GPS ANTENNA CALIBRATION AT THE GEODETIC OBSERVATORY PECNÝ, CZECH REPUBLIC

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1. INTRODUCTION

Determination of GPS antenna phase centre (PC) position at GO Pecný (GOP) uses modified relative field calibration method. Calibrated antennas are rotated around vertical axis between particular observation epochs that provides absolute PC offsets in horizontal direction. Then all epochs are processed in calculation of PC corrections together in procedure estimating PC offsets and patterns separately in more iteration.

This iterative calculation method was automated recently, that allows to process higher amount of antennas and to use more settings of the calculation (e.g. various convergence limits or iteration operating).

2. PHASE CENTRE CORRECTION MODELS

The correction from the phase centre displacement of the receiving antenna is defined as a function of zenith distance and azimuth of the incoming signal (from Hugentobler et.al., 2001):

$$\Delta\varphi = \Delta\mathbf{r} \cdot \mathbf{e} + \Delta\varphi'(\alpha, z) \qquad (1)$$

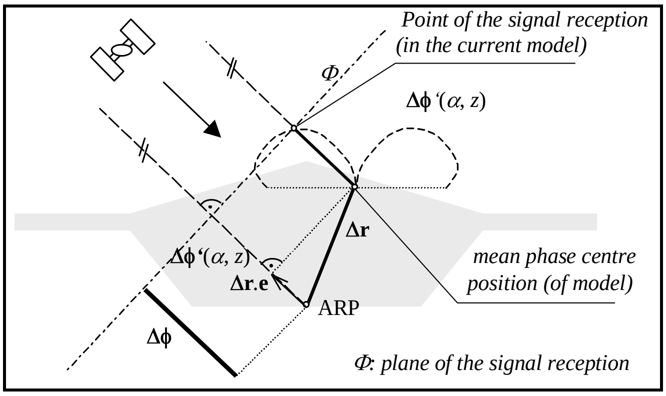

Fig. 1. Phase centre correction model scheme

Fig..2. Field calibration on GOP

Actually, there exist relative (older) and absolute (newer) phase centre correction models differing especially in resolution, accuracy and vertical values of PC correction

(vertical offsets and variation). Nevertheless, they both use the same formula (1) to express the correction.

Absolute phase centre correction for particular antenna may be obtained either directly (by absolute calibrations) or indirectly, from field phase centre calibration using absolutely calibrated antennas. Finally, absolute PC may be obtained from relative values also without re-calibration, just by conversion of PC values.

3. DESCRIPTION OF ITERATIVE CALIBRATION METHOD

The method used at GOP is developed from standard relative field calibration - method using short baseline between one fixed GPS site and second point, where one intermediate and calibrated antenna are placed. Both fixed and intermediate antenna used for calibration must have well known individual phase centre corrections.

GOP method of calibration was developed by (Kostelecký, 2002a) and contains rules of field observation and subsequent processing. Further improvement, especially in automation of processing part is described below.

3.1 Observation part of the calibration

Observation comprises setting both intermediate and calibrated antennas in two orientations (0° and 180°). This allows to suppress possible systematic effects of previous inexact horizontal calibration of intermediate antenna and to obtain absolute phase centre variation in horizontal direction. Thus, the method may be denoted as *iterative semiabsolute field calibration*.

Practically, the calibrations use as the fixed antenna an EUREF permanent station GOPE (fig.2, on the left). Thus, other possible part of calibration consisting in interchanging antennas on both endpoints to obtain more accurate calibration in vertical direction (also in Kostelecký, 2002a) is not carried out. Second point of the baseline is set on a banister next to the permanent site (figure 2, back antenna). This monumentation is not enough stable to keep coordinates fixed, hence the baseline must be measured in every calibration.

All observations are carried out in approximately 24-hour long sessions between whose the antenna on second baseline point is rotated or interchanged. The minimum necessary number of sessions is four, two for baseline calculation and two for calibration, with different orientations of intermediate and calibrated antenna. Practically, the number of observed sessions shall be at least double to exclude blunders and obtain sufficient calibration accuracy (see later apriori accuracy estimation). Then whole calibration takes 8-10 days, with 4-6 days requiring calibrated antenna.

Observations are recorded with elevation cut-off 5° to estimate phase centre pattern down to 10° elevation.

