Development of a Computer Software for the Monitoring of Subsidence

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Abstract

A computer software has been developed at the Faculty of Geoinformation Science and Engineering, UTM for the purpose of detecting subsidence of ground surface or man-made structure by using Visual Basic 6.0 and FORTRAN computer languages. This software can be used for processing data from GPS and precise levelling methods. The software requires GPS baseline vectors (ΔX, ΔY, ΔZ). Relative ellipsoidal heights based on the WGS84 ellipsoidal surface must be derived from these baseline vectors. The derived relative ellipsoidal heights are then adjusted using least square estimation method. The adjusted heights will be used for further subsidence analysis. S-transformation is used to transform results from least square estimation using minimum constraints to a selected datum. This paper examines the method of subsidence using the iterative weighted transformation. In this method, the stability of reference points must be checked through a single point test. Stable points will then be adjusted again together with object points. Lastly, the stability of object points will be determined. User of this software requires little knowledge on deformation monitoring processing, as the user needs to follow the procedure of inputting data required by the software. The output from the software will give the stability of the all control points whether they have moved or otherwise.

1. Introduction

The importance of monitoring subsidence has been discussed in Hothem (1986), Krakiwsky, (1986) and Rusli et al. (2000a, b). Subsidence of ground surface due to fluid withdrawal, caving in, cities or reservoir load and tectonic movement need to be monitored to avoid any destructive effects to the environment (Krakiwsky, 1986). One of the recent research undertaken by Universiti Teknologi Malaysia is on subsidence monitoring in Kelantan due to the withdrawal of underground water and a current research on subsidence of oil platform due to gas extraction in the gas field off Terengganu coast. These activities of groundwater and gas withdrawal and the construction of high rise building such as KLCC in Kuala Lumpur have raised the importance of deformation survey for monitoring any vertical displacement or subsidence at that area. This is necessary to avoid any disaster such as the lost of lives as what had happened in the tragedy of Highland Tower from repeating. Although many methods can be used for detecting of subsidence such as geodetic and geotechnical, the paper only discusses the geodetic method that is generally used by surveyors. This paper discusses the procedure for detecting the stability of reference stations in monitoring of subsidence (1D) based on a robust method. Computer languages of FORTRAN and Visual Basics 6.0 are used to develop the computer programs for the purpose of detecting the stability of reference stations.

2. Height determination

The heights of reference points are derived from Global Positioning System (GPS) measurement that usually computes in Cartesian Coordinates System (X, Y, Z) (Strang & Kai Borre, 1997 and Wolf & Ghilani, 1997). Before the height of reference points can be used in the computer programs, these coordinates system needs to be transformed into another coordinates system (ϕ, λ, h) which give the height of a point in the form of ellipsoidal height (h) or height difference (Δh). GPS ellipsoidal heights are very useful for deformation and subsidence studies and other applications where the relative change in height from one epoch to another is required. Demonstration test projects have yielded results showing that observations of GPS satellite signals will yield very accurate height differences at the few mm to cm level (Hothem, 1986). Conventionally, height of a point can also be obtained by geodetic levelling; and such height is always referred to as orthometric height (H). The relationship between ellipsoidal height and orthometric height as shown in Figure 1, need to be fully understood so that a common vertical datum can be used for deformation analysis.

