The Impact of the Atmosphere and Other Systematic Errors on Permanent GPS Networks

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Abstract. The Swiss Federal Office of Topography is currently building up the Automated GPS Network Switzerland, called AGNES. This GPS network will serve various purposes, like national surveying, engineering surveying, navigation, meteorology, and research.

For wide-area differential GPS (WADGPS), in particular precise real-time positioning using the GPS phase data of one or more reference stations of the AGNES network, one may expect that atmospheric refraction plays the crucial role, since the reference stations may be rather widely separated in Switzerland, typically by 50–100 km. This assumes that orbits and "absolute" tropospheric refraction for at least one of the sites are known with sufficient precision.

In the time period of the next solar maximum, the ionospheric refraction will probably be the most crucial error source, in particular for resolving the initial phase ambiguities, which is mandatory when aiming at a coordinate accuracy on the centimeter level. Nowadays, global and regional total electron content (TEC) maps, like those produced by the Center for Orbit Determination in Europe (CODE), are available and may be used to model the mean ionospheric refraction. However, on time scales of few minutes, ambiguity resolution usually suffers from short-term ionospheric fluctuations which are not accounted for by such TEC maps.

Significant height differences with respect to the nearest reference stations may also occur, especially in mountainous areas like Switzerland. This implies that not perfectly modeled tropospheric refraction may cause biases too.

We study the impact of tropospheric as well as ionospheric biases on WADGPS results and investigate whether it is possible to extract atmospheric information from networks of the AGNES-type for correcting data of mobile GPS receivers in (near) real time.

Keywords. Permanent GPS networks, WADGPS, atmosphere modeling

1 Global, Regional, and Local Permanent GPS Networks

Many permanent GPS networks were deployed for various purposes in recent years. We have to distinguish global, regional, and local networks.

1.1 The IGS and its Products

The IGS (International GPS Service) network is probably the best known global GPS network. It is documented, e. g., in Beutler et al. (1996) and in a series of annual reports (e. g., Zumberge et al. (1997)). The IGS products are of importance for all other permanent GPS arrays (at least for those where the reference frame is an important issue). Let us mention in particular

- coordinates and velocities for all IGS sites,
- precise orbits (final, rapid, predicted),
- daily values for the earth rotation parameters x, y and LOD (length of day),
- troposphere estimates for IGS sites, and
- global ionosphere maps.

It is our understanding that these products must be used (to the extent possible) by the operators of regional or local networks in order to assure consistency on the sub-centimeter level of the reference frames with (the latest IGS realization of) the ITRF.

1.2 Permanent Regional and Local Networks

Permanent regional or local arrays have been deployed and are operated for various purposes, e. g., for precise relative navigation, crustal deformation monitoring (e. g., SCIGN network, the Japanese 1000-receiver network), or for precise

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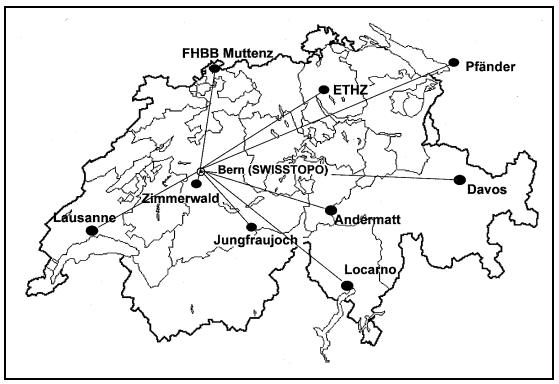

Figure 1. The reference stations of the AGNES network 1999

(near) real-time relative positioning using short data pieces, often addressed as *wide-area differential GPS (WADGPS)*.

The Canadian Active Control System (CACS) is a good example for networks of the latter type. Other examples may be found in Germany (see, e. g., Wanninger (1999)) or in the Netherlands (see van der Marel (1999)). The accuracy aimed at may vary between the 1-m and the 1-cm level.

2 The AGNES: A Local GPS Array

AGNES stands for *Automated GPS Network Switzerland*. The network serves several purposes, in particular monitoring and maintenance of the Swiss first-order control network, navigation, and research. The AGNES is being deployed and operated by the Swiss Federal Office of Topography.

