

INTERNATIONAL INSTITUTE
FOR
AERIAL SURVEY
AND
EARTH SCIENCES (ITC)
ENSCHEDA, THE NETHERLANDS

ON THE EVALUATION OF GROUND CONTROL DATA

T BOUW & M MOLENAAR

COMMISSION III, PRESENTED PAPER



FOURTEENTH CONGRESS OF THE INTERNATIONAL SOCIETY FOR PHOTOGRAMMETRY, HAMBURG 1980

ABSTRACT

On the evaluation of ground control data

The regular structure of aerotriangulation blocks simplifies the study of reliability and precision of photogrammetric point determination. As geodetic networks do not always have such a regular structure, tools should be available to check their quality. At ITC a set of programmes has been developed to analyse such networks and to adjust them. These programmes can be used by people working in practice, as well as by students who want to learn what are the limits for precision and reliability for ground control.

SOMMAIRE

A propos de l'évaluation du canevas des points d'appui

Le structure régulière des blocs d'aérottriangulation simplifie l'étude de la sûreté et de la précision de détermination de point par méthode photogrammétrique. Les canevas géodésiques n'ayant généralement pas une telle structure régulière, des moyens devraient être disponibles pour contrôler leur valeur.

Une série de programmes ont été mis du point à l'I.T.C. pour analyser et compenser de tels réseaux. Ces programmes peuvent être utilisés aussi bien par des praticiens que par des étudiants qui veulent connaître les limites en ce qui concerne la précision et le sûreté d'un canevas.

ZUSAMMENFASSUNG

Ueber die Genauigkeitschätzung von Passpunkten

Die Untersuchung nach der Zuverlässigkeit und Genauigkeit photogrammetrischer Punktbestimmung wird durch die regelmässige Struktur von Aerotriangulationsblöcken wesentlich vereinfacht.

Da geodätische Netze nicht immer eine solch regelmässige Struktur aufweisen, sollte man über Mittel verfügen um deren Qualität zu beurteilen. Das ITC hat eine Serie von Programmen entwickelt, um solche Netze analysieren und ausgleichen zu können. Diese Programme sind für den Praktiker ebenso geeignet wie für Studenten, die die Grenzen für Genauigkeit und Zuverlässigkeit der Passpunkte kennen lernen wollen.

ON THE EVALUATION OF GROUND CONTROL

by

T. Bouw & M. Molenaar

Introduction

The position of ground control points should fulfil certain requirements to guarantee the quality of photogrammetric point determination.

This quality is expressed by means of the variance - covariance matrix of the final adjusted coordinates and the boundary values of the observations. See (1, 2).

However, this quality is a function of the position and quality of the ground control points.

The problem cannow be formulated as follows:

Given the approximate position of the ground control points, how should a terrestrial network be designed, such that it meets the quality requirements?

To meet this question, a set of flexible programs has been developed at I.T.C. In this paper a description of this set will be given.

Mathematical model

For ground control 2 or more fixed points in some coordinate system are given. A set of theodolite- and/or distance measurements are used to compute the coordinates of new points.

Denote observed bearings by

\underline{b}_{ij} in which i , is the station
number, j is the number of
the targetpoint.

$i, j = \dots\dots\dots$

(The underscore denotes the stochastic character of the observations!)

In a similar way we denote the observed distances by \underline{d}_{ij} .

These observations are assumed to possess a normal distribution with mathematical expectations $E(\underline{b}_{ij}) = b_{ij}$; $E(\underline{d}_{ij}) = d_{ij}$,

variances $\sigma_{b_{ij}}^2$, $\sigma_{d_{ij}}^2$ and no correlation.

The functional relationship between observations and coordinates X_i, Y_i are for mathematical expectations: (See figure 1)

$b_{ij} = \arctan \frac{X_j - X_i}{Y_j - Y_i} + O_i \quad (1a)$
$\ln(d_{ij}) = \frac{1}{2} \ln (X_j - X_i)^2 + (Y_j - Y_i)^2 + \ln \lambda_i \quad (1b)$

(1)

O_i is the orientation parameter for point 1 and λ_i is the lengthscale factor of point i.

