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Design and Implementation of Computer Programs for Analysis and Detection of Spatial Deformation

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Abstract

This paper summarised the strategy developed for geometrical detection of spatial deformation using geodetic method. This developed strategy has been implemented in five computer programs (ESTIMATE, COMPS, COMON, DETECT AND ROBUST). The test results are also presented.

1.0 INTRODUCTION

Deformation survey or monitoring of deformation is an important area of engineering surveying. Its prime purpose is the detection of spatial deformation to provide for information on the stability and extent of any movement or deformation of an object occuring over time. Information obtained from the detection process is useful for the purpose of safety assessment, as well as for predicting and preventing the possibility of failure or disaster in the future.

The commonly adopted methods for monitoring deformation in engineering are based on the repeated observation of a survey monitoring networks at different epochs, followed by two-step analysis (i.e. independent least squares estimation (LSE) of single epoch and deformation detection between epochs). The detection of deformation uses two-epoch analysis, an absolute monitoring approach and a static model to compare the coordinates between the epochs. Further details on the relevant aspects of deformation detection can be found in Niemeier et al (1982), Chen (1983), Gruendig et al (1985), Fraser and Gruendig (1985), Teskey (1986), Chrzanowski and Chen (1986), Chrzanowski et al (1986), Secord (1986), Caspary (1987), Cooper (1987), Biacs (1989), Teskey and Biacs (1990), Chrzanowski et al (1991), Bayly and Teskey (1992) and Halim (1995a).

Extensive research work has been carried out on LSE and deformation detection in Europe and North America, involving many sophisticated methods. However, very little effort has been made to arrive at a simple and practical, but rigorous, method suitable to the practising surveyor. In most cases, the applications are restricted to two dimensional (2-D) or one dimensional (1-D) only (Dodson, 1990), whilst deformation actually occurs in 3-D. Usually, the deformation detection procedure consists of two-stage computations (Gruendig et al, 1985; Chen et al, 1990a): analysis of the reference points followed by analysis of the whole network.

This paper presents the design and implementation of computer programs for geometrical detection of spatial (3-D) deformation using geodetic methods. Section 2.0 highlights the important requirements for deformation detection. This is followed by a description of the strategy and computer programs developed for geometrical detection of spatial deformation. Section 5.0 discusses the results obtained from the application of the developed computer programs using simulated data to assess the adopted strategy. Finally, section 6.0 summarizes the outcome of the study.

2.0 REQUIREMENTS FOR DEFORMATION DETECTION

The stages of LSE and deformation detection are highly critical and need special attention because the significance of the estimated deformations depends on the observational accuracy and network design. In most engineering cases, the magnitudes of deformation to be detected are small, and at the margin of observational error. In LSE, a realistic mathematical model is needed because an erroneous model will lead to apparent deformation. During deformation detection process, it is required to transform the results into a common datum, identify a set of stable points and localize the deformation.

In general, LSE suffers from rank deficiency due to configuration and / or datum defects (Cooper and Cross, 1988, 1991). Normally, datum defects are handled by means of constraints (Koch, 1987), whilst configuration defects can be removed (during the design stage) by introducing additional measurements.

The most common choices of datum for the monitoring network are minimum constraints (or zero variance computational base), minimum trace (or inner constraints or free network) and partial minimum trace datums. The estimated solutions are called minimum constraints, minimum trace and partial minimum trace solutions respectively. A more detailed explanation can be found in Caspary (1987) and Biacs (1989).

The general procedure for detection of deformation assumes common stations and similar datum definition between the two epochs. In other words, the analysis is restricted to common points only. However, in practice, epochs may have differing network configuration, different numbers and types of observations, different numbers of stations, and possibly different datum definition. Therefore, it may be necesary to transform the LSE results of each epoch into common stations and datum prior to detection of deformation.

Another important aspect is that no stations are to be assumed stable until tested for stability. Hence, a method for identifying and testing the stable common points to be used as datum (or computational base) is needed, followed by the localization of deformations (i.e. transformations of results with respect to the selected datum points). In terms of statistical verification of the estimated results, both global and local tests are needed. Such statistical testing on the estimated deformations are used to establish whether significant movements have or have not occured between the two epochs.

3.0 STRATEGY

As shown in section 2.0, the analysis procedure requires amongst others, the independent LSE of each epoch, the transformation of LSE results into a common datum, determination of common stations between epochs, identification of a set of stable points, and the localization of deformation together with the appropriate statistical testing (globally and locally). Consequently, a strategy has been developed for 3-D LSE and one-stage geometrical detection procedure (Halim, 1995a).

In LSE, the main modules includes:

- a simple datum definition via minimum constraints with fixed coordinates
- rank defect analysis of normal equations by simplified eigenvalue decomposition (EVD)
- use of additional parameters and pseudo observables for handling systematic errors
- robustified LSE for multiple gross errors detection
- simple method of variance component estimation (VCE)
- global and local tests and reliability analyses

The strategy developed for deformation detection consist of:

- determination of common stations between epochs via S-transformations and partitioning
- a flexible one-stage computational procedure for geometrical detection of spatial deformation by iterative congruency testing and S-transformations
- robust method for deformation detection

- application of the general S-transformations equations
- an optimised computational procedure for S-transformations

The strategy for 3-D LSE and deformation detection is summarised in Figures 3.1 and 3.2 respectively.