3.2 Calculation part of the calibration

Generally, phase centres correction consists of mean phase centre position (phase centre offset) and phase centre pattern dependent on elevation and azimuth. In relative field calibration, only phase centre offsets and pattern dependent on elevation may be estimated. Dependency of pattern on azimuth cannot be resolved due to too high amount of estimated parameters. Commonly, also phase centre offsets and patterns are

estimated separately, when the offset is estimated first with approximate values of pattern that is estimated in second step, where offsets are fixed.

In GOP calibration procedure, these two estimations are iteratively repeated, until estimated offsets keeps their values from the previous cycle.

The estimation of phase centres uses Bernese GPS software v4.2 (Hugentobler et. al., 2001). Particular procedure of the estimation is limited by some conditions. First, observations are separated into about 24 hours long sessions. Second, there is a 0.1-mm accuracy limit of temporary offset storage, hard affecting the iteration process.

Ambiguity resolution and other common settings are set suitable for short baseline determination. Ambiguities are resolved using SIGMA strategy on L1 and L2. If receiver with squaring on L2 occurs, then first ambiguities on L5 linear combination are resolved. For troposphere, Saastamoinen's apriori troposphere model without parameters estimation is applied.

For the automatization of whole procedure, a set of scripts written in Perl and overlaying Bernese BPE processing is developed. Flow diagram of the calculation is shown on figure 3. The automated part of the calculation requires to have defined a campaign, to download necessary files (like orbits) and also some initial setting of scripts (used filenames, antenna names, initial PC corrections, etc.).

In the preparation, one setting is important: To avoid problems with iterative process, initial PC corrections of calibrated antenna must be set as near as possible to supposed estimation. The best are values for antenna type.

After preparation, three steps of calculation are carried out: baseline determination, calibration preprocessing and finally, phase centre estimation itself. First two steps are rather simple; the heart of the calculation lays in the last, iterative part where temporary values of phase centres corrections are gradually updated.

During this sequential PC improvement, a calculation of temporary PC averages from more sessions is necessary in each step. To suppress possible outliers, averages are weighted by Bernese RMS estimates. To remove effect of inexact baseline determination in horizontal direction, averages of horizontal offsets for opposite antenna orientations are calculated separately and then averaged with equal weight regardless on their RMS.

For phase centre pattern is supposed from the definition that its value is zero in the zenith. Due to lack in data under 5°elevation, PC patterns estimated by Bernese do not keep this condition. Hence whole estimated pattern is reduced by its value in zenith before storing. Then, the value of vertical offset is reduced by the same value. Finally, value of the pattern in horizon (poorly estimated due to data lack) is replaced by adjacent value with higher elevation (usually 10°).

Sometimes, problems with convergence or aposteriori accuracy may occur. Then following modifications may be carried out to obtain "best possible" results:

- **Limit maximal number of iterations**
- **Increase criterion for ending the iteration (expressed as maximum change of estimated offset between following loops)**
- **Change method of handling of temporary horizontal PC offsets**
- **Increase angle span in estimated PC pattern to at least 15°**
- **Change weight of vertical offset reduction after estimation of PC patterns**
- **Exclude whole session causing problems (recognisable by outliers or increased internal RMS)**

