Ground-Based GPS for Validation of Climate Models: The Impact of Satellite Antenna Phase Center Variations

Per Jarlemark, Ragne Emardson, Jan Johansson, and Gunnar Elgered

***Abstract*—The amount of water vapor in the atmosphere is an important indicator for climate change. Using the Global Positioning System (GPS), it is possible to estimate the integrated water vapor (IWV) above the ground-based GPS receiver. In order to optimally determine the IWV, a correct model of the received signal phase is essential. We have studied the effect of the satellite antenna phase center variations (PCVs) on the IWV estimates by simulating the effect and by studying the estimates of the IWV based on the observed GPS signals. During a period of five years, from 2003 to 2008, a new satellite type was introduced, and it steadily grew in numbers. The antenna PCVs for these satellites deviate from the earlier satellite types and contribute to excess IWV estimates. We find that ignoring satellite antenna phase variations for this time period can lead to an additional IWV trend of about 0.15 kg/m^2/year for regular GPS processing.**

***Index Terms*—Antennas, error analysis, Global Positioning System (GPS), meteorology.**

I. Introduction

Atmospheric water vapor feedback is thought to amplify the global climate response to increased concentrations of greenhouse gases [1]. Hence, for modeling climate change, one of the most important challenges is to properly account for water vapor in the climate warming [2]. The Global Positioning System (GPS) is a useful tool for measuring the atmospheric water vapor. In state-of-the-art GPS data processing, the observed signal phase at the receiver is used to estimate the integrated water vapor (IWV) above the receiving antenna. Many of such studies have been performed using networks of permanently installed GPS receivers [3]–[8]. A correct model of the received signal phase is essential in optimally determining the IWV from GPS. Unmodeled effects may otherwise propagate into the estimated IWV and may thus be misinterpreted as an additional water vapor. Fig. 1 shows an example of the estimated IWV from GPS at the permanent International GPS Service (IGS) site Onsala on the Swedish west coast. The results are obtained using the GPS-Inferred Positioning SYstem (GIPSY) software [9] and the Emardson–Derks simplified physical model [10] for conversion to IWV. The agreement of the results with IWV measurements from ground-based microwave radiometry is typically 1–2 kg/m^2 in terms of daily root-mean-square differences [4]. Eleven periods with a duration of one month are shown in Fig. 1. These periods are used in order to investigate the effects of the antenna phase variations.

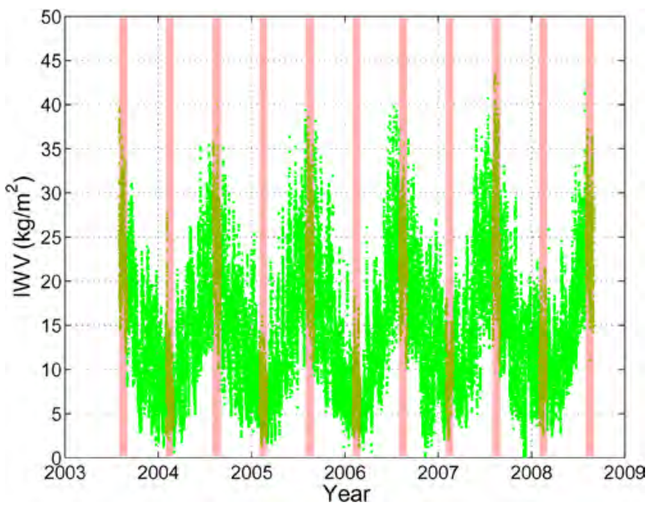

Fig. 1. Example of the estimated IWV from GPS at the Onsala site on the Swedish west coast. The results are obtained using GIPSY [9]. The shaded areas in the figure illustrate the months (August and February) used in this paper.

In the next section, we illustrate the antenna phase variations. The experimental setup and the parameters estimated in the GPS processing are described in Section III, followed by the results in Section IV. Sections V–VII contain the simulated effects, where we have studied the dependence on satellite observation distribution and station latitude, respectively. In Section VIII, we discuss the results and explain why the IWV estimates are affected by unmodeled signal phase variations and the relation between the IWV and vertical position coordinate estimates. Section IX ends this paper with the conclusion.