4.0 PROGRAM DESIGN AND IMPLEMENTATION

The developed strategy (section 3.0) has been implemented in five computer programs for 3-D application as the following (Halim, 1995a, 1995b):

a. ESTIMATE for 3-D LSE of local monitoring networks using terrestrial observations.
b. COMPS for 3-D S-transformations of LSE results from one datum to another, prior to deformation detection.
c. COMON for 3-D determination of common stations between two epochs, with the necessary re-ordering and S-transformations with respect to the common stations.
d. DETECT for geometrical detection of spatial deformation between two epochs based on congruency testing.
e. ROBUST for geometrical detection of spatial deformation between two epochs based on a robust method.

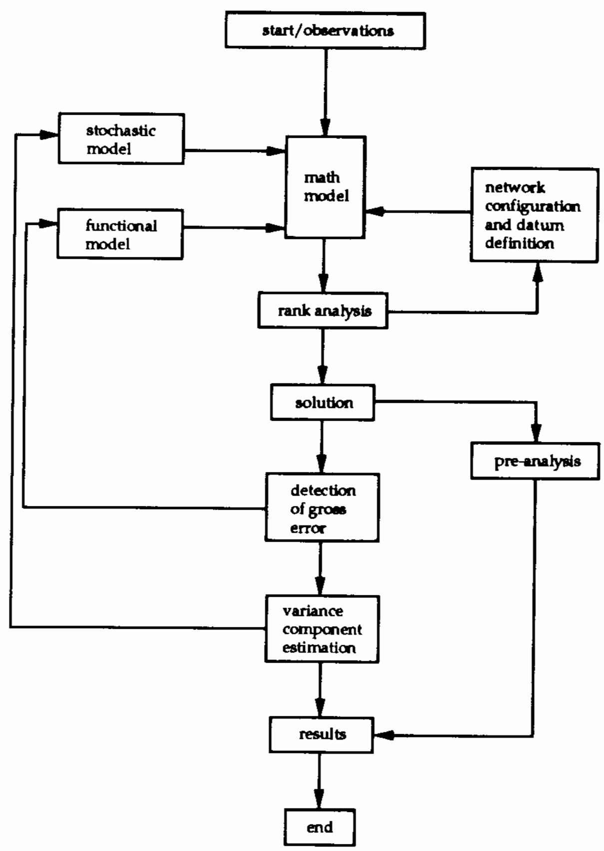


Figure 3.1 Strategy for LSE of a single epoch

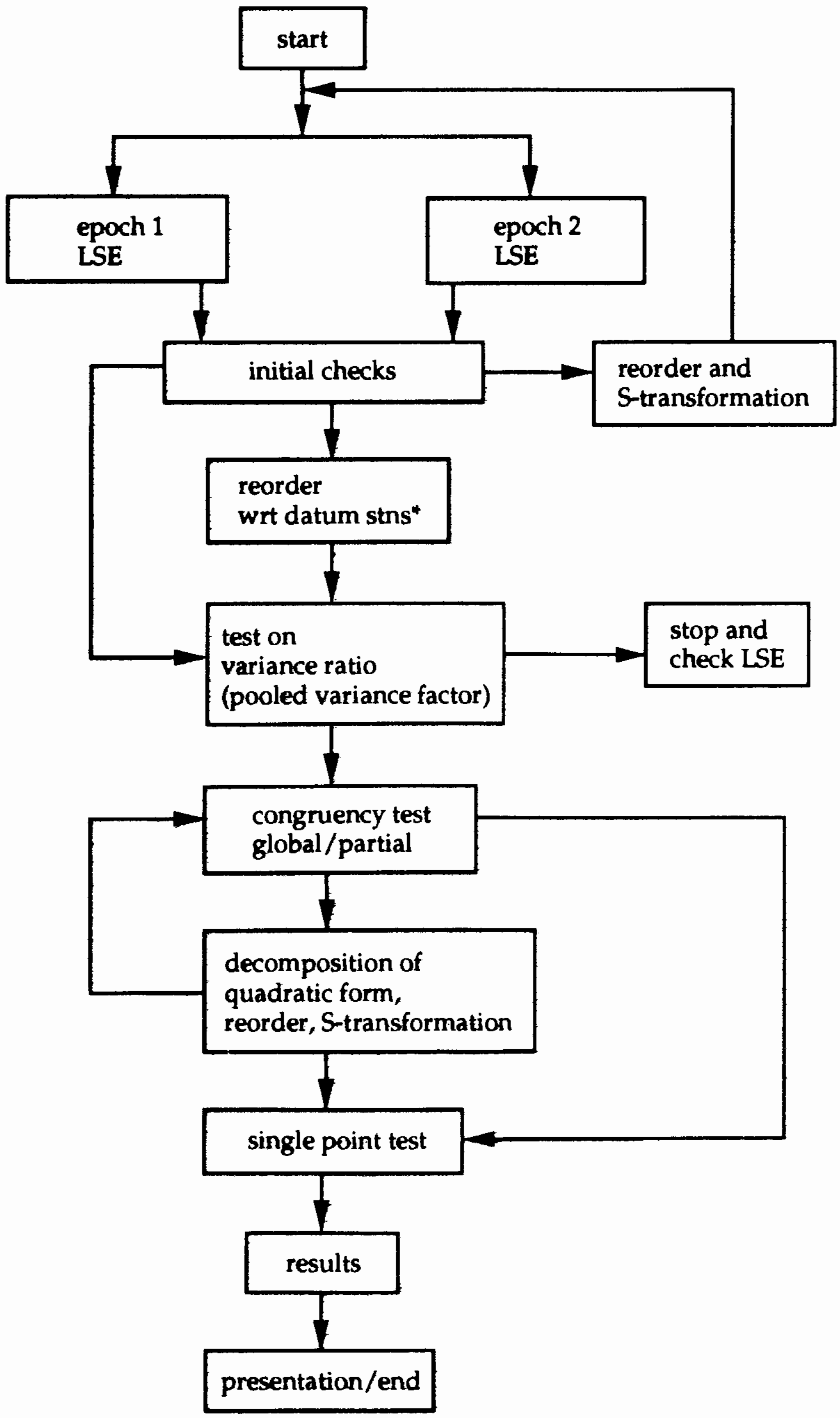


Figure 3.2 Strategy for geometrical detection of spatial deformation

Figure 4.1 demonstrates the links between the programs. ESTIMATE is useful for LSE at each epoch. If datum (and hence stable) stations are known prior to deformation detection, results from LSE can be transformed via COMPS. Generally, assuming different stations and datums, and before proceeding with deformation detection, COMON can be used to search for common stations between epochs, with the appropriate S-transformations. DETECT or ROBUST can be used for geometrical detection of spatial deformation via one-stage computation (i.e. stability determination and localization of deformation), and provide numerical results.

Figures 4.2 and 4.3 show the design of programs ESTIMATE and DETECT respectively. All the computer programs were written in FORTRAN77, and were developed for applications on both personal computer (PC) and UNIX environments. FORTRAN77 (Dyck et al, 1984) was used mainly due to its powerful computing ability, and compatibility between PC and UNIX compilers.

In general, all the programs are interactive in nature to allow users some flexibility in decision making, such as computation modes, continuation of computations, selection of significance level for statistical testing, creation of output files and termination of the programs. Whenever necessary, the programs automatically compute approximations of critical values for statistical tests, using the formulations of Cooke et al (1990). For program portability between PC and UNIX environments, all routines are developed independently, and no external routines are used.

In terms of storage, single arrays are used in most cases, using the strategy outlined by Healy (1986). Some of the dummy arrays are used repeatedly. For cofactor matrix, only upper triangles are stored in single arrays. Error checking and trapping methods are included, on both input errors and singularity. The program will be terminated automatically if either data input files are not available, on the existance of input errors or singularity.