The AGNES sites are shown in Figure 1. The distances of the AGNES sites with respect to the Zimmerwald IGS site as well as the station heights are given in Table 1. Table 1 indicates a particular difficulty in the AGNES, namely a height difference of more than 3000 m between the lowest and the highest site.

2.1 AGNES Data Analyzed

Only a small amount of the AGNES data were analyzed in our study, namely one week of data in 1998 and two days in 1999. The two data sets may be characterized as follows:

- 1998 data set: 16–22 August, 30-second data from 7 stations (`EPFL`, `ETHZ`, `FHBB`, `JUJO`, `PFAN`, `SIER`, `ZIMM`);
- 1999 data set: 8–9 April, 5-second data from 9 stations (`DACH`, `DAVO`, `EPFL`, `ETHZ`, `FHBB`, `JUJO`, `THUN`, `WICH`, `ZIMM`).

The non-AGNES sites `DACH`, `THUN`, and `WICH` were observed only from noon to noon.

Table 1. Ellipsoidal station heights in the AGNES network

Station ID	Height (m)	Dist. wrt. `ZIMM` (km)
`FHBB`	378	74
`EPFL`	459	79
`ETHZ`	595	99
`SIER`	602	65
`ZIMM`	956	0
`PFAN`	1090	190
`JUJO`	3635	54

The following information was taken over from the CODE/IGS data processing or from other sources:

- position of the Zimmerwald observatory for the two periods,
- troposphere estimates (one-hour tropospheric zenith path delay parameters) for Zimmerwald from the CODE/EUREF data processing,
- broadcast, IGS precise, or IGS (2-day) predicted orbits,
- IGS earth rotation parameters, and
- CODE global ionosphere maps.

3 Remarks Concerning Theory

When analyzing data from a permanent network like AGNES we must ask the question: *What do we have to do in order to let the AGNES user take maximum profit out of the network and its data?* The question must be answered differently for post-processing and for (near) real-time applications.

In the *post-processing mode*, the user would download the required data from the entire AGNES, use the best possible information available from the IGS (orbits, ERPs, troposphere parameters for the Zimmerwald site, if available troposphere parameters for all other AGNES sites from the AGNES operator), and produce a correct network solution using a scientific software package. From the quality point of view, there is no better solution. We will not pursue the post-

processing issue further.

In the *real-time mode*, other solutions have to be found. Let us mention a minimum and a maximum solution:

- As a *minimum solution*, the data from the closest AGNES site are downloaded and processed. The AGNES user only has to be given the coordinates of the AGNES site and maybe the current values for the troposphere corrections for the site requested. It is then entirely up to the user to process the data in the best possible way, e. g., by tabbing the best possible orbit files, etc.
- As a *maximum solution*, the AGNES operator might perform the following steps:
  (1) produce in (near) real time a correct network solution (based on the ionosphere-free linear combination) of the entire AGNES with ambiguities fixed on the double-difference level,
  (2) reconstruct zero-difference observations and relocate them to one site, e. g., the Zimmerwald site,
  (3) combine the phase and code observations for all AGNES receivers with the goal to reduce the observation noise and site-specific biases,
  (4) produce satellite- and epoch-specific linear corrections of ionospheric refraction with latitude β and longitude λ as independent arguments (epoch-specific may be replaced by "specific for a few epochs"),
  (5) produce for time intervals of, let us say, 30 minutes linear models of tropospheric zenith corrections as a function of latitude β, longitude λ, and height h, and
  (6) make available the sum of the above mentioned corrections for each satellite and epoch for each user position. In addition, one would add the antenna phase center corrections due to the user antenna in this step. Alternatively, the correction model parameters might be made available.

