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Absolute IGS antenna phase center model igs08.atx: status and potential improvements

R. Schmid · R. Dach · X. Collilieux · A. Jäggi · M. Schmitz · F. Dilssner

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Abstract On 17 April 2011, all analysis centers (ACs) of the International GNSS Service (IGS) adopted the reference frame realization IGS08 (Rebischung et al. 2012) and the corresponding absolute antenna phase center model igs08.atx for their routine analyses. The latter consists of an updated set of receiver and satellite antenna phase center offsets and variations (PCOs and PCVs). An update of the model was necessary due to the difference of about 1 ppb in the terrestrial scale between two consecutive realizations of the International Terrestrial Reference Frame (ITRF2008 vs. ITRF2005), as that parameter is highly correlated with the GNSS satellite antenna PCO components in the radial direction.

For the receiver antennas, more individual calibrations could be considered and GLONASS-specific correction values were added. For the satellite antennas, all correction values except for the GPS PCVs were newly estimated considering more data than for the former model. Satellite-specific PCOs for all GPS satellites active since 1994 could be derived from reprocessed solutions of five ACs generated within the scope of the first IGS reprocessing campaign. Two ACs separately derived a full set of corrections for all GLONASS satellites active since 2003.

Ignoring scale-related biases, the accuracy of the satellite antenna PCOs is on the level of a few cm. With the new phase center model, orbit discontinuities at day boundaries can be reduced, and the consistency between GPS and GLONASS results is improved. To support the analysis of low Earth orbiter (LEO) data, igs08.atx was extended with LEO-derived PCV estimates for big nadir angles in June 2013.

Keywords Receiver antenna calibration · Satellite antenna phase center corrections · International GNSS Service (IGS) · Global navigation satellite systems (GNSS) · GPS · GLONASS

1 Introduction

Nowadays it is well accepted that processing the data of global navigation satellite systems (GNSS) can only yield high-precision results, if the phase center positions of both the receiver and the satellite antennas are properly modeled (Steigenberger et al. 2009; Jäggi et al. 2009; Jarlemark et al. 2010). This can be achieved by referring the so-called mean phase center to a physically well-defined point of the equipment, whereas additional phase center variations (PCVs) depending on the observation direction describe the position of the actual phase center with respect to the mean phase center.

R. Schmid
Institut für Astronomische und Physikalische Geodäsie (IAPG), Technische Universität München, 80290 München, Germany
Present address: Deutsches Geodätisches Forschungsinstitut (DGFI-TUM), Technische Universität München, Arcisstraße 21, 80333 München, Germany
Tel.: +49-89-23031-1292
Fax: +49-89-23031-1240
E-mail: schmid@tum.de

R. Dach, A. Jäggi
Astronomical Institute, University of Bern, Sidlerstraße 5, 3012 Bern, Switzerland

X. Collilieux
IGN/LAREG, Université Paris Diderot, Sorbonne Paris Cité, 5 rue Thomas Mann, 75205 Paris Cedex 13, France

M. Schmitz
Geo++ GmbH, Steinriede 8, 30827 Garbsen, Germany

F. Dilssner
European Space Operations Centre (ESOC), Robert-Bosch-Straße 5, 64293 Darmstadt, Germany

From June 1996 until November 2006, all results of the International GNSS Service (IGS; Dow et al. 2009) were based on relative field calibrations of the receiver antennas, whereas the satellite antennas were ignored except for block-specific phase center offset (PCO) values. The receiver antennas were calibrated on short well-known baselines with respect to a reference antenna that was assumed to have a stable phase center, i.e. that was not affected by PCVs. This arbitrary assumption did not have a negative impact on short baselines, but caused systematic errors on long intercontinental baselines (Mader 1999).

In November 2006, the IGS switched to an absolute phase center model called igs05.atx (in the antenna exchange format ANTEX; Rothacher and Schmid 2010) together with the adoption of IGS05, the IGS realization of the International Terrestrial Reference Frame ITRF2005 (Gendt 2006; Altamimi et al. 2007). Robot-based field calibrations performed by Geo++ for most of the receiver antennas served as a basis for that absolute model (Wübbena et al. 2000). As the robot is able to tilt and rotate the antenna during the calibration process, the resulting correction values are not only independent of any reference antenna, but also cover the full range of possible antenna orientations with respect to azimuth and elevation. At the same time, the IGS started to consider calibrations for antenna/radome combinations. Those had been ignored before, although it was known that plastic enclosures protecting the antenna could have an impact on the estimated station height of several cm (Kaniuth and Stuber 2002).

The absolute model was complemented by phase center corrections for the satellite antennas, namely satellite-specific PCOs in the z-direction (principal satellite body axis closest to the antenna boresight direction; Montenbruck et al. 2015) and block-specific PCVs as proposed by Schmid and Rothacher (2003). The correction values for the satellites of the Global Positioning System (GPS) were derived from global multi-year solutions reprocessed by the German Research Centre for Geosciences (GFZ) and the Technische Universität München (TUM) using two independent software packages (Schmid et al. 2007). Consistent corrections for the GLONASS (Globalnaya Navigatsionnaya Sputnikovaya Sistema) satellites were provided by the Center for Orbit Determination in Europe (CODE).

As IGS05 was not yet available, the long-term solutions to derive the satellite antenna corrections could only be aligned to IGb00 (Ferland 2003), an IGS realization of the ITRF2000 (Altamimi et al. 2002), whose station coordinates were based on relative receiver antenna PCVs. An error of about 0.8 mm/a in the mean vertical velocity of IGb00 caused significant trends in the time series of the z-PCOs, so that the correction values for all satellites active at different time intervals had to be referenced to the epoch 2000.0 (Schmid et al. 2007). Moreover, the radome calibrations mentioned above were not available until the satellite antenna corrections were estimated.

Despite these drawbacks, the transition to igs05.atx turned out to be beneficial for the consistency of the IGS products. Those GNSS parameters that are highly correlated with the antenna phase centers, namely station heights and tropospheric corrections, could benefit most. For example, the rate of the terrestrial scale showing up in long-term solutions as well as the number of discontinuities in coordinate time series (due to equipment changes) could be reduced (Steigenberger et al. 2009). The same is true for height biases with respect to other space geodetic techniques. Besides, the consistency of the terrestrial scale amongst the IGS analysis centers (ACs) as well as with respect to the ITRF could be improved.

As regards the troposphere parameters, several authors have demonstrated the reduction of biases with respect to other observation techniques. For example, Ortiz de Galisteo et al. (2010) showed for several Spanish GPS stations that tropospheric biases with respect to results from radio sounding and sun photometry could be more or less reduced to zero. Thomas et al. (2011) detected a significantly better agreement with radiosonde measurements for a network of twelve Antarctic sites, when the absolute IGS antenna phase center model was applied. And Jarlemark et al. (2010) could find reduced trends in the integrated water vapor after considering satellite antenna PCVs.

As Prange et al. (2010) found out, the gravity field recovery from low Earth orbiter (LEO) data was also affected by the change of the phase center model. As long as the behavior of the receiver antenna on board the LEO was not properly modeled, the switch from relative to absolute corrections for the transmitting antennas caused a degradation of the low even spherical harmonic coefficients. Using empirical phase center corrections for the LEO antenna determined from carrier phase post-fit residuals (Jäggi et al. 2009) this problem could be significantly reduced.

Being in use since November 2006 (GPS week 1400) an update of the absolute IGS antenna phase center model igs05.atx became necessary, when ITRF2008 was released in May 2010 (Altamimi et al. 2011). The scale of the latter is defined by very long baseline interferometry (VLBI) and satellite laser ranging (SLR), whereas the scale of ITRF2005 was based on VLBI only (Altamimi et al. 2007). This explains partially the scale difference of −0.94 ppb between the latest two realizations of the International Terrestrial Reference System (ITRS). According to a rule of thumb proposed by Zhu et al. (2003) this scale difference would correspond to a change of about +12.1 cm in the satellite antenna z-PCOs. Due to the strong correlation between z-PCOs and terrestrial scale, the IGS scale would no longer be close to the ITRF scale, if z-PCOs as contained in igs05.atx were applied.

However, the initial absolute phase center model of the IGS was also outdated for other reasons. Whereas the original version of igs05.atx offered satellite-specific z-PCO values for each individual satellite in orbit at the release date of the model, for all satellites launched between 2006 and 2010 only block-specific values were added to the model (Dach et al. 2011). This is due to the reason that conventional IGS phase center corrections have to be available, before a satellite starts transmitting. As these block mean values were not replaced by satellite-specific estimates later on, igs05.atx degraded with each additional satellite launch. Before the general update of the phase center model, only about one quarter of the GPS constellation was affected, but more or less the complete GLONASS constellation.

Also the receiver antenna calibrations were not up-to-date any longer in 2010. Back in 2006, converted field calibrations were accepted for the IGS model, in case no robot calibration was available for a certain antenna type. Although additional antenna types had been absolutely calibrated in the meantime, the original calibrations were kept in order to save consistency. As coordinate jumps usually cannot be avoided when adopting a new reference frame, the switch from IGS05 to IGS08, the IGS realization of ITRF2008 (Rebischung et al. 2012), was the ideal chance to update the receiver antenna calibrations at the same time. Thus, it was also possible to improve all type-specific calibrations by considering additional calibrations of further individual antennas.

However, the update from igs05.atx to igs08.atx did not only allow for the correction of all the model deficiencies listed above, but was also one of the rare opportunities to implement certain improvements, especially as regards the satellite antennas. The reestimation of GPS satellite antenna corrections allowed the consideration of more GNSS data (16 instead of 11 years of data) and more IGS ACs (five instead of only two) resulting in better redundancy. As the corresponding multi-year solutions could be directly aligned to a reference frame consistent with IGS08, full consistency between reference frame and phase center model are guaranteed.

The phase center corrections for the GLONASS satellites could benefit even more. Compared to November 2006, when igs05.atx was released, the availability of operational satellites as well as the number and the spatial distribution of GLONASS-capable IGS tracking stations have dramatically improved (Dach et al. 2011). Besides, the availability of GLONASS-specific receiver antenna calibrations (Wübbena et al. 2008) should help to increase the consistency between the different GNSS, but also between tracking and transmitting antennas. Last but not least, the redundancy could be increased compared to igs05.atx by having two ACs (instead of only one) contributing GLONASS multi-year solutions covering a time span of up to 7.5 years (instead of only 15 months).

The intention of this paper is to document not only all the changes and improvements, but also the deficiencies of a conventional model that is applied for lots of global GNSS analyses. Section 2 gives an overview of all the necessary steps and names the responsible institutions. The main focus of the paper is put on the update of receiver antenna calibrations (Sect. 3), the reestimation of GPS satellite antenna z-PCOs from reprocessed IGS AC solutions provided in the SINEX (solution independent exchange) format (Sect. 4) and the recomputation of GLONASS satellite antenna corrections (both z-PCOs and PCVs) from specific combined multi-year solutions (Sect. 5). In Sect. 6, we try to quantify the benefit of using igs08.atx instead of the former igs05.atx, even though the differences are small compared to the update from relative to absolute phase center corrections in 2006. Section 7 provides details on an extension of the GPS satellite antenna PCVs for big nadir angles that was released in June 2013 (igs08_1745.atx) and that is mainly relevant for LEO applications. Finally, Sect. 8 illustrates that there is still a lot of room for improvement.