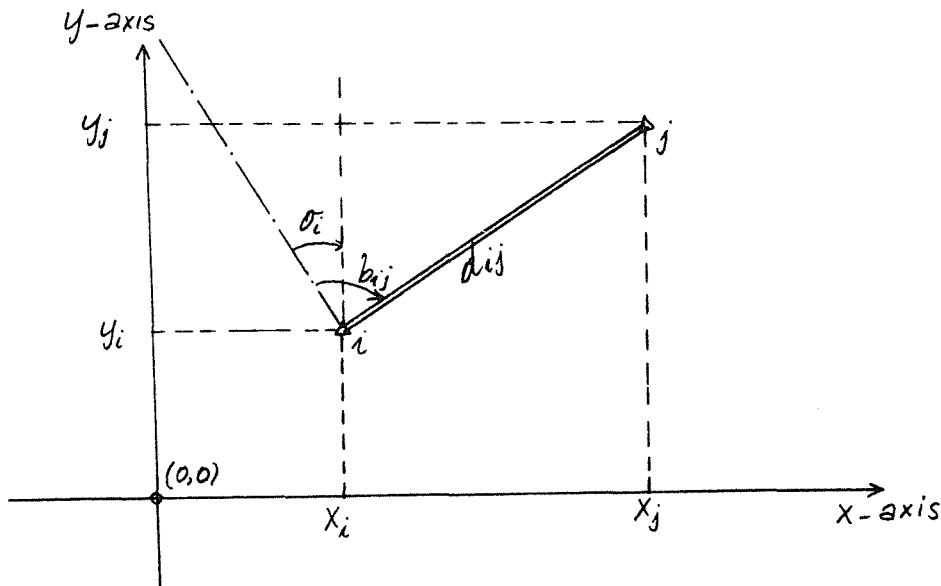


Fig. 1.

The adjustment will be based on the linearized equations (1). For observations from station i to target j we write

$$\frac{x_i - x_i}{d_{ij}^2} = p_{ij}; \quad \frac{y_j - y_i}{d_{ij}^2} = q_{ij},$$

hence the linearized equations are:

$$\Delta b_{ij} = -q_{ij} \Delta x_i + q_{ij} \Delta x_j + p_{ij} \Delta y_i - p_{ij} \Delta y_j + \Delta o_i \quad (2)$$

$$\Delta \ln d_{ij} = -p_{ij} \Delta x_i + p_{ij} \Delta x_j - q_{ij} \Delta y_i + q_{ij} \Delta y_j + \Delta \ln \lambda_i$$

(2) is valid for the mathematical expectations.

The Δ -quantities are the differences between the expectations and approximate values for observations and unknown variates, satisfying the mathematical model. Let \underline{l} be the vector of all observations with $E(\underline{l}) = l$ and approximate values l_o .

The least squares estimator is denoted by \underline{L} . Let \underline{u} be the vector of all unknown parameters with $E(\underline{u}) = u$. The least squares estimator of u is called \underline{U} . The approximate values are u_o .

(2) can now be written as

$$\Delta \underline{l} = A \Delta \underline{u}, \quad \text{in which}$$

$$\Delta \underline{l} = \underline{l} - l_o, \quad \Delta \underline{u} = \underline{u} - u_o,$$

A is the matrix with elements $(p_{ij}, q_{ij}, 1)$ ("1", for orientation or length-scale factor).

Introduce now

$$\underline{\Delta l} = \underline{l} - l_o; \quad \underline{\Delta L} = \underline{L} - l_o;$$

The least square corrections are $\underline{v}_1 = \underline{L} - \underline{l}$,

and

$$\underline{\Delta U} = \underline{U} - u_o.$$

The weight coefficients of the original observations are denoted by the diagonal matrix g_{11} .

