GROUND SUPPORT OF SATELLITE SYSTEMS

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ABSTRACT

The application of the GPS system in surveying jobs done for engineering purposes is inhibited by unsatisfactory precision of position defining, uneven precision of co-ordinates, and precision fluctuations over time. This situation is made even more difficult by the limited access to signal and by terrain obstacles which are often found at sites where engineers are working. This paper presents various aspects of strengthening the GPS system with overground support which depends on access to the constellation of GPS satellites and on the conditions the environment offers to observation. The paper also describes the results of preliminary precision analysis obtained at various configurations of the support, which significantly improve the geometry of positioning, whenever appropriate conditions are secured.

1. POSSIBILITIES FOR SUPPORTING THE GPS SYSTEM

The application of the GPS system, so commonly used by surveyors, is often limited in engineering geodesy as its precision requirements are becoming increasingly complex. These limits usually consist in insufficient precision of positions defined, uneven precision of the co-ordinates, and fluctuations of precision over time. This situation is made even more difficult by limited access to signal and terrain obstacles which are often found at sites where engineers are working.

The intention of using a system that can support GPS should be to improve the precision of positioning, ensuring comparable precision of co-ordinates, and reduction of the time-related precision fluctuations. The need for supporting GPS is particularly strong in situations where the visibility of GPS satellites is poorer because of obscuring terrain objects, when the determined position is not precise enough, or a GPS satellites constellation does not allow defining the position of a point (e.g., because of the presence of terrain obstacles).

There are various methods for supporting GPS system and they depend on the accessibility of GPS satellites constellation, the type of measurements, and on the observation environment.

One of such methods employs extra source/sources of satellite signal placed at a point whose co-ordinates are known. These devices, often called pseudosatellites, or pseudolites (acronym: PL) being an additional source of signal with diversified geometrical properties, solve the problems resulting from the imperfections of the GPS system by way of strengthening the geometry positioning and increasing the volume of signals available for measurement (Choi et al., 2000, Cobb, 1997).
Observation performed from an extra signal source on the ground may be replaced by tachymetric observations, if it is only possible, and it is a much simpler and cheaper solution though it requires a different approach to the processing of results since the observations are not readily comparable.

In extreme cases, it is also possible to completely replace GPS system with signal sources fixed on the ground (minimum 4 are required for a complete position measurement). An advantage of this solution is the user’s full control over transmission which consists of sending and receiving signal. Positioning becomes possible at places where signal from a GPS satellite can never be used: under the ground, inside tunnels, or many buildings, wherever GPS signal cannot reach or whenever its quality is unsatisfactory.

The application of pseudolite technology in geodesy is subject of research since 90’ of the previous century. At the beginning of development of this technology the transmitting GPS-frequency signal by pseudolites seemed to be good idea but it occurred that this solution has many disadvantages (Choi, 2000, Dai, 2001).

One of the main problems is that the GPS L1 and L2 frequency are licensed. A license for wide deployment of a ground based system on GPS-frequency would be very difficult to obtain, what is the big obstacle for commercial application of the technology.

The last solution based on the psedolite idea is Locata - a network of terrestrially-based transceivers of own proprietary signal structure in the 2.4 GHZ ISM band (license free) that can operate in combination with GPS or independent of GPS. (Montillet et al. 2007).

In the literature of the domain, mainly the experimental measurements are presented (Dai et al. 2001, Rzepecka et al. 2005). Often, the problem of the measurement planning and adjusting ground support to the current satellite constellation are not deeply analysed. These issues are briefly introduced in (Cosser et al., 2004), more detail analysis are presented in (Cellmer 2005).

Below are the results of a preliminary analysis of the precision of various GPS support configurations which can significantly improve the geometry of positioning, if appropriate conditions are provided.

The application of such analyses in measurements planning and designing of the satellite-ground network makes possible to obtain the possible best accuracy and at the same it allows using the technology optimally.

2. PRELIMINARY ANALYSIS OF THE PRECISION OF SATELLITE/ PSEUDOSATELLITE MEASUREMENTS

The preliminary analysis of the precision of satellite measurements rely on DOP (Dilution Of Precision) which measure the effect of satellite geometry on the precision of the positioning of a given point. The geometry of GPS satellites constellation, defined by the DOP values, changes with time, with the changing satellite positions, and with the changing position of the receiver. Having information about satellite orbits, we can define the position of GPS satellites as it is during observation time and then compare observation equations in matrix A.

