South African Journal of Geomatics, Vol. 7. No. 3, November 2018

Improving Traverse Redundancy and Precision by Running on Double lines

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DOI: *http://dx.doi.org/10.4314/sajg.v7i3.13*

Abstract

Good redundancy is required in measured quantities to isolate gross errors and improve the qualities of derived parameters. Improving the weak redundancies of traditional traverses by traversing on double lines is now possible with total stations which provide for less cumbersome measurements than previously possible and more so now that control traverses are computed by least squares adjustment using readily available computer software. Traversing on double lines requires some care in choosing traverse stations with inter-visibility to two immediately preceding and two directly succeeding stations from the instrument station. Traverses were run on double lines resulting in redundancy increase of seven per station. Local accuracy precision parameters improved also by as much as 25% and 52% with implementation at 30% and 100% of the traverse stations respectively. A chart that may be used to determine percentage number of traverse stations where traversing on double lines would be implemented to achieve set local accuracy improvements is presented.

Key words: traverse, redundancy, precision, total station, control surveys, traversing on double lines, gross errors

1. Introduction

All measurements contain errors as can be seen in the continuing differences between repeated measurements even after all systematic errors have been removed. It is the persistent and random nature of these remaining errors that make redundancies necessary in higher precision measurement systems as the only way to discover small sized blunders and minimize the impact of the random errors. Measurements with higher redundancies are generally more reliable as the character of the distribution of the random errors are clearer and together with other derivatives reveal very important characteristics of the measurements which make minimization of the influence of the random errors more accurate.

The word redundancy is used in two ways. The first is when redundancy refers to the total number of observations minus the minimum required to fix the model uniquely (Hashimi, 2004). In the second case Degrees of freedom (DoF) is a statistic that defines the redundancy of a least squares adjustment and it equals the number of measurements minus the number of unknown parameters to be estimated (Anzilic Committee on Surveying and Mapping, 2014). In this paper it is the first sense that is implied when the word redundancy is used except expressly stated.

Modern measurement science encourages higher redundancies in measurements by observing additional quantities in the systems. Ghilani (2010) describes two terms indicative of the strength or otherwise of redundancies in a measurement system. The first is the *redundancy number* with values between 0 and 1 and the second is the *relative redundancy* of the adjustment which is the total number of redundant observations in the system divided by the number of observations. If redundancy number is large (≈ 1), the blunder greatly affects the residual and should be easy to find. If redundancy number is small (≈ 0), the blunder has little affect on the residual and will be hard to find. And in the third case if redundancy number is zero (= 0), the blunder is undetectable and the parameters will be incorrect since the error has not been detected.

Improvement of precision in measurement systems is desirable as it reduces the ambiguity in the measurements. Modern studies in deformation surveys such as Beshr, A. A. E. (2015), show that improved precision implies earlier detection of movements since small amounts of deviation are detectable. Additionally such exercises as survey and alignment of large linear colliders (Herty and Albert, 2002) require very high precision surveys giving credence to the need of modern procedures that improve precision as the method being discussed here. It is also in the pursuit of improved traverse precision and precision reporting that Deakin (2012) developed some new and relatively easier procedures for reporting on the quality of traverses. This paper being presented here pursues the same goal of traverse precision improvement.

1.1. Background of Study

Of the three classical methods of control surveying, triangulation, traversing and trilateration, traversing is the enduring one. With advances in surveying by Global Navigation Satellite Systems (GNSS) classical triangulation and trilateration appear to have been largely rested. Traversing persists because it has been the suitable method of control densification in the shorter ranges and still provides opportunities and precision not yet replaced by the satellite methods. There are continuing needs to improve the quality of traverses for such uses as s expressed in Amiri-Simkooei *et al* (2012).

All traverses that start from and close on known stations have the same redundancy of 3 (Deakin, 2012). Compare this with a triangulation scheme of a braced quadrilateral with two controls in which eight angles and a baseline are observed. The redundancy in the system will be five from nine observations and four unknowns. The more other braced quadrilaterals are added the more the redundancy will increase in triangulation. For GNSS survey of a braced quadrilateral in which a point is held fixed the number of measurements is 18 (three per baseline) and the number of unknowns is 9 (three each for the three marks that need to be fixed). This results in a redundancy of nine (Anzilic Committee on Surveying and Mapping, 2014). The more the stations in this network increases the more the degree of freedom increases too. So comparatively and not minding other strengths, redundancy in traversing is very low and generally fixed at three and does not increase by increase in number of stations. The desirability to increase redundancy in traverse measurements is compelling.