2 Strategy and responsibilities

The first step of the update process was the complete revision of all receiver antenna calibrations by TUM. All the type-specific robot calibrations provided by Geo++ for the previous model igs05.atx were updated with results from individual antenna calibrations performed since 2006. Moreover, those calibrations were complemented by GLONASS-specific correction values (Wübbena et al. 2008), if available. For the remaining antenna types it was checked whether the calibration status could be improved by replacing a converted field calibration or by copying robot-based values from an antenna type that was identical in construction (see Sect. 3).

Before the satellite antenna corrections could be estimated, an IGS realization of the ITRF2008 had to be available. The Institut National de l'Information Géographique et Forestière (IGN), therefore, tried to select a set of well-distributed and stable stations from the overall set of ITRF2008 stations (Rebischung et al. 2012). However, as the update of receiver antenna calibrations mentioned above had an impact on the station positions, it was not possible to directly use the ITRF2008 coordinates. So, IGN analyzed all stations affected by a calibration update and corrected the respective coordinates, in case the position change induced by the improved phase center model was significant. Thus, a reference frame, called IGS08, could be generated that was as consistent as possible to the antenna phase center model igs08.atx. On the other hand this means that IGS08 should not be used together with any other phase center model.

In the meantime, IGN started to estimate GPS satellite antenna z-PCOs (consistent with the IGS08 scale) from weekly SINEX files of five IGS ACs that had PCO estimates included in their solutions (see Sect. 4). Those SINEX files were a result of the first IGS reprocessing campaign (Collilieux et al. 2011) that was limited to GPS observations. As the IGS reprocessing only covered the time span from 1994 to 2007, also operational SINEX files from 2008 to 2010 had to be considered, especially to derive z-PCOs for the latest satellites. By removing constraints from the PCOs and fixing the terrestrial scale to the IGS08 scale it was possible to derive z-PCO time series for each individual GPS satellite and each AC (see Sect. 4).

TUM used these time series to derive one mean z-PCO for each satellite, whereas the manufacturer values were kept for the x- and y-PCO. As the SINEX format does not allow for satellite antenna PCV estimates and as, therefore, it was not possible to derive consistent satellite antenna PCVs from the same data source, the block-specific values as contained in igs05.atx had to be kept. This looks like the biggest drawback of the new model. However, Dach et al. (2011) or Dilssner et al. (2011) have shown that current processing strategies and the usage of more recent GNSS data would still yield similar PCV results for the different GPS satellite blocks.

As the first reprocessing campaign of the IGS did not consider GLONASS observations, separate combined long-term solutions were necessary to derive consistent GLONASS satellite antenna corrections. The consistency was guaranteed by fixing all the values that were previously defined, namely the updated receiver antenna calibrations, the IGS08 scale, and the antenna corrections for the GPS satellites (see Sect. 5). This meant, however, that CODE and the European Space Operations Centre (ESOC) which took the responsibility could not start before the other steps were finished.

The availability of multi-year solutions from CODE and ESOC allowed to determine a complete set of phase center corrections for the GLONASS satellites. Thus, in contrast to GPS, also the GLONASS PCVs could be updated. And, as the solutions were set up late, they also comprised enough data to derive a significant set of phase center corrections for the first Block IIF satellite SVN62 (space vehicle no. 62) launched in May 2010.

ESOC analyzed 3 years of data altogether to have enough observations for all GLONASS satellites active at that time. CODE even reprocessed 7.5 years of data back to June 2003 to get satellite-specific z-PCOs for as many decommissioned GLONASS satellites as possible. Those estimates were an important input for the second IGS reprocessing campaign that also included GLONASS. Satellites active prior to June 2003 were added to the phase center model igs08.atx with block-specific values, at least those in orbit during the IGEX-98 campaign (International GLONASS Experiment 1998; Willis et al. 2000) or later.

After ESOC had estimated mean GLONASS corrections from the CODE and ESOC solutions, the model igs08.atx was complete and could be released together with the reference frame realization IGS08 (Rebischung et al. 2012). On 17 April 2011 (GPS week 1632), they were adopted for all IGS analyses (Ray 2011). Since then, it is only possible to add correction values for new receiver antenna types or newly launched satellites, but not to change existing values. The only exception are the z-PCOs of the latest satellites whose block-specific values could be replaced by satellite-specific estimates (cf. Tab. 6).

3 Update of receiver antenna calibrations

Since 2000, the robot-based absolute field calibration has been steadily refined by Geo++ (Schmitz et al. 2008). The routine service provides calibration results for additional individual antennas which can be used to update the type-specific IGS receiver antenna models. More or less all absolute receiver antenna models were determined with the same robot-based antenna field calibration system (cf. Tab. 1) guaranteeing the highest possible consistency.

Wübbena et al. (2008) and Baire et al. (2014) could show that there are differences between individual antennas of the same type that can have a significant impact on station coordinates. Individual antenna calibrations are vital and customary for real-time networking of reference stations (so-called RTK networks), especially for applications with high accuracy requirements for the height component. For IGS analyses, only type mean values are considered so far. The continuous calibration of individual antennas from a consecutive model series generally proofs comparability, but sometimes reveals production revisions. In the meantime, several GNSS antenna manufacturers provided absolute antenna corrections for new models to the IGS that are usually based on a five antenna sample. At least for IGS reprocessing purposes it is even worthwhile to consider the calibration of an antenna after removing it from a site.

For igs08.atx, GLONASS-specific PCVs could be considered for several antenna types. Until 2010, the GLONASS constellation was not sufficient to optimally support antenna field calibration. Furthermore, the different carrier frequencies of the GLONASS satellites visible from one certain location result in an arbitrary mixture for the frequency-dependent GLONASS PCVs.

The robot-based field calibration as performed by Geo++ takes the individual GLONASS frequencies into account (Wübbena et al. 2008) while estimating the change of the PCVs with frequency to generate so-called "Delta PCVs" with respect to GPS and with units of meter per 25 MHz. Hence, the PCVs for every individual GLONASS frequency can be derived by combining GPS PCVs with GLONASS Delta PCVs. The results are provided in the form of metric GLONASS PCVs for the frequency channel $k = 0$. PCV differences between GLONASS satellites/frequencies depend on the antenna type and are in the order of up to 1 mm, while the differences between GLONASS and GPS PCVs can amount to several mm.

3.1 Update of robot calibrations

For every antenna model in use on a reference station of either the IGS or the EUREF network, the availability of additional individual antenna calibrations was checked. The robot-based antenna calibration system applied by Geo++ stores the complete variance-covariance information which allows for a rigorous adjustment of all individual results to derive a type-specific model. Besides, also consistency checks of antenna type series are possible. As two antenna types (`JPSREGANT_DD_E`, `JPSREGANT_SD_E`) showed changes (with the serial number SN) over the years, the definition of antenna subtypes considering production revisions became necessary.

Existing models for 46 antenna types were updated with results from recent individual antenna calibrations. The correction values for further 41 antenna types with robot-based values remained unchanged compared to igs05.atx (Schmid 2011). The GLONASS-specific PCVs were analyzed with respect to the number of individual antennas and sufficient coverage of the antenna hemisphere. In total, 46 antenna types were checked and, finally, GLONASS PCVs were made available for 38 different types.

The chokering antenna `AOAD/M_T` of Allen Osborne Associates with Dorne Margolin element is of particular interest and importance to the IGS. On the one hand, it serves as the reference antenna model to convert relative field calibrations and, on the other hand, it has been intensively used on IGS sites. Unfortunately, only one single antenna (SN 404) could be calibrated for igs05.atx and only one additional unit (SN 393) could be incorporated for igs08.atx. Besides the small sample size, there are `AOAD/M_T` models with different product numbers whose phase center behavior is not known at all. More insight into this important antenna model would be highly desirable.

3.2 Revision of all antenna types

Since the adoption of igs05.atx, it was only possible to add correction values for new receiver antennas. In general, updates of existing values were not possible in order not to jeopardize the consistency of the IGS products. For a lot of IGS stations converted field calibrations were, therefore, still applied, although azimuthal phase center corrections down to the horizon from robot calibrations had been available.

With igs08.atx, robot calibrations for 15 antenna types could be added to the model to replace converted or copied relative field calibrations. For 9 additional antenna types, robot calibration results were copied from antenna types that are considered to be identical in construction (Schmid 2011). Besides, all converted calibrations slightly changed, as the correction values of the IGS reference antenna `AOAD/M_T` got updated. This concerned 90 antenna calibrations converted from National Geodetic Survey (NGS) field results and 14 types converted from the former relative IGS model igs_01.pcv.

All these changes have an impact on the users. However, the impact is much smaller than was the case with the switch from relative to absolute antenna models in 2006. If no corrections are available for a combination of an antenna with one specific radome, the values for the corresponding antenna without a radome are used within the IGS. If no corrections for the GLONASS frequencies are available, the values for the GPS frequencies are used instead.

Table 1 gives an overview of the type-specific receiver antenna models for the switch from igs05.atx to

Table 1 Number of receiver antenna calibrations per calibration method in the IGS models igs05_1627.atx (released in March 2011), igs08_1629.atx (March 2011), and igs08_1854.atx (July 2015) available at `ftp://ftp.igs.org/pub/station/general/pcv_archive/`. The percentages refer to the total number of antenna models. The absolute calibration systems in Garbsen, Hannover, and Berlin are similar 3-axis (5 degrees of freedom) robots based on Geo++ software, whereas NGS operates a completely independent 2-axis robotic calibration system.

method	igs05_1627		igs08_1629		igs08_1854		institution/remarks
CONVERTED	27		14		14		converted from igs_01.pcv
FIELD	98		90		90		NGS
Σ	125	(58%)	104	(48%)	104	(37%)	*converted relative field calibrations*
ROBOT	71		86		137		Geo++, Garbsen
COPIED	20		27		34		copied from robot-based Geo++ values
ROBOT	0		0		4		Institute of Geodesy (IfE), Leibniz Universität Hannover
ROBOT	0		0		2		Senate Department for Urban Development and the Environment (SenStadt), Berlin
ROBOT	0		0		1		NGS
Σ	91	(42%)	113	(52%)	178	(63%)	*absolute robot-based field calibrations*

igs08.atx in March 2011 and the status in July 2015. With the switch to igs08.atx, the percentage of robot-based calibrations in the IGS phase center model increased by 10% to 52%. For nearly half of the antenna types, mainly old models, converted calibrations were provided. Their percentage is continuously reduced, as only robot-based calibrations are added since 2008. In the meantime, for more than 60% of the antenna types, robot-based correction values from one consistent calibration system are available.

More interesting as regards the IGS is the actual number of IGS sites with consistent robot-based absolute phase center corrections. In January 2015, more than eight years after the adoption of absolute robot calibrations by the IGS in November 2006, state-of-the-art calibrations comprising elevation- and azimuth-dependent PCVs down to the horizon were available for about 80% of all IGS stations (Schmid 2015).