The least squares estimator for the unknowns is given by

$$\begin{aligned} \underline{U} &= u_o + \underline{\Delta U}; \\ \underline{\Delta U} &= (A^* g_{11}^{-1} A)^{-1} A^* g_{11}^{-1} \underline{\Delta l} \end{aligned} \quad (3)$$

The corrected observations are

$$\begin{aligned} \underline{L} &= l_o + \underline{\Delta L}; \quad \text{with} \\ \underline{\Delta L} &= A \underline{\Delta U}. \end{aligned} \quad (4)$$

The boundary values for observation \underline{l}_i is: (See 1, 2)

$$\nabla \underline{l}_i = \sigma_o \frac{\sqrt{\lambda_o}}{\sqrt{g_{v_i v_i}}} \cdot (\text{For } \beta = 0.80, \lambda_o \cong 17) \quad (5)$$

The overall influence of $\nabla \underline{l}_i$ on functions of the unknown coordinates u' is:

$$\bar{\lambda}_{o,i} = (\nabla_i U')^* (g_{u'u'})^{-1} (\nabla_i U') / \sigma_o^2 \quad (6)$$

with

$$\nabla_i U = A \nabla \underline{l}_i \quad (7)$$

If ∇_{l_i} has not been detected, then its effect on the adjusted observation \underline{L}_i is:

$$\nabla_{L_i} = (A g_{uu} A^* g_{ll}^{-1}) \nabla_{l_i} \quad (8)$$

Design and Implementation of the package

The overall objectives of the program package are:

- a) Interactive use should be possible with flexible input and output. User friendliness of the package should therefore be emphasized.
- b) The package must be suitable for educational purposes (e.g. student exercises in adjustment) as well as for practical applications.

According to the above, a modular and hierarchial tackle of the package is evident. The implementation language is PASCAL (4, 9).

A collection of mutually callable modules has been written. Each of the modules performs a specific task. A short description of the task of each module is given below.

INDAT

The task of the module INDAT is to collect the input data for the reconnaissance or adjustment of the geodetic network. It creates proper formatted input-files for other modules of the package.

The list of approximate coordinates is formatted according to point number x-coordinate, y-coordinate.

For planned bearings the input-format is: stationpoint, targetpoint, bearing.

If the standard deviation for bearings is of the form: $\sigma_b = \sqrt{a_2^2 + (a_2/d)^2}$ dmgr,

where d is the sidelength in km, then a_1 is read in dmgr and a_2 in dmgr x km.

The first two diagonal elements of the weight coefficient matrix g_{11} are a_1 and a_2 .

A similar procedure holds for planned or measured distances.

Input format: Station nr. target nr. obs., instru. nr.

$$\sigma_d = \sqrt{b_1^2 + (b_2 * d)^2}$$

The output of INDAT consists of 3 files, e.g. the "point-file", the "observation-file" and the "weightcoefficient-file".

NET

NET performs an evaluation of a planned geodetic network, or an adjustment of a measured geodetic network. The adjustment according to standard problem II makes use of bearings and for distances of $\ln(d)$. The computation is based on 2 or more fixed points and any number of unknown length-scale factors.

The necessary input is provided by the module INDAT.

The output of the reconnaissance is for all observations:

- boundary values ∇_{obs} ($\alpha = 0.001$, $\beta = 0.80$) of the original and corrected observations and $\sqrt{\hat{\lambda}_0}$ (the effect of an error on any possible function of the unknown coordinates in terms of its standard deviation).

To judge the external reliability (1, 2, 5) of the geodetic net the values ∇_{coord} are also computed.

This means that per observation the effect has been computed on the coordinates of the network of an error with the magnitude of the boundary value ∇_{obs} .

- the variance-covariance matrix for unknown parameters.

For the adjustment part of NET, the output is for all observations the original and adjusted value, testvalue, conclusion of the test (data-snooping (2, 5)). Besides that the usual output is given, e.g.

- The adjusted unknown coordinates and their variance-covariance matrix
- An estimate of the variance factor $\hat{\sigma}^2$.

RECON This module generates a criterion-matrix for a network. The geodetic net has to be analysed first by the module NET.

The criterion-matrix is computed for the point field under consideration with respect to the same S-base (3, 6, 7).

The output of RECON consists of all criterion circles and the standard ellipses generated by the variance-covariance matrix as obtained by NET. If required the relative standard ellipses and circles for any two points are computed too.

STRANSF STRANSF transforms the variance-covariance matrix, as obtained by NET, to another S-base.

EIG This module solves the generalized eigenvalue problem $|G - \lambda H| = 0$
G is the transformed variance-covariance matrix with respect to a certain S-base, H is the criterion-matrix as computed by RECON, with respect to the same S-base.