Previous efforts to improve redundancies in control traverses include the double run method which involves establishing two stations about 3m apart at every other traverse station thus creating a system of triangles (Wyman, 1999). This involved increasing setup stations by up to 50% auxiliary stations and introduced further directional errors by observing lines of distances as short as 3m. The effort to establish these double points was made to reduce the cumbersome distance measurement by dragging invar tapes in the earlier days of classical control traversing. These limitations may explain why the practice is no longer common.

Modern provisions to improve redundancy in traverses come from some standards and guides which provide that control traverses should be run by cross-ties, for example to several right of way or land net monuments into the control network to establish a network of interconnected (redundant) control points whenever possible. This will enable the establishment of a strong geometric figure and provide redundant observations which will take advantage of using a least squares adjustment. The traverse network should include multiple triangles (Land Surveying, Mapping and GIS Section 2008, Office of Land Surveys 2016, Total Station System (TSS) Survey Specification 2005).

The foregoing provisions recommend increase in redundancies in control traversing, but only “whenever possible”. There have not been any structured provisions on how traverse redundancies can be increased in a practically viable way. The aim of the new method being introduced is to increase redundancies in a sustainable way so as to ensure that control traverses take advantage of higher redundancies in networks.

1.2. Theoretical Concept of the New Method

A traverse angle is measured at a first station between a preceding line (line 1) and a succeeding one line (line 2). The angle and the two lines define a triangle shape with only a missing but defined line. That missing line can be measured from the end of line 2, at the second traverse station and so the triangle is completed. Traverses can thus be made a system of succeeding triangles instead of succeeding lines by sighting two consecutive preceding stations and two sequential succeeding stations. This is the method of traversing on double lines.

Figure 1 illustrates the scheme of control traversing on double lines together with the measured quantities. While there are sightings to four stations six angles are derived. Using the different combinations of the four directions from the sightings is valid for increasing redundancy since the different angles that are produced by the different combinations of the sightings will yield different sizes and signs of random errors and thus further reveal the character of the random errors in those sightings.

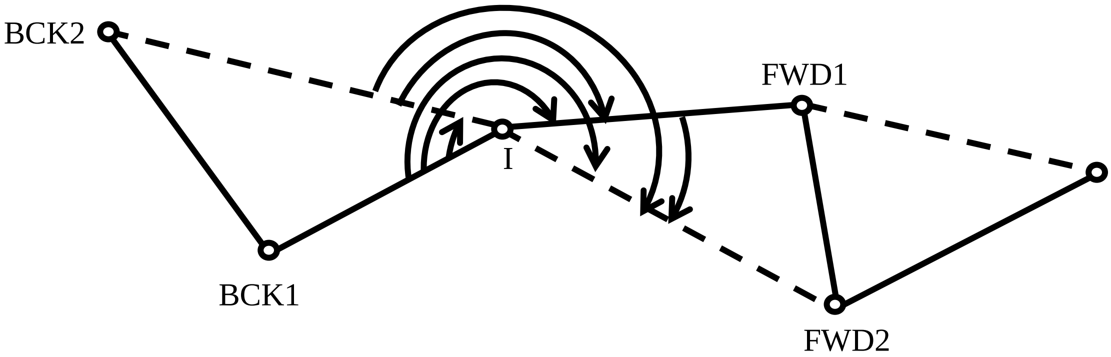

Figure 1. Scheme of Traversing on Double Lines Showing the Measured Quantities at a Station, I

In Figure 1 observation of double lines from instrument station I backwards and forward is shown. The main traverse legs I to immediate backward station BCK1 and immediate forward stations FWD1 are shown in continuous lines and the additional sightings to second backward and forward stations BCK2 and FWD2 are shown in dashed lines. Instead of the usual one angle and two distances measured at a station a complete measurement of all double line quantities will produce seven additional measurements from six angles and four distances.

The field operations of running traverse on double line and movement of instruments and targets will remain as it is in the traditional traversing. At every move of the instrument station to the next only the very last target moves to the foremost station. The forced centering method which is the recommended method of control traversing is used (Survey Department of Siri Lanka, 2014). The new method will require a little more care in choosing traverse stations so that they are visible from the previous two and succeeding two. The method can still be run even when only a single back or fore sight is feasible. Improved redundancy and precision will still be achieved if for some circumstances implementing the observation of double lines is only possible from some stations.

While the method being proposed will present some challenges to fully implement in forested areas or difficult topographies, it is fully implementable in small area surveys that require high precision such as in construction deformation monitoring. Such a project is reported in Hope & Chuaqui (2007) on total station monitoring of movements of constructions. This involved total station measurements on the high rise with a foundation that was seven-stories which occupied an old, open parking lot next to several sensitive and/or significant buildings. Sixty-five targets placed on surrounding structures were monitored with a total station theodolite, and the report stressed the need for high precision which the method of traversing on double lines would enhance.