4 Reestimation of GPS satellite antenna PCOs

4.1 Input data

GPS satellite antenna PCOs were determined from IGS reprocessed weekly solutions. In 2009, the IGS completed its first GPS data reprocessing campaign including observations for the period 1994.0–2008.0. Solutions in the SINEX format were submitted by ten ACs. They contained not only weekly station positions and daily Earth orientation parameters (EOPs), but also satellite antenna PCOs in the case of the following four ACs: CODE, GFZ, the Massachusetts Institute of Technology (MIT), and Natural Resources Canada (NRCan). Although the PCO parameters are tightly constrained to igs05.atx values, they can be reevaluated with respect to any other reference frame provided that the scale of the weekly station coordinates is constrained.

For the scope of reevaluating satellite PCOs and in order to include all the newly launched GPS satellites, these reprocessed solutions were completed with operational weekly SINEX files up to week 1577 (see Table 2). In parallel, ESOC computed homogeneously reprocessed GPS/GLONASS solutions (T. Springer, pers. comm.) that were also considered for the generation of igs08.atx. PCOs were supplied in the three directions of a body-fixed reference frame, except for the NRCan solution which only contained z-PCO estimates.

The right-handed body-fixed reference frame was defined in such a way that (Montenbruck et al. 2015)

- the $+z$-axis is the principal body axis closest to the antenna boresight direction,
- the y-axis is parallel to the rotation axis of the solar panels (the positive y-direction being defined through the x-axis orientation), and
- the $+x$-direction guarantees that the $+x$-side of the solar panels is permanently sunlit during nominal yaw-steering.

4.2 Strategy

ESOC was the only AC providing free normal equations including the parameters to be solved. So, the first step of the PCO processing consisted of transforming the solutions ($P_{\mathrm{est}}, \Sigma_{\mathrm{est}}$) provided by the four other ACs into normal equations that were free of constraints. We use the notation P_{est} for the vector of parameters and Σ_{est} for the associated variance-covariance matrix. The *constrained* normal equation can be obtained by inverting Σ_{est}. As the constraints are supplied in the SINEX files, they can be removed from all parameters: not only from

Table 2 Reprocessed (`co1`, `esp`, `gf1`, `mi1`, `em1`) and operational (`cod`, `gfz`, `mit`, `emr`) AC solutions used to recompute z-PCOs (Collilieux and Schmid 2013)

AC	solution	GPS weeks	GNSS	elevation cut-off	comments
CODE	`co1`	731–1459	GPS	3°	pole constraints cannot be removed
	`cod`	1460–1577	GPS/GLONASS		
ESOC	`esp`	782–1555	GPS/GLONASS	10°	
GFZ	`gf1`	730–1459	GPS	7°	
	`gfz`	1460–1577			
MIT	`mi1`	938–1459	GPS	10°	single satellite PCOs fixed in certain weeks
	`mit`	1460–1577			
NRCan	`em1`	783–1459	GPS	10°	127 weeks rejected;
	`emr`	1460–1577			x- and y-PCOs fixed to igs05.atx values

station positions, EOPs, and PCOs, but also from geocenter parameters and station velocities when included (CODE and MIT solutions, respectively).

We illustrate that step by examining the example of equality constraints with respect to the a priori parameter vector P_0. The *unconstrained* normal equation $N(P-P_0)=K$ can be derived by removing the inverse of the variance level of the constraint Σ_0:

$$N = \frac{1}{\hat{\sigma}_0^2}\left(\Sigma_{\text{est}}^{-1} - \Sigma_0^{-1}\right) \quad (1)$$

$$K = \frac{1}{\hat{\sigma}_0^2}\Sigma_{\text{est}}^{-1}\left(P_{\text{est}} - P_0\right)$$

where $\hat{\sigma}_0^2$ is the variance factor of the solution. Only the mandatory constraints such as UT1 tight constraints were reincluded to allow for a proper inversion of the normal equation. In case of the CODE solutions, additional constraints for all EOPs were necessary.

In the course of this initial processing step, the submitted solutions were checked in many respects. Besides the a priori values of the PCO parameters, further input data such as the covariance terms between positions and PCOs, estimated formal errors, station acronyms, and DOMES numbers (`http://itrf.ign.fr/domes_desc.php`) were verified. We had to reject 127 weekly `em1` solutions and noted that single satellite antenna PCOs had been fixed in certain MIT solutions. The latter were considered, although the PCO constraints for the affected satellites could not be removed.

In a second step, we solved for PCO parameters by adding station position constraints with respect to ITRF2008. In theory, only orientation and scale constraints were necessary to solve for EOPs and PCOs, respectively. However, in reality it is also important to constrain the origin of the frame since the network geometry may impact scale estimates. Thus, seven pseudo-observations were added to the normal equation to constrain the station position parameters. The set of stations for which these constraints were added was selected iteratively by solving for the seven parameter transformation with respect to ITRF2008. However, as the input solutions were most often loosely constrained, we recomputed specific minimally constrained formal errors of the station positions for weighting purposes.

If the vector of parameters $P=[X,E,A,O]^T$ is separated into station positions, EOPs, antenna PCO parameters, and others (geocenter parameters or station velocities), respectively, the addition of the reference frame constraints to the normal equation can be summarized as follows:

$$\begin{pmatrix} N_{11}+B\Sigma_\theta^{-1}B & N_{12} & N_{13} & N_{14} \\ N_{12}^T & N_{22}+N_{22}^c & N_{23} & N_{24} \\ N_{13}^T & N_{23}^T & N_{33} & N_{34} \\ N_{14}^T & N_{24}^T & N_{34}^T & N_{44} \end{pmatrix} \begin{pmatrix} X-X_0 \\ E-E_0 \\ A-A_0 \\ O-O_0 \end{pmatrix} = \begin{pmatrix} K_1 + B\Sigma_\theta^{-1}B\left(X_{\text{ITRF2008}}-X_0\right) \\ K_2+K_2^c \\ K_3 \\ K_4 \end{pmatrix} \quad (2)$$

Here, N_{ij} and K_i are the unconstrained normal equation blocks of the N and K matrices of Eq. (1), and (N_{22}^c, K_2^c) is the normal equation of the EOP constraints with respect to the a priori values. B is the design matrix of the "minimum constraint" pseudo-observations associated with a weight Σ_θ as defined by Altamimi et al. (2002).

Finally, in a third step, the normal equation (2) was solved by fixing x- and y-PCOs to igs05.atx values (see Sect. 4.3). The variance factor of the new solution was reevaluated by considering the removal and addition of constraints in previous processing steps as well as by varying the number of fixed parameters. As a result, time series of weekly z-PCOs were estimated for each satellite and each AC.

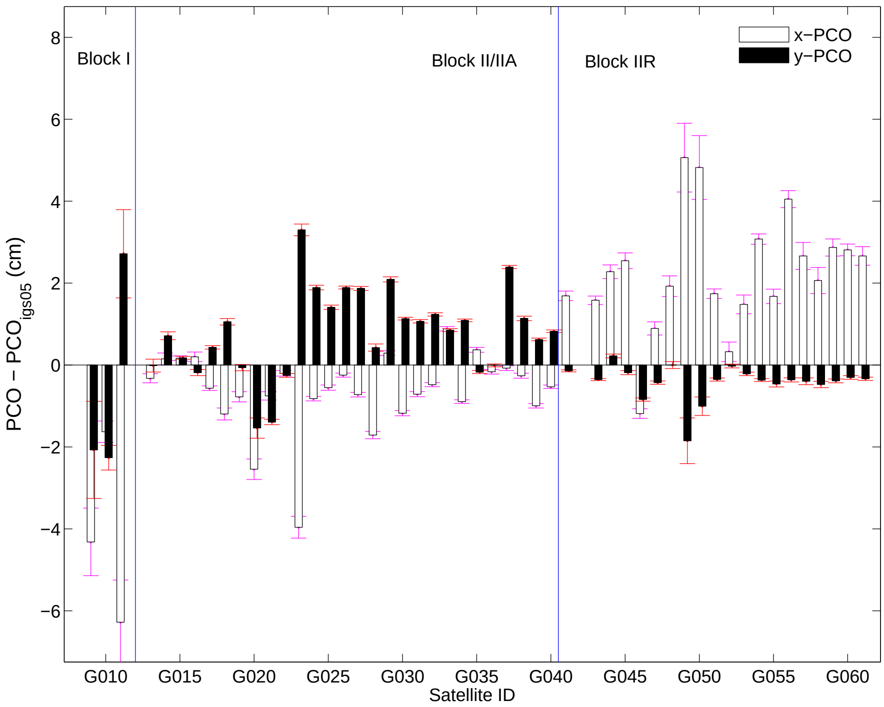

Fig. 1 Difference between the weighted mean of x- and y-PCO time series (derived from the GFZ solutions) and igs05.atx values.

4.3 Sensitivity of the strategy

In order to evaluate the strategy described in Sect. 4.2 it was compared to three alternatives. The impact (1) of keeping the origin of the frame unconstrained, (2) of directly fixing station coordinates instead of constraining frame parameters and (3) of estimating x- and y-PCOs besides the PCO component in z-direction was analyzed. Whereas Collilieux and Schmid (2013) found a median WRMS of the z-PCO time series of 4.9 cm for the GFZ solutions with the strategy finally adopted (Sect. 4.2), they got median WRMS values of 6.9, 5.2, and 4.7 cm, respectively, for the three alternatives.

Only solving for x- and y-PCOs (third alternative) yields better statistics. Figure 1 shows the differences of the x- and y-PCO estimates with respect to igs05.atx values derived from the GFZ solutions. Generally, they are smaller than 5 cm. As x- and y-PCOs can be affected by satellite attitude mismodeling (Schmid et al. 2007) and as the NRCan solutions did not include x- and y-PCOs, the latter have not been reestimated for igs08.atx. Block-specific values provided by the satellite manufacturers are still used instead.

Moreover, although our aim was to release z-PCOs fully consistent with the latest receiver antenna calibration results (see Sect. 3), we did not constrain the station position parameters to ITRF2008 coordinates corrected for calibration changes, namely to IGS08 coordinates (Rebischung et al. 2012). Indeed, as our solutions were based on igs05.atx receiver antenna phase center corrections, we adopted ITRF2008 for internal consistency reasons. Moreover, it could be shown experimentally that using IGS08 instead of ITRF2008 makes the z-PCOs more scattered on average (P. Rebischung, pers. comm.).

4.4 Signals in z-PCO time series

The long-term trends in the z-PCO parameters were considerably reduced compared to the last calibration campaign resulting in igs05.atx (Schmid et al. 2007). Averaged slopes between -22.0 and -24.8 mm/a in the z-PCO time series were determined from the two solutions used at that time. The mean trends in the newly derived z-PCO parameter time series are -3.8 ± 0.9, -1.8 ± 0.6, -1.2 ± 0.7, -1.1 ± 1.1, and -4.9 ± 0.9 mm/a for CODE, ESOC, GFZ, MIT, and NRCan, respectively. This corresponds to a reduction of about one order of magnitude. As the scale rate error of the reference frame fully maps into estimated z-PCOs according to Zhu et al. (2003), this may indicate that the absolute scale rate error of ITRF2008 is smaller than 0.3 mm/a (Collilieux and Schmid 2013), as found independently by Haines et al. (2010) and Wu et al. (2011).