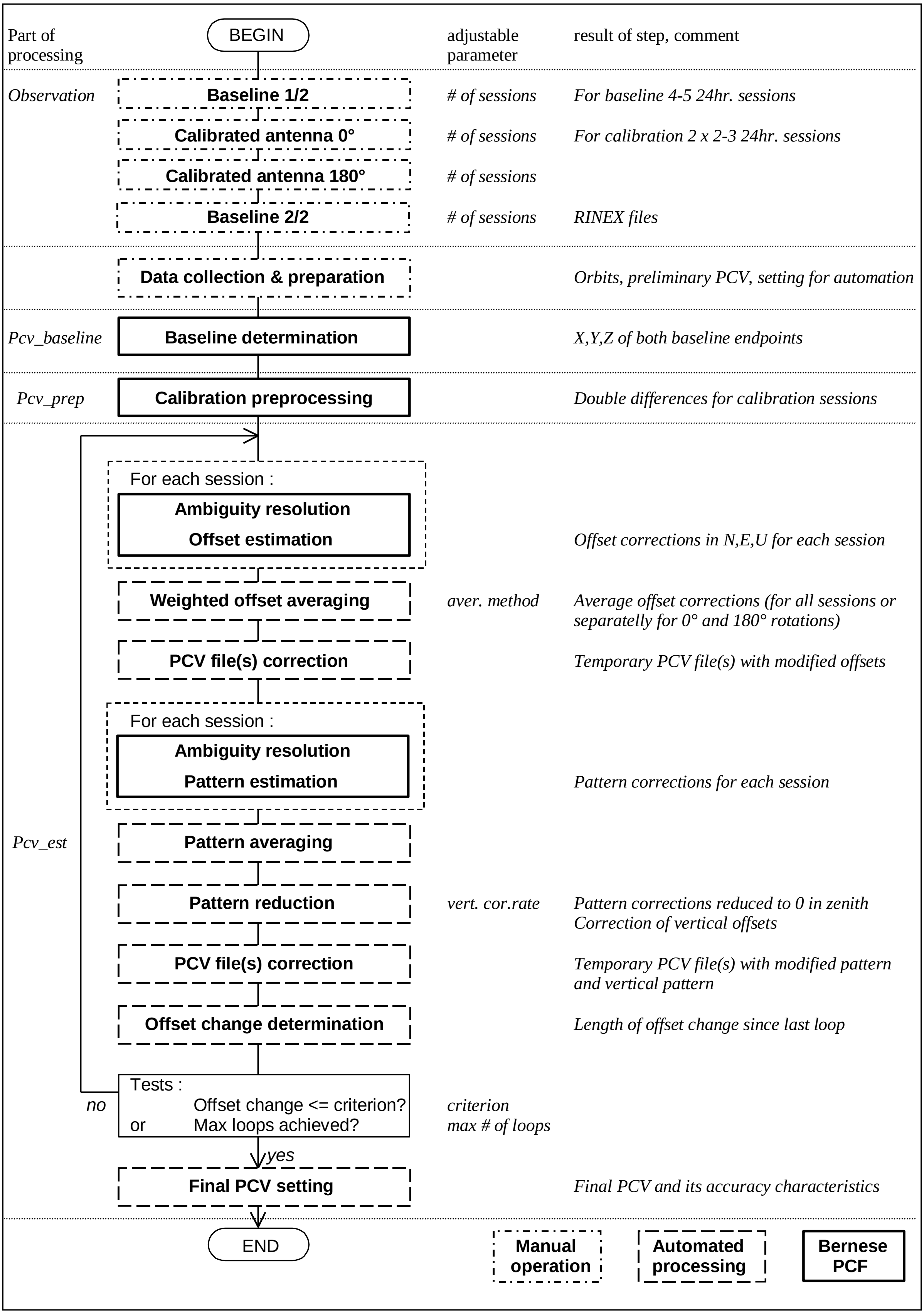

Fig. 3. Flow diagram of GOP calibration observation and processing

4. APRIORI ACCURACY OF THE CALIBRATION METHOD

For statement about accuracy of the calibration method, apriori RMS of introduced antenna calibrations and measured coordinates of baseline were preestimated.

RMS of coordinate difference measured by GPS in one 24-hour session $m_{\Delta 1}$ was developed from about dozen baselines estimated in all campaigns available on GOP. For horizontal direction (components N and E), the error is free of systematic effect of inexact calibration of intermediate antennas caused by their rotating.

$m_{\Delta 1N} = 0.26$ mm, $m_{\Delta 1E} = 0.35$ mm, $m_{\Delta 1U} = 0.63$ mm

As apriori RMS of phase centre correction, two sets of values were used:

a) Relative calibrated antennas:

$m_{C\text{-}N,E} = 0{,}4$ mm $m_{C\text{-}U} = 2$ mm

b) PCV from absolute calibration (GEO++):

$m_{C\text{-}N,E} = 0{,}2$ mm $m_{C\text{-}U} = 0{,}4$ mm

If these values of errors are considered to be systematic, then they are labelled as s_C . Values pertinent to calibrated antennas are indexed by $_{cal}$. Values relative to intermediate antenna are indexed by $_{int}$. Considering b as number of sessions used for baseline measurements and n for number of sessions used for calibration, RMS of particular calibration in GOP are developed from formulas below.

For vertical accuracy of the calibration:

$$m_{C,cal} = \sqrt{\frac{1}{n} + \frac{1}{b}} \cdot m_{\Delta 1} + s_{C,\text{int}} \qquad \textbf{(2)}$$

Here exist an unavoidable influence of intermediate antenna, so the effect is considered to be systematic.