2. Materials and methods

Two traverses run to demonstrate the feasibility of the method of traversing by observing double lines are reported here. The first traverse was of traverse leg distances of between 100m and 240m, with a total traverse length of 840m. The second traverse of total length of 2.9Km was set to meet second order criteria and the legs were of lengths 250m to 550m. The traverse field observations were made using a 2” total station on four reflector targets. Distance measurement was set on refinement mode of average of 3 readings and the general atmospheric correction factors were set for the total station. Field observation of angles and distances were by the forced centering method. Angles were estimated by an average of 5 zeroes on both faces. Grid distances on the Nigerian Transverse (modified) Mercator map projection system were determined from the mean of field measured distances. All angular values in this work are in the sexagesimal (degrees, minutes, and seconds) unit while all distances and coordinates in the meter unit except otherwise explicitly indicated.

Table 1 presents the coordinates of the control stations used in the computation of the two traverses. All the controls used in the traverses were established using dual frequency GNSS receivers in the fast static mode. Trimble Business Center™ GNSS software (Trimble Engineering and Construction Group 2011) was used to process the GNSS data in the fixed solution mode and all the coordinates were determined in the projected Nigeria (modified) Transverse Mercator map system after network adjustment. The orthometric heights were determined on the OSU 91A geoid and by a determined constant for Owerri they are here produced with reference to the Lagos mean sea level datum.

Table 1. Coordinates of Traverse Control Stations

Point ID	Easting (Meter)	Easting Error (Meter)	Northing (Meter)	Northing Error (Meter)	Elevation (Meter)	Elevation Error (Meter)
GPS001	509424.481	0.009	167528.214	0.010	119.528	0.044
GPS002	509546.442	0.009	167214.132	0.011	113.565	0.043
GPS009	509704.693	0.002	166412.574	0.003	84.503	0.008
GPS010	509745.463	0.002	165939.759	0.003	73.778	0.008
GPSD001	508726.654	0.001	167021.323	0.001	78.751	0.002
GPSD002	509010.418	0.001	167387.897	0.001	98.656	0.002
GPSD010	509784.282	0.001	165747.850	0.001	71.808	0.005
GPSD012	509821.628	0.002	165174.971	0.001	69.094	0.005

Field measured quantities used in the computation of the traverses are presented in Table 2. The grid distances of the traverses and the mean of all angles observed at each station were used in the computations. The first traverse was run beginning from instrument set up at station GPS 002 with a back sight to GPS 001 and run successively on stations PT3, PT4, PT5, PT6, PT7, PT8 and closed on control station GPS 009 with a forward sight to control station GPS010. The traverse was run on double lines. The second order 2.9Km long traverse was run with takeoff at control station GPSD002 and a back sight to GPSD001 and then run on stations RT3, RT4, RT5, RT6, RT7, RT8 and RT9 with closing setup on control station GPS010 and a forward sight to GPSD012.

It was not possible to observe full double lines at all the stations. At station RT3 double lines could only be observed to forward stations RT4 and RT5 with a single back station sight to GPSD002. At station RT4 also a single back sight could only be taken to station RT4 with forward double lines observed to stations RT5 and RT6. At station RT9, double back sight shots were taken to RT7 and RT8, but a single forward sight to control station GPSD010.

The computation of the two traverses were carried out to compare the results of the traverses using the traditional single line traverses with the results of the traverses on double lines when implemented at 100%, 90%, 70%, 50% and 30% of the stations. The traditional single line traverses were also computed for both cases by removing all extra observations and using only the traditional traverse quantities for comparison. The traverse computations were executed by least squares adjustment using Adjust software (Ghilani 2010). Table 3 presents the result of the first traverse of 840m length. Table 4 presents the result of the second order traverse of 2.9Km length.

Each station coordinate was derived together with the accuracy statistics such as the standard deviations in the eastings and northings, the semi major and semi minor axes of the error ellipses at the 95% confidence level and also the radius of the error circle at the 95% confidence level and lastly the local accuracy of the traverse. For convenience so that the different qualities of the different traverses will be apparent, the precision of the traverses were reported using local accuracy value.