Besides a linear trend, also other signals could be identified in the z-PCO time series. Harmonics of the draconitic period (351.5 days) are still prominent in the z-PCO time series as noticed earlier by Schmid et al. (2007), but significant annual variations can also be detected. Figure 2 shows that the amplitude of the annual variations in the z-PCOs derived from the ESOC solution can reach up to 6 cm (see blue circles). Moreover, they are rather consistent in phase. We found that these variations were related to neglected annual variations in the ITRF2008 coordinates that GPS observes in practice.

In order to demonstrate this hypothesis, we estimated z-PCOs after adding constant annual variations to the station coordinates of the reference frame. Those annual variations were fitted to station position time series derived from IGS combined reprocessed weekly solutions expressed in an approximated center of figure frame following Collilieux et al. (2012). As a consequence, the GPS apparent geocenter motion is not included. Figure 2 shows that the estimated annual signals in the resulting z-PCO time series are drastically reduced and no longer consistent in phase (see green triangles).

This is a consequence of the correlation between the mean station height and the averaged z-PCO value. When referring station positions to ITRF2008 using a scale constraint, a scaling factor that varies seasonally is implicitly removed from all station heights. This seasonal behavior is mostly related to the elastic deformation of the Earth's crust due to mass transfers at its surface (so-called loading effects; cf. Fig. 2 in Collilieux et al. 2011). We simply model this annual scale factor d by fitting the following deterministic model to scale parameter estimates in the ESOC solution `esp`: $d_{\texttt{esp}} = d_a \cdot \cos(2\pi t - \phi_a) \approx 1.8 \text{ mm} \cdot \cos(2\pi t - 243°)$ with d_a and ϕ_a being the amplitude and phase of the global scale factor.

According to the rule of thumb proposed by Zhu et al. (2003), this affects the z-PCO values on average by $\delta z \approx -\alpha \cdot d = -\alpha \cdot d_a \cdot \cos(2\pi t - \phi_a)$ where the factor α depends on the GPS processing strategy. Using a value of $\alpha = -18.8$ for the ESOC solution (cf. Tab. 2 in Collilieux and Schmid 2013), the bias in the z-PCOs could be evaluated to be $\delta z \approx 33.8 \text{ mm} \cdot \cos(2\pi t - 243°)$. Figure 2 shows that the application of this simple model to the original z-PCO time series (red squares) yields similar results as the more sophisticated approach where annual variations were added to the station coordinates (green triangles).

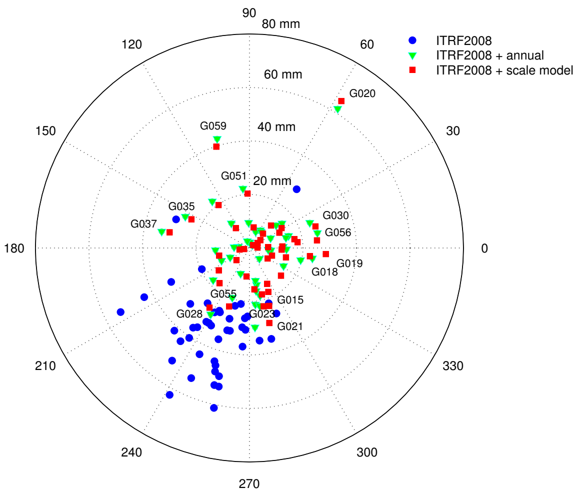

Fig. 2 Phase diagram of the annual variations in the z-PCOs derived from the ESOC solution `esp`. Each point represents one satellite. Blue circles: original solution referred to ITRF2008; green triangles: referred to ITRF2008 corrected for annual coordinate variations; red squares: referred to ITRF2008 corrected for an annual scale model. Satellite names are given in case the annual amplitude is larger than 2 cm.

This result demonstrates that, in future, it will be mandatory to model seasonal signals in station coordinates when determining all PCOs simultaneously. This is of particular importance, if few observation data are available only, e.g., in the case of newly launched satellites. Even though the impact of neglected post-seismic motions in ITRF coordinates is suspected to be smaller, it should also be investigated in future.

4.5 Derivation of mean z-PCOs

As the reason for the annual variations in the z-PCO time series (see Sect. 4.4) was not known at the time igs08.atx was generated, it was not possible to correct them before deriving mean z-PCOs over time and ACs. This means that the results presented in the following are based on time series including, amongst others, annual and draconitic variations. However, as multi-year time series are available for most of the satellites, the impact on the calculation of average values should not be dramatic.

The time series as provided by IGN (see Sect. 4.2) were used by TUM to derive mean z-PCO values. As eclipse periods mainly affect x- and y-PCOs (Schmid et al. 2007), these periods were not excluded from the processing. However, potential outliers were removed automatically with a two-step approach. First of all, weekly estimates with an – apparently too optimistic – formal error of more than 3 cm were eliminated. The resulting time series were used to calculate preliminary mean values. Then, in a next step, weekly PCO estimates outside the three-sigma limits of those preliminary averages were additionally excluded.

The final time series and the original weekly formal errors were used to derive a weighted mean z-PCO per satellite and AC. As the standard deviations derived from the time series were not comparable between ACs, an unweighted mean over up to five ACs was finally calculated per satellite. One reason for that is the fact that the z-PCO time series get more scattered in the early years of the IGS. Therefore, the standard deviation for a certain AC gets worse, the more data from that period are considered.

4.6 Evaluation of the final GPS z-PCOs

Table 3 shows the final z-PCO results for all GPS satellites contained in the initial release of igs08.atx. As there were some reassignments of pseudo-random noise (PRN) numbers over the years, only the space vehicle number (SVN) and the international designator (so-called COSPAR ID) are unambiguous. As the AC solutions covered different time spans (see Tab. 2), some ACs could not contribute to certain z-PCO estimates. In particular, this applies to the Block I satellites.

The final block mean values are 195.2 cm, 256.4 cm, 130.8 cm, and 84.7 cm for Block I, Block II/IIA, Block IIR-A, and Block IIR-B/M, respectively. The values ΔBM (see Tab. 3) show the difference of the satellite-specific z-PCOs with respect to those block mean values. There are significant deviations from the block mean of ±10 cm, ±40 cm, ±30 cm, and ±20 cm, respectively, for the four different satellite groups. This also becomes apparent from Fig. 3.

The differences Δigs05 with respect to the former model igs05.atx (Schmid et al. 2007) are positive for all satellites that already had satellite-specific estimates contained in the old model. Ignoring Block I, Block IIF and all those satellites for which igs05.atx only provided block mean values (Δigs05 values in brackets) yields a mean bias of 16.8 cm. This bias can be explained by the scale difference between successive ITRS realizations. According to the scale difference of −0.94 ppb between ITRF2008 and ITRF2005 (cf. Sect. 1), a z-PCO bias of +12.1 cm could be expected.

As the z-PCOs of the former model igs05.atx were consistent with IGb00 (as regards the global terrestrial scale) and as they were referenced to the epoch 2000.0 (Schmid et al. 2007), it is more meaningful to look at the scale difference between ITRF2008 and ITRF2000 at epoch 2000.0. The difference of −1.34 ppb (compare `http://itrf.ign.fr/trans_para.php`) corresponds to a z-PCO bias of +17.2 cm that almost perfectly matches the actual bias of 16.8 cm.

The AC-specific biases are 18.3 cm, 17.3 cm, 18.7 cm, 15.3 cm, and 14.6 cm for CODE, ESOC, GFZ, MIT, and NRCan, respectively. The biases between different ACs could be explained by independent software packages and processing strategies, in the case of MIT also by individual satellites with z-PCOs fixed to igs05.atx values in some of their solutions (see Tab. 2). If Δigs05 is reduced by the mean bias of 16.8 cm, the resulting values Δigs05_r give an impression of the overall agreement between igs08.atx and igs05.atx. If the oldest and the latest satellites are ignored again, the maximum difference is 6.3 cm and the mean of the absolute differences is 2.2 cm.

The most meaningful indicator for the quality of an individual satellite-specific z-PCO estimate is probably the level of agreement between up to five AC-specific estimates. The values ΔAC characterize the maximum difference between two of the contributing ACs. Due to the scale-related biases given above, only values exceeding significantly the expected difference of 4.1 cm pose a problem. Whereas the mean value for ΔAC over all satellites listed in Tab. 3 is 6.4 cm (i.e., 2.3 cm above the ideal value), the z-PCOs of the following five satellites are obviously those with the biggest uncertainty: SVN19, SVN49, SVN51, SVN56, and SVN62. For SVN49 and SVN62 apparently not enough observation data were available. Due to the problems described by Springer and Dilssner (2009), z-PCO estimates for SVN49 are not continuously available. Moreover, the ACs considered that satellite for their solutions at different time intervals.

Apart from the five satellites listed above, the accuracy of the GPS z-PCOs is on the level of 2–4 cm, if all values discussed in Sect. 4.6 are taken into account and if scale-related biases are ignored. In any case it is clear that the uncertainty of the z-PCOs is much smaller than the differences between individual satellites of the same satellite block (compare ΔBM). This is also illustrated in Fig. 3 that shows all AC-specific z-PCO estimates. As a last step, Block I satellites active prior to 1994 were added to igs08.atx with a rounded block mean value of 195.0 cm.

Table 3 Mean z-PCOs as contained in igs08_1629.atx (available at `ftp://ftp.igs.org/pub/station/general/pcv_archive/igs08_1629.atx`) for all GPS satellites active between 1994 and 2011. Columns 5–9 show which ACs were considered for the mean estimate. ΔBM is the difference with respect to the block mean value, Δigs05 the difference with respect to the former model igs05.atx (values in brackets denote that igs05.atx did not contain satellite-specific estimates), Δigs05_r the same difference reduced by a mean bias of 16.8 cm, and ΔAC the maximum difference between two ACs. All values in cm.

