The impact of the PCV parameters in the coordinates estimate.

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1. Introduction

In high precision GPS data analysis, any known effect which can have an impact on the final estimates, e.g. the receiver co-ordinates, must be carefully modelled and reduced.
One of these effects is the related to the phase centre of the receiver antenna. It is well known that the signal coming from the GPS satellites is referred to an electromagnetic point called antenna phase centre. This point is not a unique geometric point, such as the antenna barycentre, but varies depending on the signal frequency and the satellite elevation and azimuth, describing a surface which is peculiar of each antenna model. The impact of such an effect is quite remarkable if sub-centimetre precision is required. So, currently, its precise modelling is considered in processing GPS data of non-permanent networks which are usually designed for deformation monitoring in active fault areas or in volcanic areas. Often, in these networks different antenna types are used at the same point in different campaigns. This implies that a careful reduction for the phase centre must be accomplished to properly account for such antenna mixing. Furthermore, a similar effect occurs in GPS permanent stations when the antenna is removed or changed. In this case, the IGS standards suggest to truncate the time series of the permanent station which is re-started at the epoch of the antenna change. This is a possible solution which however implies that the continuity between estimated quantities (e.g. the site velocity) before and after the antenna change is hard to obtain. If forced centering and highly reliable phase centre models for the antennas were used, the discontinuities, which are in fact detected in the time series, could be mitigated. In this paper, an "in field" experiment is proposed to verify the impact of different phase centre models on the co-ordinate estimates in high precision GPS measurements.

2. The phase centre estimation

In a standard reliable GPS data processing, the observations must be corrected for the effect of the phase centre and referred to the ARP (Antenna Reference Point). The data are corrected for the mean position of the antenna phase centre ($\Delta\vec{r}$) and for the variation of the phase centre with respect to this mean point (Hugentobler et al., 2001). This last effect is called Phase Centre Variation (PCV). The equation describing the phase centre data reduction $\Delta\Phi(\alpha, z)$ is

$$\Delta\Phi(\alpha, z) = PCV(\alpha, z) + \Delta\vec{r} \cdot \vec{e} \qquad (1)$$

where $\vec{e}$ is the unit vector in the direction antenna-satellite, α is the satellite azimuth and z its zenith angle.

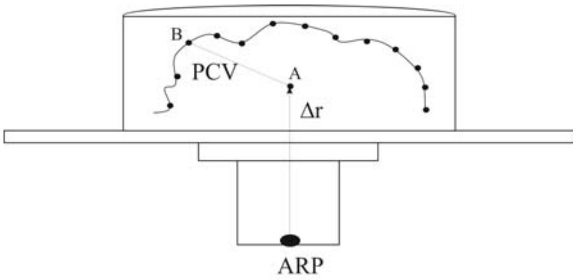

Figure. 1 - The antenna phase centre scheme**:** A is the mean position and B is the instantaneous position of the phase centre.

For well designed antennas, the PCV has sub-centimetre values which are described using a polynomial or a spherical harmonic function sampled at discrete values depending on the satellite direction.
Essentially, the $\Delta\Phi(\alpha, z)$ estimates can be obtained according to three different methods. In the first method, used for instance by the USA National Geodetic Survey (NGS) (Mader, 1999), the parameters are estimated with respect to a reference antenna, usually a Dorne/Margolin choke ring antenna type, using field measures. The PCV of the reference antenna are set to zero and its offsets $\Delta\vec{r}$ are fixed to a certain values. For any other antenna, a set of so-called *relative* parameters is provided. This set of parameters is given by the three components (North, East, Up) of mean position of the phase centre and by a set of values describing the PCV in function of the satellite elevation only, whereas the dependence by the satellite azimuth is neglected. Since the reference antenna is the same for all the calibrations, in first approximation, these parameters can be used in any combination of antennas at the ends of a baseline. When the baselines are long, the elevations of one common satellite are not the same at the ends of the baseline due to the earth curvature. So, *absolute* values for the offsets and the PCV parameters are required: they can be obtained through absolute calibration. This second method for estimating $\Delta\Phi(\alpha, z)$ is based on measurements that are performed in anechoic chambers (Schupler, 1995). These are chambers, having internal walls covered with RF-absorbing material that reduces the signal reflections (Shupler and Clark, 2001), where an artificial GPS signal is used.
In the last years, the Universität Hannover and the Geo++ company (Menge et al., 1998) have implemented a new procedure for estimating *absolute* $\Delta\Phi(\alpha, z)$ values based on field GPS observations. In this third estimation method, the antenna is mounted on a calibrated robot that rotates and tilts the GPS antenna in several thousand different orientations. The calibration estimates are based on sidereal day time differences of the GPS observations, that are not effected by multipath (Wübbena et al., 2000). In this way, the *absolute* estimates of $\Delta\Phi(\alpha, z)$ depending both on elevation and azimuth have been carried out.
So, three different estimates of the phase centre of the GPS antennas are available. Due to the fact that *relative NGS* and *absolute Geo++* parameters are "in field" estimates, they can probably better describe the antennas behaviour in real measurement campaigns.
Hence, we decided to compare only these two sets of values to test their quality in terms of sub-centimetre co-ordinates stability while performing antenna changes.