II. Background

In GPS processing, all measurements are described as originating from an electrical phase center of the satellite antenna. However, the force models used for the orbit modeling apply for

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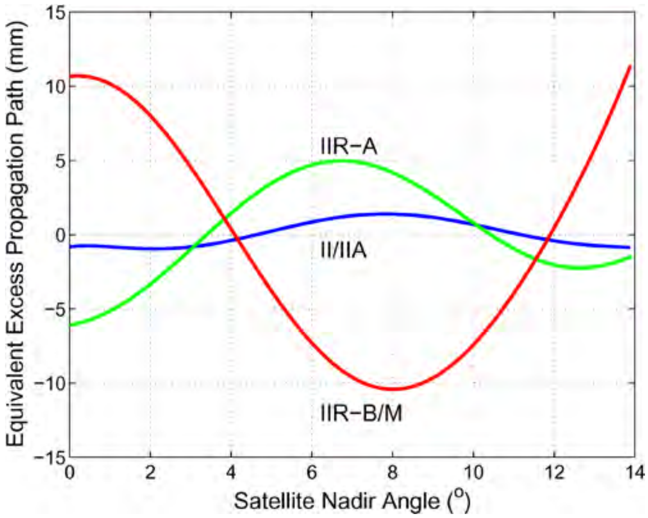

Fig. 2. Antenna PCVs for the three satellite types: (blue) II/IIA, (green) IIR-A, and (red) IIR-B/M.

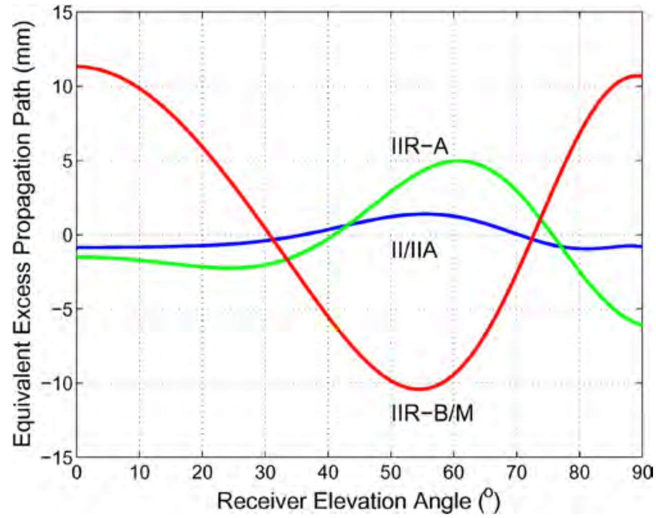

Fig. 3. Antenna PCVs for the three satellite types: (blue) II/IIA, (green) IIR-A, and (red) IIR-B/M.

the center of mass. Hence, the precise satellite coordinates and clock products used in much state-of-the-art processing refer to the center of mass of the satellites [11]. Difficulties to find the distance between the phase and mass centers lead to an inconsistency of the GPS observations. For each GPS satellite, such a distance between the antenna phase center and the center of mass does exist. However, studies [12] have shown that this distance consists of the following: 1) mean value, i.e., a phase center offset (PCO), and 2) variations as a function of the nadir angle, i.e., a phase center variation (PCV). Schmid *et al.* [12] model PCVs for three different satellite types as a function of the nadir angle based on several years of GPS observations. Fig. 2 shows the PCVs for the three satellite types presently in use, i.e., II/IIA, IIR-A, and IIR-B/M. Unmodeled phase variations at the satellite antenna are observed as an elevation-dependent additional phase delay at the receiving antenna.

The pattern can be transformed to an elevation-dependent additional phase delay, as seen by the receiver on the ground. Fig. 3 shows the phase delay as a function of the elevation angle. Most elevation-angle-dependent error sources have a large influence on both the vertical coordinate of the position estimate and the estimate of the signal delay due to the atmosphere, which in turn maps to the IWV values.

As shown in Fig. 3, the amplitude of the PCV is larger for the satellites of type IIR-B/M. The number of satellites of type IIR-B/M has steadily increased during the experiment period from 0 to 10. Fig. 4 shows the number of each satellite type during this period. The increase of the type IIR-B/M satellites has been at the expense of the type II/IIA satellites.

In much of the state-of-the-art GPS processing prior to November 6, 2006, the vertical component of the PCO, i.e., the direction pointing toward the center of earth, was assumed to be 1.023 m for the satellites of type II/IIA and zero for the other satellite types. In processing, since that date, the PCOs shown in Fig. 5 have been applied separately for each satellite for the entire life of the satellite. Fig. 5 shows the recommended PCO for each satellite in use during our study period [13]. A constant value of 1.023 m, which was used previously, is