The solution of the generalized eigenvalue problem provides an overall test

for the precision of the network design.

If $\lambda_{\max} \leq 1$ then the objectives of the design are met, if not, the eigenvector belonging to λ_{\max} gives an indication of the possible weak spots in the design.

See for further details (3).

The output of the module consists of the eigenvectors and eigenvalues of $|G - \lambda H| = 0$.

Remarks:

This concludes the informal description of the package.

As said before, the package is written in PASCAL, more precisely, a subset with respect to type-definitions and a super-set with respect to array parameters. The language was designed and implemented by the first author at I.T.C., Enschede. See (4, 8).

All programs written in this language are compatible with "official" PASCAL. With slight modifications the package can run on any PDP11, using the usual DEC operations systems such as DOS-BATCH, RT-11, RSX-11M.

At I.T.C. we use the VAX-11/780 running under the VMS operating system.

The following figure depict the possible calling sequence of the treated modules.

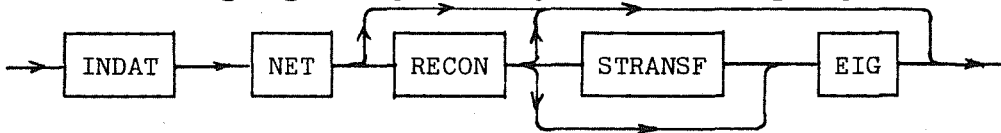


Fig. 2.

Example: As a very simple example we treat the evaluation of the NET, sketched below.

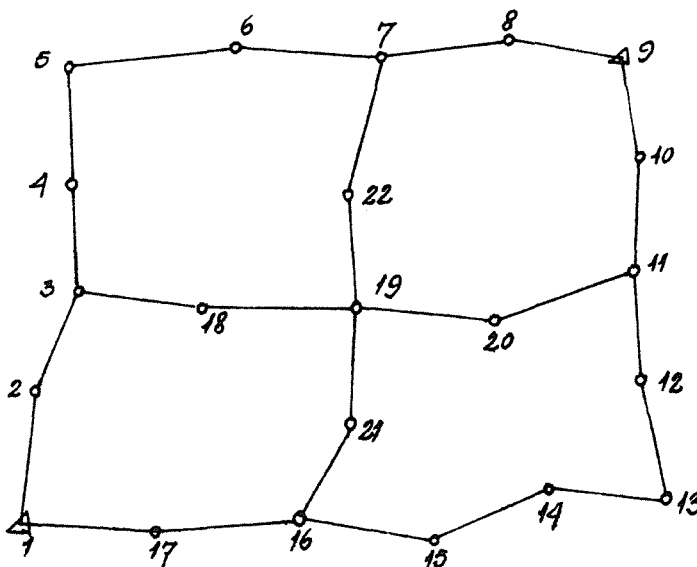


Fig. 3.

Example 1:

17 points 34 bearings 17 distances
$\sigma_{b_{ij}} = 10 \text{ dmgr}$ $\sigma_{d_{ij}} = 1.5 \text{ cm/km}$ $d_{ij} \approx 1 \text{ km}$
The points nr. 18-22 are "added" after evaluation of Example 1.

It is a simple closed traverse consisting of 17 points. In each point bearings and distances are planned to be measured. The points 1 and 9 are fixed as our S-base.

After entering the module INDAT, NET and RECON are invoked.

The maximum boundary values of the bearings taken in station 16 to target points 17 and 15 are 177.5 dmgr before - and 167.9 dmgr after an adjustment! For the distances we find as a maximum 70.4 cm respectively 69.8 cm in the sides $1 \longrightarrow 2$ and $11 \longrightarrow 12$.

The overall $\sqrt{\lambda_0}$ is equal to 56.6!

The poor behaviour of this type of single closed traverses is of course, well known. However, it might be surprisingly, that in spite of the variances for bearings of 10^2 dmgr^2 and distance-measurements of $1.5^2 \text{ cm}^2/\text{km}^2$,

"distance- and bearing errors" smaller than 70 cm and 178 dmgr can remain undetected with a probability $\geq 1 - \beta \approx 0.20$.

