A GEODETIC NETWORK SOLUTION THROUGH COMBINATION OF GPS AND TERRESTRIAL OBSERVATIONS

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Abstract

Surveying networks are usually computed using either terrestrial observations or GPS observations. Occasionally, however, various reasons (efficiency, lack of particular observations, etc.) give rise to the need for the combination of both kinds of measurements. This paper attempts to examine the reasons leading to such a combination, the basic issues involved and, subsequently, to evaluate the combination-results in terms of accuracy through a network case study. The network has been measured during two summer courses on the Geodesy module on a Greek island by N.T.U.A. It consists of six points that are apart at distances that vary from 500m to 2 km. Three network solutions were carried out for comparison needs. The first solution used only GPS measurements, while the second used only terrestrial ones. The third solution involved with the combination of the GPS measurements and the terrestrial measurements. The analysis of the results of the above-mentioned solutions elevates the possibilities of the proceeding and the issues that need to be taken into consideration in such an attempt.

1. Reasons for the combination of GPS and terrestrial observations

In order to pinpoint the benefits from combining GPS and terrestrial data, it would be helpful to overview specific problems of each method, and also, to outline the tasks in which one complements the other (Piniotis, 2002).

1.1 Limitations of terrestrial techniques

The measuring techniques in surveying engineering rely on optical instruments. This characteristic introduces limitations, as the line of sight can be easily obstructed. These points of difficulty in terrestrial observations will be mentioned in the following paragraphs:

i) Triangulation is the technique that is widely used in networks for the determination of accurate coordinates. As in other conventional terrestrial techniques (traversing, etc.), triangulation presupposes intervisibility between stations. Thus, in geodetic network planning, triangulation-points must be located at top of mountains in order to satisfy the intervisibility requirement. In addition, triangulation networks should maintain the geometric strength (errors should be uniformly distributed), hence the need for triangulation points to be located at evenly distributed sites (Balodimos, Stathas, Arabatzi, 2000).
GPS has superseded these problems. Measurements do not require an established line of sight between two stations. The receivers are put wherever is necessary and GPS observations are being recorded regardless of the topography of the field-site. Apart from that, geometry is not so important for GPS networks as it is for terrestrial survey networks. The selection of the location of network points is independent of geometrical criteria due to the homogeneous character of the GPS surveying accuracy.

ii) Conventional terrestrial techniques are affected by weather conditions. Shimmer, fog and rain may disturb visibility and obstruct EDM signals, while wind may cause centering errors and bad targeting.

Consequently, adverse weather conditions may postpone terrestrial measurements and interfere with schedules and deadlines, with potential financial implications.
On the other hand, GPS techniques are not affected by weather conditions. Due to the fact that radio frequencies are used to transmit the signals from the satellites to the receivers, weather is not an issue in the GPS measuring process.

iii) Another characteristic of the terrestrial techniques is that the accuracy of the collected data is dependent on the instrument operator. The skills of the latter play a major role in achieving high-level accuracy. On the contrary, the accuracy of GPS data is not affected by the above factor.

1.2 Limitations of GPS techniques

On the sole basis of the above analysis one might tend to conclude that GPS is the solution to all surveying problems and could be used in all situations. This is definitely not the case, as the following paragraphs will hopefully illustrate.

i) GPS surveying techniques presuppose a clear view of the sky, in order for the receiver to track satellites without obstructions. The signals may be obstructed by overhanging branches or structures and this may result into undesirable satellite geometry (PDOP) and thus into poor quality data. If the satellites tracked by the receiver are evenly spread in the sky, a good geometry for trilateration (mathematical operation to compute a position on the ground, given the position of the satellites and the pseudo-range distances to the satellites) is provided (Hofmann-Wellenhof, Lichtenegger, Collins, 1993). In the case of obstructions, the number of the tracked satellites may be reduced to those that are closer together in the sky, resulting into poor trilateration geometry and erroneous position computation. Furthermore, obstructions may result in such a large reduction of the number of tracked satellites, that the positioning problem becomes insoluble. These phenomena lead to repetitions of the measurement procedure, something undesirable from a financial perspective.

