New Modern Height Determination Techniques – Report about the WG 5.2 Activities in 1998–2002

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ABSTRACT

The surveyor, thanks to the rapid evolutions of the available equipments, has today a wide range of possibilities opened to him when he has to perform altimetric determinations. The present paper presents the possibilities opened to him, through the report of the WG 5.2.

RESUME

Emploi optimal des différentes techniques de mesures altimétriques. Rapport d'activités du groupe de travail 5.2 en 1998-2002

Le géomètre dispose actuellement d'une grande variété de procédés de mesure des altitudes et des dénivelées. Le présent article présente une analyse comparative des solutions qui apparaissent les plus adaptées pour quelques cas courants, au travers des études du groupe de travail 5.2.

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1. ACTIVITIES OF THE WG 5.2 DURING THE PERIOD 1998-2002

The group had his main meeting at the "Jubilee Seminar : 25 years of motorised levelling in Sweden" 15-17 March 1999, Gävle, Sweden. For this seminar several lectures were given on the central theme of the WG 5.2 (New Modern Height Determination Techniques). The following lines have been widely discussed within the group, and the resulting paper has been already presented in Gävle with minor improvements since then : it may be considered as a result of the work of the WG 5.2. After this important Gävle event, the topics were presented and discussed once more at three FIG congresses, in Prague (21-26 May 2000), Malta (18-21 Sept. 2000) and Hanoï (16-17 November 2001). In parallel, in a few countries like France (Kasser, 2001), the GPS has started to be widely used for the maintenance of a national levelling network, so that one may consider that significant operational results are proposed in the present report paper.

2. A SHORT REVIEW OF AVAILABLE METHODOLOGIES FOR ALTIMETRIC DETERMINATIONS

The different techniques for altimetric determination are well-known. For each of them we shall recall their specific advantages and drawbacks.

2.1 Direct (or Geometric, or Geodetic) Levelling

Direct levelling is performed with a level and one or two graduated rods. The various errors are described in many papers.

- The level may be optico-mechanical or digital, which implies different levels of security regarding possible blunders, and also different levels of precision. The precision may range from 0.3 (in exceptional conditions, with very specific instruments and field procedures) to 3 $mm.km^{-1/2}$ and more.

- The equipment has to be used at least by 1 observer + 1 helper for the rod. For maximal precision it requires 1 observer and 2 helpers for the staffs. When the team works along roads, it is often mandatory to have one extra worker to protect from the traffic. And the equipment may be mounted on vehicles to improve the efficiency (motorised levelling). Thus the team varies from 2 to 4 people.

- The daily production depends strongly on the equipment and the composition of the team, from 4 km/day to more than 30 km/day.

2.2 Indirect (or Trigonometric) Levelling

It relies upon the use of theodolites and EDM, in order to measure the zenith angle and the slope distance from one station to another. This methodology is generally much faster than direct levelling and of lesser accuracy due to refraction effects. An exception is the trigonometric levelling using simultaneous reciprocal measurements. This method can be motorised and has been widely developed and used at IGN-France since 1982 for the national levelling network (NGF). Its main features include :

- The possibility to have a large variation of production cost between low and high accuracy measures. The specification of maximum sight line length has a very important impact on the accuracy and on the daily production.

- A very limited reduction of production in mountainous areas.

- The use of a tacheometer allows for rapid levelling operations with a limited accuracy if the employed ranges are long. But if the tacheometer includes a reflectorless EDM, this will provide a very convenient situation for a 0.5 to 1 cm accuracy height determination of natural topographic details close to the station.

2.3 Use of GPS

- GPS may be used for heighting. Its main features for such operations are :

- The benchmarks do not have to be along roads, but require an open sky above them, which is not suitable in dense urban areas.

- The error determination is comparably large and depends from the duration of the measurements, hardly better than 1 cm and generally close to 2 cm rms (one should not assimilate the internal consistency provided by computations with the accuracy), but the dependence with distance between stations is very low.

- An excellent knowledge is required of the Zero-Altitude Surface, the ZAS (close to the geoid and often wrongly presented as the same thing), as GPS provides only geometric observations, and height is a geopotential information. Only in a limited number of countries (among which most of European countries) is this information available with a precision comparable with GPS vertical component's one for 2 hours long sessions.

If the ZAS is not available, the surveyor will have the possibility to use GPS on a limited zone by measuring the discrepancy between the official altitude and the ellipsoidal height. For that he will get GPS measurements over a set of benchmarks from the national network, with a density as homogeneous as possible in the zone (typically 1 benchmark every 3 / 4 km may be correct if the area is not too mountainous ; if the area is mountainous, the precision requirement will probably be lower so that such a density may also be acceptable). If the discrepancy has only a variation of a few cm, a simple mathematical interpolation model between the benchmarks will provide the necessary correction, with an accuracy compatible with the 2 cm rms of the GPS vertical component.

The use of GPS for topographic applications is now sometimes proposed in real-time differential configuration (RTK), which means a more expensive equipment, but no post processing work. The main feature of this configuration will be the possibility to have a correct radio-link (emission authorizations, topography allowing a correct reception far from the emitting station). But it must be taken into consideration that post-processing GPS data allows sometimes to benefit *a posteriori* from data that in real-time did not work properly (ambiguity resolution after an interruption of reception), which means that real-time applications must be used only when requested, and sometimes may be completed by a classical post-processing activity in case of difficulties.