Although the programs provide the results numerically, a more helpful presentation of the results is in the form of graphics plots. For this purpose, a special graphics program developed by Chandler (1994) at the Engineering Surveying Research Centre (ESRC) City University (London) called DCRE is used. This program runs under the INTERGRAPH MicroStation environment, and has a flexible on-screen graphics capability of showing plots of results of LSE and deformation detection. For example, plots of points, station names, error ellipses and deformation vectors can be produced. Error ellipses can be also portrayed in three axes, xy, xz and yz.

In order to use DCRE, the outputs of all five implemented programs are produced so that they are compatible with input for DCRE. Each program can produce an additional specialised output file as input for DCRE if requested. Three types of input format for DCRE are used for plots of the networks, plots of stations with ellipses, and plots of deformation vectors with ellipses.

Programs ESTIMATE, COMPS and COMON produced deformation files suitable for deformation detection. For initial datum definition in detection process these files may be edited.

ESTIMATE is capable of processing sixteen types of terrestrial surveying data. Programs COMPS, COMON, DETECT and ROBUST, however, are capable of processing LSE results obtained from any combinations of surveying, photogrammetry and / GPS data, because the datum defect forms part of the input data (Halim, 1995a).

In practice, interpretation of the results obtained from the usage of the above programs is very helpful. In LSE (via ESTIMATE), the solutions should pass both the global and local tests. Failure of the above tests requires the application of strategies outlined earlier. Moreover, the precision and reliability analyses must be acceptable too. In geometrical detection of spatial deformation (program DETECT or ROBUST), it is expected that all datum points will be stable, while non-datum points can be either stable or unstable as indicated by the single point test (Halim, 1995a).

In program DCRE, views can be rotated about three axes, and the standard views are: top, bottom, right, left, front, and isometric view. Top (or plan), front and right views can be used to show ellipses and deformation vectors in xy, xz and yz planes respectively. The isometric view is useful for portraying the trend of overall movements. Figure 4.4 is an isometric view of a cube to show the concept of 3-D views.

