AN INTEGRATED GPS AND TOTAL STATION INSTRUMENT FOR CULTURAL HERITAGE SURVEYING: THE LEICA SMARTSTATION EXAMPLE

A. Biasion, A. Cina, M. Pesenti, F. Rinaudo
DITAG, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, ITALY
andrea.biasion@polito.it, alberto.cina@polito.it, manuele.pesenti@polito.it, fulvio.rinaudo@polito.it

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ABSTRACT

Total stations and GPS receiver are normally used separately for terrestrial survey of cultural heritage, and the natural development has been the production of a single instrument where both a GPS and a total station work together. Several problems, such as the different reference systems used by the two techniques, require a geodetic approach to solve them.
Leica Geosystems was launched SmartStation, an innovative product that integrates a GPS double frequency receiver and a Total Station series 1200. The real integration is obtained from a new firmware that is able to manage and store both kinds of measurements: angle and distance, RTK and other GPS observations. The GPS observations are functionally to the reference system set-up, while total station measurements provide the north direction of the reference system, and carry out a detailed survey using celerimetric measurements.
A new instrument implies a new survey methodology, compared to classical techniques. Several survey scenarios can highlight the main advantages, that is no control points are needed, and there are no long traverses, or resections.
To evaluate these new technologies and compare them with traditional ones, a case study survey has been conducted on the Porte Palatine, an archaeological building site in Turin, where a topographic referenced network was signalized and measured. The comparison focused on the time-saving, the staff needed to conduct the survey (skilled and/or unskilled), and the easiness of the survey operations.

1. INTRODUCTION

In several application fields of cultural heritage survey it is potentially interesting to integrate survey data from different sources but for the different phases of a traditional survey several instruments are necessary. This paper describes how the idea of integration should be applied to the topographic survey world, and how Leica Geosystems Inc put this into practice. The first part of the paper emphasizes how survey methods will change with the introduction of new instruments. Several survey scenarios are considered, in order to compare them with traditional survey techniques. Some evaluations and considerations about the geodetics approach have to be made, in order to evaluate the results of a case study, in which the SmartStation instrument was tested. The results of this test are then reported.

2. TOPOGRAPHIC SURVEY REQUIREMENTS

Over the last few years, modern technologies have provided many powerful instruments for who are employed in various way in the cultural heritage survey field. Modern methodologies for topographic and geodetic surveys are closely connected to the available instruments, and are influenced by them.
Modern optical instruments can now measure angles and distances without using prisms with a range of nearly 500 m, an accuracy of 3mm + 2ppm for distance measurements, and 1 mgon or better for angle measurements. With GPS receivers, in Real Time acquisitions or post processing adjustments, it is possible to obtain precisions of few centimetres in RTK technique.
Each technique has and applies its own topographic and geodetic approach to the same application field.
One of the natural developments of the instruments is the integration between different survey instruments. Several attempts and trials had been conducted for many years. Figure 1 shows an old example of integration of an optical theodolite with a EDM. The level of integration between these two instruments is actually lower than a modern Total Station, but in a certain way, it can be considered an ancestor of the modern Total Station, where the integration is effective.

Figure 1: A distancemeter mounted onto the top of a theodolite

Other integrations are usually adopted in geomatics fields, for example integrated GPS and INS for direct photogrammetry or Laser Scanner (aerial or terrestrial) and GPS + IMU.

1.1 Integration

An effective integration between two measurements instruments does not simply mean that they can work together, but just being in charge of different aspects of the same survey session. Integration means that data acquired can be shared and harmonically used together to get some results usually not directly obtainable.

3. LEICA SMARTSTATION

In 1993 Leica Geosystem registred a USA Patent for a "*Surveying system including an electro-optic total station and a portable receiving apparatus comprising a satellite position-measuring system* ". This has now been implemented in an instrument which is called Leica SmartStation.

Figure 2: TPS and GPS integrated in SmartStation

3.1 How does it run

Smartstation combines an high performance TPS and a powerful GPS receiver. The instrument works as illustrated in figure 3. The combined and simultaneous acquisitions of two GPS receivers (one generic GPS receiver as the Master reference station, and the other Smartstation GPS as a Rover station). In RTK mode, this configuration provides a high precision positioning for the Rover receiver, up to the order of few centimetre, for baselines since to almost 30 Km.
The reference Master station can of course be substituted by a Reference Network, when one is available. In this case, the accuracy of the GPS positioning depends on the specifications of the reference network.