The analysis of the matrix of co-factors $(A^\top A)^{-1}$ reveals the properties of error propagation (Meng et al., 2004). Co-factors NDOP, EDOP, VDOP, and TDOP, which are respective values from this matrix trace, define the precision of the individual co-ordinates. We can, therefore, forecast the DOP values which refer to a place and time planned for the measurements, and we can predict the precision which is possible to reach.
This paper describes the preliminary precision analyses done for a specific situation: observation point with Warsaw’s geographical co-ordinates (52°35’ N, 21°04’ E), on March 26, 2009, during 24h. Data on the current position of satellites were taken from the Trimble Planning programme. Since the satellites’ movement is roughly synchronized with the spinning movement of the Earth, the above-described conditions are recurrent every day. Figure 1 shows the routes of satellites flying over Warsaw.

![Skyplot for Warsaw on March 26, 2009 (cut-off angle -15°).](image)

As can be seen in the drawing, there is an “observation hole” in the north, typical of medium geographical latitudes. This leads to a shortage of observations made from northern direction and, as a result, it spoils the precision of positioning in this direction. Should some terrain obstacles be also present there to obscure satellites’ visibility from the south, the precision of positioning may drop significantly and any positioning may even become impossible at all.

Based on the satellite position data, DOP coefficients were calculated during a period of 24 hours on the planned observation date. Figure 2, which shows the curve of GDOP coefficient changes (geometrical blurring of position and time), also shows a considerable fluctuation of this coefficient. Its value grows over 5 several times during the 24-hour period and measurements should not be made at all whenever it is higher than 5. Its maximum value reaches 49 which completely rules out any reliable positioning.

![GDOP diagrams for Warsaw on March 26, 2009.](image)
Table 1 shows maximum and average daily values of DOP coefficients, respective for the individual co-ordinates.

<table>
<thead>
<tr>
<th></th>
<th>NDOP</th>
<th>EDOP</th>
<th>VDOP</th>
<th>TDOP</th>
<th>GDOP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max</td>
<td>13.5</td>
<td>3.6</td>
<td>36.0</td>
<td>30.7</td>
<td>48.7</td>
</tr>
<tr>
<td>Min</td>
<td>0.6</td>
<td>0.5</td>
<td>1.2</td>
<td>0.8</td>
<td>1.7</td>
</tr>
<tr>
<td>Average</td>
<td>1.2</td>
<td>0.8</td>
<td>2.3</td>
<td>1.7</td>
<td>3.3</td>
</tr>
</tbody>
</table>

This means that the precision of defining the individual co-ordinates may vary. We get lower precision in determining elevations because all signal sources are placed 15° over the horizon and we find the precision of co-ordinate N to be lower than that of co-ordinate E which is an effect of scarce observation from the north. The aim of our analyses will be to identify the best position for a pseudosatellite so as the extra observation it allows could also:

- eliminate the critical moments of poor precision,
- reduce precision fluctuation,
- improve the precision of individual co-ordinates

through providing an optimum geometry of defining positions.

In order to identify the optimum pseudosatellite position, a detailed analysis of the position of GPS satellites was carried out at moments of critical poor precision (Fig. 2). A weak constellation of GPS satellites at those moments, which can be seen in Fig. 3, gives high values to the GDOP coefficient.

Fig. 3. GPS satellites visibility at critical moments.

There is no doubt that an extra source should be placed close to the horizon in order to improve precision, especially the precision of elevation measurement. But still there is the question of azimuth’s relation to the observation point. To determine it, analysts calculated DOP coefficients for the whole horizon every 5 degrees apart (assuming elevation angle 0°). Figure 3 above shows the position of the pseudosatellite for which the lowest DOP coefficient values were obtained. Grey colour shows areas in which precision can be improved significantly.

The analysis of these three cases shows that placing an extra source within the azimuth of 270° may offer a significant precision improvement at each of those moments.
Figure 4 shows a 24-hour GDOP coefficient curve for a GPS satellites constellation supported with an extra source placed on the horizon within the azimuth of 270°. Table 2 presents the maximum and average values of individual DOP coefficients compared with the values the GPS system alone.

![Fig. 4. Diagrams of GDOP coefficient for PL supported GPS measurements in Warsaw on March 26, 2009.](image)

**Tab.2. Comparison of DOP coefficients GPS and PL-supported GPS measurements**

<table>
<thead>
<tr>
<th></th>
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<tbody>
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<td><strong>max</strong></td>
<td>13.5</td>
<td>3.6</td>
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</tr>
<tr>
<td><strong>GPS</strong></td>
<td>min</td>
<td>0.6</td>
<td>0.5</td>
<td>1.2</td>
<td>0.8</td>
</tr>
<tr>
<td>average</td>
<td>1.2</td>
<td>0.8</td>
<td>2.3</td>
<td>1.7</td>
<td>3.3</td>
</tr>
<tr>
<td><strong>max</strong></td>
<td>3.6</td>
<td>1.5</td>
<td>2.4</td>
<td>1.7</td>
<td>4.2</td>
</tr>
<tr>
<td><strong>GPS+PL</strong></td>
<td>min</td>
<td>0.6</td>
<td>0.5</td>
<td>1.1</td>
<td>0.6</td>
</tr>
<tr>
<td>average</td>
<td>1.0</td>
<td>0.7</td>
<td>1.4</td>
<td>0.9</td>
<td>2.1</td>
</tr>
</tbody>
</table>

This means that the expected effect was obtained, i.e., the critical moments of poor precision were eliminated, a better precision performance was reached on the individual co-ordinates, and DOP coefficient value fluctuation was reduced.