SVN	PRN	COSPAR	Block	C	E	G	M	N	z-PCO	ΔBM	Δigs05	Δigs05_r	ΔAC
9	13	1984-059A	I	x	–	x	–	–	205.78	11	32	15	0
10	12	1984-097A	I	x	–	x	–	x	187.54	−8	13	−4	6
11	3	1985-093A	I	x	–	x	–	–	192.39	−3	24	7	8
13	2	1989-044A	II	x	x	x	x	x	271.22	15	18	1	4
14	14	1989-013A	II	x	x	x	x	x	284.95	29	21	4	6
15	15	1990-088A	II	x	x	x	x	x	246.86	−10	16	−1	7
16	16	1989-064A	II	x	x	x	x	x	252.11	−4	16	−1	5
17	17	1989-097A	II	x	x	x	x	x	242.28	−14	17	0	4
18	18	1990-008A	II	x	x	x	x	x	258.18	2	19	2	7
19	19	1989-085A	II	x	x	x	x	x	297.16	41	23	6	11
20	20	1990-025A	II	x	x	x	–	x	256.52	0	15	−2	4
21	21	1990-068A	II	x	x	x	x	x	252.39	−4	18	1	5
22	22	1993-007A	IIA	x	x	x	x	x	245.14	−11	18	2	5
23	23, 32	1990-103A	IIA	x	x	x	x	x	277.72	21	20	3	5
24	24	1991-047A	IIA	x	x	x	x	x	260.38	4	15	−2	4
25	25	1992-009A	IIA	x	x	x	x	x	248.90	−7	19	3	5
26	26	1992-039A	IIA	x	x	x	x	x	245.94	−10	15	−2	7
27	26, 27, 30	1992-058A	IIA	x	x	x	x	x	263.34	7	16	−1	5
28	28	1992-019A	IIA	x	x	x	–	x	233.85	−23	13	−3	5
29	29	1992-089A	IIA	x	x	x	x	x	251.43	−5	16	−1	7
30	30	1996-056A	IIA	x	x	x	x	x	261.27	5	15	−2	4
31	31	1993-017A	IIA	x	x	x	x	x	225.65	−31	15	−2	6
32	1, 24, 26, 30	1992-079A	IIA	x	x	x	x	x	238.08	−18	18	1	5
33	3	1996-019A	IIA	x	x	x	x	x	279.26	23	17	1	8
34	4	1993-068A	IIA	x	x	x	x	x	242.00	−14	14	−3	5
35	1, 3, 5, 25, 30	1993-054A	IIA	x	x	x	x	x	262.20	6	16	−1	4
36	6, 10	1994-016A	IIA	x	x	x	x	x	287.86	31	20	3	8
37	1, 7, 24, 30	1993-032A	IIA	x	x	x	x	x	235.22	−21	13	−4	6
38	8	1997-067A	IIA	x	x	x	x	x	257.81	1	17	0	4
39	9	1993-042A	IIA	x	x	x	x	x	246.14	−10	12	−5	5
40	10	1996-041A	IIA	x	x	x	x	x	254.65	−2	16	−1	5
41	14	2000-071A	IIR-A	x	x	x	x	x	134.54	4	17	0	7
43	13	1997-035A	IIR-A	x	x	x	x	x	138.95	8	19	2	8
44	28	2000-040A	IIR-A	x	x	x	x	x	104.28	−27	13	−4	3
45	21	2003-010A	IIR-A	x	x	x	x	x	140.54	10	11	−6	7
46	11	1999-055A	IIR-A	x	x	x	x	x	114.13	−17	17	0	4
51	20	2000-025A	IIR-A	x	x	x	x	x	134.36	4	19	2	11
54	18	2001-004A	IIR-A	x	x	x	x	x	129.09	−2	16	−1	6
56	16	2003-005A	IIR-A	x	x	x	x	x	150.64	20	20	3	10
47	22	2003-058A	IIR-B	x	x	x	x	x	90.58	6	11	−5	5
59	19	2004-009A	IIR-B	x	x	x	x	x	84.96	0	18	1	4
60	23	2004-023A	IIR-B	x	x	x	x	x	80.82	−4	21	4	5
61	2	2004-045A	IIR-B	x	x	x	x	x	77.86	−7	16	0	6
48	7	2008-012A	IIR-M	x	x	x	x	x	85.29	1	(15)	(−2)	5
49	1, 6, 8, 24, 27, 30	2009-014A	IIR-M	x	x	x	x	x	96.56	12	(27)	(10)	20
50	5	2009-043A	IIR-M	x	x	x	x	x	82.26	−2	(12)	(−5)	6
52	31	2006-042A	IIR-M	x	x	x	x	x	97.14	12	22	5	7
53	17	2005-038A	IIR-M	x	x	x	x	x	82.71	−2	18	1	6
55	15	2007-047A	IIR-M	x	x	x	x	x	68.11	−17	(−2)	(−19)	7
57	29	2007-062A	IIR-M	x	x	x	x	x	85.71	1	(16)	(−1)	8
58	12	2006-052A	IIR-M	x	x	x	x	x	84.08	−1	(14)	(−3)	7
62	25	2010-022A	IIF	x	x	–	–	–	166.32	–	26	9	22

SVN: space vehicle number, PRN: pseudo-random noise number, COSPAR: international designator (Committee on Space Research), Block: IGS satellite block designation according to Schmid et al. (2007), C: CODE, E: ESOC, G: GFZ, M: MIT, N: NRCan. The value for SVN62 was derived from a separate combined GPS/GLONASS solution (see Sect. 5).

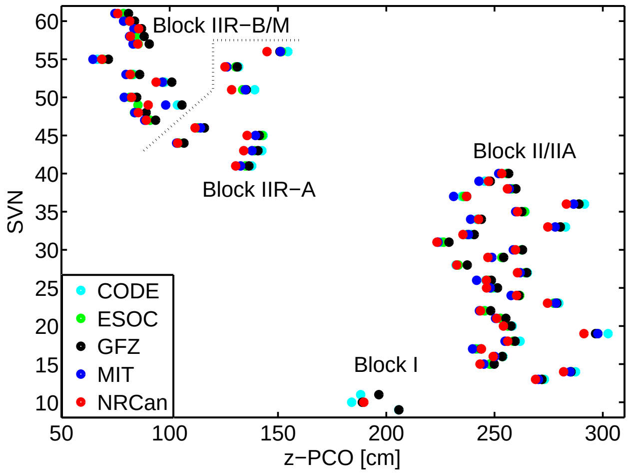

Fig. 3 AC-specific z-PCO estimates [cm] for all GPS satellites (SVN: space vehicle number).

5 Reestimation of GLONASS satellite antenna corrections

5.1 Motivation and background

The former igs05.atx parameters for the GLONASS constellation (13 GLONASS and 4 GLONASS-M satellites at that time) were estimated by CODE in August 2006 using 15 months of observation data of a relatively sparse GLONASS tracking network (about 30 stations) with the majority of sites being located in Europe. The estimates for two of the GLONASS-M satellites (GLONASS no. 713 and 714) were based on about three months of data only. When the phase center corrections for igs08.atx were estimated, none of the 17 satellites from 2006 was active anymore.

In order to keep the number of additional model parameters low, only one mean set of nadir-dependent PCVs for all satellites was estimated for igs05.atx. In a second step, this pattern was fixed to derive a consistent set of satellite-specific z-PCOs. The horizontal antenna PCOs were fixed to the nominal values provided by the satellite manufacturer. The 21 GLONASS-M space vehicles (GLONASS no. 715–735) launched since December 2006 were added to igs05.atx step-by-step with block-specific PCVs, the nominal horizontal PCOs and a rounded block mean z-PCO value of 230.0 cm.

As mentioned in Sect. 3, igs08.atx is the first IGS model to offer specific receiver antenna phase center corrections for the GLONASS frequencies. Such GNSS-specific calibration values were available for more than half of the GLONASS-capable antennas contained in the network processed by CODE in 2009 and 2010. Due to the high correlation between receiver and satellite antenna PCVs, an impact on the GLONASS satellite antenna phase center corrections has to be expected.

5.2 Strategy

Two IGS ACs volunteered to update the antenna corrections for the GLONASS satellites to be added to igs08.atx: ESOC using the NAPEOS software (Springer 2009) and CODE using the Bernese GNSS Software package (Dach et al. 2007). The CODE group reprocessed nearly 8 years of GPS and GLONASS data using the updated receiver antenna phase center corrections (cf. Sect. 3), whereas ESOC started the reprocessing effort with the year 2008 when the GLONASS tracking network was much denser than in 2003. Further details on the processing strategies of these two solutions are given in Tab. 4.

Finally, the two groups agreed on the following procedure to derive GLONASS satellite antenna corrections fully consistent with the corresponding corrections for the GPS satellite antennas (cf. Sect. 4):

1. Generation of cumulative normal equations with receiver antenna phase center corrections fixed to updated frequency-specific calibrations, if available (see Sect. 3). The GPS satellite antenna PCOs were fixed to the reestimated values from Sect. 4 (see Tab. 3).
2. Estimation of z-PCOs for each individual GLONASS satellite with GLONASS satellite antenna PCVs set to zero to minimize the magnitude of the pattern to be estimated in the subsequent step.
3. Estimation of one common set of nadir-dependent satellite antenna PCVs for all GLONASS satellites (except for GLONASS no. 714) with z-PCOs fixed to the results from the previous step.
4. Elimination of the remaining PCO-dependent fraction from the PCVs
5. Calculation of mean PCVs from CODE and ESOC results
6. Reestimation of satellite-specific z-PCOs with satellite antenna PCVs fixed to the mean values from the previous step
7. Calculation of mean z-PCOs from CODE and ESOC results

Together with the phase center corrections for the GLONASS satellites, also new values for GPS Block IIF satellite SVN62 were estimated, as the PCVs available for that new satellite block were based on the results of one AC by then (Schmid et al. 2010).

Table 4 Processing strategies of CODE and ESOC to derive antenna phase center corrections for the GLONASS satellites.

	CODE	ESOC
Number of GLONASS stations	30 to 40 in 2003, most of them in Europe; global coverage from 2007 onwards; about 100 stations in 2008, about 120 in 2010	
GLONASS satellites considered (GLONASS no.)	701, 711–738, 783–784, 787–789, 791–798 (total: 42 satellites)	701, 712–738, 795 (total: 29 satellites)
Time interval	from 8 June 2003 to 30 January 2011	from 20 January 2008 to 26 February 2011
Software	Bernese GNSS Software, Version 5.1 (Dach et al. 2007)	NAPEOS, Version 3.6 (modified; Springer 2009)
Data	double-difference GPS/GLONASS carrier phase observations	zero-difference GPS/GLONASS carrier phase and code pseudo-range observations
Sampling rate	3 min	5 min
Elevation cut-off angle	3°	10°
Weighting	elevation-dependent: weight $w = \cos^2 z$ with zenith angle z	
Ambiguity fixing	only for GPS measurements (85–90% per day)	only for GPS measurements (68–80% per day)
Inter-frequency biases	implicitly by the assumption of a constant value per day for each station/satellite	estimated weekly for each station/satellite
Station coordinates	fixed to a coordinate/velocity solution generated beforehand using a no-net-rotation condition for IGS08 sites	no-net-scale and no-net-rotation conditions for IGS08 sites (Rebischung et al. 2012)
Orbits	72-hour orbital arcs; 6 initial osculating elements, 3 constant plus 2 periodic radiation pressure parameters; pseudo-stochastic pulses at noon and midnight	24-hour orbital arcs; initial positions and velocities, 3 constant plus 2 periodic radiation pressure parameters; 3 tightly constrained along-track parameters (one-cycle-per-revolution parameters); Earth albedo and infrared radiation pressure model (ANGARA; Fritsche et al. 1998)
Earth rotation	piecewise linear modeling with a resolution of one day for ERPs	daily pole coordinates and drifts; UT1 and LOD are estimated
Ionospheric refraction	first-order effect eliminated by forming the ionosphere-free linear combination; higher-order effects only corrected by CODE according to Fritsche et al. (2005)	
Tropospheric refraction	a priori tropospheric zenith path delays (ZPDs) computed according to Saastamoinen (1973) using the Global Pressure and Temperature model (GPT; Boehm et al. 2007); ZPDs are mapped to slant delays using the hydrostatic Global Mapping Function (GMF; Boehm et al. 2006); ZPDs at 2 h intervals are estimated as continuous piecewise linear functions using the wet GMF; horizontal gradients only estimated by CODE with 24 h resolution	
Satellite antenna PCOs	satellite-specific z-PCO estimation for all GLONASS satellites and GPS Block IIF satellite SVN62; x- and y-offsets fixed to manufacturer values; z-PCOs of GPS Block II/IIA/IIR satellites fixed to values reestimated from reprocessed AC SINEX files (cf. Sect. 4 and Tab. 3)	
Satellite antenna PCVs	block-specific estimation (one common set of PCVs) for all GLONASS and GLONASS-M satellites (except for GLONASS no. 714); satellite-specific estimation for GLONASS no. 714 and SVN62 (GPS Block IIF); maximum nadir angle of 14° and 15° for GPS and GLONASS, respectively; purely nadir-dependent, piecewise linear modeling with 1° resolution; sum condition to prevent the normal equation system from becoming singular; PCVs of GPS Block II/IIA/IIR satellites fixed to igs05.atx values (Schmid et al. 2007)	
Receiver antenna corrections	PCOs/PCVs fixed to updated receiver antenna calibrations (cf. Sect. 3); frequency-specific corrections for GLONASS applied, if available	