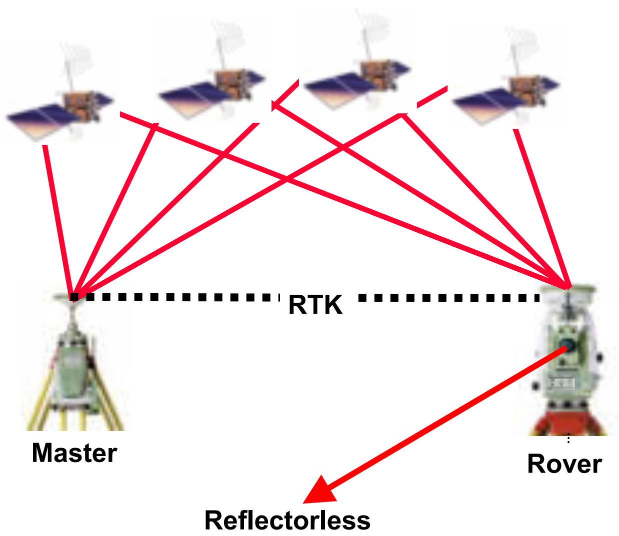


Figure 3: Working plan of the SmartStation

The electro-optical SmartStation instrument is now ready for a detailed survey, as its own coordinates in an absolute reference system are known.

3.2 SmartStation Integration

The Smartstation integration concept is obtained from:

- Components combined in a single body, with no external cables for communication between the TPS and GPS;
- Data from both instruments are saved in a single database, in one unique mass memory storage device;
- The two instruments are controlled by the same TPS keypad;

The real integration is however carried out by the software. The internal software in SmartStation provides a "dialogue" between the TPS and GPS, and each instrument exploits measurements from the other to integrate its own measurements.
The following two examples provide the necessary explanations:

1. Stationing on unknown coordinate points it is possible to measure RTK coordinates and an azimuth direction in order to provide a reference system for electro-optical instrument measurements.

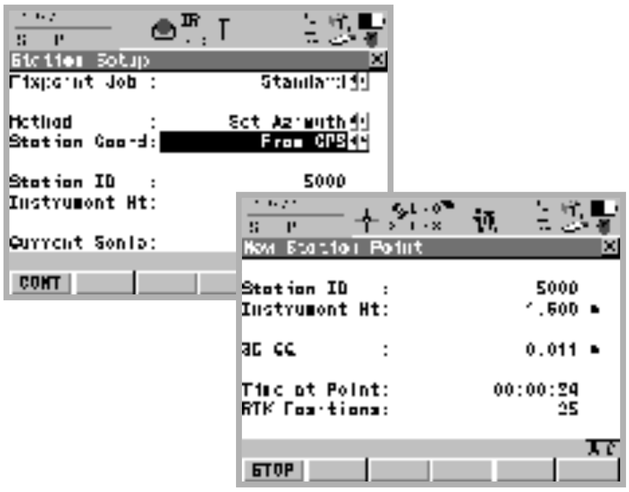


Figure 4: GPS positioning in SmartStation

2. Positioning a station on a generic point for a detailed survey, the absolute coordinates of the station point (red E, N, H coordinates in fig. 5) are available with the GPS RTK positioning, but there is still uncertainty about the reference system orientation (N? in white). If the electro-optical instrument is used, it's possible to measure another known-coordinate point (reference or fixed point) in order to fix the bearing direction for the reference system of the station (red line).

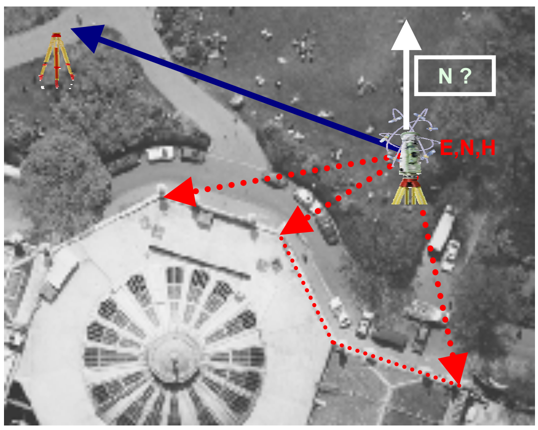


Figure 5: TPS for SmartStation orientation

Although SmartStation has been developed to integrate TPS and GPS, the two instruments can both work independently, separately from each other. The TPS can be used as a traditional Total Station, while the GPS has to be used with an external controller. The SmartStation GPS antenna actually contains the receiver, but it is controlled by SmartStation software. In order to obtain independent use, it is necessary to have an external control pad.