To obtain a global indicator of the strength of this type of net, the module EIG gives after solving $|G - \lambda H| = 0$, $c_0 = 0$, $c_1 = 1$

as a $\lambda_{\max} = 3.08 > 1$.

The conclusion after this evaluation could be:

This set-up of the network does not meet the specifications.

Therefore a second approach has been investigated, see fig. 2.

5 points are "added" and the results are:

bearings: $\nabla_{\max} = 138 \text{ dmgr}$, resp. 126.2 for station 14 to target points 13 and 14 resp. 24.0 cm, distances: $\nabla_{\max} = 25.4 \text{ cm}$ for sides

$1 \longrightarrow 2$, $12 \longrightarrow 13$.

$\sqrt{\lambda_0} = 20.6$. A significant improvement of the strength has been obtained with respect to the first design.

EIG computed as a final result $\lambda_{\max} = 1.58 > 1$.

It remains for the photogrammetrist/geodesist to decide if the network meets the specifications now.

Within the framework of the photogrammetric project one has to balance between a great number of (cost)-factors. Planning of extra observations surely can reduce the ∇_{\max} and $\sqrt{\lambda_0}$, λ_{\max} quantities, but if it is always economical, is hard to answer.

However, it is hoped by the authors that the package described can give fairly good indicators for the evaluation of ground control.

APPENDIX 1

The size of the modules is (in bytes)

INDAT	788
NET	19760
RECON	10810
STRANSF	4000
EIG	4846 +
	<hr/>
	47300 bytes.

The executive time is, as usual, a function of the size.

To give an indication, a network of 100 points 300 unknown parameters and a given working set of 500 pages of 512 bytes uses about 20 minutes CPU-time.

Doubling the working set will reduce the CPU-time by a factor of about 2.

APPENDIX 2

The following "job" program and printout demonstrates the use of the package. Underlined strings are typed in by the user.

```
BEGIN
  WRITE('DO YOU WANT TO RUN INDAT?(Y OR N) #');READLN(ANSWER);
  IF ANSWER = 'Y' THEN INDAT;
  WRITELN;WRITELN;
  WRITE('DO YOU WANT TO RUN NET?(Y OR N) #');READLN(ANSWER);
  IF ANSWER = 'Y' THEN NET;
  RECON;
  EIG;
END.
```

START PROGRAM: JOB.INT
DO YOU WANT TO RUN INDAT?(Y OR N) #N

DO YOU WANT TO RUN NET?(Y OR N) #Y

NET _ MODULE

A : RUNS ADJUSTMENT PACKAGE
E : EXIT PROGRAM
H : WRITES THIS TEXT
R : RUNS RECONNAISSANCE PACKAGE

#R
RECONNAISSANCE ROUTINE ENTERED

OUTPUT_FILE : R.RES
FILE IS OPENED FOR OUTPUT
POINTS AND CO-ORDINATES
INPUT_FILE : P1.HAM
FILE IS OPENED FOR INPUT
OBSERVATIONS

INPUT_FILE : O1.HAM
FILE IS OPENED FOR INPUT
WEIGHTCOEFFICIENTS FOR THE OBSERVATIONS
INPUT_FILE : G1.HAM

FILE IS OPENED FOR INPUT
DOES THE G-MATRIX FOR UNKNOWN PARAMETERS EXIST?(Y OR N) #N

A_IALFA ROUTINE IS ENTERED
GIVE THE POINTNUMBERS OF THE S-BASE:

#1 9
HOW MANY LENGTH-SCALE FACTORS HAVE TO BE COMPUTED? #1

G_ALFABETA ROUTINE IS ENTERED
MATINV ROUTINE IS ENTERED

G MATRIX FOR UNKNOWN PARAMETERS
OUTPUT_FILE : G.MAT

FILE IS OPENED FOR OUTPUT
DO YOU WANT TO COMPUTE THE BOUND.VAL. FOR THE COORD?(Y OR N)#Y
GIVE THE MIN. VALUE FOR BOUND.VAL. TO BE PRINTED IN CM. #10
READY

