Optical Plumbing versus RTK-GNSS – Staking out on high Levels

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Abstract

Staking out high-rise buildings always involves the problem to ensure the absolute verticality, from storey to storey until completion of the top floor. At least from a construction height of 100 meters on, systematic and random deflections will appear due to solar radiation, constant wind pressure and gusts, varying loads of construction devices like cranes and design causes.

Conservatively, engineering surveyors mostly choose precision zenith plumping to transfer stable ground networks or grids to the top; however, this proves to be a cumbersome method and affords cautious selection of observation times to be agreed with the civil engineers. On first sight RTK-GNSS observations at the highest storey could provide a splendid alternative to save time and effort. Can they really replace the plumbing work? This is to be discussed.

Theoretical considerations will be illustrated and contrasted by practical experience from the recent project of building the daring twin towers of the European Central Bank in Frankfurt.

Key words: high-rise buildings, construction, verticality, precision plumbing, RTK, GNSS.

1 SPECIFIC SURVEYING CHALLENGES OF SKYSCRAPERS

In contrast to a few low-rise buildings with exceptional oblique design (like e.g. the famous UFA-Palace in Dresden) high-rise buildings have to strictly obey verticality. Hence, it is the surveyor's prior task to ensure rigorous verticality of the structure from the very beginning of construction until completion *(Kägi, 2006)*. Staking out has to be accomplished according to the CAD or BIM models which assume perfect conditions in their geometrical part. In actual fact the construction is subject to various and varying loads and will thus show deformations resulting in instantaneous deviations of the actual position and attitude from the nominal one *(Grethen, 2003)*.

Insolation causes the structure to bend away from the sun with a specific delay and behaves systematically with the sun's azimuth and elevation. The influence shows a diurnal and a seasonal variation. Constant wind pressure will induce a corresponding deflection and wind gusts can stimulate an oscillation. Heavy load cranes attached to the structure will produce random tilts dependent on their particular load and working position. Moreover, some effective construction related biases have to be taken into account. We are familiar with the impact of differential subsidence, but there is also a more complex, varying effect due to the specific way of construction and the construction progress and phase. Usually only the height component will be affected, while for fancy architectural concepts even distinctive horizontal deformations may be encountered calling for preventative counteractions of civil engineers *(Bachmann, 2013)*. An ideal geodetic measurement system would be capable of staking out and monitoring at a time *(Wunderlich, 2013)*.

The common way of building skyscrapers is to erect a central core of reinforced concrete by slip-form technique and then to cast concrete platforms by means of climbing formwork (steel rigs), mostly lagging two storeys behind the core's raising stage. The storeys are supported by columns which are subject to compression because of the load applied. This effect increases with height and load and generates a maximum impact at the mean height of the structure as the levels themselves always are built at the nominal design elevation. It is superimposed by concrete shrinking and differential raft settlement. The key problems manifest during elevator installation and – most of all – when the façade assembly starts before completion of the structural work. Concluding, the surveying engineer has to set out and monitor alternately.

Today's high-rise building projects require tolerances of ± 2.5 to 4 cm of which the surveyor is granted only a fifth. To meet the regulations staking out has to be ensured within a total uncertainty of ± 5 to 8 mm.

2 THEORETICAL CONSIDERATIONS

As intended within the scope of the present paper, two different approaches to repeatedly establish precise geodetic reference at each storey or rig position for staking out shall be discussed. They may be distinguished as interior approach by precision plumbing and exterior approach by RTK-GNSS. In the first case we have - at specified times - to transfer the network geometry of benchmarks at the building's ground floor up to the storey under construction, in the latter one – during every production cycle - we permanently determine the actual position of the top platform from exterior or virtual reference stations at stable sites.

2.1 PRECISION PLUMBING

The imperative precondition for the plumbing approach is to determine the position and to enforce the execution of a sufficient number (three to six) of slab penetrations to gain vertical lines of sight, passing through all storeys. It is very important that the section is large enough to account for implementation tolerances and for deformed states of the structure. 20 x 20 cm^2 prove as minimum for buildings up to 200 m high. Having more than three holes often turns out as good provision because from time to time workers will block some of the openings.

When the building has risen to more than 50 m switching to a stepped approach can be recommended considering accuracy, continuous sight and personal effort. The measurements have to be done before sunrise and daily beginning of the construction works to ensure a neutral status of the structure; i.e. from 4 to 6 o'clock. At this time the builder's hoists are not in operation and they must not be used without an approved operator.

It is a pity that the leading manufacturers discontinued the production of high precision optical plummets. Only a few smaller manufacturers still offer such kind of instruments. On the other hand we find a great choice of laser plummets of medium precision (Fig. 1). By observing in two or four directions of the alidade and repeating the measurements the accuracy improves. The laser points are caught by a transparent grid plate (Fig. 2) or an optical sensor above which a target can be built up. Three zenith plumbings forming a triangle of targets on the highest platform are sufficient to enable free-stationing of the total station there with high accuracy. By means of the TPS the main axes and control points can be staked out by only using relative measurements.

