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Generation of Suitable Coordinate Updates for an Inertial Navigation System

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Preface

This is the first issue of the Technical Report of the Department of Geodesy at Stuttgart University. It replaces two other series which are known in geodesy and photogrammetry: the Technical Reports of the Institute of Geodesy and the publication series of the Institute of Photogrammetry. The Department of Geodesy is formed by four institutes, which are responsible for teaching, research and development in geodesy and surveying and also for an MSc programme. These institutes are in particular the Institute for Applications of Geodesy to Civil Engineering (IAGB), the Institute of Geodesy (GI), the Institute of Navigation (INS) and the Institute of Photogrammetry (IfP). The objective background of the new series of Technical Reports is to strengthen our efforts in publication and to provide interested readers more regularly with research results, not only by two institutes, but also by the whole department. We, the Editorial Board, hope that this effort is helpful to our readers and stimulates our Ph.D. students who will become authors of future issues.

The Department of Geodesy of Stuttgart University has more than 100 scientists working on such relevant topics as geodetic measurement techniques, kinematic measurement techniques in close range, general modeling of geometrical and topological networks, satellite geodesy, three-dimensional geodetic networks, inertial navigation systems, geodetic boundary value problems, marine geoids, relativistic models in geodetic positioning, precise range and range rate equipment (PRARE), scanning laser altimetry, radar calibration, GPS for navigation and remote sensing, optical remote sensing, SAR interferometry, GIS, digital photogrammetry and sensor integration. Therefore, the output of some relevant scientific work done in this broad spectrum makes the effort of publication worthwhile. Furtheron we hope that every issue will contribute to our reader's profit.

Dieter Fritsch
Wolfgang Keller
Erik W. Grafarend
Klaus Linkwitz
Philipp Hartl
Manfred Ruopp

Stuttgart 10th October 1994
The Editorial Board

Acknowledgement

In order to make coordinate-updates available for an inertial navigation system *the satellite global positioning system* offers a great potential being studied in the following *Technical Report* by *H.J.Euler*. A particular problem in kinematic positioning, the set-up of observational equations is tackled here, namely the study of the impact of *uncertainties* in the satellite position and velocity. Observational equations of type pseudo-ranges and carrier-phases are linearized including unkowns for satellite-positions and - velocities, for which some *stochastic prior information is available,* following a proposal by *G.Veis* (Smithsonian Contributions to Astrophysics, Vol. 3, No.9, Washington D.C.1960, Ph. D. Thesis), *E.Grafarend and E.Livieratos* (Rank defect analysis of satellite geodetic networks I - geometric and semi-dynamic mode: manuscripta geodaetica *3* (1978) 107-134), *E.Grafarend and B.Schaffrin* (Von der statischen zur dynamischen Auffassung geodätischer Netze: Zeitschrift für Vermessungswesen *113* (1988) 79-103) and *E.Grafarend* (The modeling of free satellite networks in spacetime, in: Proc. International Workshop on Global Positioning Systems in Geosciences, ed. *S.P.Mertikas*, Department of Mineral Resources Engineering, Technical University of Crete, pages 45-66, Chania, Greece 1993). Within the framework of "Sonderforschungsbereich 228" "*High Precision Navigation*", Stuttgart University, *H.J.Euler* performed this project work. His engagement into the study and the financial support by "Sonderforschungsbereich 228" are gratefully acknowledged.

Erik W. Grafarend
Stuttgart, 10 October 1994

FINAL PROJECT REPORT

FOR

GENERATION OF SUITABLE COORDINATE UPDATES FOR AN INERTIAL NAVIGATION SYSTEM

from

Dr.-Ing. Hans-Jürgen Euler

funded by

Sonderforschungsbereich 228
"Hochgenaue Navigation"

0 Introduction

The primary goal of this project is the development of a program system for the computation of coordinates of a moving antenna. It is not intended to develop a system for the integration of inertial navigation data and GPS data. Coordinates computed with this program should aid in the evaluation and reduction of specific errors found in inertial navigation data.
As measurements the program will utilize double differences of pseudoranges and carrier phases. The double differences have the advantage of reduced or removed external influences like clock offsets and atmospheric effects. The widely adopted opinion that double differences bring problems with the correlation between measurements does not invoke any problems since the evaluation of coordinates is essentially of a baseline type (two receivers).
External information like satellite positions and reference station coordinates has to be included as stochastic information with appropriate uncertainty.
The designated output are the estimated coordinates of reference station, satellite positions and moving antennas with their covariances.

1. The observation equations

In the literature one finds two different concepts for processing of GPS observations. The first algorithms used the so-called double difference observation (see e.g. Remondi, 1984, Scherrer, 1985). One drawback using the double difference is the fact that the correlation between this synthetic observations has to be taken into account. Especially when processing data of large networks the evaluation of big correlation matrices is inconvenient.

In 1985 C. Goad proposed non-difference observations as a better way for computations in a network mode. Later commercial available software were developed using undifferenced data (e.g. TOPAS, (Landau, 1988) or GEONAP (Wübenna, 1988)). The convenience of no correlation has to be paid with a larger amount of unknowns in the processing algorithm. For this reason and other possibilities of modelling the unknowns both software are using sequential filtering instead of conventional least squares adjustments. For more details the reader is referred to the extensive GPS literature.

For kinematic measurements usually only two receivers are involved. This is the typical baseline type and it is very easy to carry out correlations between observations and the full potential of double differences can be used. Therefore double differences are depicted as the primary observation type throughout this study. The double difference pseudorange observation can be obtained with:

$$DDP^{S1S2}_{R1R2} = P^{S1}_{R1} - P^{S2}_{R1} - P^{S1}_{R2} + P^{S2}_{R2} \tag{1.1}$$

DDP^{S1S2}_{R1R2} *is the double difference pseudorange*

P^{Sj}_{Ri} *pseudorange observation of sat j and rec i*

Similar one might build the double difference phase observation:

$$DD\phi^{S1S2}_{R1R2} = \lambda\ (\phi^{S1}_{R1} - \phi^{S2}_{R1} - \phi^{S1}_{R2} + \phi^{S2}_{R2}) \tag{1.2}$$