ii) Signals transmitted by satellites and, in particular, weak GPS signals may be subject to radio-frequency interference. Signal interference may hinder the satellite-tracking process of the receiver or result into erroneous observations.
In countries where new surveying techniques have been introduced only recently (e.g. Greece), the existence of passive GPS stations is very rare. In that case, in most surveying applications, GPS receivers are placed on existing control points (usually pillars), which are usually located at mountain tops (because they have been established by means of conventional terrestrial techniques). Mountain tops, however, are a common location of telecommunication antennas, whose function may introduce interference to GPS signals. Consequently, in those countries, signal interference may be a regular phenomenon in GPS surveying techniques.

iii) Another usual problem with GPS surveying techniques surfaces when data collection takes place near reflective environments. This is due to multipath, one of the major GPS error sources, caused by the reflection of the satellite signals on surfaces neighboring the GPS receiver. Multipath causes phase measurement errors and of course, erroneous positioning results (Cross, 2001).

iv) GPS-instruments are still very expensive comparing to those required by conventional techniques. Despite the fact that the price of one receiver is only slightly higher than that of a total-station instrument, at least two GPS receivers are required in survey works, which is very costly.

v) It should be mentioned that GPS height information refers to the surface of the reference ellipsoid. What is generally required, is orthometric height information, which refers to the surface of the geoid (an approximation of the shape of the earth). GPS heights can be converted to orthometric heights through the use of geoid models. These models derive the geoid-ellipsoid separation N between the geoid and the ellipsoid. The limitation of such a conversion is that the accuracy of the finally obtained heights is as good as the accuracy of the geoid model used for their derivation. On the contrary, orthometric heights are directly obtained from terrestrial techniques.

vi) It should also be noted that, due to its theoretical foundation, GPS can not operate under ground. On the contrary, terrestrial techniques have no such limitations. Linking underground survey works (terrestrial observations) with surface GPS survey works is another example of the usefulness of the combination of the two methods.

Finally, account should be taken of the fact that, terrestrial techniques have been used for the establishment of geodetic frameworks in many countries, over a long time span. The last two decades though, geodetic frameworks have been mostly measured by means of GPS techniques, giving rise to the need for links between the new networks and the existing ones.

Following the above analysis, the complementary nature of the two methods and the benefits from their combination become apparent. Taking into consideration financial aspects, specific field-topography problems and the nature of the obtained results, surveyors can maximize efficiency and productivity through the combination of GPS and terrestrial observations.

2. Basic issues involved in the combination of GPS and terrestrial observations

As the combination of GPS and terrestrial observations is instrumental in surveying engineering, it would be worthwhile to address the issues that play a determinant role in the event of such a combination. The basic considerations are as follows:

i) Correlation of GPS observations: Unlike terrestrial observations, GPS generic observations, as obtained from the GPS baseline processing, are correlated. This is reflected upon their variance-covariance matrix, which-unlike terrestrial observations-is a full matrix consisting both of diagonal and off-diagonal elements. The aforementioned correlation should be taken into account in order for the GPS observations to properly contribute to the final results.

ii) Height reference surfaces: A fundamental distinction between terrestrial and GPS observations is that, the height information obtained from each kind of observations is referenced to a different surface. In specific, heights obtained from terrestrial observations (orthometric heights) refer to the surface that most closely approximates the true shape of the earth, termed geoid, whereas heights obtained from GPS observations (ellipsoid heights) refer to the surface of a reference ellipsoid that approximates the geoid surface (Iliffe, 2000). This differentiation should be addressed, since it has a crucial impact on the process of reductions of the observations, in the case of a combined solution.

iii) Coordinate systems: Another basic difference between GPS and terrestrial observations concerns the coordinate systems to which they refer. Observations obtained by GPS refer to the World Geodetic System ’84 (WGS’84), a global coordinate system, whereas terrestrial observations refer to a “natural” coordinate system, that of the gravity field of the earth (Cross, 2001). Hence, on the occasion of combined GPS and terrestrial observations, the appropriate coordinate system transformations should be employed for the derivation of the final results in the desirable coordinate system.

iv) Deflection of the vertical: In order to combine terrestrial and GPS data, both kinds of measurements should be referenced to the same surface that is the reference ellipsoid. As known, GPS measurements refer to the aforementioned surface. Hence, for the combination to be successful, all the measured terrestrial observations (directions, horizontal and vertical angles, distances) need to be reduced to the reference ellipsoid. For this purpose the magnitude of the deflection of the vertical should be known. It is obvious that an accurate astrogeodetic map or local determinations of the geoid separation by astrogeodetic leveling are needed in order for the correct reductions to be applied. The necessity of these reductions depends on the magnitude of the network (maximum baseline length), on the extent of the geoid separation and on the desired accuracy according to the scale of the map to be produced.