Table 2. Field Determined Quantities of the Traverses

First Traverse: 840m Long Traverse					Second Order 2.9Km Long Traverses				
BCK	STN	FWD	Angle ° ‘ “	Grid Distance STN to FWD (m)	BCK	STN	FWD	Angle ° ‘ “	Grid Distance STN to FWD (m)
GPS001	GPS002	PT3	168 52 8.9	113.590	GPSD001	GPSD002	RT3	204 31	406.323
GPS001	GPS002	PT4	185 25 46.5	240.702	GPSD002	RT3	RT4	266 42	267.511
PT3	GPS002	PT4	016 33 34.1	240.702	RT4	RT3	RT5	003 16	515.871
GPS002	PT3	PT4	210 21 39.3	135.745	RT3	RT4	RT5	186 47	249.270
GPS002	PT3	PT5	202 46 09.1	273.016	RT5	RT4	RT6	008 17 5.4	536.646
GPS001	PT3	PT4	202 01 44.4	135.745	RT3	RT4	RT6	195 04	
GPS001	PT3	PT5	194 26 14.2	273.016	RT4	RT5	RT6	195 20	292.211
GPS002	PT3	GPS001	008 19 54.9		RT6	RT5	RT7	003 29 43	544.014
PT5	PT3	PT4	07 35 30.2	135.745	RT3	RT5	RT7	202 21	
PT3	PT4	PT5	165 01 56.9	139.620	RT3	RT5	RT6	198 51	
PT3	PT4	PT6	174 23 23.5	239.939	RT4	RT5	RT7	198 50	
GPS002	PT4	PT5	178 49 49.8	139.620	RT3	RT5	RT4	003 30	249.271
GPS002	PT4	PT6	188 11 16.4	239.939	RT5	RT6	RT7	187 32 0.9	252.983
GPS002	PT4	PT3	013 47 52.9	135.745	RT5	RT6	RT8	181 56	
PT5	PT4	PT6	009 21 26.6	239.939	RT4	RT6	RT7	194 35	
PT4	PT5	PT6	201 52 45.1	104.678	RT4	RT6	RT8	189 00	542.123
PT4	PT5	PT7	189 27 40.5	207.212	RT4	RT6	RT5	07 03 41.6	292.213
PT3	PT5	PT6	194 29 54.7	104.678	RT8	RT6	RT7	005 35	
PT3	PT5	PT7	182 04 50.1	207.212	RT6	RT7	RT8	169 33	291.388
PT4	PT5	PT3	007 22 50.4	273.016	RT6	RT7	RT9	173 56	
PT7	PT5	PT6	012 25 04.6	104.678	RT5	RT7	RT8	173 35	
PT5	PT6	PT7	155 28 37.7	107.373	RT5	RT7	RT9	177 59	
PT5	PT6	PT8	169 06 43.5	227.934	RT5	RT7	RT6	004 02	252.982
PT4	PT6	PT7	168 00 01.3	107.373	RT8	RT7	RT9	004 23	549.432
PT4	PT6	PT8	181 38 07.1	227.934		RT8	RT7		291.389
PT4	PT6	PT5	012 31 23.6	104.678	RT7	RT8	RT9	189 18 21	259.856
PT7	PT6	PT8	13 38 05.8	227.934	RT7	RT8	GPSD010	185 09	
PT6	PT7	PT8	205 12 34.4	126.166	RT6	RT8	RT9	184 27	
PT6	PT7	GPS009	193 26 28.2	232.293	RT6	RT8	GPSD010	180 17	549.355
PT5	PT7	PT8	193 06 19.6	126.166	RT7	RT8	RT6	04 51 01.2	
PT5	PT7	GPS009	181 20 13.4	232.293	GPSD010	RT8	RT9	04 09 20.1	
PT6	PT7	PT5	012 06 14.8	207.212	RT8	RT9	GPSD010	172 07	290.791
GPS009	PT7	PT8	011 46 06.2	126.166	RT7	RT9	GPSD010	177 02	290.793
PT7	PT8	GPS009	154 55 26.8	111.794	RT7	RT9	RT8	04 55 11.7	259.854
PT7	PT8	GPS010	166 42 42.8	583.447	RT9	GPSD010	GPSD012	186 37	
PT6	PT8	GPS009	166 29 49.7	111.794	RT8	GPSD010	GPSD012	182 54	
PT6	PT8	GPS010	178 17 05.7	583.447	RT9	GPSD010	RT8	03 42 50.9	
PT6	PT8	PT7	011 34 22.9	126.166					
GPS009	PT8	GPS010	011 47 16	583.447					
PT8	GPS009	GPS010	194 32 59.3						
PT7	GPS009	PT8	346 41 26.7	111.794					
PT7	GPS009	GPS010	181 14 26						
PT8	GPS009	PT7	13 18 33.3	232.293					

Notes: BCK = Back sighted Station. STN = Instrument Setup Station. FWD = Forward Sighted Station

The local positional accuracy of a control point is a number that represents the uncertainty, at the 95% confidence level in the coordinates of this control point relative to the coordinates of other directly connected or measured adjacent control points. The reported local accuracy is an approximate average of the individual local accuracy values between this control point and other observed control points used to establish the coordinates of the control point (Surveys Division 2013).