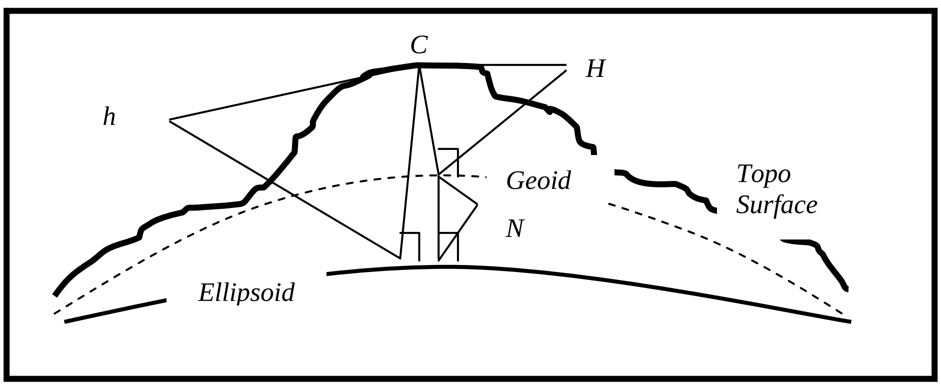

Figure 1: Vertical position or elevation of point C in object space is given in terms of its vertical distances above or below a datum surface. H indicates the orthometric height, h is the ellipsoidal height and N is the geoid-ellipsoid separation.

3. Adjustment and Analysis of Control Network

In every deformation survey, at least two epochs of observation of a network of reference stations are required for the deformation process to be carried out. These observation data have to go through a least square estimation (LSE) process to detect any error that may exist during observation. All systematic and random errors must be eliminated before deformation process can be carried out. The procedure of LSE for a levelling network has been discussed in Caspary (1987), Halim (1995) and Wolf & Ghilani (1997) among others. In the LSE, the observations of each epoch made on the reference stations are adjusted independently and the adjusted heights of each station are computed. One of the reference stations which is considered as datum point in the network need to be held fixed in order to compute the adjusted or estimated heights of other stations in the network. The computation involves the following equations:

$$v_{ik} = Ax - \Delta h_{ik} \tag{1}$$
$$H_i = H_i^0 + \delta H \tag{2}$$
$$\hat{v} = A\delta H - \Delta h \tag{3}$$
$$(A^T WA)^{-1} \delta H = A^T W \Delta h \tag{4}$$
$$\delta H = (A^T WA)^{-1} A^T W \Delta h \tag{5}$$
$$\hat{\sigma}_0{}^2 = \left(\frac{v^T W v}{df} \right) \tag{6}$$
$$Q = (A^T WA)^{-1} \tag{7}$$

Statistical tests are used to assess the results of LSE. The tests used in this study are test on estimated variance factor (i.e. global test) and the outlier test (i.e. local test). The one-tailed global test is adopted in this study. If the global test passes, it is assumed that, overall, there are no model or gross error, and the results of LSE can be accepted. Failure of this test indicates the model is incorrect or incomplete, or the existence of gross errors in the measurements. Hence, further investigations or statistical test are needed. The outlier or local test examines the standardized residuals (result from Eq. 3) where the observations contain any gross error or free from gross error. The statistical tests are carried at a 95% confidence level. More details on statistical tests are found extensively in surveying literature, for example Mikhail (1976), Cooper (1987), Leick (1990) and Cooper & Cross (1991) to name a few.

In this study, the LSE results for each epoch passed both global and local tests and thus the deformation detection can be proceeded straight away. From the LSE process, the most important parameters required for the next stage of processing in deformation analysis are the estimated height of reference stations in the network (H_i) for each epoch, covariance matrix (Q) of each epoch and their degree of freedom (df).

4. Deformation Analysis

The procedure of deformation detection can be found in Wolf & Ghilani (1997), Halim (1997) and Chen et al. (1990). The analysis of the vertical displacement of the reference station can be carried out as follows:

$$d_i = H_i^{(2)} - H_i^{(1)} \tag{8}$$
$$Q_d = Q_1 + Q_2 \tag{9}$$
$$\hat{\sigma}_{01}^2 = \left(\frac{v^T W v}{df_1} \right) \quad \text{first epoch} \tag{10}$$
$$\hat{\sigma}_{02}^2 = \left(\frac{v^T W v}{df_2} \right) \quad \text{second epoch} \tag{11}$$
$$\left[F\left(\alpha/2; df_2, df_1\right)\right]^{-1} < \hat{\sigma}_{01}^2 / \hat{\sigma}_{02}^2 < \left[F\left(\alpha/2; df_1, df_2\right)\right] \tag{12}$$
$$\hat{\sigma}_{o_p}^2 = \frac{\left[df_1\left(\hat{\sigma}_{01}^2\right) + df_2\left(\hat{\sigma}_{02}^2\right)\right]}{df_p} \tag{13}$$