$DD\phi^{S1S2}_{R1R2}$ *is the double difference phase*

ϕ^{Sj}_{Ri} *phase observation of sat j and rec i*

λ *appropriate carrier phase wavelength*

The weight matrix taking into account correlations between observations of one type can derived with:

$$Q^{-1}_{DD} = \frac{1}{2\ n\ \sigma^2} \begin{bmatrix} n-1 & -1 & -1 & \dots & -1 \\ -1 & n-1 & -1 & \dots & -1 \\ -1 & -1 & n-1 & \dots & -1 \\ \dots & \dots & \dots & \dots & \dots \\ -1 & -1 & -1 & \dots & n-1 \end{bmatrix} \tag{1.3}$$

where n *number of satellites*

σ^2 *variance of observations*

The analytical derivation of this formula can be found in Hofmann-Wellenhof and Lichtenegger (1988) and Euler (1990).
The non-linear observation equation is given with

$$DDP_{R1R2}^{S1S2} = \rho_{R1}^{S1} - \rho_{R1}^{S2} - \rho_{R2}^{S1} + \rho_{R2}^{S2} + \Delta\rho_I + \Delta\rho_T \tag{1.4}$$

for pseudorange observations or similar for phase observations

$$DD\Phi_{R1R2}^{S1S2} = \rho_{R1}^{S1} - \rho_{R1}^{S2} - \rho_{R2}^{S1} + \rho_{R2}^{S2} + \Delta\rho_I + \Delta\rho_T + N_{R1R2}^{S1S2}\,\lambda \tag{1.5}$$

where

ρ_{Ri}^{Sj} *computed slope distance between satellite j and receiver i*

$\Delta\rho_I$ *ionospheric correction*

$\Delta\rho_T$ *tropospheric correction*

N_{R1R2}^{S1S2} *double difference ambiguity*

The slope distances between receivers and satellites are defined with the length of the following vector differences:

$$\rho_{R1}^{Sj} = |\vec{x}^{Sj}(t_{R1}^{Sj}) - \vec{x}_{R1}| \tag{1.6}$$

and

$$\rho_{R2}^{Sj} = |\vec{x}^{Sj}(t_{R2}^{Sj}) + \dot{\vec{x}}^{Sj}\,(t_{R2}^{Sj} - t_{R1}^{Sj}) - \vec{x}_{R1} - \Delta\vec{x}(t_{R2})| \tag{1.7}$$

with

$\vec{x}^{Sj}$ *satellite position vector*

$\dot{\vec{x}}^{Sj}$ *satellite velocity vector*

$\vec{x}_{R1}$ *reference station coordinates*

$\Delta\vec{x}$ *coordinate difference between R1 and R2*

t_{Ri}^{Sj} *transmit time of signal from Sj to Ri*

For the linearization of the observation equation one needs the partial derivatives with respect to the reference station coordinates, satellite position and velocity and the coordinate difference between reference station and moving receiver. In case of phase observations the partial derivative with respect to the ambiguity unknown is needed in addition. The total amount of partial derivatives can be assembled using the following subset of partials for each possible type of unknowns:

$$
\begin{aligned}
&\frac{\partial \rho_{Ri}^{Sj}}{\partial w^{j}} = c_{i(w)}^{j} && \textit{(satellite position)} \\
&\frac{\partial \rho_{R2}^{Sj}}{\partial \dot{w}^{j}} = c_{2(w)}^{j} \quad (t_{R2}^{Sj} - t_{R1}^{Sj}) && \textit{(satellite velocity)} \\
&\frac{\partial \rho_{Ri}^{Sj}}{\partial w_{1}} = -c_{i(w)}^{j} && \textit{(reference station)} \\
&\frac{\partial \rho_{R2}^{Sj}}{\partial \Delta w} = -c_{2(w)}^{j} && \textit{(coordinate difference)}
\end{aligned}
\tag{1.8}
$$

where

$$
\begin{aligned}
c_{1(w)}^{j} &= \frac{w^{Sj}(t_{R1}^{Sj}) - w_{R1}}{\rho_{R1}^{Sj}} \\
c_{2(w)}^{j} &= \frac{w^{Sj}(t_{R1}^{Sj}) + \dot{w}^{Sj}\,(t_{R2}^{Sj} - t_{R1}^{Sj}) - w_{R1} - \Delta w}{\rho_{R2}^{Sj}}
\end{aligned}
\tag{1.9}
$$

$$\textit{with} \quad w = x,\ y \ \textit{or} \ z$$

The formulation of the slope distance for the second receiver is quite unusual but gives the possibility to compute directly the coordinate difference between reference station and the moving receiver. In the covariance matrix one can pick up directly the associated uncertainty values without additional computations. The in first view inconvenient taylorization of the satellite position for R2 is necessary since a main task of this investigation is the requirement that the orbit has to be included as stochastic information. Otherwise one would not have the possibility to transform the high accuracy of the measurements (at least few meters for pseudoranges and hundreds of meter for phases) in high accuracy relative coordinates between reference station and moving receiver. This knack gives the facilities to involve orbit accuracies of 100 meters and more. The great impact will be reduced by the double differencing as it is assumed for this observation type. However, one has to take into account in addition the satellite velocity with its uncertainty.

It is remarkable that all unknowns beside the satellite velocity are influenced by the geometry between satellites and receivers only. The satellite velocity unknown is also dependent on the difference between the signal transmit times on that specific satellite. With receivers which internal clocks are not synchronized very well with GPS time the uncertainty of satellite velocity has an increased impact. This is especially important when using data of older receiver types

such as the TI-4100. However modern receivers such as TRIMBLE's and ASHTECH's should have only a maximum difference of the internal clock to GPS time always smaller or equal to one millisecond. In the difference one will have no more than two milliseconds which limits the influence essentially. The transmit time differences are not only dependent on the receiver clocks. The difference of the geometric distances between satellites and receivers divided by the speed of light gives an additional delay which might be neglected in comparison to the receiver clocks as long as the measurements are taken in a local network.
So far it seems recommendable to summarize the number of unknowns in comparison with the number of observations. The reference station has three unknowns over full observation period. The same is valid for ambiguity unknowns in case that phase observations are involved and all cycle slips are recovered. For the moving antenna each measuring epoch will result in three coordinate differences unknowns while each satellite contributes six unknowns at each epoch. As observations besides the double differences stochastic information is available for the satellite positions and velocities and the reference station coordinates.
Tables (1.1) and (1.2) give better impression of specific numbers.

unknowns	lifetime	elements	epochs	satellite	station	total
x(R1)	ne	3	0	0	1	3
dx(R2)	1	3	ne	0	0	3 ne
x(S)	1	3	ne	ns	0	3 ne ns
xd(S)	1	3	ne	ns	0	3 ne ns
N	e	1	0	ns - 1	0	ns - 1

Table (1.1) Summary of unknowns

observation	elements	epochs	satellite	station	total
x(R1)	3	0	0	1	3
x(S)	3	ne	ns	0	3 ne ns
xd(S)	3	ne	ns	0	3 ne ns
P1 (C1)	1	ne	ns - 1	0	ne(ns-1)
L1	1	ne	ns - 1	0	ne(ns-1)
L2	1	ne	ns - 1	0	ne(ns-1)
P2	1	ne	ns - 1	0	ne(ns-1)

Table (1.2) Summary of observations

The following abbreviations are valid in tables (1.1) and (1.2):

x(R1)	reference station coordinates
dx(R2)	moving receiver coordinate differences with respect to the reference station
x(S)	satellite coordinates
dx(S)	satellite velocity
N	double difference unknowns
L1	carrier phase measurement on L1
L2	carrier phase measurement on L2
P2	pseudorange on L2
ne	number of epochs
ns	number of satellites