Table 3. Results of the Least Squares Adjustment of the 840m Long Traverses

Results of the traditional traversing on single lines on all stations									
Station	X	Y	Sx	Sy	Su	Sv	t	r(95	Local Accuracy: 0.0096
PT3	509607.227	167118.176	0.0024	0.0033	0.0037	0.0017	149.22°	0.0075	
PT4	509611.947	166982.515	0.0034	0.0045	0.0047	0.0032	162.56°	0.0100	
PT5	509652.676	166848.969	0.0040	0.0051	0.0051	0.0039	166.21°	0.0113	
PT6	509643.704	166744.678	0.0039	0.0051	0.0051	0.0039	167.53°	0.0112	
PT7	509679.734	166643.532	0.0033	0.0047	0.0047	0.0032	170.69°	0.0100	
PT8	509667.420	166517.970	0.0020	0.0035	0.0037	0.0017	161.44°	0.0075	
Results of traversing on double lines at 100% of all traverse stations									Local Accuracy: 0.0046
Station	X	Y	Sx	Sy	Su	Sv	t	r(95%)	
PT3	509607.228	167118.175	0.0013	0.0019	0.0021	0.0010	152.02°	0.0042	
PT4	509611.950	166982.511	0.0015	0.0022	0.0023	0.0014	162.17°	0.0047	
PT5	509652.682	166848.968	0.0017	0.0024	0.0024	0.0016	165.97°	0.0051	
PT6	509643.710	166744.673	0.0016	0.0024	0.0024	0.0016	166.47°	0.0051	
PT7	509679.739	166643.530	0.0014	0.0022	0.0022	0.0014	168.95°	0.0046	
PT8	509667.423	166517.968	0.0010	0.0018	0.0019	0.0009	162.31°	0.0038	
Results of traversing on double lines at 90% of all traverse stations									Local accuracy: 0.0050
Station	X	Y	Sx	Sy	Su	Sv	t	r(95	
PT3	509607.229	167118.175	0.0014	0.0021	0.0023	0.0010	152.41°	0.0046	
PT4	509611.951	166982.509	0.0016	0.0027	0.0027	0.0015	162.22°	0.0056	
PT5	509652.683	166848.967	0.0018	0.0026	0.0026	0.0017	164.83°	0.0055	
PT6	509643.711	166744.672	0.0017	0.0025	0.0026	0.0016	164.97°	0.0054	
PT7	509679.739	166643.530	0.0014	0.0022	0.0023	0.0014	168.33°	0.0047	
PT8	509667.423	166517.968	0.0011	0.0018	0.0019	0.0009	161.89°	0.0038	
Results of traversing on double lines at 70% of all traverse stations									Local Accuracy: 0.0052
Station	X	Y	Sx	Sy	Su	Sv	t	r(95%)	
PT3	509607.229	167118.174	0.0014	0.0021	0.0023	0.0010	152.03°	0.0047	
PT4	509611.952	166982.509	0.0017	0.0027	0.0028	0.0015	161.51°	0.0057	
PT5	509652.684	166848.967	0.0018	0.0026	0.0027	0.0017	163.20°	0.0057	
PT6	509643.712	166744.672	0.0018	0.0026	0.0027	0.0017	163.42°	0.0056	
PT7	509679.740	166643.529	0.0015	0.0023	0.0024	0.0015	165.63°	0.0050	
PT8	509667.424	166517.968	0.0012	0.0021	0.0022	0.0010	162.80°	0.0044	
Results of traversing on double lines at 50% of all traverse stations									Local Accuracy: 0.0064
Station	X	Y	Sx	Sy	Su	Sv	t	r(95%)	
PT3	509607.228	167118.176	0.0015	0.0022	0.0025	0.0010	151.62°	0.0050	
PT4	509611.950	166982.511	0.0018	0.0030	0.0031	0.0016	161.41°	0.0064	
PT5	509652.681	166848.971	0.0021	0.0031	0.0032	0.0020	162.39°	0.0067	
PT6	509643.708	166744.676	0.0022	0.0032	0.0032	0.0021	164.25°	0.0068	
PT7	509679.735	166643.534	0.0023	0.0034	0.0035	0.0022	161.85°	0.0073	
PT8	509667.419	166517.975	0.0018	0.0030	0.0032	0.0015	161.13°	0.0064	
Results of traversing on double lines at 30% of all traverse stations									Local Accuracy: 0.0075
Station	X	Y	Sx	Sy	Su	Sv	t	r(95%)	
PT3	509607.227	167118.176	0.0016	0.0023	0.0026	0.0012	150.68°	0.0052	
PT4	509611.950	166982.513	0.0023	0.0032	0.0033	0.0021	160.46°	0.0070	
PT5	509652.680	166848.971	0.0032	0.0035	0.0036	0.0030	150.88°	0.0082	
PT6	509643.706	166744.679	0.0034	0.0037	0.0038	0.0033	161.77°	0.0087	
PT7	509679.734	166643.534	0.0029	0.0040	0.0041	0.0029	167.91°	0.0087	
PT8	509667.419	166517.974	0.0019	0.0034	0.0035	0.0016	161.72°	0.0071	