where $df_p = df_1 + df_2$

The test on the variance ratio is carried to examine the compatibility of the independent variance factors (Eq. 10 and 11) of the two epochs (Caspary, 1987 and Biacs, 1989). The test can either be one-tailed or two-tailed at significant level α. If the variance ratio test is passed, the pooled variance factor may be computed as in Eq. (13). The failure of this test indicates improper weighting of the observation and requires the examination of observational data or LSE results. The analysis of deformation should be stopped at this stage. For more details, refer Caspary (1987), Biacs (1989), Chen et al. (1990) and Halim, (1997).

The new vector of displacements d_r and its cofactor matrix Q_{dr} for the reference stations from Eq. (8) and (9) are transformed into a common datum (which employ S-transformation) by using the equation below:

$$\tilde{d}_r = \left[I - H_r (H_r{}^T W_r H_r)^{-1} H_r{}^T W_r\right] d_r = S_r d_r \tag{14}$$

and

$$Q_{dr} = S_r Q_{dr} S_r{}^T \tag{15}$$

S-transformation is applied for transforming the new displacement vector in Eq. (14) and its cofactor matrix in Eq. (15) into the computational base defined by the datum point. Elements of *I* in Eq. (14) are one (unity) for datum and zero for non-datum points. For levelling network (1D) with one origin station, the elements of *H* are one i.e.

$$H = \left[1 \;\; 1 \;\; 1 \;\; .... \;\; 1\right]^T \tag{16}$$

The displacement of each station is then tested by a single point test at a 95% confidence level. Initially, only the datum points will go through the deformation process to check the stability of the datum points. Later, all reference stations that include datum and object points are processed again in order to determine reference stations that have moved vertically or still stable.