Even few epochs of data will lead to a large equation systems.
Table (1.3) shows the sizes of normal equation systems to be solved with the propagated model. With 7 satellites and 10 epochs the normal equation stored in symmetric mode and double precision numbers needs about 803 kBytes of storage. In case of 100 epochs of data one needs about 78 MBytes. Both examples are relatively small. Under usual conditions the number of epoch may exceed one thousand.

type	satellites	epochs	Pi	Pi+Li	Pi+L1+ L2	P1+L1 P2+L2
unknowns	7	10	453	459	465	465
obser- vations	7	10	483	543	603	663
unknowns	7	100	4503	4509	4515	4515
obser- vations	7	100	4803	5403	6003	6603
unknowns	4	100	2703	2706	2709	2709
type	satellites	epochs	Pi	Pi+Li	Pi+L1+ L2	P1+L1 P2+L2
obser- vations	4	100	2703	3003	3303	3603

Table (1.3) confrontation of number of unknowns and observations under various conditions

2. Least Squares Modelling

In the following chapter the least squares tools will be summarized. The implemented approaches are so-called mixed models because some of the unknowns are directly "observed". The satellite coordinates and velocities and the coordinates of the reference station are known with a certain accuracy. This parameters are included in the model as pseudo observations with individual

uncertainties.
Sections 2.1 and 2.2 just give a comprehensive summary of the formulas. The complete theory and further examples can be found in the literature as Middel and Schaffrin (1988), Schaffrin (1989) and Middel (1991).

2.1 Best inhomogeneous LInear Prediction (inhom BLIP)

The observation equations are given with:

$$y + v = A\,x \quad ; E(v) = 0;\ D(v) = D(y) = P_y^{-1}$$

$$\kappa + e = x \quad ; E(e) = 0;\ D(e) = D(\kappa) = P_\kappa^{-1}$$

y	*observations*	
v	*random errors of observations*	
A	*design matrix*	
x	*unknowns*	(2.1)
κ	*pseudo observations of the unknowns*	
e	*random errors of the observed unknowns*	
$E()$	*expectation*	
$D()$	*dispersion*	
P_y^{-1}	*weight matrix of observations*	
P_κ^{-1}	*weight matrix of pseudo observations*	

The system of normal equations are denoted by:

$$(A^T P_y A + P_\kappa)\,x = A^T P_y\,y + P_\kappa\,\kappa \tag{2.2}$$

while the prediction of the unknowns is:

$$\tilde{x} = (A^T P_y A + P_\kappa)^{-1}\,(A^T P_y\,y + P_\kappa\,\kappa) \tag{2.3}$$

and the Mean Square Prediction Error (MSPE) is:

$$D(\tilde{x} - x) = (A^T P_y A + P_\kappa)^{-1} \tag{2.4}$$

2.2 Best homogenous Linear weakly Unbiased Prediction (homBLUP)

The observation equations are represented with:

$$
\begin{aligned}
y + v &= A\,x \quad ; E(v) = 0;\ D(v) = D(y) = P_y^{-1} \\
a\,\kappa + e &= x \quad ; E(e) = 0;\ D(e) = D(\kappa) = P_\kappa^{-1};\ E(a) = 1
\end{aligned}
\tag{2.5}
$$

In addition to the given model of 2.1 the pseudo observations are scaled with the factor a. The system of normal equations are given with:

$$
\begin{aligned}
(A^T P_y A + P_\kappa)\,x \; - \; P_\kappa\,\kappa\;a &= A^T P_y\,y \\
-\kappa^T P_\kappa \quad x + \kappa^T P_\kappa\,\kappa\,a &= 0
\end{aligned}
\tag{2.6}
$$

where the unknowns can be evaluated by:

$$
\begin{aligned}
a &= \frac{\kappa^T P_\kappa (P_\kappa + A^T P_y A)^{-1} A^T P_y\,\kappa}{\kappa^T P_\kappa\,\kappa - \kappa^T P_\kappa (P_\kappa + A^T P_y A)^{-1} P_\kappa\,\kappa} \\
\tilde{x} &= (A^T P_y A + P_\kappa)^{-1} (A^T P_y\,y + a\,P_\kappa\,\kappa)
\end{aligned}
\tag{2.7}
$$

The Mean Square Prediction Error is:

$$
MSPE\begin{pmatrix} \tilde{x} \\ a \end{pmatrix} = \begin{bmatrix} P_\kappa + A^T P_y A & -P_\kappa\,\kappa \\ -P_\kappa\,\kappa & \kappa^T P_\kappa\,\kappa \end{bmatrix}^{-1}
\tag{2.8}
$$

3. Solving and Inverting the Normal Equation System using Helmert's Blocking Method

The extensive size of the equation systems is shown in chapter 1. Even with only 10 epochs of data the storage capabilities of an usual personnel computer system is exhausted. Systems resulting from 100 or more epochs of data can be handled on mainframes only.
On the other hand one sees easily that the over-whelming part number of unknowns has a "lifetime" of one epoch. Only few unknowns get directly a contribution of the measurements from all epochs. It is obvious that a separation of unknowns in the observation equation system will lead to special normal equations.
The following example illustrates the advantages with a small 3 epoch system.
The observation equations:

$$
\begin{aligned}
A_1\, x_1 &+ 0\, x_2 + 0\, x_3 + A_{g1}\, x_g = y_1; \quad D(y_1) = P_{y_1}^{-1} \\
0\, x_1 &+ A_2\, x_2 + 0\, x_3 + A_{g2}\, x_g = y_2; \quad D(y_2) = P_{y_2}^{-1} \\
0\, x_1 &+ 0\, x_2 + A_3\, x_3 + A_{g3}\, x_g = y_3; \quad D(y_3) = P_{y_3}^{-1}
\end{aligned}
\tag{3.1}
$$

A_i, x_i	*part needed in epoch i only*
A_{gi}, x_g	*part for all epochs*
y_i	*observations of epoch i*

will lead to the normal equations:

$$
\begin{bmatrix}
A_1^T P_{y_1} A_1 & 0 & 0 & A_1^T P_{y_1} A_{g1} \\
0 & A_2^T P_{y_2} A_2 & 0 & A_2^T P_{y_2} A_{g2} \\
0 & 0 & A_3^T P_{y_3} A_3 & A_3^T P_{y_3} A_{g3} \\
A_{g1}^T P_{y_1} A_1^T & A_{g2} P_{y_2} A_2 & A_{g3}^T P_{y_3} A_3 & A_g^T P_y A_g
\end{bmatrix}
\begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_g \end{bmatrix}
=
\begin{bmatrix}
A_1^T P_{y_1} y_1 \\
A_2^T P_{y_2} y_2 \\
A_3^T P_{Y_3} y_3 \\
A_g^T P_y y
\end{bmatrix}
$$

with:

$$
A_g^T P_y A_g = A_{g1}^T P_{y_1} A_{g1} + A_{g2}^T P_{y_2} A_{g2} + A_{g3}^T P_{y_3} A_{g3}
$$

$$
A_g^T P_y y = A_{g1}^T P_{y_1} y_1 + A_{g2}^T P_{y_2} y_2 + A_{g3}^T P_{y_3} y_3
$$

or for the sake of clearness:

$$
\begin{bmatrix}
N_{11} & 0 & 0 & N_{1g} \\
0 & N_{22} & 0 & N_{2g} \\
0 & 0 & N_{33} & N_{3g} \\
N_{1g}^T & N_{2g}^T & N_{3g}^T & N_{gg}
\end{bmatrix}
\begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_g \end{bmatrix}
=
\begin{bmatrix} Y_1 \\ Y_2 \\ Y_3 \\ Y_g \end{bmatrix}
\tag{3.3}
$$