5.3 Agreement between CODE and ESOC

Figure 4 illustrates the agreement between CODE and ESOC for the block-specific GLONASS PCVs as well as for the satellite-specific estimates for GLONASS no. 714 and GPS Block IIF satellite SVN62. As regards the GLONASS estimates, the differences are always below the 1 mm level. The slightly bigger differences for SVN62 probably result from the limited amount of observation data.

Moreover, the differences between the two ACs are much smaller than the differences between the newly estimated mean PCVs (denoted by igs08.atx in Fig. 4) and the former igs05.atx values. The corrections with

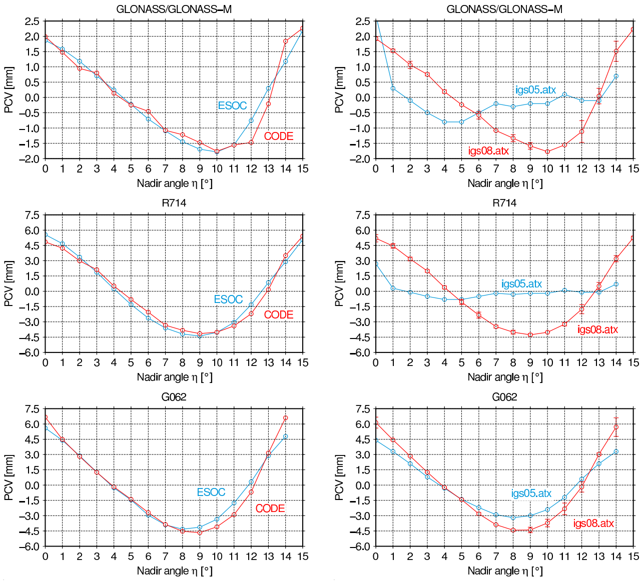

Fig. 4 Block-specific satellite antenna PCV estimates for GLONASS (top, different scale), satellite-specific values for GLONASS no. 714 (middle) and GPS Block IIF satellite SVN62 (bottom). The plots on the left demonstrate the good agreement between CODE (red) and ESOC (blue) estimates, the plots on the right show the comparison between igs08.atx (red) and the former igs05.atx values (blue).

respect to the igs05.atx values are typically of the order of 2 mm. For GLONASS no. 714, the corrections are bigger, as the exceptional behavior of that satellite was not considered in the igs05.atx model. Exceptional PCVs had already been reported by Dilssner et al. (2010), Dilssner et al. (2012) and Dach et al. (2011).

Differences between the z-PCO estimates of the two ACs are provided in the last column of Tab. 5 (ΔAC). On average, there is a bias of 6.4 ± 2.3 cm. ESOC estimates are generally bigger than those from CODE. The biggest differences exceeding the 10 cm level show up for three satellites launched in 2003 and 2005, as ESOC only reprocessed data back to 2008 (see Tab. 4). Ignoring the satellites launched prior to 2006, a bias of 5.8 ± 1.4 cm remains between ESOC and CODE.

This bias can be due to any scale-related difference in the AC-specific processing strategies (see Tab. 4). For instance, a bias of about 1.4 cm is caused by the modeling of Earth albedo and infrared radiation pressure in the ESOC solution (Dilssner et al. 2010). Generally, the IGS08 scale is transferred from the GPS part of the combined solution (with station coordinates and satellite antenna z-PCOs fixed) to the GLONASS part. Therefore, the handling of station coordinates and inter-frequency biases is essential. However, also the different elevation cut-off angles (cf. Cardellach et al. 2007) or other differences in the observation modeling could have an impact.

Generally, the bias has about the same order of magnitude as the ΔAC values detected for the GPS satellites (see Tab. 3). As there is no independent information to decide which AC solution might be closer to reality, both solutions were averaged. In case a satellite was only considered in the CODE solution, the corresponding z-PCO was corrected by half the bias (about +3 cm) to keep consistency.

The block mean values are 210.3 cm and 244.1 cm for GLONASS and GLONASS-M, respectively. The differences between the individual z-PCOs and those block mean values (ΔBM) are considerably smaller than in the case of GPS. If GLONASS no. 714 is ignored, ΔBM hardly exceeds 1 dm. Like for the GPS satellites, all differences Δigs05 with respect to the former phase center model are positive. However, with a mean of 12.3 cm (if the satellites launched late in 2005 are ignored), the bias is closer to the theoretical value derived from the scale difference between ITRF2008 and ITRF2005 (see Sect. 4.6).

For the sake of completeness, also GLONASS satellites active between 1998 and June 2003 were added to igs08.atx. In 1998, the IGS had conducted the so-called IGEX-98 campaign (Willis et al. 2000) aiming at the collection and analysis of GLONASS data. As no z-PCO estimates were available for those satellites, they were assigned a rounded block mean value of 210.0 cm.

6 Validation

6.1 Impact on global GNSS solutions

GPS/GLONASS orbit overlaps

ESOC used one-day orbital arcs for the computation of the GLONASS satellite antenna corrections (see Tab. 4). This offers the opportunity to compare the discontinuities of the satellite orbits at day boundaries between the new (igs08.atx) and the old (igs05.atx) phase center model for satellite and receiver antennas. The ESOC contribution to the GLONASS extension from Sect. 5 was evaluated as regards all day boundaries in January 2011. The results in Fig. 5 show a clear improvement when switching from igs05.atx to igs08.atx.

Station coordinate repeatability

Another widely used parameter to assess the quality of a GNSS solution is the repeatability of the station coordinates. It is derived from the weekly solutions used for the CODE contribution to the GLONASS extension (see Sect. 5) considering the years 2009 and 2010. Figure 6 shows the difference between solutions using

Table 5 Mean z-PCOs as contained in igs08_1629.atx for all GLONASS satellites active between 2003 and 2011. Columns 5–6 show which ACs were considered. ΔBM is the difference with respect to the block mean value, Δigs05 the difference with respect to the former model igs05.atx (values in brackets denote that igs05.atx did not contain satellite-specific estimates), Δigs05_r the same difference reduced for a mean bias of 12.3 cm, and ΔAC the difference between ESOC and CODE. All values in cm.

GLO	Slot	COSPAR	Block	C	E	z-PCO	ΔBM	Δigs05	Δigs05_r	ΔAC
711	5	2001-053A	GLONASS	x	–	211.33	1	20	8	–
783	18	2000-063C	GLONASS	x	–	206.94	−3	14	2	–
784	8	1998-077B	GLONASS	x	–	207.64	−3	–	–	–
787	17	2000-063A	GLONASS	x	–	220.82	11	15	3	–
788	24	2000-063B	GLONASS	x	–	222.23	12	15	3	–
789	3	2001-053B	GLONASS	x	–	210.36	0	10	−2	–
791	22	2002-060A	GLONASS	x	–	209.93	0	10	−3	–
792	21	2002-060C	GLONASS	x	–	209.79	−1	12	0	–
793	20, 23	2002-060B	GLONASS	x	–	212.27	2	12	0	–
794	2	2003-056B	GLONASS	x	–	204.92	−5	9	−3	–
795	4	2003-056C	GLONASS	x	x	211.48	1	11	−1	10
796	1	2004-053A	GLONASS	x	–	210.09	0	16	3	–
797	8	2004-053C	GLONASS	x	–	196.20	−14	11	−1	–
798	19, 22	2005-050C	GLONASS	x	–	210.31	0	6	−6	–
701	6	2003-056A	GLONASS-M	x	x	233.03	−11	14	1	11
712	7, 8	2004-053B	GLONASS-M	x	x	242.75	−1	10	−2	5
713	24	2005-050B	GLONASS-M	x	x	249.54	5	17	5	6
714	6, 17, 18, 23	2005-050A	GLONASS-M	x	x	217.94	−26	26	14	14
715	3, 14	2006-062C	GLONASS-M	x	x	250.56	6	(21)	(8)	4
716	15	2006-062A	GLONASS-M	x	x	250.51	6	(21)	(8)	4
717	10	2006-062B	GLONASS-M	x	x	236.90	−7	(7)	(−5)	5
718	17	2007-052C	GLONASS-M	x	x	253.49	9	(23)	(11)	6
719	20	2007-052B	GLONASS-M	x	x	244.82	1	(15)	(2)	6
720	19	2007-052A	GLONASS-M	x	x	249.84	6	(20)	(7)	5
721	13	2007-065A	GLONASS-M	x	x	241.79	−2	(12)	(−1)	5
722	3, 9, 14	2007-065B	GLONASS-M	x	x	254.85	11	(25)	(13)	4
723	11	2007-065C	GLONASS-M	x	x	242.54	−2	(13)	(0)	6
724	18	2008-046A	GLONASS-M	x	x	244.84	1	(15)	(2)	6
725	21	2008-046B	GLONASS-M	x	x	232.98	−11	(3)	(−9)	7
726	22	2008-046C	GLONASS-M	x	x	240.17	−4	(10)	(−2)	7
727	3, 4	2008-067A	GLONASS-M	x	x	238.05	−6	(8)	(−4)	7
728	2	2008-067C	GLONASS-M	x	x	246.63	2	(17)	(4)	7
729	8	2008-067B	GLONASS-M	x	x	255.80	12	(26)	(13)	5
730	1	2009-070A	GLONASS-M	x	x	250.03	6	(20)	(8)	5
731	22	2010-007A	GLONASS-M	x	x	241.10	−3	(11)	(−1)	6
732	23	2010-007C	GLONASS-M	x	x	231.82	−12	(2)	(−11)	8
733	4, 6	2009-070B	GLONASS-M	x	x	245.98	2	(16)	(4)	6
734	5	2009-070C	GLONASS-M	x	x	248.93	5	(19)	(7)	8
735	24	2010-007B	GLONASS-M	x	x	248.30	4	(18)	(6)	9
736	9, 16	2010-041C	GLONASS-M	x	x	240.17	−4	(10)	(−2)	4
737	12	2010-041B	GLONASS-M	x	x	250.84	7	(21)	(8)	4
738	16	2010-041A	GLONASS-M	x	x	251.61	7	(22)	(9)	5

GLO: GLONASS number, Slot: almanac slot designation, COSPAR: international designator (Committee on Space Research), Block: satellite block designation, C: CODE, E: ESOC.

igs05.atx and igs08.atx ($\text{RMS}_{\text{igs05.atx}} - \text{RMS}_{\text{igs08.atx}}$). Most of the values are positive indicating an improvement of the RMS of the coordinate time series when switching to igs08.atx, in particular as regards the north and up components.