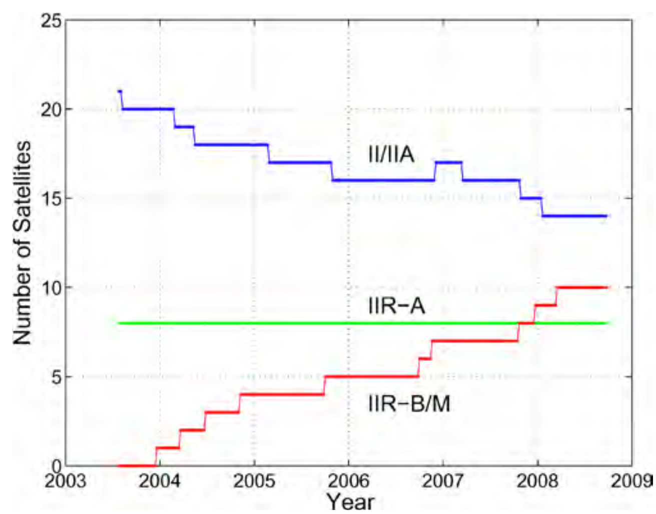

Fig. 4. Number of satellites of types (blue) II/IIA, (green) IIR-A, and (red) IIR-B/M from 2003 to 2008.

already removed from the satellites of type II/IIA. Hence, what is shown is the additional knowledge after the determination of separate phase offsets.

In addition to the modeling of the satellite antennas, a similar work was performed for the ground receiver antennas. A set of PCOs (rPCO) and PCVs (rPCV) was derived for different receiver antenna types [13].

We have studied the effect of satellite antenna phase variations mainly on the IWV estimates and the implication for climate interpretations. That is, we have primarily focused on the effects of the PCO and PCV models presented earlier. We have chosen sites where no changes have been made to the receiving antennas during our period of study, and thus, the rPCO and rPCV have an insignificant effect on the estimated IWV trends. This paper has been performed both by simulating the effects and by studying the estimates based on the observed data. We have used observations from three permanent IGS sites [14] at three different latitudes, namely, Onsala, Sweden,

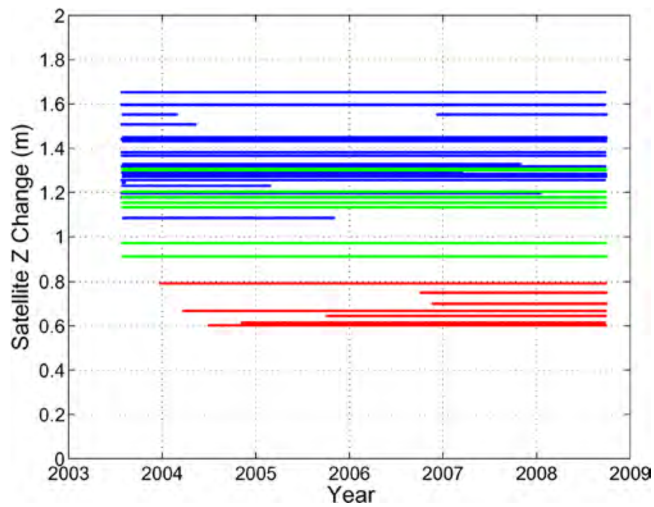

Fig. 5. Change in the applied satellite antenna vertical PCO for each satellite in use from 2003 to 2008. The colors indicate the type of satellite with the coding (blue) II/IIA, (green) IIR-A, and (red) IIR-B/M.

at 57° N; Matera, Italy, at 41° N; and Kourou, French Guiana, at 5 ° N.

III. Experimental Setup

We have studied the effect of the satellite PCOs and PCVs on the IWV estimates both by studying the estimates of the IWV using observed GPS signals and by simulating the effects. In both cases, the data have been processed using a Kalman filter technique (e.g., see [15]), which is a minimum variance estimation algorithm in the special case where the system is a linear stochastic dynamical system. The main model of the filter is the assumed linear relationship between measurements z and the variables x that we want to estimate. This relationship is described by the observation matrix H containing the partial derivatives

$$z = Hx + v \tag{1}$$

where v is the measurement noise.

The observed GPS signals were processed with the GIPSY v4.04 software using the precise point positioning (PPP) method [9] based on the satellite orbits provided by the Jet Propulsion Laboratory. Hence, we solve, in the processing, for the 3-D station coordinates, the atmospheric zenith total delay, and the receiver clock offset. The processing of the data with the correction models applied was performed by correcting the effects directly in the Receiver Independent Exchange Format observation files prior to the processing (GIPSY software v5.0 includes an option to correct for such effects.).

We performed simulations based on the PCO and PCV models. The simulations were carried out in order to display the difference in the resulting IWV with and without the correction models. In this paper, we consider this difference in the resulting IWV as the error in the IVW results. The simulations were performed in MATLAB using an in-house simulation software package, with the modeling and processing strategy imitating the PPP method [9]. All process parameters were identical for all simulations and identical to those in the GIPSY processing. In our application, the formulation of the Kalman filter equations is almost perfectly linear when estimating a set of variables x from (1), i.e.,

$$\hat{x}(z + \delta z) = \hat{x}(z) + \hat{x}(\delta z) \tag{2}$$

for small errors δz. Hence, these errors can be treated separately to derive their effects $\hat{x}(\delta z)$ on the sought variables. We constructed simulated measurement errors based on the models. These errors were used as input to the simulation software, as δz in the Kalman filter formulation. No other errors were fed into the simulation software. This strategy provides the error in the zenith wet delay, given the simulated measurement errors and, thus, the corresponding error in the IWV.