3. TYPICAL HEIGHT DETERMINATION SITUATIONS FOR SURVEYORS.

Almost in all cases, high precision altimetric operations are requested as soon as, at least potentially in some part of the area, water has to flow driven by gravity only (e. g. sewerage, irrigation, drainage). Moreover, all national levelling networks have been set up for these reasons too.

We shall select typical works where surveyors are requested to perform levelling production.

A) Fundamental Levelling of the National Network

Although such an activity is generally done directly by a national office, it may be in some countries at least partially observed under the control of this office, and this highly specialized activity is interesting to analyze. The goal is to provide benchmarks everywhere in the country, with a variation of density for benchmarks close to the population density, a millimetric local precision and a long range error figure as low as possible. This network must be observed at the lowest cost (compatible with this precision) possible, and regularly checked because of benchmarks destruction. The information about altitudes must be widely accessible at the lowest cost possible, every surveyor being encouraged to use this unique national height system so as to maximize national economy and synergy between various public and private surveying operations.

B) Urban Densification Network

The goal is to provide levelling over a large number of marks, some of them being often natural ones (sewer plates, sidewalk borders, etc...), the other ones being benchmarks with special attention paid to their conservation. The applications are mostly related to water driven by gravity (sewerage systems for example). In most cases, the requested accuracy is high (1 mm to 5 mm relatively to the national levelling network). The client is the technical service of the town, and generally he will look much more at the density, the cost and the conservation rather than the precision.

C) Semi-Urban Network

Such networks will be requested for the preparation of new works, town housing developments, implantation of a new plant, extension of sewerage network, setting up new benchmarks for a new road, highway, or fast train (TGV) line, etc... The required accuracy will be of the same type (0.5 to 1 cm relatively to the national network), but the density of the benchmarks will be low, using classical benchmarks.

D) Rural Height Determinations

They may be requested because the national network is not dense enough, if some new water organisation is planned (e. g. in flat areas, for drainage, in villages for water supplies, etc...). The density will be low, but the references will be perhaps very far from the site.

E) Stability Monitoring

In order to check the movements or deformations of a bridge, a dam, a high building, or for common buildings during an underground tunnel boring, the main point will be the highest accuracy possible, with local references established only for these works, possibly with no link to the national network.

F) Control and Real Time Guidance of Construction Machines

This goal appears more and more important for future productivity gains in civil engineering, and especially for the construction of roads, highways or train lines. There are many possible specifications of precision. The base layer thickness for roads should be monitored within 5 cm, and the last layers, that are formed with quite expensive materials, should have a thickness control to within 5 mm. Increasingly it is requested that any geometric control be permanent, without any interruption for setting up the instruments elsewhere in a new section, and be perfectly reliable whatever the profiles to achieve.

4. WHAT TECHNIQUE IS OPTIMAL TODAY FOR THESE TASKS ?

For the **case A,** a large part of the network should be observed with motorized levelling or trigonometric motorized levelling for sections in mountainous areas. But the question arises about the possibility to use also GPS. One must remember that the various "orders" for levelling are due to the enormous difficulties that geodesists experienced in the past with the least square adjustments of even modest systems of equations. The "first order" goal was to provide the national reference system with a density acceptable for letting the further densification in user-oriented benchmarks not too demanding in terms of observations and computations. The first order was up to now a technical necessity, but its benchmarks were not particularly valuable for the normal users. In some countries, these benchmarks may even be quite difficult to exploit : in France up to 20 years ago, most of them were along railways lines, and thus were quite dangerous to use at the era of the TGV. If there exists in the country a good geoid computation providing a centimetric or sub-centimetric ZAS, we should now consider that any high precision ZAS is the materialisation of the altimetric reference itself, in conjunction with a well defined geodetic datum (e. g. EUREF in Europe). The ZAS may be considered as a geoid, deformed so as to follow the medium and long wavelengths of the errors due to the systematisms in traditional spirit levelling. Thus the use of the ZAS and of the permanent GPS stations will provide everywhere an excellent access to the national vertical reference. But as GPS vertical determinations exhibit a large noise (typ. 1 cm rms for 3 h observations on 15 km baseline), it appears as a good compromise to mix GPS baselines with traditional digital levelling (Kasser, 2001).

For the **case B**, GPS will not be profitable : too many situations exist where the sky is not fully visible (close to buildings, trees, etc...), and too many benchmarks impossible to pick up directly with the antenna, so that an auxiliary tacheometer will be requested, limiting the benefit of the GPS advantages. And the real-time differential equipments will generally not work properly between the buildings, with their shadow zones. Our opinion is that trigonometric levelling with a tacheometer using a reflectorless EDM will be the best device, as:

- It allows to measure natural objects (sewer plates, marks on concrete borders, etc...) which is often required, if necessary with only 1 people.

- The accuracy obtained will be acceptable.

