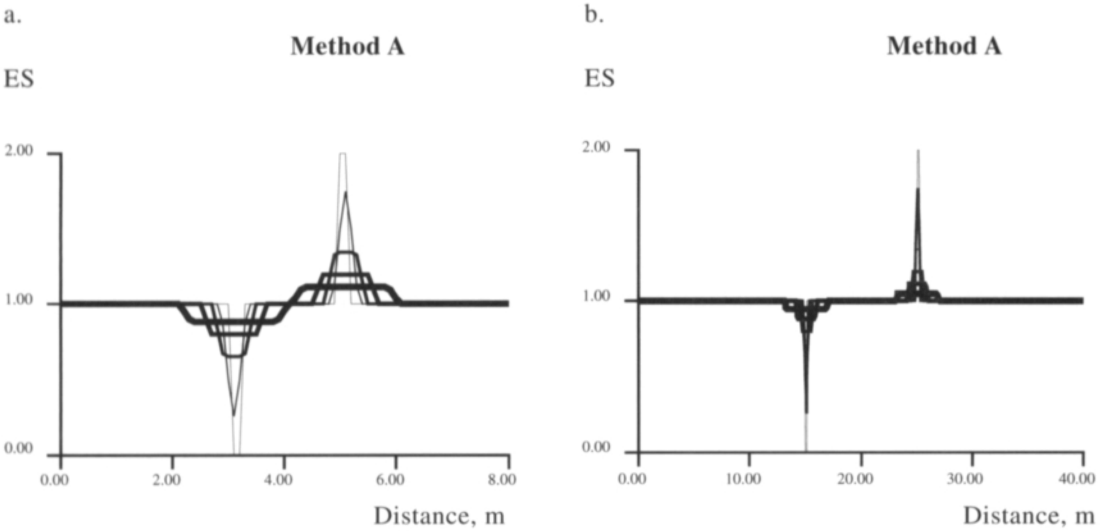


Fig. 29. The Effect Sum (ES) in method A for optimum working widths (a) 2 m and (b) 10 m. In both figures cross targeting error is 0.2 m and edge angle is 15, 30, 45, 60, 75 or 90° (from thicker to thinner line).

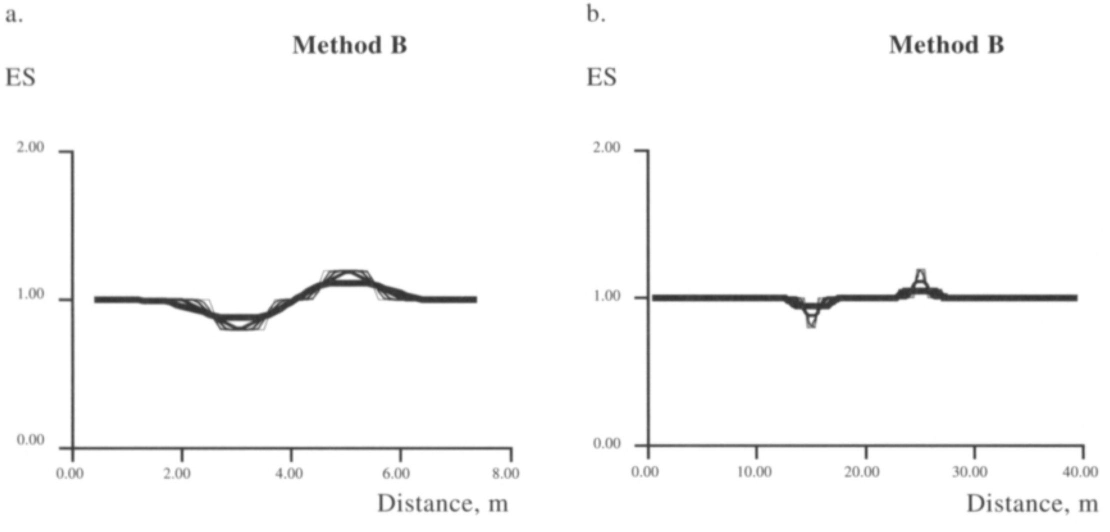


Fig. 30. The Effect Sum (ES) in method B for optimum working widths (a) 2 m and (b) 10 m. In both figures cross targeting error is 0.2 m and edge angle is 15, 30, 45, 60, 75 or 90° (from thicker to thinner line).

The final yield in the soil-plant system results from the growth process. The amount of yield with a certain amount of input depends on the sensitivity of the soil-plant system to the input. Field trial results show that the final result can be highly variable (e.g. Heikkilä 1980, Jaakkola and Turtola 1985, results in Ch. 3 of this study). The formation of the yield in the plant includes the process of both taking and utilizing the input taken. These processes must be separately described if detailed causes for a varying input/output ratio (sensitivity) are required (Karvonen and Varis 1992). The situations where different factors restrict the growth can be categorized e.g. in four classes where the models of growth are a bit different (de Witt ref. Karvonen and Varis 1992).

In method C, the effect of a basic logistic transfer function (Gustafsson et al. 1982) was added to the Trans-block of the simulation model. No integration was implemented. The shape of the function is quite arbitrary and its accuracy is non-relevant in this context. However, because it is the natural shape of growth, it is in accordance with the growth patterns presented by e.g. Karvonen and Varis (1992) and Peltonen (1992). The transfer function was scaled so that the output would reach unity somewhat above the unity value of the EC. Full effect is achieved at an ES of c. 1.3. This was done to imitate the normal target of production where the maximum is not required but the target is to get an optimum output. The optimum point is normally somewhat below the maximum (Peltonen 1992). (Fig. 31) The transfer function changes the result dramatically. It gives less extra output with overlapping compared with losses in the miss area. This shows as diminished output in overlapping areas compared with the results with method A (Figs 32a and 32b, comp. Figs 29a and 29b).

The effect in the missing area seems to be quite similar to method A because neither method A nor method C include averaging (comp. with method B, Fig. 30). Actually the missing area gets lower effects in method C than in method A because the transfer function from ES to output is quite low in the ES´s range from 0 to 0.7 (Fig. 32).

This result is true when we operate in the upper part of the transfer function. If the operating point changes to the left (effect level diminishes) the overlapping area gives more marginal output (output units/input unit). It is, though, normal to operate near the top of the transfer function, except in low-input production where the operation point is on the straight part of the transfer function or, in extremely-low-input production, in the region of exponential growth. In the latter case it can even be economically beneficial to have overlap if the quality changes of the product are not important. Normally, overlapping is not required in any case because of the risk of quality variation. If the operating point lies in the lower part the model would give same results in CV because the ECs used and the transfer function are symmetric. The third option would be an operation point in the linear part of the transfer function. With small changes in the input the output is analogous to the results of method A (Fig. 32), with a level shift because of the difference in sensitivity. For sharp changes in EC the output is smoothed compared with the methods without integration.

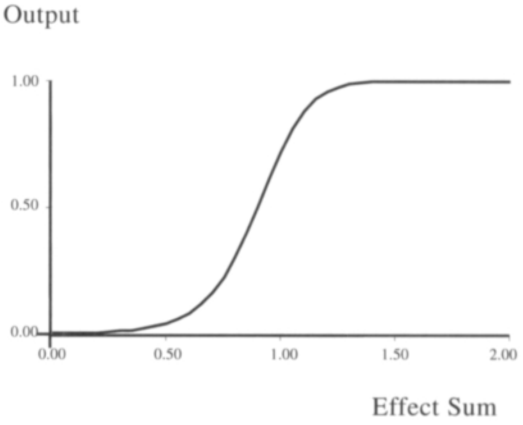


Fig. 31. A simulated logistic transfer function $dy/dx = 9y-9y^2$.

The next step, method D, was to combine both the integrating effect of method B, imitating the gathering function of plant roots, and the logistic transfer function of method C that describes S-shaped response.

The output was more smoothed, as expected. The output is much less sensitive to the varying ES than in methods A and C that do not include integration. (Figs 33a and 33b, comp. to Figs 29 and 32)

CVs were calculated for the outputs. The figures above show only some examples of the results. CVs for all the used models (A–D) and

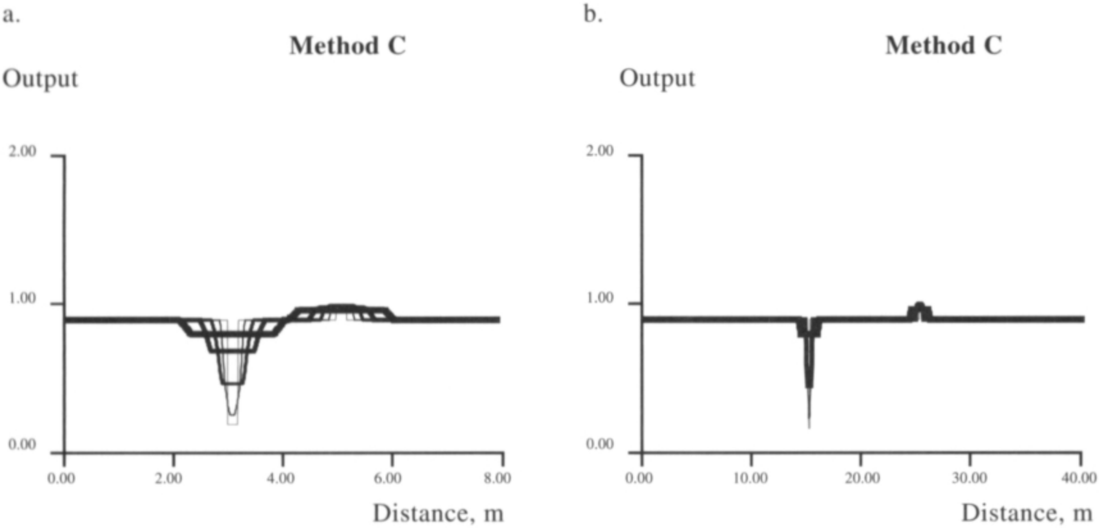


Fig. 32. The output of Production Locations in method C for optimum working widths (a) 2 m and (b) 10 m. In both figures cross targeting error is 0.2 m and edge angle is 15, 30, 45, 60, 75 or 90° (from thicker to thinner line).

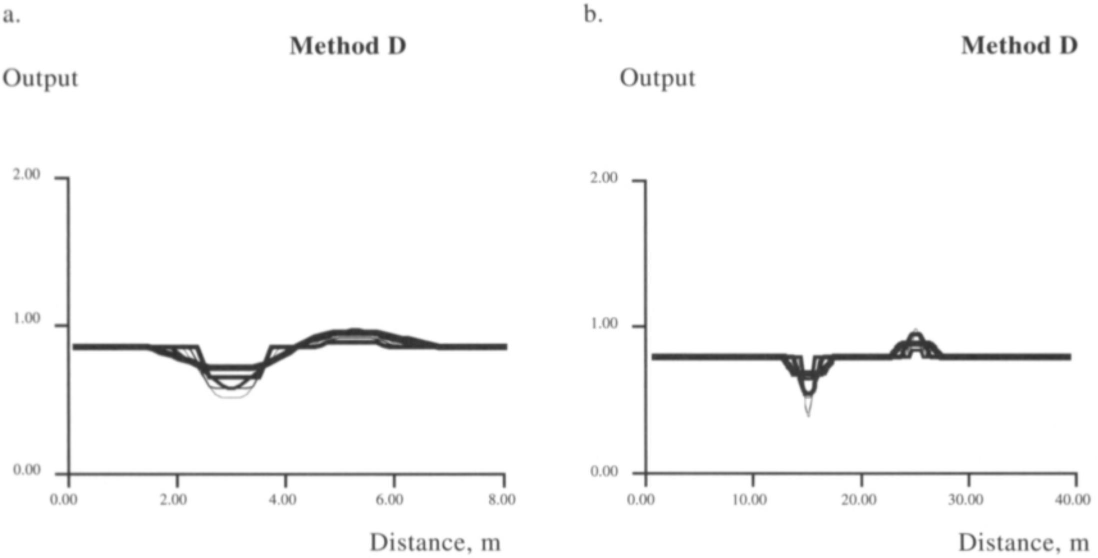


Fig. 33. The output of Production Locations in method D for optimum working widths (a) 2 m and (b) 10 m. In both figures cross targeting error is 0.2 m and edge angle is 15, 30, 45, 60, 75 or 90° (from thicker to thinner line).

simulation combinations are listed in App. 4. CV values for edge angle 15° and optimum working width of two meters were not calculated because of the invalid negative value of b (width of the even part of EC) with these shape parameters (see Fig. 26 above) (App. 4)

The simulations above would give a zero CV without the targeting error because without the error the EC would be a straight line at the effect level wanted. Therefore CVs differing from

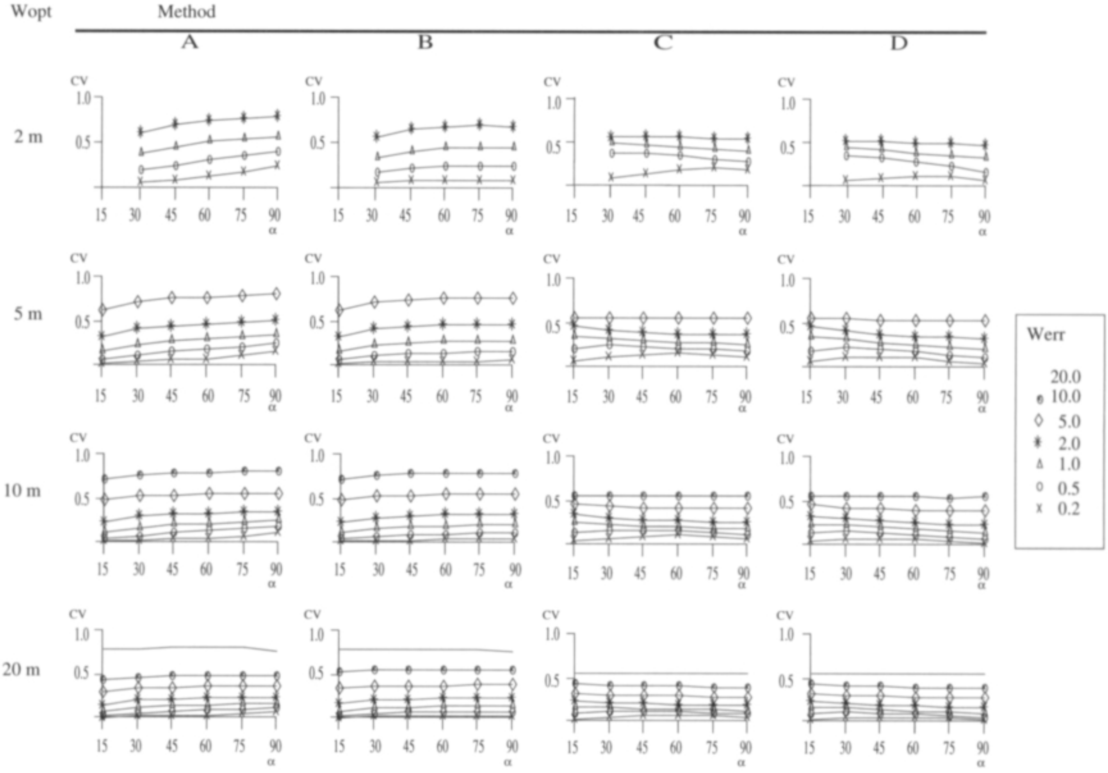


Fig. 34. The effect of cross targeting error (Werr = 0.2–20 m) on the evenness of output quality of Production Locations. The quality is expressed as Coefficients of Variation, CVs, of the Effect Sum, ES. CVs are calculated for optimum working widths (Wopt) of 2–20 m. Four different simulation models with different transfer functions are used. A = the model with unconditioned EC, B = the model with smoothed EC, C = the model with logistic transfer function from unconditioned EC and D = the model with logistic transfer function from smoothed EC.

zero indicate only the effect of the improperly positioned EC. Furthermore, as the targeting error is the only affecting variable within shape groups of the ECs, the CVs can be used as indicators for the effect of the targeting error (with that particular EC type). The resulting CVs for a certain targeting error change with edge angle and optimum working width of the EC.

The graphical presentations of the data (Fig. 34) show visually the changes in CVs when different methods were used. There are great differences between the methods used. It can clearly be seen that the smoothing methods (B and D) that filter the high frequencies of the effect give lower CVs and therefore also an increased tolerance. At a certain CV-level different accuracies for targeting are allowed. Method D that includes both smoothing and an S-shaped transfer function gives most tolerance. (Fig 34)

The requirements for targeting accuracy can now be calculated by setting a limit (CVmax) for the CV. The maximum targeting error (Wermax) is linearily interpolated between rows (App. 4, Table1) that surround the CVmax wanted as shown in following equation (eq. 2).

The calculation results for different simulation methods are shown in Appendix 4. For example, in method A, if we have Wopt of 2 meters, α of 30° and a CVmax of 0.3, the maximum allowed targeting error is 0.76 meters

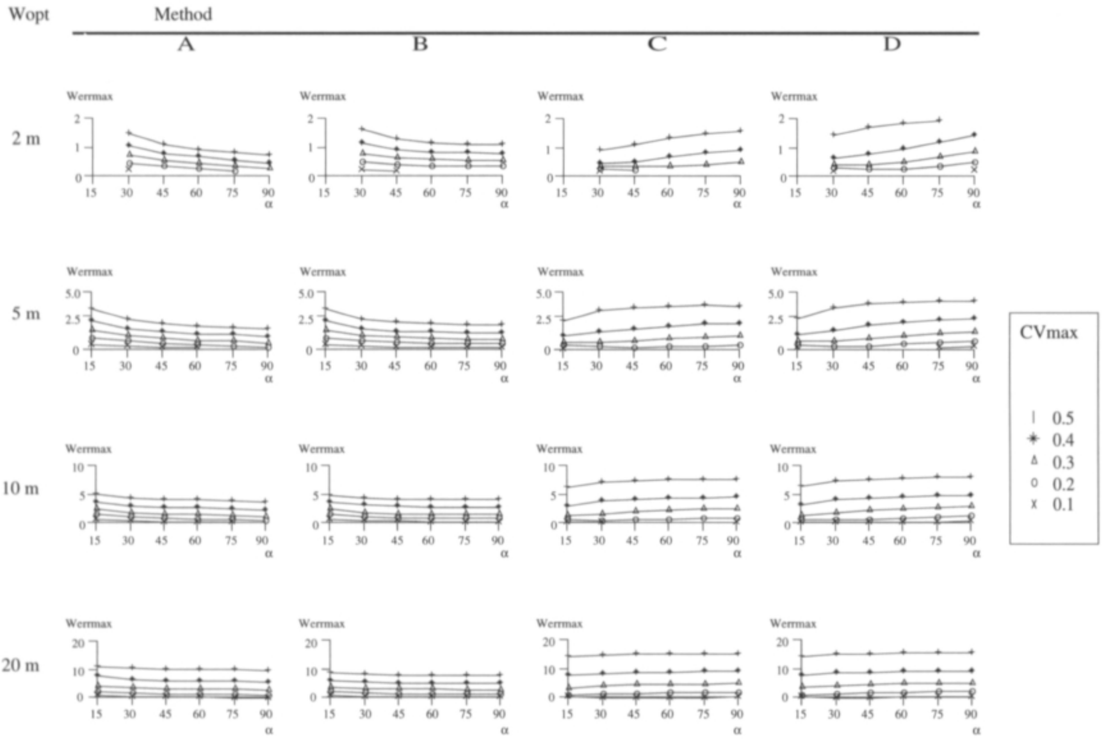


Fig. 35. Maximum targeting errors (Werrmax) for different optimum working widths (Wopt = 2–20 m), CV limits (CVmax = 0.1–0.5) and edge angles (α = 15–90 °). Four simulation models with different transfer functions are used. A = the model with unconditioned EC, B = the model with smoothed EC, C = the model with logistic transfer function from unconditioned EC and D = the model with logistic transfer function from smoothed EC.

$$[2]\ \mathrm{Werrmax} = \mathrm{Werr}_1 + (\mathrm{Werr}_2 - \mathrm{Werr}_1) * (\mathrm{CVmax} - \mathrm{CV}_1) \div (\mathrm{CV}_2 - \mathrm{CV}_1)$$

where Werrmax = maximum allowed cross targeting error
Werr_1 = Werr of the row with lowe rCV
Werr_2 = Werr of the row with higher CV
CV_1 = lower CV of the two rows
CV_2 = higher CV of the two rows
CVmax = maximum allowed CV

(=0.5+0.5x(0.3-0.207)÷(0.383-0.207) meters) (see App. 4). Generally, high working widths allow most tolerance in targeting. Narrow working widths require a higher absolute accuracy with the same CV-limit as high working widths. The relative accuracy requirement is quite constant. The edge angle has much effect on the required targeting accuracy, as expected. With methods A and B the right angle requires the most accurate targeting. With methods C and D that include an S-shaped transfer function, there is the tendency of cutting the high and low points of the Effect Sum. There are some CV-limits that produce a curve with minimum point at an other edge angle than the used minimum, 15°. This is natural because the logistic transfer function emphasizes EC level changes in between the low and high levels of the ES (Fig. 35)

2.4.1.1 Discussion of the simulations with Effect Curves

The amount of integration and shape of transfer functions have apparently a remarkable influence on the results. They were not researched in detail because this was not the main issue in the interpretation of the results. The main result is that the model operates both technically and logically right. It gives increasing coefficients of variation with ascending targeting errors. The integrating effects and the transfer function which were used smooth and modify the output correctly. Therefore the results indicate a technical and logical validity of the model. (Gustafsson et al. 1982) Method D, that shows the highest tolerance, is the most valid one of the methods used because it includes the smoothing effect of plant roots and the most nature-like (logistic) transfer function. The practical use of the simulation model needs calibration of these functions. For total validation of the models a field test setup is necessary. This was not done because the target of this research was not to find the exact forms of the functions but to show their effect on the measures of targeting accuracy achieved. The main result is that the target PL should be modeled to get reasonable results. This result is the starting point of continued research that will find accurate requirements of targeting for individual cases. This continued work has begun in 1991 at the Department of Agricultural Engineering and Household Technology with case-studies that measure the variation of PLs. The Keimola case-study was the first one of them (Ch. 3). Further tests are being carried out at Viikki Experimental Farm (Haapala 1994b, Hirvenoja 1995).

Increasing working width decreases the requirements for targeting accuracy because the percentual error areas get smaller with the same position error. This is due to the fact that less passes are needed to cover the area and thus there are less possibilities for overlapping or missing. A two-hectare field (100x200 m), which is the standard field size and shape for work studies in Finland (Orava 1980), gets 5 to 50 passes with the optimum working widths used in the simulation above. In practical work the situation is somewhat more complicated because wide working widths cause an increase in driving errors (Auernhammer 1990). Smoothing rises the allowed targeting error with high edge angles because it cuts high frequencies (i.e. sharp edges) of the ES curve. The ten-value (1 m) smoothing filter has a bandwidth of c. 0.45 [1/m] which means that changes of ES bigger than c. 0.69 in the calculation interval used (=0.1) are attenuated below -3 dB (to c. 70.8% of original amplitude). Expressed in edge angle this means c. 82° (=arctan(0.69/0.1)). This effect is shown in the Werr curves (Fig 35 above): methods C and D with filtering show tolerance for sharp edge angles. The filter together with an S-shaped transfer function smooths efficiently the effects of overlapping (Fig. 35).

The results include only one criteria, i.e. the variation of output. If there was another simultaneous output function, the situation would be quite different, e.g. in plant production we have the yield and the leaching functions. The overall behaviour of the leaching process is such that leaching amounts increase along with the fertilization rate. It has an exponential starting phase as the nutrient uptake by the plants diminishes. If a limit is set for leaching we can see changes in the allowed targeting errors. The leaching function emphasizes negative effects of overlapping. Consequently the total effect of these two criteria would probably be that there is an optimum point (or area) where leaching is not too high and the yield is not too low. The existence of such an area further tightens the requirements for targeting accuracy, compared with method D.

The simulation results apply for treatments inside the field area. Use of optimum working widths results in overlapping the field edge. Only the squared EC ($\alpha = 90°$) could exactly cover the field area with the effect aimed at if accurately targeted. This implies that other EC types have a seed value of CV. The CVs calculated here do not include field edge overlapping. This has little influence on the results when the field size is big as compared with the working width.

It is clear that responses to an EC change as different target PLs are treated. The transfer functions change in shape and magnitude. Thus we get quite varying optimum points that also vary in tolerance. The requirements for targeting therefore vary as well: inputs to the PLs have to be targeted with individual targeting accuracies. The model is here used to demonstrate the need for PL-based models in estimating the targeting accuracy of PDC. Positioning with a positioning method like GPS (see Ch. 4) is based on nearly independent positioning results. The positioning result has a basic accuracy with some random noise. The set requirements for targeting accuracy (Fig. 35, Table 2 in App. 4) are values that the positioning method should fulfill with a certainty required, i.e. at a confidence level (e.g. 95%). Requirements for positioning accuracy are actually the targeting accuracies filtered through an additional transfer function. This transfer function is dependent on dynamics of the machines used in position dependent tasks. For simplification, the set limit for targeting is here used as a goal for the positioning system. Strictly speaking this is not the case as the machinery used should be assessed together with the positioning system.

2.4.1.2 Conclusions of the simulations with Effect Curves

Increasing working width decreases the requirements for cross targeting accuracy. Smoothing (method B, in method D together with logistic transfer function) raises the error allowed specially with high edge angles. Method D, including both the transfer function and smoothing, shows the highest tolerance. The logistic transfer function changes the situation with edge angle (a): a critical value for the edge angle can be found. Higher and lower edge angles allow larger targeting errors than the critical angle.

The model for setting targeting and corresponding positioning accuracy limits needs the EC of the implement and the transfer function from it to the output of the target PL. Otherwise the requirements are not realistic.The EC of the implement and the model of the target production system itself affect the accuracy required. On the other hand, depending on the goals of PDC, there can be different criteria for targeting accuracy. In nature there are typically logistic transfer functions. Logistic functions act differently in different operating points in the transfer function curve. High level inputs are sensitive to both overlapping and missing and they are dependent on accurate targeting. Low-input production gives the output more linearly because the transfer function is in the phase of constant growth. Extremely low input levels benefit from overlapping but do not suffer much from missing. However, the requirements for constant quality of the output set limits for targeting accuracy in the extremely low input production, too. Furthermore, the output is a function of inputs to an area rather than a point. This smooths the output and sets looser targeting requirements. The used ten point (1 m in length) moving average did not, however, have considerable effect on the requirement calculated for targeting accuracy, except for high values of edge angle.

2.4.2 Accuracy in direction of travel - a simulation model for effects of nitrogen targeting accuracy

The model for setting the requirements for targeting accuracy should have an accurate enough model for the PL. Therefore the steps from model A to D were not repeated. Nitrogen fertilizing was chosen as an example because nitrogen is considered one of the main components in leaching, and its spatial nature of variation is known since the 19th century (Larsen et al. 1991, Catt 1993, Kauppi 1993).

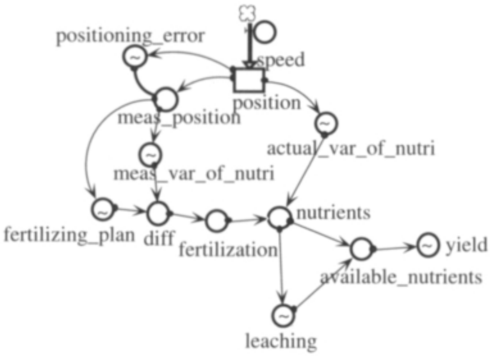


Fig. 36. Upper level Stella® diagram for the model for setting requirements for length targeting accuracy in N-fertilization (Haapala 1991).

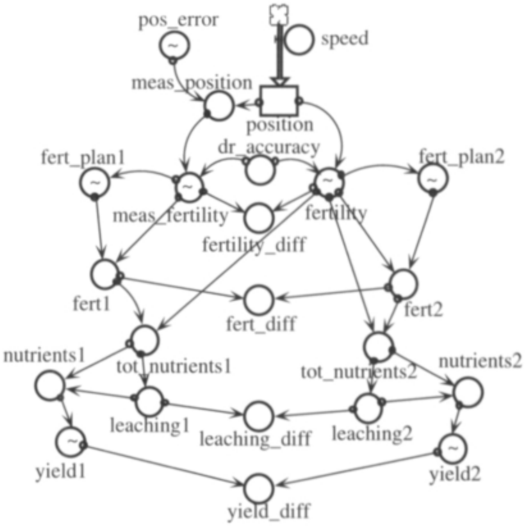


Fig. 37. The model for setting requirements for length targeting error in N-fertilization.

The model for nitrogen targeting used here is not a detailed explanation model. A complete model for nitrogen dynamics in our conditions would include a layered structure, and it should have submodels for plant uptake, mineralization, immobilization, leaching and denitrification (Johnsson et al. 1987, Pesonen 1992). The effect of solar energy variation in different growing seasons should be incorporated (O´Callaghan et al. 1994). Furthermore, to achieve best results in Finland, the effects of the cold winter period should be incorporated (Rekolainen and Posch 1993).A somewhat simplified model would use submodels for plant uptake and nutrient utilization (Varis 1989, Karvonen and Varis 1992).

An explanation model is out of the scope of this study. The model presented is simplified to show the problem area: length targeting with a target system that has two logistic transfer functions. The model is not suitable for other uses (e.g. for yield forecasting). The model includes transfer functions for yield formation and nitrogen leaching. Other growth factors than nitrogen are not expected to modify these system outputs. The transfer functions are scaled with available data to get reasonable fit to the real processes of yield formation and leaching. Dynamics is introduced to the models through variable positioning error that introduces targeting data. The model has two branches: the optimum (theoretical) branch (to the right in Fig. 36) where the targeting is perfect with no errors, and the other one with targeting error (to the left in Fig. 36). Both branches have the same actual variation in available soil nutrients, i.e. “the test field” is equal for both branches. The error branch reads the setpoint according to the measured position. If there is a big enough error in targeting the error branch reads wrong setpoints. The error can be divided into error in positioning information and human error in driving. Difference variables for the two brances can also be counted. (Figs 36 and 37)

The following simulation results (Fig. 38) are for a ten-meter random length positioning error and a half-meter random driving error. The fertility is assumed to change in sinus form. The examples show that, on a varying field, it is possible to have remarkable errors in yield, and some in leaching as well, when fertilizer targeting is poor. The transfer functions that were here quite ambigous, determine the exact errors. It is clear, though, that the magnitude of the error

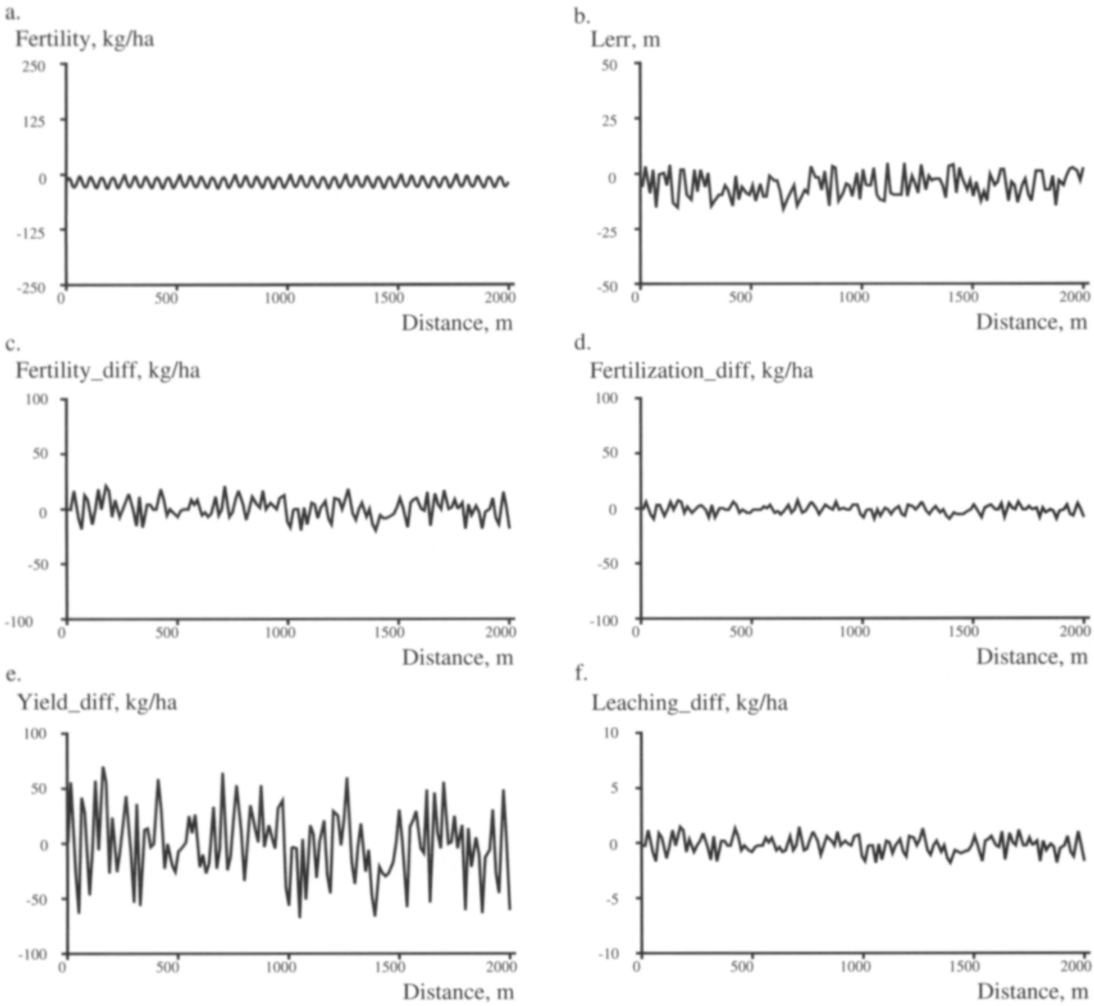


Fig. 38. A simulation for N-fertilization. (a) Sinus function for soil fertility changes. (b) Length targeting error (Lerr). The error consists of a ten-meter positioning error and a half-meter driving error. Both error components are random. (c) Error in measured fertilization need (Fertility_diff). (d) Error in fertilization (Fertilization_diff). (e) Error in yield (Yield_diff). (f) Error in leaching (Leaching_diff). Errors in (c), (d) and their consequences in (e) and (f) are due to the length targeting error (b) (Haapala 1991).

affects the results, and a ten-meter error is not adequate.

Further simulations used Jaakkola and Turtola´s (1985) material on yield of barley and leaching on Finnish clay soils to calibrate the transfer functions. Data of 1980 was selected because it represented a normal year with no special growth-limiting environmental factors. The fertilizing level was calculated based on the simulated soil nutrient content. The advice of Kemira Ltd that is commonly used in Finland (Viljavuuspalvelu 1990), was used. Lodging was introduced to the functions by setting a limit for N uptake whereafter the yield would collapse.

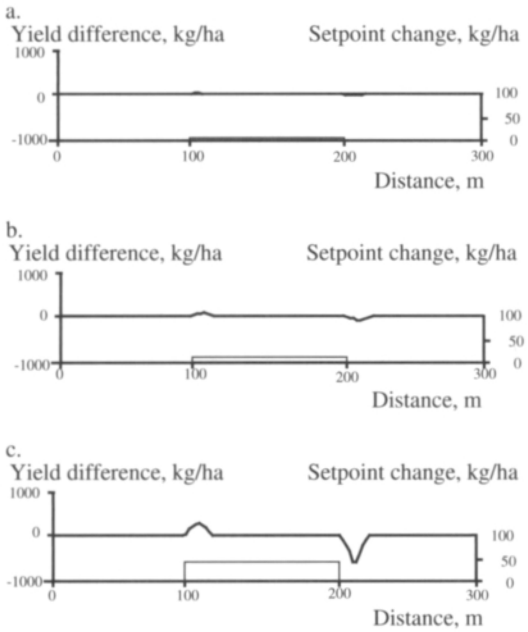


Fig. 39. Simulated yield difference with a square wave setpoint change in N-fertilization. Length targeting error is 10 meters. Wave height is (a) 5 kg/ha, (b) 10 kg/ha and (c) 50 kg/ha (Haapala 1991).

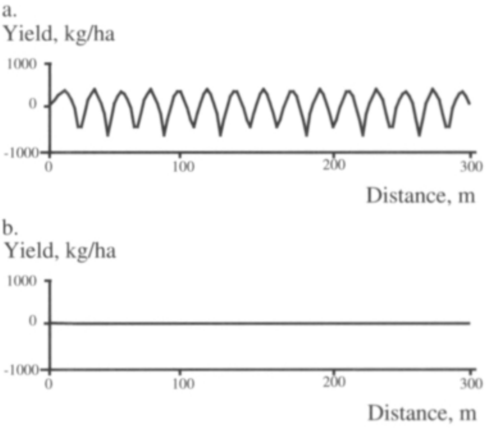


Fig. 40. Simulated yield difference with a sinus wave setpoint change in N-fertilization. Wave height is 50 kg/ha. Length targeting error is (a) 10 meters and (b) 20 meters (Haapala 1991).