For horizontal accuracy of the „old“ method of calibration (averaging neglecting antenna orientation):

$$m_{C,cal} = \sqrt{\left(\frac{1}{n} + \frac{1}{b}\right) m_{\Delta 1}^2 + m_{C,\text{int}}^2} \qquad \textbf{(3)}$$

The effect of intermediate antenna is suppressed, but not really cancelled, so it enters into the equation as an accidental error.

When unweighted average of north and south estimations is applied to horizontal offsets, then their RMS falls even more:

$$m_{N,E,cal} = \frac{m_{\Delta 1}}{\sqrt{n}} \qquad \textbf{(4)}$$

The effect of intermediate antenna calibration is fully cancelled. However, this cancellation is possible only for horizontal offsets, in vertical direction, whole effect of this error persists. Numeric values of the apriori accuracy show table 1.

In real observation, another errors, not considered in this error model, may occur and affect the calibration results and accuracy. It is especially multipath, asymmetric

elevation mask and satellite coverage of the sky and baseline instability. These effects shall be explored in future.

Table 1: Apriori accuracy of semiabsolute field calibration

Calibration sessions (n)	**2**	**4**	**4**	**4**	**6**
Baseline sesisons (b)	**2**	**3**	**4**	**5**	**5**
Days of observation. (b+n)	**4**	**7**	**8**	**9**	**11**
m_N [mm]	**0.18**	**0.13**	**0.13**	**0.13**	**0.10**
m_E [mm]	**0.25**	**0.18**	**0.18**	**0.18**	**0.14**
m_U (rel. calibrated antenna) [mm]	**2.6**	**2.5**	**2.4**	**2.4**	**2.4**
m_U (abs. calibrated antenna) [mm]	**1.03**	**0.88**	**0.84**	**0.82**	**0.78**

Table 2: Calibrations carried out using semiabsolute method on GOP

Antenna	number	radome	Antenna or station	camapign	remark
TOPCON CR3_GGD	70579	CONE	site PLZE	PCCRPL05	
		NONE	~	~	
	70314	CONE	site VSBO	PCZI2004	
		NONE	~	~	
	70427	CONE	Topcon VÚGTK	PCLE2005	
		~	~	PE_K1_05	
	70442	CONE	site LYSH	PCLE2005	
		NONE	~	~	
	70184	CONE	G.O. Pecný, backup	PCLE2004	
		NONE	~	~	
Trimble Zephyr Geod.	79423	TZGD	site KUNZ	PCZI2004	
		~	~	PCLE2004	
		~	~	PE_K2_05	
		NONE	~	PE_K2_05	
	18079	TZGD	site LYSH	PCZI2004	
		NONE	~	~	
Trimble 22020.00+GP	16598	NONE	from Viageos	PE_K1_05	
	16591	NONE	~	PE_K1_05	
	91699	NONE	from VTOPÚ	VTOPÚ	
Trimble 22020.00+GP	? - 1	NONE	from VTOPÚ	VTOPÚ	
	? - 3	NONE	~	~	
Trimble 14532.00	13429	NONE	Pecný – intermediate	PEBASEOF	
	66682	NONE	~	~	
Ashtech 701946.022	3301	SNOW	site GOPE (since 06)	~	
Ashtech 701073.3	110	SNOW	site GOPE (past)	~	
Trimble 29659.00	29909	NONE		~	
Topcon Regant	117	NONE	site PLZE – old	PCLE2004	
LEICA AT 504	102923	LEIS	site TUBO – new	PH_LEI05	2x, AC
		NONE	~	~	2x, AC
AC: Absolutely calibrated					

5. CALIBRATIONS CARRIED OUT ON GOP

More calibration campaigns were observed since 2001. However, these data were waiting for processing in lately developed automated calculation system. Actually, data from following campaigns were processed:

- **5 calibration campaigns between 1.2004 and 12.2005**
- **One campaign with absolutely calibrated antenna**

Additionally, results from campaigns serving to test the method accuracy in 2001 (still without automated processing) were assumed (Kostelecký, 2002b). The result (see table 2) is collection of 33 individual calibrations covering 26 antenna/radome combinations including all six antennas of Czech VESOG (Research and Experimental Network for GNSS Observations) network and comparative calibration of absolutely calibrated antenna LEIAT504 LEIS #102923. This number of calibrations already allows checking calibration accuracy and exploring some systematic effects, how it is shown below.