- The cost of the equipment is compatible with the economic activity of surveyors, tacheometers being the everyday tools of most of them.

- The use of a very high tripod (> 2.2 m for example) or of mural benchmarks set up very high on the walls is a very useful feature, due to the difficulty to get the optical axis unobstructed by passing-by people, trucks or cars.

Another solution would be the use of a digital level with one cheap fibreglass rod (invar rods are much more expensive), but this will prove less efficient if the density of points to survey is high.

For the **case C**, considering the low density requested, we may consider the use of digital levels because of their low cost, or the use of high precision tacheometers with reciprocal simultaneous angle measurements if the equipment is available. The latter would be preferable if the area is large (or very long), and/or with difficulties of communications (for example for a new highway where there are no roads to go from a station to the next one).

For the **case D**, the GPS will generally be the best economical solution, as soon as the work to be performed is not too small an area. Of course the use of real-time differential GPS may be considered if the topography allows for it : it will provide a better security for the quality of satellite measurements and the integrity of the collected data will be tested before leaving the zone. Thus it will be more interesting in situations where the cost of a remeasurement due to a lack of data integrity would be high.

For the **case E**, the use of optico-mechanical levels should probably be preferred for their unsurpassed precision. And as a complement we may note that for stability controls, digital levels and GPS receivers may be used as automatic continuous monitoring devices :

- For digital levels, the required length of rod may be fixed, for example to a building, and monitored automatically by the digital level controlled by a PC. Multiple targets may be surveyed if the digital level is motorised (one command for the direction, one command for the focus), and the accuracy of such measurement reaches easily the 0.1 mm level, even for distances ranging beyond 20 metres.

- For GPS, the requested receiver will have at least a single frequency capability, but of course phase measurement and if possible a large internal memory. Such an equipment may then be permanently installed on a given device, with a reference station not too far away (e. g. less than 1 km when monitoring a bridge), a power supply and if necessary a data link. Considering the possibility to filter the results, even vertical movements as small as 2 to 5 mm may be detected over periods of several days.

For the **case F**, three methods may be considered : GPS, laser equipments and automatic (unmanned) tacheometers. All of these have been tested, but clearly the "pros and cons" are not the same for each of them. For example :

- GPS, in real-time differential mode with multiple antennas on the machine and its blade, may provide an excellent permanent control as long as there is no problems of "shadow" zones where the satellites cannot be received (high trees, high buildings, bridges or tunnel sections). But generally its accuracy is not sufficient for the last layers, as it cannot guarantee better than 1 cm (and in good situations !...), and up to now the cost of the equipment is high. But it will be perfectly compatible with even very complicated profiles. The CIRC European Project has provided quite useful data about this methodology.

- Motorized automatic tacheometers provide a much better precision, and may achieve millimetre accuracy, even in zones with "shadows"where GPS could not be used. But new stations have to be set up every 50 to 200 m (depending upon the topography, as from the stations nothing must limit the sight on the machine), and the continuity of the work requires at least two fully operational equipments. But the cost of the equipment is probably lower than for the GPS, and it is much more versatile and usable on many different situations, not only in guidance of construction machines.

- Laser equipments also allow to achieve a millimetre accuracy, and their ease of setting up is quite appreciated ("2-slopes" configuration, an improper terminology but an efficient technique), and their cost is low but they do not allow for complicated slope or profile variations and their range is limited, which requires the permanent management of at least two instruments (and more generally three) if the continuity of the guidance service is requested.

In any case, a careful estimation of the effects of refraction should be performed, as tacheometers and laser equipments may be sometimes used on very long ranges (more than 500 m is an achievable range for some lasers, and an automatic tacheometer may easily work much farther). Thus it must be pointed out that on such ranges, the errors induced by refraction are often larger than instrumental errors.

Methodology **Case examined**	**Direct levelling**	**Trigonometric levelling**	**GPS**
A/ National network	xx (motorized levelling)	x (mountainous areas), reciprocal simultaneous zenithal measurements	x (limited number of reference stations)
B/ Urban network	x	xx	
C/ Semi-urban network	x	xx	
D/ Rural network			x
E/ Stability controls	x (high precision, possibility of continuous measurements)		x (low precision, continuous measurements)
F/ Construction machine guidance	x (laser equipments)	x (automatic motorized tacheometers)	x (low precision)

5. CONCLUSION

Each given type of work requires a careful analysis, as usual, and a regular re-evaluation to the method that is optimal at a given date. But surveyors will have noticed that since a few years, "precise height determinations" are not always equivalent to "direct levelling". Here we have presented a few examples : the relevance of the analysis presented is probably quite dependent on the economic conditions in each country. But we consider that sometimes the GPS may be used, sometimes not. The same applies for the use of tacheometers. Thus we encourage the surveyors (i) not to overestimate the accuracy of GPS (this paper does not want to emphasize this classical question of the vertical precision of GPS, but any surveyor must be aware of the large discrepancy between the repeatability of GPS - a few mm - and its real precision - generally more than 2 cm -) and underestimate the problems posed by the different reference frames of GPS and national levelling network, and (ii) to have in mind for each work a clear and regularly updated idea about the economic and precision aspects relative to the methods available.

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