3. PRELIMINARY ANALYSIS OF SATELLITE MEASUREMENT PRECISION, SUPPORTED WITH LENGTH OBSERVATION

A similar analysis can be done, if we include additional observation of distance instead of the observation of satellite pseudodistance (observation equations will then include no component responsible for time). This time, a smaller precision improvement was obtained but the optimum direction of support remains all the same. Figure 5 and Table 3 present the result of such an analysis.

The introduction of an additional distance offers smaller effects than an additional satellite observation. Such a support also requires a different approach to processing of the measurement results because the observations are not homogenous.
Fig. 5. Diagrams of GDOP for GPS with additional observation of distance.

Table 3. Comparison of DOP, GPS and GPS with additional observation of distance

<table>
<thead>
<tr>
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<td>0.8</td>
<td>2.3</td>
<td>1.7</td>
<td>3.3</td>
</tr>
<tr>
<td>max</td>
<td>1.5</td>
<td>1.4</td>
<td>8.1</td>
<td>6.7</td>
<td>10.7</td>
</tr>
<tr>
<td>min</td>
<td>0.6</td>
<td>0.5</td>
<td>1.2</td>
<td>0.8</td>
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</tr>
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4. ANALYSIS OF GROUND NETWORK INDEPENDENT OF GPS

With the same coefficients in hand, we can make an analysis of a network independent of GPS, relying on the same fixed sources. We will look at the simplest network comprising 4 pseudolites, the smallest number required for a 3D positioning. The best arrangement of transmitters seems to be 3 of them deployed at even distances around the receiver and one in the zenith. Figure 6 shows the distribution of GDOP coefficient values obtained from such a pseudosatellite deployment.

Fig. 6. GDOP coefficient values for various receiver positions.
In practical life, it is often impossible to place the additional source in the zenith. Therefore, the GDOP coefficient was analysed in relation to the elevation angle of the “key” transmitter. The results of this analysis are shown in Fig. 6 below.

![Graph showing GDOP values depending on the “key” PL elevation angle.](image)

Fig. 7. GDOP values depending on the “key” PL elevation angle.

As can be seen in the graph, the elevation of this instrument has a strong impact on GDOP coefficient (it changes the value of the VDOP coefficient). The higher the instrument is placed, the better result can be obtained. We can also see that the GDOP coefficient does not grow higher than the acceptable value of 5 for the angle of 20° and more, while the improvement of the DOP coefficient becomes increasingly small for angles of 45° and more. When it comes closer to zero, that is, all the instruments are at the same level, the DOP coefficient approaches infinity and any positioning becomes impossible.

It is possible, however, to use a reversed system instead of the above-described network, i.e., to use a transmitter for the positioning of the required point and deploy 4 receivers at known points. It is possible to define the position of a moving transmitter based on observations captured by the receivers deployed at points whose co-ordinates are known. From a geometrical point of view, there is no difference between a PL-based system and a reversed system, hence the above-presented precision analyses may just as well be used in this case.

5. SUMMARY

The precision analyses performed showed a significant improvement of the geometrical conditions of positioning, thanks to the use of pseudosatellites and a little smaller improvement when distance observation is added. However, these analyses were done with the assumption that there were no obstacles obscuring GPS satellite visibility. Should such terrain obstacles be present, the obtained improvement would have been even more significant.

The result of the analyses has also refuted the intuitive suggestion that the northern “observation hole” requires additional observation or distance from the northern direction. What measurement planning does require is a detailed analysis of the measurement place and time, an analysis of the observation environment (terrain...
obstacles) and picking up the pseudosatellite’s right position for the actual observation scene. An analysis of the simplest, GPS-independent network offers promising results in terms of geometric precision. In practice, however, analysis of this type should be done based on detailed terrain data and when there is a true possibility to deploy transmitters in the area.

6. DIRECTIONS FOR FURTHER STUDIES

Further studies in this area will focus on:
- developing tools able to identify the best possible location of the additional signal source(s) at a given time and place of observation,
- developing tools able to define the precision of ground networks,
- an attempt to define the principles of designing satellite-ground networks,
- an attempt to practically check the GPS support system.

REFERENCES

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