Normally, when determining the IWV from the total atmospheric delay estimates, we subtract a hydrostatic part [16] from the total delay based on independent pressure measurements and thus obtain the delay in the atmosphere mainly due to water vapor, i.e., the wet delay. The wet delay can be used to estimate the IWV based on temperature-dependent scaling factors (e.g., see [10]). In this paper, however, we evaluate the difference in the IWV estimates from the solutions by changing only the PCV and PCO models. Hence, the hydrostatic delay is identical in the solutions and is therefore cancelled when calculating the difference. For the same reason, in the following, we use a simplified conversion factor of 6.3-mm atmospheric delay per kg/m^2 IWV [10].

For both observed and simulated data, we studied a period from mid 2003 to mid 2008. We have chosen two months (February and August) every year for the processing. During these months, we estimated the IWV every 5 min. We studied the effects of using only observations above a specific elevation angle, i.e., an elevation cutoff angle. The cutoff angles that we used were 5°, 10°, 15°, and 20°. Today, the cutoff angles 10° and 15° are the most commonly used, and hence, the focus was on those results.

IV. Effects of Antenna Mismodeling

As described in the previous section, we can process the GPS observations both with and without applying the antenna phase center corrections. Fig. 6 shows the difference in the estimated IWV between these two solutions for the Onsala site. The blue triangles illustrate the mean values for each month. The red line in the figure is the least square fit to the estimated IWV differences. The slope of this line is 0.071 kg/m^2/year, with a 1σ uncertainty of 0.005 kg/m^2/year. Hence, ignoring the antenna phase variations when processing the GPS data from this time period can lead to a misinterpretation of an additional IWV trend of about 0.07 kg/m^2/year for this type of GPS processing, assuming that the models are correct. The uncertainty is based on the use of a straight line to fit the data points, given a χ^2 per degree of freedom that is equal to one. The uncertainty says nothing about the validity of such a straight line model. A straight line is, however, a reasonable model when studying climate variations.

In the figure, in addition to the PCO and PCV effects, the rPCO and rPCV effects are also included for the completeness

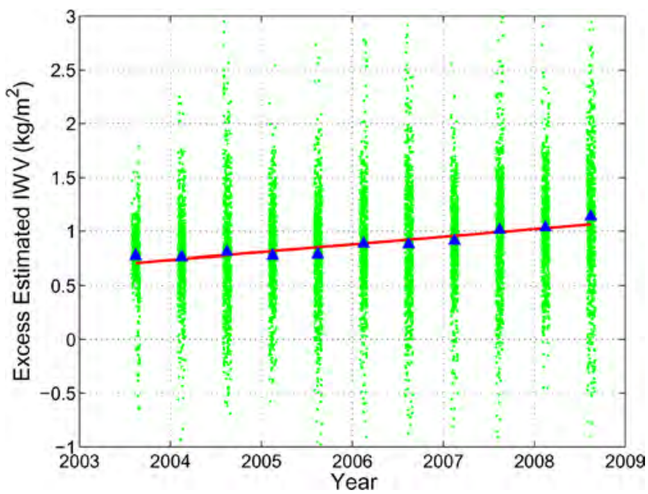

Fig. 6. Error in the estimated IWV when omitting the PCO, PCV, rPCO, and rPCV corrections. The figure shows the estimated IWV without corrections minus the estimated IWV with corrections. The observed data are acquired at Onsala and are processed with an elevation cutoff angle of 10°.

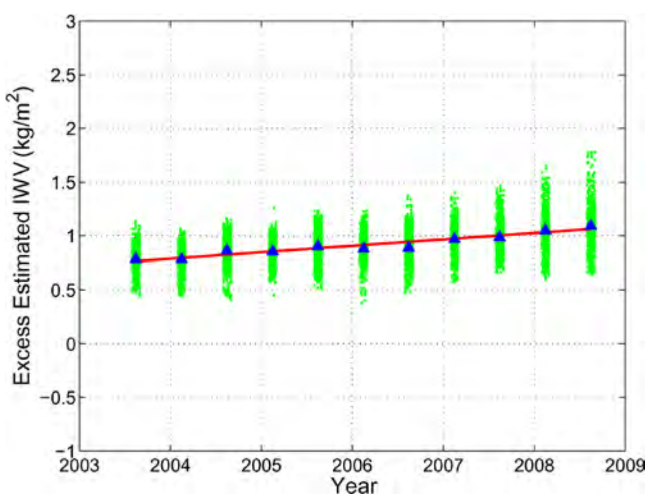

Fig. 7. Simulated error in IWV when omitting the PCO, PCV, rPCO, and rPCV corrections. The figure shows the IWV without corrections minus the IWV with corrections. The data are simulated for the Onsala site and are processed with an elevation cutoff angle of 10°.

of the GPS solution. The contribution from the latter two is, however, only a constant offset value.