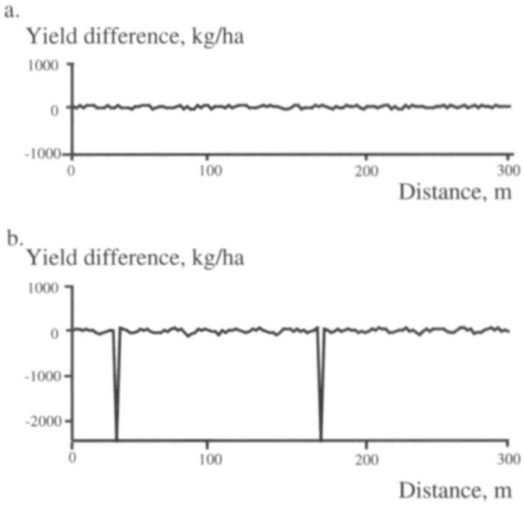
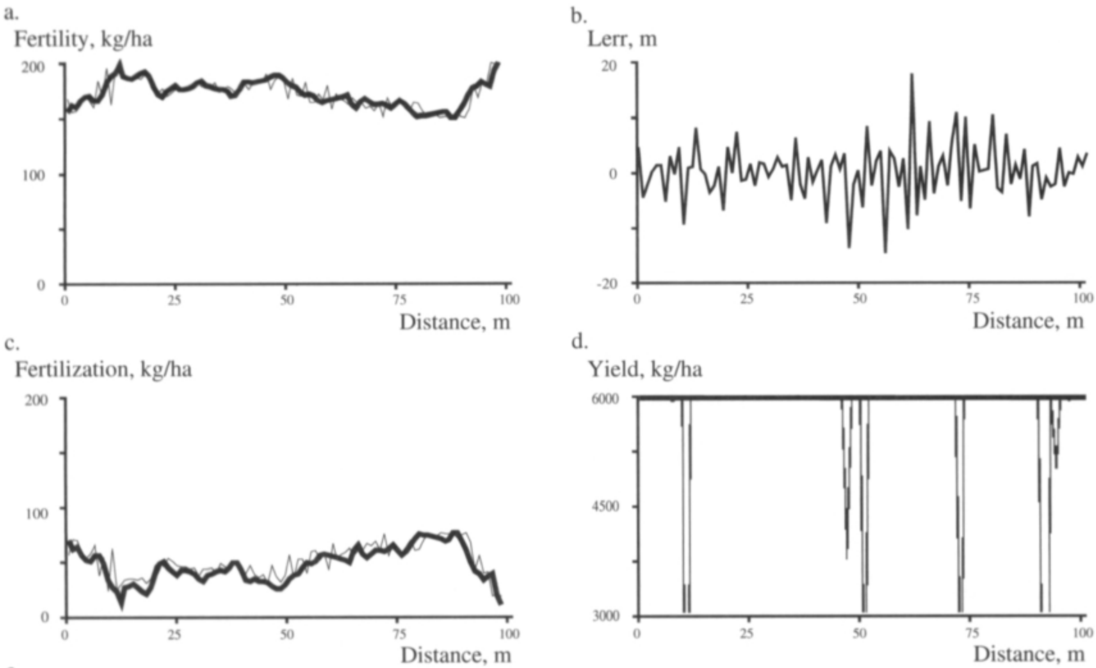


Fig. 41. Simulated yield difference with a sinus wave setpoint change in N-fertilization. Wave height is 50 kg/ha. Length targetin error is (a) randomly ±5 meters and (b) randomly ±10 meters (Haapala 1991).

The requirement s for accuracy were set by finding (iteratively) the most sensitive factor in the output of the PL. First the setpoint change (fertilizing) was a single, square wave that got up in the distance of 100 m and came down at 200 m. Amplitude of the wave was increased from 5 kg/ha to 50 kg/ha. The targeting error was either 5, 10, 15 or 20 meters. The simulation step, dt, was one meter in distance. The Runge-Kutta method (Gustafsson et al. 1982) that produces accurate results with some more calculation effort needed, was used in solving the differential equations. The simulations show how the constant targeting error and the variable height of the square wave affect the yield. All the runs have the same basic soil N-content, 50 kg/ha, and the same lodging point, 70 kg/ha (in N-uptake). The results for a square wave height of 50 kg/ha are very clear whereas heights of 10 kg/ha and 5 kg/ha are quite insensitive (Fig. 39). The constant targeting error affects only the length of error area.

Secondly, the effects of dense steps in the setpoint were tested. The aim was to check the effect of constant steps on the output when there is also a constant (systematical) error in target-



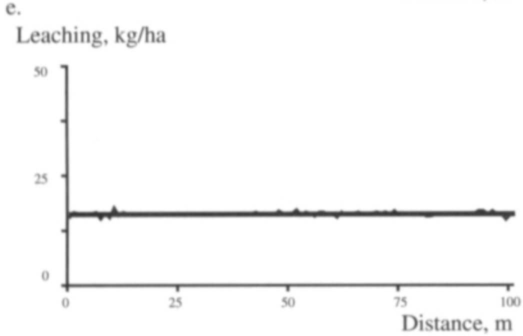
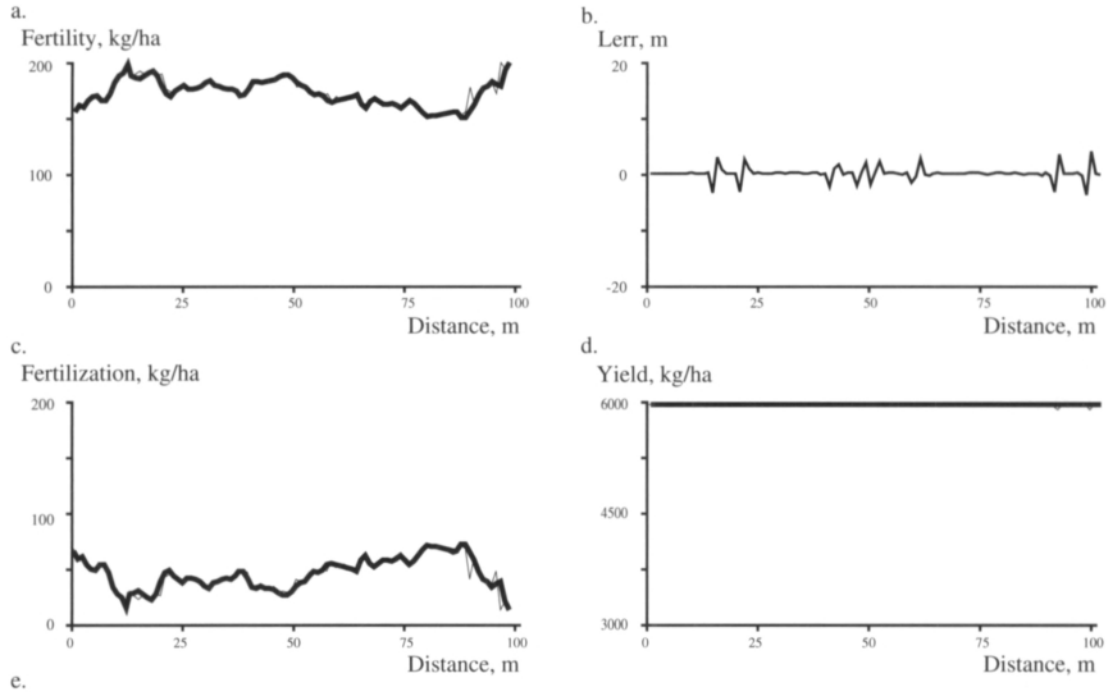


Fig. 42. (a) Actual (thick line) and simulated (thin line) soil fertility. (b) The used sample of measured positioning error in travel direction (Lerr) of post processed DGPS (Differential Global Positioning System). (c) Theoretical optimum (thick line) and simulated (thin line) fertilization. (d) Yield with theoretical optimum (thick line) and simulated (thin line) fertilization. (e) Leaching with theoretical optimum (thick line) and simulated (thin line) fertilization. The simulated values are calculated with positioning errors based on DGPS test results in Viikki on day no 351 in 1990. The fertility values are from measured yields in Keimola in 1991.

ing. The targeting error was increased from 0.5 meters to 20 meters. The step height was systematically increased. Other variables were kept constant. Results show that with a suitable constant targeting error even high steps are not counted for in the yield output. This is because of resonance: the setpoints are taken from a position where it is right for the current PL. (Fig. 40) This critical error is hypothetical because in natural variation the resonance situation can not last long. In further tests it was found that infield variation is quite random including a spectrum of frequencies (Ch. 3). The resonance situation is important because in fields there can be areas, specially boundaries of soil types, with undulating properties. If a systematical error is found in targeting, e.g. because of a systematical error in the positioning device used, the resonance can cause lodging or increased leaching. Therefore a systematic error is not wanted in any circumstances.

In reality the positioning error is not constant but varies randomly, as found in literature and enclosed positioning tests (see Ch. 4). This random nature of the output of positioning devices affects targeting through the transfer functions



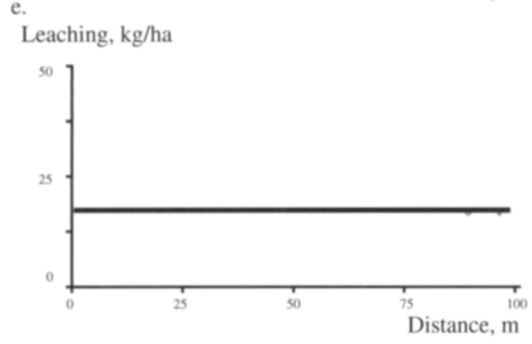


Fig. 43. (a) Actual (thick line) and simulated (thin line) soil fertility. (b) The used sample of measured positioning error in travel direction (Lerr) of on line DGPS (Differential Global Positioning System). (c) Theoretical optimum (thick line) and simulated (thin line) fertilization. (d) Yield with theoretical optimum (thick line) and simulated (thin line) fertilization. (e) Leaching with theoretical optimum (thick line) and simulated (thin line) fertilization. The simulated values are calculated with positioning errors based on on line DGPS test results in Viikki in 1993. The fertility values are from measured yields in Keimola in 1991.

of the equipment used, smooth the output and hide the findings that were made in simulations with constant errors (Figs 38–40 above). In high N-levels the random positioning error can cause random lodging patterns. This can happen also with low N-levels, apart from the previous results of simulation with constant error, when boundary areas of different fertilization needs are treated. The transfer function of N-fertilizing to yield is logistic or spherical (Waddington et al. 1983, Peltonen 1992). This implies that high N-levels are the most sensitive ones. As stated in the previous chapter with cross targeting error there is a certain optimum area in the fertilizer doze.

Based on the simulations above, it was reasoned that the most critical combination is found on a field where there are high changes in need for fertilization and where high N-levels are used. A simulation series was run with raising N-levels. Eventually, in an N-level of 220 kg/ha aimed at (an N-fertilizing level of 170 kg/ha), it was found that lodging became the restricting factor. This N-level is of a slightly higher level compared with recommendations of the leading fertilizer supplier in Finland (Kemira Ltd) (Peltonen 1992). At this level, a wave height of 50 kg/ha showed clear increase in lodging pattern as the targeting accuracy got poorer. An error of ±5 m was found to get no lodging but ±10 meters had a few lodging patterns. (Fig. 41)

The final simulations were made with the empiric data from Viikki positioning tests (see Ch. 4) and Keimola yield variation tests (see Ch. 3). This test was made to compare the results with those that were achieved with hypothetical targeting and soil variation data. The setpoints for N-fertilizing were calculated, quite mechanically, so that the greatest negative deviation from the average yield would get 100 kg/ha of information, 100-meter samples of the positioning data from 1990 and 1993 were selected for modeling the targeting accuracy. The data came from the same test route position (from the results between check points 6–9, Ch. 4, App. 10) to enable comparison of the positioning accuracies of the two different positioning devices. In the first set of data from 1990, the accuracy in travel direction was ±7.9 meters (95%). (Fig. 42)

The second set of data was selected from the on-line DGPS-tests in 1993. The length positioning was much more accurate (± 3.34 m (95%)) (Fig. 43). The results with data from 1990 positioning tests show five considerable lodging patterns (Fig. 42 above). Data from more accurate positioning in 1993 shows no lodging (Fig. 43). With the leaching function used there were no alarming differences in the amount leached between perfectly positioned and with both of the samples used of GPS data.

2.4.2.1 Discussion of the simulations in the direction of travel

The results are scaled for the fertilization of barley. In the tests of Keimola (Ch. 3) wheat was used. The crop is not, however, important but the shape of the transfer function which is similar (e.g. Waddington et al. 1983, O´Callaghan 1995). On the other hand, the results do not show general requirements. It is doubtful if general requirements could ever be set because the PLs have considerable variation in their capability to convert inputs to yield (comp. Bouma and Finke 1993, Delcourt and De Baerdemaeker 1994). The model developed can be used to calculate requirements for targeting accuracy in length direction if the involved transfer functions are calibrated to local conditions.

Alternative triggers of poor targeting can be accomplished (comp. Han and Goering 1992, Delcourt and De Baerdemaeker 1994). Lodging part of the model worked well but leaching as a trigger showed little reaction to the N-levels used. This is due to the low sensitivity of leaching in the reference material used (Jaakkola and Turtola 1985). In other conditions, specially in sandy soils, leaching might be a good trigger for environmentally poor targeting of inputs (Catt 1993, Kauppi 1993).

2.4.2.2 Conclusions of the simulations in the direction of travel

The method developed for setting the requirements of targeting and positioning accuracy can be utilized in other applications of PDC. Other transfer functions and trigger values must then be selected. The thought model and procedures are generally usable.

The results show that in a varying field, with a high operating point of a logistic transfer function, the targeting must be most accurate. With constant targeting error and a square wave setpoint change, the area of erroneus output is proportional to the targeting error. With an undulating setpoint there might be areas of resonance where the control amplifies or smoothens the output. Actual positioning systems, however, which most often have random noise components, smoothen the findings of simulations with constant error. Random components may also cause local overdrafts which may introduce lodging in such places where a corresponding constant error did not show any of it. Lodging as a trigger of poor targeting leads to requirements around ±5 meters (95%). In situations where there are comparable parameter values leaching does not react sensitively enough to be used as the main trigger.

2.4.3 Accuracy in space for PDC - conclusions based on simulations of cross- and length targeting accuracy

The requirements for targeting accuracy for PDC are highly dependent on local conditions. Production Locations vary in space and time. The most sensitive parameter, the trigger for poor targeting, may change if circumstances vary. The level of production inputs has considerable effect on the choice of trigger. Low-input and high-input production strategies need different indicators. Simulations in work direction and in cross direction were made a little differently. Cross requirements for accuracy can be found if a limit for the variation of yield is set. In work direction the requirements depend on a trigger variable. This difference is due to the fact that the production system is more sensitive to sideways errors. This is because Effect Curves of the implement tend to be more varying in this direction and the shape of the ECs is such that it needs better attention (driving accuracy). Driving along previous pass sets requirements for a much higher order to the sideways accuracy.

Simulations suggest that the most sensitive situations for targeting are on a highly varying field and on high expectations of yield. There is a risk of lodging which is the most sensitive trigger. On the other hand product quality limitations set limits to targeting errors in low-input systems because input responses are high and poor accuracy would lead to varying quality. The first situation yields an accuracy limit of ±5 meters to targeting of N-fertilizing in work direction. In cross targeting the requirements depend on allowable variation of production output. Equal levels of CV for each direction is a possible strategy for selection of the criterium. It is not easy to set this accurately on the basis of the simulations made because of different input levels. Dependence on edge angle is to be considered in cross targeting. The requirements varied considerably depending on the working width used too. The values for a two-meter working width for a CV-limit of 0.1 is 0.214 meters and for a 20-meter width it is 0.395 meters. When the limit is raised to 0.3 the figures are 0.434 and 3.736 respectively. (Table 1 in App. 4) Generally the requirements in driving accuracy are 2–10 times higher when compared with those for length direction. Typical requirements for fertilization would be ±0.5 meters in cross and ±5 meters in length direction. For other PDC-works requirements are set accordingly.

Evidently there are situations where specific methods for the measurement of every single one of the three space directions is needed. The need for sideways accuracy and accuracy of the height coordinate, which is not specially treated in this study, are typically higher than that of the working direction. Detailed requirements depend on the specific work. The height is normally referenced to some surface. The same priciple of referencing is possible in some cases with driving accuracy. This difference in requirement standard needs to be considered when positioning systems are selected.

3 The Keimola survey

3.1 Soil fertility and yield variation of spring wheat

The aim of the survey was to evaluate potentialities of position dependent control with a case data of in-field variation. In PDC, in-field variation of yield (Searcy et al. 1987, Borgelt and Sudduth 1992, Stafford and Ambler 1992) and related soil properties (Diaz et al. 1992) are important inputs for local decision-making. Internationally the existence of in-field variation of soil properties and plant growth has been known for quite a long time (e.g. Peck and Melsted 1973, Catt 1993). In Finland corresponding results can be found in the works of e.g. Kivinen (1935), Kaila and Ryti (1951), Jokinen (1983) and Puustinen et al. (1994).

Researching into this local variation is quite laborous because of the dense sampling needed to get accurate local estimates (Jokinen 1983, Delcourt et al. 1992). The variation requires different sampling strategies to be followed according to the accuracy and resolution desired (Lindén 1981, Jokinen 1983, Di et al. 1992, Haapala 1992). Representative samples for a certain area consist of subsamples the number of which can be calculated as follows (eq. 3, Snedecor 1948 ref. Jokinen 1983):

$$[3]\quad n = \frac{t^2 v^2}{p^2}$$

where n = required number of subsamples
t = Student's t - statistic
v = coefficient of variation
p = allowable error in percentage

As a conclusion, the variation can be seen either as a cause of measurement uncertainty or as true indications of the state of the real world. The variation indicates that the soil-plant systems are individual and need different control inputs. Actually this difference in interpretation does not mean different theories of the origin of the variation but rather shows the scale of interest of the observer with a certain application in mind.

The survey consisted of measurements of soil fertility and yield of spring wheat in a 1.56 ha field in Keimola, Vantaa (Fig. 44). The field was in ordinary grain production. The whole area was of the same crop and equal treatments had been given to all parts of the field. No animal manure had been used in the near past. Within the field the main reason for variation was the inherent variation and cultivation history.

The measurements were carried out on August 31st just one day before harvest. Two 50 m sample lines were selected. The aim of the selection was to get a varying (line 1) and an even (line 2) line. The criteria for the selection were plant height, colour and visually judged density of the plant population. There was a slight slope (c. 2.5%) in line 2. (Fig. 44)

Samples were taken at 0.5 m intervals from two neighboring seed lines. Yield samples were taken out of areas of 1/8 m^2 (0.25 m x 0.25 m) in such a manner that the two seed lines were covered. Immediately after this the soil samples were taken from the same locations. (Fig. 45) The samples were taken in the direction of fertilizer rows to avoid effects reported by Urvas and Jussila (1979). The grid size was selected according to the possible error of yield measurement. The same resolution was selected for soil sampling because accurate joining of soil and yield sample data was needed.

The placement error of the sample grid in distance along the sample lines was estimated to be maximum ±1 cm with the method used. This error is due to a human error in setting the grid to the right position. The worst case is found when the area where the grid should hit is completely empty of stems and the surrounding areas are at the highest density of the population.

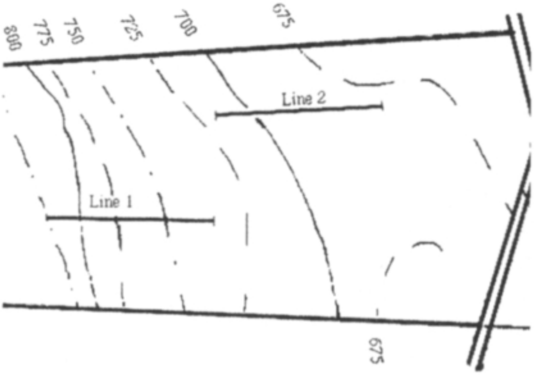


Fig. 44. The test field in Keimola showing positions of the test lines 1 and 2 and the elevation curves in centimeters above mean sea level.

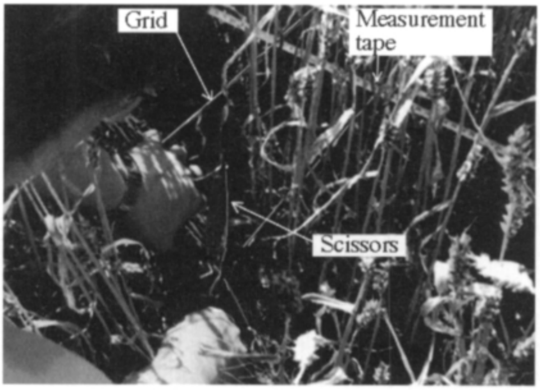


Fig. 45. Taking the yield samples. The samples were the total yield (straw and grain) from areas of 1/8 m^2 in a sampling distance of 50 cm A 50-meter measurement tape and a sampling grid of steel (0.25 m x 0.25 m) was used.

In this hypothetic situation an infinite error could be reached. In practise this is not probable. An empiric worst case error for a single sample was calculated: the highest measured population density was assumed outside the right grid position and the lowest one inside it. The range of measurements (Ch. 3.1.2) was from 304 to 864 1/m2 (19–54 stems in sample). In theoretical extreme case, where 864 1/m^2 is outside and 304 1/m^2 inside the right position, an error of ±1 cm in grid position can introduce an error of ±1.4 stems (=1/25x(54-19)) to the sample value and the error is +7.4% (=+1.4/19x100%) of it. In opposite case, where 304 1/m^2 is outside and 864 1/m^2 inside, a -2.6% (= -1.4/54x100%) error in sample value is found. Actual probable errors for single samples caused by grid positioning are smaller because in real populations maximum and minimum values are not parallel. Minimum and maximum variable values also indicate the trend in population. In yield samples there is no clear trend but neighboring values show some big differences. However, the greatest differences are rare. Therefore the actual estimated error is far below ±5%, as wanted. This is the case for the soil samples, too. Apart from yield there are soil variables with clear trends but neighboring samples have comparably small differences. The main error source is not the sampling but analyzing error. (Ch. 3.1.1 and 3.1.2, Dally et al. 1984, p. 545)

3.1.1 Soil variation

Soil samples were collected in little boxes the numbers of which were mixed before sampling. The mixing was successful because the box number and distance in the sample line showed low correlation (r (Spearman) was -0.331 in line 1 and 0.142 in line 2). After the sampling the boxes were organized in ascending order. The samples were analyzed in this number order (personal conversation with Mr Mäntylahti from Viljavuuspalvelu Ltd 1995). Dual samples were taken in five meter distance, ten dual samples per line. These operations were done to enable judgement of the analyzing error (accuracy, autocorrelation).

The samples were analyzed in Viljavuuspalvelu Ltd for pH, total-N, P, K, Ca and Mg. The analyses were those included in normal soil fertility analysis (Vuorinen and Mäkitie 1955) with the addition of total-N analysis. The pH was measured from soil-water suspension with a galvanic element. Total-N was measured with the Kjeldahl method (Walsh and Beaton 1973). For further analyses an extraction with acidous ammonium acetate (0.5 M CH_3COONH_4, 0.5 M CH_3COOH) was done. This extract was analyzed with photometers to get values for P, K, Ca and Mg content. In addition to these, soil organic matter content and soil type were determined with manual methods (Vuorinen and Mäkitie 1955).

In Keimola, the pH was quite high, 5.9 - 7.1, the mean value 0.5 units higher in line 1 than in line 2. Variation was small (CVs of 0.03), quite as expected (comp. Jokinen 1983). In line 1 pH-values had a positive trend in direction of soil sloping: pH increased as the soil declined. Dual samples indicated some differences of 0.2 units with pH-values smaller than 6.6. Soil total N was at a 33% higher level in line 2 than in line 1. It showed no trend inside the lines. Dual samples indicated poor repeatability of concentration measurement. P-values had a negative trend in the direction of soil sloping in line 1. There were some local jumps in the values, some more in line 2 than in line 1. Dual samples had some peak differences which mean that the jumps may be caused by analyzing errors. K varied very little inside the lines. In line 1 it seemed to have a negative trend in direction of soil sloping. There was a considerable (c. 80 mg/l) difference in the mean value between lines. Dual samples had little difference excluding one point in line 2 where the peak seams to be an analyzing error. Ca-values had a clear trend in line 1, reaching high levels in the lower part of the line. The analyzing system had apparent difficulties in measuring such high values. In line 2 the level was lower. Dual samples had low differences in both lines. In line 1, Mg had a strong positive trend in soil slope direction. In line 2 the trend was not very clear. In line 1 the values exceeded 1000 mg/l whereas in line 2 the values were around 500 mg/l. Dual samples showed an outstanding accuracy. (App. 5)

In Finland organic matter content of soil is given in six classes (Jokinen 1983, Viljavuuspalvelu 1990):

<3%	vm	"little organic matter"
3–5.9	m	"some o.m."
6–11.9	rm	"rich in o.m."
12–19.9	erm	"very rich in o.m."
20–40	Mm	"mull soil"
>40%		"peat"

In Keimola three of these classes were found. In line 1 there was a trend towards more organic matter in direction of soil sloping. In line 2 the organic matter content was lower and there was no trend. Dual samples gave little evidence on misjudging. Only some differences were found in transition zones between classes. (App. 5)

Mineral soil types are classified according to main fraction diameter. The classification differs a little from that of e.g. Great Britain (Heinonen 1978 vs. Mott 1988). The types found in Keimola and their English counterparts are:

HsS	silty clay or silty clay loam
HeS	clay or clay loam
HtS	sandy clay or sandy clay loam
LjS	sandy clay with 2–6 % of organic matter

The sandy soil classes HtS and LjS were combined (HtS/LjS). In line 1 the soil had a trend from clay to coarser types. In line 2 the soil was coarser and no trend could be found. Dual samples showed only normal differences in zones where soil types changed. (App. 5)

The dual samples showed that some measurements (pH, K, P and N) had error sources. The differences in dual sample results (App. 5) show that there might be differences in accuracies of the analysis methods for individual nutrients. The same extract was used for P, K, Ca and Mg analyses (Mäntylahti 1995) and possible changes in analysis results should occur simultaneously. As this is apparently not true (App. 5), the errors are most probably connected with the analysis phase itself, not the extraction.

Autocorrelation analysis was performed to find out if the analyzing technic had a "memory" error where the previous sample value would affect the next one. The autocorrelations were calculated for the data in right sampling order and in analyzing order of the boxes. Results (App. 6) show that pH, N and K analyzes have

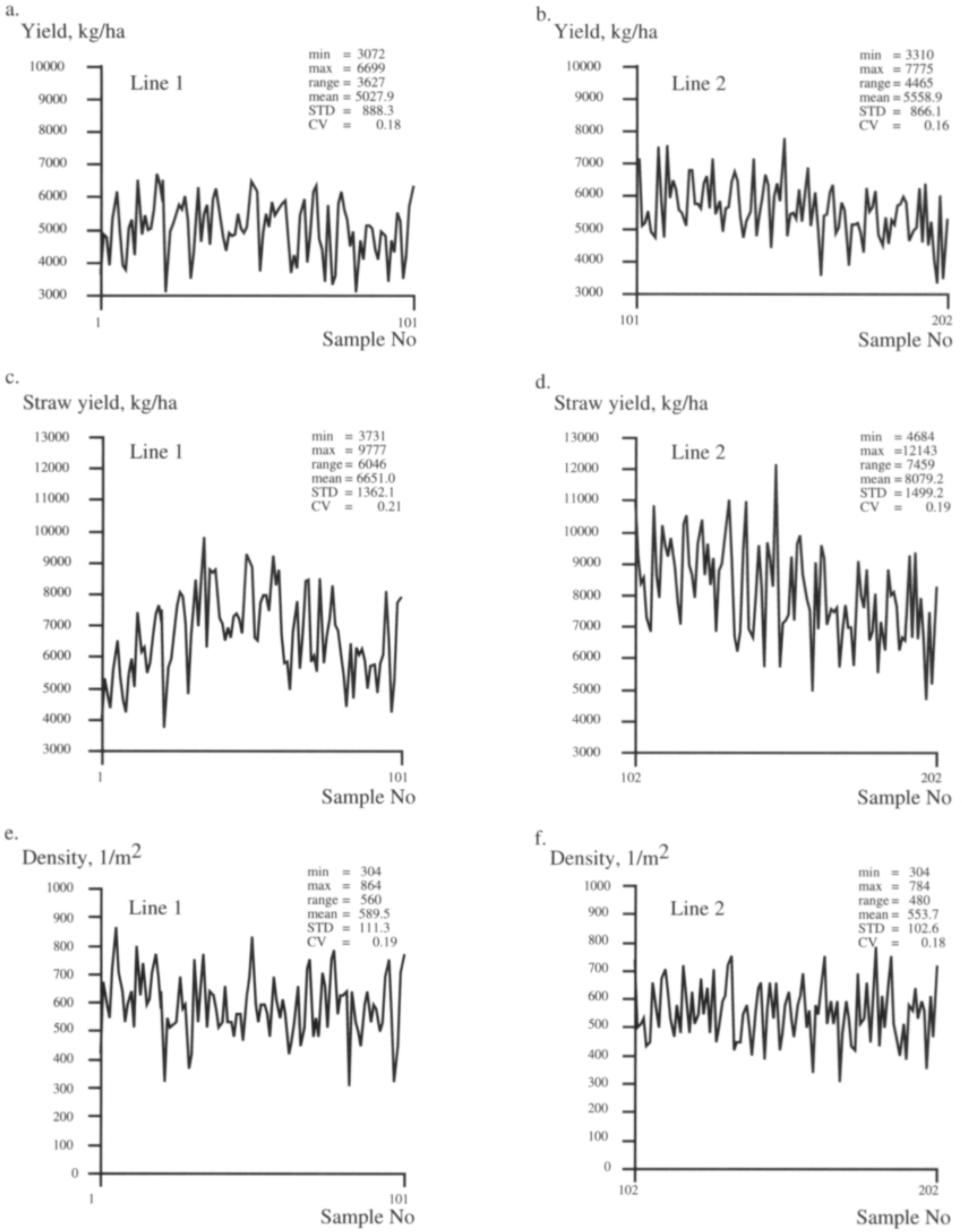


Fig. 46. Yield results in Keimola in 1991. Yield of spring wheat at 15% (w.b.) moisture content (a) in line 1 and (b) in line 2. Straw yield of spring wheat at 15% (w.b.) moisture content (c) in line 1 and (d) in line 2. Plant density [1/m^2] of spring wheat (e) in line 1 and (f) in line 2. STD = standard deviation. CV = coefficient of variation.

autocorrelation in box number order, whereas P, Ca and Mg are less autoregressive.

The autocorrelations give evidence that the measurement of pH, N and K have memory effect and P does not have it. The analyses of Ca and Mg have a slight memory effect. Differences in dual sample values of pH, N and K (App. 5) could be caused by the memory effect. Differences in dual P analyses (App. 5) are not, however, due to autocorrelation but they are of random nature. Autocorrelations cause interference to further statistical analyses (comp. Ch. 2.2, Eq. 1). Statistical analyses for pH, K and N are therefore somewhat inaccurate.

3.1.2 Yield variation

The yield samples gave density of plant population [1/m^2], water content of grain and straw [% w.b.], grain yield [kg/ha] and straw yield [kg/ha]. Plants were calculated manually from the samples and the total sample was weighed. Kernels and straw were separated and weighed. The water content of the grain and straw were measured with ASAE´s oven method (130°C for 19 hours, unground sample) that should give repeatability of better than 0.2 %-units (ASAE 1989). Yield samples weighed 10 gramms and straw samples 3 gramms before the oven treatment. Grain and straw yields were corrected to 15% (w.b.) water content.

The average yield was some 500 kg/ha higher in line 2 than in line 1. Line 2 was very even in visual judgement but actually the yield components varied nearly as much as in line 1 (Fig 46). The difference in appearance was due to the low frequency straw yield variation in line 1 (Fig. 46c). Population density was c. 30 1/m^2 higher in line 1. Its variation was high (CV was 0.18 - 0.19) in both lines.(Fig. 46)

In Keimola, the yield was measured with a higher resolution (0.5 m) than in normal yield measurements made in most other researches. This gives possibilities of simulating various sampling methods, as done later on in chapter 3.2. The true variation can be viewed with e.g. geostatistics (see Ch. 1, App. 2, Clark 1984). Semivariograms gave interesting results on the form of yield variation. (Fig. 47).

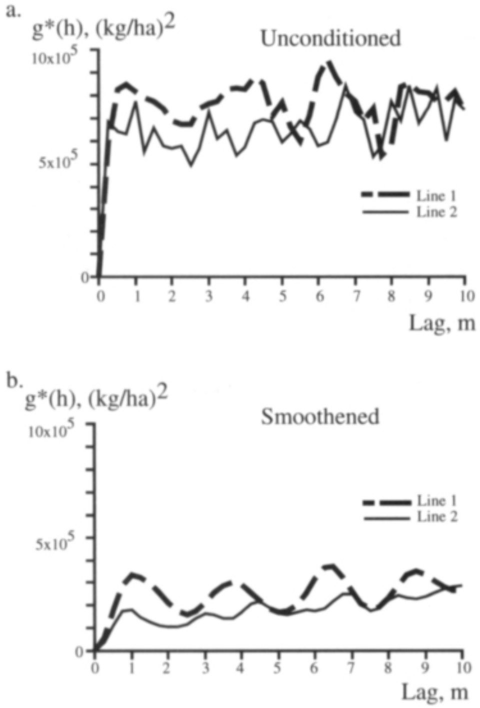


Fig. 47. Semivariogram for (a) unconditioned grain yield and (b) for filtered grain yield.

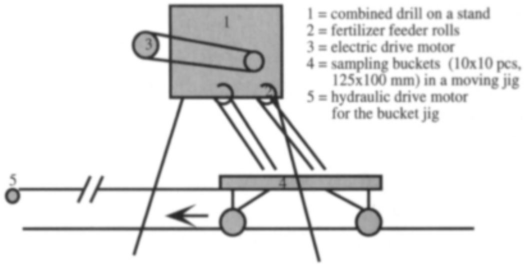


Fig. 48. The test setup for measurement of feed rate dynamics of a drill. Schematic (Fig. is based on Nousiainen 1995).

The sharp rise in the semivariogram shows (Clark 1984) that the yield is a quite random phenomenon. Subsequent yield measurements

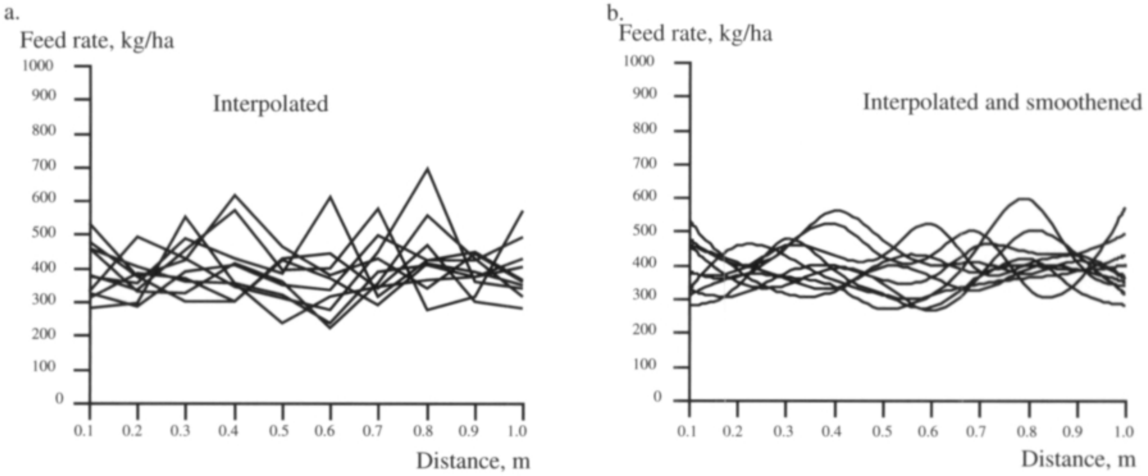


Fig. 49. Output of granular fertilizer of a combine drill feeder in tests in Viikki in 1993. Setpoint = 400 kg/ha. Output of ten feeders in figure. (a) Unconditioned data and (b) smoothed data. (Calculated based on Nousiainen 1995)

have little influence on each other. This confirms that the production locations are individual (comp. Ch. 1) and leads to the need of dense yield measurement. The range of influence is in raw data approx. half a meter and in the filtered data approx. one meter. There are also fluctuations that seem to be of a constant wavelength. Filtering the data with a ten-value moving average leads to a clearer picture of 2–2.5-meter long waves (Fig. 47 above).

The probable reason for this sinus form variation is some object that has rotating parts. Most probably this is due to variations in seed and/or fertilizer output of the combined drill used; the output of a roll feeder tends to oscillate. In tests made at the Department of Agricultural Engineering and Household Technology (Nousiainen 1995), an electric motor was used to turn a combined drill that was placed on a test stand. A set of sampling buckets (10x10 pcs, 125x100 mm) were drawn at a constant speed from under the operating feeders. The turning speed of the motor and the feed axle and the velocity of the moving sampling bucket jig were measured. The samples were weighed with a laboratory scale connected to a PC computer with RS-232-C serial interface. Corrections for irregularities in sampling bucket form and forward speed were calculated. (Fig. 48)

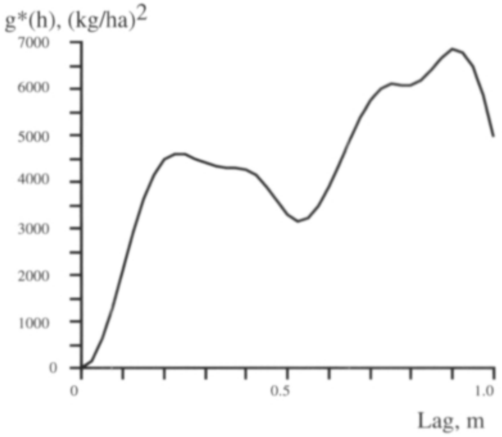


Fig. 50. Semivariogram of the feedrate of a combine drill in tests in Viikki in 1993. (Calculated based on Nousiainen 1995)

For further calculations four additional points were interpolated in between each subsequent pair of the fertilizer flow values measured. This data was further smoothed with a moving average of three values. The procedure reduces high frequencies in the results but they are higher than that of the variation of interest. A clear oscillation with c. 0.5 meter wave length is shown in the resulting output (Fig. 49).

Semivariograms were constructed to find out possible periodical behaviour of the output. Linear interpolation was used to add 9 points between measurement points. This reduces only such high frequency variations which are not interesting in this case. The resulting semivariograms (e.g. Fig. 50) confirm that the output seems to oscillate in sinus form. The oscillation is due to the feeder construction that accumulates some of the fertilizer and pushes it out in quite regular intervals. The fact was found in summer 1994 during video analysis of the feeder output.

3.2 Extracting Production Locations from the Keimola data

Position Dependent Control needs exact Production Locations. The PLs should be located efficiently to get the best results. In this study, Keimola test data was used as case data to evaluate possible methods for PL extraction. Statistical analyses were made to find out which measured variables had influence on the grain yield. The hypothesis was that the data had spatially variable structure and position-fixed PLs would give the best determining (local) regression models. (comp. Bhatti et al. 1991, Wendroth et al. 1992)

3.2.1 Linewise Production Locations

The data was first calculated separately for the two sample lines with no assumption for spatial variability inside the lines. The variables measured were coded (Table 3) .

Table 3. Coding of variables in statistical analyses of spring wheat yield in tests in Keimola in 1991. x_1 - x_7 are input variables and x_8 and x_9 state variables for the grain yield.

X_1 = CONST = constant of the regression eq.
X_2 = PH = pH-value
X_3 = CA = Ca content
X_4 = N_TOT = total nitrogen
X_5 = P = P content
X_6 = K = K content
X_7 = MG = Mg content
X_8 = POP = density of plant population
X_9 = STRAW = straw yield

Table 4. Influence of individual soil parameters on spring wheat yield in tests in Keimola in 1991. Partial correlations are calculated separately for the two sample lines.