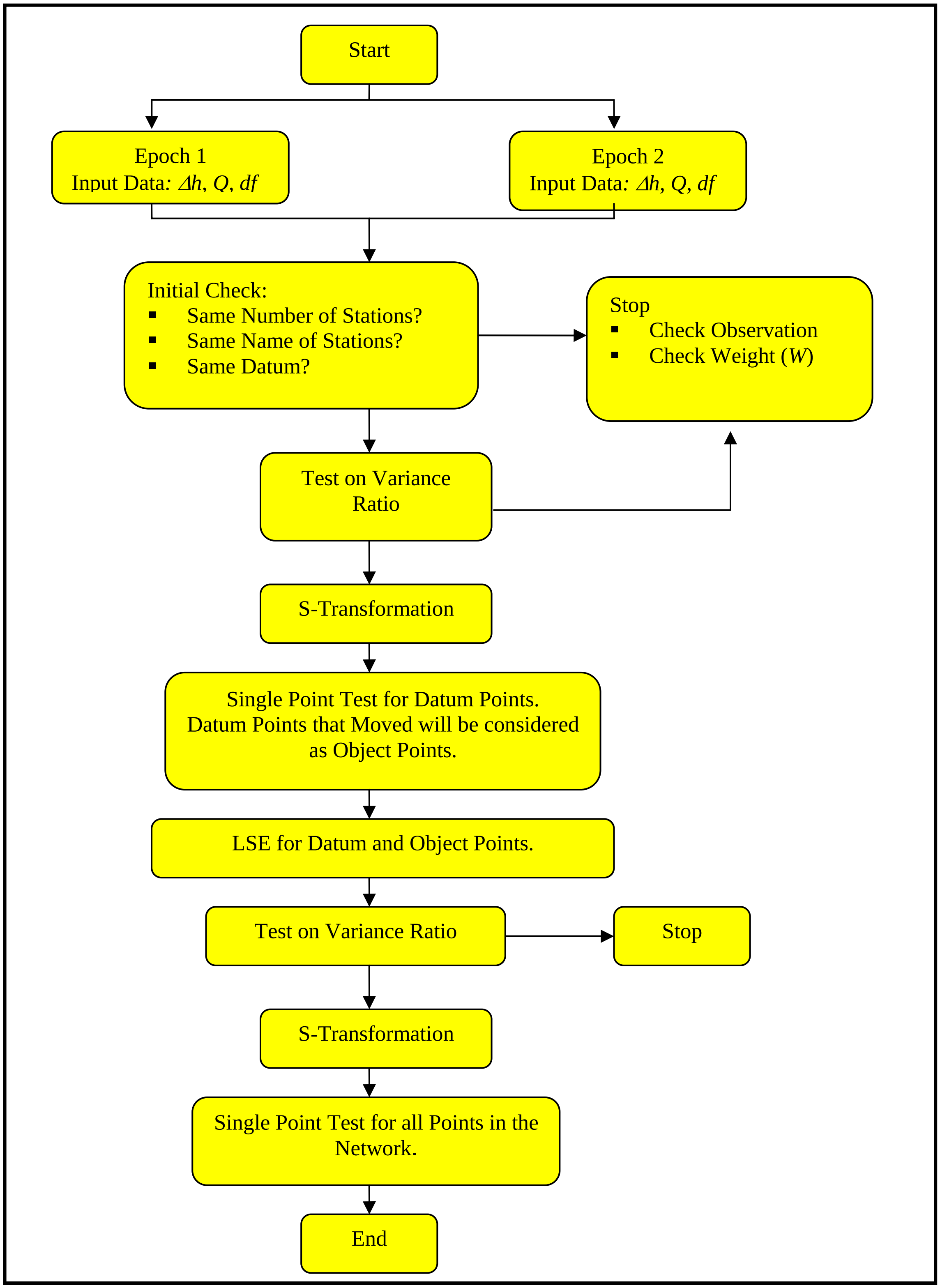

Figure 2: Flowchart of the developed computer program.