From the comparison of the two solutions it cannot be concluded whether the improved RMS values result from the introduction of GNSS-dependent receiver antenna corrections, from the increased number of robot-based calibrations, from the improved terrestrial reference frame IGS08, or from any other source. Nevertheless, it is obvious that the coordinate repeatability benefits from the switch to a new reference frame (IGS08) and the updated phase center model igs08.atx.

Fig. 6 Change in the repeatability of weekly station coordinates (north, east, and up components) when switching from igs05.atx to igs08.atx phase center corrections for 111 GPS-only (top) and 137 combined GPS/GLONASS stations (bottom). A positive value indicates an improvement of the RMS of the coordinate time series. The colors of the bars refer to different calibration statuses given above the plots. In case the status changed from igs05.atx to igs08.atx (see Sect. 3), the bar is split into two columns (left half referring to igs05.atx, right one to igs08.atx).

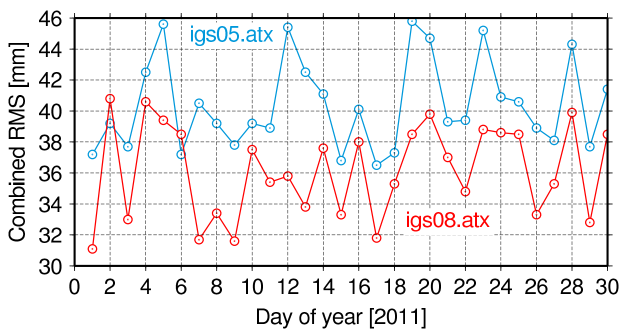

Fig. 5 RMS of the orbit discontinuities at day boundaries for all GPS and GLONASS satellites using the antenna model igs05.atx (blue) and igs08.atx (red), respectively.

6.2 Consistency between GPS and GLONASS antenna phase center corrections

In the CODE solution intended to derive satellite antenna phase center corrections for GLONASS (Sect. 5), so-called GPS/GLONASS bias parameters were additionally included for validation purposes:

– three-component bias parameters for the *station coordinates* that are equivalent to independent sets of weekly coordinates for GPS and GLONASS to compensate for deficiencies in the GPS- and GLONASS-specific receiver antenna PCOs and

– *troposphere* bias parameters (one constant bias per station and week) to absorb deficiencies in the GPS- and GLONASS-specific receiver antenna PCVs.

For a detailed description of these bias parameters we refer to Schaer and Meindl (2011).

From each weekly CODE solution of the years 2009 and 2010 two sets of coordinates were extracted: one with GPS/GLONASS bias parameters fixed to zero (default solution) and another one with bias parameters estimated applying separate zero-mean conditions over the X-, Y-, and Z-coordinate biases of all stations. The differences between these two sets of coordinates give an impression of the impact of deficiencies in the GNSS-specific receiver antenna corrections on the station coordinates as well as of the consistency of the GPS and GLONASS satellite antenna corrections with respect to each other. Figure 7 shows the resulting differences for solutions based on IGS08/igs08.atx on the one hand (bottom) and for another set of solutions based on the former reference frame IGS05 and the corresponding phase center model igs05.atx for comparison on the other hand (top).

For each week in 2009 and 2010 one symbol per station is displayed in Fig. 7. As the variation of the coordinate differences over time is rather small, the GPS/GLONASS bias parameters turned out to be highly stable. As regards the east component, all weekly coordinate differences are within ±1 mm. For the north component the scatter is slightly higher, probably due to the imbalance of combined GPS/GLONASS tracking sites on the northern and southern hemisphere. As expected, the vertical component shows the highest scatter (note the different axis scale in Fig. 7) and also systematic deviations from zero for many stations.

It is noticeable that the majority of the IGS05-based height differences has a positive sign. This indicates a scale inconsistency between GPS and GLONASS that could be caused by deficiencies in the satellite antenna PCOs. The IGS08-based vertical coordinate differences are much closer to zero which is a clear indication for a better consistency between the GPS and GLONASS PCOs contained in igs08.atx. However, also the vertical differences derived with the improved phase center model reveal systematic effects that might be related to the antenna type. Most stations equipped with Trimble antennas show negative differences, whereas the sign of the differences is mainly positive for stations equipped with Leica or Topcon antennas.

The troposphere bias parameters exhibit a mean offset of about 1.5 mm between GPS and GLONASS over all combined stations, if IGS05/igs05.atx are applied. This systematic bias vanishes, if the latest reference frame realization IGS08 and the updated phase center model igs08.atx are used. The initial bias could either result from deficiencies in the GLONASS satellite antenna PCVs (GPS PCVs did not change) or from the neglect of GNSS-specific receiver antenna PCVs in the igs05.atx model.

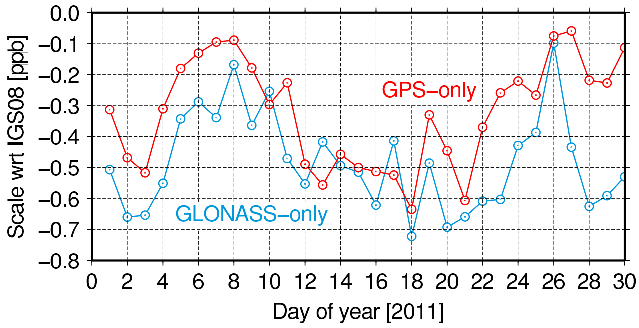

Fig. 8 Terrestrial scale difference with respect to IGS08 for daily GPS-only (red) and GLONASS-only (blue) ESOC solutions using tracking data from January 2011.

ESOC independently evaluated the consistency of the GPS- and GLONASS-derived terrestrial scale. Figure 8 shows the scale difference with respect to the IGS08 reference frame for daily GPS- and GLONASS-only solutions using the igs08.atx corrections. The inherent scale inconsistency between GPS and GLONASS is below 0.2 ppb. For solutions based on igs05.atx, Dilssner et al. (2010) had reported a scale discrepancy of about 1 ppb.

7 PCV extension based on GPS data from low Earth orbiting satellites

The absolute phase center model presented in the previous sections is solely based on terrestrial measurements, which limits the estimation of GPS and GLONASS satellite antenna PCVs to a maximum nadir angle of 14° and 15°, respectively. This is not sufficient for the analysis of spaceborne GNSS data collected by LEO satellites that record – depending on the missions' orbital altitude – observations at nadir angles of up to 17°.

As currently no LEO mission records GLONASS signals, only the GPS satellite antenna PCVs can be extended to nadir angles beyond 14° utilizing GPS tracking data from several LEO missions. In order to achieve estimates that are consistent with igs08.atx to the extent possible, GPS satellite orbits and clocks are fixed to reprocessed solutions obtained with igs08.atx applied. Due to significant near-field multipath effects arising in the LEO spacecraft environment (Jäggi et al. 2009) it is necessary to solve for GPS and LEO antenna PCVs simultaneously.

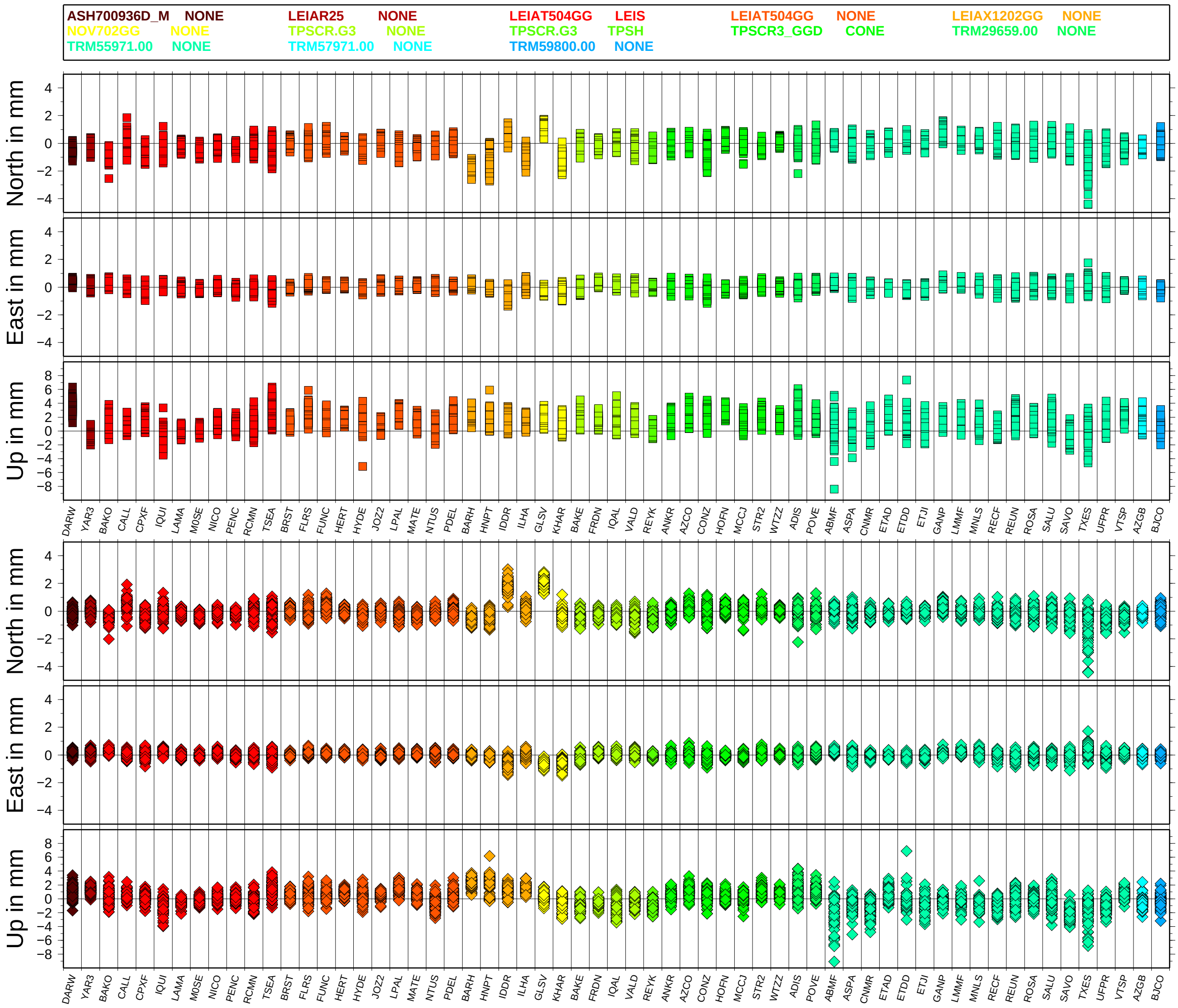

Fig. 7 Weekly coordinate differences (north, east, and up component for 61 different stations; different scale for the up component) between the default CODE solution without bias parameters and an alternative solution with estimated GPS/GLONASS biases. One set of coordinate differences was derived from two solutions based on the reference frame IGS05 and the corresponding antenna phase center model igs05.atx (top), another one based on IGS08 and the updated igs08.atx model (bottom). The colors refer to the antenna types given above the plots.