Note 1: All values in this table except for t are in meters

Note 2: X and Y = Easting and Northing coordinates respectively; Sx and Sy = standard error in the X and Y coordinates respectively; Su and Sv = Semi major and Semi minor radii of the error ellipse respectively; t = azimuth of error ellipse; r(95%) is the radius of the error circle at 95% confidence level.

Table 4. Results of the Least Squares Adjustment of the Second Order 2.9Km Traverses

Results of traditional traversing on single lines at all traverse stations									
Station	X	Y	Sx	Sy	Su	Sv	t	r(95%)	
RT3	509370.074	167576.964	0.0037	0.0044	0.0049	0.0030	146.94°	0.0103	Local Accuracy: 0.0137
RT4	509507.932	167347.710	0.0045	0.0054	0.0054	0.0045	6.05°	0.0122	
RT5	509610.222	167120.395	0.0065	0.0057	0.0069	0.0051	58.49°	0.0150	
RT6	509655.331	166831.687	0.0081	0.0054	0.0084	0.0050	71.30°	0.0175	
RT7	509661.275	166578.773	0.0083	0.0049	0.0085	0.0046	75.75°	0.0174	
RT8	509720.787	166293.527	0.0068	0.0041	0.0069	0.0039	78.95°	0.0142	
RT9	509732.026	166033.911	0.0042	0.0030	0.0043	0.0029	76.39°	0.0091	
Results of traversing on double lines at 100% of all traverse stations									
Station	X	Y	Sx	Sy	Su	Sv	t	r(95%)	
RT3	509370.077	167576.955	0.0032	0.0028	0.0033	0.0027	113.12°	0.0075	Local Accuracy: 0.0077
RT4	509507.926	167347.696	0.0036	0.0027	0.0036	0.0027	91.75°	0.0079	
RT5	509610.213	167120.384	0.0039	0.0026	0.0040	0.0026	82.64°	0.0084	
RT6	509655.323	166831.680	0.0042	0.0023	0.0043	0.0023	81.69°	0.0087	
RT7	509661.271	166578.768	0.0041	0.0023	0.0041	0.0022	81.03°	0.0085	
RT8	509720.789	166293.523	0.0034	0.0018	0.0035	0.0018	82.21°	0.0070	
RT9	509732.029	166033.911	0.0026	0.0020	0.0026	0.0020	79.96°	0.0057	
Results of traversing on double lines at 90% of all traverse stations									
Station	X	Y	Sx	Sy	Su	Sv	t	r(95%)	
RT3	509370.077	167576.955	0.0033	0.0030	0.0035	0.0028	119.51°	0.0077	Local Accuracy: 0.0084
RT4	509507.927	167347.697	0.0037	0.0030	0.0037	0.0030	95.41°	0.0082	
RT5	509610.214	167120.384	0.0042	0.0029	0.0042	0.0028	81.85°	0.0089	
RT6	509655.325	166831.681	0.0046	0.0027	0.0047	0.0026	80.86°	0.0096	
RT7	509661.273	166578.769	0.0046	0.0027	0.0046	0.0026	80.27°	0.0096	
RT8	509720.790	166293.524	0.0040	0.0022	0.0040	0.0022	81.14°	0.0082	
RT9	509732.030	166033.911	0.0031	0.0023	0.0031	0.0022	78.27°	0.0067	
Results of traversing on double lines at 70% of all traverse stations									
Station	X	Y	Sx	Sy	Su	Sv	t	r(95%)	
RT3	509370.078	167576.954	0.0034	0.0035	0.0039	0.0029	136.62°	0.0085	Local Accuracy: 0.0098
RT4	509507.927	167347.695	0.0038	0.0037	0.0039	0.0036	132.20°	0.0092	
RT5	509610.214	167120.381	0.0044	0.0038	0.0045	0.0037	74.61°	0.00101	
RT6	509655.325	166831.681	0.0054	0.0038	0.0055	0.0037	75.17°	0.0118	
RT7	509661.273	166578.768	0.0052	0.0035	0.0053	0.0033	75.84°	0.0111	
RT8	509720.787	166293.522	0.0048	0.0034	0.0048	0.0033	78.55°	0.0103	
RT9	509732.026	166033.910	0.0032	0.0028	0.0033	0.0028	69.58°	0.0074	
Results of traversing on double lines at 50% of all traverse stations									
Station	X	Y	Sx	Sy	Su	Sv	t	r(95%)	
RT3	509370.077	167576.956	0.0034	0.0035	0.0040	0.0029	138.11°	0.0086	Local Accuracy: 0.0099
RT4	509507.925	167347.699	0.0039	0.0040	0.0041	0.0038	142.75°	0.0097	
RT5	509610.214	167120.383	0.0045	0.0038	0.0046	0.0038	72.30°	0.0103	
RT6	509655.327	166831.678	0.0055	0.0039	0.0056	0.0038	75.45°	0.0118	
RT7	509661.274	166578.767	0.0052	0.0035	0.0053	0.0034	75.98°	0.0111	
RT8	509720.788	166293.521	0.0048	0.0034	0.0048	0.0033	78.77°	0.0103	
RT9	509732.027	166033.909	0.0032	0.0028	0.0033	0.0028	69.86°	0.0074	
Results of traversing on double lines at 30% of all traverse stations									
Station	X	Y	Sx	Sy	Su	Sv	t	r(95%)	
RT3	509370.077	167576.956	0.0034	0.0036	0.0040	0.0029	138.46°	0.0086	Local Accuracy: 0.0103
RT4	509507.925	167347.699	0.0039	0.0040	0.0041	0.0038	145.45°	0.0097	
RT5	509610.214	167120.383	0.0045	0.0039	0.0046	0.0038	71.14°	0.0103	
RT6	509655.327	166831.678	0.0055	0.0040	0.0056	0.0038	74.77°	0.0119	
RT7	509661.274	166578.767	0.0053	0.0036	0.0054	0.0034	75.51°	0.0113	
RT8	509720.789	166293.522	0.0053	0.0037	0.0054	0.0036	77.79°	0.0114	
RT9	509732.027	166033.910	0.0039	0.0029	0.0040	0.0028	75.71°	0.0085	