	Variable	Corr. coeff.	F-value	P
Line 1				
n=101	PH	-0.179	3.272	0.074
	CA	-0.132	1.767	0.187
	N_TOT	0.022	0.047	0.828
	P	0.127	1.631	0.205
	K	-0.015	0.023	0.879
	MG	-0.111	1.224	0.271
	POP	0.682	86.127	0.000***
	STRAW	0.802	178.031	0.000***
Line 2				
n=101	PH	-0.138	1.929	0.168
	CA	0.105	1.11!	0.294
	N_TOT	0.024	0.057	0.811
	P	-0.005	0.002	0.962
	K	0.224	5.219	0.024**
	MG	0.326	11.763	0.001***
	POP	0.658	75.716	0.000***
	STRAW	0.897	406.100	0.000***

The effect of individual variables on the yield were first analyzed. Correlation analysis showed that there were no clear correlations except for internal crop variables (state variables of the production system) such as density of plant population (POP) and straw yield (STRAW). Input variables (inputs of the production system) K and Mg had somewhat higher correlations. The correlations were generally higher in line 2 than in line 1. (Table 4) .

Corresponding regression estimates also showed that only the state variables had a con-

Table 5. Coefficients of determination (r^2) and regression coefficients of the best regression functions in regression analyses of spring wheat yield in tests at Keimola in 1991. Both input and state variables for the yield are included.

	Function	r^2	c_1	c_2	c_3	c_4
Line 1	f_3***	0.670	6528***	-667**	-6.62	0.53***
Line 2	f_4***	0.814	4669**	-451	-4.66	0.52***

Table 6. Coefficients of determination (r^2) and regression coefficients of the best regression functions in regression analyses of spring wheat yield in tests at Keimola in 1991. Only input variables for the yield are included.

	Function	r^2	c_1	c_2	c_3
Line 1	f_7	0.033	11550***	-989	0.12
Line 2	f_7***	0.147	11128***	-1326**	5.52***

Table 7. Coefficients of determination (r^2) and regression coefficients of the best regression functions in regression analyses of spring wheat yield in tests in Keimola in 1991. Only state variables are included

	Function	r^2	c_1	c_2
Line 1	f_8***	0.643	1551***	0.52***
Line 2	f_8***	0.804	1374***	0.52***

siderable coefficient of determination. Regression estimates were calculated separately for the two lines. (App. 7) Linear stepwise regressions were calculated for nine different functions as follows (see classification above) to find the structure of interactions:

1) $f_1=c_1+c_2x_9$
2) $f_2=c_1+c_2x_8+c_3x_9$
3) $f_3=c_1+c_2x_7+c_3x_8+c_4x_9$
4) $f_4=c_1+c_2x_2+c_3x_9$
5) $f_5=c_1+c_2x_2+c_3x_4+c_4x_9$
6) $f_6=c_1+c_2x_2$
7) $f_7=c_1+c_2x_2+c_3x_7$
8) $f_8=c_1+c_2x_8$
9) $f_9=c_1+c_2x_9$

The functions f_1–f_5 have both state and input variables (see Table 3 above), f6 and f_7 input variables and f_8 and f_9 internal ones. The results show that best coefficients of determination were achieved with functions f_3 and f_4 which include Mg content (x_7), population density (x_8) and straw yield (x_9) for line 1 and pH and straw yield for line 2 (Table 5) .

In Position Dependent Control, the input variables (x_1–x_7) are more interesting than the internal ones (state variables x_8 and x_9). The primary question is how the inputs affect the yield. Therefore stepwise regressions (f_6 and f_7) with no state variables were calculated. The best coefficients of determination were achieved in both lines with function f_7 that includes pH (x_2) and Mg content (x_7) (Table 6) .

It was found that f_8 including population density (x_8) was the best one of the only-state-variable models (Table 7) . The coefficients of determination of input variables were very low. There are several reasons for this. The input variables were measured straight after yield measurement. There are, however, differences in the take-up schedule of the nutrients. Some nutrients are mainly taken up in the beginning of growing season and others later (e.g. Karvonen and Varis 1992). Thus the measurement timing was not perfect. The measurements express the fertility situation in the upper root zone at harvest time. They also express the level of nutrients in the field for slowly varying nutrients (P, Ca). Autocorrelations in determination of soil sample nutrients (Ch 3.1. above) have also a negative effect on the validity of the results.

3.2.2 Yield-based Production Locations

The next hypothesis was that equal yield levels in a varying field would stand for equal Production Locations. In this case, the situation is viewed from the output, the yield, to the transfer function of the PL. The thought model is that as the fertilizer input has been constant all over the field and the yield is still varying, there must be areas within the lines that have different transfer functions (see Fig. 46 above). On the other hand, Position Dependent Control has the inbuilt assumption of locally varying transfer functions. The contrary hypothesis claims that measured yield levels do not indicate the model of the PL. The question is whether the yield level is strong enough as an indicator of the differences in PLs or not.

3.2.2.1 Simulation of yield level selection

To evaluate the hypotheses, areas for calculation of local regressions were selected from the yield data based on the lenghts of equal yield levels. Several algorithms were developed for this selection. A good area selection algorithm should react to possible sharp changes in yield level. These changes indicate that the soil is altering. Furthermore, a good algorithm should select reasonable amount of areas with a suitable number of observations for the calculations. The basic yield data was measured with such a high resolution (0.5 m) that the data could be used as reference of "true variation" in calculations that simulate the action of other, more sparsely sampling yield measurement methods. For comparison, different sampling technics were simulated. Simulations of automatic integrating and various line and point sampling methods were made. Representative results of these calculations are gathered in the following figure (Fig. 51).

Automatic sampling, such as measurement of grain flow in a combine harvester (e.g. Demmel et al. 1992), integrates the yield (Vansichen and De Baerdemaeker 1992). The measurement result is integral of the yield from the previous few meters. This effect was imitated by filtering the densely measured Keimola yield data with a moving average. Changes in this filtered data were compared with a trigger value. When the data changed more than the trigger, a change in yield, an edge, was found. The edges were signs of yield level change. According to the hypothesis, these changes are signs of different Production Locations. A 150 kg/ha trigger value was found to give over ten edges per sample line (Fig. 51a). Pure edge detection does not, however, work properly: slow changes are not detected. A modified edge detection algorithm with averaging of the integrated data was developed (Fig. 51b). Averaging smoothens the integrated result and leads to more valid indications. A higher (e.g. 200 kg/ha) trigger value reduces the amount of detected PLs , as expected. This is natural because there are less high edges in the yield level to be detected.

Accumulative line sampling was simulated by accumulating the raw data samples and averaging them. Sample values were calculated at fixed intervals. The results show that this kind of sampling leads to fewer detections of yield changes than automatic sampling with same averaging distance (comp. Figs. 51a and 51c). When compared to the modified automatic sampling algorithm, the accumulative line sampling algorithm gave approx. the same amount of detections but in different locations (comp. Figs 51b and 51c). Increasing accumulation distance in accumulative line sampling smoothened out the result and hided apparent areas of different production potential (comp. Figs 51c and 51d). Again, higher trigger values would reduce the amount of detections.

The last simulations were done with point-sampling. Single samples were chosen from the Keimola raw data with various distances. Point samples showed great variation in sample values and lead to quite random decisions in finding the edges (Figs 51e and 51f). This is analogic to the results with the measurement of drain quality (deBoer 1987, Haapala 1992). Again, a higher trigger value (e.g. 200 kg/ha) would lead to fewer detections. The result is, though, very sensitive to the points selected.

Normally manual sampling is not pure point sampling but includes some averaging (Jokinen 1983, eq. 3 above). This was simulated with local averaging (Figs 51g and 51h). Eleven points (5.5 meters in distance) of the data formed one sample. Sample intervals of up to 20 meters were used. The filtering effect is quite strong, and thus higher trigger values have little effect on the number of PLs encountered.

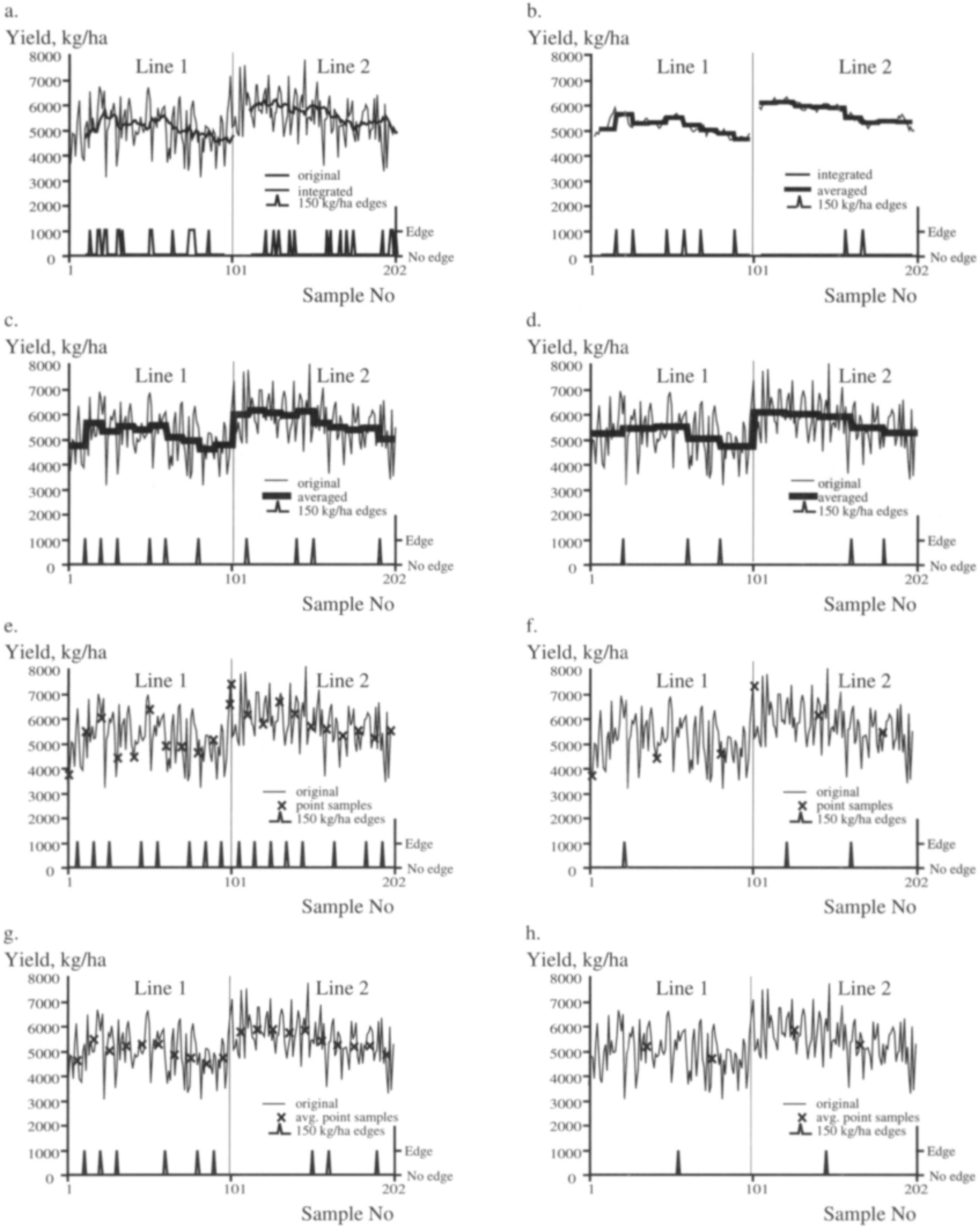


Fig. 51. Edge (150 kg/ha) detection in Keimola wheat yield measured with simulated (a) automatic sampling (moving average of 10 values), (b) automatic sampling with further integration (local averages of 11 values), (c) accumulative line sampling (avg. of 10 values), (d) accumulative line sampling (avg. of 20 values), (e) point-sampling with point distance of 5 m, (f) point-sampling with point distance of 20 m, (g) averaging point sampling (avg. of 11 points) with point distance of 5 m, (h) averaging point sampling (avg. of 11 points.) with point distance of 20 m.

3.2.2.2 Choosing sampling methods for extracting PLs from yield data

In position dependent adaptive crop production, the sampling methods should make it possible to find different areas in the field. This is true both for the yield and other measurements such as the nutrient content, soil type, pest infections, etc. The sampling method should have a suitable resolution for each individual case. The simulations with yield measurements show that sampling methods have built-in differences in resolution and thus also in the capability to find the areas. This is due to the introduction of filtering (integration/averaging) of the data. (Comp. Haapala 1992)

Yield-based area finding algorithms should include edge detection and averaging. Pure edge detection does not count for slow changes in measurement values. A better algorithm includes comparing the current measurement value with an average of preceeding measurements. Area finding algorithms should be calibrated for each kind of variation individually. The calibration procedure needs information in the true variation of the target and the resolution wanted.

Practical sampling mostly includes estimation (interpolation) because it is not economical to collect all available data (Clark 1984, Lesch et al. 1992). Total sampling is not feasible for most inputs (e.g. soil sampling) and state variables such as biomass: it would interfere with the on-going production processes. The yield measurement, however, can be made with total sampling.

Automatic total sampling, e.g. measurement of the yield with a real-time yield meter in a combine harvester, is a good method because of its capability to give continuous measurement values and thus to give a good coverage with little effort. On the other hand influences of integration must be corrected, e.g. the driving direction should be known to be able to shift the results back to the right location in driving direction. Time delay from the PL to the registration of its yield and forward speed of the combine should be known. In a Minnesota experiment (Ault et al. 1993) the best available resolution of automatic yield measurement was 12 meters. This was due to integration and spread of the grain inside the combine. For best results, cutting width measurement is also needed. (Searcy et al. 1987, Demmel et al. 1992, Stafford and Ambler 1992, Vansichen and De Baerdemaeker 1992)

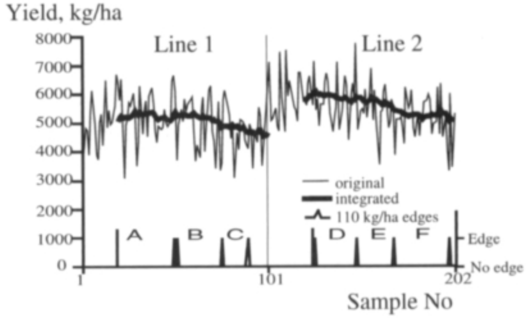


Fig. 52. Simulation of automatic sampling. 110 kg/ha edges are detected from integrated wheat yield in Keimola. Moving average of 20 values is used in integrating the raw data. Areas A..F are selected.

Point sampling, if used, has to be dense and/or each sample should consist of several subsamples. This is analogical to soil sampling (comp. e.g. Jokinen 1983, eq. 3 above). Otherways PL-areas are not properly detected. Manual point sampling is very laborous and can not be used in this context. Automatic sampling machines should be used to get enough data for PDC.

The sinus variation of the yield, which is most probably due to variation of the combi drill´s output (Ch. 3.1.2 above), has to be considered when sizes of the PLs and measurement methods for finding their limits are selected. Automatic continuous sampling was chosen because it is the most probable measurement method for the huge amount of yield data needed in PDC. Moving average of 20 values was used to smooth the sinus wave. For Keimola data, iterative calibration resulted in a trigger value of 110 kg/ha that gave sufficient amount of data per subarea and reasonable distribution of the subareas. (Fig. 52)

3.2.2.3 Local regressions for PLs that are selected on the basis of yield levels

Six subareas (A–F in Fig. 52 above) were selected for the calculation of local regressions. Input variables pH, Ca, N, P, K and Mg were used in stepwise regression analysis. The only function from the previous linewise calculations that got a reasonable coefficient of determination was f_7 which included pH and Mg. Additional functions were used as follows:

10) $f_{10}=c_1$
11) $f_{11}=c_1+c_2x_5$
12) $f_{12}=c_1+c_2x_2+c_3x_5+c_4x_6$
13) $f_{13}=c_1+c_2x_2+c_3x_3+c_4x_4$

Some areas had higher coefficients of determination than those calculated for whole sample lines. Some areas had, however, very poor r^2´s (Table 8, comp. Table 7 above).

3.2.3 Fixed-length Production Locations

The variation of r^2 seems to have some correlation with the area size: the smallest PL, C, has the best r^2. PL C also has the most detailed model. (Table 53 above) This is in accordance with the idea of position fixing. A hypothesis can be made that the models are local and cannot be judged with the measurement of outputs, e.g. the yield, alone.

For comparison of this hypothesis and the previous one with yield level as the fixing variable (Ch. 3.2.2), stepwise regressions were calculated for fixed 5-meter lengths. Stepwise regression analysis was done for the 5-meter lengths of unconditioned yield data from Keimola. New functions (f_{14}–f_{27}) were introduced:

14) $f_{14}=c_1+c_2x_3+c_3x_6$
15) $f_{15}=c_1+c_2x_6$
16) $f_{16}=c_1+c_2x_2+c_3x_3+c_4x_7$
17) $f_{17}=c_1+c_2x_6+c_3x_7$
18) $f_{18}=c_1+c_2x_4+c_3x_6$
19) $f_{19}=c_1+c_2x_2+c_3x_3+c_4x_5+c_5x_6+c_6x_7$
20) $f_{20}=c_1+c_2x_5+c_3x_6$
21) $f_{21}=c_1+c_2x_2+c_3x_3+c_4x_4+c_5x_7$
22) $f_{22}=c_1+c_2x_5$
23) $f_{23}=c_1+c_2x_2+c_3x_3+c_4x_4+c_5x_5+c_6x_6+c_7x_7$
24) $f_{24}=c_1+c_2x_4+c_3x_5+c_4x_6$

Table 8. Coefficients of determination (r^2) and regression coefficients of the best regression functions in regression analyses of yield of the Keimola tests. Only input variables included.

PL	n	Function	r^2	c_1	c_2	c_3	c_4
A	33	f_{10}	0.000	3428			
B	25	f_{11}	0.087	9194	99.2		
C	14	f_{12}	0.589	14279	-2309	243.2	-52.6
D	23	f_{10}	0.000	8713			
E	19	f_7	0.254	1770	1513	17.4	
F	30	f_{13}**	0.282	26633***	-3102**	0.55	-8521*

25) $f_{25}=c_1+c_2x_4+c_3x_7$
26) $f_{26}=c_1+c_2x_2+c_3x_4+c_4x_5+c_5x_6+c_6x_7$
27) $f_{27}=c_1+c_2x_4$

Some very high r^2´s (0.8–0.99) were achieved. As can be seen, the best functions are locally different. This indicates soil variation within short distances. Again, there are spots with very poor coefficients of determination. These spots may have influencing factors other than those measured, e.g. plant diseases. All the poorly regressing areas have only the constant as significant predictor which also points to some extra influence. (Table 9)

3.3 Discussion of the Keimola tests

Soil and yield variability in Keimola was of the same type as in international studies. There was great variation of the soil and nutrients in short distances, as reported by e.g. Peck and Melsted (1993), Mulla (1988), Ovalles and Collins (1988), Ndiaye and Yost (1989), Goovaerts and Chiang (1992), Delcourt et al. (1992), Bouma and Finke (1993), Delcourt and De Baerdemaeker (1994) and McBratney (1992). Domestic research is also in accordance with the variation types found (Kivinen 1935, Kaila and Ryti 1951, Jokinen 1983 and Puustinen et al. 1994).

Table 9. Coefficients of determination (r^2) and regression coefficients of the best local regression functions for yield in 5-meter lengths in Keimola tests. Only input variables included.

PL	n	Function	r^2	c_1	c_2	c_3	c_4	c_5	c_6	c_7
1	10	f_{10}	0.000	5112**						
2	10	f_{14}	0.632	7240***	2.28**	-24.0				
3	10	f_{10}	0.000	6962**						
4	10	f_{15}	0.196	6579*	-16.2					
5	10	f_{16}	0.667	4278*	-1926	-0.38	9.42**			
6	10	f_{17}	0.450	7064***	-33.9	11.1*				
7	10	f_{18}**	0.622	583	10263*	-28.9*				
8	10	f_{19}	0.986	5646***	-8333***	0.11	90.3**	-119***	49.9***	
9	10	f_{20}	0.606	3688	256	-53.9**				
10	11	f_{21}	0.686	3492*	3795	0.41*	15006*	-13.2*		
11	10	f_{14}	0.370	8781	-1.45	14.0				
12	10	f_{22}	0.273	6077***	121					
13	10	f_{23}^{0}	0.994	15559**	-2909***	0.97***	-30967***	431**	-18.1***	-13.7***
14	10	f_{18}^{0}	0.547	406.9	12163*	18.7*				
15	10	f_{24}	0.639	6065**	9445	612*	-53.3**			
16	10	f_{25}	0.532	8080	-14969	32.2**				
17	10	f_{26}	0.862	-1972	-2470	32265**	-364	18.1*	56.6**	
18	10	f_{10}	0.000	7684*						
19	10	f_{10}	0.000	7418***						
20	11	f_{27}	0.228	13093**	-18712					

Position-fixing proved to be efficient in those points where the models used included enough parameters and the parameter measurement (sampling and analyzing) was accurate enough. The selection of the starting point of distance measurement in test lines was totally random and the PL size used (5 m in length) was constant. In spite of this simplification the results were good: local fixed-length PLs were found to give best r^2´s of the methods used.

The PL size used (5 meters in length) is in accordance with the previous simulations (ch. 2.4.2) and with the judgements of international researchers (e.g. Auernhammer 1990, Stafford and Ambler 1990, Petersen 1991, Han and Goering 1992). The PL-based method used is different from these technic-based approaches. It is based on the variation of PLs rather than possibilities of the current technic. Therefore the method is more accurate and valid.

The basic reasons for some low coefficients of determination (r^2´s) in the 5-meter PLs are measurement methods and conditions in the field. The measurements did not cover all effects, timing of sampling was not perfect, analyzing accuracy of the samples was not adequate in some parameters and fertility of the soil was (too) good. In some locations there could be dominating factors that were not measured (e.g. soil compaction, variations in input level, see Fig. 2 in Ch. 1). The soil parameters measured have dynamic behaviour. Therefore measurement time is important if good correlation is needed. The samples were taken just before harvest, and for dynamic parameters like soil total N and K (Richter 1986) the results show only the left-over amount of nutrients that is not necessarily correlated with plant uptake (Karvonen and Varis 1992, Peltonen 1992). Autocorrelations that indicate memory effect in analyzing the pH and the nutrients K and total N (App. 6) introduce an additional error component to the regression analyses and the coefficients of determination (Dally et. al 1984, Hari 1991, Lankinen et al. 1992, eq. 1 above). The field was in good fertility state. It was rich in Ca, K and P. There was 33–213 mg/l total N in the soil. The pH was 5.9–7.1 which is a very good level for silty or sandy clays. The organic matter content was above 3% (3–19.9%). The yield level was comparably high for a Finnish field (3072–7775 kg/ha). All these figures show that there was no eventual shortage of nutrients. In these conditions some PLs are sensitive to fertilizing and others are dominated by different factors.

The error budget of measurements and modeling was varying and no exact value for every part of it can be shown (comp. Fig. 19 above). However, the measurement methods and the data was equal for all the compared methods of PL extraction (line, yield and fixed-length based PLs). Therefore the results are comparable and only dependent on the success of finding the PL sizes and their locations. In the good regressing PLs both the model, its parameters and related measurement technic are adequate. It is assumed that, with adjusted fit to the actual in-field variation, even better results are achievable with position-fixing as compared with the other methods. However, all the results depend on the actual variation (comp. Delcourt and De Baerdemaeker 1994 and Fig. 11 above)

3.4 Conclusions of the Keimola tests

Soil fertility varies within very short distances. Values of pH, Ca, Mg, N, P and K all show variation and usually also a trend in the sample line. This variation of soil properties is seen in yield variation. The case data showed that, in a normal wheat stand, yield variation can be 15–17% of the mean value (CV 0.15–0.17). Densely measured yield can be found to vary in sinus form. This is probably due to the variation of seed output of the drill. This effect can easily be filtered out from the data if the scale of interest is not on below-one-meter variation.

Soil analyzing methods may have a memory effect: subsequent analyses affect each other. In Keimola such effects were found in pH, N and K analysis. This error source should be eliminated if accurate results are required. In practise, as memory effect is not easily removed, neighboring samples should be analyzed one after another. This is because memory effect smoothens sharp changes in data that are more likely in samples that are in random order.

Selecting the Production Location size and its location has a remarkable effect on the controllability of the production. Good PLs give quite high coefficients of determination for controllable soil fertility parameters in regression analyses of the yield. Selection of the PLs on the basis of yield variation does not give good results. Equal yield levels do not stand for equal PLs: PLs have very different transfer functions from the input parameters to the yield. A simple distance-based selection gives better results than yield based selection.

The good fit found in some Production Locations ensures that position-fixing can be efficient if the PLs are adequately well known. For best practical results, the PLs must be intensively measured and the data be fixed to the position. We need to have a network of PLs with a variable resolution (in this case-study a constant resolution of 5 meters was adequate for quite good controllability) and results from measurements of the input and output variables of these PLs. The variables, including automatic yield measurement, should be measured with a method that gives values in the resolution required, either directly or through interpolation (e.g. with the methods of kriging).

It must be realized that measurement methods of in-field variation affect the accuracy of knowledge of the variation achieved. For this reason, variations measured with different methods should not be compared. Automatic sampling methods integrate the data and most manual sampling methods average it. The sampling method, whatever it is, should be calibrated for each kind of variation. The calibration should begin with knowledge of the resolution wanted. Thereafter suitable method and averaging and integration within the method are selected. Economical methods for the measurement of the huge data amount required are necessary.

4 Positioning

Positioning methods are crucial in Position Dependent Control where local information is used. Positioning is used to localize the information measured. It is also used as a control input for the PDC e.g. in variable rate application (Auernhammer 1990, Harrison et al. 1992).

4.1 Coordinate systems

Position is referred to "the location of a point with respect to a specific or implied coordinate system" (Oxford Illustrated 1984). Positions are given in these coordinate systems agreed. In surveying, several coordinate systems are used. On the resulting maps the position is often expressed as level coordinates. There are equations for making conversions between the different coordinate systems. (Langley 1992, Lankinen et al. 1992) Coordinate systems can be global or local. Global systems have reference ellipsoids, i.e. mathematical surfaces that estimate Earth surface. Local systems are referred to locally defined datums that can be defined by local gravity and astronomic north (Local Astronomic coordinate system, LA); or direction of normal to a reference ellipsoid and geodetic north (Local Geodetic coordinate system, LG). (Lankinen et al. 1992) Besides these there are various freely defined local coordinate systems that have local fixes.

Surveying is traditionally done in the gravity field of the Earth. The gravity field defines the orthometric height H (height from mean sea level). (Milbert 1992). One special potential level is the geoid that corresponds to the local mean sea level (Oxford Illustrated 1984). The geoid surface is given as height difference from surface of an Earth-estimating ellipsoid.(Fig. 53)

The curvature of the Earth is a significant error source in leveling. The curvature is e.g. 78.5 millimeters in one kilometer distance. The curvature is expressed with (eq. 4, deBoer 1987):

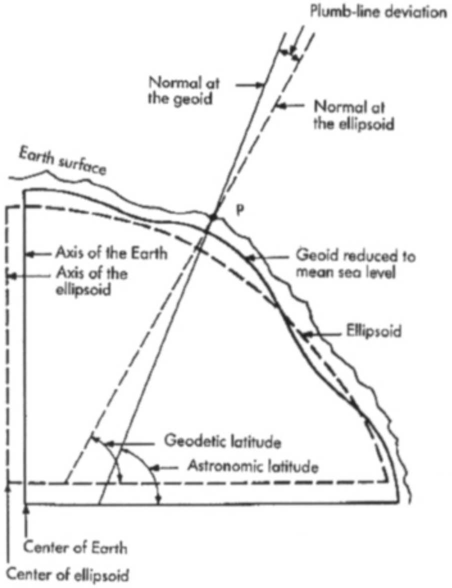


Fig. 53. Ellipsoid and geoid in leveling. Plumb line deviation is the angle between the normals of ellipsoid and geoid (Toft 1987).

$$[4]\quad \text{Curvature} = \frac{s^2}{R}$$

where s = distance and

R = radius of the Earth (c. 12800 km)

Non-geocentric ellipsoids are used in geodetic coordinate systems (G). There are traditionally many geodetic reference ellipsoids in use; e.g. the ellipsoids for North America and Europe are different. This dates to historical reasons and the fact that good local fit to the geoid is required. Geodetic (ellipsoidal) coordinates of point P are the (geodetic) latitude and longitude. Latitude (ϕ) is measured in the meridian plane that passes through P. It is the angle in this plane between the equatorial plane (x-y) and a line perpendicular or normal to the surface of the ellipsoid at P. Longitude (λ) is the angle measured in the equatorial plane between the zero-meridian and the meridian plane that passes through P. Height coordinate, h, is measured along the normal of the ellipsoid. (Fig. 54, Langley 1992, Lankinen et al. 1992)

Now that positioning is getting global there is a need for a standard ellipsoid with the origin at Earth center (geocentric ellipsoid). It should have good global fit to the geoid. This kind of ellipsoid, the WGS72 (World Geodetic System 1972), was first introduced in connection with the Transit satellite navigation system. The newest version currently in use is WGS84. Positioning results that base on global ellipsoids differ considerably (e.g. 500 m) from local geodetic coordinate systems. For this reason satellite positioning receivers often have built-in coordinate conversion software to convert WGS84-coordinates to the local system. (Toft 1984, Langley 1992) On the other hand, national surveying is moving towards the use of WGS84 in many countries, including Finland.

In Finland, besides the geodetic coordinate system that is based on an international geocentered reference ellipsoid from 1924 (the Haytords ellipsoid) and European (geodetic) Datum 1959 (ED50) there are local coordinate systems (e.g. the so called Helsinki coordinate system). Mapping is based on KKJ- (abbr. of the Finnish word for map coordinate system, Fig. 55, MMH 1988) level coordinates and N60-heights (N60 is referred to the mean sea level in Finland in 1960). (Rainio 1988, MMH 1988, Lankinen et al. 1992, Ahonen 1993)

Local information is usually presented in level coordinate systems. Three-dimensional space coordinate systems are needed in measurement and calculation of these level coordinates. (Toft 1987, MMH 1988, Langley 1992, Lankinen et al. 1992, Milbert 1992)

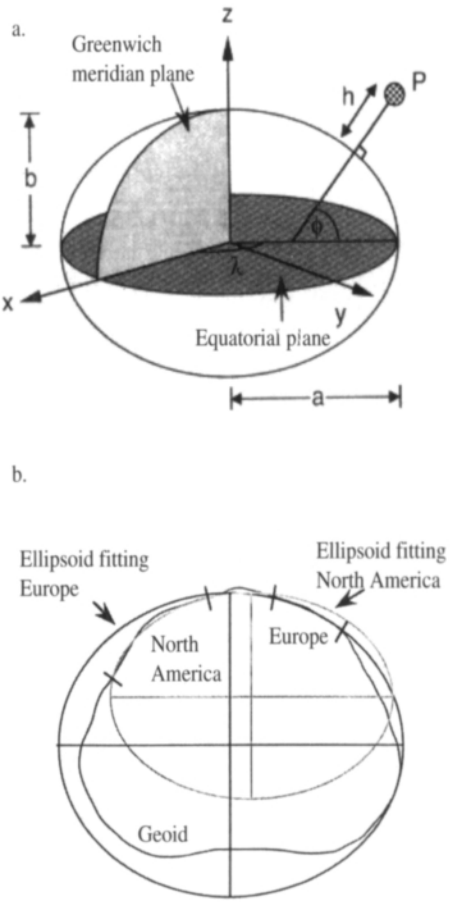


Fig. 54. (a) The geodetic coordinate system. (b) An example of different reference ellipsoids. Flattening and geoid changes are exaggerated for clarity (Langley 1992).

Position Dependent Control needs both local and global coordinate systems. PDC of farm machines is a local solution. The working area is usually so small (fields of one farm or a single field) that the variation of coordinate systems has neglectful effects on positioning accuracy. Positioning accuracy requirements are moderate (targeting accuracy of ±5 meters in PDC of fertilizer application, Ch. 2 above). Furthermore, these applications do not need absolute but relative coordinates. It is good enough to have the location relative to a local reference point (Stafford and Ambler 1991). Local solutions can have local coordinate systems with virtually no connection to global systems. Simple levelled instruments could be used in position

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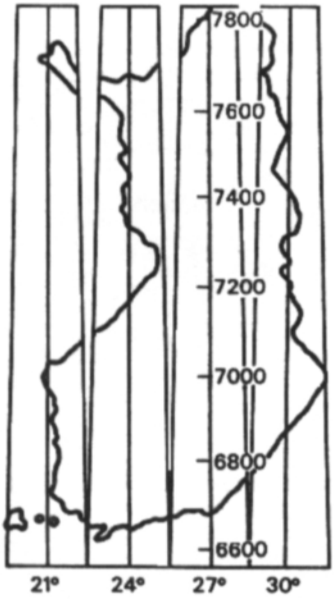

Fig. 55. The KKJ map coordinate system. Finland is divided in four projections (Gauss-Gruger cylinder projections), the center meridians of which are 21°, 24°, 27° and 30° eastern length and the origins are (approx.) at the intersection of the center meridian and equato. (MMH 1988)

measurements because the curvature of the Earth (eq. 4 above) is not significant in short distances. On the other hand, this locality also gives us the freedom to choose the coordinate system to work with. For simplicity and to avoid transformation errors it is good to adopt one coordinate system in which the whole Position Dependent Control system (planning, realizing, measurement of output) works.

WGS84 that defines the coordinate system of GPS satellite navigation is a good choice to work with because, in future, most carthography will be based on it. These kinds of global systems can be used to tie several local measurement systems together and enable local information transfer to wide area information systems.

$$[5] \quad \frac{r_\varphi}{R} = \cos\varphi \qquad \Rightarrow \frac{\Delta\lambda}{\Delta\varphi} = \cos\varphi$$

where r_φ = radius of the plane parallel to equatorial plane at φ

R = radius of the sphere at equator

φ = latitude

λ = longitude

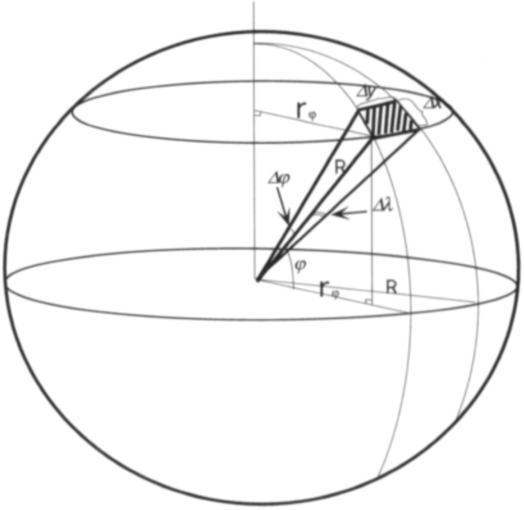

Fig. 56. Notations for equation 5.

The easiest way to get coordinates for the Production Locations (Ch. 1.2 above) is to round the WGS84´s ellipsoidal coordinates (latitude and longitude) down to the wanted resolution. WGS is ellipsoidal so the obtained metric resolution on Earth surface depends on the latitude. The flattening of the ellipsoid is so small (c. 1/300) that spherical coordinates can be used in calculations (eq. 5, notations: Fig. 56). According to this calculation, in southern Finland (c. 60°) a resolution of 1/1000´ in φ and λ would give around 0.9x1.8 meters (x and y) and in northern Finland at 70° c. 0.6x1.8 meters, respectively. This is adequate for positioning in PDC-applications with a targeting accuracy requirement of a couple of meters (Ch. 2).

4.2 Positioning, orientation and navigation

Positioning is closely related to vehicle navigation. Navigation (lat. navigare, to sail) includes determination of the location of the user and the target. IEEE (1989) says that navigation is "the process of directing the movement of a craft so that it will reach its intended destination". Determination of the user´s location is positioning. Target position (direction and distance) tells us how we are orientated in relation to the target. If the vehicle moves in a fixed network (e.g. street or road network), navigation also needs route selection and guiding (Karppinen 1990). Harris and Krakiwsky (1989) divide vehicle navigation into locationing (determination of geographic coordinates), positioning (converting coordinates to a format suitable for digital information system), route selection (selecting the best path from existing road network), kinematic positioning (constant measurement of coordinates) and route guidance (giving driving instructions) (Fig. 57).

Navigation aids are needed if a previously defined route is to be followed. The driver can have a map screen where the actual position is marked. Route guidance signals can be shown on the same screen. The route guidance can be given to the driver with various signals, such as directing arrows or audible signals. Driving instructions can also be coded to synthetic speech. Whatever the media is, it is important that the information is qualitatively and quantitatively right. The information must be important and in a useful format. Information ergonomics is researching this information exchange process. (Lunenfeld 1989, Karppinen 1990)

Adaptive Position Dependent Control of field operations needs both positioning and navigation. Collection of local information includes positioning. If we want to return to the sample points (e.g. same soil sampling locations every year), navigation may be needed. Local information is also collected during the realization phase. This information consists of measured output and functioning of the machines and realtime measurement data from the production location. In theory, the realization phase does not necessarily need navigation, because setpoint values are taken from the GIS. It is, though, reasonable to have orientation and speed measurement to better be able to adjust machines according to future setpoints in the direction of travel. Full navigation is needed if the vehicle is to be driven along a preset route. Vehicle navigation can also be used to facilitate the driver´s task and free her/his capacity for other purposes than steering. This enables her/him to concentrate on the actual work task. It is even possible to use autopilots or automatic steering.(Table 10)

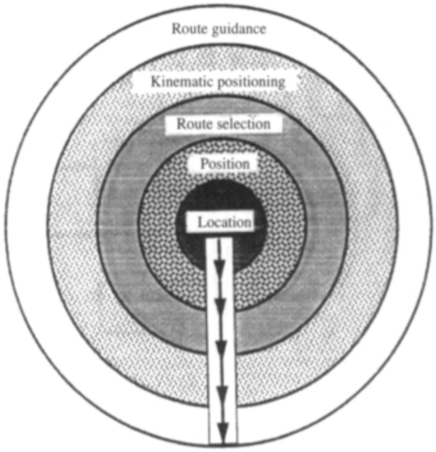

Fig. 57. Concepts of vehicle navigation (Harris and Krakiwsky 1989).

4.3 The map in Position Dependent Control

A map can be used to enhance positioning accuracy. The so called Map Matching Technic requires that the operation area has certain allowed routes e.g. roads (Karppinen 1990a). An algorithm compares the measured vehicle position and the possible routes and corrects actual position to the route if necessary. (Fig. 58)

Table. 10. Need of positioning, orientation and navigation in Position Dependent Control. The cases in brackets have some use of the technic but it is not necessary to use it.