6. EFFECT OF RADOME ON PHASE CENTRE POSITION

Four antennas TPSCR3 GGD were calibrated independently with and without CONE radome. The comparison shall check, how consistent are PC differences between individual PC calibrations of the same antenna (with and without radome) with equivalent difference of values relevant to antenna types obtained from NGS for relative PC model (Mader, 2005).

The results of the comparison for individual antennas are visible on figure 4. The plots show differences of whole phase centre corrections (including also offsets projected in dependence on elevation angle). Separate lines are shown for particular frequencies (L1 and L2) and also for particular directions (North, East).

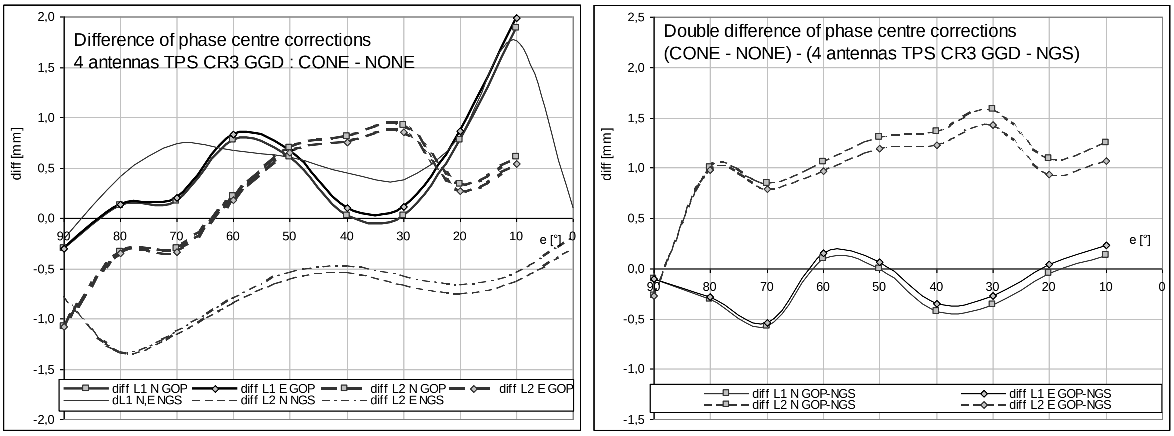

Figure 4: a) Differences of PC correction for antennas with and without radome: average of four GOP calibrations and NGS result. b) Difference between results of NGS and GOP

The comparison of NGS and GOP differences between PC with and without radome shows very good agreement on L1 (difference < ±0.5 mm) and systematic shift of the correction on L2 (about 1mm). However, this shift is independent on elevation (with tolerance about 0,5 mm), thus signal from any direction is loaded by similar systematic value.

The conclusion of the test is, that on GOP determinated effect of CONE radome on TPSCR3 GGD antennas agree with NGS values.

7. BACKWARD CALIBRATION OF INTERMEDIATE ANTENNAS

Two intermediate antennas are used for the calibrations: Trimble 14532 #13429 and #66682 with relative calibrations carried out in year 2001. Quality of their calibration was checked in frame of campaign purposed to calculate PC of absolutely calibrated antenna LEIAT504. Setting its absolute calibration as known, also absolute PCs of the intermediate antennas were calculated. Original relative and new absolute calibration is compared using differences to PCs relevant to antenna type (either relative, or absolute). This „antenna individuality“ shall be equivalent in both absolute and relative PC model, so it can be used for comparison. The result, dependent on elevation, is shown in figure 5.

The comparison shows that the „individuality“ of particular antennas differ in relative and absolute PC models in mm level. However, with exclusion of L2 in antenna #66682, these differences are independent on elevation (with about 1-mm tolerance). Again, the incoming signal is loaded by error independent on the elevation (with one exclusion). It seems that the one calibration of antenna #66682 is not fully correct – which one (relative or absolute) may be proven by additional tests.