3. The field experiments

The GPS observations are biased by several error sources, such as multipath, ionospheric and troposphere effects, mismodelling of the phase centre and so on.

To focus on this last effect, a sharp reduction of the other error sources is required. In our case, this has been obtained by placing two antennas at a distance of about 4 m on top of the roof of our Department (fig. 2). Also, forced centering was used to ensure sub-millimetre repeatability in mounting the antennas on the two markers A and B.
On the marker A, the TRM33429.00+GP antenna was kept fixed for the whole experiment period, whereas on the marker B different Trimble® antennas have been mounted, such as TRM33429.00+GP, TRM22020.00+GP and TRM41249.00, called respectively M, C and Z. In Table I, the used antennas and the number of different experiments performed with each antenna are listed: M-I means that an antenna I of type M was used, M-II that the antenna II of type M was used, an so on.
The M-I and M-III antennas have been tested more times, to repeat the experiments with different satellite configurations.
Each antenna couple (10 in the whole) has continuously observed at least for four days. The logging interval and the cut-off angle were respectively 30” and 15°.

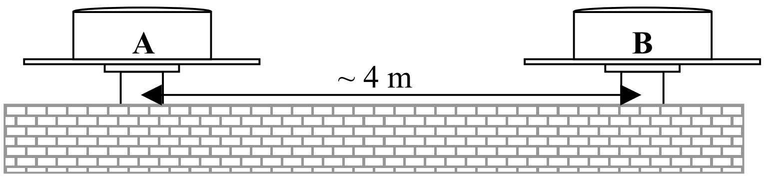

Figure 2 - Scheme of the experiments: A = fixed antenna; B = testing antennas

Table I: Test antennas used on marker B during the experiments

	M-I	M-II	M-III	C-I	C-II	Z–I	Z-II
number of repetitions	3	1	2	1	1	1	1

The GPS observations have been processed using the software Bernese v.42 (Hugentobler et al., 2001).
As the length of the baseline is very short, only the L1 frequency processing has been considered and no troposphere parameters have been estimated. As mentioned before, the data have been reduced using both complete *absolute* Geo++ (varying with azimuth and elevation) and *relative* NGS parameters (varying with the elevation only) to test for co-ordinates stability.
For each experiment, the daily solutions have been adjusted obtaining for both parameters sets 10 co-ordinate estimates relative to the marker B. The repeatability among daily solutions is for each antenna couple extremely high since the standard deviation of the adjusted co-ordinates has a magnitude of 0.2 mm for the whole set of proofs. Hence, these data can be properly used to verify the impact of the different phase centre parameters on co-ordinate repeatability since the other error sources are in fact drastically removed.
The co-ordinate differences are shown in Tables II, III and IV, respectively for latitude, longitude and height.

Table II: Modulus of the differences between the adjusted latitude: a) absolute PCV parameters; b) relative PCV parameters. Values in mm.