E

R E C O N _ M O D U L E

GIVE INSTRUCTION
IF YOU WANT TO RUN RECON : R
IF YOU WANT TO STOP : E
#R

OUTPUT_FILE : REC.RES
FILE IS OPENED FOR OUTPUT
POINTS AND CO-ORDINATES
INPUT_FILE : P1.HAM
FILE IS OPENED FOR INPUT
DO YOU WANT TO READ IN THE GRS-MATRIX?(Y OR N):Y
INPUT_FILE : G.MAT
FILE IS OPENED FOR INPUT
MUST G-MATRIX FOR CO-ORD BE WRITTEN TO RESULT FILE?(Y OR N) #N
DOES THE CRITERION MATRIX EXIST?(Y OR N) #N
GIVE THE PARAMETERS C0,C1 OF THE CRITERIONMATRIX

#0 2
MUST H-MATRIX BE WRITTEN TO RESULTFILE?(Y OR N) #N
HRS-MATRIX
OUTPUT_FILE : H.MAT
FILE IS OPENED FOR OUTPUT
HOW MANY RELATIVE STANDARD-ELLIPSES MUST BE COMPUTED?

#5
GIVE THE POINTNUMBERS: P1, P2
3 7
3 11
#3 16
#7 11
#11 16

GIVE INSTRUCTION
IF YOU WANT TO RUN RECON : R
IF YOU WANT TO STOP : E
#E

E I G _ M O D U L E

GIVE INSTRUCTION
IF YOU WANT TO RUN LAM : R
IF YOU WANT TO STOP : E
#R

OUTPUT_FILE : EIG.RES
FILE IS OPENED FOR OUTPUT
POINTS AND CO-ORDINATES
INPUT_FILE : P1.HAM
FILE IS OPENED FOR INPUT

H - MATRIX
INPUT_FILE : H.MAT
FILE IS OPENED FOR INPUT
1 9 0.300000E 2

DATA IS READ IN
G-MATRIX INPUTFILE:
INPUT_FILE : G.MAT
FILE IS OPENED FOR INPUT
DATA IS READ IN

GIVE INSTRUCTION
IF YOU WANT TO RUN LAM : R
IF YOU WANT TO STOP : E
#E

EXIT PROGRAM: JOB.INT

Output of NET module in case of a reconnaissance

STANDARD DEVIATIONS FOR OBSERVATIONS

BEARINGS:

$SGRT(A1A^2 + (A2/D)^2)$ DMGR., $D=$ DIST. IN KM., $A1=$ 10.0 DMGR. $A2=$ 0.0 DMGR*KM

DISTANCES:

$SGRT(B1A^2 + (B2*D)^2)$ CM., $D=$ DIST. IN KM., $B1=$ 0.0 CM. $B2=$ 1.5 CM/KM

BOUNDARY VALUES OF BEARINGS IN DMGR

STATION	TARGET	NARLA1	NARLA2	$\sqrt{LAM-RARU}$	par.	\tilde{v}_x	\tilde{v}_y
1	2	121.5	107.9	7.6	3	10.3	5.8
					4	12.2	6.7
					5	12.4	8.6
					14	7.0	10.7
					15	6.0	12.8
					16	5.1	11.2
					17	121.8	107.9
4	12.2	6.7					
5	12.4	8.6					
14	7.0	10.7					
15	6.0	12.8					
16	5.1	11.2					

BOUNDARY VALUES OF DISTANCES IN CM

1	2	70.4	69.8	45.3	2	1.2	65.7					
					3	2.0	60.3					
					4	8.0	58.5					
					5	18.1	56.1					
					6	13.0	41.3					
					7	6.3	25.3					
					8	6.0	10.7					
					10	10.1	1.3					
					11	13.0	5.7					
					12	17.8	9.2					
					13	19.8	11.7					
					14	15.8	9.3					
					15	11.5	9.1					
					2	3	66.7	66.2	47.7	3	25.9	46.0
										4	26.2	41.0
5	28.8	35.0										
6	20.8	28.8										
7	11.8	20.0										
10	11.1	3.2										
11	16.0	9.4										
12	22.4	14.9										
13	26.7	18.3										
14	21.0	17.0										
15	15.8	18.0										