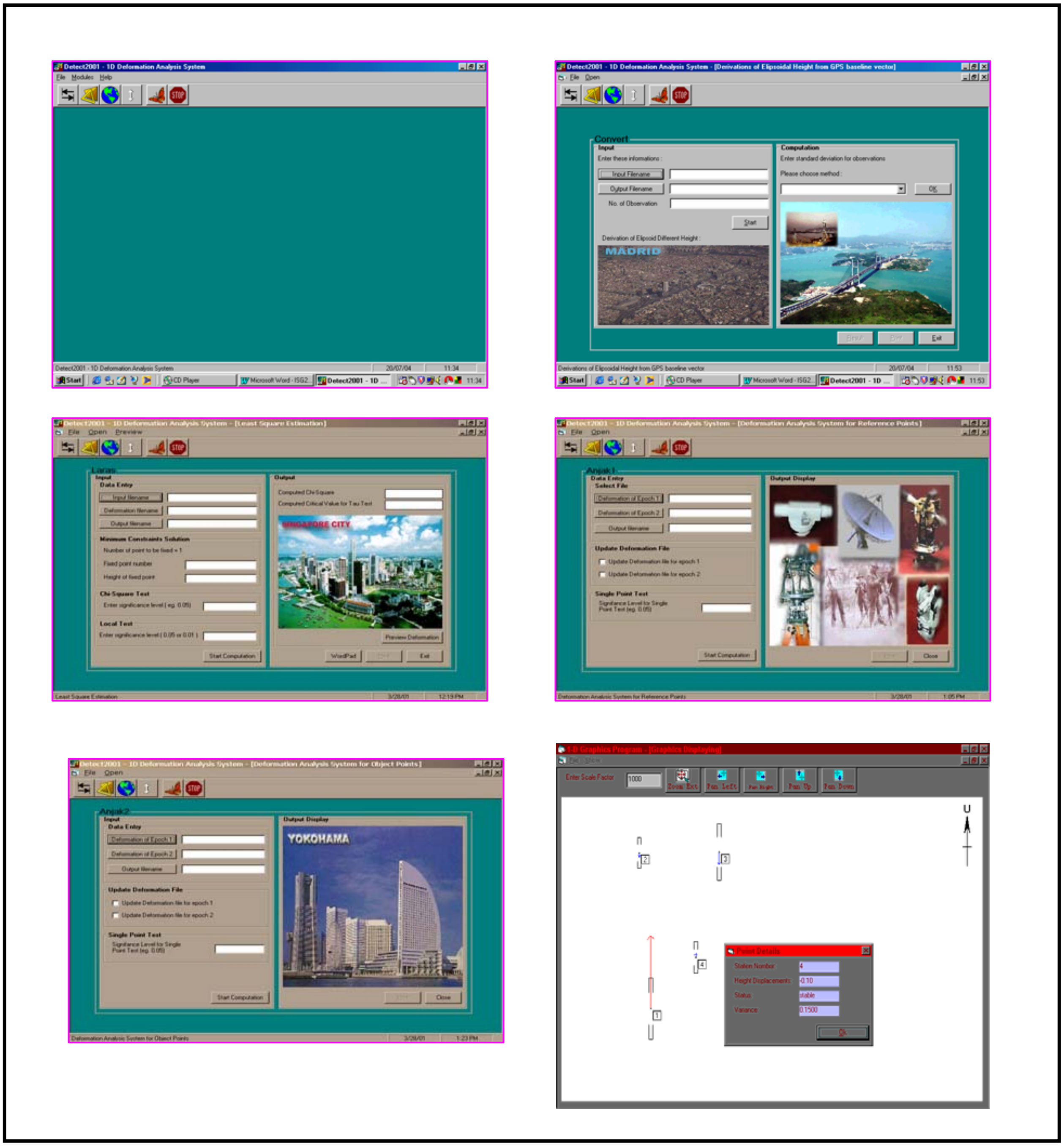

Figure 3: Menus or windows that are available in the computer program developed in this study.

5. Program Design and Implementation

A computer program has been developed for 1-D application for detecting vertical displacement. The process of LSE which employed Eq. (1) to Eq. (7) is designed to compute 1D least square estimation of each epoch. For the deformation analysis, it employed Eq. (8) to Eq. (14); is designed to detect vertical movement between two epochs which identify the stations in the network that are stable or have moved. The solution of minimum constraint is applied in the deformation analysis where one of the stations was held fixed. All the parameters and variance-covariance matrix is referred to zero variance reference base or station that was fixed as datum (Cooper & Cross, 1991). This computer program is developed initially using the FORTRAN computer language. The computer language of Visual Basic 6.0 is then used for the purpose of giving a better presentation in the use of the computer programs. The output of from the computer program will state the reference station that has moved or otherwise.

Figure 2 shows the flowchart of the computer program developed for this study. Figure 3 shows the menus or windows that are available in the computer program. The user needs to input or insert the necessary data or information that are required by each menu in order to proceed to the next stage of the computing process.

6. Test Results

An example from a GPS campaign for subsidence monitoring in Kelantan is used for testing the computer programs developed in this study. There are 8 control stations in the network. During the process of LSE all bad data are discarded by carrying out the local test and the same procedure is carried out again until all the observation are free from random error. For the deformation analysis, the same datum must be used for both epochs, as the use of different datum will give wrong interpretation of the displacement that occurred.

Table 1: Relative ellipsoidal height with their standard deviations between GPS stations for epoch 1 and 2.

Baseline	Relative Ellipsoidal Height (Δh m)		Weight (m)
	Epoch 1	Epoch 2	
6 – 7	2.298270	2.307025	0.009
6 – 2	2.179922	2.179100	0.009
1 – 5	-4.525404	-4.544646	0.090
1 – 7	-6.021587	-6.021854	0.009
2 – 8	2.729931	2.720721	0.009
2 – 4	-0.053724	-0.035782	0.009
2 – 1	6.145713	6.133368	0.009
8 – 6	-4.914435	-4.915922	0.009
8 – 7	-2.612950	-2.602692	0.009
5 – 6	-3.788773	-3.791836	0.009
5 – 7	-1.481413	-1.482717	0.009
4 – 8	2.784914	2.762096	0.009
4 – 6	-2.128706	-2.139787	0.009
4 – 5	1.641006	1.659544	0.009
3 – 4	2.515383	2.4814367	0.009
3 – 6	0.353994	0.359675	0.009
3 – 7	2.662570	2.665955	0.009
1 – 8	-3.414667	-3.404054	0.009
2 – 3	-2.549543	-2.532979	0.009

Table 2: Adjusted ellipsoidal heights for all datum points in the network for both epochs, output from the LSE process.