Fig. 7 shows the results from the simulations. Also in this figure, the rPCO and rPCV effects are included in order to imitate the solution based on the observed data. The results of the simulations are similar (both concerning the slope and the offset) to the results based on the observations. The slope of the straight line here is 0.059 kg/m^2/year, with a 1σ uncertainty of 0.001 kg/m^2/year. This uncertainty value is a representative of the simulated results in this paper. Note also the variations in the simulated results within each monthly batch. These originate from the small differences in the satellite constellation from day to day.

V. Contributions From Different Components

As seen in the previous section, the use of the antenna phase center models in the GPS processing affects the estimated IWV. By simulating these variations, we can separate the different

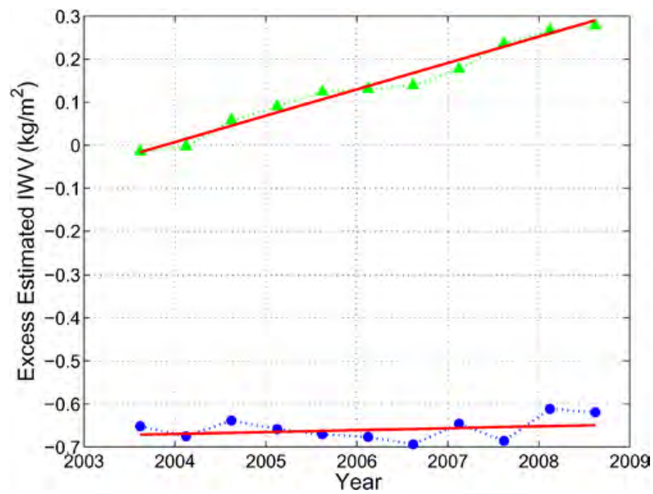

Fig. 8. Simulated error in IWV when omitting the (blue circles) PCO and (green triangles) PCV corrections. The figure shows the IWV without corrections minus the IWV with corrections. The red straight lines are the least square fits to the data points.

effects and their respective influence on the results. Now, we study the influence of the PCV and PCO models separately on the estimated IWV for the Onsala site using a cutoff angle of 10°. The results are produced similarly to the results in the previous section. For clarity, we show the results as monthly average values, i.e., two values per year. Fig. 8 shows the simulated effects on the estimated IWV by applying the PCO and PCV corrections separately. Note that the rPCO and rPCV corrections are not taken into account. Hence, results are not directly comparable to those in Fig. 7. The effect of the PCO is a relatively insignificant trend in the estimates, while applying the PCV results in an increase of approximately 0.3 kg/m^2 over the five-year period. Hence, processing the GPS observations during this period without applying the PCV models produces results that can be misinterpreted as an existing IWV trend of 0.06 kg/m^2/year.

Fig. 9 shows the effects on the estimated vertical position component of applying the PCO and PCV corrections. For the vertical coordinate estimate, the effect of applying the PCO, approximately 5 mm over the five-year period, is dominating over the effect of applying the PCV. This result is the opposite of what we found for the IWV estimate. Hence, processing the GPS observations during this period without applying the PCO models produces results that can be misinterpreted as a vertical change of -1 mm/year.

It is important to remember that, in our simulations, we have not included the effects on orbit and satellite clock estimation and their secondary effect on the estimates, which could have an effect on parts of the results. However, we do not believe that the inclusion of this effect has any significant impact on the IWV results of the PCV simulations due to the relatively rapid spatial variations, as seen from a tracking network, of the PCV compared to those of the satellite orbits and clock parameters.

VI. Elevation Dependence

The previous results were produced using an elevation cutoff angle of 10°. We know from several studies of