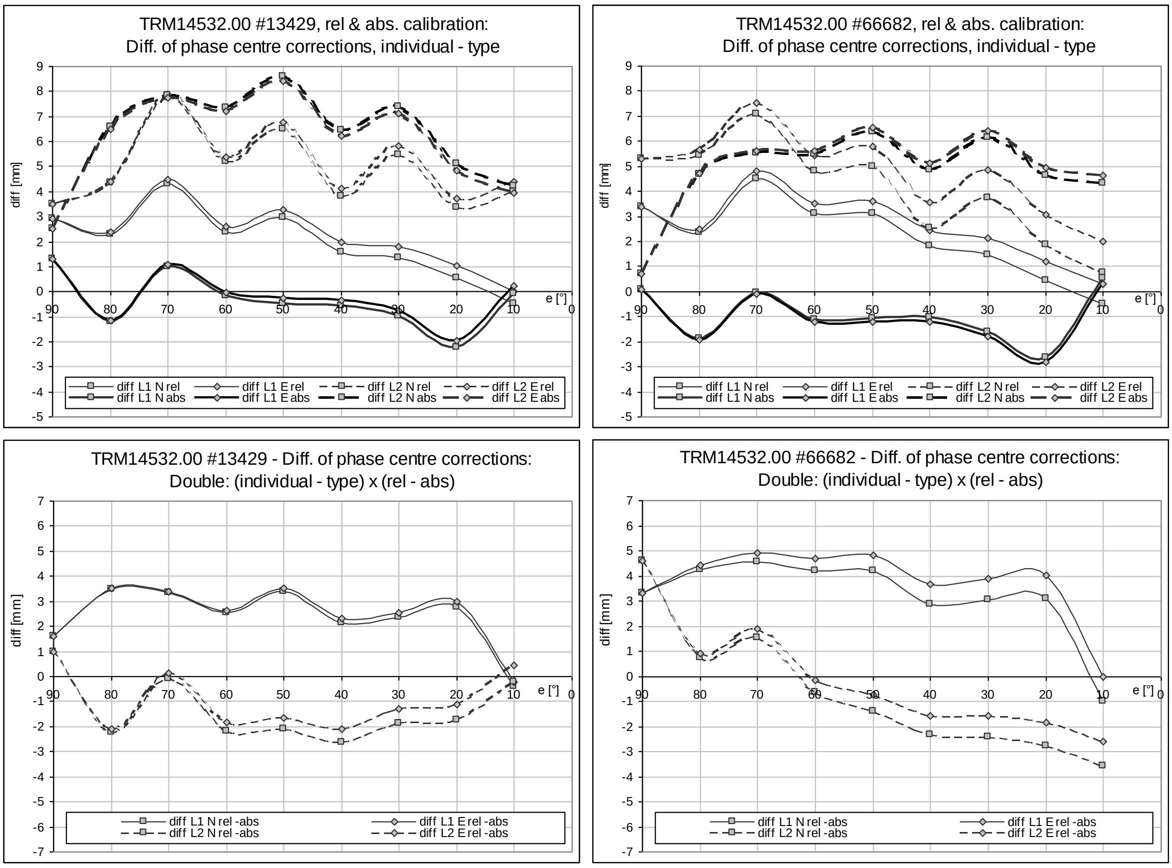

Figure 5: a, b) Differences of PC correction between type and individual values for intermediate antennas in both relative and absolute PC model. c, d) difference of there values between absolute and relative PC model

8. ACHIEVED ACCURACY OF GOP CALIBRATIONS

Aposteriori accuracy of calibrations was developed from 7 multiple calibrations of identical antennas. Table 3 shows RMS for particular components and frequencies. In twins of calibrations, usually one calibration used only minimal number of sessions. Thus resulting values are compaed with apriori values in first column of table 1. This comparison shows good agreement of apriori and aposteriori values in all components.

Table 3: Aposteriori RMS of estimated calibration

Component / RMS	L1 N [mm]	L1 E [mm]	L1 U [mm]	L2 N [mm]	L2 E [mm]	L2 U [mm]	Pattern L1 [mm]	Pattern L2 [mm]
Apriori	0,18	0,25	1,03	0,18	0,25	1,03	-	-
Aposteriori	0,17	0,29	1,03	0,16	0,27	1,16	0,26	0,53

9. INDIVIDUAL PC CORRECTION AND GOPE COORDINATES

This test checks effect of PC modification on GOPE on estimated coordinates in real network. Because site GOPE belongs to EUREF Permanent Network, a „real test“ was carried out: Reprocessing of 14 days GOP EUREF subnetwork in more variants differing in PC correction. Processing used Bernese 5.0 BPE RNX2SNX example (*http://*) with modification recommended for EUREF subnetwork processing (elevation cut-off 10°, no troposhere gradients). Obviously, GOPE was also excluded from candidate sites for network coordinate constraint to allow observing its movements.