Station	Adjusted Ellipsoidal Height (m)	
	Epoch 1	Epoch 2
1	4.9700	4.9700
2	-1.1685	-1.1715
3	-3.7221	-3.7019
4	-1.2109	-1.2179
5	0.4347	0.4335

Table 3: Adjusted ellipsoidal heights for both datum and object points in the network for both epochs; output from the LSE process.

Station	Adjusted Ellipsoidal Height (m)	
	Epoch 1	Epoch 2
1	4.9700	4.9700
2	-1.1697	-1.1707
3	-3.7183	-3.7062
4	-1.2164	-1.2147
5	0.4335	0.4363
6	-3.3530	-3.3531
7	-1.0523	-1.0461
8	1.5612	1.5566

Table 4: Result of single point test on datum point.

Station	Displacement before and after S-transformation (m)		Satistical Value vs Critical valuel	Status
	before	after		
1	0.0000	0.0030	0.0387 < 7.747	Stable
2	-0.0030	0.0001	0.0000 < 7.747	Stable
3	0.0202	0.0232	2.6315 < 7.747	Stable
4	-0.0071	-0.0041	0.0939 < 7.747	Stable
5	-0.0039	0.0009	0.0026 < 7.747	Stable
Value of Pooled Variance Factor = 1.9850 Test on Variance Ratio = Passed				

Table 5: Result of single point test on all reference stations (datum and object points)

Station	Displacement before and after S-transformation (m)		Satistical Value vs Critical valuel	Status
	Before	after		
1	0.0000	-0.0031	0.3752 < 4.165	Stable
2	-0.0010	-0.0041	0.8435 < 4.165	Stable
3	0.0121	0.0089	3.0891 < 4.165	Stable
4	0.0017	-0.0014	0.1034 < 4.165	Stable
5	0.0029	-0.0003	0.0031 < 4.165	Stable
6	-0.0001	-0.0032	0.4222 < 4.165	Stable
7	0.0062	0.0031	0.3080 < 4.165	Stable
8	-0.0047	-0.0078	2.0015 < 4.165	Stable
Value of Pooled Variance Factor = 0.8276 Test on Variance Ratio = Passed				

Table 1 shows the height differences between stations for epoch 1 and 2 with their respective weight (W). The adjusted height of each station for both epochs in Table 2 is computed by using Eq. (5). With the station 1 held fixed, the displacement between stations for both epochs is computed by using Eq. (8). At this stage, the weight matrix W_r is selected by arranging all the w_i in a sequence of their increasing algebraic values. A new weight is assigned to each station with middle value is given weight 1 and the rest zero. Eq. (14) and (15) are then applied to the new displacement vector d_r and its cofactor matrix Q_{dr} for the reference stations and the new displacement of each stations is tested at a significance level $\alpha = 0.05$. The result from this program shows that all stations in the network are stable and do not experience any significant vertical displacement.

7. Conclusion

The developed computer program is useful for detecting any vertical movement that might occur by using observation from precise levelling or GPS. Observables from GPS and precise levelling need to be examined to ensure that data are free from any systematic error and of the same datum. In detecting subsidence where the heights of stations are considered, this method is considered simple and straightforward to use and able to give a good interpretation of any vertical displacement of the reference station that moved. The graphic images produced from the computer program give an attractive presentation and better interpretation of any subsidence of the reference stations. Users with little knowledge and understanding of deformation survey will be able to use this computer program with ease.

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