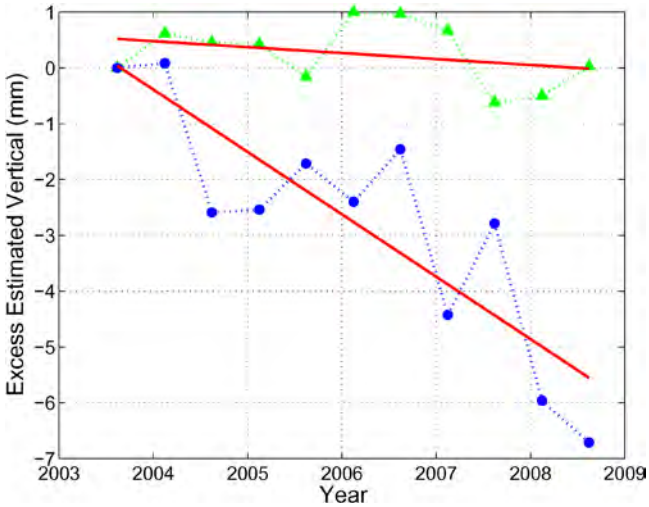

Fig. 9. Simulated variation in vertical positions when omitting the (blue circles) PCO and (green triangles) PCV corrections. The figure shows the position without corrections minus the position with corrections. The results are adjusted so that the results for the first month are zero. The red straight lines are the least square fits to the data points.

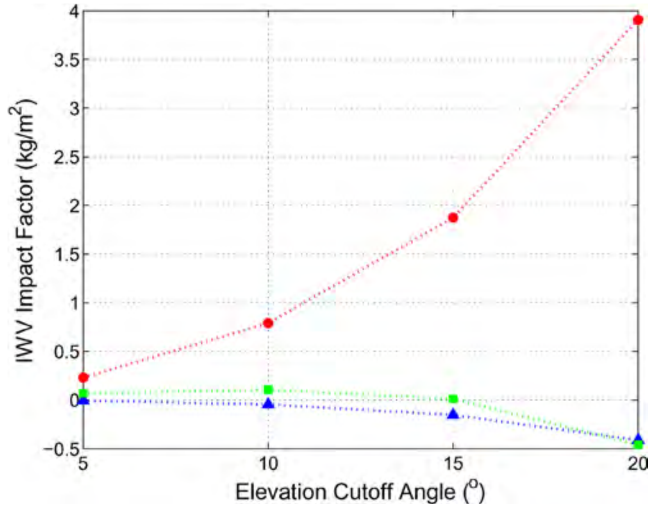

Fig. 10. Simulated contribution to the IWV estimates from the different satellite types, namely, (blue triangles) II/IIA, (green squares) IIR-A, and (red circles) IIR-B/M, for different cutoff angles.

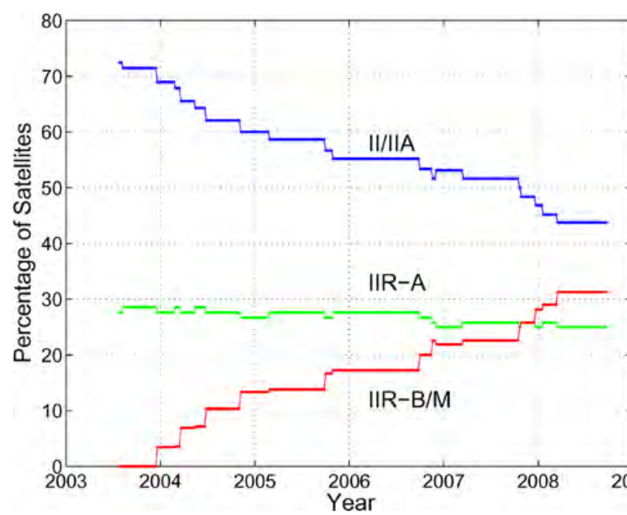

Fig. 11. Relative number of satellites of types (blue) II/IIA, (green) IIR-A, and (red) IIR-B/M as percentage of the total number of satellites from 2003 to 2008.

elevation-dependent error sources that the results may vary significantly if the elevation cutoff angle is changed. Thus, we studied the impact of the chosen cutoff angle on the IWV by simulations. We include only the PCV when investigating the elevation dependence due to the minor effect that the PCO has on the estimate of a trend in the IWV. In order to illustrate the different contributions at different elevation cutoff angles, we study each satellite type separately. Fig. 10 shows the contribution on the IWV estimates from the different satellite types for elevation cutoff angles ranging from 5° to 20°. The results in the figure are produced using the constellation of February 15, 2006, at the Onsala site. However, the errors in the IWV estimates are based on a hypothetical scenario that all satellites are of only one type. By combining the information of Fig. 10 with the relative amount of the different satellite type, it is possible to obtain a rule of thumb for the impact on the IWV estimate at different times.

Fig. 11 shows the relative number of the different satellite types. By multiplying the relative occurrence of the satellite types with their corresponding impact factor, the excess IWV at a certain time and the elevation cutoff angle can be approximated.