2. Application

This paper attempts to evaluate the results of the combination of GPS and terrestrial observations on the occasion of small area (close-range) networks (maximum baseline length: 2.0 km). The study case, on which the combination is applied, is a surveying network located on Inousses Island (Aegean Sea –Greece). This network consists of 6 points (figure 1) and has been established by the Laboratory of General Geodesy (L.G.G.) of the Department of Rural and Surveying Engineering (D.R.S.E.) of the National Technical University of Athens (N.T.U.A.) for educational purposes, during two summer field-courses on the Geodesy module.

The criteria for the choice of the network-points were the regularity of the resulting shapes (that the points created), the mutual visibility between the points and the covering by the network of the limited area that was going to be surveyed in 1:100 scale.

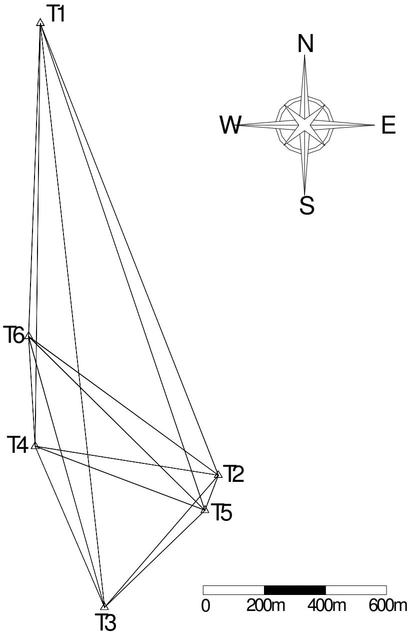

Fig.1. The Geodetic network

This network was measured by using:

- Terrestrial methods

The measurements were carried out by using the total station Leica TCR303 with the corespontal reflectors, which provides accuracy ± 10^{cc} in the angle measurements and ± 2mm ± 2ppm in the distance measurements. Horizontal and vertical angles were measured in four measurement periods and distances in both directions.

The measurements at each point lasted about one hour and the total time for all the network measurements including the relocation time of the instruments was about 10 hours.

- GPS methods

The aforementioned network was also measured by GPS using the static method. The receivers used were the Trimble 4600 LS, which measure only in L1 frequency and C/A code. In total, 15 baselines were measured for about forty minutes each. In this case the total time of measurements was about 15 hours.

2.1 Network adjustment using terrestrial data

The terrestrial data adjustment was carried out in the Greek Geodetic Reference System 1987 (GGRS ′87) by using a Qbasic programme. As functional relationships the distance, horizontal angle and vertical angle observation equations were used. The point T1 and the T1-T2 direction were considered fixed in the adjustment.

The observations used in this adjustment were:

- 26 horizontal angles
- 11 vertical angles
- 14 slope distances

The a priori errors were $\pm 15^{cc}$ for the measured angles and ± 3mm for the distances. These results serve as a benchmark, against which the results of the combination of GPS and terrestrial observations are evaluated. The resulting coordinates and their standard deviations are as follows:

Point	X (m)	Y (m)	H (m)	σ_X(mm)	σ_Y(mm)	σ_H(mm)
T1	692929.390	4266390.470	178.730	-	-	-
T2	693512.174	4264912.983	34.823	± 0.6	± 1.6	± 17.3
T3	693139.354	4264481.209	27.876	± 2.6	± 1.8	± 17.3
T4	692912.291	4265007.706	16.777	± 1.9	± 2.3	± 16.0
T5	693468.406	4264798.454	19.933	± 2.2	± 2.3	± 17.9
T6	692890.914	4265367.120	57.622	± 2.6	± 2.3	± 16.1

Table 1. Terrestrial data adjustment results

2.2 Network adjustment using GPS data

The adjustment using GPS data was carried out using, the GPSurvey Trimnet Software (Trimnet Plus, 1992). The following table outlines the quality of the baselines' solution:

From Station	To Station	Ratio	Reference Variance
T1	T2	51.4	1.168
T1	T6	37.3	0.999
T2	T4	27.6	1.514
T3	T1	37.1	1.605
T3	T2	20.6	1.458
T3	T4	24.6	2.332
T3	T5	26	1.689
T4	T1	21.8	1.391
T5	T1	9.7	2.220
T5	T2	6.3	1.210
T5	T4	7.1	1.672
T6	T2	4.5	1.319
T6	T3	37.6	1.920
T6	T4	68.7	0.717
T6	T5	10.5	5.223

Table 2: Baseline ratios & reference variances of GPS measurements.