4. SURVEY SCENARIOS

In cultural heritage surveing, we can see many applications and several scenarios could appear. Each one requires an adequate planning to obtain the best results from the survey operations. Some scenarios are analyzed in this paragraph, to describe how survey methodology could change with the introduction of this kind of integrated instruments.
In general, it is possible to illustrate the methodological advantages of the use of an integrated instrument, such as the SmartStation.
Considering a traditional TPS survey (Fig. 6), or whenever GPS equipment is not available, long, open topographic traverses have to be set up to “bring” the reference system across the “uncovered” area, with some obvious problems. In particular, the accuracy decrease if the polygon geometric configuration is not well-planed.

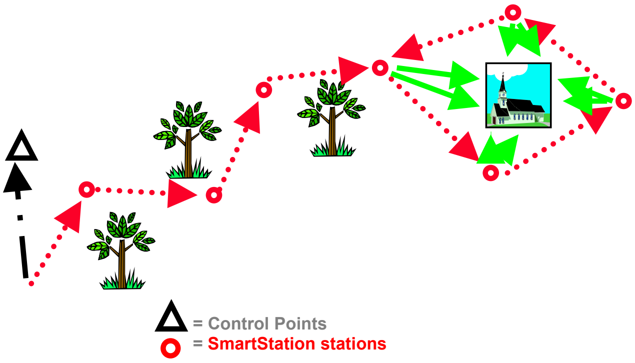


Figure 6: Open topographic traverses

With the SmartStation, this situation is solved without long traverse, control points, or resections (Fig. 7).

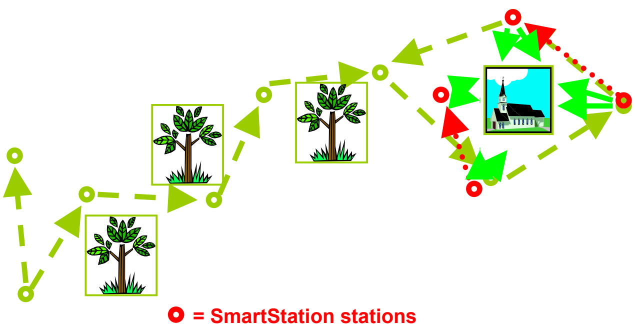


Figure 7: Survey without topographic traverses

With the SmartStation survey methodology, two further scenarios exist, with or without control points in the survey area.

4.1 Topographic survey with control points

In this situation, control points are present in the survey area, but are not sufficiently well placed to be used directly for survey stations.

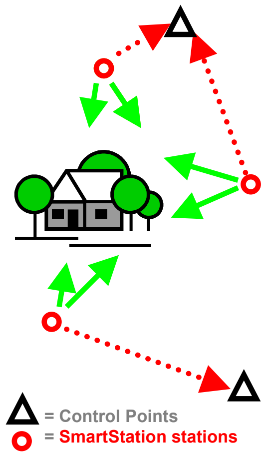


Figure 8: SmartStation survey using control points

SmartStation locations can be placed in the most convenient sites for a detailed survey.
Only one control point has to be visible from the SmartStation location, in order to provide the right bearing to the TPS.
The visibility between the two SmartStation locations is not necessary.

4.2 Topographic survey without control points (with mutual visibility between station points)

In this scenario, there are no control points in the survey area, or it is not convenient to occupy them.

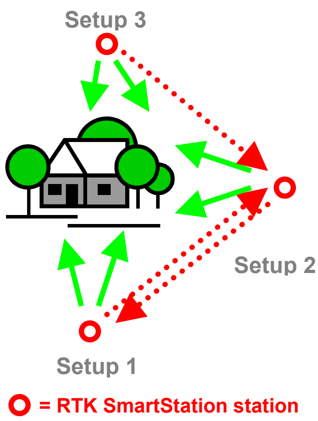


Figure 9: SmartStation survey without using control points with stations mutual visibility

SmartStation can be placed in the most convenient sites for a detailed survey.
The mutual visibility is required between the SmartStation locations, as each station can be used to orient the next stations.