3

NUMBER OF DEGREES OF FREEDOM = 12

ESTIMATION OF THE VARIANCE FACTOR TIMES 1E10 = 1.2901

BEARINGS:	STATION	TARGET	OBSERVATION	CORR.OBS	CORRECTION	TESTVALUE	CONCLUSION
	1	2	-0.0014	-0.0018	-0.0004	-0.97	
	1	17	99.9990	99.9994	0.0004	0.97	
	2	3	37.4336	37.4334	-0.0002	-0.54	
	2	1	199.9994	199.9996	0.0002	0.54	
	3	18	99.9990	99.9990	-0.0000	-0.01	
	3	2	237.4331	237.4331	-0.0000	-0.10	
	3	4	379.5162	379.5162	0.0000	0.11	

DISTANCES:

1	2	1000.000	1000.003	0.003	0.72
2	3	901.400	901.400	0.000	0.10
3	18	999.999	999.993	-0.006	-1.02
3	4	790.577	790.578	0.001	0.63

S-BASE IS (X,Y):

1	0.000	0.000
9	4500.000	3500.000

POINT	DELTA-X	DELTA-Y	CORRECTED-X	CORRECTED-Y
2	-0.016	0.000	-0.016	1000.000
3	-0.018	0.014	499.982	1750.014
4	-0.030	0.018	249.970	2500.018
5	-0.026	0.025	-0.026	3500.025
6	-0.022	0.037	1249.978	3500.037
7	0.007	0.006	2500.007	3375.006
8	-0.006	-0.009	3499.994	3749.991
10	-0.001	-0.021	4749.999	2499.979

131

Output of RECON module

C2 = 0.00 C1 = 2.00

POINT STANDARD-ELLIPSES

POINT	R	L1	L2	PHI
2	2.51	1.55	1.40	260.1417
3	2.52	2.12	1.65	261.5772
4	3.13	2.48	2.07	258.5518
5	3.94	2.06	2.86	125.9292
6	3.32	2.64	2.29	255.1569
7	2.60	2.06	1.70	229.5112
8	2.04	1.51	1.42	227.1271
10	2.11	1.56	1.46	275.5794
11	2.68	2.05	1.71	278.8653
12	3.42	2.60	2.26	267.7287
13	4.07	3.05	2.79	100.2305
14	3.40	2.72	2.32	258.9252
15	3.34	2.68	2.22	251.1360
16	2.69	2.28	1.76	242.2182
17	2.14	1.83	1.56	243.9699
18	2.40	2.19	1.64	253.0450
19	2.39	2.06	1.47	246.2422
20	2.50	2.15	1.65	263.3042
21	2.65	2.28	1.72	240.2721
22	2.40	2.06	1.59	236.9894

RELATIVE STANDARD-ELLIPSES

POINTNUMBERS	R	L1	L2	PHI
5 7	2.53	2.07	1.89	256.8961
3 11	3.84	2.57	2.30	256.1955
3 16	3.56	2.35	2.26	225.3513
7 11	3.82	2.42	2.34	174.4699
11 16	2.63	2.22	1.90	230.7448

R = radius of the criterion circle

L₁ = half major axis of standard ellips

L₂ = half minor axis of standard ellips

PHI = angle between major axis and positive y-axis.

REFERENCES

- (1) Baarda, W. : Statistical Concepts in Geodesy,
Netherlands Geodetic Commission, Vol. 2, nr. 4.
- (2) Baarda, W. : A Testing Procedure for use in Geodetic Networks.
id., Vol. 2, nr. 5.
- (3) Baarda, W. : S-Transformations and Criterion Matrices.
id., Vol. 5, nr. 1.
- (4) Bouw, T. : A description of the PASCAL-O system.
- internal report, I.T.C., Enschede.
- (5) Molenaar, M. : Essay on empirical accuracy studies in Aerial
e.a. Triangulation. I.T.C.-Journal 1978-1.
- (6) Molenaar, M. : A further inquiry into the theory of S-transfor-
mations.
- in preparation, I.T.C., Enschede.
- (7) Molenaar, M. : S-transformations and criterion matrices in
photogrammetry. I.T.C., Hamburg Commission III.
- (8) Kathleen Jensen : PASCAL, User manual and Report, Second edition,
Niklaus Wirth Springer-Verlag.
- (9) Digital Equipment Corporation : VAX11-780 - Architecture Handbook.