We use undifferenced and ionosphere-free GPS data of the LEO missions GRACE-A, GRACE-B (Tapley et al. 2004), MetOp-A (Edwards et al. 2006), Jason-2 (Lambin et al. 2010), and GOCE (Drinkwater et al. 2003) from 2009 to extend the phase center model with respect to the nadir angle for the Block IIA, IIR-A, IIR-B, and IIR-M satellites. In this way all types of GPS satellites are included that are relevant as regards the lifetime of the most important LEO missions (in terms of the GPS-based precise orbit determination; cf. Fig. 9). Jason-2 data from the second half of 2011 (after the launch of SVN63, the second Block IIF satellite) are used in addition to get extended PCV estimates for Block IIF.

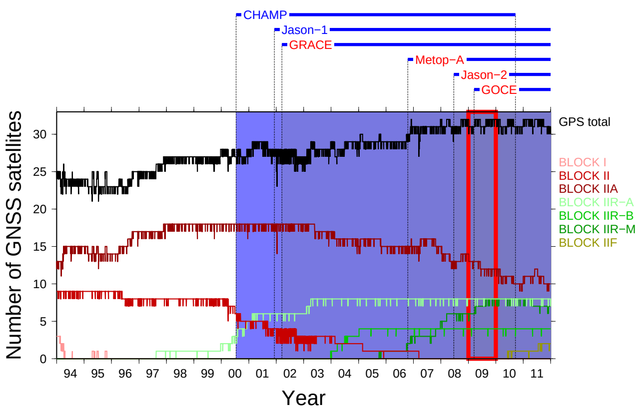

Fig. 9 Number of active GPS satellites together with the operation phases of selected LEO missions.

GPS orbits and clock corrections from the CODE reprocessing (as described in Tab. 4) are introduced as known, as those are consistent with the PCOs and PCVs from igs08.atx. LEO reduced-dynamic orbits relying on the CODE reprocessed products were computed beforehand according to Jäggi et al. (2006) and also introduced as known. It is important to emphasize that, in the latter step, no empirical LEO PCVs were taken into account to obtain unbiased PCV estimates. The GPS PCOs and PCVs from igs08.atx serve as a priori information for the transmitter antennas, the PCVs being extended with constant values beyond 14°. The PCOs for the LEO receiver antennas as provided by the different mission operators are adopted.

LEO PCV parameters are set up as elevation- and azimuth-dependent piecewise linear functions with a resolution of 5°×5°. A zero-mean condition over all grid points of each LEO antenna prevents the normal equation system from becoming singular. PCV parameters for the GPS transmitter antennas are set up as purely nadir-dependent piecewise linear functions with a resolution of 1° for each single satellite. Again a zero-mean condition is applied, and the PCVs of two Block IIA satellites are constrained to their a priori values. The latter constraint is required due to the simultaneous estimation of LEO and GPS PCVs. Eventually block-specific values are constructed on the level of normal equations for the different types of GPS satellites.

Figure 10 shows the agreement of the LEO-only solution with an independent solution based on terrestrial measurements computed according to Dach et al. (2011). The block-specific values (bottom) generally agree on the sub-mm level for all nadir angles up to 14°. Slightly larger differences with respect to igs08.atx occur for the Block IIR-A satellites, as already observed by Dach et al. (2011) who used terrestrial GPS data from the global IGS network. In order to avoid changes of the PCV values contained in igs08.atx by adding LEO-derived information, the final PCV estimates of the LEO-only solution were generated by constraining the PCV estimates for nadir angles $\leq 14°$ to igs08.atx values. A small kink at 14° results from that constraint (cf. Schmid 2014).

Whereas CODE and ESOC closely cooperated on optimizing the estimation strategy (Jäggi et al. 2012), the final results are based on a CODE-only solution. The latter were published in June 2013 (GPS week 1745) and can be found in Schmid (2014).

8 Summary and outlook

After a coordinated effort of five different institutions, the IGS antenna phase center model could be updated

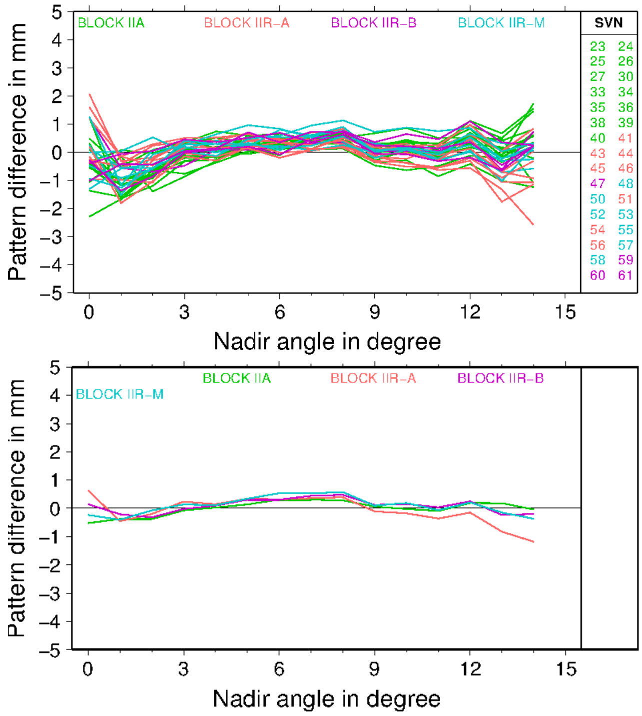

Fig. 10 Differences between the LEO-only solution and a terrestrial solution for satellite-specific (top) and block-specific (bottom) PCVs.

from igs05.atx to igs08.atx in April 2011. As the phase center corrections of both the receiver and the satellite antennas could be based on more calibration/observation data, it is assumed that nearly all components of the model gained in accuracy. Besides, the consistency with respect to the corresponding reference frame IGS08 as well as between GPS and GLONASS could be improved.

In September 2012, the z-PCOs of the (then) seven latest GPS/GLONASS satellites were updated in preparation of the second IGS reprocessing campaign (see Tab. 6). Those estimates were derived from operational AC solutions, NGS being the sixth AC to consider satellite antenna PCO estimates for its SINEX files. For the thirteen satellites launched in the meantime (SVN64–SVN69, SVN71–SVN73, GLONASS no. 743, 747, 754, and 755), preliminary block-specific mean values are in use that will be replaced with results from the second IGS reprocessing campaign that also forms the basis of the upcoming ITRF2014.

Whereas igs08.atx could help to improve the consistency between GPS and GLONASS, new constellations like the European Galileo, the Chinese BeiDou or the Japanese QZSS (Quasi-Zenith Satellites System) were ignored until July 2015. During the IGS 2014 Workshop in Pasadena, it was decided to add conventional satellite antenna PCO values for all new GNSS taking into ac-

Table 6 Updated mean z-PCOs as contained in igs08_1706.atx (released in September 2012) for satellites launched after the release of igs08.atx or shortly before. For abbreviations and explanations compare Tab. 3 and 5. Δigs08 is the difference with respect to the value that was in use before the update. All values in cm.

SVN/ GLO	PRN/ slot	COSPAR	Block	C	E	G	M	NG	NR	z-PCO	ΔBM	Δigs08	ΔAC
62	25	2010-022A	IIF	x	x	x	x	x	x	159.73	–	−7	4
63	1	2011-036A	IIF	x	x	x	x	x	x	156.13	–	(−9)	5
742	4	2011-055A	GLONASS-M	x	x	–	–	–	–	238.11	−6	(−7)	0
744	3	2011-064A	GLONASS-M	x	x	–	–	–	–	256.31	12	(11)	0
745	7	2011-064B	GLONASS-M	x	x	–	–	–	–	263.72	20	(19)	1
746	17	2011-071A	GLONASS-M	x	x	–	–	–	–	274.36	30	(29)	4
801	3, 4, 8, 26	2011-009A	GLONASS-K1	x	x	–	–	–	–	206.68	–	(32)	5

NG: NGS, NR: NRCan

count the IGS axis definition related to the yaw-steering attitude mode (Montenbruck et al. 2015). Apart from that, the estimation of satellite antenna phase center corrections from tracking data of the IGS Multi-GNSS Experiment (MGEX; Montenbruck et al. 2014) could already be demonstrated (e.g., for BeiDou, by Dilssner et al. 2014).

In case new frequencies are used, additional correction values are also needed for the receiver antennas. As long as the number of satellites transmitting the new frequencies is limited, the calibration of receiver antennas in the field is difficult. Therefore, anechoic chamber measurements making use of artificial GNSS signals are currently the only option. The University of Bonn (Zeimetz 2010) already provided chamber calibrations for a limited set of antenna types to the IGS that will have to be merged with the igs08.atx robot calibrations for the legacy frequencies.

As satellite antenna PCVs are treated as known parameters in the IGS reprocessing campaigns, a separate reprocessing effort will be necessary to update the GPS satellite antenna PCVs. In order to cover all satellite generations back to the Block I satellites, the full history of IGS data would have to be reanalyzed. For all this effort to be worthwhile, other optimizations of the PCV modeling should be considered at the same time.

First of all, azimuth-dependent PCVs as proposed, e.g., by Schmid et al. (2005) or Dilssner et al. (2012) should be taken into account. Those show a clear correlation with the individual helical antenna elements. Besides, LEO data should be considered to a greater extent. LEO observations have the advantage that they do not suffer from tropospheric refraction and that they allow the estimation of phase center corrections for the GNSS transmitter antennas without fixing the terrestrial scale (Haines et al. 2015).

As the IGS phase center model relies on fixing the ITRF scale so far, the IGS scale information is not considered to be independent from VLBI and SLR. If LEO-derived satellite antenna corrections were applied, the IGS could provide an independent scale to be used for future ITRF realizations. In the latter case, the phase center corrections for the transmitter antennas would have to rely on ground calibrations for the receiver antennas on board the LEOs. At least the radial LEO antenna PCOs cannot be separated from the transmitter antenna PCOs.

As current LEO-only data could only be used to calibrate the transmitter antennas of the GPS satellites, terrestrial data will still be needed for all other GNSS. Therefore, the simultaneous analysis of terrestrial and LEO data should be fully exploited (Dilssner et al. 2011). Ideally, an improved model for the GNSS satellite antenna PCVs should be available before the start of a new (the third or subsequent) IGS reprocessing campaign. The release of pre-launch calibrations for the transmitter antennas of any GNSS would also be desirable.

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