4.3 Topographic survey without control points (without mutual visibility between station points)

In this situation, there are no control points in the survey area, and it is not possible to have the mutual visibility between two SmartStation stations.

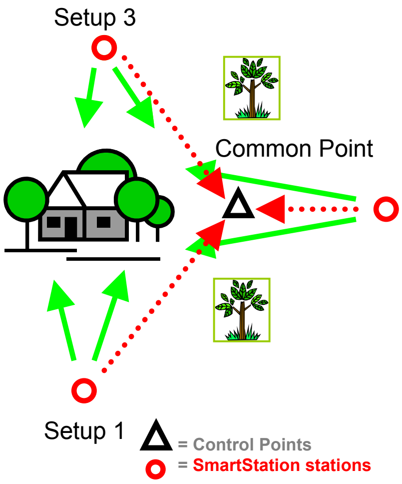


Figure 10: SmartStation survey without using control points without stations mutual visibility

SmartStation can be placed in the most convenient sites for a detailed survey.
A point with a mutual visibility between two stations has to be measured. Its calculated coordinates are used to relate the measurements from two or more different SmartStation locations.
In the next two paragraph two practical scenarios are described, where a cultural heritage survey could be performed, in order to compare traditional survey techniques with the new methodology introduced by SmartStation.

4.4 Topographic survey in remote areas

If archaeological sites are considered, for example, we normally refer to isolated sites, or rural areas, far from urban or anthropic areas.
It's also possible that vegetation makes a continuous RTK survey difficult, therefore a TPS has to be used. Without control points, but with a reference station that send RTK corrections, it's necessary to operate in a traditional way:

- Fix a network of GPS points around the site, and transfer the GPS coordinates into the TPS;
- Locate the TPS on each point of this network, oriented to other points and perform the detailed survey.

This means:

– Points have to be occupied twice, once with GPS, and once with TPS;
– If a point is first occupied with TPS and then with GPS, the fitting operations have to be done in the post-processing stage;
– Two instruments are needed, and probably two teams of technicians.

With SmartStation

- The instrument can be placed in an adequate position for a detailed survey;
- GPS coordinates are obtained each time to georeference the instrument for each point;
- The other points that are used before for the survey (but are not required to be fixed points) are measured with electro-optical instrument. This procedure fixes the bearing between two points.

This methodology offers several advantages:

+ Points are occupied only once;
+ Only one instrument is required, and only one team;
+ Less time is needed;
+ Station points can be chosen in a proper way for the best survey results.

4.5 Topographic survey in urban areas

An urban area is usually characterized by the existence of valuable examples of cultural heritage, but this means topographic survey are not so easy to be carried out. High buildings or trees in fact make it impossible to use GPS, and cars, traffic, and the buildings too, hamper topographic traversing, or make it difficult to station on control points.
If a SmartStation is used it is possible to fix the RTK where GPS signals are available (and also RTK corrections): that are road junctions, and other open spaces. With one of the previously described setups, it is possible to use the instrument for a detailed survey in an appropriate way.

5. GEODETIC CONSIDERATIONS

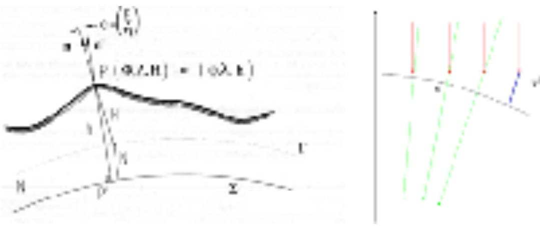
In order to understand the key of the innovation, introduced by the new instrument produced by Leica, if is necessary to digress a little and talk about different reference systems, inherent to different techniques that are physically integrated in the new SmartStation and whitch are managed by a single interface.
Classical planimetric measurements refer to a local ellipsoid (in Italy is used a Hayford ellipsoid oriented in Monte Mario in Rome), the orthometric quotes refers to the geoid, and between two surfaces there are differences of few meters. GPS base and coordinates refer to geocentric ellipsoid WGS84, with different semiaxis and flattening than the other cited surfaces, and WGS84 diverges from the other surfaces by even more than 50 m.
Angular measurements are closely connected to the gravity field that can be considered vertical to a plane (Fig. 11B) in a more restricted range with respect to the length of normal GPS bases.
It can be said that directly measured distances are invariant and independent to three dimensional reference system changes.