In most algorithms for the solution of linear equation systems the matrix will be reduced to an upper-triangle matrix. The solution of the last value in the unknown vector can be obtained directly by numerical scalar operations. The backsubstitution of the results in the previous rows lead to the successive solution of the total system. There is no big difference between an ordinary

matrix and a helmert block matrix and it is well-known that one may use the same technique in the latter case.
After three reduction steps the system looks like:

$$\begin{bmatrix} N_{11} & 0 & 0 & N_{1g} \\ 0 & N_{22} & 0 & N_{2g} \\ 0 & 0 & N_{33} & N_{3g} \\ 0 & 0 & 0 & N^*_{gg} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_g \end{bmatrix} = \begin{bmatrix} Y_1 \\ Y_2 \\ Y_3 \\ Y^*_g \end{bmatrix} \tag{3.4}$$

with:

$$N^*_{gg} = N_{gg} - N^T_{g1} N^{-1}_{11} N_{g1} - N^T_{g2} N^{-1}_{22} N_{g2} - N^T_{g3} N^{-1}_{33} N_{g3}$$
$$Y^*_g = Y_g - N^T_{g1} N^{-1}_{11} Y_1 - N^T_{g2} N^{-1}_{22} Y_2 - N^T_{g3} N^{-1}_{33} Y_3$$

As one can see for the reduction only matrices available at a specific epoch are needed. Instead of waiting till the end of the data collection the reduction might be performed at each epoch and the reduced general part of the normal equation has to be stored in core during the computations. The matrices with a lifetime of one epoch can be stored on permanent media for further use. Later when the unknowns of the general part are estimated, it is very easy to compute the unknowns with one epoch lifetime:

$$x_i = (N_{ii})^{-1} \; (Y_i - N_{gi} \, x_g) \tag{3.5}$$

Formally files with several thousand epochs worth of data are no longer a problem even for small PC's as long as the loss of numerical precision during the computational effort is negligible. Looking at the example of chapter 1 the order of the system held in core is with 7 involved satellites at no time larger than 15.
The goal of this study is not only the computation of unknowns. We are interested in addition in the covariances. Therefore the full normal equation matrix has to be inverted. However there is no need to step back from the scheme used above. The procedure of the Gauss-algorithm might be utilized in conjunction with the Helmert blocking. In the Gauss-algorithm one has to extend the matrix to be inverted with an identity matrix of the same size. Numerical manipulations carried through for each complete row which bring the original matrix to an identity matrix will transform the extended part to its inverse. After the third reduction the blocked matrix system with extension would look like:

$$\begin{bmatrix} N_{11} & 0 & 0 & N_{g1} & I & 0 & 0 & 0 \\ 0 & N_{22} & 0 & N_{g2} & 0 & I & 0 & 0 \\ 0 & 0 & N_{33} & N_{g3} & 0 & 0 & I & 0 \\ 0 & 0 & 0 & N^*_{gg} & Q^{*T}_{g1} & Q^{*T}_{g2} & Q^{*T}_{g3} & Q^*_{gg} \end{bmatrix} \tag{3.6}$$

and bringing the left part to an identity matrix:

$$\begin{bmatrix} I & 0 & 0 & N^{-1}_{11}N_{g1} & N^{-1}_{11} & 0 & 0 & 0 \\ 0 & I & 0 & N^{-1}_{22}N_{g2} & 0 & N^{-1}_{22} & 0 & 0 \\ 0 & 0 & I & N^{-1}_{33}N_{g3} & 0 & 0 & N^{-1}_{33} & 0 \\ 0 & 0 & 0 & I & Q^T_{g1} & Q^T_{g2} & Q^T_{g3} & Q_{gg} \end{bmatrix} \tag{3.7}$$

One part solution is already known. It is:

$$Q_{gg} = (N_{gg} - N^T_{g1} N^{-1}_{11} N_{g1} - N^T_{g2} N^{-1}_{22} N_{g2} - N^T_{g3} N^{-1}_{33} N_{g3})^{-1} \tag{3.8}$$

which is of course the inverse of the reduced general part.
The off-diagonal matrices giving the covariance between the general unknowns and the epoch unknowns are:

$$\begin{aligned} Q_{g1} &= -N^{-1}_{11} N_{g1} Q_{gg} \\ Q_{g2} &= -N^{-1}_{22} N_{g2} Q_{gg} \\ Q_{g3} &= -N^{-1}_{33} N_{g3} Q_{gg} \end{aligned} \tag{3.9}$$

It is easy to recognize the scheme in these equations. The full reduction to identity on the left part invokes the formulas for the complete inversion. The fundamental formulas are for the covariance block within one epoch:

$$Q_{ii} = N^{-1}_{ii} + N^{-1}_{ii} N_{gi} Q_{gg} N^T_{gi} N^{-1}_{ii} \tag{3.10}$$

and the covariance block between epochs:

$$Q_{ij} = N^{-1}_{ii} N_{gi} Q_{gg} N^T_{gj} N^{-1}_{jj} \tag{3.11}$$

while the generalized version of (3.9) reads:

$$Q_{gi} = -N_{ii}^{-1} N_{gi} Q_{gg} \tag{3.12}$$

The arrangement of the blocks in complete system is:

$$\begin{bmatrix} Q_{11} & Q_{12} & Q_{13} & Q_{g1} \\ Q_{12}^T & Q_{22} & Q_{23} & Q_{g2} \\ Q_{13}^T & Q_{23}^T & Q_{33} & Q_{g3} \\ Q_{g1}^T & Q_{g2}^T & Q_{g3}^T & Q_{gg} \end{bmatrix} \tag{3.13}$$

4. The software package

The models illustrated in chapter 1 - 3 are implemented in computer software. All programs carried out during this study are written in Microsoft C 6.0. The C standard provides in contrast to the FORTRAN standard the possibility to allocate dynamic arrays during execution.
The software package called MACCOI consists of several executable modules. MACCOI stands for Moving Antenna Coordinate Computation with Orbit Influence. The whole computation can be managed from a small interactive program called MACCOI_M.
In the remaining part of the chapter the capabilities of the package will be demonstrated by explaining the different menu items. The control parameters for the main program MACCOI are stored in a file called MACCOI.CFG. This file can be changed by a DOS-editor and the menu program is not needed. A printout of the control file can be found in the appendix.