Note 1: All values in this table except for t are in meters

Note 2: X and Y = Easting and Northing coordinates respectively; Sx and Sy = standard error in the X and Y coordinates respectively; Su and Sv = Semi major and Semi minor radii of the error ellipse respectively; t = azimuth of error ellipse; r(95%) is the radius of the error circle at 95% confidence level.

3. Results and discussion

The computation of the traverse was carried out by least squares adjustment method. Adjust, a least squares adjustment software obtained from Ghilani (2010) was used. Due to high redundancy it was futile to use a non-rigorous adjustment method. Table 5 presents the local accuracies achieved in the two traverses when traversing on double lines was implemented at specified percentages of the total number of traverse stations while Figure 2 presents the cases graphically.

Table 5. Comparison of Local Accuracies of Traversing on Double Lines at Different Percentage of All Stations of the Traverses

Traverse	0% Traditional Single Line Traverse	30%	50%	70%	90%	100%
First Traverse: 840m Long Traverse (Series 1 in Figure 2)	0.0096m	0.0075m	0.0064m	0.0052m	0.0052m	0.0050m
Second Traverse: 2nd Order 2.9Km Long Traverse (Series 2 in Figure 2)	0.0137m	0.0093m	0.0085m	0.0082m	0.0079m	0.0078m