	Positioning	Navigation
Collection of local information		
- registration of the information	X	
- returning to the location	X	(X)
Realizing the control		
- real time measurements	X	
- control of the machines	X	(X)
- functioning of the machines	X	
- driving along preset route	X	X

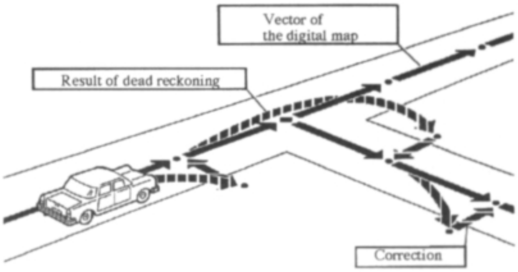

Fig. 58. Principle of map matching in crossroad driving (Wiedenhof and Van Hooren 1987).

Map matching algorithms have been developed both for crossroad and direct driving. Algorithms find straight parts and crossings and correct the position if needed. If a vehicle runs a certain distance without changing its direction beyond a specified limit, the algorithm regards the road at that time as straight. One or more corresponding vectors of the map are selected. The number of possible vectors are limited through determining an area where the vehicle most probably exists. The correction is made to the selected route if necessary. (Harris et al. 1988, Morisue and Ikeda 1989)

4.3.1 The digital map

Navigation and automatic vehicle positioning systems require digital maps that enable extensive calculations. The map matching technic described above can be utilized in areas that are numerically mapped. Numerical mapping methods are widely adapted so that electronic maps, stored in e.g. CD-ROM disks, and map matching are expected to belong to all independent positioning systems in the future. (Morisue and Ikeda 1989, Karppinen 1990a) Digital maps come both in raster and vector format. So called hybrid maps contain both types. In raster format the mapped area is divided into small sized squares for coding. Vector format includes the targets, e.g. outlines of the areas and roads, converted to straight lines (vectors). Vectors are given with their start and end points and nodes. Generally, raster maps use much memory and require more calculation power than vector maps. This, however, changes with the complexity of the data presented. Vectors are better for symbolic representation (interpretation of “what”) and rasters for that of positions (“where”). (Karppinen 1990, Tomlin 1990, Artimo 1992, Lankinen et al. 1992, Parmes 1994)

Finnish mapping is switching over to digital methods. Old map originals are digitized and new maps are converted to digital format from satellite and aerial photographs or land surveys. Digitizing the old maps is both manual and automatic. Manual digitizing is done through pointing the position on the map attached to a digitizing board and inputting the local information on the keyboard. Automatic digitizing includes map scanning to raster format and raster map vectorizing with dedicated software. Local information of the old maps can often be automatically transfered through scanning in color, line width and other such parameters. Stereo mapping is done with special aerial photographs. The 3D-image is viewed with special equipment that enables the user to pinpoint the surface with a cursor and input the local data to that 3D-point. Surveying is turning digital concurrently with increased use of digital tachymeters and geodetic satellite navigation devices. Roads are mapped with inertial and satellite navigation. (Byman and Koskelo 1991, Rainio 1991, Offermann 1993, Ahonen 1994b)

The accuracy of old paper maps is sometimes too poor for vehicle guidance that is one of the most demanding applications (Juhala 1993). New maps should be based on more accurate surveying. New standardized Electronic Chart Display Information Systems (ECDIS) are being developed that use accurate digital maps. Maritime use of electronic nautical charts is catalyzing this development. (Montgomery 1992, Alexander 1994) Normally, map manufacturing includes coordinate conversions and error fixing (Lankinen et al. 1992). Positioning methods are used to get reference points (GCPs, Ground Control Points) for the fixing so that the map fits better to the actual world. (Byman 1990, Perry 1992) Mapping without ground control is the ultimate goal in the development of Global Navigation Satellite Systems (GNSS). This development is expected to come true when the GNSSs provide an accuracy of better than one decimeter (Lapine 1994).

4.3.2 The map in Position Dependent Control of field operations

Maps are important in Position Dependent Control; the data used is position-fixed and thus a map is the natural way to represent it. The PDC data is stored in a Geographical Information System (Ch. 2.3.3). The GIS-user may get the local information partly in map format and partly by inputting it at a map coordinate. The map also acts as a graphical user interface to the GIS and map screens and printouts of the GIS data are produced on request (Rainio 1988, Artimo 1992). Furthermore, the map is used as a guide in navigation (Karppinen 1990, Langley 1993)

In PDC of field operations the map is needed in planning and realizing of field tasks. The planning requires information on relative orientation of the production locations and individual fields. The planning phase uses maps for decision support; thematic maps are shown on the computer screen. If local information is fed to the GIS via the map image, then accuracy of the map should be such that the requirements for targeting accuracy and resolution are fulfilled in the following realization phases. For position dependent control of nitrogen application a targeting accuracy of ±5 meters and coordinate resolution of 1/1000′ (in WGS84) were set in previous chapters. Some other position dependent tasks may need better performance. Moore et al. (1993) reports the need for good resolution maps for terrain analysis in connection with the soil specific management.

Much of the local information is given in raster format, e.g. results of satellite or aerial photograph processing (Tomlin 1990). This is true in agriculture, too. Satellite and aerial IR- and NIR- (Near Infra Red) images and video recordings give information on numerous agricultural parameters, such as plant variety, plant development stage, the need for plant nutrients, raining or plant protection, and effect of treatments. (e.g. Williams and Shih 1989, Blazquez 1990, Evans 1992, Fouche 1992, Hough 1992, Gupta 1993). This information must be shown on the map screen with overlaying possibility of different data.

The realization phase needs the map for showing vehicle/equipment position to the user. In this task the map is not acting as a coordinate input media but rather as a background. If the user uses on-line data input to the GIS, then the positioned coordinate could be used as an index and the accuracy requirement is put on the positioning system instead of the map. It is, though, preferrable to have also the option to select target points outside the current positioned location of the user for data input, e.g. when areas of abnormal plant growth are documented. Good map accuracy is then necessary.

In the field there are normally no fixed networks, except with the use of so called tramlines or when row crops are produced. The tramlines are made by leaving some seed lines without seed in regular spacings, e.g. four meters. These lines act as guiding lines for the following tasks. The tramlines, if mapped, can act as the necessary fixed network, and map matching algorithms can be used. A kind of map matching is also possible in row crop production. In tasks that use parallel passes the previously driven route could be used as a guide for the next pass.

Maps for PDC must be up-to-date because local control is required. Therefore it must be easy to make possible changes in the shape of the fields. In Finnish official registers there are considerable differences in farm sizes. This is due to different mapping systems and various calculation methods of area changes. Area changes are results of e.g. partitioning of the estates (Ahonen 1994a), and during the past century drainage operations have made considerable changes in field shapes (Puustinen et al. 1994). Pipe drainage has made it possible to change crop production patterns freely. The mapping system must be very flexible to manage these yearly dynamics of production locations.

Digital ground referenced maps, that are frequently updated, are the only types meeting these requirements. Hybrid maps with both raster and vector data are needed. In practise the mapping is done with satellite navigation (GPS- satellite navigation equipment, see Ch. 4.4 and 4.5) and the map is stored in a GIS-database for further processing. Requirements for up-to-date information are met when the mapping information is in GIS-format and the necessary changes are done frequently.

As a conclusion, the digital GIS-based maps are needed for the use of agricultural and environmental planning. Different requirements are set by the farmers, extension service, administration and research (Salo 1994). The spatial data exchange through network services which is under construction (Rainio 1988), could be used to spread the spatial data including the digital maps. New GPS/GIS-based surveying is producing high quality maps. However, only some areas of agricultural Finland are currently covered. This work should be completed to get the maps necessary for Position Dependent Control. However, the need for up-to-date high precision maps may need the use of complementary mapping methods. For this purpose, updating the field map can also be assisted with high-resolution aerial photography (comp. e.g. Fouche and Booysen 1991). A light-weight RC-plane with a small camera or video and GPS is a potential source of cost-effective map updates (Haapala 1994b).

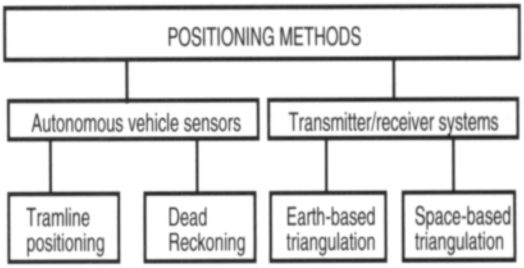

Fig. 59. Classification of positioning technics of agricultural vehicles (Muhr and Auernhammer 1992).

4.4 Classification of positioning systems

Positioning systems can be divided into many kinds of operational classes, e.g. Stafford and Ambler (1991) divide them into global and local methods. Global methods are globally available whereas the local ones are, according to their name, just for local use. Satellite navigation systems are global and vision-based route finding is local. Karppinen (1990a) classifies the methods into autonomous and non-autonomous. The autonomous ones need no external information to the vehicle. The non-autonomous methods use external information sources and information exchange. In autonomous positioning the charges are all paid by the user and in non-autonomous systems the costs can be divided into private and community parts. Inertial navigation and Dead Reckoning (DR) are autonomous whereas GPS (Global Positioning System) satellite navigation is a non-autonomous navigation system. Muhr and Auernhammer (1992) combine the classifications for agricultural vehicle navigation purposes (Fig. 59).

The following classification that is used in presenting different navigation systems is mainly based on the division of Karppinen (1990a) and Stafford and Ambler (1991), and the terminology of Muhr and Auernhammer (1992).

4.4.1 Autonomic vehicle sensor systems

Inertial and Dead Reckoning (DR) navigation are autonomic sensor systems (Karppinen 1990a). Inertial navigation is used in ships and aeroplanes. Inertial navigators are expensive so they are not commonly used in land navigation except in tanks and corresponding military technology. (Fig. 60)

The inertial navigation begins at a determined point. The change of position is calculated out of acceleration and time. The best accuracies are 10–50 ppm (of the distance traveled). The system is independent of electromagnetic waves, refractions, line of sight and weather conditions. Thus it is possible to measure the position even beneath water and under the ground. Drawbacks of the system are, in addition to the high price, the regular need for calibration and the long starting phase. Newer technics include laser gyros which are cheaper but somewhat more inaccurate. (Karppinen 1990a, Santala 1992)

Dead Reckoning that was first utilized in maritime is nowadays used for many purposes. It is also called vector navigation. DR is defined as "the determining of the position of a vehicle at one time with respect to its position at a different time by the application of vector(s) representing course(s) and distance(s)" (Douglas-Young 1981, IEEE 1984). Positioning information is achieved by vehicle start point, heading and distance measurement (Fig. 61). Heading and distance are generally measured with odometers, which are distance measurement devices. They are installed to vehicle transmission. The most common way is to measure the rotation of wheels or shafts. Heading measurement is inaccurate because slippage, tire pressure changes, tire wear, angular velocity of the tires and lane changes affect the accuracy. (Hakala 1992) In practise, it is necessary to have other methods for heading measurement. The most common method is to use an electronic compass, and ultrasonic beacons are also used. The ultrasonic beacon transmits ultrasonic waves that reflect back from the soil surface. The drive speed is calculated from the Doppler effect of transmitted and received signals. The heading can be calculated with two of these beacons which are installed at opposite sides of the vehicle.One posiible technic is the gas rate gyro, where the direction change of the vehicle is sensed with acceleration-induced flow changes of circulating gas. (Karppinen 1990a)

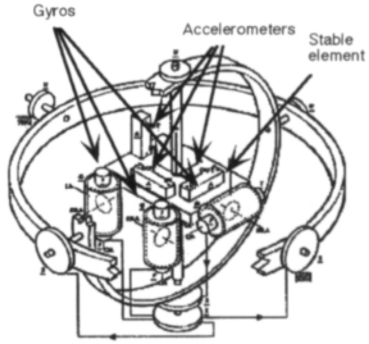

Fig. 60. Schematic picture of an inertial navigator. The navigation is based on revolving gyros and accelerometers (Slater 1964 ref. Karppinen 1990a).

The accuracy of Dead Reckoning is typically c. 3–4 % of the distance measured (Hakala 1992). This is because each point is based on all the previous points and their cumulated measurement errors (comp. eq. 1 in Ch. 2.3.3). Errors can be reduced if the driver checks out the reaching of the target point or feeds in the right point coordinates at regular intervals. The right coordinates can also be fed in using external beacons, but then the system is no longer purely independent.

In city conditions these external reference beacons can be found in e.g. traffic lights (Morisue and Ikeda 1989, Nobbe 1990 ref. Karppinen 1990b, Fig. 62). GPS satellite navigation can also be used in reference measurements

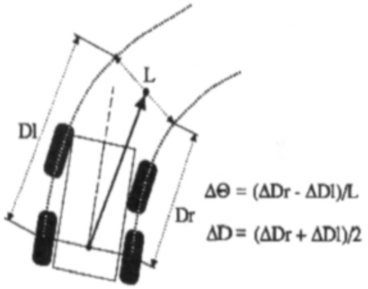

Fig. 61. Principle of Dead Reckoning. Heading (θ) and distance (D) are measured cumulatively to calculate positions (P) (Hall 1986 ref. Karppinen 1990a).

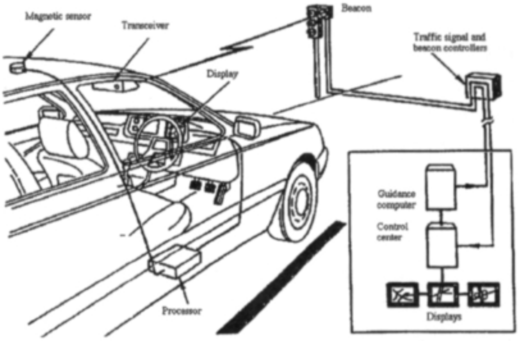

Fig. 62. A short distance radio beacon navigation system attached to traffic lights (Nobbe 1990).

(Vuopala 1990). Karppinen (1990a) says that pure Dead Reckoning-devices can no longer be marketed as vehicle navigators but other supporting systems must be integrated. This is also what the market situation shows with increased selling of hybrid navigation systems (Krakiwsky 1994).

4.4.2 Transmitter/receiver systems

Non-independent positioning systems are mostly based on the use of radio waves. The exact position of either the transmitter or the receiver, the one which is stationary or otherwise fixed, must be known. The distance between the transmitter and the receiver varies from a few meters to thousands of kilometers. In addition to radio navigation, laser positioning is used in some transmitter/receiver applications. The latest development is networking the transmitter/receiver systems. (Harris and Krakiwsky 1989, Iwaki et al. 1989, Palmer 1989, Saito and Shima 1989, Shmulevich et al. 1989, Karppinen 1990a, Rintanen 1992, Lapine 1994)

4.4.2.1 Short and medium distance systems

Short distance radio navigation has been developed for city navigation as illustrated above (Fig. 63 above). Independent navigation systems like DR are often supported by this kind of methods and/or compass devices to correct for cumulative error. The situation can also be the opposite: independent methods support non-independent ones. This was the case with a Finnish road mapping system, where Dead Reckoning was acting as a backup for GPS. DR had to be used in 3–10% of the traveled distance (Byman and Koskelo 1991).

Maritime radio navigation equipment is mainly designed for coastal navigation, but it is also used in land navigation (Chandan et al. 1989). DECCA was developed during World War II. LORAN-C and Omega are the other commonly used maritime radio navigation systems. Radio beacons are much used in maritime applications. DECCA consists of land stations that constantly transmit synchronized (70–130 kHz) signals. DECCA covers the most important European coasts. The method measures phase differences of the signals of at least three stations. Two land station signals can be used to calculate a hyberbola on which the vehicle is located. The third signal forms an other hyberbola with one or the other of the previous signals. The vehicle is situated on the intersection of these hyberbolas. (Douglas-Young 1981, Henttu and Nyman 1990, Fig. 63). One DECCA chain covers a range of 450 km in average and positioning accuracy varies from 20 meters to three kilometers (1σ, see. App. 9 for the representation of accuracy). The master is located in the center and the slaves are at 80–250 km distance. The accuracy gets worse when the angle of locating hyberbolas diminishes. The optimum is reached when the angle is 90 degrees. Other components that impair the accuracy are local interferences caused by the islands and the coastline, internal chain errors, thunderstorm, space reflections, bad weather and interferences caused by vehicle instruments. The accuracy is generally best during the day when the weather conditions are stable. In spite of its errors DECCA is widely used, specially in fishing fleets, because of its constant availability and high repeatability of the positioning result. (Toft 1987, Henttu and Nyman 1990)

LORAN-C -navigation system (Long Range Navigation) is also based on hyberbola geometry. The secondary (slave) transmitters are situated at a longer distance than those of DECCA, so the coverage is broader. There are three to four secondary transmitters 500–1000 kilometers from the master. LORAN-C chains cover all American coastal areas, Japanese waterways, areas in the Pacific, the nortern Atlantic, the Mediterranean and parts of northern Europe. Apart from DECCA, all stations transmit constant (100 kHz) signal bursts. The stations are identified by timing of these bursts. Also the hyberbolas are determined from time difference in signals instead of phase measurement. Accuracy of LORAN-C is affected by the same components as in DECCA. Absolute accuracy can be around 500 meters (2σ) and relative accuracy some 15–60 meters (1σ) (Toft 1987, Henttu and Nyman 1990)

Omega, a third hyperbola navigation system, was initiated in 1961. The navigation system consists of eight land stations (named A–H) in total. They are at long distance from each other (up to 6000 nautical miles). The stations transmit phase-synchronized signals (10.2, 11.05, 11.33, 13.6 kHz) and a station-specific extra frequency. Because of the deflections in low frequency transmission it is possible to reach global coverage with only eight stations. The positioning is based on phase measurement as in DECCA. The absolute accuracy of Omega is typically two to four nautical miles (2σ). (Toft 1987)

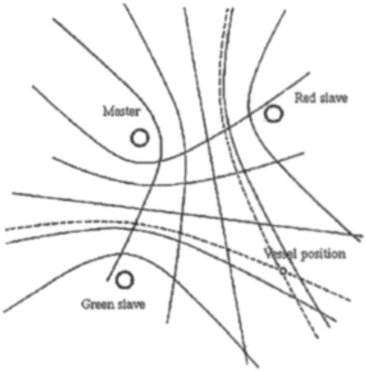

Fig. 63. Principle of DECCA hyberbola navigation (Henttu and Nyman 1990).

Radio beacons are widely used. They are nondirectional radio transmitting stations that operate in the low frequency (LF) and medium frequency (MF) bands. A radio direction finder (RDF) is used to point the bearing of the transmitter. Accuracies of typically 3° (2σ) are achieved (this means c. 50 m at 1 km). Aerospace and maritime applications use radio beacons. There are also a number of private radio location systems on the market that operate in frequency areas of c. 100 kHz to 9500 MHz. Their range decreases with increasing frequency. They are used where radio determination (determination of position and velocity with radio waves) coverage is not available, accuracy is not sufficient and the availability is not continuous. (GPS World 1994, RTCM 1994)

Laser positioning is much used in geodetic surveying using so called tachymeters (combined electro-optical distance and angle measurement devices). For positioning of moving vehicles a servo tachymeter can be used. It follows a prism attached to the target. Some experimental systems use scanning or rotating lasers with beam angle measurement and prisms and/or fotodiodes in the tranceiver or receiver. Outstanding accuracy (typically c. 5 mm/km) can be achieved in moderate distance (1–3 km) of the transmitter.

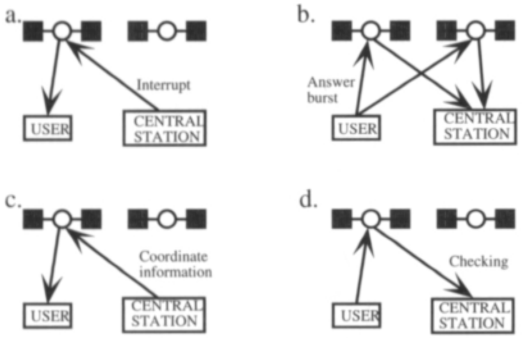

Fig. 64. RDSS (Radio Determination Satellite Service) satellite navigation (Lähteenmäki 1987).

Fig. 65. Orbits of GPS (Global Positioning System) satellites (Sonnenberg 1988).

(Shmulevich et al. 1989, Lehr and Prasuhn 1990, Rintanen 1992)

4.4.2.2 Long distance systems

Satellite navigation is a long distance (space-based triangulation, see fig. 60 above) radio navigation method. By definition, satellite navigation is "...a method to derive navigational parameters like position and velocity by using radiosignals transmitted from satellites" (Krüger et al. 1994). In most systems the positioning is globally available. Important global satellite positioning methods are Transit/NNSS, GPS and GLONASS, which are based on orbiting geosynchronized satellites and RDSS that is geostationary. (Karppinen 1990) Besides these there are local satellite positioning systems, e.g. Starfix that operates in the U.S. continent (Ott 1988).

Transit/NNSS (Navy Navigation Satellite System) was originally developed for the U.S. Navy for the positioning of Polaris-type submarines. There are seven satellites orbiting the Earth at an altitude of 1075 kilometers. The positioning is made on the basis of Doppler shift of the satellite signal as the satellite passes the vehicle. The main drawback of the system is the time of 35–100 minutes between each position determination. Various intelligent receivers have been developed that use DR to keep track on vehicle dynamics between the Transit positioning points. For single frequency (400 MHz) receivers the absolute accuracy is 80–500 meters (2σ) and for dual frequency (150 and 400 MHz) receivers it is 25–37 meters (2σ). The improvement is due to corrections of ionospheric delay of the signal. Since the Transit technic is getting old and newer systems replace it, the system is to be shut down in 1996. (Toft 1987, Ollaranta 1988, Karppinen 1990).

RDSS (Radio Determination Satellite Service) satellites are geostationary. RDSS receivers also act as transmitters. (Lähteenmäki 1987, fig. 64) The RDSS system has a low positioning accuracy (c. 250 m). It is mainly used for data transmission in IVHS- (Intelligent Vehicle/Highway Systems) applications (Krakiwsky 1994).

The U.S. NAVSTAR GPS (Navigation System with Time and Ranging Global Positioning System) is based on 21 geosynchronized satellites. The satellites orbit the Earth at c. 20200 km altitude, the orbiting period being c. 11 hours and 58 minutes. The constellation (relative orientation of the satellites in the sky) ensures that at least four satellites are constantly and globally at Least 5 degrees above the horizon. It means a 24-hour global coverage for 3D-positioning. (TOFT 1987, Hartman 1992, Krüger et al. 1994). GPS positioning service is currently (1995) free of charge - users just have to buy a receiver to begin to use it. The price of the receiver is in the order of that of a common microcomputer. There

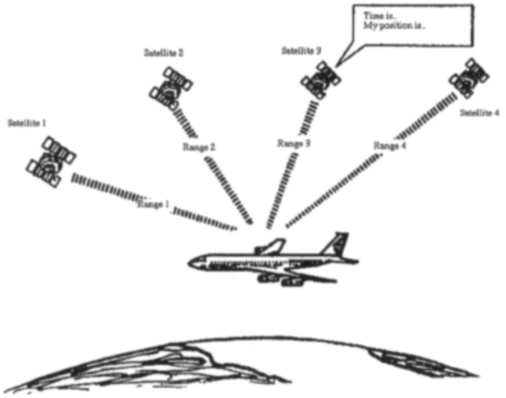

Fig. 66. 3D-positioning with GPS. Four satellites are needed (Toft 1987).

are numerous makes and models available. The smallest receivers are about the size of a credit card. (Chan and Schorr 1994, GPS World 1995)

GPS is widely used on dry land and on sea. In the future air traffic will use it too. Using GPS in the airplanes was not possible for safety reasons until recently because of the incomplete satellite constellation. In 1994 the constellation was fully realized, consisting of 21 active satellites and 3 spares (GPS World 1994). GPS uses the geocentered WGS84 reference ellipsoid (Ch. 4.1 above) as its basic coordinate system. Positioning results can be converted and given in other coordinate systems as well. Three-dimensional positioning (e.g. latitude, longitude and altitude) requires four satellites. Three satellites are used to measure the spatial location and the fourth is for time correction. The time correction is needed to synchronize the receiver´s clock with the satellite clocks. (Toft 1987, Figs 65 and 66, Bäckström 1990, Parm 1992, Tyler 1993, Van Dierendonck 1995)

System clocks of GPS are very precise because in radio navigation an error of one nanosecond causes a 30-centimeter error in position. Cesium and rubidium atomic clocks are used. GPS signals are transmitted in two carrier frequences L1 and L2. L1 is 154 times and L2 120 times the basic frequency (10.23 MHz) of the atomic clocks in the satellites, i.e. 1575.42 MHz for L1 and 1227.6 MHz for L2. The carriers are modulated with two types of digital codes: one or two of the so called PRN-codes (pseudo random codes) C/A- (coarse acquisition) and P- (precise), and navigation message. The satellite joins the PRN-code and navigation message for modulation. The combined codes are often called C/A- and P-codes according to the PRN-code type used in modulation. The combined codes include the information needed for position determination and system health control. There are also receivers, so called codeless receivers, that do not use the PRN codes but the carrier phase for position determination. (Toft 1987, Tyler 1993, GPS World 1994, Krüger et al. 1994)

A new accurate GPS technic is the so called RTK- (Real-Time Kinematic) GPS. It is a very accurate carrier-based GPS method with a real-time positioning accuracy around 30 millimeters. The technic is based on OTF (On-The-Fly) ambiguity resolution, which determines the correct number of initial integer cycles in carrier phase measurements. This number of cycles is known if the receiver can continuously track all the needed satellites but, in case of losing lock on a signal, a phase slip may occur. There are several ways to calculate the ambiguities e.g. using a search space and various validation and rejection criteria. The search space is a probable volume in the space where the right phase could have been lost. Confidence limits of 95 to 99 % are used in defining this ellipsoidal space.A coded solution, using the PRN-codes can be used during the phase slip, or the remaining satellite connections can be used to limit the search space. The speed of ambiguity solution algorithms and related datalinks is a bottle neck for the accuracy of RTKGPS. (Tyler 1993, Abidin 1994, Seeber 1994)

Full accuracy of GPS is not available for all users. The best accuracy is reserved for authorized use such as the U.S. military. The basic accuracy of GPS (permitted accuracy for unauthorized use), denoted by SPS (Standard Positioning Service) uses only the C/A-code on L1, and is set to the level of c. 100 meters (95%). To achieve this, degradation of accuracy, Selective

Availability (SA), was introduced by U.S. DoD. SA was realized through adding intentional random timing errors in the navigation message. In addition to this the P-code is encrypted (antispoofing, Y-code) to prevent unauthorized use. the best accuracy, the so called PPS (Precision Positioning Service), that is in authorized use only, uses both L1 and L2 and the P-code. (Toft 1987, Tyler 1993, Van Dierendonck 1995) Supplementary information on GPS technics is in app. 10.

GLONASS (Global Navigation Satellite System) is a satellite navigation system of the former Soviet Union currently run by Russia. It is a system corresponding to GPS, where the satellites are situated a bit differently than in GPS. The altitude is 19100 kilometers and the orbiting period is 11 h 15 min. The orbits are such that GPS is reported to have some difficulties in coverage near the polar regions and GLONASS near the equator. In comparison to GPS, GLONASS expresses satellite positions in a slightly different format and uses a different reference ellipsoid (SGS-85). GLONASS-satellites use transmission frequences in the L-band as GPS. The frequencies are, however, different for each satellite and individual satellite codes are not present in the transmitted data. GLONASS constellation is not yet fully realized, though, it is anticipated that all the 24 satellites will be operational in 1995. Joint GPS/GLONASS receivers are developed and tested. These receivers give full global coverage with good accuracy. Coverage problems are not a major issue to land users but to aerospace where true 100% coverage is needed for safety reasons. (Hartman 1992, GPS World 1994, Johnson 1994).

Enhanced satellite navigation

Currently satellite navigation, specially GPS, is conquering the market of vehicle navigation. It is superior in the sense that it is globally available, relatively cheap and accurate enough for most navigation applications. In spite of this satellite navigation has some weak points that lead to a necessity of backup systems and special enhancement technics. GPS is used here as an example.

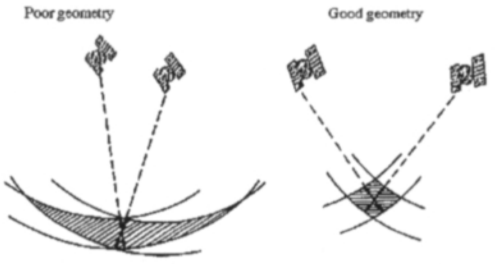

Fig. 67. Effect of satellite geometry on positioning accuracy (Toft 1987).

GPS needs constant visibility to four satellites for 3D positioning. The 5° cutoff angle, that was used in dimensioning the satellite constellation for 24-hour coverage, is too low in terrain use. A clear line-of-sight is not possible and short positioning pauses occur. On the other hand, satellite geometry (relative orientation of the satellites in the sky) also affects positioning accuracy. The best geometric situation for satellite positioning, which is based on several range measurements, is the right angle (90°) between all satellite signals. If the angle is very sharp (or wide), the intersection point is unclear and the accuracy declines. (Toft 1987, Fig. 67) In vehicle receivers a higher cutoff angle is used to get better reliability of continuous positioning. This is done on the cost of somewhat degraded accuracy. (Krakiwsky 1994)

As mentioned above propagation of radio signals can get interference from obstacles and atmospheric effects. Reflections and interference sources of vehicle instruments must also be considered. These lead to possible interruptions in the availability of GPS positioning. This is why satellite positioning systems are often equipped with integrated technologies such as e.g. DR, inertial navigation, map matching, LORAN-C, radar, LEO- (Low Earth Orbit) satellites and RDSS-satellites. The above mentioned technics act as backups, complementary systems or fully integrated parts of GPS positioning (Parm 1992, Alexander 1994, Krakiwsky 1994).

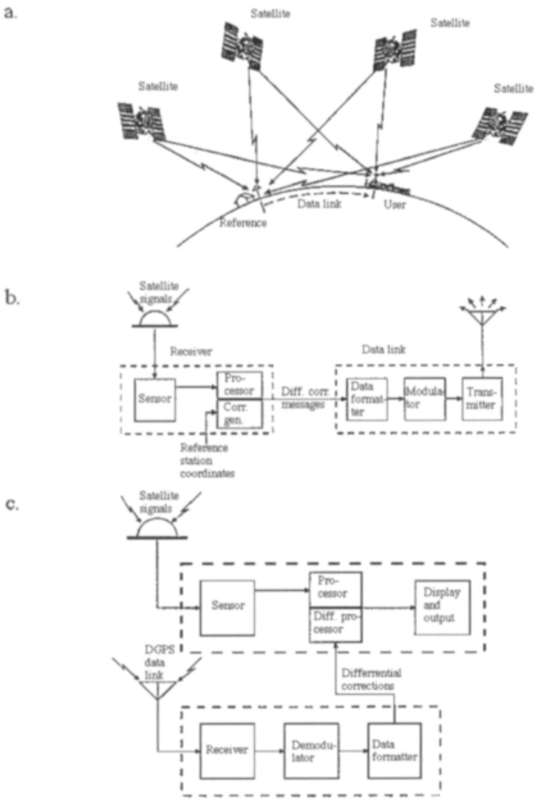

Fig. 68. Differential GPS. (a) Geometry of DGPS, (b) differential reference station block diagram and (c.) DGPS-receiver block diagram (RTCM 1994).

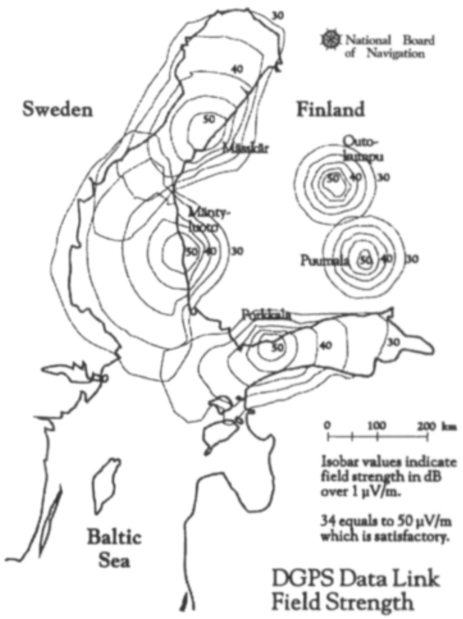

Fig. 69. Simulated data link strength of the Differential GPS network of the Finnish National Board of Navigation (Bäckström 1990).

Various technics are being developed to enhance GPS accuracy in spite of the Selective Availability (SA) and encryption of the P-code (antispoofing, Y-code). In differential GPS (DGPS) there is an additional fixed GPS-receiver, the reference station, the position of which is accurately known. The fixed receiver is not moving so it can continuously calculate corrections to the positioning results. In total the accuracy can be corrected to 2-meter level. (Toft 1987, Koskelo 1990, Bäckström 1992, Parm 1992, Krüger et al. 1994, Mueller 1994) The above mentioned codeless receivers that use the carrier phase and estimate the ambiguities offer an expensive but accurate solution. Advanced kinematic carrier phase technics can give real-time DGPS accuracies of below 10 centimeter. For this, short distance (<20 km) to the reference station is required. (GPS World 1994, Fig. 68)

Differential corrections remove the effect of Selective Availibility (SA) almost entirely but the corrections lose their validity after a period of time as SA changes. Improvements of c. ±100 meters (in average 30 meters 1σ) can be achieved. Ionospheric refractions can introduce errors of 3–6 meters at night and 20–30 meters during the day. An improvement of c. 0–4 meters can be achieved through elimination of ionospheric effects when there is moderate distance (<100–200 km) between the receivers. Tropospheric delays can cause up to 30-meter errors with low satellite angles. They are easily modelled. Variations in the index of refraction between the receivers can, however, cause errors of c. 1–3 meters. Different paths of signals and variability of the ionosphere and troposphere cause so called decorrelation which increases with distance.

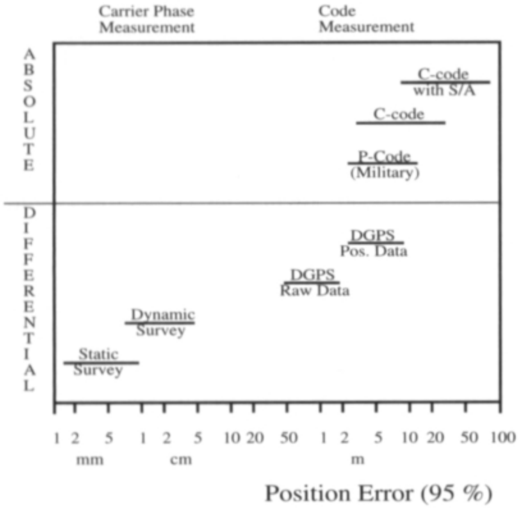

Fig. 70. Accuracies of different GPS (Global Positioning System) methods.DGPS = Differential GPS. (Krüger et al. 1994)

Ephemeris errors (difference between actual position of the satellites and the position reported in navigation message, c. 3 meters, max. 30 meters under SA) are removed. Satellite clock timing errors are removed. (Toft 1987, Bäckström 1990, Koskelo 1990, Tyler 1993, RTCM 1994) DGPS transmission is standardized by the U.S. Coast Guard Radio Technical Comittee for Maritime Services (RTCM-SC104-standard). This standard expresses the recommended data message format and user interface. (RTCM 1994)

There are both post-processed and real-time differential systems. Post-processed DGPS uses post-processing software to calculate corrections to the GPS signals saved. Post-processed DGPS is used in applications where realtime accuracy is not needed, e.g. in collecting data from random locations or locations that are not found with positioning. In real-time DGPS the accuracy is enhanced during the work. Differential corrections can be sent to one or several moving receivers if they are equipped for it. Normally the transmission is done through radio beacons or modems. (Toft 1987, Bäckström 1990, Koskelo 1990, Parm 1992, Tyler 1993, Ekfäldt 1994, Krüger et al. 1994, Mueller 1994)

Basic DGPS is a local system (Ø 100 - 200 km max.) because it is necessary that both the moving receiver and the fixed one use the same satellites. The distance to the base station the affects reliability of the differential correction. The terrain can block the visibility of satellites. Updating frequency of the correction has also a significant effect on the accuracy, so datalink speed is important. Furthermore, the improvement is much dependent on quality of the used differential correction software and hardware. (Bäckström 1990, Koskelo 1990, Ekfäldt 1994, Krüger et al. 1994) Differential corrections can be either locally or more globally available. The latest development in DGPS is the use of Wide Area DGPS (WADGPS-) systems that are based on reference station networks. In future, these networks can offer global differential corrections (Mueller 1994).

In Finland the National Board of Navigation (NBN) has built public differential correction stations mainly in the coast areas (Bäckström 1990, Fig. 70). They send differential corrections according to RTCM-SC104-standard (Langley 1994, RTCM 1994, App. 8). This service can be used for DGPS within some hundreds of kilometers, on land not so far as on sea. To use this service a special RTCM-radio receiver is connected to the moving DGPS-receiver. The RTCM reveiver is quite expencive (c. 10000 - 25000 FIM). Though, this is less expensive than to build a separate differential station (c. 200000 FIM). In Finland the service is still free of charge. The use of public RDS (Radio Data System) radio stations to transmit RTCM differential corrections was initiated in Finland in the summer of 1994. This is more economical than the use of the NBN system because of the relatively low prices of RDS-receivers (1500–3000 FIM in 1995). The situation is changing when annual fees are introduced to the RDS service (e.g. c. 5000 FIM/a for an accuracy of 5 m 95%; the situation in 1995).

Achievable accuracies of different GPS technics are shown in following figure (Fig. 70, Krüger et al. 1994). The absolute and differential modes are separated. The accuracy of differential mode is very much dependent on the devices and software used. Thus the figures must be regarded as approximations.

Differential GLONASS (DGLONASS) is expected to have accuracy comparable to DGPS, or maybe an even better one. As GLONASS developes towards operational stage in 1995, standardization of differential GLONASS technic is initiated. (RTCM 1994) In future, one of the goals in satellite navigation is to develope Global Navigation Satellite System. This networked system will include GPS and other global satellite systems integrated to an all-civil system (Krüger et al. 1994). Many countries do not rely on pure GPS because it is owned by a single nation and run by its military. The development of GNSS is specially hoped for in the European countries (Preiss 1994). On the other hand GPS is turning partly civilian when U.S. DoT (Department of Transportation) is taking partial duty of GPS system management (Parkinson 1993, Wiedemer 1993).