(a)

Geo++	M-I	M-II	M-III	C-I	C-II	Z 1	Z 2
M-I	0.1 / 0.2 / 0.1						
M-II	0.2 / 0.2/ 0.3	--------					
M-III	0.0 / 0.1 / 0.2	0.2	--------				
C-I	0.7 / 0.6 / 0.5	0.9	0.7	--------			
C-II	0.5 / 0.5 / 0.4	0.7	0.5	0.2	--------		
Z 1	0.5 / 0.5 / 0.4	0.7	0.5	0.2	0.0	--------	
Z 2	0.6 / 0.5 / 0.4	0.8	0.6	0.1	0.1	0.1	--------

(b)

NGS	M-I	M-II	M-III	C-I	C-II	Z 1	Z 2
M-I	0.1 / 0.2 / 0.1						
M-II	0.2 / 0.2 / 0.3	--------					
M-III	0.0 / 0.1/ 0.2	0.2	--------				
C-I	1.5 / 1.5 / 1.4	1.7	1.5	--------			
C-II	1.4 / 1.4 / 1.3	1.6	1.4	0.1	--------		
Z 1	0.0 / 0.1 / 0.2	0.2	0.0	1.5	1.4	--------	
Z 2	0.1 / 0.0 / 0.1	0.2	0.1	1.5	1.4	0.1	--------

Table III: Modulus of the differences between the adjusted longitude: a) absolute PCV parameters; b) relative PCV parameters. Values in mm.

(a)

Geo++	M-I	M-II	M-III	C-I	C-II	Z 1	Z 2
M-I	0.1 / 0.1 / 0.2						
M-II	0.3 / 0.4/ 0.3	--------					
M-III	0.5 / 0.6/ 0.4	0.1	--------				
C-I	0.1 / 0.2 / 0.0	0.2	0.3	--------			
C-II	0.6 / 0.7 / 0.5	0.3	0.1	0.5	--------		
Z 1	0.6 / 0.7 / 0.5	0.2	0.1	0.5	0.0	--------	
Z 2	0.8 / 0.9 / 0.7	0.4	0.3	0.7	0.2	0.2	--------

(b)

NGS	M-I	M-II	M-III	C-I	C-II	Z 1	Z 2
M-I	0.1 / 0.1 / 0.2						
M-II	0.3 / 0.4/ 0.3	--------					
M-II	0.5 / 0.6 / 0.4	0.1	--------				
C-I	0.5 / 0.4 / 0.6	0.8	1.0	--------			
C-II	0.0 / 0.1 / 0.1	0.4	0.5	0.5	--------		
Z 1	1.2 / 1.1 / 1.2	1.5	1.6	0.7	1.1	--------	
Z 2	0.9 / 0.8 / 1.0	1.2	1.4	0.4	0.9	0.3	--------

Table IV: Modulus of the differences between the adjusted ellipsoidal heights: a) absolute PCV parameters; b) relative PCV parameters. Values in mm.

(a)

Geo++	M-I	M-II	M-III	C-I	C-II	Z 1	Z 2
M-I	0.2 / 0.7 / 0.5						
M-II	0.3 / 0.5 / 1.0	--------					
M-III	0.2 / 0.4 /0.9	0.1	--------				
C-I	0.6 / 0.8 / 1.3	0.3	0.4	--------			
C-II	0.3 / 0.1 / 0.4	0.6	0.5	0.9	--------		
Z 1	0.3 / 0.1 / 0.4	0.6	0.5	0.9	0.0	--------	
Z 2	0.1 / 0.1 / 0.6	0.4	0.3		0.2	0.2	--------

(b)

NGS	M-I	M-II	M-III	C-I	C-II	Z 1	Z 2
M-I	0.2 / 0.7 / 0.5						
M-II	0.3 / 0.5 /1.0	--------					
M-III	0.2 / 0.4 / 0.9	0.1	--------				
C-I	5.7 / 5.9 / 6.4	5.4	5.5	--------			
C-II	4.8 / 5.0 / 5.5	4.5	4.6	0.9	--------		
Z 1	4.3 / 4.5 / 5.0	4.0	4.1	1.4	0.5	--------	
Z 2	4.5 / 4.7 / 5.2	4.2	4.3	1.2	0.3	0.2	--------