The proposed maximum solution is closely related to proposals made by Wanninger (1999) or van der Marel (1999). Our approach differs in the following respects:

- We try to avoid epoch-by-epoch corrections wherever it is possible, because they have the tendency to increase the noise.
- We do *not* make the attempt to model tropospheric refraction for each satellite and each epoch. Experience tells that it is sufficient to introduce one zenith path delay parameter per hour and station.
- Estimation of orbit and troposphere parameters is routinely performed in the above step (1). This step is not time critical. One solution every hour would be sufficient.
- If IGS predicted orbits of sufficient quality are available the orbit improvement may be skipped in step (1). If not, one (maybe two) orbit parameters for each satellite are sufficient to remove all problems.
- An epoch-by-epoch correction is only considered for modeling ionospheric refraction.
- We strive for full consistency of all phase and code observations in the above combination step (2), a non-trivial issue, which we will not address here.

In Section 4 we address issues related to processing step (1); in Section 5 we will address issues related to a user of AGNES products.

4 Processing Data of Permanent GPS Networks

For the AGNES operator it must be the goal to generate a phase solution based on the ionosphere-free linear combination (LC). To achieve this goal he has to resolve the ambiguities using, at one point or another, the basic L1 and L2 observations.

The network operators are in a good position because they may assume their GPS receiver/antenna locations to be known in the ITRF with centimeter accuracy. If code observations with an rms error smaller than about 0.3 m rms were available, wide-lane ambiguity resolution would be trivial using the Melbourne-Wübbena LC of phase and code measurements (see Beutler et al. (1990)).

In the AGNES, at least under the AS regime, this is not the case. Consequently, we were obliged to apply ambiguity resolution techniques *without* using code observations. It was decided to resolve the wide-lane ambiguities first and to resolve the L1 ambiguities afterwards. Other techniques, like the QIF technique (see Rothacher and Mervart (1996)), might have been used as well. The method used here gives more insight into the dependency on different bias types. We were processing one-day data pieces.

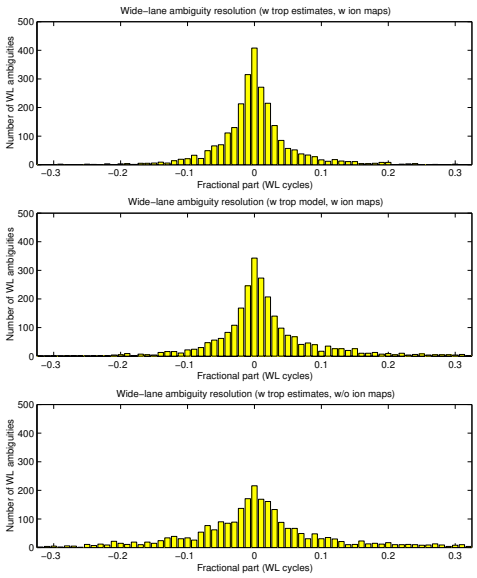

Figure 2. Wide-lane (WL) ambiguity resolution

4.1 Wide-Lane Ambiguity Resolution and Ionospheric Refraction

Figure 2 gives an impression of the wide-lane ambiguity resolution. We see a histogram of the fractional parts of the wide-lane ambiguities at the moment they were fixed to integer numbers. The best strategy (taking over the troposphere estimates from an ambiguity-free network solution and applying the corrections from our global ionosphere maps) is reflected in the top subfigure, the second strategy (using an a-priori troposphere model) is only marginally worse, the third strategy (not taking into account the ionosphere maps), given in the bottom subfigure, is clearly inferior. Precise orbits were used in all cases, but this was not a crucial issue—even broadcast orbits would have been sufficient to resolve the wide-lane ambiguities.

In the first case 98.2%, in the second 97.4%, in the third 95.2% of the wide-lane ambiguities could be resolved using an elevation cut-off angle of 10^o. The ambiguities that could not be resolved were always associated with low elevations.

In summary we may state that wide-lane ambiguity resolution does not pose a serious problem even if the orbit information is not of the best quality. Double-difference wide-lane ambiguity resolution is in practice and in essence limited by our ability to model the ionosphere—let us say on the 0.2 wide-lane wavelength level. Under usual conditions this should not pose a serious problem.

We used in essence a post-processing scheme. May it be transferred to real time? One might argue that this is not the case, because in practice we will always have the problem of rising satellites over an area, when we will have to make the attempt to resolve ambiguities based on short time spans. Whereas this is true, one has to point out that the problem is limited to exactly one satellite—all other ambiguities (in addition to all receiver positions, orbits, etc.) are known with sufficient accuracy to allow for a rapid resolution of the wide-lane ambiguity. The practical consequences, when ambiguity resolution is not possible instantaneously, are limited, as well: good differential atmospheric corrections are not available immediately after a satellite rises over the area.