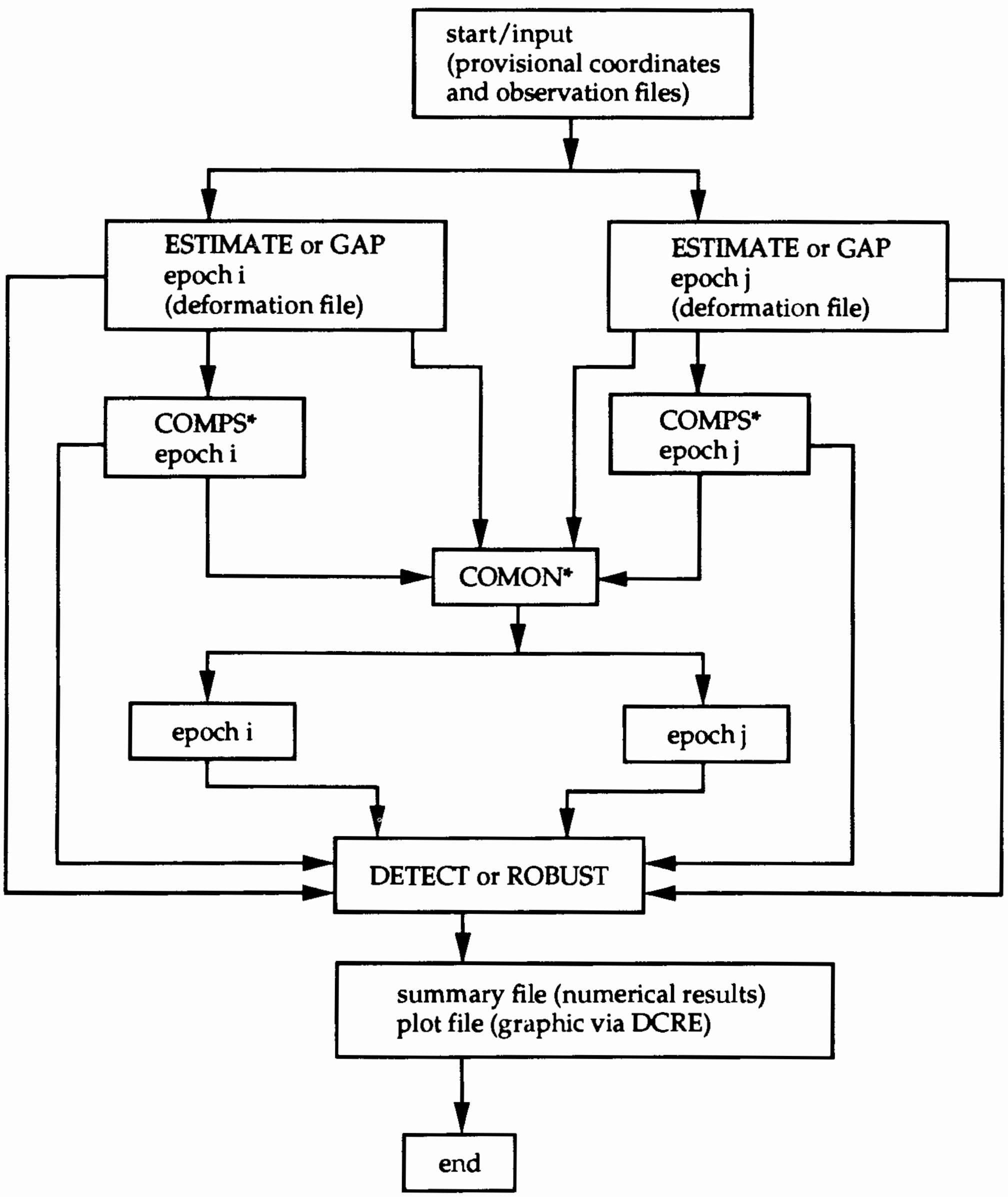


Figure 4.1 Linking the programs for geometrical detection of spatial deformation

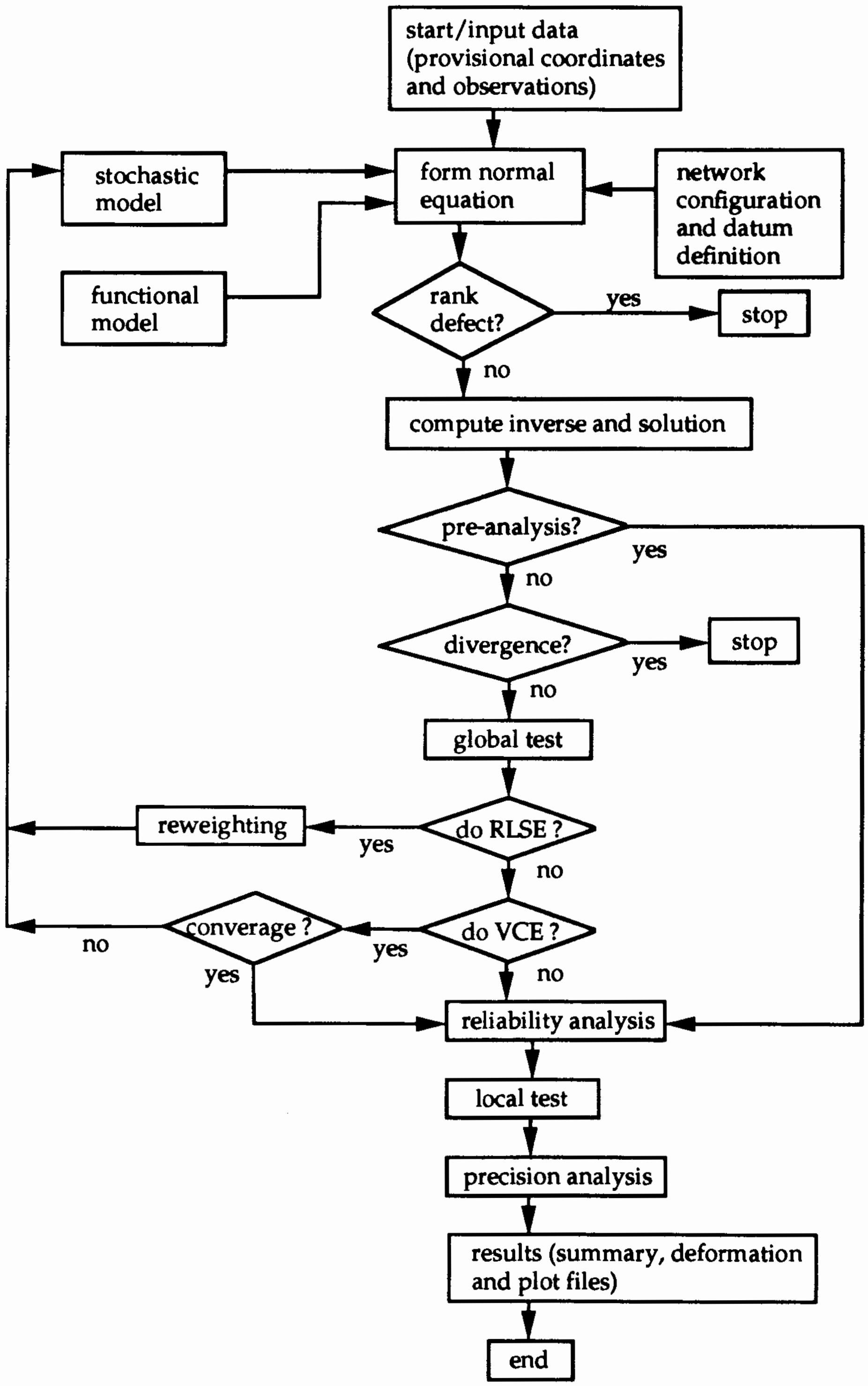


Figure 4.2 Flowchart for program ESTIMATE

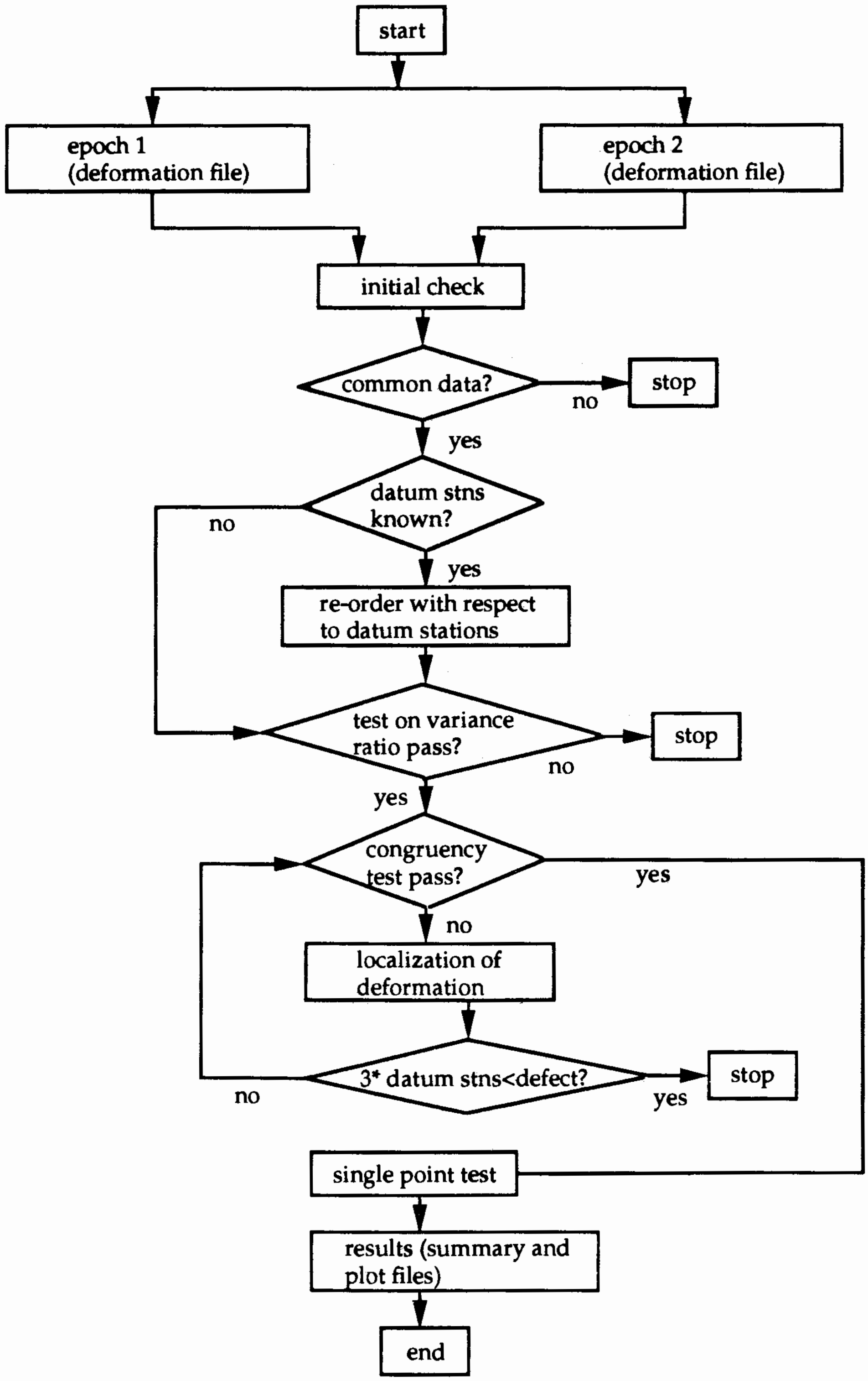


Figure 4.3 Flowchart for program DETECT

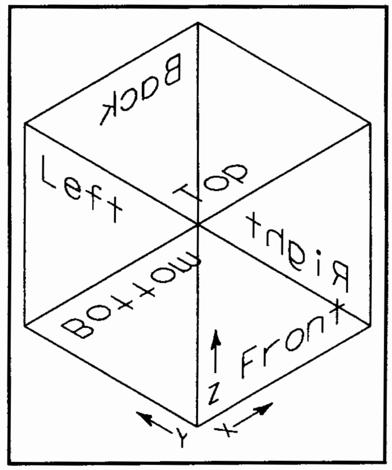


Figure 4.4 Concept of 3-D views

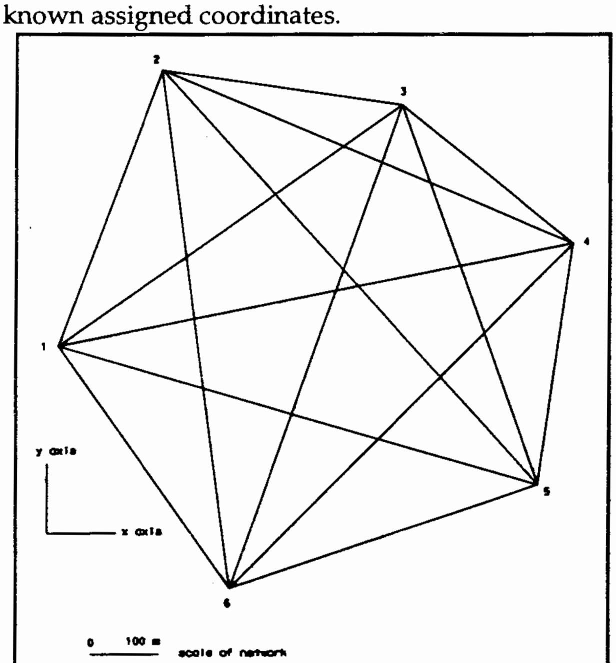
Graphically (program DCRE), plots of displacement vectors for stable datum points will be within the ellipses describing the confidence regions. On the other hand, plots of displacement vectors for unstable non-datum points (i.e. with significant movement) will be outside the ellipse.

5.0 TEST RESULTS

A simulated surveying network has been used to demonstrate the applicability of the strategy for detection of spatial deformation. The significance level for testing in LSE and deformation detection was chosen as 0.05, except for the single point test, where a significance level of 0.01 was used.