4.5 Positioning methods for Position Dependent Control in agriculture

The agricultural need of positioning methods is potentially high, but in the short term the market volume is neglectful compared with other uses. The agricultural dilemma is that the technics should be very resistant to harsh field conditions and have a low price at the same time. That is why no dedicated agricultural devices can be developed. There are, though, some special requirements in agriculture so, when other sources are used, some R/D should be made. In future special agricultural positioning systems can be available (Mangold 1994). The car industry is the most probable source for agricultural positioning electronics because of its high volume and low prices. It has concentrated on fleet management and route guidance (Karppinen 1990, Krakiwsky 1994). Agricultural and automobile positioning requirements differ at least in speed range and environmental conditions. The accuracy requirement for fleet management is not very high. On the other hand, field operations also lack the fixed road network.

Maritime and aerospace technics are partly applicable to land navigation. (Karppinen 1990, Bäckström 1990, Forssell 1994) Some of the methods used (e.g. Decca and Loran-C) are not accurate enough for some agricultural needs (Gill and Ward 1989, Rhoades et al. 1990), but the basic dead reckoning (DR, measurement of speed and angle) is widely used (Vuopala 1990, Wejfelt 1990, Rintanen 1992). DR is often a vital part of integrated navigation systems (Hakala 1992, Krakiwsky 1994). Inertial navigation can be used in applications where the high cost can be tolerated (Santala 1992). There are some difficulties in optical positioning (e.g. Schmulevich et al. 1987) in field conditions because an uninterrupted line-of-sight is required. Furthermore, the use of prisms and other optical devices needs extra care.

Satellite navigation is the newest general positioning technique. It finds increasing markets in almost all areas of positioning and navigation (Toft 1987, Karppinen 1990, Møller 1990, Juhala 1993, Tyler 1993, Chan and Schorr 1994, Krakiwsky 1994, GPS World 1995). The major drawback of satellite navigation is that the most usable systems (GPS and GLONASS) are built for military uses. This leads to some uncertainty of availability in international crisis situations.

4.5.1 Earlier applications of positioning in agriculture

Various methods have been used in agricultural positioning tasks. Part of these could be used in Position Dependent Control. Autonomous positioning methods (classification of positioning methods: Ch. 4.4 above) have been the first actual positioning methods in agriculture. For quite a long time steering accuracy has been enhanced by using so called tramlines. In agricultural plant production the tramlines act as guiding lines. The

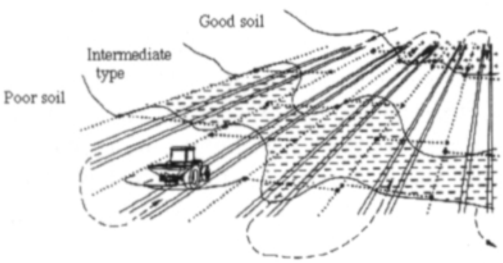

Fig. 71. Tramline positioning (Auernhammer 1990).

tramline system requires implements that are multiples of the tramline spacing in width (e.g. a 4-meter seeder, a 12-meter fertilizer and a 16-meter sprayer). Recently distance measurement has been added to tramline systems to get a simple in-tramline positioning. (Schumacher and Fröhlich 1989, Auernhammer 1990, Wejfeldt 1990, Fig. 71). Positioning can also be independent of the tramlines if we have the previous passage clearly visible and measure the distance along it. This kind of positioning has been used in yield mapping (Stafford and Ambler 1992, Auernhammer et al. 1994) and in a Japanese mini-combine and grass cutter (Yoshida et al. 1988). In row plant production it is also possible to position the machines in this way (Brown et al. 1991).

Dead Reckoning is a widely used autonomous positioning method in agriculture. Distance measurement is quite easy to implement with pulse or radar sensors (Hakala 1992). Heading measurement is most usually accomplished with an elctronic compass. Inertial navigation is also tested but it is too expensive for most uses (Bernhardt and Damm 1992). Applications include fertilizing (Schumacher and Fröhlich 1989, Auernhammer 1990), spraying (Landers 1992) and yield mapping (Auernhammer and Muhr 1992). DR is used both as the only positioning method or in combination with other methods. Often DR is used as a backup method for other methods (Krakiwsky 1994) or as an integrated part of a hybrid positioning system (Patterson et al. 1985, Schumacher and Fröhlich 1989, Auernhammer 1990, Bernhardt and Damm 1992).

Ultrasonic and other types of proximity sensors have been tested in off road situations (Schumacher and Fröhlich 1989, Mäkelä et al. 1991). These systems are suited for fixed routes where the route can be marked and followed. Machine vision applications are being developed for some areas (Searcy and Reid 1989, Møller 1990, Brown et al. 1991, Mäkelä et al. 1991, Brown and Wilson 1992). These also require some objects to identify. The above mentioned methods find some applications in row crop production.

Positioning of vehicles that move freely in the field is technically very challenging. This has recently been applied to plant production. These free positioning applications can be divided into local (AGNAV 1988, Palmer 1989, Shmulevich et al. 1989, Searcy et al. 1990, Palmer 1991, Nieminen and Sampo 1993) and global (Auernhammer 1990, Petersen 1991, Roberts 1991, Hough 1992) systems. Local systems require infrastructure, a transmitter-receiver (transceiver) network, and are therefore quite expensive. In global systems only part of the costs are paid by the user. GPS satellite navigation, which is of the latter type, is expected to be a general positioning system for agriculture, too. (Møller 1990, Auernhammer and Muhr 1991, Larsen et al. 1991, 1994, Petersen 1991, Göring 1992, Perry 1992, Bauer and Schefcik 1994)

Non-autonomous transmitter/receiver positioning systems have been developed after the autonomous ones. In research, optical positioning methods have been used (Shmulevich et al. 1989, Mäkelä et al. 1991, Rintanen 1992). There are, though, limitations for optical methods in agriculture because an uninterrupted line-of-sight is needed to get the positioning result. This is difficult to fulfill because transmitters and senders are near the ground level. It is also difficult to install and keep clean the mirrors and prisms.

Radio-based systems are the major research topic in transmitter/receiver (or non-autonomous) positioning in agricultural positioning today. First, maritime radio navigation systems were used. Land use of DECCA has been tested in University of Dublin. The results show that

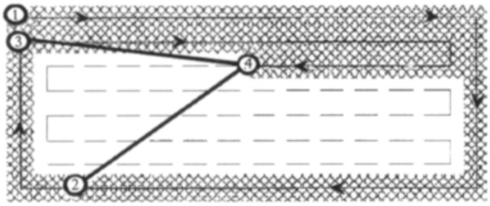

Fig. 72. An example of using a local radio positioning system in agriculture. 1. The driver drives once around the field, In spot 2 she/he sets a portable beacon to the ground and puts it on. An other beacon is set in spot 3. Then the driver drives in parallel to the previous pass. Thereafter the work continues with parallel passes. In the turning the driver presses "next pass" button. The driver has an indicator that shows deviation from the right route (AGNAV 1988)

e.g. trees, electric transmission lines and other obstacles interfere considerably with the positioning. The achieved accuracy (36–107 m) does not fulfill agricultural requirements. (Gill and Ward 1989) The design accuracy of LORAN-C was 0.25 nautical miles (0.46 km, 95 %) and the relative accuracy is typically 20–100 meters (RTCM 1994). Besides maritime use LORAN-C is used in the U.S.A. and Canada in navigation of civilian air traffic. Land use in fleet management is under research. The accuracy is expected to be around a few hundred meters (Chandan et al. 1989, RTCM 1994). Rhoades (1990) reports an accuracy of 50 meters for LORAN-C in survey work. Rhoades et al. (1990) obtained an accuracy of 16 meters (90%) in locating soil salinity samples. These results are achieved in static measurement through filtering. LORAN-C covered c. 90% of Canada in 1990 (Lachapelle 1989). In 1991 LORAN-C coverage was expanded to the mid-continent of the U.S.A. (RTCM 1994).

Local radio and microwave systems have been introduced for agricultural use. The coverage is 750–1500 meters. The accuracy can be in good weather as good as 0.1–0.25 meters. The accuracy is so good that these systems are used as replacement for marker systems. Local topography, specially big height differences, and obstacles cause interference. (AGNAV 1988, Palmer 1989, Hane ref. Møller 1990, Searcy et al. 1990, Fig. 72)

Unmanned fully automatically steered vehicles have been developed for restricted areas such as mines, industry or military. These are applications that can afford the high price of the infrastructure needed and where safety requirements can be met. (Choi et al. 1989, Mäkelä et al. 1991, Petersen 1991, Juhala 1993) Some experimental local applications are also developed for agricultural uses (e.g. AGNAV 1988, Schmulevich et al. 1989, Yoshida et al. 1989, Palmer 1989, Nieminen and Sampo 1993)

4.5.2 Choosing the method for further tests: Why GPS?

Choosing positioning methods for agriculture is a matter of compromize and it is an individual task for every single application. Agricultural requirements for positioning accuracy range from a few centimeters to several meters (e.g. Choi et al. 1989, Auernhammer 1990, Larsson 1990, Ch. 2.4.2, App. 4). The need for accuracy can be viewed from different directions and at several levels. The starting point can be the technic used or the target. If we use the technic we come to the decision that the accuracy could be something dependent on the span of a boom, width of a cutting blade, length of the machine, spacing of nozzles, etc. If the target, the biological process in the field, is more important, then we must design our machines accordingly. Then the positioning accuracy is limited by the process and its sensitivity to errors in the site-specific tasks. (See Ch. 2 above)

The most promising use of navigation is Position Dependent Control. In agriculture this means adaptive in-field control of agricultural machines. DGPS accuracy is in the order needed in agrochemical application (Ch. 2). DGPS is expected to be used in applications that need an accuracy of c. 2–5 meters. (Buschmeier 1990, Møller 1990 Buschmeier 1991, Kloepfer 1991, Petersen 1991, Schnug et al. 1991, Auernhammer et al. 1994a, Stafford 1994) Applications that need sub-meter accuracy, and can afford the cost, may use RTKGPS (Real-Time Kinematic GPS) (Abidin 1994).

Local positioning systems (AGNAV 1988, Palmer 1989, Mäkelä et al. 1991, Rintanen 1992) are not suitable for general use. They are suited for applications that can afford the high price and operation range limitation of the infrastructure needed (Auernhammer et al. 1994b). The high price must be justified with corresponding increase in the output. This means that all or most of the users in the region must join the system installed. This is not necessarily possible because it presumes some homogenity in the production profile. Local positioning systems are to be considered in connection with special applications where product prices are high and PDC is very favorable (e.g. some vegetable production). Sometimes it is not possible to achieve accurate enough positioning with other methods, e.g if the area is badly covered. Then local systems are the only alternatives.

Satellite navigation GPS is an outstanding choice for Position Dependent Control. Its benefits are (Toft 1987, Hirvenoja 1993, Tyler 1993, Auernhammer et al. 1994b, Chan and Chorr 1994, Krakiwsky 1994, GPS World 1994, GPS World 1995):

1. Global availability.
2. Relatively low total costs.
3. Simplicity of use.
4. Growing markets.
5. Intensive use in vehicle navigation systems

GPS is a very user-friendly positioning system. After powering the receiver on it starts to give coordinates. When using GPS all the components of the positioning system, except the possible differential reference station, can be put inside the vehicle. It does not need user calibration because the receiver is digital and calibration during operation is done in the control segment. There is no need for local infrastructure, which would be too costly. This is true especially in countries like Finland where farms are small and heterogenous in production, thus making it difficult to adapt any uniform regional positioning methods. The basic reciever is not expensive. It is small: hand-held receivers are about the size of a cellular phone and a six-channel ´black box´ receiver with an antenna fits into a packet of cigarettes. Today almost all units are designed to work with a computer. (Hirvenoja 1993, Chan and Chorr 1994, GPS World 1995) GPS is also widely recommended for agricultural use. (Auernhammer 1990, Møller 1990, Buschmeier 1991, Kloepfer 1991, Petersen 1991, Schnug et al. 1991) GPS has been used in e.g. yield mapping (Christensen 1991a, Christensen 1991b, Roberts 1991), remote mapping of agricultural land (Perry 1992) and sprayer control (Petersen 1991, Stafford et al. 1994).

The main drawbacks are:

1. Need for backup in some situations.
2. Dependence on military policy.
3. (Affordable) accuracy is not good enough for some purposes.

Backup systems include DR that operates during possible GPS pauses and various signpost systems that give external reference on request (Mäkelä et al. 1991, Hakala 1992, Krakiwsky 1994). In-field navigation is somewhat more difficult than on-road navigation, because of slippage and the fact that no fixed reference structure exists. Slippage is a main problem for distance measuring odometers. Compasses, ground speed radars and inertial navigators are better than wheel sensors in this sense. (Hakala 1992). Image analysis is also a potential system for supporting other positioning systems (Brown et al. 1991, Mäkelä et al. 1991, Juhala 1993). All of the above mentioned systems are more expensive than odometer-based DR (Hakala 1992). The lack of road network makes map matching technic more difficult to utilize. Sensing the previous pass is a kind of modification of map matching. Actually the traditional aids like marker systems can be used to enhance driving accuracy while GPS is giving the position for site-specific implement control. Odometers, electric compasses and/or doppler sensors can be used to backup GPS and measure distance travelled on the pass identified by GPS.

An ordinary GPS-receiver is not suitable for agricultural use because of its inaccuracy. A typical value is around 100–150 meters (RMS). A

DGPS system is quite expensive (>10000 FIM including data links, GPS World 1995) but it is still much cheaper than optical (Rintanen 1992) or local radio beacon (AGNAV 1988) systems. The accuracies of DGPS-sets vary quite much, mostly depending on calculation technics, make and version. The best versions are claimed to be capable of a sub-meter accuracy in real-time kinematic mode. This is still not usable when trying to guide autonomous robot-tractors, but it seems to be a realistic option when talking about spatially selective field operations. (Auernhammer 1990, Buschmeier 1990, 1991, Stafford and Ambler 1991) Real-time kinematic GPS (Tyler 1993, Abidin 1994, GPS World 1994) may be used in autonomous applications. It is, however, very expensive (GPS World 1995).

Palmer (1989) criticizes GPS economy. He urges that integrated systems are required and that they are too expensive. He thinks that inertial navigation should be used as a backup system. The research, however, is very eager at promoting cheap integrated systems that use e.g. DR and DGPS (Chandan et al. 1989, Hakala 1989, Harris and Krakiwsky 1989, Karppinen 1990a, Rintanen 1992, Haapala 1994a, Krakiwsky 1994). Positioning is getting cheaper as the market grows (Koskelo 1990, Chan and Chorr 1994, GPS World 1995).

All in all, it is not possible to get a single solution for accurate and reliable positioning. The solution is unique for the application and consists of various integrated technics. GPS is a potential component in the major part of these solutions that include vehicle navigation (Krakiwsky 1994).

4.6 Positioning tests at Viikki Experimental Farm

On the basis of literature and simulations of targeting accuracy requirements (Ch. 2.4 above), GPS and DGPS were selected for tests (Ch. 4.5 above). Based on literature (Ch. 4.4), DGPS was expected to fulfill the set accuracy requirement of better than ±5 meters (95%).

The aims of these tests were to check the suitability of the GPS-technic used for the needs of agricultural positioning. Positioning data was also used in simulations of the effect of targeting accuracy (Ch. 2 above). Positioning tests were conducted in a test route. The route was positioned with geodetic measurements with an absolute accuracy of better than 5.3 centimeters (1σ, App. 8). The acquired GPS-data was compared with this known route. In addition to the test route the receivers were tested on road and in urban areas, both in quite covered situations. Final test reported here were done in conncetion with practical drilling work. The tractor was driven along an accurately located reference formed by a revolving laser beam.

Two basic types of GPS receivers were tested. Post-processed differential GPS and real-time differential GPS. The first receiver type was an accurate geodetic receiver and the other one a vehicle receiver with a facility for DR-backup module.

The relative inaccuracy of vertical coordinate measurement in GPS compared with its horizontal coordinates was expected not to cause any trouble because Finnish fields are rather plane (Puustinen et al. 1994, comp. Tyler 1993). Actually, it is possible to lock GPSs height measurement to a certain level, in cases where height fluctuations are neglectible, and use 2D-positioning (Toft 1987). If this is not the case, it is even possible to add a more accurate height measurement to the system (Haapala 1990). On the other hand, differential GPS could be accurate enough so that no remedies would be needed.

The sensitivity of GPS signals to obstacles such as trees or buildings was expected to call for a backup system (comp. Lachapelle and Henriksen 1995). Dead Reckoning was selected as a commonly used economical solution (Karppinen 1990, Krakiwsky 1994) for this purpose. Intelligent filtering of the positioning result was expected to be needed in field conditions where driving speed is comparatively low and where multiple turns are made. It was expected that

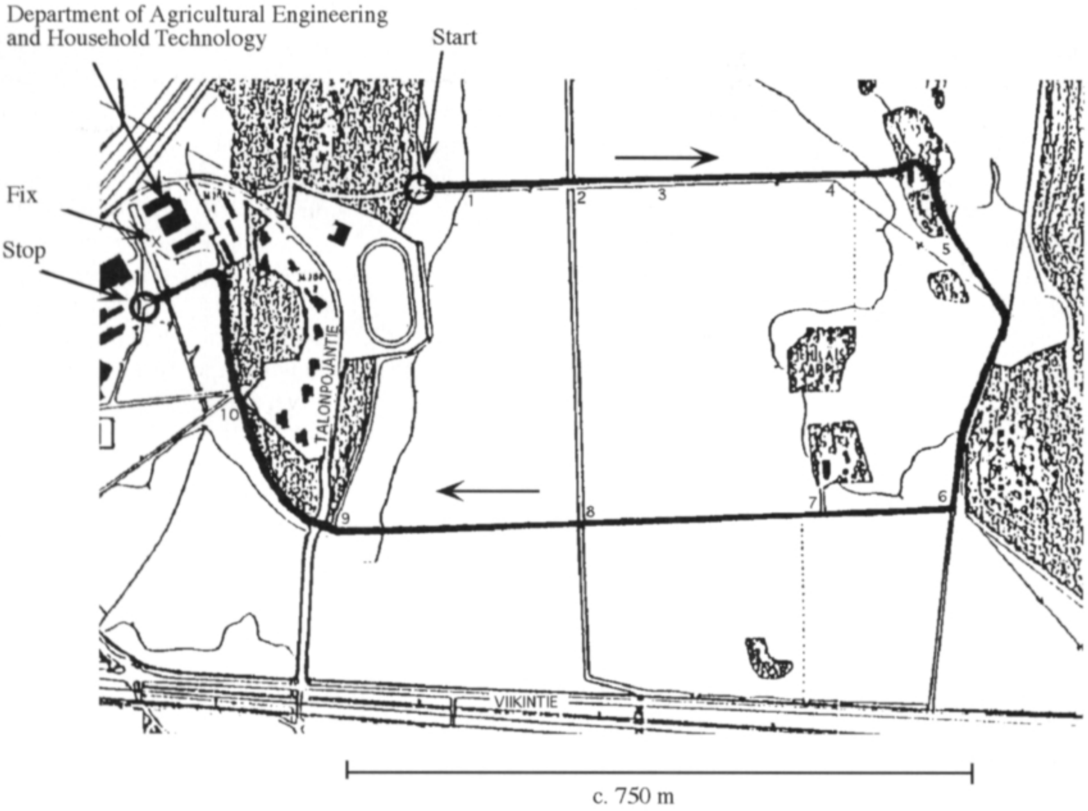

Fig. 73. Test route for DGPS tests at Viikki Experimental Farm. Driving direction is shown with arrows. "Fix" = fixed point at the Dept. of Agric. Engineering and Household Technology. Check points are marked with numbers (1–10).

heading information could be needed. Weighing the positoning results in driving direction would then be a solution for the possible problems for low-speed driving, where in-built filters of the GPS-receivers are not efficient enough.

4.6.1 The test route

The test route was situated at the Viikki Experimental Farm near the Department of Agricultural Engineering and Household Technology. It was selected in such a way that it would consist of open and covered areas. The route was c. 2200 m in total length. There were five datums that were geodetically positioned. The absolute positioning accuracy of these points was better than max. ±33 mm (RMS) (accuracy of starting triangulation points max. ±8 mm and accuracy of geodetic GPS ±25 mm, App. 9). Ten assisting checkpoints were added. Checkpoints were used to input check codes to the positioning file. Check codes were input when the vehicle passed the checkpoint. Their accuracy was c. one meter in distance (due to manual input). The route was later measured with a tachymeter with an accuracy of better than c. ±20 mm (the inaccuracy was mainly due to manual positioning of the rod). The total inaccuracy of the route position was in the worst case max. c. ±53 mm (this equals a 33 mm probable error: Dally et al. 1984). (Fig. 73)

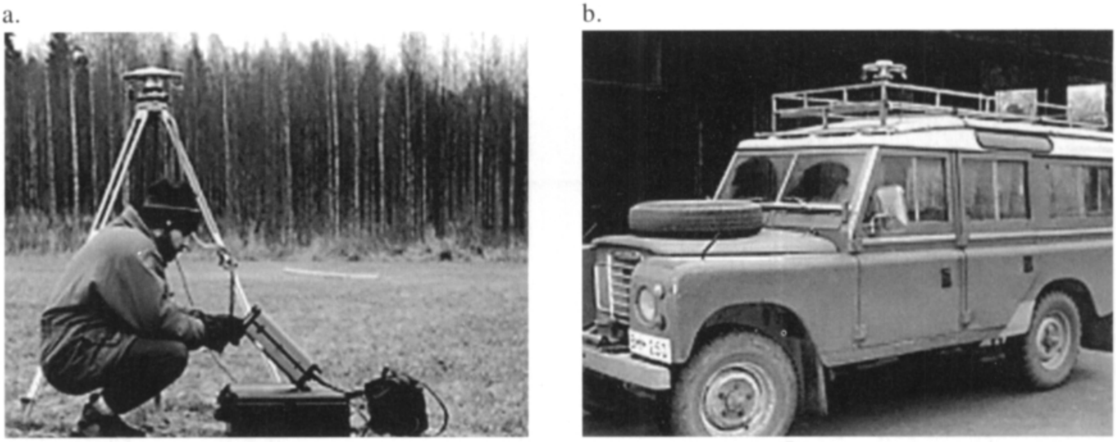

Fig. 74. Tests in 1990 –91. (a) The stationary receiver. (b) The vehicle with an installed receiver. GPS antenna shown on the roof. (Photos: Hannu Haapala).

4.6.2 Tests with post-processed DGPS

A geodetic GPS-receiver (Ashtech XII) was tested in December 1990 and March 1991. Two such receivers were in use, one of which was stationary and the other in the moving vehicle (a Land Rover) . Differential corrections were made with post-processing in the office. (Fig. 74)

During the tests, positioning data were saved in the memories of both receivers and they were later downloaded to a PC via an RS-232C serial interface. Because of the geodetic origin of the receivers the positioning file (c. 1 MB per test) included much useless information which was rejected in further analyses. Coordinates, check codes, time, satellite availability data and GQ-(Geometric Quality) parameters (see App. 12) were kept for further use.

Differential corrections were done with a special post-processing software in office with the positioning results of the stationary and the moving receiver. The resulting coordinates were transformed from WGS84 ellipsoidal coordinates to kkj map coordinates (Lankinen et al. 1992, Fig. 55 above). The transformation was completed with a computer program made in C-programming language by the supplier of the receiver.

4.6.3 Tests with real-time DGPS

In 1993 two real-time DGPS-receivers (Trimble® Placer GPS/DR, Fig. 75, and Trimble® SVeeSix) were tested. Both receivers are based on the same receiver technics and are suitable for vehicular applications. They are designed for the use of differential corrections. The Placer GPS/DR can also use Dead Reckoning . Differential corrections are made in (near) real time (max. timelag of c. 2 seconds). In the tests the corrections were received with a special radio receiver (Trimble NavBeacon XL) from a correction station of the Finnish National Board of Navigation in Porkkala (Fig. 69 above) or from a local reference. The transmission protocol of the corrections was RTCM 104 v. 2.0 (Langley 1994, RTCM 1994).

A dead reckoning module, including an electronic compass, was attached to the receiver. The DR-module also used pulses (130 1/m) given by the doppler radar of the tractor for distance measurement. An odometer (a distance wheel) was used as a separate distance reference measurement. The measurements were synchronized in time. An agricultural tractor (Valmet® 805-4, Figs 76–78) or an off-road car (Toyota Landcruiser) was used as installation platform.

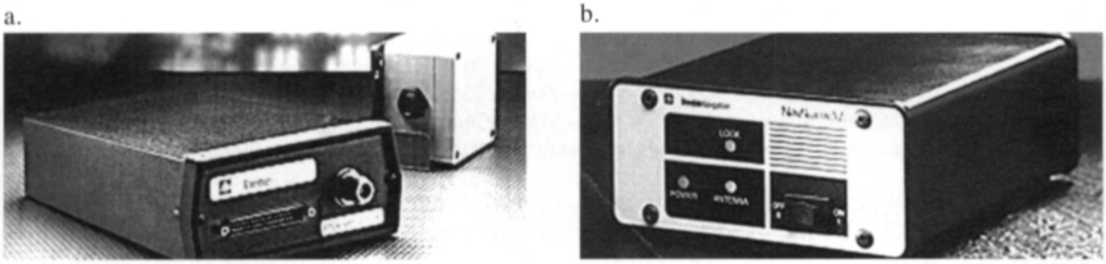

Fig. 75. (a) The DGPS/DR (Differential GPS satellite navigation with DR backup) receiver (front view, size c. 150x50x250 mm) and the DR module and (b) the RTCM-radio beacon (c. 150x75x250 mm). (Courtesy: Trimble Navigation Inc)

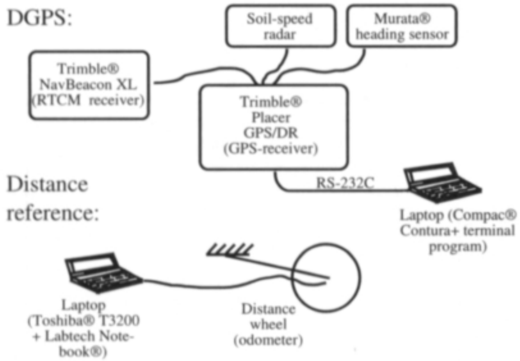

Fig. 76. Components of 1993 DGPS/DR (Differential GPS satellite navigation with DR backup) tests.

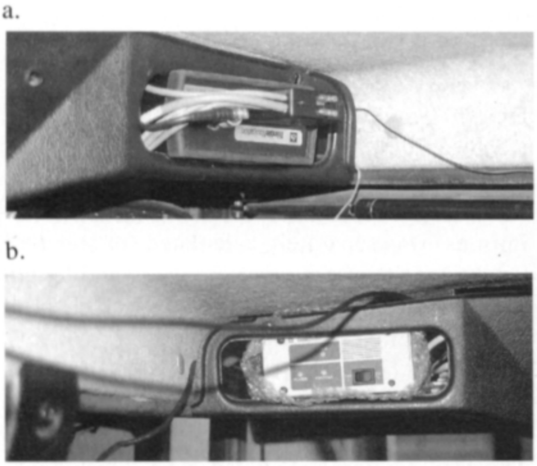

Fig. 77. The DGPS/DR installed in an agricultural tractor in 1993. (a) the GPS/DR module and (b) the RTCM receiver installed in tractor cabine. (Photos: Markku Hirvenoja).

Fig. 78 The tractor with distance wheel. (Photo: Markku Hirvenoja).

```
>RLN37347016+602274232+0250406677-000011550000+000013370404BD25EC151F14BB000260000032;*3D<
>RLN37349625+602274248+0250406701-000012380000+000013370404BD25EC151F14BB000260000032;*30<
>RLN37352813+602274258+0250406771-000014200000+000013370404BD25EC151F14BB000260000032;*38<
>RLN37355938+602274267+0250406819-000015140000+000013370404BD25EC151F14BB000260000032;*3C<
>RLN37359125+602274288+0250406864-000014910000+000013370404BD25EC151F14BB000260000032;*33<
>RLN37361828+602274333+0250406942-000016850000+000013370404BD25EC151F14BB000260000032;*3F<
```

Fig. 79. A sample of the positioning data in 1993. The format in view is TAIP (Trimble ASCII Interface Protocol. Optionally TSIP (Trimble Standard Interface Protocol, binary) or NMEA 0183 (National Marine Electronics Association, ASCII) can be used. (RTCM 1992)

Differential corrections were calculated in the receiver in real time. The data were collected into a portable PC that was connected to the DGPS/DR receiver via an RS-232C port. Optionally, the PC´s RS-232C port was used to control the receiver. DR operated automatically: if the receiver did not get GPS positions at a certain time, it started to use the piezo chrystal and the radar signals for backup. The positioning data (e.g. Fig. 79) included information on the type of positioning currently used.

4.6.4 Positioning accuracy in the test route

In vehicle positioning and navigation, repeated measurements are usually not possible because of the movement. The measurement error can not be reduced through pure averaging. That is why various dynamic filters are developed. The simplest ones are based on floating weighed average and the advanced ones employ statistical modelling (e.g. the Kalman filter) (Bäckström 1990).

In 1990–91 the receiver used doppler filtering with an assumption of forward movement. This caused the filter to lose its direction when the vehicle was stopped. The positioning result started to wander around the actual location. The East-West component was just about a fourth of the North-South component. This may be due to the momentary satellite constellation. (Fig. 80)

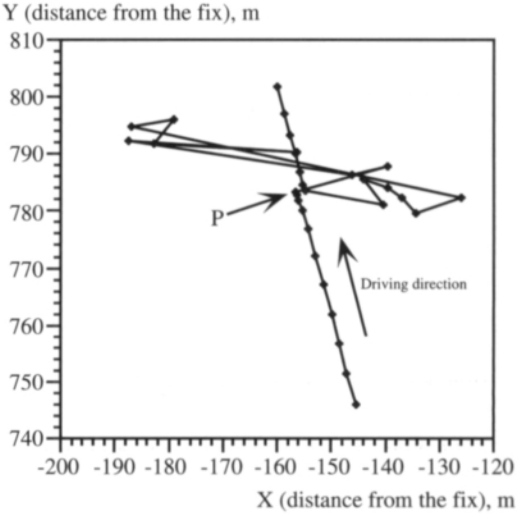

Fig. 80. The positioning result when the vehicle was stopped for a moment (c. 12 seconds) in location P.

When the vehicle was moving there were no problems with the filtering. Even quick turns were adequately positioned. In 1993 Trimble DGPS/DR used a Kalman filter (a statistically weighed filter, Toft 1987). It did not react to stopping the vehicle but caused slight stretching in turns. (Fig. 81) The accuracy (see App. 9 for definitions) was separately calculated for standard deviations (s) of the errors in cross and length direction. The standard deviations measured were multiplied by 1.96 to get error axes in 95% confidence level. (Dally et al. 1984, Toft 1987, Lankinen et al. 1992, App. 9) An uncertainty-ellipse was calculated with these axes. (Fig. 82). The accuracy was calculated for a selected distance (from checkpoint 6 to 9 in Fig. 74 above) in the southern part of the route. 122–285 points were included in each calculation because of different driving speeds. This does not affect the

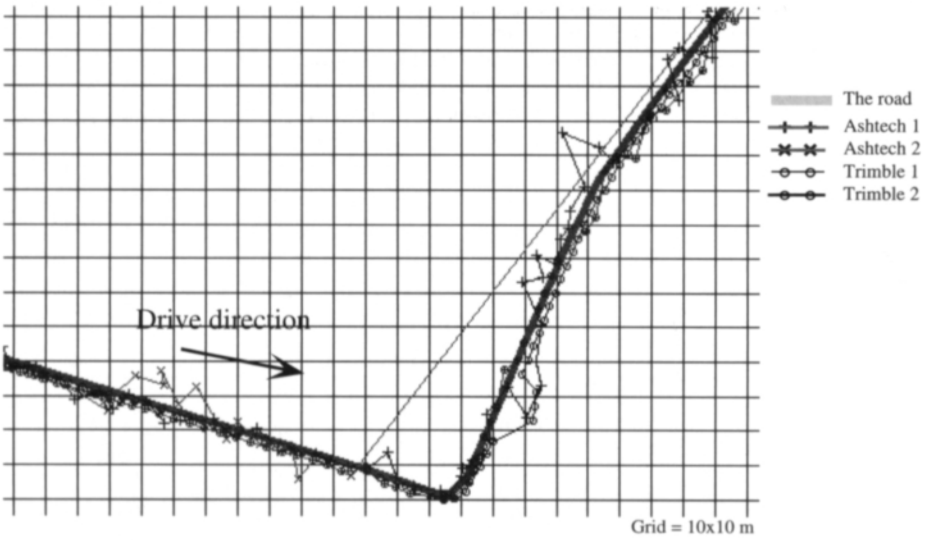

Fig. 81. Positioning in a tight turn with the doppler filter of Ashtech XII receiver (post-processed DGPS) and with the Kalman filter of Trimble Placer DGPS/DR receiver (real-time DGPS). Two separate runs with both receivers are shown.

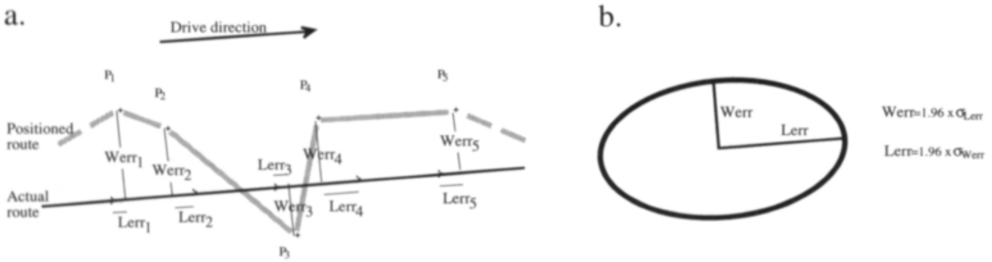

Fig. 82. Calculation of positioning accuracy. (a) Differences of actual positions and positioning results were calculated, (b) standard deviations of errors (σ_{Werr} and σ_{Lerr}) were multiplied by 1.96 to get radius of uncertainty (95% confidence level).

results because GPS positioning results are practically independent of each other, i.e. each point was separately positioned (Fig. 83). Covariance of the errors in direction of the cross and length coordinate axes (Lankinen et al. 1992) was insignificant.

In 1990–91 there was no reference measurement of the distance travelled. In calculations the positions were projected to the road line. As the forward speed was kept constant and positioning frequency was constant, it was assumed that the actual distances between the points were constant. The measured distance data was centered to the test distance. Deviations were calculated as above (see Fig. 82 above). Because of the slow driving speeds, frequent measurement and variation in GPS result, some 4–20% of the calculated distances were negative. In 1993 a distance wheel (2000 pulses per revolution) was used to check for forward speed. The speed measurement was used to select lengths of data for comparison. Differential corrections were calculated in (near) real time at one second intervals. The DPGS results show that there

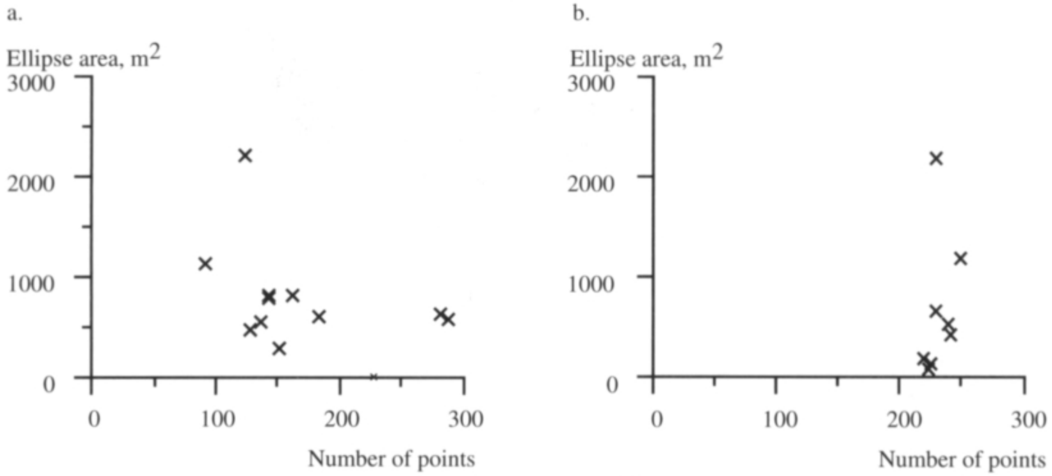

Fig. 83. Effect of number of the points used in calculation on the area of uncertainty-ellipse for (a) tests with post-processed DGPS and (b) tests with real-time DGPS. DGPS = Differential Global Positioning System.

were some points with exactly same coordinates. They were probably due to an overload of the receiver in differential calculations; the amount of these errors was smaller with the differential disabled. The results were calculated with and without these double points.

A summary of selected positioning results is shown in the following table (Table 11). It includes values from the same checkpoint interval in the test route. The table includes results for differential GPS with post-processed (1990–1991) and real-time differential corrections. For comparison, one test with no differential corrections (93 0801:3) is shown. (Table 11) Additional data from the tests appear in Appendix 11.

The results indicate a considerable difference in the accuracies of the receivers. The vehicle receivers were able to achieve as accurate results without differential corrections as the geodetic receiver with them. However, the difference is much due to the differences in geometric quality between test years. In 1990–91 PDOP- (Position Dilution of Precision) values (App. 12: geometric quality indicators) were adequate only a few hours a day because of the incomplete satellite constellation. In 1993 the constellation was ready with good geometric quality (all PDOPs were below 2.25). (Fig. 84)

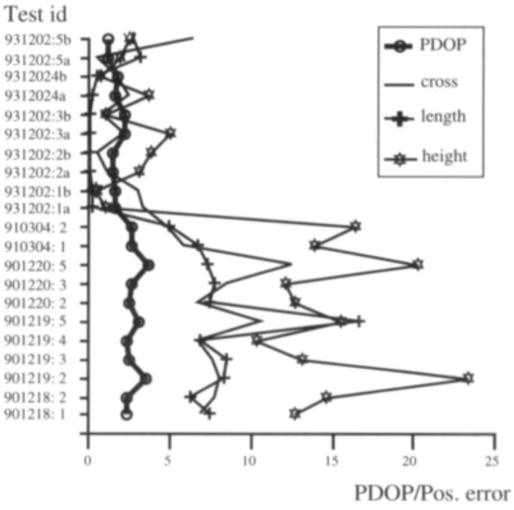

Fig. 84. PDOP values and corresponding uncertainty in positioning in positioning tests in Viikki in 1990..-91. The tests are numbered in chronological order (see table 11).