VII. Latitude Dependence

The observation angles to the GPS satellites will differ for sites at different latitudes. As the elevation cutoff angle has a clear effect on the impact of the unmodeled PCV, we can expect that the distribution of the observations and, thus, the latitude of the GPS receiver also have an impact. Fig. 12 shows the satellite coverage for the Onsala, Matera, and Kourou sites together with the number of binned observations for elevation angles between 0° and 90°. The number of high-elevation observations is relatively similar for the three sites. One could believe that the number of high-elevation observations should be lower for the most northern sites due to the coverage, as seen in a polar plot. This is, however, not the case due to the slower passage at high elevations of the satellites over these sites. For the Kourou site, the number of observations at elevation angles between 15° and 30° is significantly higher than for the other sites, while the number of observations above an elevation of 60° is lower. These differences in the distribution of the observations have an impact on how the unmodeled elevation-dependent effects propagate into the IWV estimates.

As the choices of the elevation cutoff angle and the latitude of the GPS location have an impact on the estimated IWV, we can, by analogy with Fig. 8, study the trends in the estimated IWV for the three sites that we have chosen for this paper and for the most commonly used elevation cutoff angles. Table I shows such estimated slopes for the three sites in the study for 10° and 15° cutoff angles. As indicated previously, the effect on the IWV trend is larger for the solutions processed with higher elevation cutoff angles. This is the case for all three sites. We also notice that the effect is much less significant for the Kourou site than for the other two, which have very similar results.

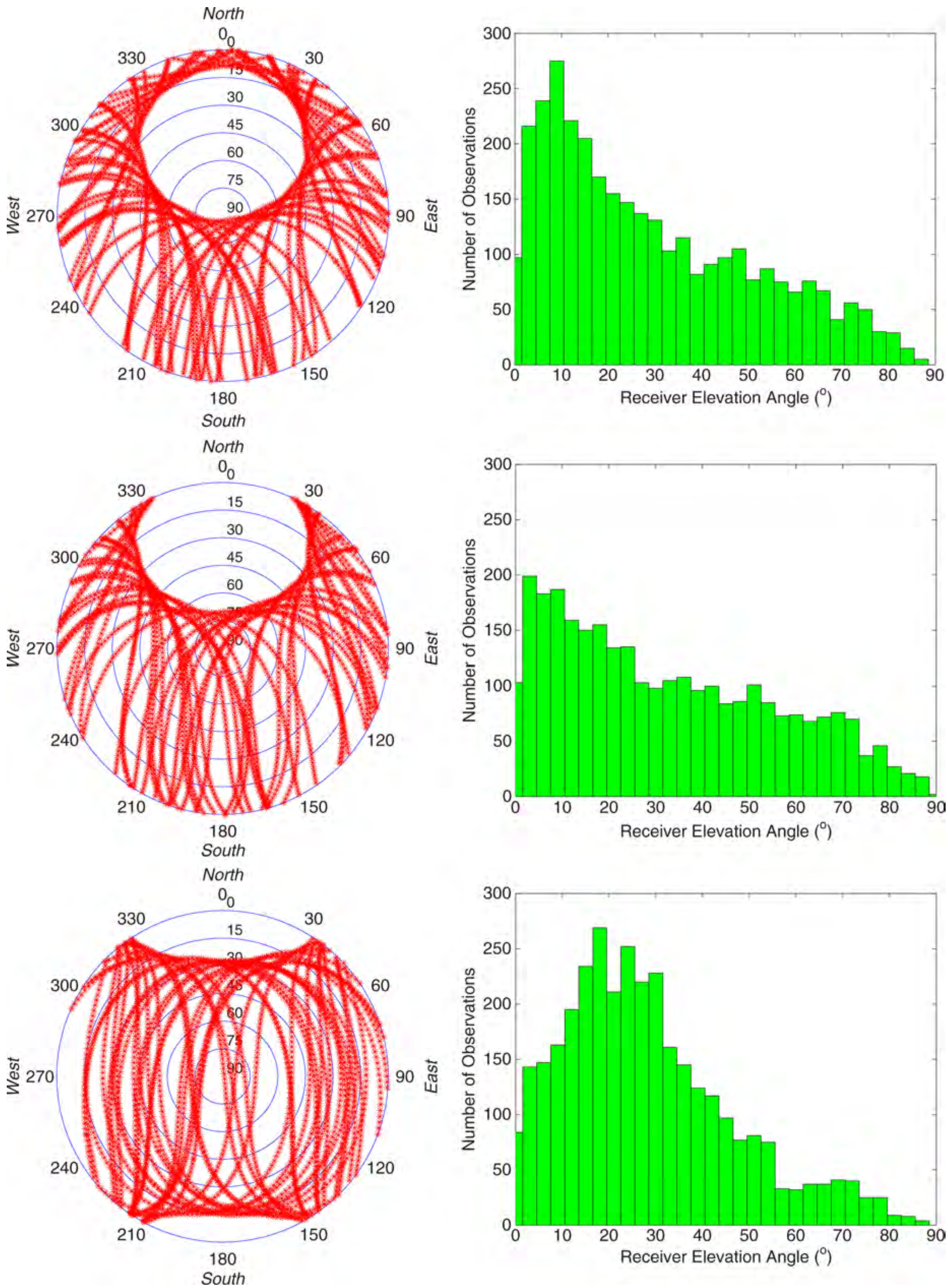

Fig. 12. Satellite coverage for the (top) Onsala, (middle) Matera, and (bottom) Kourou sites. The observations are acquired every 5 min during one day.