4.1 Entrance menu of MACCOI_M

```
            I n t e r a c t i v e   I n p u t   M a n a g e m e n t

                     P r o g r a m   f o r   M A C C O I

1        Transform RINEX V1.0 observation file to internal binary file

2        Transform RINEX V1.0 navigation file to internal binary file

3        Edit internal binary file

4        Create and update control file for MACCOI

5        Start MACCOI main program

0        exit to DOS


         Give command: _
```

Figure (4.1)

The meaning of the commands shown in figure (4.1) is as follows:

1 starts a program used for the transformation of observation data delivered in RINEX V1.0 (Gurtner et al, 1989) to internal binary format.

2 starts a program for the transformation of navigation data (broadcast orbit) from RINEX V1.0 to internal binary format.

3 calls a binary file editor. This editor gives the user the capability to modify the internal binary observation file. Besides the approximate initial station coordinates the observation health bytes of each epoch can be modified. The health bytes hold the available information about the validity of the data stored. Particular observations are reachable to mark as invalid or the cycle slip health bit might be set.

4 creates and modifies the control data file. The control data file holds all information needed for the computation with module MACCOI.
See paragraphs 4.3 - 4.6 for more details.

5 starts the computation module MACCOI.

0 returns to DOS level.

The first two items provide the interface to import data for computations. RINEX V1.0 was introduced as a manufacture independent ASCII data representation suited for GPS data. In future additional systems such as GLONASS (russian system similar to GPS) are supported. Since most manufacturers provide routines for the transformation between receiver dependent binary formats to the RINEX standard this interface provides the most advantages. The commands 1 and 2 are needed only once for each dataset. The created binary datasets can be used for all different computational purposes within the software system.

4.2 The binary file editor

The binary file editor started with command 3 of the entrance menu provide the possibility to alter the internal binary observation file. In general there is no need to change the internal binary file using the editor as long as all information concerning the phase and pseudorange quality are available through the RINEX ASCII file. However the user of the software system might see the necessity to exclude certain observations from the computation or to mark for a possible cycle slip. Both can be done by the binary file editor. In the editor the health byte of each satellite-station combination is displayed by epochs. The status of both wavelength are handled separately in two health bytes where five bits describe in comprehensive form the quality of the associated data. Three of several possible combinations are given below.

fcrpd...	f	denotes that the carrier phase observation is measured in full wavelength
	c	denotes that this is the first measurement after a possible cycle slip
	r	denotes that the pseudorange measurement has a good quality and might be used in computations
	p	denotes a valid carrier phase measurement
	d	denotes a good Doppler measurement (no use of Doppler in this stadium of program development)
11111111		no valid information for this satellite station epoch combination
h..pd...	h	denotes that the carrier phase observation is measured in half cycles
	.	at second position denotes that there is no cycle slip
	.	at third position denotes that the pseudorange measurement is invalid

The binary editor is capable to show all data on station-epoch basis. The display fields for the health bytes are free for changes and the user can modify the switches. For instance if some phase measurements are presumedly wrong the 'p' in the health byte representation (position 5) has to be changed to '.' for the appropriate satellites in order to eliminate the observations for computations. The health byte switch for cycle slips can be set by typing a 'c' at the second position and so on. Note that the data is not removed from the internal binary file. Setting back the health byte switches activates again the associated data for further computations.
In addition the capability of changing the approximate station stored in the binary file header is provided. This approximate coordinates are used as starting values in the main program MACCOI for the computations. Usually it is not necessary to change these values as long as the values presented in RINEX are valid.

4.3 File path description menu

Figure (4.2) shows the file path description menu. In this menu the organization of the current project can be changed.

```
                    File path selection menu

Project path ..................     e:\trimble

Observation file name .........     d:\observ\trimble\trimble.wid

Broadcast orbit file ..........     e:\trimble\16001031.orb

Output file name ..............     trimble5.out

Tempfile path .................     f:\tmp
```

Figure (4.2)

Project path	gives the project path where MACCOI has to search for data files as long as no other specifications are given with file names.
Observation file name	is the name of the binary file created from the RINEX ASCII observation file.
Broadcast orbit file	is the name of the binary orbit file.
Output file name	is the name of the file where all the result will be printed during execution of MACCOI. The file will hold all information in ASCII. The file will be created on the directory specified in project path when the output file name does not include any drive or directory specification.
Tempfile path	specifies drive and directory where MACCOI can store its internal temporary files. MACCOI stores for instance the preeliminated observation information in such a temporary binary file during execution. When determining all epoch information in the second part the program needs this information in order to compute the epoch position and associated values. Note that the size of that dataset is dependent on the length of observation time used for computations. It is recommended to store that file on a large RAM drive if available.

4.4 Output control menu

Figure (4.3) shows the menu controlling the output specifications of MACCOI.

```
                    Output control selection menu

print A - matrix (epochwise) (y/n) ........  n
print N - matrix (epochwise) (y/n) ........  n
print observation "residuals" (y/n) .......  y
limit to mark "residuals" in meter ........  1000.0000
one epoch results (epoch data only) (y/n) .  y
print normal equations (y/n) ..............  n
print covariance matrices (y/n) ...........  n
scale cov. with estim. sigma**2 (y/n) .....  n
print correlation matrices (y/n) ..........  y
print corr. betw. moving coord. (y/n) .....  y
print full correlation in epoch (y/n) .....  n
print correlation between epochs (y/n) ....  y
print first and consecutive only (y/n) ....  y
print consecutive only (y/n) ..............  n
```

Figure (4.3)

A - matrix (epochwise)	The design matrix will be printed for each epoch. Since the design matrix is not created completely only relevant parts are printed.
N - matrix (epochwise)	The part of normal matrix will be printed for each epoch.
observation "residuals"	The discrepancy between computed and observed observations will be printed. The computed observations are dependent on the approximate values. However these "residuals" give a good overview on the data behavior.
limit to mark residuals	"Residuals" exceeding the given limit will be printed with a special marker in order to make it easier to find such observations in the output.
one epoch results	The results for the first iteration of each epoch will be printed in the output file. Internally the program computes one iteration with the data for the current epoch in order to get better approximate values for the moving antenna coordinates. These results will be printed. There might be discrepancies up to several meters in comparison to end values of the computation involving all available data. Note that at least one type

of pseudorange observations should be included in the computations.

normal equations	The reduced normal equations holding the general information of the computation run will be printed to the output file.
covariance matrices	The covariance matrices (inverse of the normal equation matrix) will be printed to the output file.
scale cov. with estim.sigma**2	The covariance values will be scaled with the estimated covariance of the unit weight before they will be printed to the output file.
correlation matrices	The correlation matrices will be printed to the output file. The correlation matrices are defined as usual with the exception that the diagonal elements (under all circumstances 1.0) is replaced with the square root of the diagonal element of the covariance matrix.
corr. betw. moving coord.	The correlation or covariance or both (depending on the switches above) of coordinates of the moving antenna between different epochs will be printed to the output file. When this option is specified the covariance (or correlation) of coordinate differences are printed in addition.
full correlation in epoch	The full correlation between epochs will be printed to the output file. In addition to the covariance of the coordinates of the moving antenna the values for the satellite coordinates and velocities are given. This option increases essentially the space needed for the output file. In most cases the previous described output form is sufficient.
first and consecutive only	Both of the previous options result in the computation of every possible epoch combination. Under most circumstances the correlation between the first and the current epoch and the previous and the current epoch is needed. This option reduces the size of the output file.
consecutive only	This option provides an additional reduction of the output file size since only consecutive epochs are printed.