As it can be seen, the estimated co-ordinates obtained using the *absolute* parameters are more homogeneous with respect to the ones derived by using the *relative* parameters. Furthermore, the differences are below one millimetre in the three components when using the *absolute* parameters while, in some cases, differences greater than one millimetre are reached with the *relative* parameters. The worst impact on co-ordinates repeatability is in the height estimated using *relative* parameters. So, these tests have shown that, at least for this set of antennas, the *Geo++ absolute* phase centre parameters have better performances. This can also be checked by comparing the average values of the co-ordinate differences obtained using the two parameter sets (see table V: experiment results are grouped according to the antenna types)

Table V: Average values of the co-ordinate differences in mm

	Different antennas		Same antenna model	
	Geo++	NGS	Geo++	NGS
latitude	0.7	1.3	0.2	0.2
longitude	0.6	1.2	0.3	0.3
height	0.6	6.0	0.5	0.5

3.1 The absolute NGS parameters

In the last years a new set of PCV parameters was made available by NGS, the so-called *NGS absolute* parameters. These new values have been obtained with an absolute calibration of the used reference antenna with the GEO++ procedure. This calibration allowed to transform the *NGS relative*

measurements into absolute calibrations for all the tested antennas (Mader and Czopek, 2002): obviously, these values are only satellite elevation dependent, as the relative ones.
The processing of two of the most interesting cases shown before has been repeated using the NGS absolute parameters also: it has been taken into account the substitution of a TRM33429.00+GP (M-I) with a TRM22020.00+GP antenna (C-I). Table VI shows the high quality of the *NGS absolute* parameters. In fact, this model drastically reduces the offset in the height component (from 5.7 mm to 0.6 mm), thus reaching the same precision of the *Geo++ absolute* parameters.
However, in applications where sub-millimetre precision are required to identify millimetric deformations, we still think that it is better to use the Geo++ values, because an overall higher precision is obtained.

Table VI: Differences in the co-ordinate estimate when the antenna M-I is replaced by the antenna C-I. Values in mm.

	(M-I) – (C-I)		
	Absolute Geo++	Absolute NGS	Relative NGS
Latitude	0.7	1.6	1.5
Longitude	0.1	0.5	0.5
Height	0.6	0.7	5.7

4. Conclusions

The described and discussed tests have shown that the *Geo++ absolute* phase parameters seem to lead to better results in terms of co-ordinates repeatability. These *absolute* parameters describe the antenna phase centre patterns as a function of satellite elevation and azimuth and thus are not isotropic as the *relative* (and *absolute*) ones estimated at NGS. Thus, in high precision applications, in case millimetre precision is required, it would be safer using these *absolute* parameters. Besides the tests shown in this paper, we experienced the quality of the *absolute* parameters also in processing data collected during campaigns on a high precision non-permanent GPS network.
Since 1999, the Politecnico di Milano, the Università di Milano and the Università di Trieste are involved in the monitoring of the postseismic deformations of Umbria-Marche area (Italy) after the seismic event on September 26 and 27, 1997 (Aoudia et al., 2003). A non-permanent GPS network of ten points, distributed along two transects orthogonal to the fault line, has been designed and realised.
In this network, the centering problem on the points have been carefully taken into account: a sub millimetre precision centering has been reached by using a properly designed steel pillar for the antenna mount system (Barzaghi et al, 2003). Furthermore, usually, in the yearly campaigns, the same physical antennas are placed in the same points. However, in 1999 the Monte Stinco point was occupied with a TRM33429.00+GP antenna, whereas in 2000 a TRM22020.00+GP was used. When the data were processed using *relative NGS* parameters and the variations on the baseline lengths between 1999 and 2000 were considered, Monte Stinco showed an anomalous behaviour if compared with the one derived by geophysical models of viscoelastic relaxation. On the contrary, using the *absolute Geo++* parameters, the Monte Stinco observed length variation turned out to be closer to the value predicted by the geodynamical models (see Table VII).
This result confirms the different behaviour of the Geo++ and relative NGS parameters as described in cap. 3. The Geo++ parameters seem to have a better performance also in this field case.

Table VII: Monte Stinco – Spello baseline variation between 1999 and 2000 (values in mm)

Geodynamical model prediction	Relative NGS	Absolute Geo++
3	8 ± 2	5 ± 2

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