In this adjustment the point T1 was also considered fixed. The final results of the network adjustment using only GPS data for the same points and their standard deviations are as follows:

Point	X (m)	Y (m)	H (m)	σ_X(mm)	σ_Y(mm)	σ_H(mm)
T1	692929.390	4266390.470	178.730			
T2	693512.181	4264912.964	34.799	± 1.7	± 2.1	± 4.5
T3	693139.365	4264481.184	27.858	± 1.7	± 2.0	± 4.5
T4	692912.291	4265007.686	16.758	± 1.7	± 2.0	± 4.4
T5	693468.415	4264798.439	19.912	± 2.0	± 2.4	± 5.3
T6	692890.913	4265367.106	57.619	± 1.7	± 2.2	± 4.7

Table 3. GPS data adjustment results

2.3 Combination of GPS and terrestrial measurements in the network solution

In order for the combination results to be evaluated, an adjustment is carried out using the Trimnet software (Trimnet Plus, 1992). The latter, combines GPS measurements from five points (T1,T2,T3,T4 and T5) and terrestrial measurements from or to one point (T6). The GPS observations included in this adjustment are 10 baselines between the above five points (without T6). The terrestrial observations included in this adjustment are 12 horizontal angles, 5 vertical angles and 5 slope distances with the corresponding instrument and target heights. The standard errors input for the observations are the same that were input in the adjustment of the terrestrial observations. The T1 point was considered fixed. The obtained adjustment results are the following:

Point	X (m)	Y (m)	H (m)	σ_X(mm)	σ_Y(mm)	σ_H(mm)
T1	692929.390	4266390.470	178.730			
T2	693512.172	4264912.984	34.802	± 2.5	± 4.6	± 4.7
T3	693139.361	4264481.209	27.863	± 1.9	± 5.8	± 4.6
T4	692912.291	4265007.705	16.762	± 1.8	± 4.1	± 4.6
T5	693468.408	4264798.460	19.915	± 2.5	± 4.9	± 5.4
T6	692890.915	4265367.114	57.626	± 3.9	± 3.7	± 24.3

Table 4. GPS and Terrestrial data adjustment results

3. Comparison

The following table presents the differences between the first solution that used only terrestrial data by the solution that used only GPS data and the solution that used the combination of GPS and terrestrial data.

As it comes out of the table 5:

- The differences ΔX and ΔY between the three solutions is of the order of the determination uncertainties in each one, except from the differences between terrestrial and GPS measurements in Y direction that is about 2cm, probably because of the network geometry.
- The differences in ΔH between the three solutions is of the order of 2cm that occur perhaps due to the GPS uncertainties in the determination of the H direction.

Differences between terrestrial and GPS				Differences between terrestrial and GPS + Terrestrial		
A/A	**ΔX (mm)**	**ΔY (mm)**	**ΔH (mm)**	**ΔX (mm)**	**ΔY (mm)**	**ΔH (mm)**
T2	6	19	23	2	1	21
T3	7	25	18	7	0	13
T4	0	20	19	0	1	15
T5	9	2	21	2	6	18
T6	1	14	3	1	6	4

Table 5. Differences between the first solution and the two others

4. Conclusions

The comparison of the results illustrates that:

- The combination of terrestrial and GPS measurements may be realised by success in networks that cover surveying field-works in 1:1000 or 1:500 scales.
- This proceeding would be very useful for the completion of old networks that have been measured by conventional techniques, by using GPS observations. The newly collected GPS data and all the previously collected terrestrial data will be included in a common adjustment.
- The ability of a simultaneous adjustment of GPS and terrestrial data, permits:
  - *i)* The measurement of large-scale networks by simultaneously using conventional and GPS techniques, saving time and money.
  - *ii)* The complementarity of the two measurement techniques on occasions that due to special conditions (as lack of GPS signals or lack of intervisibility etc.), one of the above can not operate.

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