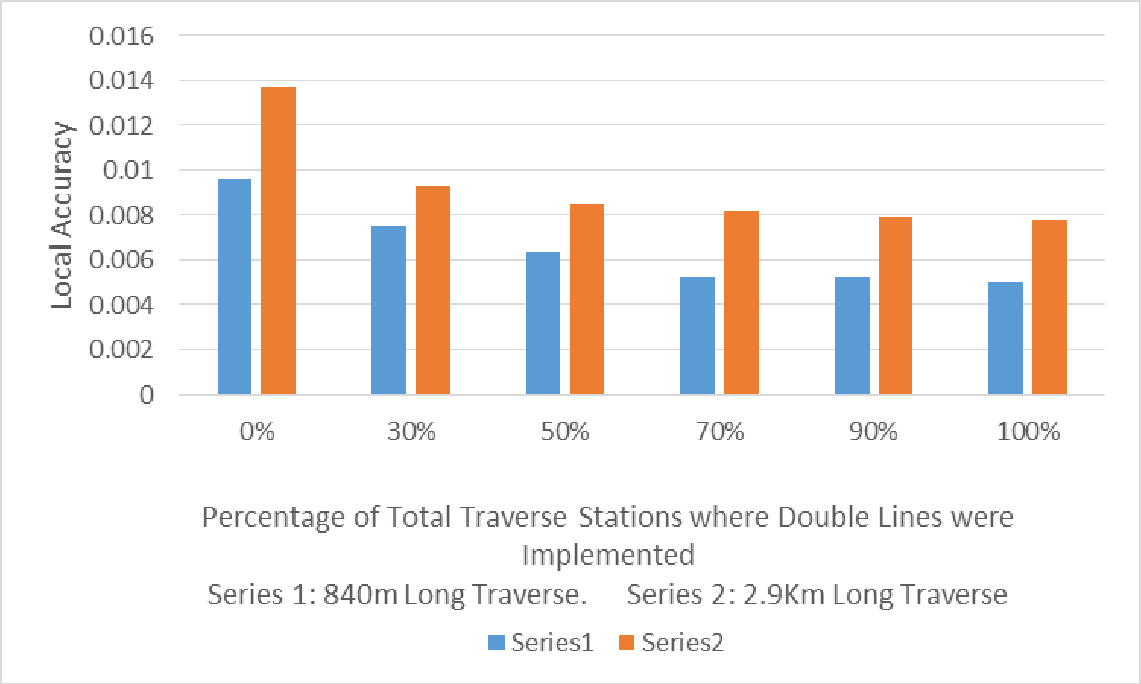

Figure 2. Improvement of Traverse Precision by Traversing on Double Lines

The result shows significant improvement of the local accuracies at all levels from when observing on double lines was implemented at 30% of the total number of traverse stations through to when it was implemented at 100% of the stations.

In the first traverse case there was a 22% and 52% improvement of local accuracies respectively at the 30% and 100% implementation level. In the 2.9Km long second order traverse there was a 25% improvement of local accuracy at the implementation of traversing on double lines at 30% of the stations from the zero percent implementation of the traversing on double lines, which is the traditional traversing on single lines case. At the implementation of traversing on double lines at 100% of the stations there was a 44% improvement of local accuracy from the 0% implementation of traversing on double lines, the traditional traversing on single lines case.

4. Conclusion and recommendations

The two closed link traverses reported here were run to demonstrate the feasibility of traversing on double lines and the significant improvements the method brings to traversing in terms of improved redundancies for tracking gross errors and to improve precision of the determined parameters. The forced centering method was used. At each set up the back sights were taken to the directly preceding two stations and forward to the two immediately succeeding stations. The simplicity of the field operations lies in the fact that just as in the traditional traversing only the last target set up would be moved to the fore as instrument station moved to a new position.

The running of traverses on double lines is promising today because the cumbersome dragging of 30m-long heavy invar tapes over double long distances has been eliminated by the use of the total station. Additionally the computation of the high redundancy traverse has been made possible by the least squares adjustment of the traverses in use today more commonly due to the availability of high speed miniaturized personal laptop computers.

The method of control traversing on double lines which by its structure may also be termed triangulated traversing has been shown to improve the redundancy in the traverse by as much as seven times the number of traverse stations when complete double lines are observed at all stations. The quality of the traverse results improved significantly by up to 52% or more in terms of the reduction in the magnitude of the variances of the coordinates and the local accuracies of the traverses.

If due to visibility problems it is not possible to observe all the double lines at any station it is still helpful to observe the intervisible additional lines. Significant improvements were recorded even when the number of stations on which double line observations were only 30%. However there should be a fair spread of the points at which the double lines are observed in all the parts of the traverse otherwise undue accumulation of errors at one part of the traverse could distort the efforts.

The method of control traversing by observation of double lines is strongly recommended to be adopted for all control traverses so as to achieve higher precisions by traversing. It is further recommended that since a triangular figure cannot provide for the observation of double lines that all control traverses be designed to run on figures of not less than four sides.

Traversing on double lines recommends itself to studies where it is desirable to keep the uncertainties very low such as in deformation studies and projects monitoring. It must be said that for open areas and projects requiring quite higher precisions traversing on triple and quadruple and even quintuple lines are expected to further improve the already very significant marks demonstrated in this research.

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