5.1 Integrating measurements and reference systems

In a first approach two steps are necessary to refer zenithal angles and azimuthal directions to a local plane:

1. first real gravity field has to be reported to a normal ellipsoidal one, through the scalar relation:
   $\mathbf{W} = \mathbf{U} + \mathbf{T}$
   where W, U, and T are the real , normal and anomaly potential of gravity field.
   The primary axis of theodolite is oriented by the vertical.
   As expressed in Fig. 11A, is necessary to know the vertical deviation $\varepsilon(\xi, \eta)$ and the geoid undulation. To change reference system from geoidic coordinates (referred to vertical) to geographic coordinates (referred to ellipsoidic normal) we can use the follow formulas:
   $\varphi = \Phi - \xi$
   $\lambda = \Lambda - \eta / \cos(\Phi)$
   $h = H - N$
2. then the normal ellipsoidal gravity field has to be transformed into a parallel one in order to consider

planimetrical survey ranges larger than 15 km and altimetrical ones larger than a few hundreds of metres.



(A) (B)

Figure 11: Corrections from real to a parallel gravity field

In 3D survey classical observations (angles and height gradients) can be corrected with a validity of about 30 km using the following relations to pass from normal gravity field to parallel gravity field:

$$C(\zeta) = \frac{1}{s\sin(\zeta_0)}\left[(e_i - e_j),(n_i - n_j),(u_i - u_j)\right]^T \delta'$$

$$C(\vartheta) = \frac{1}{s^2\sin^2(\vartheta_0)}\left[(e_i - e_j),(n_i - n_j),(0)\right]^T \delta'$$

$$C(\Delta) = \left[(e_i - e_j),(n_i - n_j),(u_i - u_j)\right]^T \delta'$$

$$\delta' = \frac{1}{\sqrt{e_i^2 + n_i^2}}\begin{bmatrix} e_i\delta \\ n_i\delta \\ 0 \end{bmatrix}$$

while GPS observation can easily be rotated in a local reference system with a classical rototranslation algorithm:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} X_0 \\ Y_0 \\ Z_0 \end{bmatrix} + R(\varphi,\lambda)\begin{bmatrix} e \\ n \\ u \end{bmatrix}$$

Another approach is to reduce all measures in geoid's plane. The first step is to reduce slant distance to a reference surface (local sphere). The distances between points (d_0 in Fig. 12) can be reduced to a geodetical distance (d_g) which lie down on the reference surface using the relation:

$$d_g = \left(1 - \frac{h}{R}\right)d_0 = m_Q d_0$$

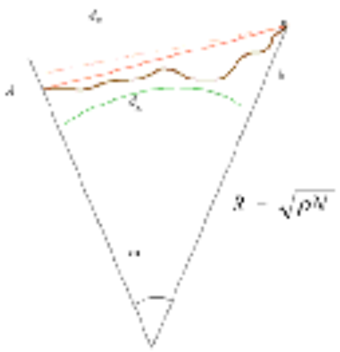


Figure 12: distance reduction to a local reference surface

The second step is to reduce a geodetic distance to cartographic distance that lie down on a Gauss cartographic plane:

$$d_C = m_L d_g \qquad m_L = 0.9996\left(1 + \frac{x^2}{2\rho N 0.9996^2}\right)$$

For a third approach, in order to consider a geocentric Cartesian system it's necessary to reduce only classical observations (no GPS coordinates or bases, already expressed in this reference system, or distances, that not depend from the reference system):

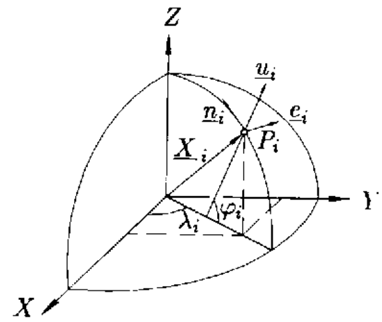


Figure 13: Relationships between the local and global reference systems

direction:

$$\vartheta_{ij} = \frac{-(X_j - X_i)\sin\lambda_i + (Y_j - Y_i)\cos\lambda_i}{-(X_j - X_i)\sin\varphi_i\cos\lambda_i - (Y_j - Y_i)\sin\varphi_i\sin\lambda_i + (Z_j - Z_i)\cos\varphi_i}$$

zenithal angle:

$$\zeta_{ij} = \frac{-(X_j - X_i)\cos\varphi_i\cos\lambda_i + (Y_j - Y_i)\cos\varphi_i\sin\lambda_i + (Z_j - Z_i)\sin\varphi_i}{\sqrt{(X_j - X_i)^2 + (Y_j - Y_i)^2 + (Z_j - Z_i)^2}}$$

quote difference:

$$\Delta_{ij} = h_j - h_i = (X_j - X_i)\cos\varphi_i\cos\lambda_i + (Y_j - Y_i)\cos\varphi_i\sin\lambda_i + (Z_j - Z_i)\sin\varphi_i$$