The comparison of different sources of differential correction gives no significant difference. The level of accuracy with both systems is very good, except for the link failure in last test run. (Table 11)

Table11. Accuracies (95%) for positioning tests in test route at Viikki Experimental Farm in 1990, 1991 and 1993. Results for the south part of the test route (reference points 6–9, Fig. 74 above). Test id is in format [YYMMDD:N] where Y=year, M=month, D=day and N=test number in that day. [a]=test with NBN´s differential correction, [b]=test with differential correction from a local reference station, **=results without dual points. GPS = Global Positioning System. PDOP = Position Dilution of Precision.

1990–91: Ashtech® XII geodetic GPS-receiver with post-processed differential corrections.

test id	cross	length	height	ellipse, m^2	n	PDOP	comment
901218: 1	6.87	7.49	12.68	646.62	279	2.36	
901218: 2	7.78	6.26	14.69	612.02	285	2.30	
901219: 2	8.06	8.40	23.35	850.79	141	3.50	
901219: 3	7.59	8.50	13.21	810.72	140	2.40	
901219: 4	6.75	6.96	10.38	590.37	135	2.30	
901219: 5	10.66	16.70	15.50	2237.09	122	3.10	
901220: 2	6.74	7.47	12.68	632.69	182	2.50	
901220: 3	8.52	7.80	12.07	835.11	159	2.60	
901220: 5	12.52	7.30	20.20	1148.52	90	3.70	
910304: 1	5.83	6.77	13.84	495.98	125	2.58	time resolution better
910304: 2	4.88	5.01	16.34	307.23	149	2.55	time resolution better

1993: Trimble® Placer GPS/DR vehicle navigation module, real-time differential corrections with Trimble® NavBeacon XL and DR (Murata® piezo compass + doppler radar).

test id	cross	length	length**	ellipse, m^2	ellipse, m^2**	n	comment
930730:1	0.60	4.03	3.23	30.39	24.35	194	
930730:2	1.79	3.26	1.10	73.33	24.74	190	
930730:3	1.59	2.97	0.28	59.34	5.59	186	
930730:4	1.18	4.12	1.13	61.09	16.76	198	
930730:5	1.04	4.51	0.40	58.94	5.23	188	
930801:1	3.92	6.64	0.65	327.09	32.02	118	
930801:2	0.89	3.77	0.92	42.16	10.29	301	
930801:3	50.09	4.01	3.33	2524.09	2096.07	169	without differential

1993: Trimble® SVeeSix vehicle navigation module with real-time differential corrections received with Trimble® NavBeacon XL from NBN´s reference station in Porkkala (fig. above) or with Satelline® 2-ASx radio modem from a local Trimble® reference station .

test id	cross	length	height	ellipse, m^2	n	PDOP	comment
931202:1[a]	3.38	0.18	0.93	7.65	228	1.54	
931202:1[b]	3.03	0.18	0.46	6.85	228	1.54	
931202:2[a]	1.06	0.16	3.00	2.13	218	1.36	
931202:2[b]	0.50	0.16	3.73	1.01	221	1.38	
931202:3[a]	2.21	0.16	5.03	4.44	239	2.14	
931202:3[b]	0.78	0.16	0.95	1.57	223	2.14	
931202:4[a]	2.47	0.18	3.62	5.59	237	1.54	
931202;4[b]	1.74	0.55	0.62	12.03	248	1.72	
931202;5[a]	0.55	3.21	1.90	22.19	228	1.20	
931202;5[b]	6.42	2.71	2.52	218.63	273	1.20	radio link failure

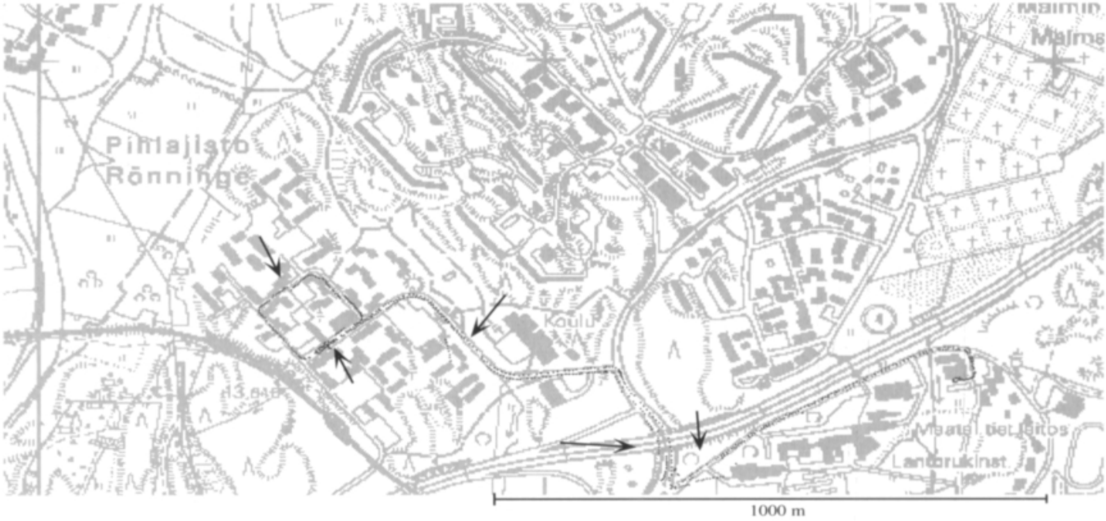

Fig. 85. Road test with a real-time DGPS-receiver in 1993. Arrows indicate positions where the system used Dead Reckoning instead of DGPS. The route is drawn on a numeric map of the area supplied by National Survey. DGPS = Differential Global Positioning System.

4.6.5 Positioning accuracy in road tests

In addition to the tests in the test route, some road tests were made in order to get more information on the reliability of DGPS in covered circumstances. The geodetic receiver was tested in 1991 on a ten-kilometer road test along the Helsinki bypass road “Ring-I”. In Ring-I there are several sight obstacles, mainly road bridges and noise walls. Because of the covered situation, differential positioning was not possible except in a few points. This was due to the incomplete satellite constellation; a calculation of differential corrections needs the same satellites to be used for positioning of both the fixed and the moving receiver. Also the receiver had slow recovering time when satellite contact was lost beneath the bridges. In 1993, with the real-time DGPS, the same test and some extra driving in even more covered situations were made. The results show remarkable progress: obstacles (road bridges, high houses) make only short pauses to GPS measurements. (Fig. 85)

In 1993, dead reckoning was used as a backup. In case of loss of sight to the satellites the Dead Reckoning was activated. The first version of the tested DR-software was not operating correctly but caused sudden jumps in the positioning result (positions with arrows in Fig. 85) Later on the software was updated and the error was corrected.

4.6.6 Positioning accuracy in field work

In 1994 the DGPS tests continued in connection with actual field works. A six-channel Trimble SVeeSix® DGPS receiver module was installed in the tractor and the differential corrections were received in RTCM from a nearby (<200 m distance) reference station. The transmission was done with a radiomodem (9600 bps). The drive routes required were planned in office and marked with the help of a digital tachymeter in the field. A laser transmitter with revolving laser beam was placed at the end of every second of the drive passes. The tractor driver drove along the laser plane with the help of directing arrows. (Fig. 86)

The location of the laser beam was estimated to be accurate within c. ±20 mm. This esti-

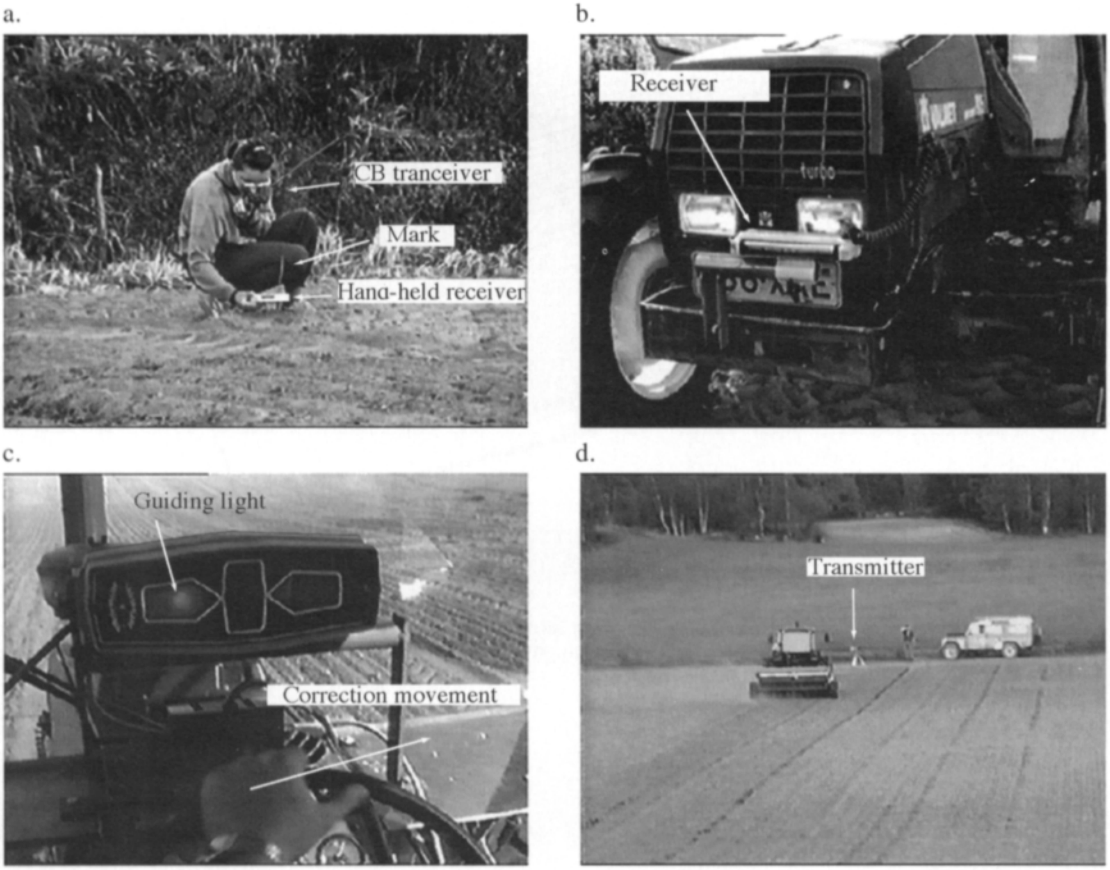

Fig. 87. Driving the tractor along a laser beam in 1994. (a) Aligning the transmitter to the marked position, (b) the receiver in tractor front, (c) the display in tractor cabine, and (d) drilling along the beam. Figures grabbed from video tape: Hannu Haapala.

mate consists of the numerical error of calculations and the human error in positioning the tachymeter (c. ±10 mm in total) and placement of the laser transmitter (c. ±10 mm). The driving accuracy of the driver was c. ±80 mm. The estimations yield a worst case error budget of c. 100 mm for the tractor, which also was detectable in the resulting grain stand. In addition to this, as the receiver antenna was mounted on the roof of the tractor, there are high frequency error sources due to the oscillations of the tractor. These are, however, compensated for by the filter in the receiver. All in all, the error sources are neglectful (<5%) when compared to the actual positioning errros of the receiver. Thus the reference was accurate enough for the test, and can be assumed to be a straight line in the field.

The results (Fig. 88) show good positioning accuracy. The positioning results of the parallell passes did not cross each other in the field. In practise this ensures that the error was below 2 meters during the test. This is better than the specifications for the receiver (<10 m, Trimble Navigation 1992) promise. Also the dynamics of the receiver was good because the changes in direction at the corners are clearly shown. (Fig. 88)

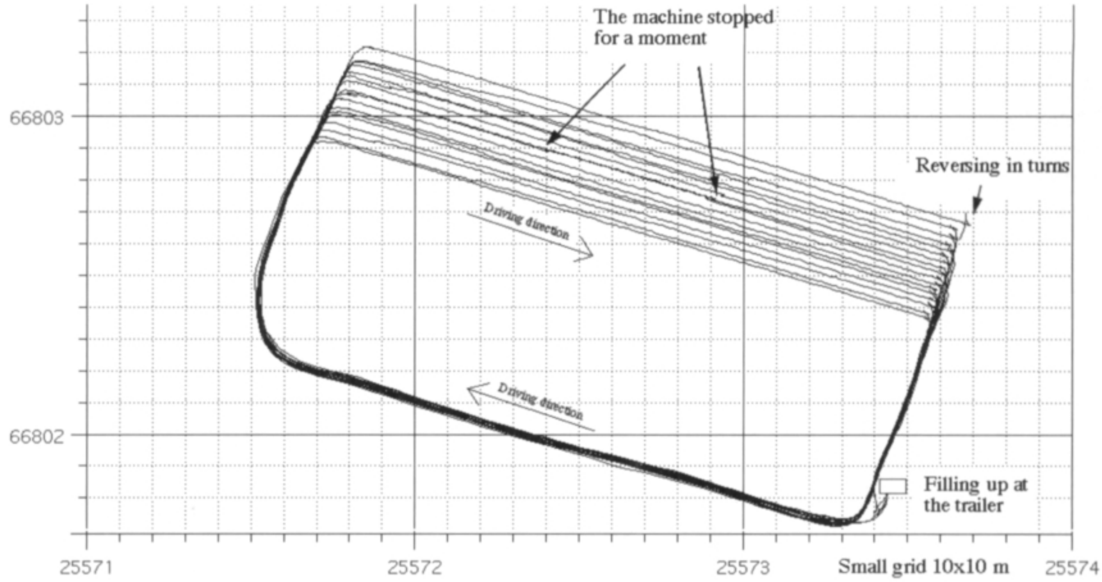

Fig. 88. Positioning accuracy of real-time DGPS module in laser-guided combined drilling in Viikki in 1994. The tractor is driven along a sight line formed by an accurately (<±20 mm, 95%) positioned laser level. The parallell drive passes are 2 meters apart. (Hirvenoja 1995)

4.6.7 Discussion of the positioning tests

The results are for some GPS-receiver makes and models but they are typical choices in the GPS positioning market of the test time. The Ashtech M XII® that was introduced in 1989 is still on the market. Trimble Placer® that was used in 1993 at the test route and Trimble SVeeSix® used in 1994 field tests are currently also being sold (GPS World 1995). Thus the receivers used can be used as indicators of the top level of development in their test time. They can be used to rank the GPS technics (GPS without corrections, differential GPS with post-processing and real-time DGPS).

The environment and circumstances during the tests have a considerable effect on the reliability of the results. This was taken into account by setting controllable things constant; the test route was measured accurately and it was constant for all the tests, data from same locations (check points 6 - 9) were selected for comparison and drive speed was constant. However, the satellite constellation was not selected; the tests were made independently of possible poor constellation times. This was done because there should be no such moments in the completed constellation. In 1993 the constellation was ready (GPS World 1992). With the test setup used, a comparison between these situations was possible. If the goal had been a comparison of GPS-receivers of the same types (e.g. real-time DGPS-receivers on the market in 1993) the tests should have been made in similar satellite constellations. This kind of test could only be carried out simultaneously for all the receivers involved.

Road tests were not made in exactly the same situations. The purpose of the road tests was to get a practical picture of the performance of the receivers in covered areas. So the results of road tests must be used just to put the receivers and the GPS technics used in qualitative order. The difference in performance was so significant that the test method is adequate for this classification.

The field test in 1994 was performed on precisely positioned reference lines. This kind of reference is unique because no such system was found in literature. Tramlines have been used as reference by Stafford and Ambler (1994) which is not possible with drilling. The driving accuracy was good (< 80 mm) because of the laser guidance system. The receiver used was tested in 1993 and it was well known. The reference station for differential corrections was in short distance from the receiver. Therefore the results show a practical measure for the achievable positioning accuracy in field conditions.

The progress in positioning accuracy from 1991 to 1993/1994 is due to the satellite constellation that was completed (comp. e.g. Juhala 1993) and improvements made in receiver technology toward dedicated vehicle sensors. In 1990/1991 a local differential reference receiver was used. In 1993 differential correction signals came from a NBN reference station situated in a lighthouse in Porkkala (Fig. 70) that used all the visible satellites above the horizon. The RTCM-receiver used could get the correction signal in quite difficult conditions (even inside a building). This made it easy to have DGPS if the receiver just had contacts to any satellites. There was also a considerable difference in the number of pauses in GPS positioning and recovering time between receiver types; the geodetic receiver had several pauses and recovered slowly, and the vehicle receivers had only few short pauses. This is due to the different satellite search algorithms of the two receiver types. The geodetic one started to search for new satellites rapidly (c. 2 seconds) after losing the contact. The search went through all the satellites and returned to the lost ones only after a complete search. The vehicle receivers waited for a longer time to get a new contact. They also preferred to use satellites with a higher elevation angle. This together with the better suited search algorithm made them much more usable in covered areas (comp. Lachapelle and Henrikssen 1995).

The accuracy results of post-processed DGPS are on a comparable level to other simultaneous researches (Buschmeier 1990, Byman 1990, Byman and Koskelo 1990, Kloepfer 1991, Petersen 1991, Stafford and Ambler 1991, Muhr and Auernhammer 1992, Perry 1992, Juhala 1993, Tyler 1993, GPS World 1994, Ekfält 1994, Krüger et al. 1994, Krakiwsky 1994). The results in 1993 with real-time DGPS/DR are comparatively accurate (Beuche and Hellebrand 1993). Results in covered areas are very accurate (Byman and Koskelo 1990, Spruce et al. 1993). Field test results in 1994 are very accurate for the used economical receiver type (comp. Trimble Navigation 1992). This is also true when compared with other methods for positioning in off-road conditions (Palmer 1989, Shmulevich et al. 1989, Mäkelä et al. 1991).

4.6.8 Conclusions of the positioning tests

The results show that differential GPS is considerably more accurate than GPS. The tested DGPS-receivers designed for vehicle use are accurate enough to adaptive Position Dependent Control of fertilizing and other tasks with comparative need (±5 m, c. 100 m^2) of targeting accuracy. Pure GPS without differential corrections is not capable of the accuracy desired. An economical vehicular DGPS receiver module, when equipped with receiving capabilities for differential corrections, is suited for this use. The positioning methods tested are not, however, suitable for guidance of the implements or unmanned vehicles, or other exact operations such as individual treatment of plants, which may need an accuracy in the order of ±50 - 100 mm. For this, future research with Real Time Kinematic (RTK-) GPS is necessary.

GPS does not need backup systems in open areas. In the vicinity of high obstacles such as forests, hills and houses there are some difficulties. Modern vehicle receivers are equipped with efficient satellite selection algorithms that use satellites that are somewhat higher and thus visible. This makes it possible to have position fixes in quite covered situations, of course at the cost of a little less accuracy due to the degradation of the geometric quality. In covered areas, Dead Reckoning or other backup systems must be used if 100% coverage is needed.

5 Examination of the results and conclusions

The literature reviews, simulations and measurements were made in order to find the potential of Position Dependent Control, the requirements for it and possible technical solutions. Future research requirements were also viewed. (see Introduction) The research done answers quite satisfactory to the research problems.It gives indication on the huge possibilities of PDC in sustainable agriculture. It also shows the important role and increased need of accurate and reliable data in locational control. Finally, it builds a basis for new research activities both in agricultural and general locational control areas.

The research was initiated as a continuation of the author´s earlier research on adaptive control and measurement of the vertical coordinate (Haapala 1988, Haapala 1992). The combination of these methods was thought to improve the accuracy of site-specific processes. The measurement of level coordinates would be required to achieve local control. At the time the research started there were no reported agricultural site-specific control systems. Therefore the system developed is mainly based on the author´s view on the problem area.

The used research methodology is based on systems analysis. The process-oriented approach was selected because the soil is a complex spatially variable process. Systems analysis and simulation are especially suited for this kind of problems (Gustafsson et al. 1983). The process models of soil are variable and they cause significant variation in the production output as well (Bouma and Finke 1993). Thus more accurate production methods are needed.

Adaptive Position Dependent Control, as described in the present study, is the basic control strategy for sustainable agricultural production. The field can be divided in Production Locations that are treated as individual processes. In Position Dependent Control the PLs are modelled in application-specific detail. The selection of correct local production methods and their optimal intensities needs the knowledge of these local models.

Positioning is in a central role in Position Dependent Control. Positioning errors in data collection and control cause inaccurate targeting of production inputs. Thus the errors in positioning cause economical losses and increase environmental stress. In this study, a new approach to the problem of setting the requirements of targeting accuracy was used. The local process models were expressed as transfer functions from the local site-specific task to the production output. The targeting error of the site-specific task was introduced to the model of local production. The caused variation of the production output was examined, and the requirements for targeting accuracy were set as a function of allowed variation in the output.

Only some combinations of models and site-specific actions were used because a complete examination brings no extra value to the research results. The most important result is the thought model and the sequence of setting the requirements. This procedure is different from former research that is mainly starting from the technique used and not the process models in the field. The accuracy requirements derived from local production models are, however, in coarse accordance with earlier calculations and expert judgements. (Holstmark and Nilsson 1989, Larsson 1990, Stafford and Ambler 1991, Muhr and Auernhammer 1992) The starting point being theoretically more accurate and site-specific than the former methods are, it is clear that PL-based production functions are better than former models in describing the production-based requirements. The calculations of local regressions for the yield (Ch. 3.2.1) assure this. Thus the requirements for targeting and positioning accuracy can be calculated more accurately with the developed method than with former ones.

Petersen et al. (1993) used an analogic thought model in assessing data quality for Decision Support Systems (DSSs). The used sequence of setting the requirements in this study is in accordance with their thought model which tells that the requirements for data accuracy must be set (in opposite direction than traditionally done): from the use of the data to resolution and accuracy requirements, and not from the available data to the result achievable. Thus the requirements of targeting accuracy should emegre from the processes involved and not the equipment used. Equipment should be adapted to the process and not the process to the inflexible and outmoded equipment.

Requirements for positioning accuracy can be set with the addition of the transfer function from targeting error to the positioning infromation needed, i.e. the process from positioning information to the actual targeting of the site-specific task should be known. This transfer function includes conversion of the positioning signal to steering operation and the dynamics of the implement. This process may be very complicated, specially if human operation is involved. Exact description of this process was left out of this study because it is highly varying. However, it must be kept in mind when the presented requirements for targeting and measured positioning results are compared. The transfer function from positioning to targeting is an important topic for continued research.

The variation of soil and yield was sampled with a case-study. This information was needed because the level of local variation has not been measured with adequate resolution in Finland before. The case-study method was selected because no full-sized field research is needed: if the variation should be spatially distributed, it should, according to the assumptions of geostatistics, be found independent of the variable values but only depend on the relative orientation of the samples (Clark 1984). Thus a case-study, if wide enough, should reveal the site-specific nature of the variation as well. The case-study was performed in an ordinarily grown wheat stand. This was done in order to have the possibility of generalization. The generalization can be done quite confidently because the literature gives further evidence of the universal nature of variation in soils and yields (e.g. Bouma and Finke 1994, Delcourt and De Baerdemaeker 1994, Ch. 3).

The results of yield and soil parameter variation are unique because such a dense combined and positioned measurement has not been realized in Finland before. The variation measured is of the same level as in researches in other countries and domestic researches concerning either of them. (e.g. Kivinen 1951, Kaila and Ryti 1951, Jokinen 1983, Delcourt et al. 1992, Stafford and Ambler 1992, Stafford et al. 1994) General remarks of the variation results can also be used for other site-specific measurements. They show that different sampling methods have inbuilt filtering of the data and thus capability to find the different areas in the field. Automatic total or point-sampling methods are the best alternatives for collecting site-specific data because of the ease of use and adequate accuracy. There are though restrictions for the use of these methods that require certain sampling strategies to be followed.

The simulation of finding the different areas (Production Locations) in the field (Ch. 3.2) was done to examine if the local production model is more fixed to the coordinate in the field than to individual soil and yield parameters. The spatial nature was quite easily shown: fixed-length Production Locations gave the best local regressions (Ch. 3.2.3). This is because equal yields do not mean equal production models (comp. Delcourt and De Baerdemaeker 1994). Yield data from Keimola were used in simulation to find the areas. This was done because yield measurement is frequently used for this purpose.

The simulation models are valid only for the assumptions made in the calculations. Shapes and scalings of the Effect Curves and the transfer functions are not intended to be constant but to vary with the variable conditions in the machines and the Production Locations. Therefore the modelling should be regarded as a solution for setting the requirements for targeting and positioning accuracy in Position Dependent Control rather than complete system descriptions or explanation models. If the method for setting the requirements of targeting and positioning accuracy is utilized in other applications of Position Dependent Control, different transfer functions and trigger values must be chosen.

The positioning test results of 1990–1991 with post-processed Differential GPS satellite navigation are in accordance with earlier and currently available results. Test results of summer 1993 with real-time DGPS with and without Dead Reckoning backup are very accurate in comparison with the literature. (Buschmeier 1990, Byman and Koskelo 1990, Schnug et al. 1990, Kloepfer 1991, Mäkelä et al. 1991, Petersen 1991, Stafford and Ambler 1991, Muhr and Auernhammer 1992, Perry 1992, Tyler 1993, Krakiwsky 1994).

5.1 Potentialities of Position Dependent Control in field crop production

Production Locations have varying properties it is natural that the inputs must vary, too. If we do not vary our production methods and their effects, we do not get optimum outputs. This implies a diminished efficiency of the inputs in production in comparison with individually optimized inputs. High efficiency of inputs in the production system (measured as e.g. product units per input unit) is an important indicator of system health. Through better adaptability to local needs and potentialities, adaptive Position Dependent Control makes it possible to get simultaneously both a better economy and less environmental stress. This kind of production is based on the ideas of sustainable agriculture. The current methods which do not vary the inputs cannot be optimal and thus have the tendency not to be sustainable.

Position Dependent Control is a control system based on the idea of Production Location. It can be used to give the PLs various amounts of inputs. The system is in accordance with the ideas of sustainability if the input amounts are right compared with the criteria for sustainability. The system itself is not a quarantee of sustainability but merely a tool for its realization in position dependent tasks. Different criteria for sustainability lead to different local optimum inputs. Thus the production strategy is seen only as a collection of production goals for this anticipated position dependent production system. The system can be utilized in various applications; agricultural production in the fields is one of the possible areas.

In-field variation of agricultural lands gives high potential for PDC. Fertility parameters vary both in between areas and within very short distances. This is seen in yield variation. In a normal, apparently even wheat stand the difference of mean yield between parallel sample lines at 20-meter distances was 530 kg/ha. The variation inside the densely (at 0.5 m distances) sampled lines was 15–17 % of the mean value (CV 0.15–0.17). Geostatistical calculations with filtered yield showed that the yield was varying in sinus form with a wavelength of c. 2–2.5 meters. It was concluded that this was probably due to a variation of the seed output of the combined drill.

Simulations with the yield and soil data proved that the information should be attached to areally limited Production Locations. The best results in the selection of the PL sizes were achieved with a simple fixed-length (5 m) algorithm. The results show that the identification of the PLs should be based on the yield and several other measurements. Yield-based algorithms do not give the best results, if small areas are to be identified, because of the varying nature of the PLs. They should be completed with extra soil and yield parameter measurements. Site-specific models that are built in required detail use these measurements to accomplish tools for site-specific decision processes.

The economical impact of the PDC depends on the initial conditions of the target area and the possibilities of manipulating it. If the target does not vary or the variation is not controllable, there is little to be done with PDC. The PDC also requires easily and accurately controlled machinery. The total cost of the machines and the control system should be paid back in the form of increased efficiency and reduced losses. Economical sustainability changes with the time perspective. The short-term effects give weight to the local economy wheras the long-term ones to broader, even global, views. Environmental effects should be evaluated and given a price to enable setting accurate site-specific optimums for the control system.

5.2 Requirements for the methods for attaching field crop information to a coordinate system

The requirements for the Position Dependent Control system are mainly based on the required accuracy of the control. The accuraqcy of control depends mostly on the resolution chosen, i.e. the Production Location size. The PL size, again, requires a certain level of accuracy of the positioning methods and information management systems used. The maximum change in control values, and the PL size and driving speed used give reaction speed requirements for the controllers in the realization of the PDC.

The central role of Production Location size sets a need for setting the basic resolution for each area that is to be controlled with Position Dependent Control. The basic resolution must be set according to the requirements of both the production and the machinery. The model developed for setting requirements for cross targeting accuracy can be used to set this limit for the production. There are, though, other factors not included to the model that have an effect on the basic resolution, e.g. driving geometry of the machines and physical limits of controllability of some machine types. New machines can be developed but there will always be limits for mechanical operation and flexibility. Automatic robots need more accurate resolution than the control of the output of the implements. There are eventually two main categories for the need of targeting and positioning accuracy: the production-based optimums and the technically set achievable limits. In Position Dependent Control there is the aim to bring these limits somewhat closer to each other.

5.2.1 Requirements based on yield and soil parameter variation

The sampling methods in Position Dependent Control should make it possible to find different areas in the field. This is true both for the yield and other measurements such as the nutrient content, soil type, pest infections, etc. The sampling method should have a suitable resolution for each individual case. The simulations with yield measurement results show that sampling methods have built-in differences in resolution, and thus capability to find the areas. This is due to the introduction of filtering (integration and averaging) the data. Automatic sampling methods integrate the yield and the most manual sampling methods average it. The accuracy of sample value determination is selected according to the parameter´s use in the production system or system model. The sampling method should be fitted for each kind of variation. This procedure of method choosing and calibration should begin with the knowledge of the resolution wanted. The resolution and operating speed bring requirements in frequency domain and limits for sensitivity and bandwidth of the sampling in both time and distance domain. Finally, suitable averaging and integration are selected.

Yield-based Production-Location-finding algorithms should include edge detection and averaging. Pure edge detection does not count for slow changes in the measurement values. A better algorithm includes comparing the current measurement value with an average of preceeding measurements. Area finding algorithms should be calibrated for each kind of variation individually. The calibration procedure needs information of the true variation and the resolution needed. In this study, the selection of the PLs on the basis of yield variation did not give as good results as simple distance-based selection. However, the distance-based selection had some very high r^2's but still some zero values. It was concluded that the production models are local but these spots had some extra inputs not measured that dominate the PLs´ processes.

In practical Position Dependent Control the Production Locations may be selected on the basis of automatically measured yield. This method does not, however, give the best results because it is not position-fixed: equal yield levels do not stand for equal PLs. This is why the simple distance-based selection gave the best results in the calculations. A conclusion of the results is that a fixed network of PLs with a resolution of c. 5 x 5 meters is required, and measurements of the input and output variables of these PLs is to be arranged. The input variables should be measured with a method that gives values for this 5-meter resolution, either directly or through interpolation. The geostatistical interpolation methods, e.g. kriging, may be used.

5.2.2 Simulated requirements

Depending on the goals of Position Dependent Control there can be different requirements for targeting and positioning accuracy. On the other hand, the implement and the model of the target PL affect the accuracy required. The machines can realize the desired changes in treatments with different accuracies and the plants react differently in different coordinates.

The simulation models developed used the Effect Curve of the implement to give standardized format for the representation of the characteristics of uniformity of operation. The same kind of standardized representation was utilized in modeling the transfer function from implements´ EC to the output of the target Production Location. The transfer function of the target PL is important because otherwise the set requirement of targeting accuracy is not realistic. Coefficients of variation were used as criteria for the success of targeting.

The idea of simulating the requirements in modified scales dates back to the necessity of generalization. Machines with comparable modified characteristics can be simulated with just one model type, and the same analogy is valid for the PL-types. Actually, a dictionary of EC- and PL-model types could be made to simplify the setting of targeting accuracy. Only a CV-limit should be given for the output of the modeled system with known EC and PL types to get the requirement for positioning accuracy. Setting the individual CV-limits for each case requires continued research.

Cross targeting accuracy can be simulated with a model that includes an Effect Curve of the implement and a model for the target Production Location. Coefficients of variation can then be used as a criteria for the success of targeting. The results show that increasing working width reduces the requirement for targeting accuracy. If the model of the PL includes smoothing, it raises the allowed targeting error especially with sharp edged ECs. A model that includes both a logistic transfer function and smoothing shows the highest tolerance. The last one is the model type for plant production, including the smoothing effect of plant roots and the logistic growth function. The results give allowable targeting errors for a set CV level, e.g. a CV limit of 0.3 gives for a ten-meter EC with an edge angle of 45° an error of maximum 2.44 meters (App. 4).

The requirement for length targeting accuracy was simulated with an example model for nitrogen application. The thought model of setting the requirement can be utilized in other applications. An accuracy requirement of c. ±5 meters was achieved.

5.3 Possible solutions

As a conclusion, in agricultural PDC, the setpoints are given locally according to the local growth potential, the previously set goals and the restricting factors such as the environmental impact and the economy. The setpoints are finetuned so that they can be realized with the actual technology in use. The result is a formation of areas, the Production Locations, that are treated separately and with unique setpoints. A map screeen acts as graphical user interface to the GIS that holds the local information. The treatment zones that may consist of several PLs are marked on the map with corresponding colour and/or fill and are converted to local setpoints. The overall system could be as follows:

> The computer uses the data stored in a GIS file to calculate optimum values for the local inputs, e.g. fertilizing. The nutrients needed are shown on the map screen. This can be accepted if the user has the technology (fertilizers, implements) to realize them. Optionally larger areas of constant input are treated. These are formed with clicking the PLs or zones to be joined with the mouse. Deviations from the optimum are shown both in terms of expected yield and leaching. The user iterates until satisfactory results are gained. These setpoints are saved in transfer format. If positioning is accurate enough it is possible to plan wanted routes on the screen. The route is drawn on the map and saved in an other transfer file.
>
> The setpoints are realized according to the calculated setpoints that are transfered to the tractor computer with a memory card. A map screen is used to show the driver the actual position of the tractor and the selected local information, and possibly the route guidance information. The driver can follow the automatic control and check for its proper operation. Various local information can be selected on the screen: e.g. last years´ yield information helps her/him to make notes on specially high or low yielding spots. These notes can be input to a log file that can be downloaded in the office for planning feedback.

Electronic ground referenced maps are the only types to meet the requirements of Position Dependent Control. Hybrid maps with the possibility of using both raster and vector data are needed. Mapping is done with a positioning system, e.g. with GPS-equipment, and coordinates are fed to a GIS-database. Updating of the field map can also be done with high resolution aerial photography or video recording.

The site-specific setpoints of PDC are realized when the implement is at the production location. Calculation of setpoints is not fully automatic but it is also affected by the knowledge and values of the user. There are also setpoints that are calculated in real time. Direct measurements belong to Position Dependent Control as an integrated part. As they develope they can be selected instead of off-line measurements. This change in measurement technic does not, however, diminish the need for a GIS because production processes are site-specific.

To realize PDC *a basic survey* that finds out the variation type is necessary. The survey should be done with a resolution that is at least twice as high as all predictable future applications of the data (the universal sampling theorem, Haugen 1990). The second phase is to determine the trigger value of variation: how high deviations are of importance. These critical values have to be defined in terms of accepted range, frequency and local concentration of the variation. The size of the target is derived from the critical values and actual variation. This also leads the selection of variation measurement technics. In other words, the maximum size that could be managed with constant treatment has to be defined.

It is not possible to get a single method solution for accurate and reliable positioning. The solution is unique for the application and consists of various integrated technics. The GPS/DGPS satellite navigation is a potential component in the major part of these solutions that include vehicle navigation. The GPS can be used for all the position dependent operations including data sampling and guidance to previously sampled positions. The fully automatic robots and route guidance are also possible applications but very expensive for the time being.

For the sake of simplicity and to avoid transformation errors, it is good to adopt one coordinate system in which the whole system (planning, realizing, measurement of output) works. The WGS84 which defines the coordinate system of GPS is a good choice to work with because, in future, most carthography will be based on it. The easiest way to get the coordinates for the Production Locations is to round the WGSs´ ellipsoidal coordinates (latitude and longitude) down to the wanted resolution. A resolution of 1/1000´ is adequate for most PDC-applications with a targeting accuracy requirement of ±5 meters.

Differential GPS is considerably more accurate than GPS. The tested DGPS receiver designed for vehicle use is accurate enough for the PDC of fertilizing and other tasks with comparative need (±5 m, c. 100 m^2) of targeting accuracy. The pure GPS without differential corrections is not capable of the accuracy desired. The positioning methods tested are not, however, suitable for guidance of the implements or automatic unmanned vehicles which may need an accuracy in the order of ±50–100 mm. For this, future research with Real-Time Kinematic GPS with On-The-Fly ambiguity resolution is necessary.

The GPS does not need backup systems in open areas. In the vicinity of high obstacles such as forest, hills and houses there are some difficulties. Modern receivers are equipped with efficient satellite selection algorithms and they use satellites that are somewhat higher and thus visible. This makes it possible to have position fixes in quite covered situations, at the cost of a little less accuracy due to a degradation of the geometric quality. In covered areas, Dead Reckoning or other backup systems must be used if 100% coverage is needed.

5.4 Future developments

Simulation models could be used for evaluation of the suitability of different technics for the Position Dependent Control. Test procedures of implements and machines could be changed so that the test results would produce the Effect Curves of the implements/machines. These ECs would be imported to a *simulation model of a test field*. The test field would consist of variable Production Locations with transfer functions from the EC of the implement to production outputs. The outputs would be e.g. the economical result and the environmental impact. The test results would then contain a much more practical evaluation of the implement/machine than nowadays.

The simulation models should have the data of the EC type and their variation, the PLs with their parameters and a positioning data generator. The positioning data generator could also be replaced by actual positioning results. In this way the model could also be used for tests of the positioning methods in various situations. The comparisons of positioning equipment could be made with the same PLs. On the other hand, if sufficiently good models are used, the PLs could also be tested, e.g. fertilization planning or evaluation of land improvement could be done. (Fig. 89)

The results of this study may be used in guiding future research activities that should concentrate on practical Position Dependent Control. Enhanced mapping of the yield and soil variations should be done to get a broader picture of the potentialities of PDC in Finland. Easy methods for the measurement of this huge amount of data should be developed. Aerial photography and video recording are potential methods for this purpose because of their good resolution. The modern high resolution satellite imaging technics are also possible. Radiometric measurements are also available. Besides these, methods for ground control point measurements and calculation algorithms for geostatistical estimation should be developed.