In later construction phases when the cladding is assembled an additional problem arises. Where the building envelope is completed, the atmospheric conditions unfavourably change as no ventilation is active and often construction heaters blow hot air. Heavy refraction and turbulence effects of ± 5 cm magnitude are reported and can only be prevented by pipe installations (see Fig. 3).

Figures 1 to 3 Laser plummet, transparent grid plate, pipe protection (Almesberger, 2014)

As a matter of fact, precision plumbing is a rather cumbersome method; nevertheless, it delivers an accurate reference system on each storey and has demonstrated its successful application in many projects. It should be complemented by three dual-axis inclination sensors arranged in a vertical line at appropriate building levels to attest the required neutral status of structure during the measurement.

2.2 REAL-TIME-KINEMATIC GNSS

Applying RTK technology leads to a completely different concept. Rover antennas will be mounted on the corners of the climbing formwork to continuously determine absolute position which after some corrections and transformation to the site reference system can be used to position a TPS. The measurements of the total station to 360° prisms mounted directly below the antennas are used for free-stationing and at the same time to check the results of GNSS. All data is sent to the site surveying office by WLAN communication lines, checked, combined and adjusted and swiftly returned to the TPS to load it with the actual coordinates. The process will be repeated as soon as the structure's movement requires an update.

As the climbing platform will sometimes not be levelled enough, dual-axis inclinometers with sufficient working range are attached on the pile below the prism-antenna mount to deliver the tilt corrections for the GNSS-positions. One of the available solutions *(Whitworth, 2010)* makes use of the Leica GNSS Spider software and the SmartNet NRTK correction service as virtual reference stations are not subject to signal obstruction compared to reference receivers on site. The whole procedure of staking out by a TPS using the Collocated Active Prisms and inclination sensors (Fig. 4) is very well described in *Cranenbroeck, 2010*. *Whitworth, 2012* reports a three-dimensional coordinate quality of better than ± 25 mm for *Renzo Piano's* 306 m high London skyscraper *The Shard*, which was the requirement for the design compliance.

Figure 4 Collocated Active Prism and inclinometer (Whitworth, 2010)

Summing up, the modern approach saves a lot of labour and time. However, it affords considerable investment in four dual-frequency RTK receivers and special software and has to rely on robust data communication. Regarding accuracy, plumbing still proves superior.

3 PRACTICAL EXPERIENCES

3.1 NEW EUROPEAN CENTRAL BANK PREMISES (NEP)

Practical experience was gained in course of the recent staking out of the NEP in Frankfurt, Germany (Fig. 5). The architects *Coop Himmel(b)lau*, Austria designed twin towers of 165 m and 185 m height, connected by oblique steel diagonals. The special touch of the shapes is caused by the continuous change of the floor plan from a trapezoid to a rectangle in upward direction at one tower and in the opposite way at the other one, thus resulting in torsion of the façades. At the same time this particular design leads to translations and rotations of each storey because of the changing centre of gravity and the effects described in section 1. The civil engineers therefore apply approximated initial deformations to counteract, which have to be confirmed by engineering surveying. The problem is amplified by the fact that the stiffness of both structures isn't reached until the giant steel diagonals are installed – which have to fit.

3.2 APPLICATION OF PRECISION PLUMBING AND INVESTIGATION INTO RTK-GNSS

To meet the challenging demands for staking out and to prove the proper impact of the counteractions, a comprehensive surveying concept was developed by the engineering company *Gemmer & Leber*, Germany (IGL, 2011), assisted by the *TUM Chair of Geodesy*. It provided 4 and 6 plumbing ducts and precision plumbing to transfer geodetic reference from ground to top. The a priori quality proof was supplied by careful selection of instruments to be employed, systematic planning of the application and thorough study of variance propagation. Depending on the number of steps (1 to 3), the theoretical accuracies (mean error in plane) of the plumbing procedure was found to be ± 3.8 mm for the first 50 m increasing to ± 5.5 mm for the highest storeys at 165 m, resp. 185 m. This was fair enough to ensure observing the surveyor's share of staking out by free-stationed TPS, which was ± 8 mm for the NEP project.

Figure 5 NEP Twin Towers, Frankfurt (Walter Wunderlich, 2011)

From a construction height of 100 m on, the concept included three inclinometers mounted at the core in a vertical line (one fixed at 70 m, the others climbing higher) and GNSS receivers at the top. The inclinometers served to monitor the deformation status while the receivers were used to investigate RTK-GNSS possibilities for replacing or at least checking plumbing.

In practice plumbing fulfilled the expectations, but needed high effort and work at night. With a view to achieve accuracies better than 1 cm, RTK-GNSS had to be replaced by static sessions of 45 minutes due to unfavourable signal shading of the core and protective windshields. Detailed information can be found in *Almesberger, 2014* and in *Amtmann, 2013*.

4 CONCLUSION

Precision plumbing confirms as a reliable, but laborious approach and lacks automation. It is repeated for each new construction cycle and delivers the floor reference for relative staking out by TPS. RTK-GNSS depends on good signal conditions, robust data communication, correction service availability and powerful software. Reliable transformation parameters have to be determined in advance. The GNSS approach contains high automation potential and delivers continuous absolute position and orientation of the top platform to be used by TPS for staking out. Collocated Active Prisms and inclinometers prove necessary.

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