6. A CASE STUDY: THE PORTE PALATINE ARCHAEOLOGICAL SITE IN TURIN

The test area chosen for the new Leica instrument was the Porte Palatine, an archaeological building site in the north part of Turin. The area is located near the centre of town and even if in a place with large spaces there are several buildings of 3-4 floors around.

Figure 14: Views of the Porte Palatine archaeological site with the new Leica SmartStation at point 300

The focus of the test was to compare classical surveying procedures used in previous campaign of the same archaeological site with the one of which we described in Section 4 that best fit to our case.

For a survey of the site in the past has been necessary to pass through some steps that require lot of time:

- materialization of four ground control points well distributed around the area and data collection for realization of the respective monograph (Fig. 15);

- mutually collimation of ground points and realization of a local reference system with an arbitrary origin fixed assigning coordinates X = 1000 m, Y= 1000 m and Z = 1000 m to point 200 (Fig. 15);
- orientation of the four points in a global reference system (national IGM95) using TPS and/or GPS instrument;
- survey of the points.

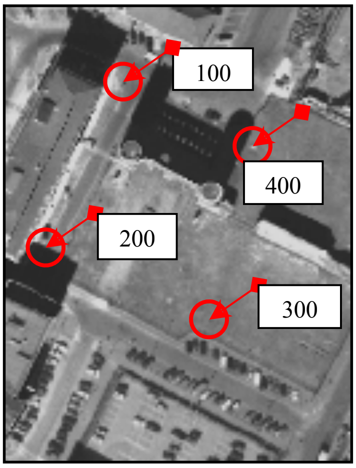


Figure 15: Schema of the classical surveying mode

To make the most of potentials offered by new integrated instrument, having no high precision datum point in the neighbourhood of the archaeological site oriented in national IGM95 or in a global reference system, we decide to proceed as follows and as illustrate in Section 4.2.

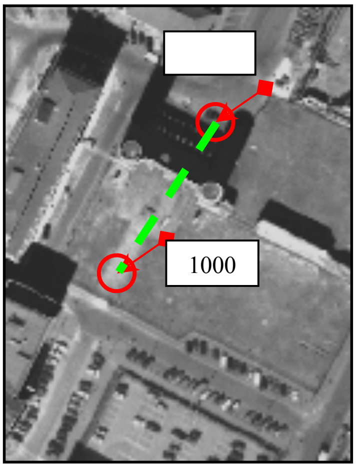


Figure 16: Schema of the second surveying mode

We decided to pass trough these steps:

- individualization of two collimation points (1000 and 2000 in Fig. 16) with mutual visibility located on opposite side of the building;
- measuring of distance and azimuthal angle of the direction from 1000 to 2000;
- survey of the points.

In this way it was possible to by-pass three phases like the first mentioned in classical procedure that usually need some working hours, up to half a day, obtaining a points survey with the same accuracy.

At the same time, in this case, a more free choice of station positioning had allowed to avoid two practical problems, in fact point 400 no longher exists as it was placed in the actual yard area beside Porte Palatine and point 200 is too close to a building and it is not possible to determinate its coordinates using DGPS technique beacouse of signal lost.

7. CONCLUSIONS

According to the preliminary remarks and the results achieved, it is possible to consider the Leica Smartstation as a valuable new solution for cultural heritage survey. The main advantages connected to the new instrument are:

- the coordinates of the points are obtained in a global reference system: during the survey operations the XYZ coordinates are directly measured;
- real–time 3D survey: the planimetrical and the altimetrical components of a traditional measure scheme are not divided;
- the methodologies of the survey and the scenarios changed with the improvements previously shown, making the survey operations easier.

As the accuracy obtained by the SmartStation measurement is comparable with classical measure instruments, the great deals for the users are represented by:

- the easiness approach to the survey operations;
- the survey speed, that increases from traditional measure instruments.

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