Economical methods are necessary for the positioning. For this purpose, differential GPS with and without Dead Reckoning should be tested. The new accurate Real-Time Kinematic GPS systems should be tested for autonomous vehicle operation and driver assistance. Alternative manual methods (e.g. sight lines, marker systems, tramline positioning) can also be developed for the change-over time from conventional methods to PDC. PDC needs flexibly controlled machines and implements, and therefore the controllability of crop production machines is to

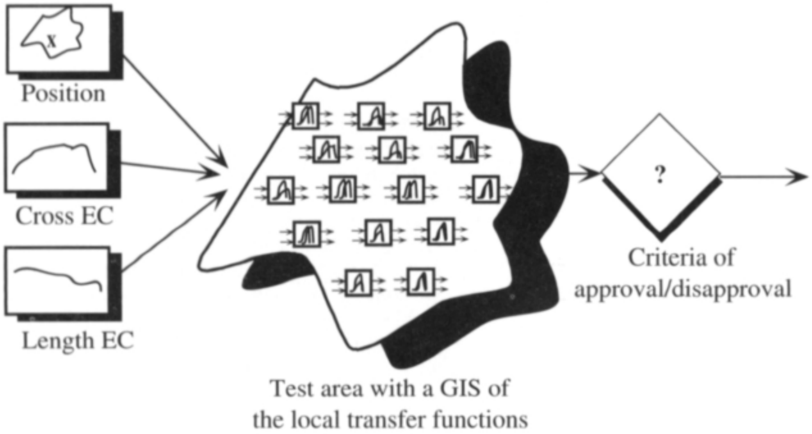

Fig. 89. A future model for testing implements/machines, positioning devices and target Production Locations (PLs). The position, the Effect Curves (ECs) and the transfer functions can be measured or simulated. EC = Effect Curve. GIS = Geographical Information System.

be tested and developed. Networking the PDC-information to Computer Aided Farming systems and national GISs should be investigated.

Special PDC-software should be developed that has modules for planning, realizing and feedback. The planning software should include the capability to give advice and recommendations to the user. AI methods should be used to make the decision-making process easier. Intelligent, learning PL models could be developed where fuzzy logic could be utilized. Data from possible plant varieties and other inputs, the PLs of the field and history of the PLs are needed. Deviations from the optimum and risks of user-made selections should be shown to the user in clear format; i.e. *a ´risk meter´* should be incorporated into the system. The planning software should convert the plan to setpoints of individual machines and implements, i.e. *implement drivers* should be developed. The other alternative is to make *implement controllers* that are calibrated for a standard setpoint signal. The realizing software consists of finding the setpoints according to position information and giving them to the controllers of the machine or implement. The controllers are set up or programd in a conventional way to realize the given setpoints. There are several ways to do this. There is a need for international standardizing of the formats of data transfer between office and the implement. Control methods for PDC should be developed. Special adaptive control strategies should be designed for plant production that has long delays and transition times and risks of annual variation.

Technological and economical impacts of PDC at different possible realization levels should be investigated. The change-over time from conventional technic to PDC must be designed. Basic requirements for a field to be controlled and the controlling machines should be stated. These requirements should be given in clear format: e.g. drainage, pH and nutrient values should be adequate and the machines controllable and in a good condition. The sustainability of PDC is an important research activity of future studies. It is clear that the PDC can be used to control the PLs in a more sustainable way. However, the major question is: *What kind of control strategies are sustainable?*

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SELOSTUS

Paikkakohtainen säätö kasvintuotannossa

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Koordinaattiin sidotussa peltoviljelyssä kaikki tuotannon suunnitteluun ja toteutukseen liittyvä tieto kohdistuu paikkakoordinaateilla rajattuihin alueisiin, tuotantopaikkoihin.

Tutkimuksen tavoitteena oli saada vastaukset seuraaviin kysymyksiin:

1. Millainen potentiaalinen käyttö on koordinaattiin sidotulla peltoviljelyllä?
2. Mitä vaatimuksia koordinaattiin sidontaan käytetyn menetelmän tulee täyttää?
3. Mitä mahdollisia ratkaisumalleja voidaan käyttää?

Pellolla kasvuolosuhteet vaihtelevat lyhyilläkin etäisyyksillä. Keimolassa tehdyn kenttäkokeen perusteella normaalissa, näennäisesti hyvin tasaisessa kevätvehnäkasvustossa sato vaihteli voimakkaasti. Mittauksessa käytettiin 0,25 x 0,25 metrin näytealaa, jolta sato kerättiin kokonaisnäytteinä. Samasta kohdasta otettiin viljavuusnäytteet. Satonäytteitä otettiin kahdesta 50 metrin mittaisesta linjasta 0,5 metrin välein, ts. näytteeseen tuli puolet linjan vehnästä. Saatu aineisto osoittautui erittäin vaihtelevaksi.

Koordinaattiin sitomisen vaikutusta simuloitiin valiten Keimolasta saadusta aineistosta alueita, joiden aineistoille laskettiin paikalliset matemaattiset mallit. Yhtenä koejäsenenä oli satotasoon perustuva alueen valinta. Selvästi parhaat ennusteet saatiin kuitenkin matkaan sidotulla alueen valinnalla. Tästä voitiin päätellä, että satotasot eivät ennusta maaperän ominaisuuksia vaan päinvastoin: tietty paikka maassa tuottaa sille ominaisen sadon.

Tutkimuksessa käytettiin matemaattisia malleja simuloitaessa erilaisten tuotantopanosten kohdentamistarkkuuden vaikutusta. Kohteena oleva alue pellolla, tuotantopaikka, mallinnettiin sadonmuodostuksen ja huuhtoutuman suhteen. Mallissa tuotantopaikkaan annettava käsittely kuvattiin vaikutuskuvioiden avulla. Paikannusvirheen ansiosta vaikutuskuvion kohdentamisessa esiintyy virheitä, joiden ansiosta tuotantopaikat saavat vääriä käsittelyn tasoja. Simuloinnissa selvitettiin erilaisten paikannusvirheiden vaikutusta tuotantopaikasta saatavaan sato- ja huuhtoumatulokseen. Tulosten perusteella saadaan maksimi paikannusvirheet eri tilanteissa.

Paikannuslaitteet ovat keskeisessä asemassa koordinaattiin sidotussa viljelyssä. Paikannuslaitekokeissa käytettiin satelliittinavigointilaitteistoja. Vuonna 1990/1991 kokeissa oli geodeettinen GPS (Global Positioning System) laitteisto jossa käytettiin differentiaalilaskentaa jälkikäteen. Vuosina 1993 ja 1994 kokeissa olivat reaaliaikaiseen differentiaalikorjaukseen kykenevät laitteet. Laitteet testattiin tarkoitusta varten tarkasti mitatulla koeajoreitillä Viikissä. Lisäksi vuonna 1993 tehtiin maantie- ja kaupunkiajoja. Vuonna 1994 laitteistoa testattiin edellisten lisäksi käytännön kylvötyön yhteydessä. Tulosten mukaan DGPS (Differential Global Positioning System) on tarpeeksi tarkka koordinaattiin sidottuun viljelyyn. Paikannustarkkuus on normaaliolosuhteissa nykyisellä satelliittikonstellaatiolla parempi kuin vaatimuksena ollut ±5 metriä.

Kirjallisuuden ja tutkimustulosten perusteella on selvää, että pellon vaihtelun hallinta ei ole mahdollista muutoin kuin siten, että peltoa viljellään paikkakoordinaattiin sidottuina tuotantopaikkoina. Viljelyyn liittyvät tiedot sidotaan paikkoihin ja työkoneita säädetään näihin kohteisiin yksilöllisesti tehdyn suunnitelman mukaisesti. Tekniikassa on tähän käyttökelpoisia ratkaisuja. Eräs toimiva ratkaisumalli on paikkatietojärjestelmä (GIS) yhdistettynä tiedonkeruuseen, laskentaan ja paikkakohtaiseen säätöön. DGPS satelliittinavigointi sopii tämän järjestelmän paikannusmenetelmäksi. Peltoviljelyssä esiintyviin eri paikannustehtäviin on saatavilla tarpeeksi tarkkoja GPS-laitteita.

Paikkakohtainen säätö edellyttää normaalia huomattavasti joustavammin säädettäviä työkoneita. Lisäksi tarvitaan suunnitteluohjelmistoja, jotka käyttävät tuotantopaikkamalleja. Potentiaalisia laitteita ja menetelmiä on jo nyt olemassa kaikkiin paikkakohtaisen säädön osiin. Ongelmaksi muodostuukin niiden yhteenliittäminen toimivaksi järjestelmäksi, joka on myös taloudellisesti kestävällä pohjalla. Tämän jälkeenkin jäämme miettimään, miten tuotantopaikkoja tulisi käsitellä aikaansaadulla järjestelmällä. Kysymys voidaan muotoilla esimerkiksi seuraavasti: *mikä on kestävän kehityksen periaatteen mukaista säätöä?*

Appendix 1

Systems analysis

Systems analysis is a method science that describes its targets as systems. Systems analysis is informal or formal. Informal systems analysis is made with literal descriptions and other informal methods. The formal type is based on modeling and simulation. (Gustafsson et al. 1982)

A system is a restricted area of the reality. A model is a presentation of the system, often a simplification of the real system. Model types are many, ranging from scale models or literal presentations to mathematical models. Mathematical models are further divided to time and event based types. (Gustafsson et al. 1982)

Simulation is an experiment made with mathematical models. Time based simulation can use either continuous or discrete time. Computer simulations use discrete time because of the digital operation. Event based simulation is used when it is more important to describe compatibility of the operational parts of the system, e.g. in simulation of work chains, than to imitate the structure or dynamics in the system. (Gustafsson et al. 1982)

In this study formal systems analysis and mathematical models are utilized. Time based dynamic and static models are used. The models are partly dynamic and there is also static calculation. The simulation time is discrete because computer models are used. Empirical data submodels are used in some parts of the models. The model type is called pseudoparallel because both static and dynamic parts are included (Gustafsson et al. 1982).

Systems analysis includes modeling, simulation and validation phases (Fig. 1). In a mathematical model the modelled system is described with a block diagram, a state model or a transfer function. The block diagram shows the system model in a graphical way. The state model comprices of differential equations that describe state variables of the system. The transfer function shows how system output is changed as a function of input. (Haugen 1990,) The model can be coded to a simulation language or an informal format, like a literal description (Gustafsson et al. 1982). If system components are clearly defined (e.g. physical relationships) the total model is a composition of component descriptions. In other case, the total model is designed on the basis of measurements - a so-called data model. The data model is fitted to measured data. (Gustafsson et al. 1982)

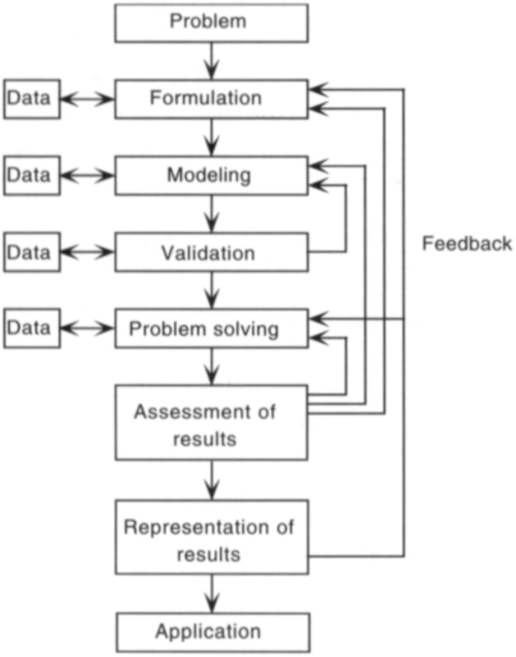


Fig. 1. Phases of systems analysis (Gustafsson et al. 1982).

Appendix 1

The modelling requires that the system is identified: a suitable model cathegory is selected. Identification is the process of defining system type according to inputs and outputs. The right system type is the one inside a system type cathegory that acts good enough like the system that is modelled. Validation is done with independent data. The ready model is used to solve the target problem. (Zadeh 1962 ref. Gustafsson et al. 1982)

The system and its model are also very important in control. It is a common practise in control technics to tune controllers by testing the target system (Haugen 1990). This empiric method is feasible if the system is testable. Hypothetic systems can not be tested, so testing is only possible with real systems. Testing methods include e.g. trial and error, Ziegler-Nichols, Cohen-Coons and autotuning. In the trial and error method controller parameters are systematically changed in order to get wanted step response. In the Ziegler-Nichols method interference is given to the system and a critical amplification, where the output starts to oscillate, is found. Cohen-Coons is a method where the system is tested without controller. A test step is given and transfer function is found. Controller parameters are calculated from the characteristics of the transfer function.

Simulation is used if the controlled system can not be tested. This may be due to the fact that the system is hypothetic or that it is too risky or expensive to perform the empirical test. Simulation is often very well justified because (Gustafsson et al. 1982):

1. The target can be a hypothetical system that does not exist in reality.
2. It is too expensive, risky or time consuming to test the real target (e.g. simulation of consequences of nuclear power plant blow up).
3. Surrounding factors of the system can not be controlled. A model is constructed in which these factors are not in effect.
4. A mathematical model is a good target for discussion and critisism. Misunderstanding can be avoided, because the models are formal and not personal thinking models of the discussers.
5. Theories are important tools in science to join knowledge and hypotheses. Theories are models that describe systems and explain their operation.
6. Models are pedagogically valuable. They can effectively pass information of the systems of interest.
7. Modelling itself gives information on systems and enhances undestanding of their operation.

Simulation is needed for the same reasons in adaptive Position Dependent Control of plant production (numbering refers to the reasons above):

1. Position Dependent Control is a hypothetical system because it has not been fully realized. Known solutions (e.g. Schnug et al. 1990, Auernhammer 1994) are so new that no further conclusions can be done. The results can not be generalized, because of different e.g. natural circumstances, economic and social environment and plant species and varieties in different countries. Components of the Position Dependent Control are used separately in other solutions, e.g. in computer science, chartography and automobile industry or in different parts of agriculture (e.g. in tilth, seeding, fertilizing, crop protection, harvest, soil testing).
2. It is expensive to test the Production Locations, because it requires intensive sampling and thus much work. Finding the maximum amounts of residues and leakage with real processes is not ethically justified. Test results have a long time lag, even many years.
3. Weather is uncontrollable and soil variation is not fully controllable. Many of the start values of the variables in a Production Location can not be choosen.

4...7. Apply also for Position Dependent Control.

Appendix 2

Geostatistics

In geostatistics a variable value is assumed to consist of a trend and some variation around it. The trend is not assumed to be stationary but only the variation around it. Geostatistics looks at differences between the samples instead of their similarities. This is done with the assumption that differences between samples only depend on distance between sample points and their relative orientation. This means that all sample values in same distance from each other (e.g. 50 m) and in same relative orientation are expected to differ by a surtain amount, i.e. the distribution of the differences is dependent on only the distance. If this is true with all the differences it is true also for their mean and standard deviation. This yields to (Eq. 1, Clark 1984):

$$[1] \quad m^*(h) = \frac{1}{n}\sum\left[g(x) - g(x-h)\right]$$

where m*(h) = measured mean value of the difference between sample values
g = grade (measured sample value)
x = position of one sample in the pair
x+h = position of the other pair
n = number of pairs

The sample area can be so small that there is no local trend in sample values. Then there is only the variance of the differences, expressed as follows (Eq. 2, Clark 1984):

$$[2] \quad 2\gamma^*(h) = \frac{1}{n}\sum\left[g(x) - g(x-h)\right]^2$$

$2\gamma^*(h)$ is called (experimental) variogram because it varies with the distance (and direction). $\gamma^*(h)$ is known as the semi-variogram. The semi-variogram passes the origin because samples taken in exact the same location have no difference. As the distance gets longer the graph rises. In ideal case when sample distance gets long enough they get independent on each other. This kind of semi-variogram is to geostatistics as the normal distribution is to statistics. The distance in which samples get independent is called the range of influence of a sample. The value of g at which the graph levels off is the sill of semi-variogram. The sill of a semi-variogram equals the sample variance (Clark 1984).

Kriging is the technique in geostatistics used to estimate local values from weighed randomly located samples. Reliability for each estimate is given as a (kriging) variance. Kriging gives each included sample value an optimized weight which minimizes variance of the estimate. The estimate can be given for a wanted area. (Clark 1984) Additional variables can be incorporated to the analysis with so called cokriging (Oliver and Webster 1991).

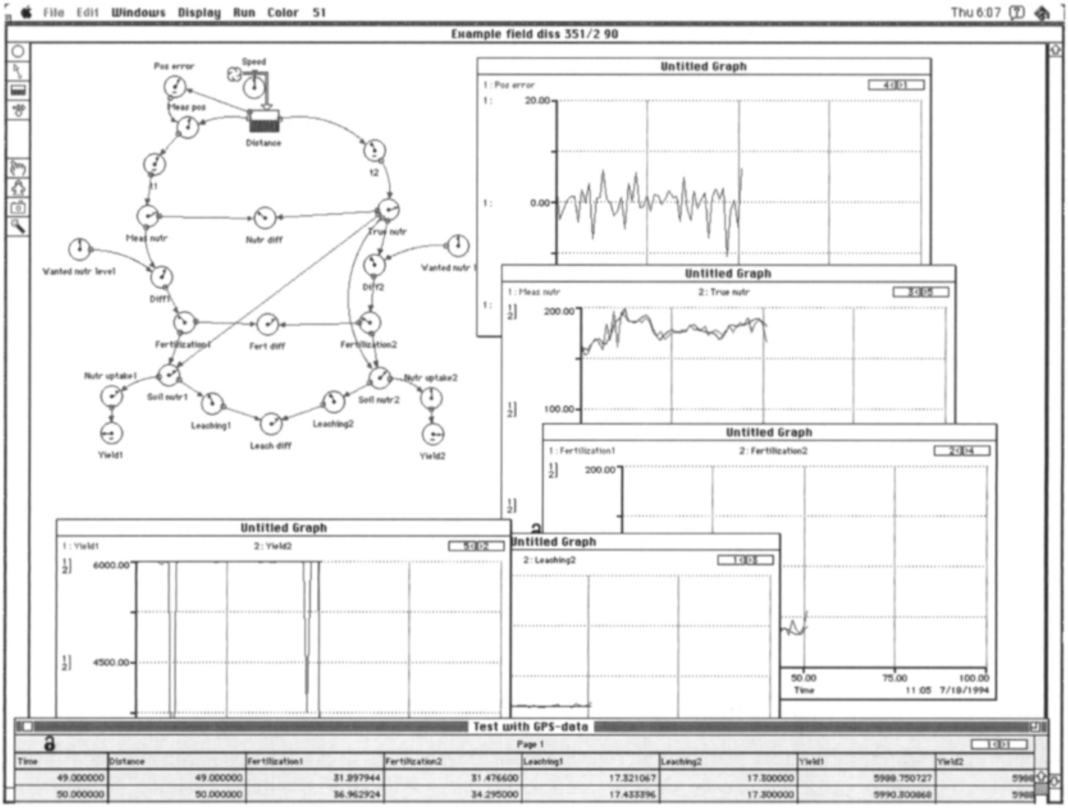
Geostatistics has been used in measurement of yield and soil properties (Nielsen and Alemi 1989, Bhatti et al. 1991). Delcourt et al. (1992) have measured the variations of two winter wheat fields in Belgium. They used a fixed raster of 20 meters. Experimental semi-variogrammes show considerable variation which is different in different directions. The variation could be characterized by local models. Additional applications in agricultural research are design of sampling strategies (Flaig et al. 1986, Ovalles and Collins 1988, Di et al. 1989, Thompson 1992) and finding patterns in the acquired data (Mulla 1988, Mulla and Annendale 1989). Natural resource management and land planning applications use complex geostatistics to relate soil data with its environment (Webster and Oliver 1990). Generally, semivariogrammes can be used to search for causes of the variation (Oliver 1987).

In this study, the size of PL is further analyzed in Keimola variation tests (ch. 3). Geostatistics is used to calculate the variation of yield, soil parameters and the output of a combined drill.

Appendix 3

Stella®-simulation environment

Stella® was selected because it is specially developed for simulation of dynamic systems and its modeling phase is very informative. Stella® gives graphic tools for setting up the model structure and doing the simulation. The model diagramme is built by selecting icons (Fig. 1) with a mouse. (Autti et al. 1989)



Time	Distance	Fertilization1	Fertilization2	Leaching1	Leaching2	Yield1	Yield2
49.000000	49.000000	31.897944	31.476600	17.321067	17.300000	5988.750727	5988
50.000000	50.000000	36.962924	34.295000	17.433396	17.300000	5990.300868	5988

Fig. 1.The main window of Stella® simulation programme. A simulation model is run. The model is built with graphical icons. During the run the icons show animation of the states of the variables. Graphical and tabular representations are shown in real time.

Possible inputs of the equations come from the diagramme. Equations are edited by double-clicking the icons. Equations can be replaced with data through importing the data to a table and routing the wanted x-variable to the table icon. The equations are automatically updated in background while changes are made in the diagramme. Tables and diagrammes are assigned with the mouse by selecting the wanted variables to be included. Scaling can be done with the help of autoscaling that runs the model to get minimum and maximum values for the y-scale. (Autti et al. 1989)

Reporting and documentation facilities are inbuilt. Besides the report editor and the direct printouts that are available, all the diagrammes, equations, tables and other outputs are compatible with Macintosh´s clipboard. The data can be exported via the clipboard to other Mac programmes or edited in e.g. graphical programmes. The figures in this study were saved in Stella and inported to and edited in a graphical programme to get uniform outlook. The resulting numbers were often exported to a spredsheet programme or to a statistical programme. Documentation is done inside the windows that open when icons are double-clicked. The document is free text that describes the action of the current icon or other relevant data (see App. 4 for an example).

Stella® uses three alternative calculation methods for simulation. The basic Euler method or two Runge-Kutta variations. The Runge-Kutta method was used in this study to get better accuracy. (Comp. Karvonen and Varis 1992) An example of the simulation model equations is shown in following table.

Table. The equations of the model for setting the requirement for cross targeting accuracy. The final version with both the integrating effect of the yield and the transfer function from the input (effect) to the yield is listed. Lines beginning with DOCUMENT written by the author include important information on the variables.

```
y(t) = y(t - dt) + (dy) * dt
INIT y = 0
DOCUMENT:  Crosswise position in meters. A function of simulation time.
dy = 1
DOCUMENT:  Change in crosswise position as a function of simulation time. DT is here 0.1 units.
a = 15
DOCUMENT:  Edge angle in degrees [°]. In this version "a" is equal for all ECs. NOTE! Do NOT give an angle that is out of operation range (e.g. an angle below 26.6 °
with Wopt of 2 m, or an angle over 90°)!
Alfa = a/360*2*pi()
DOCUMENT:  Edge angle converted to radians.
Eff_curve_1 = (if y<(W_1+Wopt) then 1 else (if y<(W_1+Wopt+(1/tan(Alfa))) then (-tan(Alfa)*(y-W_1-Wopt)+1) else 0))
DOCUMENT:  Shape of this EC given in terms of simulation time (=crosswise position y).
Eff_curve_2 = if(y<W_2) then 0 else (if (y<(W_2+(1/tan(Alfa)))) then ((y-W_2)*tan(Alfa)) else (if y<(W_2+Wopt) then 1 else (if y<(W_2+Wopt+(1/tan(Alfa))) then (-
tan(Alfa)*(y-W_2-Wopt)+1) else 0)))
DOCUMENT:  Shape of this EC given in terms of simulation time (=crosswise position y).
Eff_curve_3 = if(y<W_3) then 0 else (if (y<(W_3+(1/tan(Alfa)))) then ((y-W_3)*tan(Alfa)) else (if y<(W_3+Wopt) then 1 else 1))
DOCUMENT:  Shape of this EC given in terms of simulation time (=crosswise position y).
Eff_sum = Eff_curve_1+Eff_curve_2+Eff_curve_3
n_1 = 0
DOCUMENT:  Number of working width (from left).
n_2 = 1
DOCUMENT:  Number of working width (from left).
n_3 = 2
DOCUMENT:  Number of working width (from left).
Output = MAX(Trans_1-Trans_2)
Werr_1 = 0
DOCUMENT:  Position error of this EC. Positive values give movement to the right and vice versa.
Werr_2 = 20
DOCUMENT:  Position error of this EC. Positive values give movement to the right and vice versa.
Werr_3 = 0
DOCUMENT:  Position error of this EC. Positive values give movement to the right and vice versa.
Wopt = 20
DOCUMENT:  Optimum working width [m]. The working width that gives the best evenness of effect. Usually includes overlapping. In this version, overlapping is equal
for both sides because of constant edge angle.
W_1 = 0.5*Wopt-0.5/tan(Alfa)+n_1*Wopt+Werr_1
DOCUMENT:  Actual position of the left hand side edge of the EC.
W_2 = 0.5*Wopt-0.5/tan(Alfa)+n_2*Wopt+Werr_2
DOCUMENT:  Actual position of the left hand side edge of the EC.
W_3 = 0.5*Wopt-0.5/tan(Alfa)+n_3*Wopt+Werr_3
DOCUMENT:  Actual position of the left hand side edge of the EC.
Trans_1 = GRAPH(Eff_sum)
(0.00, 0.001), (0.0488, 0.00145), (0.0976, 0.0021), (0.146, 0.00304), (0.195, 0.00441), (0.244, 0.00639), (0.293, 0.00924), (0.341, 0.0134), (0.39, 0.0193), (0.439, 0.0278),
(0.488, 0.04), (0.537, 0.0572), (0.585, 0.0815), (0.634, 0.115), (0.683, 0.161), (0.732, 0.222), (0.78, 0.3), (0.829, 0.394), (0.878, 0.501), (0.927, 0.614), (0.976, 0.721),
(1.02, 0.811), (1.07, 0.88), (1.12, 0.928), (1.17, 0.958), (1.22, 0.976), (1.27, 0.987), (1.32, 0.993), (1.37, 0.996), (1.41, 0.998), (1.46, 0.999), (1.51, 0.999), (1.56, 1), (1.61,
1), (1.66, 1), (1.71, 1), (1.76, 1), (1.80, 1), (1.85, 1), (1.90, 1.00), (1.95, 1), (2.00, 1.00)
Trans_2 = GRAPH(Eff_sum)
(0.00, 0.001), (0.0488, 0.00145), (0.0976, 0.0021), (0.146, 0.00304), (0.195, 0.00441), (0.244, 0.00639), (0.293, 0.00924), (0.341, 0.0134), (0.39, 0.0193), (0.439, 0.0278),
(0.488, 0.04), (0.537, 0.0572), (0.585, 0.0815), (0.634, 0.115), (0.683, 0.161), (0.732, 0.222), (0.78, 0.3), (0.829, 0.394), (0.878, 0.501), (0.927, 0.614), (0.976, 0.721),
(1.02, 0.811), (1.07, 0.88), (1.12, 0.928), (1.17, 0.958), (1.22, 0.976), (1.27, 0.987), (1.32, 0.993), (1.37, 0.996), (1.41, 0.998), (1.46, 0.999), (1.51, 0.999), (1.56, 1.00),
(1.61, 1.00), (1.66, 1.00), (1.71, 1.00), (1.76, 1.00), (1.80, 1.00), (1.85, 1.00), (1.90, 1.00), (1.95, 1.00), (2.00, 1.00)
```

Appendix 4

Table 1. The effect of cross targeting error (Werr)) on the evenness of output quality of Production Locations. The quality is expressed as Coefficients of Variation, CVs, of the Effect Sum, ES. CVs are calculated for four optimum working widths (Wopt). Four different simulation models with different transfer functions are used. A= the model with unconditioned EC, B = the model with smoothed EC, C = the model with logistic transfer function from unconditioned EC and D = the model with logistic transfer function from smoothed EC. There are missing values because of the invalid negative value of b (width of the even part of EC) with these shape parameters.

model	Wopt [m]	Werr [m]	α [°]					
			15	30	45	60	75	90
A	2	0.2		0.086	0.113	0.144	0.191	0.259
	2	0.5		0.208	0.265	0.322	0.368	0.409
	2	1.0		0.385	0.473	0.520	0.550	0.578
	2	2.0		0.614	0.709	0.757	0.788	0.807
	5	0.2	0.037	0.053	0.070	0.089	0.118	0.178
	5	0.5	0.090	0.129	0.164	0.199	0.227	0.265
	5	1.0	0.177	0.244	0.292	0.321	0.340	0.366
	5	2.0	0.337	0.426	0.462	0.480	0.493	0.518
	5	5.0	0.642	0.735	0.766	0.784	0.795	0.822
	10	0.2	0.026	0.038	0.050	0.064	0.084	0.128
	10	0.5	0.065	0.092	0.117	0.142	0.163	0.189
	10	1.0	0.126	0.174	0.209	0.230	0.243	0.262
	10	2.0	0.240	0.305	0.330	0.344	0.353	0.366
	10	5.0	0.495	0.537	0.552	0.560	0.566	0.577
	10	10.0	0.737	0.781	0.796	0.805	0.811	0.817
	20	0.2	0.018	0.026	0.035	0.045	0.060	0.081
	20	0.5	0.044	0.064	0.082	0.100	0.115	0.128
	20	1.0	0.085	0.120	0.146	0.161	0.170	0.179
	20	2.0	0.160	0.209	0.227	0.237	0.244	0.250
	20	5.0	0.321	0.354	0.365	0.371	0.376	0.380
	20	10.0	0.457	0.479	0.487	0.491	0.494	0.499
	20	20.0	0.799	0.806	0.811	0.814	0.821	0.777
B	2	0.2		0.077	0.094	0.104	0.109	0.113
	2	0.5		0.189	0.230	0.251	0.260	0.265
	2	1.0		0.357	0.427	0.456	0.468	0.473
	2	2.0		0.579	0.660	0.691	0.704	0.697
	5	0.2	0.036	0.050	0.060	0.065	0.069	0.071
	5	0.5	0.090	0.123	0.146	0.158	0.165	0.167
	5	1.0	0.177	0.237	0.272	0.288	0.296	0.299
	5	2.0	0.337	0.423	0.453	0.465	0.470	0.479
	5	5.0	0.640	0.731	0.758	0.769	0.774	0.776
	10	0.2	0.025	0.035	0.042	0.046	0.049	0.050
	10	0.5	0.063	0.087	0.103	0.112	0.116	0.118
	10	1.0	0.125	0.168	0.192	0.204	0.209	0.211
	10	2.0	0.239	0.299	0.320	0.329	0.332	0.334
	10	5.0	0.498	0.538	0.550	0.555	0.557	0.561
	10	10.0	0.734	0.775	0.788	0.793	0.795	0.796
	20	0.2	0.018	0.025	0.030	0.033	0.035	0.036
	20	0.5	0.045	0.062	0.073	0.079	0.082	0.084
	20	1.0	0.088	0.119	0.136	0.144	0.148	0.150
	20	2.0	0.169	0.211	0.227	0.233	0.235	0.236
	20	5.0	0.352	0.380	0.389	0.393	0.395	0.395
	20	10.0	0.539	0.558	0.565	0.567	0.568	0.570
	20	20.0	0.796	0.802	0.806	0.807	0.810	0.777

Appendix 4

Table 1. (cont´d)

model	Wopt [m]	Werr [m]	α [°]					
			15	30	45	60	75	90
C	2	0.2		0.098	0.142	0.205	0.214	0.209
	2	0.5		0.399	0.394	0.361	0.327	0.297
	2	1.0		0.509	0.486	0.458	0.434	0.413
	2	2.0		0.574	0.573	0.570	0.565	0.556
	5	0.2	0.089	0.127	0.155	0.167	0.149	0.120
	5	0.5	0.211	0.258	0.253	0.231	0.208	0.189
	5	1.0	0.358	0.346	0.316	0.296	0.279	0.265
	5	2.0	0.480	0.430	0.407	0.392	0.380	0.378
	5	5.0	0.576	0.570	0.568	0.567	0.565	0.568
	10	0.2	0.063	0.090	0.110	0.119	0.106	0.085
	10	0.5	0.151	0.185	0.181	0.165	0.148	0.134
	10	1.0	0.258	0.248	0.226	0.212	0.200	0.189
	10	2.0	0.351	0.311	0.293	0.282	0.273	0.266
	10	5.0	0.471	0.442	0.430	0.423	0.418	0.417
	10	10.0	0.574	0.570	0.569	0.568	0.568	0.569
	20	0.2	0.045	0.064	0.078	0.084	0.075	0.060
	20	0.5	0.107	0.131	0.128	0.117	0.105	0.095
	20	1.0	0.184	0.177	0.161	0.150	0.142	0.134
	20	2.0	0.251	0.222	0.209	0.201	0.195	0.189
	20	5.0	0.340	0.318	0.309	0.304	0.300	0.297
	20	10.0	0.444	0.428	0.422	0.419	0.416	0.416
	20	20.0	0.571	0.569	0.569	0.568	0.568	0.569
D	2	0.2		0.088	0.117	0.142	0.119	0.087
	2	0.5		0.360	0.343	0.291	0.241	0.188
	2	1.0		0.467	0.438	0.403	0.370	0.333
	2	2.0		0.536	0.523	0.512	0.502	0.482
	5	0.2	0.086	0.116	0.130	0.121	0.091	0.052
	5	0.5	0.205	0.241	0.223	0.188	0.156	0.122
	5	1.0	0.351	0.330	0.291	0.264	0.241	0.216
	5	2.0	0.472	0.418	0.388	0.369	0.354	0.346
	5	5.0	0.569	0.557	0.550	0.546	0.542	0.542
	10	0.2	0.061	0.082	0.092	0.086	0.065	0.037
	10	0.5	0.146	0.172	0.159	0.134	0.111	0.087
	10	1.0	0.253	0.237	0.209	0.189	0.172	0.155
	10	2.0	0.347	0.302	0.280	0.265	0.254	0.243
	10	5.0	0.467	0.435	0.421	0.412	0.406	0.402
	10	10.0	0.569	0.563	0.560	0.557	0.556	0.556
	20	0.2	0.043	0.058	0.065	0.061	0.046	0.026
	20	0.5	0.104	0.122	0.113	0.095	0.079	0.062
	20	1.0	0.180	0.168	0.148	0.134	0.122	0.110
	20	2.0	0.248	0.215	0.199	0.189	0.181	0.173
	20	5.0	0.338	0.313	0.303	0.297	0.292	0.287
	20	10.0	0.442	0.425	0.418	0.413	0.410	0.409
	20	20.0	0.569	0.566	0.564	0.563	0.562	0.562

Appendix 4

Table 2. Maximum targeting errors (Werrmax) for different optimum working widths (Wopt = 2 m - 20 m), CV limits (CVmax = 0.1 - 0.5) and edge angles (a = 15 - 90 °). Four simulation models with different transfer functions are used. A= the model with unconditioned EC, B = the model with smoothed EC, C = the model with logistic transfer function from unconditioned EC and D = the model with logistic transfer function from smoothed EC. "-" denotes an accuracy requirement better than 0.2 m and "+" a requirement bigger than current Wopt. There are missing values because of the invalid negative value of b (width of the even part of EC) with these shape parameters.

model	Wopt	CVmax	α [°]					
			15	30	45	60	75	90
A	2	0.10		0.234	-	-	-	-
	2	0.20		0.480	0.372	0.294	0.216	-
	2	0.30		0.760	0.584	0.463	0.385	0.283
	2	0.40		1.065	0.824	0.697	0.587	0.483
	2	0.50		1.501	1.114	0.949	0.862	0.770
	5	0.10	0.556	0.386	0.297	0.230	-	-
	5	0.20	1.146	0.810	0.641	0.505	0.425	0.275
	5	0.30	1.772	1.308	1.045	0.913	0.823	0.674
	5	0.40	2.623	1.856	1.636	1.494	1.393	1.225
	5	0.50	3.605	2.716	2.379	2.193	2.069	1.884
	10	0.10	0.788	0.548	0.424	0.339	0.260	-
	10	0.20	1.651	1.197	0.951	0.830	0.732	0.573
	10	0.30	2.710	1.965	1.752	1.617	1.520	1.369
	10	0.40	3.885	3.232	2.946	2.782	2.668	2.488
	10	0.50	5.105	4.522	4.298	4.167	4.076	3.909
	20	0.10	1.200	0.819	0.642	0.500	0.420	0.323
	20	0.20	2.740	1.902	1.664	1.512	1.404	1.293
	20	0.30	4.605	3.889	3.582	3.403	3.279	3.155
	20	0.40	7.908	6.850	6.436	6.197	6.031	5.854
	20	0.50	11.265	10.645	10.408	10.272	10.177	10.042
B	2	0.10		0.262	0.213	-	-	-
	2	0.20		0.533	0.433	0.397	0.380	0.372
	2	0.30		0.831	0.678	0.620	0.595	0.584
	2	0.40		1.194	0.932	0.864	0.836	0.824
	2	0.50		1.643	1.314	1.188	1.135	1.120
	5	0.10	0.559	0.405	0.341	0.312	0.297	0.290
	5	0.20	1.144	0.837	0.716	0.660	0.635	0.624
	5	0.30	1.770	1.338	1.156	1.066	1.023	1.005
	5	0.40	2.624	1.877	1.708	1.631	1.597	1.560
	5	0.50	3.613	2.750	2.462	2.344	2.295	2.211
	10	0.10	0.797	0.580	0.486	0.445	0.427	0.419
	10	0.20	1.655	1.246	1.062	0.979	0.951	0.939
	10	0.30	2.704	2.014	1.842	1.770	1.737	1.724
	10	0.40	3.865	3.269	3.041	2.944	2.902	2.874
	10	0.50	5.047	4.524	4.346	4.269	4.236	4.193
	20	0.10	1.143	0.837	0.715	0.659	0.634	0.623
	20	0.20	2.505	1.878	1.706	1.630	1.596	1.581
	20	0.30	4.147	3.574	3.352	3.259	3.220	3.203
	20	0.40	6.285	5.553	5.301	5.201	5.158	5.139
	20	0.50	8.957	8.367	8.155	8.073	8.038	7.998

Table 2. (cont´d)

model	Wopt	CVmax	α [°]					
			15	30	45	60	75	90
C	2	0.10		0.202	-	-	-	-
	2	0.20		0.302	0.269	-	-	-
	2	0.30		0.401	0.388	0.383	0.428	0.512
	2	0.40		0.504	0.531	0.701	0.842	0.942
	2	0.50		0.959	1.157	1.377	1.503	1.608
	5	0.10	0.227	-	-	-	-	-
	5	0.20	0.473	0.367	0.338	0.356	0.458	0.574
	5	0.30	0.803	0.738	0.873	1.043	1.205	1.307
	5	0.40	1.344	1.641	1.928	2.136	2.319	2.342
	5	0.50	2.614	3.493	3.737	3.855	3.945	3.920
	10	0.10	0.326	0.232	-	-	-	0.291
	10	0.20	0.730	0.620	0.711	0.877	1.006	1.137
	10	0.30	1.451	1.825	2.153	2.379	2.551	2.669
	10	0.40	3.222	4.046	4.342	4.504	4.626	4.660
	10	0.50	6.425	7.270	7.514	7.641	7.741	7.722
	20	0.10	0.467	0.362	0.331	0.347	0.449	0.562
	20	0.20	1.242	1.519	1.819	1.983	2.155	2.295
	20	0.30	3.648	4.445	4.727	4.881	4.997	5.128
	20	0.40	7.895	8.727	9.020	9.184	9.308	9.344
	20	0.50	14.427	15.093	15.313	15.433	15.530	15.510
D	2	0.10		0.214	-	-	-	0.239
	2	0.20		0.324	0.310	0.317	0.398	0.541
	2	0.30		0.434	0.443	0.541	0.728	0.886
	2	0.40		0.686	0.800	0.988	1.227	1.451
	2	0.50		1.481	1.732	1.893	1.986	+
	5	0.10	0.235	-	-	-	0.241	0.407
	5	0.20	0.487	0.401	0.427	0.580	0.759	0.913
	5	0.30	0.825	0.831	1.089	1.346	1.524	1.643
	5	0.40	1.405	1.796	2.218	2.529	2.739	2.822
	5	0.50	2.864	3.773	4.070	4.226	4.333	4.353
	10	0.10	0.337	0.259	0.235	0.287	0.428	0.598
	10	0.20	0.753	0.716	0.914	1.150	1.340	1.514
	10	0.30	1.504	1.975	2.433	2.709	2.908	3.074
	10	0.40	3.327	4.213	4.554	4.749	4.887	4.953
	10	0.50	6.610	7.541	7.848	8.022	8.147	8.181
	20	0.10	0.481	0.395	0.419	0.563	0.744	0.898
	20	0.20	1.293	1.673	2.018	2.304	2.513	2.711
	20	0.30	3.736	4.590	4.912	5.147	5.351	5.539
	20	0.40	7.985	8.881	9.224	9.427	9.573	9.649
	20	0.50	14.563	15.323	15.612	15.783	15.909	15.947

Appendix 5

Soil variation in Keimola.