4.5 Computation control menu

In figure (4.4) the computation control menu is given.

```
                    Computation control selection menu

use pseudoranges L1 (y/n) .....        y
use pseudoranges L2 (y/n) .....        n
use carrier phase L1 (y/n) ....        y
use carrier phase L2 (y/n) ....        n
number of ambiguities on L1 ...        5
number of ambiguities on L2 ...        0
use hom BLUP model (y/n) ......        n
position kappa in [m] .........        1.0000
velocity kappa in [m/s] .......        0.00001000
reference satellite ...........        12
start of computation [GPS s] ..        227200.000
stop of computation [GPS s] ...        227220.000
```

Figure (4.4)

options 1 to 4	allow the specification of observations to be used in the computational step. Note it is possible to use phase data only for the computation. However it is recommended to include pseudorange data in order to stabilize the system and to give the possibility to update approximate coordinates of the moving antenna.
options 5 to 6	allows to specify the maximum number of ambiguities needed for each wavelength. This information will be used in order to set up the sequence of unknowns in equation systems.
hom BLIP model	switches between computational models.
option 8 to 9	specifiy the kappa values used in case of hom BLIP model.
reference satellite	allows to give the reference satellite number for double differences. In case 0 is specified the program will use an arbitrary satellite.
start of computation	specifies the GPS time of first epoch to be included in computations.
stop of computation	specifies the GPS time of last epoch to be included in computations.

4.6 Weight specification menu

Figure (4.5) shows the menu which allows to specify the uncertainties of real and pseudo observations. One divided by the square of the uncertainty will be used as the associated weight and placed on the diagonal of the weight matrices used for computations.

```
                    Observation weight control menu

uncert. ref. station x [m] ....      10.00000
uncert. ref. station y [m] ....      10.00000
uncert. ref. station z [m] ....      10.00000
uncert. sat. position x [m] ...      100.00000
uncert. sat. position y [m] ...      100.00000
uncert. sat. position z [m] ...      100.00000
uncert. sat. velocity x [m] ...      0.00100000
uncert. sat. velocity y [m] ...      0.00100000
uncert. sat. velocity z [m] ...      0.00100000
uncert. pseudorange L1 [m] ....      2.500
uncert. pseudorange L2 [m] ....      2.500
uncert. carrier phase L1 [m] ..      0.0020
uncert. carrier phase L2 [m] ..      0.0020
```

Figure (4.5)

5. Computational results

The program system was tested using a kinematic-static observation dataset which was collected during the International Workshop Darmstadt 1988. The measurements were performed by TRIMBLE Navigation, Sunnyvale California using two TRIMBLE 4000 SLD receivers. The primary goal was the demonstration of kinematic capabilities of TRIMBLE products for kinematic applications for the determination of static coordinates during short visits with the moving antenna. The ambiguity unknowns were solved with a static measurement at the beginning of the observation period. In subsequent visits of other stations the accuracy of the computed coordinates were at millimeter level (Hyatt and Goad, 1988).

The software package developed during this study has not the goal of evaluation of static coordinates. However the test dataset is suitable for numerical tests with MACCOI.

The TRIMBLE 4000 SLD receivers measures pseudoranges under utilization of the C/A-code with an accuracy of several meters. The instrument is actually a dual frequency receiver but the early versions were not able to maintain lock on the L2 phase measurements during motion of the antenna. Therefore the instruments were just used as single frequency receivers with an increased number of tracking channels (10 instead of 5).

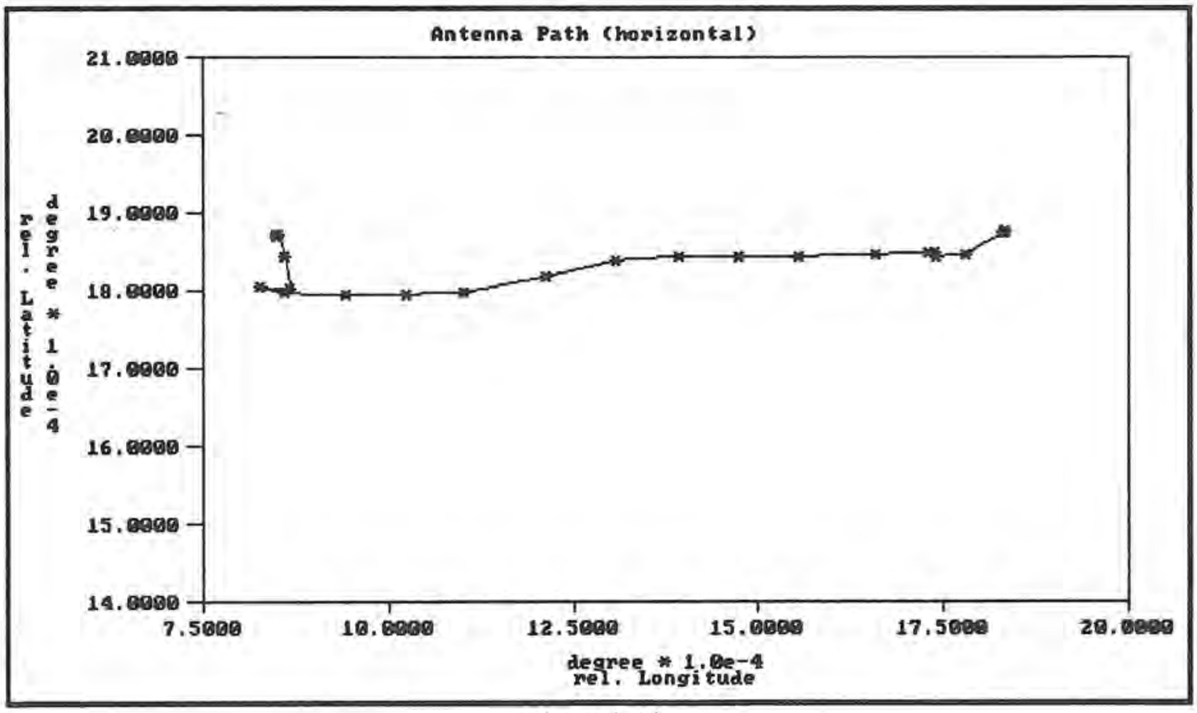

Figure (5.1)