4.2 Narrow-Lane Ambiguity Resolution, Tropospheric Refraction, and Orbit Quality

After having successfully resolved the wide-lane ambiguities using the wide-lane LC, we may resolve the L1 ambiguities using the ionosphere-free LC of L1 and L2.

In this step we have the advantage that the ionosphere is completely eliminated and cannot bias our solution. The effective wavelength in the ionosphere-free LC, however, is now about 11 cm, which means that other systematic errors become relevant. We have to consider orbit-induced errors and unmodeled tropospheric effects.

Figure 3 shows a histogram of the fractional parts of the narrow-lane ambiguities at the moment of fixing them to integers. The top subfigure shows our best solution: precise orbits are taken over from the CODE/IGS data processing. In the second subfigure tropospheric refraction is not estimated, but computed using a standard atmosphere model (Saastamoinen in connection with a standard atmosphere). In the bottom subfigure of Figure 3, broadcast instead of CODE precise orbits were used.

The standard deviations for the fractional parts of the narrow-lane ambiguities are 0.092 cycles in the first case (top subfigure), 0.112 cycles in the second, 0.133 cycles in the third case, where broadcast orbits are used. In the first case 95.2%, in the second 92.4%, in the

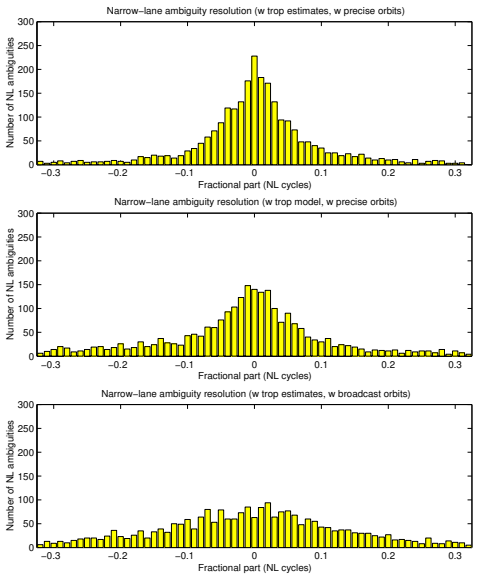

Figure 3. Narrow-lane (NL) ambiguity resolution

third 91.0% of the narrow-lane ambiguities could be resolved.

Figure 3 tells us that both orbits of excellent quality and accurate troposphere parameters are mandatory for a network of the size of AGNES.

It is obvious that much better than broadcast orbits are required. Wanninger (1999) and other authors propose to reduce the orbit and tropospheric effects by a linear model over the area. We have proposed an alternative method above, and test runs were made using one day of data: By using the IGS predicted orbits as a-priori orbits and introducing only the argument of latitude u_0 as a free orbit parameter for each satellite we obtained the same observation rms error for the ambiguity-free solution, and we were able to resolve the same number of ambiguities as in the best case when using (and not altering) the IGS final orbits as a-priori orbits. The results when improving the broadcast instead of the predicted orbits were not of comparable quality. This is explained by the fact that the reference frame is slightly different for broadcast orbits.

Let us get one aspect straight. Orbits, as established by CODE or other IGS analysis centers, based on a world-wide network may be extrapolated for, let us say, six hours in such a way that the quality is sufficient to provide results of the type of the top picture in Figure 3. The problem is at present that the IGS predicted orbits are based on data with a latency of one to two days instead of few hours.

What about tropospheric refraction? Figure 3 gives an answer as well: For a network of the AGNES-type it is necessary to solve for tropospheric zenith delays for each site with a relatively high time resolution (say 30 minutes to one hour). The aspect is somewhat less dramatic than the orbit aspect, but the impact is clearly visible as well (compare middle subfigure with the top subfigure in Figure 3).