Local results are shown in the figures below (Figs 1 and 2). Lines 1 and 2 have been calculated separately. Dual sample values are separated with vertical lines. Statistics of the variables are shown in Table 1.

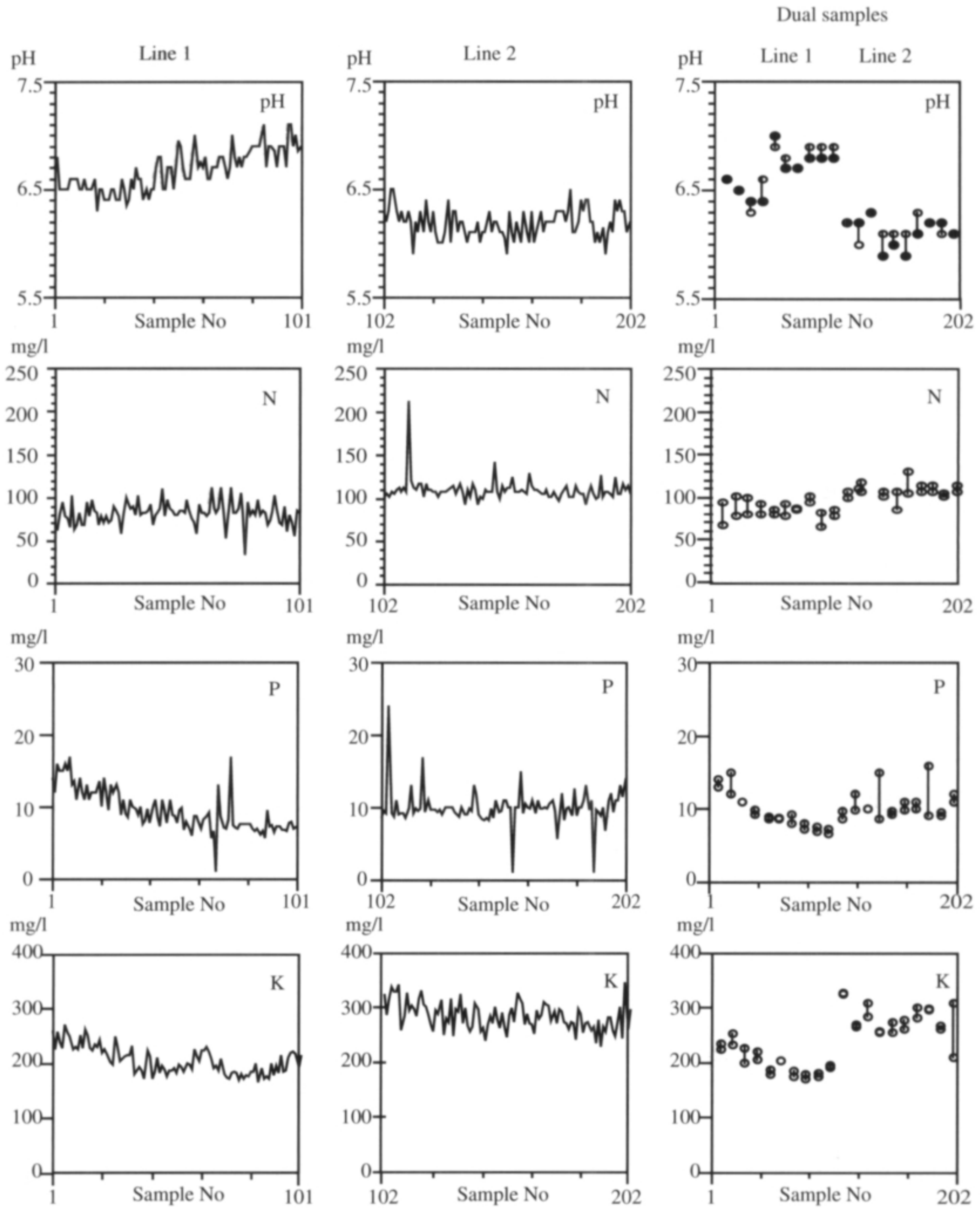


Fig. 1. Soil variation in Keimola. Analyzing results of pH, soil total N, P and K. The columns include analysing results for line 1, line 2 and dual sample values for both line 1 and line 2.

Appendix 5

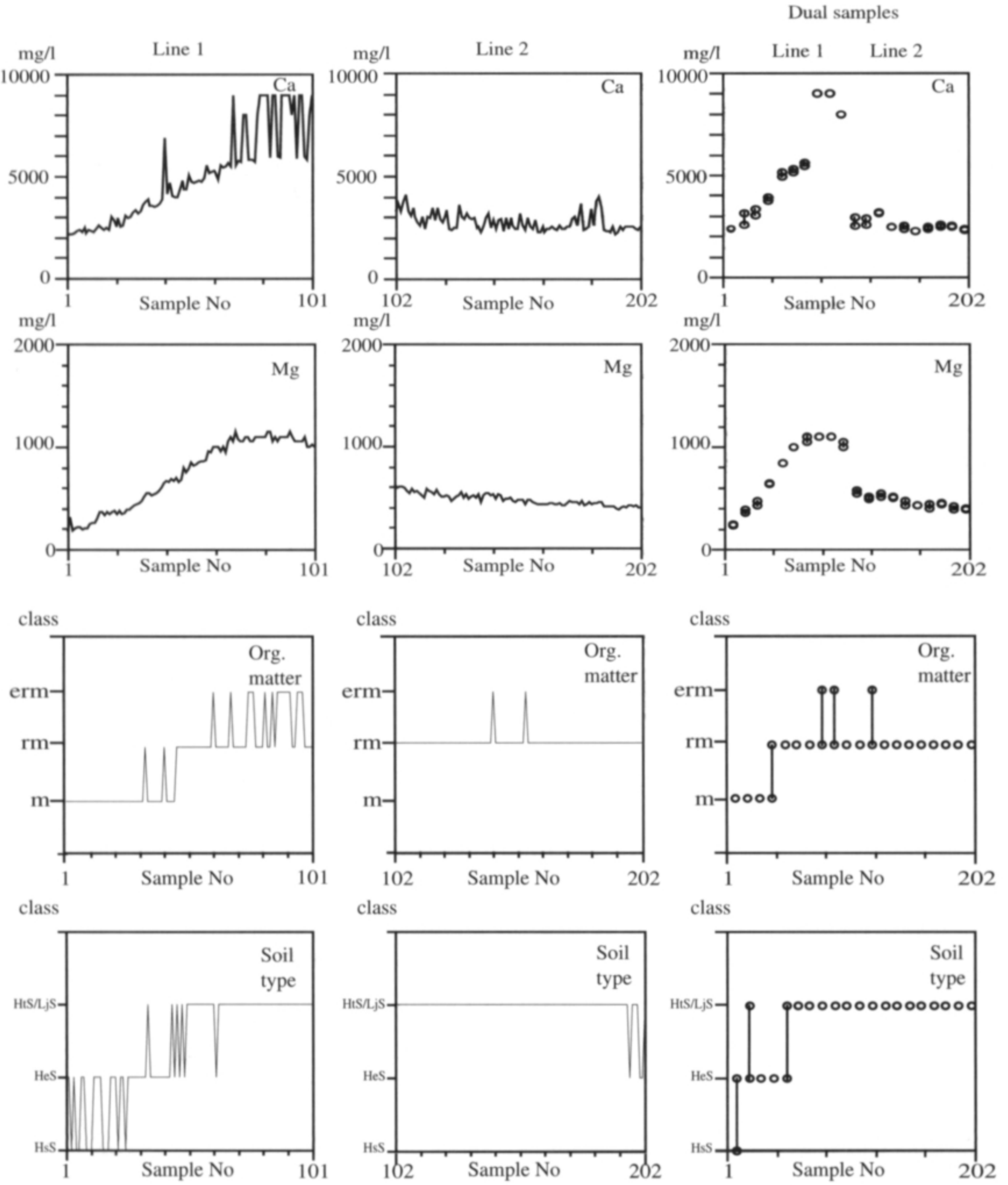


Fig. 2. Soil variation in Keimola. Analyzing results of Ca, Mg, soil organic matter content and soil type. The columns include analysing results for line 1, line 2 and dual sample values for both line 1 and line 2.

Appendix 5

Table 1. Statistics on soil variation in Keimola. Dual= difference in dual samples. Concentrations are in [mg/l]. STD = standard deviation. CV = coefficient of variation.

Variable	Line	n	min	max	range	mean	STD	CV
pH	1	101	6.3	7.1	0.8	6.68	0.19	0.03
pH	2	101	5.9	6.5	0.6	6.18	0.13	0.03
pH dual	1	10	0.0	0.2	0.2	0.08	0.06	0.79
pH dual	2	10	0.0	0.2	0.2	0.10	0.09	0.94
N	1	101	33	113	80	81.9	13.2	0.16
N	2	101	93	213	120	109.8	12.6	0.12
N dual	1	10	0	552	552	159.8	177.2	1.11
N dual	2	10	11	379	368	123.8	128.6	1.04
P	1	101	1	17	16	9.6	2.9	0.30
P	2	101	1	24	23	10.0	2.4	0.24
P dual	1	10	2.5	27.5	25.0	14.0	8.5	0.61
P dual	2	10	0	25	25	9.5	8.1	0.85
K	1	101	166	271	105	205.0	25.0	0.12
K	2	101	227	346	119	283.4	25.6	0.09
K dual	1	10	0	3	3	0.8	0.8	1.03
K dual	2	10	0	6	6	2.1	2.5	1.21
Ca	1	101	2079	9000	6921	4964.4	2248.8	0.45
Ca	2	101	2158	4087	1929	2760.9	436.3	0.16
Ca dual	1	10	1	27	26	10.8	7.9	0.74
Ca dual	2	10	1	99	98	19.3	29.2	1.52
Mg	1	101	170	1150	980	737.8	328.5	0.45
Mg	2	101	380	619	239	477.3	57.0	0.12
Mg dual	1	10	0	50	50	19.9	22.3	1.12
Mg dual	2	10	4	39	35	19.4	12.8	0.66

Appendix 6

Autocorrelations for soil analyses

The left column shows the autocorrelation for samples in analyzing order, the right column in actual sample order in the field. If there is a considerable autocorrelation in analysing order (like for pH, N and K) then there might be a memory effect in the analyzing system, i.e. subsequent samples in analysis have an effect on each other. Otherways the variation is random (like for P).

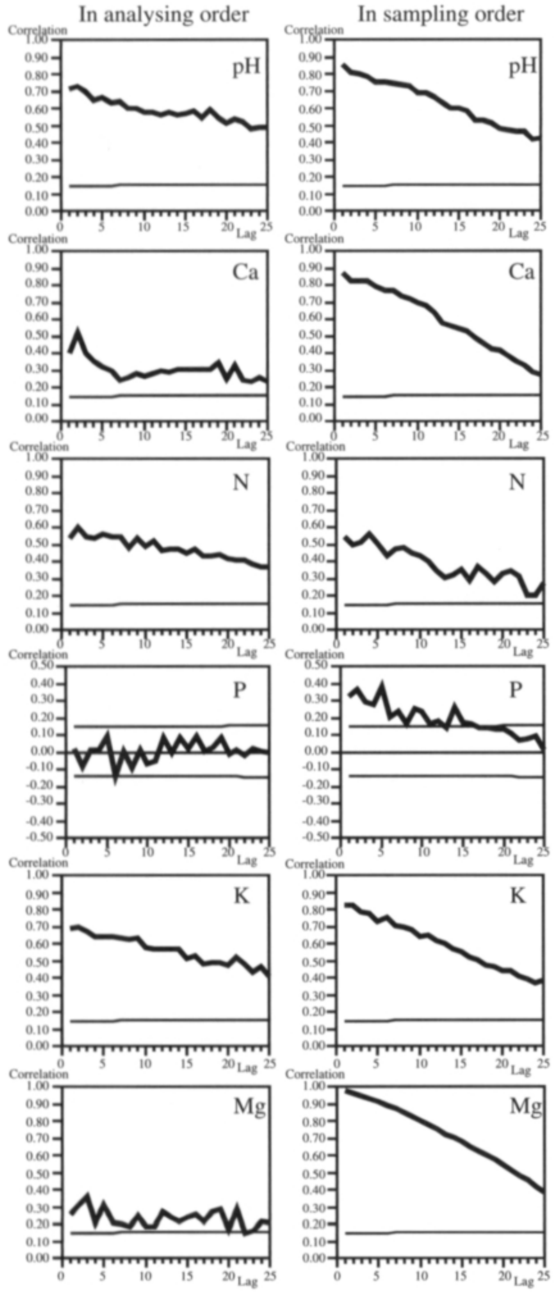


Fig. Autocorrelations in analysing order (left) and in actual sampling order (right) for pH, Ca, N, P, Kand Mg. Thin lines show the 95% confidence limits. Lag length is 0.5 m.

Appendix 7

Linewise regression estimates for yield

Table 1. Linewise egressions for wheat yield in Keimola in 1991. “-” = r^2<0.001.

Variable	Line	c_1	c_2	r^2
pH	1	10637	-839	0.032
	2	11110	-897	0.019
Ca	1	5288	-0.05	0.018
	2	4982	0.21	0.011
Soil total N	1	4907	1.48	-
	2	5377	1.65	0.001
P	1	4651	39.25	0.016
	2	5576	-1.69	-
K	1	5140	-0.55	-
	2	3417	7.56	0.050
Mg	1	5248	-0.30	0.012
	2	3195	4.95	0.106
Density	1	1818	5.45	0.465
	2	2482	5.56	0.433
Straw yield	1	1550	0.52	0.643
	2	1374	0.52	0.804

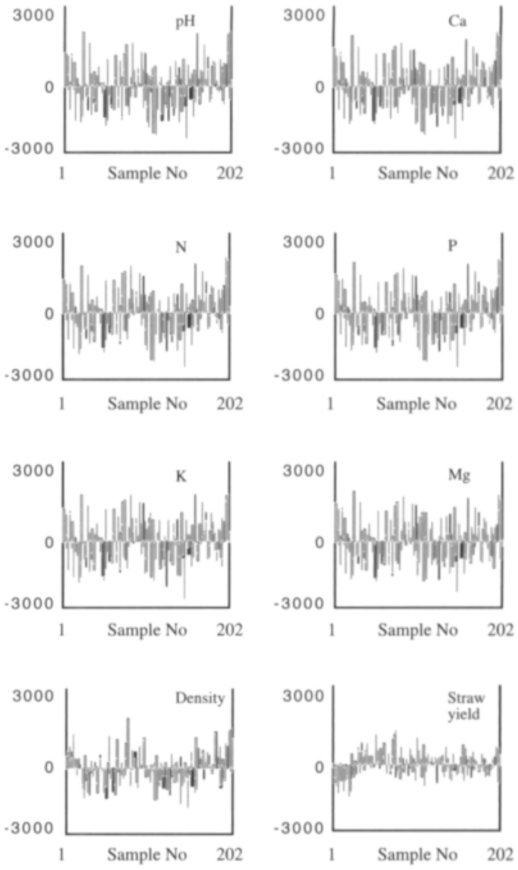
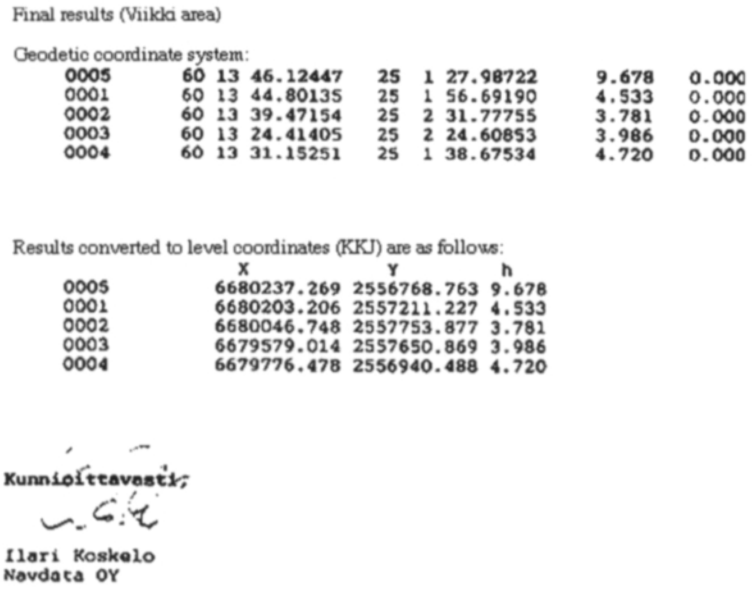


Fig. Regression residuals for linewise regressions for wheat yield in Keimola in 1991.

Appendix 8

Report of geodetic measurement of the reference points in test route in Viikki Experimental Farm. (Point numbers 0001 - 0005 refer to figure below.)



Final results (Viikki area)

Geodetic coordinate system:

0005	60	13	46.12447	25	1	27.98722	9.678	0.000
0001	60	13	44.80135	25	1	56.69190	4.533	0.000
0002	60	13	39.47154	25	2	31.77755	3.781	0.000
0003	60	13	24.41405	25	2	24.60853	3.986	0.000
0004	60	13	31.15251	25	1	38.67534	4.720	0.000

Results converted to level coordinates (KKJ) are as follows:

	X	Y	h
0005	6680237.269	2556768.763	9.678
0001	6680203.206	2557211.227	4.533
0002	6680046.748	2557753.877	3.781
0003	6679579.014	2557650.869	3.986
0004	6679776.478	2556940.488	4.720

Kunnioittavasti,

Ilari Koskelo
Navdata OY

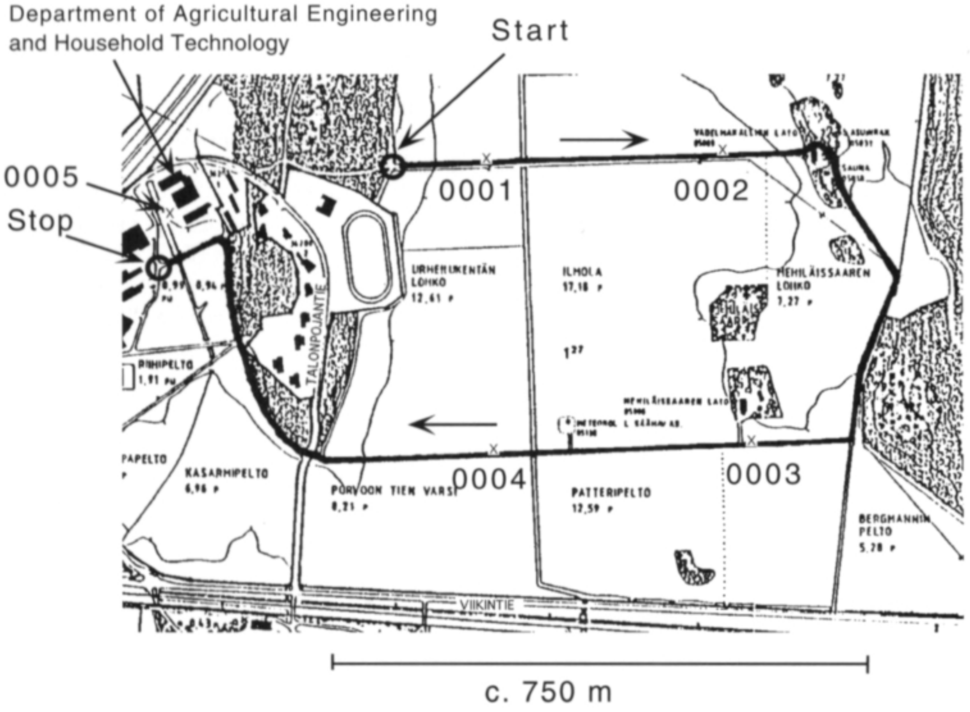


Fig. 1. Fixed reference points at the test route for DGPS tests at Viikki Experimental Farm.

Appendix 9

Positioning accuracy

Basic terms (Jääskeläinen 1978, Dally et al. 1984, Toft 1987, Hakala 1990, Lankinen et al. 1992)

Accuracy stands for a qualitative charasteristic whereas error is a deviation from true value. If accuracy is 100 meters it means that the positioning result may differ with 100 meters.

Propability is expressed as a fraction or percentage. A 50% propability for 100 meter error means that 50% of the measurements are more accurate than 100 meters or that every second value in average is more accurate than 100 meters. It is not, however, possible to say which one of two measurents is better. This is because of the statistical nature of propability.

Systematic errors follow a deterministic pattern and they have a specific reason. Systematic errors can be corrected with control measurements and calibration. They are predectable, if their reason is known well enough.

Fixed errors are systematic errors that are caused by inaccuracies in chart and table coordinates for positioning systems like Loran and Decca. Coordinate calculations include simplification that does not emphasis actual local circumstances. Wave propagation is affected by various factors and the simplification causes coordinate distortion.

Random errors are of random size and distribution. They can not be adjusted or compensated for. They are also called *variable errors.* Random errors are e.g. human errors, instability in electromagnetic wave propagation, in instruments and their components. Averaging multiple measurement values (filtering) is the only way to reduce random errors.

A fault is the end of the wanted operation of a unit (system, device, component). Faults are caused by mix-ups, instrument failure or abnormal observation conditions. Faults are irregular and thus they can not be treated with statistics.

Total error is the sum of all involving errors. If the mathematical expression of a result that consists of several measurements is known, e.g. volume of a cylinder V=(p/4)dl (where d is the diameter and l is the length), we can calculate the total error with standard deviations of the individual measurements. There are special summing, multiplication and division rules for this purpose. It is not, however, possible to have the necessary repetitions in all cases (e.g. in positioning of a freely moving vehicle). Then the average and the standard deviation are not (reliably) available. The error can be estimated, which is not reliable, or we can use the chain rule of differential calculus. The error can be expressed with partial derivates of the involved measurements. Partial derivates can show either the maximum error (Eq. 1, Dally et al. 1984) or the propable error (Eq. 2, Dally et al. 1984)

Partial derivates (sensibilities of the result y to each measurement x_n) are calculated from the equation of the result. Measurement errors dx_1, dx_2,..., dx_n are often estimates. The maximum error (Eq. 1) can be mathematically derived but the propable error (Eq. 2) is empirical. The maximum error (Eq. 1) shows the situation where maximum errors are simultaneuosly in all the involving measurements. This is very unlikely, so the propable error is a more realistic estimate for the total error.

[1] $$dy]_{max}=\left|\frac{\partial y}{\partial x_1}dx_1\right|+\left|\frac{\partial y}{\partial x_2}dx_2\right|+..+\left|\frac{\partial y}{\partial x_n}dx_n\right|$$

[2] $$dy=\sqrt{\left(\frac{\partial y}{\partial x_1}dx_1\right)^2+\left(\frac{\partial y}{\partial x_2}dx_2\right)^2+..+\left(\frac{\partial y}{\partial x_n}dx_n\right)^2}$$

where $dy\,\big]_{max}$ = maximum error in measurement of y

dy = propable error in measurement of y

$\frac{\partial y}{\partial x_n}$ = partial derivative of y to measurement x_n

dx_n = error in measurement of x_n

Appendix 9

Models for positioning error

The general model for navigation system components is a three-dimensional presentation. This type is easily converted to plane use (two-dimensional) or to other special reduced types. The position P(x,y,z) is calculated based on the previous one P(x_1,y_1,z_1), change in position and an error term as follows (Eq. 3, Hakala 1989):

[3] $$(x,y,z)=(x_1,y_1,z_1)+(\tilde{x},\tilde{y},\tilde{z})+\Delta(x,y,z)$$

The change of position is given by (Eq. 4, Hakala 1989):

[4] $$\tilde{x}=x-x_1$$
$$\tilde{y}=y-y_1$$
$$\tilde{z}=z-z_1$$

The error term includes error in previous positioning and error during the position change (Eq. 5, Hakala 1989):

[5] $$\Delta(x,y,z)=\Delta(x_1,y_1,z_1)+\Delta(\tilde{x},\tilde{y},\tilde{z})$$

The errors are calculated from errors in range and angle measurements (Eq. 6, Hakala 1989, Fig. 1):

[6] $$d=\sqrt{\tilde{x}^2+\tilde{y}^2+\tilde{z}^2}+\Delta d$$
$$h_1=\arcsin\frac{\tilde{x}}{\sqrt{\tilde{x}^2+\tilde{y}^2}}+\Delta h_1$$
$$h_2=\arcsin\frac{\tilde{z}}{d}+\Delta h_2$$

In space, the uncertainty of position is a volume around calculated position. It is a sphere (or an ellipsoid, an irregular space) that has the radius (or variable radius) of the calculated error (Fig. 2).

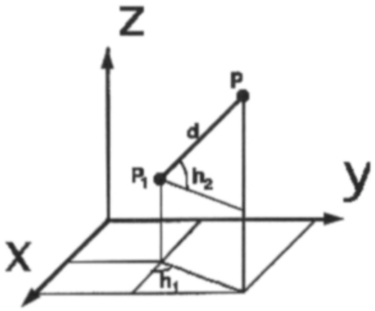


Fig. 1. Basic notations of the navigation system (Hakala 1989).

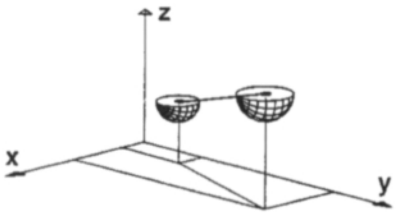


Fig. 2. Position uncertainty. Only the lower halves of the spheres are shown. (Hakala 1989).

In two-dimensional case the uncertainty is presented as a circle and in one-dimensional case as a line. The uncertainty can be different in each direction, which gives flattened, ellipsoidal, oval or otherways modified presentations.

Appendix 9

Calculating the accuracy

The inaccuracy is expressed with terms CEP, 1σ or 2σ. CEP (*Circular Error Propable*) gives the inaccuracy at 50% confidence level. 1σ (or RMS, *Root Mean Square*) gives the inaccuracy at 67% and 2σ at 95% confidence level.

In some positioning methods error compensation is realized with an additional reference method. The reference gives either continuously or periodically an accurate position, which can be used to compensate for the error. DR is a good exsample of a method tha needs periodic updates (Karppinen 1990). The reference can also be differential, which means that errors of equal direction and amplitude are removed. Differential GPS (DGPS) uses two receivers to do this kind of compensation. (Toft 1987, Koskelo 1990)

Hakala (1989) describes a DR reference measurement as follows (Eq. 7):

[7] $$(x, y, z) = (x_f, y_f, z_f) + \Delta(x_f, y_f, z_f)$$

The index f stands for fixed point. This equation describes a reference station that gives its position result and an estimate for the corresponding error.

Lankinen et al. (1992) define an error ellipse with semiaxes u and v (Eq. 8).

[8]

$$u^2 = \tfrac{1}{2}\left[(m_x^2 + m_y^2) + \sqrt{(m_x^2 - m_y^2)^2 + 4m_{xy}^2}\,\right] \text{ and}$$

$$v^2 = \tfrac{1}{2}\left[(m_x^2 + m_y^2) - \sqrt{(m_x^2 - m_y^2)^2 + 4m_{xy}^2}\,\right]$$

where

m_x = mean error of x

m_y = mean error of y

m_{xy} = covariance of x and y

This ellipse is used in the calculations of positioning accuracy of GPS in this study. GPS positions are virtually independent. In this case the covariance part of the equation is removed and u is defined solely by m_x and v by m_y, respectively.

Appendix 10

Supplementary information on GPS

The C/A-code modulates the L1 carrier with 1.023 Mb/s and the P-code modulates both L1 and L2 with 10.23 Mb/s. The P-code is transmitted both on L1 and L2 whereas the C/A is only found on L1. The navigation message is transmitted with 50 bps data speed. These combined data are simultaneously transmitted by all the satellites. Spread-spectrum modulation is used to combine the C/A-code of L1 and the C/A- and P-codes of L2 to one wide-bandwidth signal. Spread-spectrum modulation changes the signal from being power-dominated to bandwidth-dominated. This decreases interference in radio communication. P-code and C/A-code modulated carriers are added in quadrature (90° difference in space) to permit separation in the receiver. A bandwidth of 20.46 MHz (twice the bandwidth of P-code) is needed for both L1 and L2 (Fig. 1, Toft 1987)

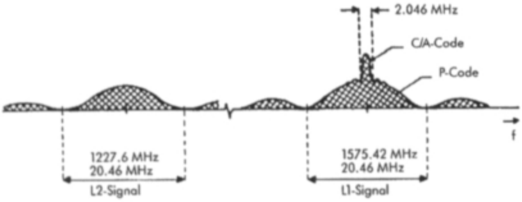


Fig. 1. The transmitted GPS signal spectrum with spread-spectrum modulation (Toft 1987).

The navigation message is a dataframe of 1500 bit and it is transmitted with 50 bps, i.e. sending one dataframe takes 30 seconds. It includes clock correction and satellite ephemeris (orbital) data, special messages and almanac information. The almanac consists of an overview of all GPS satellites, their orbital (ephemeris) information, clock corrections and atmospheric delays.(Toft 1987)

The receiver detects, synchronizes and demodulates the received signal. For demodulation, the receiver e.g. multiplies the signal with a locally generated copy of the satellite-specific PRN-code. (Toft 1987, Anon. 1994g) So called codeless receivers do not use PRN-codes but either square the L1 signal or cross-correlate the L1 and L2. The codeless methods give carrier cycle ambiguities (the unknown amount of carrier cycles between the satellite and the receiver). (Tyler 1993, Van Dierendonck 1995) Recently special OTF (on-the-fly) ambiguity resolution technics have been developed that enable ambiguity resolution in real time. This gives possibilities of below 10-cm accuracies of GPS even in real-time kinematic mode. (Koskelo 1990, Abidin 1994)

C/A is used to identify the satellite, to enable the GPS-receiver to lock on to the satellite signal and to enable measurement of satellite signal delay. C/A is 1023 bit long and it is repeated every millisecond. The P-code is altogether 6.05×10^{12} bit long but it is repeated in sequences of one week. All satellites have equal P-code generators but each satellite-specific one-week code comes from a different part of the nearly 38-week long code. GPS time is calculated from the time where P-code is reset (Saturday midnight) in Z-counts (1.5 s). One week is 403200 Z counts. The C/A-code includes instruction on how to lock on the P-code e.g. the current Z count. (Toft 1987)

Different receiver design technics, including multi-channel parallel, single-channel multiplexed and sequential systems, are available. The multi-channel parallel design is expected to be most used in future GPS-receivers. It has dedicated channels for each satellite in sight that are used in positioning (3–4) and usually extra channel(s) for acquisition of new satellites rising from the horizon. (Van Dierendonck 1995) The design affects the receiver´s ability to be locked to the amount of satellites required and thus to give continuous positioning information. It also affects the times needed for start and restart of positioning after pauses. Satellite search algorithms are important in this sense, too. (Koskelo 1990) Dual frequency receivers that use both L1 and L2 have the ability to compensate for ionospheric effects.

Appendix 11

Supplementary GPS test results

Table 1. Accuracies (95 %) for positioning tests in test route at Viikki Experimental Farm in 1990, 1991 and 1993. Results for the south part of the test route (reference points 6..9, fig. 74 in ch. 4). Test id is in format [YYMMDD:N] where Y=year, M=month, D=day and N=test number in that day. [a]=test with NBN´s differential correction, [b]=test with differential correction from a local reference station. "-" = not available. *=invalid data, **=results without dual points. Comments tell the reasons for the rejection.

1990..-91: Ashtech® XII geodetic GPS-receiver with post-processed differential corrections.

test id	cross	length	height	ellipse, m^2	n	PDOP	comment
901218: 1	6.87	7.49	12.68	646.62	279	2.36	
901218: 2	7.78	6.26	14.69	612.02	285	2.30	
901218: 3*	14.73	17.41	18.40	3222.64	225	3.37	missing points
901219: 1*	9.78	6.88	-	853.33	-	4.14	systematic offset
901219: 2	8.06	8.40	23.35	850.79	141	3.50	
901219: 3	7.59	8.50	13.21	810.72	140	2.40	
901219: 4	6.75	6.96	10.38	590.37	135	2.30	
901219: 5	10.66	16.70	15.50	2237.09	122	3.10	
901220: 1*	-	-	-	-	-	-	data not saved
901220: 2	6.74	7.47	12.68	632.69	182	2.50	
901220: 3	8.52	7.80	12.07	835.11	159	2.60	
901220: 4*	17.07	45.76	-	9815.88	-	3.77	offset for 20 points
901220: 5	12.52	7.30	20.20	1148.52	90	3.70	
910304: 1	5.83	6.77	13.84	495.98	125	2.58	time resolution better
910304: 2	4.88	5.01	16.34	307.23	149	2.55	time resolution better

1993: Trimble® Placer GPS/DR vehicle navigation module, real-time differential corrections with Trimble® NavBeacon XL and DR (Murata® piezo compass + doppler radar).

test id	cross	length	length**	ellipse. m^2	ellipse. m^2**	n	
930730:1	0.60	4.03	3.23	30.39	24.35	194	
930730:2	1.79	3.26	1.10	73.33	24.74	190	
930730:3	1.59	2.97	0.28	59.34	5.59	186	
930730:4	1.18	4.12	1.13	61.09	16.76	198	
930730:5	1.04	4.51	0.40	58.94	5.23	188	
930801:1	3.92	6.64	0.65	327.09	32.02	118	
930801:2	0.89	3.77	0.92	42.16	10.29	301	
930801:3*	50.09	4.01	3.33	2524.09	2096.07	169	without differential

1993: Trimble® SVeeSix vehicle navigation module with real-time differential corrections received with Trimble® NavBeacon XL RTCM radio beacon from NBN´s reference station in Porkkala or with Satelline® 2-ASx radio modem from a local Trimble® reference station .

test id	cross	length	height	ellipse, m^2	n	PDOP	comment
931202:1[a]	3.38	0.18	0.93	7.65	228	1.54	
931202:1[b]	3.03	0.18	0.46	6.85	228	1.54	
931202:2[a]	1.06	0.16	3.00	2.13	218	1.36	
931202:2[b]	0.50	0.16	3.73	1.01	221	1.38	
931202:3[a]	2.21	0.16	5.03	4.44	239	2.14	
931202:3[b]	0.78	0.16	0.95	1.57	223	2.14	
931202:4[a]	2.47	0.18	3.62	5.59	237	1.54	
931202;4[b]	1.74	0.55	0.62	12.03	248	1.72	
931202;5[a]	0.55	3.21	1.90	22.19	228	1.20	
931202;5[b]	6.42	2.71	2.52	218.63	273	1.20	radio link failure

Appendix 12

Indicators of geometric quality

The coordinate system and types of position measurements allways set a limit for positioning accuracy. The measured position is not an accurate point but an area, the size of which is defined by the error margins of the coordinate system and the involved range and distance measurements. (Fig. 1)

This difference in coordinate systems leads to the fact that the positioning accuracy is allways worse than the individual range and distance measurements are. This difference is called GDOP (*Geometrical Dilution of Precision*). GDOP is best when the coordinate lines intersect at a right angle (Fig. 2) GDOP is typically > 1.5 (Toft 1987, Krüger et al. 1994).

In three-dimensional case the term is called PDOP (*Position Dilution of Precision)* and it is typically > 2.5. Horizontal and vertical components are called HDOP and VDOP, respectively. Their valkues are typically > 1.5. A general term for these indicators is GQ (*Geometric Quality*). (Toft 1987, Krüger et al. 1994)

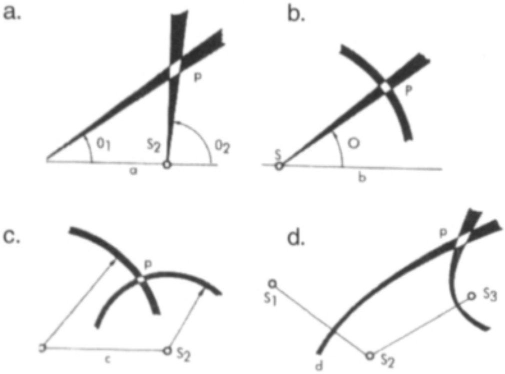


Fig. 1. Different coordinate systems and the obtainable accuracy in position determination. (a) Direction finding (e.g. visually or by radio beacon) , (b) distance and direction (e.g. radar), (c) two distances (e.g. GPS) and (d) hyperbola (Loran, Decca and Omega). (Gløersen ref. TOFT 1987)

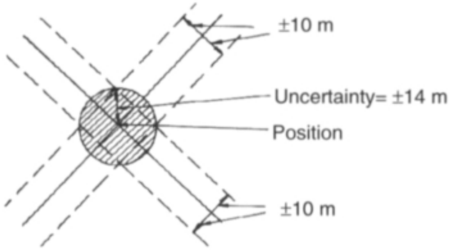


Fig. 2. The resulting position accuracy is best when the two coordinate lines intersect each other at an angle of 90°. The total inaccuracy is illustrated by the hatch-marked propability area, which is a circle with a radius of √2 times the range accuracy. (Toft 1987)