Figure (5.1) shows the ground path of the moving antenna in units of 10**(-1) degree. The total observation interval has a length of 10 minutes and combines static and kinematic parts of the test. The uncertainty of pseudorange measurements were assumed to be 5 meter while the uncertainty of carrier phase observations were to assumed to be 0.002 meter. The uncertainties of the pseudo observations were set in case of satellite positions to 100 meters and velocity to 0.001 meter per second. The accuracy of the reference station was 10 meters. The integer biases of the phase ambiguities were estimated as real numbers which results in the high uncertainty of coordinates differences between the reference station and the moving antenna shown in figure (5.2)

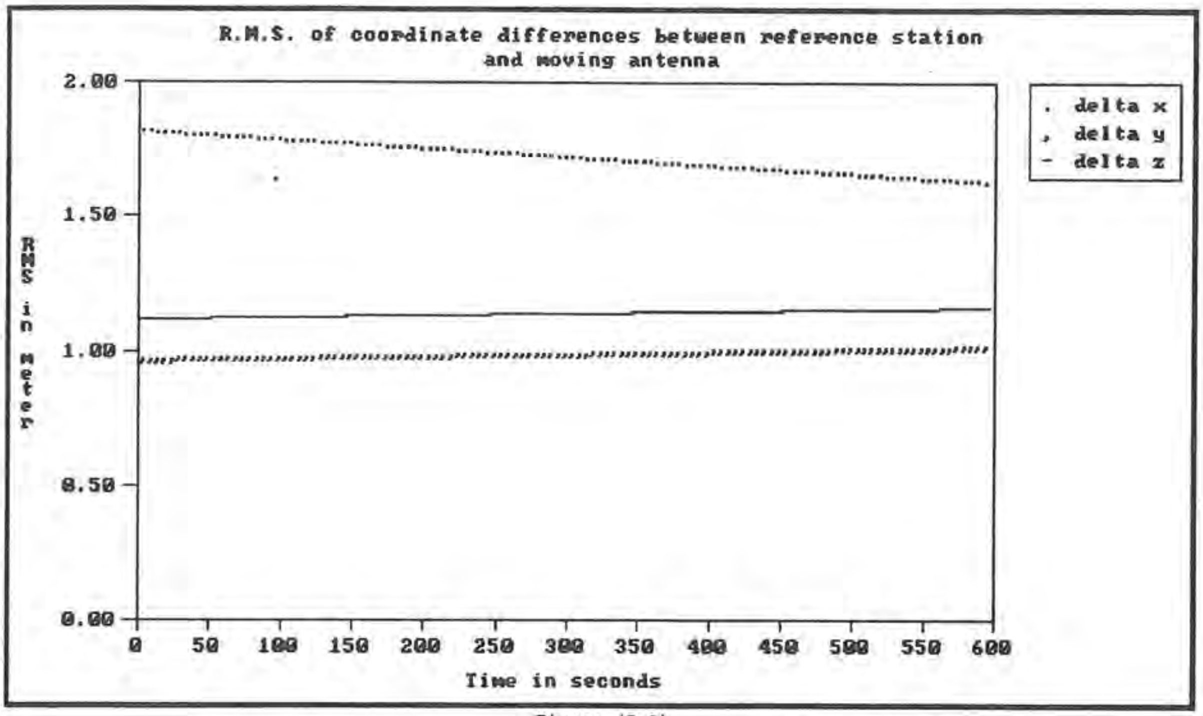

Figure (5.2)

The results for this type of difference are not better than one meter. This is of cause better than the results of pure pseudorange measurements and worse than usual accuracies reached with carrier phase measurements. The better results in comparison to pseudorange observations are due to the averaging of several epochs of measurements. The carrier phases serve only as connectors between different epochs and support the averaging process of the pseudoranges. The different sizes of uncertainties are due to the geometrical satellite constellation during the measurement period. The higher uncertainty in the x-component was quite usual in our region with Block I satellites.

The better performance of differences within the antenna path are depict in figures (5.3) and (5.4). Figure (5.3) shows the accuracies for differences between the coordinates of the first measurement epoch and the current epochs. The increasing sizes of the uncertainties in all components are remarkable. This is probably the result of non-fixed integer ambiguities which will be seen as a coordinate drift as long as the antenna is not moved.

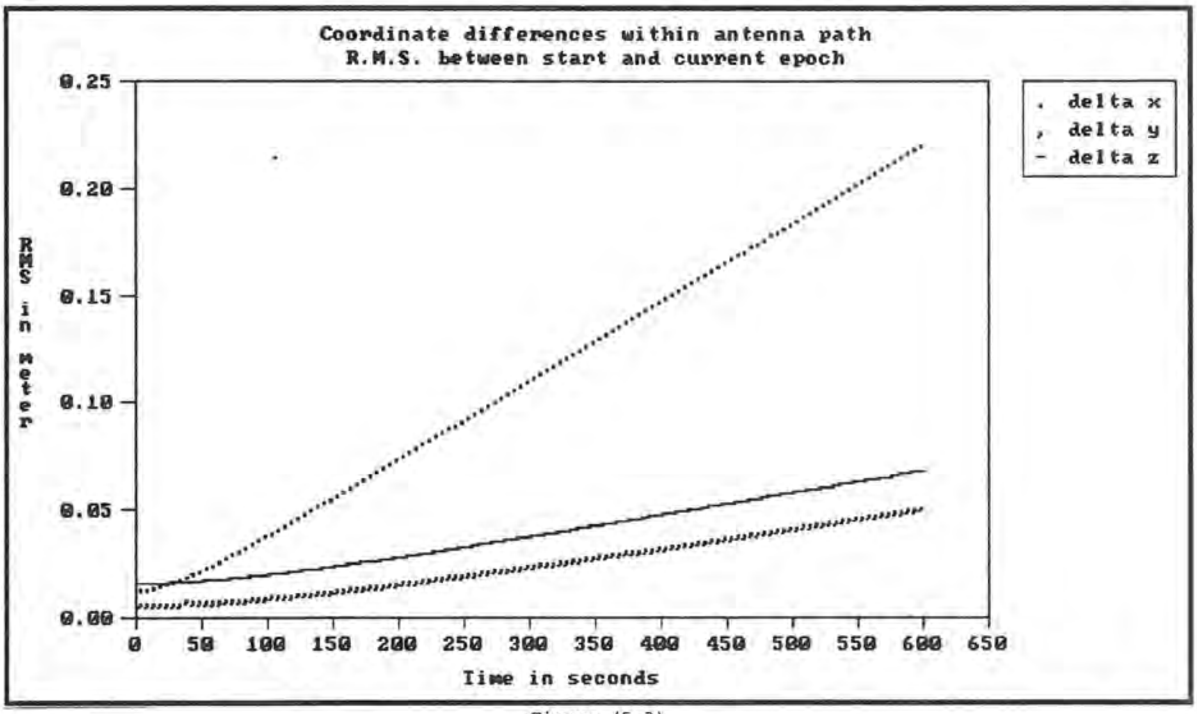

Figure (5.3)