Figure 5.1 is a simulated six station 3-D network consisting of 54 uncorrelated observations (12 slope distances with a simulated random error σ of 5 mm, 30 horizontal directions with σ of 5 secs and 12 height differences with σ of 5mm). The randomized observations are free from both systematic and gross errors because they are derived from known assigned coordinates.

Figure 5.1 Test network (plan view)



The rank deficiency is 4 (i.e. 3 translation and one rotation about z axis), and is removed by fixing coordinates x_1, y_1, z_1 and y_3. The number of parameters is 20 (14 coordinates and 6 orientation unknowns), giving rise to 34 degrees of freedom. The commonly accepted significance level α of 0.05 is used for most statistical testing.

The following deformations were simulated at stations 3, 5 and 6 to generate data for a second epoch:

station	simulated deformation (m)		
	dx	dy	dz
1	-	-	-
2	-	-	-
3	-0.050	+0.100	-0.100
4	-	-	-
5	+0.010	+0.050	-
6	-	-	+0.300

Table 5.1 Simulated deformation

LSE for each epoch was carried out, using program ESTIMATE, by minimum constraints, i.e. fixing x_1, y_1, z_1 and x_3. This was followed by deformation detection using DETECT.

The LSE results for each epoch passed both global and local tests. The variance estimated factors were 0.814 and 0.593 for the first and second epochs respectively.

As both epochs use the same stations and datum, deformation detection can be proceeded straight away. LSE results for each epoch passed the test on variance ratio, indicating the compatibility of the variance factor of each epoch. An initial run of DETECT lead to the failure of global congruency test, confirming the existence of deformation.