„Standard“ variant of calculation, equivalent with GOP EUREF subscription, uses relative phase centre model with „type“ values and without radome distinction on sites.

Two tests of PC change were carried out: Test of individual calibration and test of overall switch from relative to absolute PC model.

9.1 Individual vs. Antenna-type calibration

In this test, only phase centre correction on GOPE (relative for antenna type without radome) was replaced by semiabsolute individual calibration. All other phase centres stood unchanged. Individual PC corrections of antenna ASH 701946.022 #3301 differs from type values by about 1 mm in horizontal offsets and by few mm in vertical offset and pattern.

Resulting coordinates show that whole network was affected by this change on ~0.1 mm level. Coordinates of GOPE itself changed significantly (table 4). Horizontal coordinate movement (~4 mm) corresponds with difference of phase centre offsets on L3 linear combination (figure 6a). As showed in (Filler, 2005), horizontal coordinate shift in networks using QIF ambiguity resolution strategy is connected with difference of horizontal offsets on L3. The difference observed here confirms this assumption.

Significant vertical shift (-13 mm) may be explained only as an effect of strong elevation dependency of PC patterns difference, although this difference does not vary more than by 6 mm.

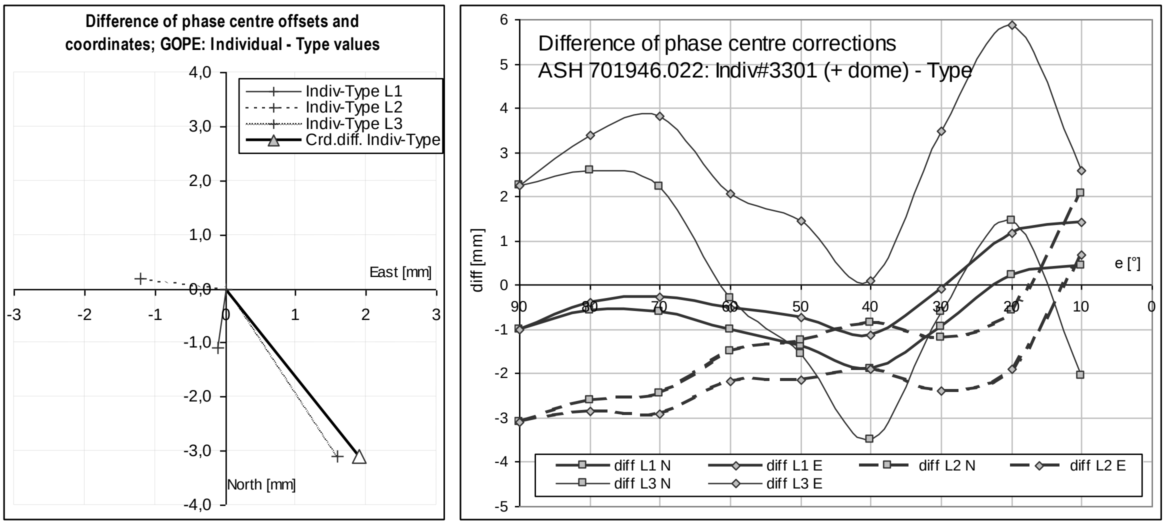

Figure 6: Comparison of type and individual relative calibration on GOPE station.
a) Difference of horizontal PC offsets on L1, L2 and L3, and resulting horizontal coordinate displacement. b) Differences of phase centre correction on L1-L3 in dependency on elevation angle