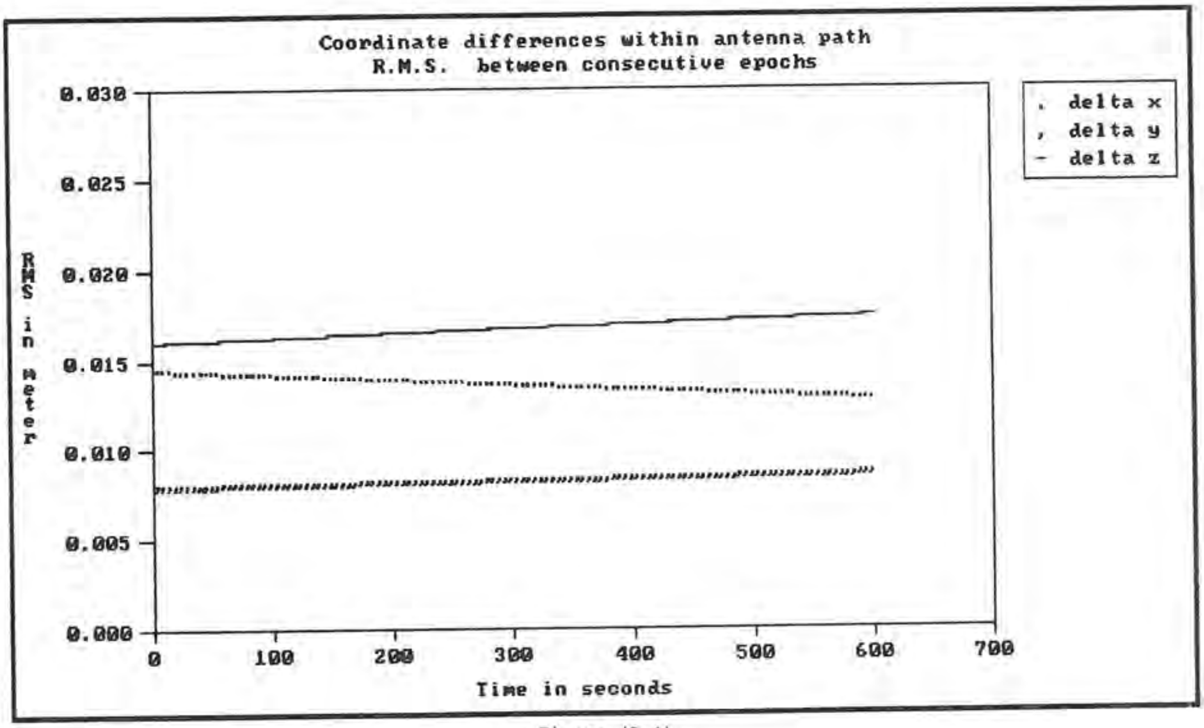

Figure (5.4)

The spike around 40 seconds of observation time is induced by a missing phase measurements on one epoch.

In figure (5.4) the accuracies of coordinate differences within the antenna path for consecutive epochs is shown. The peak of less accuracy is at the same epoch. Since the epoch with one missing satellite is now used in two differences the spike is shown twice. The increasing

uncertainty with time is vanished in this figure. The remaining changes are reflecting the change of satellite geometry during that time.
The effects on unknowns with stochastic information is very little in comparison with the assumed uncertainties. The double differencing removes a large part of the information which may contribute to the refinement on reference station coordinates and satellite unknowns. However the effect on the covariances of other unknowns is still taken in consideration.
The accuracies of the estimated ambiguity unknowns are to bad in order to allow a fixing to integer numbers. A higher performance of the pseudorange measurements would be helpful or alternatively one or two more satellites could improve these results.

6. Summary

In this study the possibilities of GPS data for coordinate determination for inertial navigation systems are shown. The high performance for coordinate differences between reference station and moving antenna was not reached. For centimeter level coordinate difference one has to solve for the integer biases of the ambiguity unknowns.
Several reasons are responsible for this lack of accuracy. First only data from a so-called C/A code receiver was available in kinematic mode for test computations. Data collected with P code receivers have better pseudorange measurements which stabilizes the computation of relative coordinates between reference station and moving antenna. Especially data of ROGUE receivers would be helpful since one might get pseudoranges with accuracies up to 0.2 meters as long as the satellites are not to close to the horizon (Euler and Goad, 1991). Another possibility would be a TI-4100 which has compared to the ROGUE the disadvantage of only 4 channels. In the near future other receivers from ASHTECH and TRIMBLE with P code pseudoranges at least on the L2 wave are available. At this time only little is known about these instruments and one has to wait for tests from manufacturer independent institutions.
Another reason for the impossibility of solving the integers is the number of available satellites during the test measurements which was at no time larger than 6. It was shown by Loomis (1989) that a number of 7 satellites are needed in order to solve for the integers while moving. However even with unsolved ambiguities the coordinate differences within the antenna path are possible with centimeter accuracy. Especially over short periods of time the accuracy is very good. With longer distances in time between the coordinates this performance is diminishing which is again a result of not fixed integers.
For the future kinematic data with more satellites should be tested. This and better pseudorange measurements are the key to better results as obtained and described in section 5.

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Appendix

Sample output of control file MACCOI.cfg:

project path	e:\trimble
widefile name	trimble.wid
broadcast orbit	d:\trimble\data\16001031.orb
output file	trimble8.out
tempfile path	f:\
A-matrix(epochwise)	0
N-matrix(epochwise)	0
obs. residual	1
limit of residual	1000.000
epoch results	1
normal equations	0
covariances	0
scale covariances	0
correlation	1
coord. corr. only	1
full corr. epoch	0
corr. betw. epochs	1
first & consecutive	1
consecutive only	0
pseudoranges L1	1
pseudoranges L2	0
carrier phases L1	1
carrier phases L2	0
# of ambiguities L1	5
# of ambiguities L2	0
hom BLUP model	0
position kappa	1.0000
velocity kappa	0.0000100
reference satellite	12
start of computation	227200.000
stop of computation	227800.000
uncert. ref. sta. x	10.00000
uncert. ref. sta. y	10.00000
uncert. ref. sta. z	10.00000
uncert. pos. sat. x	100.00000
uncert. pos. sat. y	100.00000
uncert. pos. sat. z	100.00000

uncert. vel. sat. x	0.00100
uncert. vel. sat. y	0.00100
uncert. vel. sat. z	0.00100
uncert. prange L1	5.00000
uncert. prange L2	5.00000
uncert. phase L1	0.00200
uncert. phase L2	0.00200

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