VIII. Discussion

A general problem with using least square techniques such as Kalman filtering is that unmodeled effects in the observations propagate into the estimates of the sought parameters. The better this unmodeled effect happens to match the partial derivatives, modeling the relation between the observations and the parameters, the greater is the influence on the sought parameters. In GPS processing, the elevation-dependent effects

TABLE I
SIMULATED EFFECT ON THE IWV ESTIMATES IF THE PCVs ARE NOT TAKEN INTO ACCOUNT. THE SLOPES ARE BASED ON AN OBSERVATIONAL PERIOD FROM MID 2003 TO MID 2008. THE 1σ UNCERTAINTIES FOR THE SLOPE ESTIMATES ARE 0.001 AND 0.002 $kg/m^2/year$ FOR THE CUTOFF ANGLES 10° AND 15°, RESPECTIVELY

Site	Latitude	IWV Slope ($kg/m^2/year$) Cutoff Angle	
	°N	10°	15°
Onsala	57	0.06	0.14
Matera	41	0.08	0.16
Kourou	5	0.03	0.08

tend to propagate into a combination of a vertical movement of the site, an atmospheric delay change, and a change in the site's clock offset.

A specific elevation-dependent unmodeled error can thus affect only the vertical estimates, while another can affect the estimates of the atmospheric delay change only. In most cases, both the vertical and atmosphere delay estimates are influenced, but as shown in this paper, the elevation-dependent errors exist, which, to a large extent, only have an impact on one of the estimated parameters.

As shown in Fig. 3, the PCVs are elevation-dependent effects. Not modeling these PCVs results in errors in the estimated atmospheric zenith total delay and, thus, also in the IWV estimates. The PCV can relatively well be described by the partial derivatives at higher elevation angles. However, the partial derivative representing the delay due to the neutral atmosphere is large below 30°, and it grows rapidly with lower elevation angles. Its elevation dependence can be approximated by the function 1/sin(elevation). The PCV of satellite type IIR-B/M, in contrast to the earlier types, has a pronounced signature at lower elevation angles, e.g., below 30°. Although strong, this signature is relatively small compared to the partial derivative representing the atmospheric delay. That is, processing without the PCV model, observations at low elevation angles will contradict an interpretation of a strong excess IWV component, also for observations of satellite type IIR-B/M.

As a consequence, low-elevation-angle observations are beneficial for the GPS processing that is ignoring the PCV corrections. Even when taking into account the PCV, low-elevation-angle observations may be useful (e.g., [17]), for example, by reducing the effect of other elevation-dependent error sources. Also, the latitude dependence seen in Section VII can be explained by the influence of low-elevation observations. At Kourou, with its relatively high number of observations below 30°, a significantly smaller sensitivity to the satellite type IIR-B/M introduction is seen.

Down weighting of low-elevation observations when processing GPS data is a common practice and is beneficial for different reasons. However, performing down weighting while omitting the satellite antenna PCV in the processing reduces the positive effect of the low-elevation observations. Hence, this can, in specific cases, lead to larger errors.

IX. CONCLUSION

Processing of GPS data without the inclusion of correct antenna models leads to an error in the IWV estimate. In particular, omitting the satellite antenna PCV causes an apparent trend in the IWV. For example, it can lead to an additional IWV trend of up to 0.15 $kg/m^2/year$ for regular GPS processing for the time period 2003–2008. Although we have selected an inauspicious period, given the changes of the satellite types, this can be compared to linear trends estimated from Swedish and Finnish GPS data (without using corrections for antenna PCVs) that are acquired over a ten-year period, which range from -0.05 to 0.1 $kg/m^2/year$[7].

The apparent trend depends on the growing number of satellites of type IIR-B/M. The size of the apparent trend varies with the latitude of the observing site, the chosen elevation cutoff angle, and the weighting of the observations. In general, observations at low elevation angles with relatively high weighting reduce the effect.

Normally, by keeping the configuration fixed in GPS processing, we do not expect false trends in the time series of the estimates. Changes in, for example, hardware or software often introduce a discrete step. We have presented an example when changes in the infrastructure of the satellite system introduce false trends in the IWV estimates, through small discrete steps, even when the user configuration is held fixed.

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