Initially, all stations were used to define the datum. Starting with 6 datum stations, the successive process of removing suspected points from the datum was repeated until a (partial) congruency test passed. This resulted in 3 datum stations (1, 2 and 4) for the final computations. All the datum points passed the single point test and were confirmed as stable. Points 3, 5 and 6 failed the single point test and were suspected as significantly deformed. The estimated deformation obtained via DETECT for each case was very close to the simulated deformation (Table 5.1), as summarized in Table 5.2.

For further verification, COMPS was used to transform the LSE results of each epoch with respect to a new datum defined by stations 1, 2 and 4. The coordinate differences between epochs were computed using DETECT, and the results are the same as the estimated solution in Table 5.2.

The graphical presentation of the solution using DCRE is depicted in Figures 5.2 to 5.5, and clearly shows that stations 3, 5 and 6 lie outside the ellipses. The deformation trend shown in Figure 5.2 indicates the movement of stations 3, 5 and 6. Figure 5.3 demonstrates movement of stations 3 and 5 in the xy directions, while Figures 5.4 and 5.5 show movement of station 6 in the z direction and station 3 in the xz and yz directions respectively.

station	dx	dy	dz
1	-	-	-
2	0.001	-	-
4	-0.001	-	-
6	0.001	-0.001	0.300
3	-0.050	0.100	-0.100
5	0.012	0.051	-

Table 5.2 Estimated deformation via DETECT
(Datum stations comprised of stations 1, 2 and 4. Unit m)

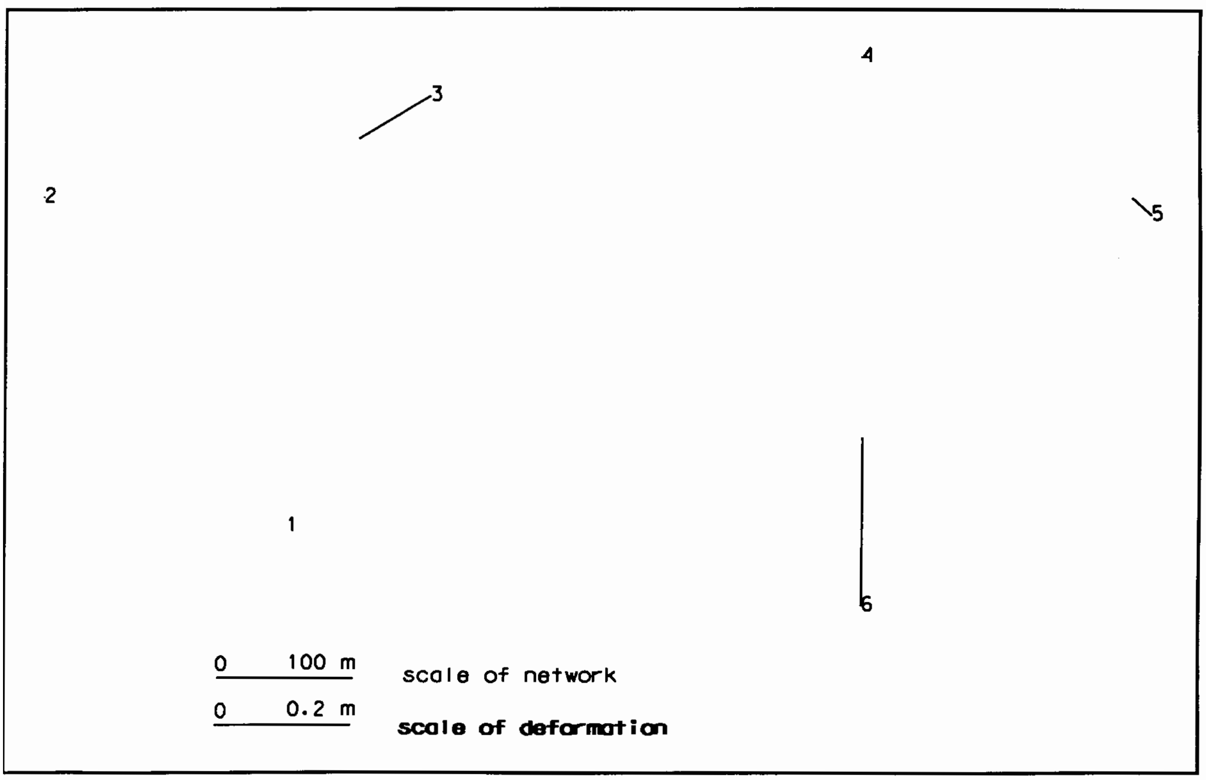


Figure 5.2 Estimated deformation via DETECT (isometric view)

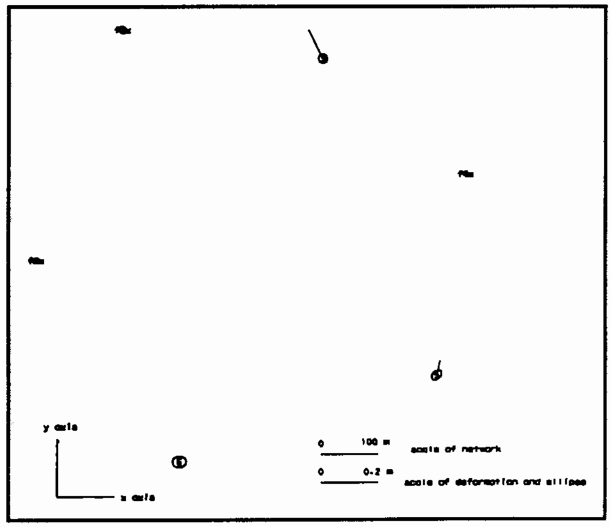


Figure 5.3 Estimated deformation via DETECT (plan view)