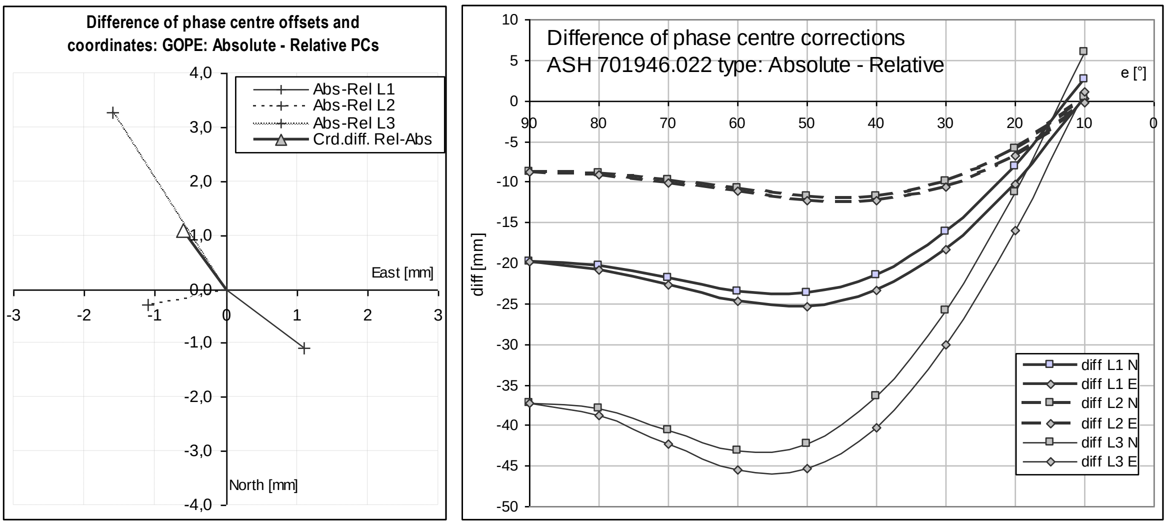

Figure 7: Comparison of relative and absolute calibration on GOPE station.
a) Difference of horizontal PC offsets on L1, L2 and L3, and resulting horizontal coordinate displacement. b) Differences of phase centre correction on L1-L3 in dependency on elevation angle

Table 4: Differences of GOPE coordinates in case of PC change

GOPE Coordinate displacement	dN [mm]	dE [mm]	dU [mm]
Individual – Type	-3,10	1,90	-13,60
Relative – Absolute	1,10	-0,60	-10,20

9.2 Relative vs. absolute PC model

In this comparison, the absolute PC model connected with radome distinction was applied to the network calculation. This model is to set in IGS and EUREF networks soon. Phase centre corrections are modified on all sites.

As result of absolute PC model implementation, all site coordinates are strongly affected – on mm level in horizontal direction and up to few cm in vertical direction. In horizontal plane, GOPE shifts in direction of PC offset difference on L3 (as in previous case), but only by about 1/3 of the value (figure 7a). In this case, the coordinate shift does not respond to whole L3 offset difference. This suppression may be caused by constraining the network on more sites with various antenna types and (thus) with various differences of PC offsets between relative and absolute PC model.

Height movement –10 mm is again affected by different dependency of PC patterns on elevation. Because this difference is ten times higher than in the case of individual calibration, the most of the effect seems to be suppressed. As in horizontal direction, this suppression may be caused by similar development of PC correction (pattern) on sites constraining the network to the datum and GOPE.

10. CONCLUSION

Using automated procedure of semiabsolute phase centre estimation, totally 26 antennas were calibrated. The automated method allows carry out the iterative procedure of calibration easily in the future.

Test of radome effect on phase centres showed systematic PC change when CONE radome is put on calibrated TPSCR3 GGD antennas. The value of the effect agrees with NGS values.

Backward calibration of intermediate antennas showed similar behaviour of antenna's "individuality" in relative and absolute calibration, with one exception caused probably by inexact calibration.

Aposteriori accuracy of calibrations was developed from 7 multiple calibrations of identical antennas. There is good agreement of apriori and aposteriori RMSs.

From the comparison, also a clear effect of individual calibration on GOPE coordinates is visible. In horizontal direction, the shift agrees with values of PC offsets on L3 linear combination. In vertical direction, the shift exceeds one cm. Implementation of absolute PC model causes similar coordinate shifts, in horizontal direction partially predictable.

11. OUTLOOK

PC calibrations actually carried out on GOP allow obtaining absolute PCV only in horizontal direction. More accurate PCV in vertical direction may be obtained using absolutely calibrated intermediate antenna and switching antennas on the baseline. It becomes possible at summer 2006, when new calibration platform will be built nearby the GOPE antenna. This monumentation stabilises the baseline and allows extension and further development of calibration techniques on Geodetic Observatory Pecný.

12. REFERENCES

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