NEW MODERN HEIGHT DETERMINATION TECHNIQUES

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Key words:

ABSTRACT

The surveyor, thanks to the rapid evolutions of the available equipment, 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, with special attention paid to the use of GPS methodology.

RÉSUMÉ

METHODES MODERNES DE MESURES ALTIMETRIQUES

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, avec un approfondissement particulier de l'emploi du GPS.

1. A SHORT REVIEW OF AVAILABLE METHODOLOGIES FOR ALTIMETRIC DETERMINATIONS

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

1.1 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 and will not be presented here.

- The level may be opto-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. Today it appears that the best digital levels do not allow for an accuracy equivalent to the one provided by high precision older levels (automatic levels, or spirit levels as well). But their ease of use is considerably better, and blunders are quite unlikely to occur.

- 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.

1.2 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.

- the possibility to achieve the same precision standards as the direct levelling, with a quite different error model. The standard deviation is generally higher (due to the much better aiming capability of levels with a parallel plate micrometer), and on the other hand the bias are generally much smaller (the line of sight being more or less statistically normal to the refraction index gradient, which is not the case with direct levelling).

- a productivity that stays at a high level even in mountainous areas.

The use of a tacheometer allows for rapid levelling operations with a limited accuracy if the ranges used are long. And 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. This feature is very useful in urban areas.

1.3 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. And we shall remember that most surveying works are performed in urban areas.

- The error determination is comparably very large and depends from the duration of the measurements, hardly better than 2 cm rms (one should not assimilate the internal consistency provided by computations with the accuracy), and the dependence with distance between stations is very low. The error increases with the height difference, and depends strongly of the observations duration and type of computation.

- An excellent knowledge is required of the Zero-Altitude Surface 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, 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 authorisations, 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 it is requested, and sometimes may not be the best choice.

Permanent stations provide now an interesting situation for the surveyor, as they allow to reach the national altimetric reference (within a short observation time in a radius of 10-15 km around the station) with only one GPS receiver used. Such stations are now installed, either by national agencies (e. g. Swedesurvey in Sweden, L+T in Switzerland, IGNF in France, ...), or by city technical administrations to lower their own production costs, or by scientific groups (for example to monitor tectonic activities). The observer will go back to its office after field observations, and he will download (generally through Internet, in Rinex format) the observations at the nearest permanent stations before processing with his preferred software.

2. 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.

2.1 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 specialised activity is interesting to analyse. 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 maximise national economy and synergy between various public and private surveying operations.

2.2 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.

2.3 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.

2.4 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.

2.5 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.

2.6 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.

3. WHAT TECHNIQUE IS OPTIMAL TODAY FOR THESE TASKS?

For the case A, a large part (if not all) of the network should be observed with motorised levelling or trigonometric motorised levelling for sections in mountainous areas. But the question arises about the possibility to use GPS in parts. 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 became quite dangerous to use at the era of the TGV. If there exists in the country a good geoidal computation providing a centimetric or sub-centimetric ZAS, we should now consider that the first order notion be replaced by an equivalent notion of reference national height network based on stations observed with GPS and the highest precision methodology possible, of course with ZAS corrections, but these stations being regularly spaced without any terrestrial observations between them. The mean distance between them could be from 50 to 100 km, their global precision being around 2 cm (with a much better repeatability, around 3 to 5 mm, but who cares really about repeatability?). This would provide a zero surface much more horizontal than commonly achieved with classical methods, and thus very low bias, at the cost of a higher standard deviation. But the general goals of the national network would be fulfilled at a much better cost than today.

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 equipment 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 equipment 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.

- Motorised 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 equipment. 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 equipment 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 equipment 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.

4. 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 emphasise 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 rms -) 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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