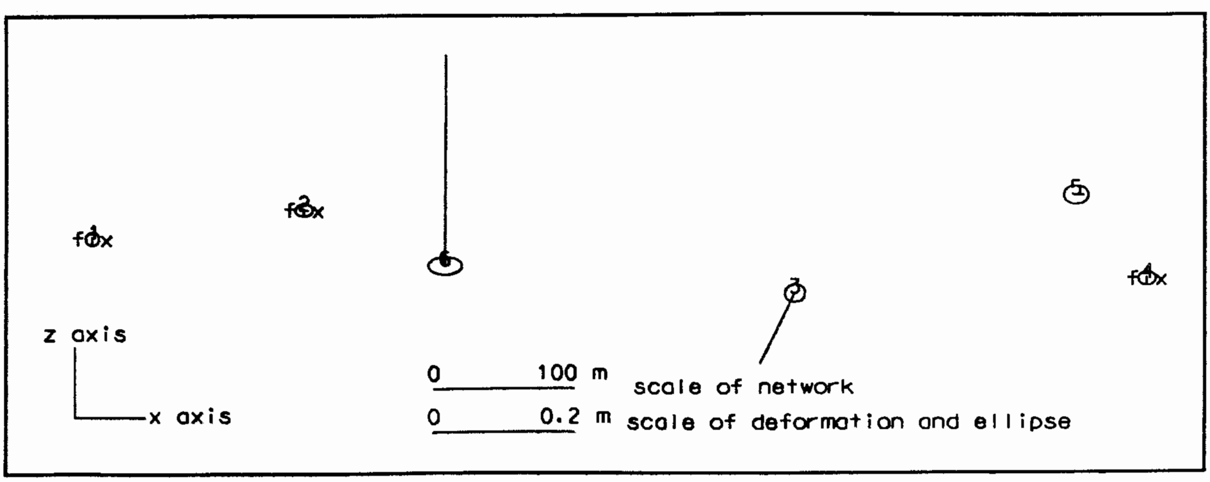


Figure 5.4 Estimated deformation via DETECT (front view)

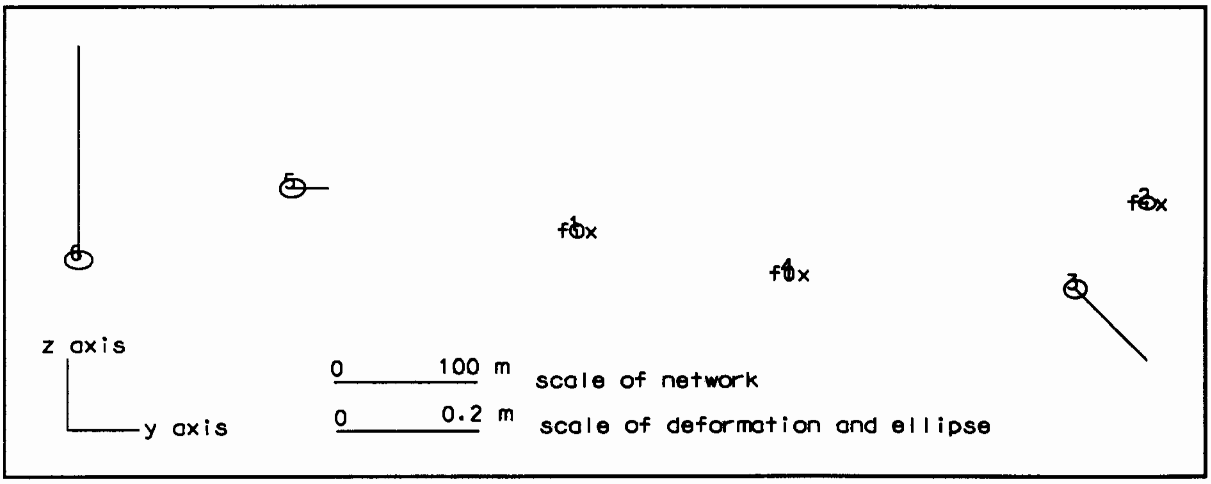


Figure 5.5 Estimated deformation via DETECT (right view)

6.0 CONCLUSIONS

The results obtained in section 5.0 show that the computer programs are applicable for the geometrical detection of spatial deformation. Agreement of the results with known data demonstrated that the adopted procedure has fulfilled its expectations.

The developed programs have been successfully applied using real data. To date, five real photogrammetric monitoring schemes undertaken by ESRC, with up to 169 stations were analysed for detecting the significance of spatial deformation between epochs. The results obtained confirmed the suitability of the strategy in practical applications (Cooper, 1994; Robson, 1994; Halim, 1995a; Robson et al, 1995).

The programs can be refined to make them more attractive and user friendly. For example by the inclusion of on-screen graphics display so that the relevant plots can be viewed directly during computation.

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