5 AGNES User Aspects

Let us first address the question what kind of biases an AGNES user has to cope with, assuming that he successfully removed all phase ambiguities. The following experiments were all performed with the data of 19 August 1998. We assumed 5-minute data pieces. We were considering the Zimmerwald site as an unknown user receiver in the rest of the AGNES, when processing the data in the network mode; we were processing the baseline `FHBB-ZIMM` assuming `FHBB` known, when performing baseline-specific solutions. 288 5-minute solutions could be made using the data material of 24 hours. Our experiments may be summarized as follows:

- With few exceptions the ionosphere-free LC was processed. In view of the network size this is in general the only acceptable solution. Exceptions might be considered for short distances to the closest AGNES site.
- With few exceptions the rms repeatability is of the order of 5–10 mm for the horizontal coordinates and of the order of 15–30 mm for the height. These values would probably be acceptable in most cases in practice.
- The gain in quality, when processing the data in the network-, as opposed to the baseline-mode was about 1.3. This may be expected because one may easily show that the rms error σ_{new} of the user position may be computed in the following way as a function of the rms of observation σ_{obs}:

$$\sigma_{new} \sim \sigma_{obs} \cdot \sqrt{\frac{n+1}{n}} \qquad (1)$$

The case $n = 1$ corresponds to a baseline-specific processing, $n \to \infty$ corresponds to the best possible case. This explains the gain of 1.3 mentioned above (with $n = 6$).

- IGS precise orbits gave repeatabilities better by a factor of about 1.5–2 when compared to broadcast orbits. IGS predicted orbits did not give better results than broadcast orbits.
- 5-minute data pieces are not sufficient to solve for tropospheric parameters *and* station coordinates.

For a common user of AGNES it will be absolutely essential to resolve the ambiguities with short data pieces (one epoch to fifteen minutes). There are many degrees of freedom "in this game," however. Let us mention a few of them:

- One parameter is the baseline length. We performed tests using the data of the 1999 campaign. The baselines Zimmerwald-Wabern (6 km), Zimmerwald-Thun (17 km), and Zimmerwald-FHBB (74 km) were analyzed using 5-minute data pieces for the two short and 15-minute pieces for the long baseline.
- We may use different LCs and phase/code combinations. We used phases only and processed L1 and L2 simultaneously (FARA method).
- We may or may not introduce epoch- and satellite-specific stochastic ionosphere parameters; if we do so, we may vary the a-priori variance.

Already this (very much reduced) list shows that a thorough analysis would contain an exorbitant number of test runs. Our results may be summarized briefly as follows:

5.1 6-km Baseline Zimmerwald-Wabern

Using 5-minute data pieces and a cut-off angle of 15^o, most tests lead to a safe resolution of L1 and L2 ambiguity parameters. It was not necessary to introduce stochastic ionosphere parameters. Even broadcast orbits were sufficient to resolve the ambiguities. From 132 possible 5-minute intervals 131 could be successfully resolved, one was rejected. The result is as expected. If a user is operating at a distance of less than 10 km to a reference site, he is best advised to use the data of this station without any modification.

5.2 17-km Baseline Zimmerwald-Thun

Tests without setting up stochastic ionosphere parameters were still quite successful: from 143 possible 5-minute intervals only between 5 and 20 could not be resolved. 20 failures were reported, when the global ionosphere maps were not used. This clearly demonstrates that a good ionosphere model is a prerequisite for successfully resolving ambiguities on baselines longer than 10 km.

All ambiguities could be safely resolved when epoch- and satellite-specific stochastic ionosphere parameters were set up. 7 (correct) solutions were rejected when the a-priori ionosphere maps were not used. Even the least accurate orbits (broadcast) and the most trivial troposphere modeling technique (a-priori model based on standard atmosphere) proved to be sufficient for the job.

5.3 74-km Baseline Zimmerwald-Muttenz

After a few attempts, only tests with 15-minute data pieces were made. Even then, ambiguity resolution without introducing stochastic parameters was very problematic: failure rates up to 50% were common. This situation might be improved by absorbing part of the ionosphere signal by a linear, satellite-specific model.

The situation improved when stochastic ionosphere parameters were introduced. Success rates of well over 90%—even when the a-priori model for tropospheric refraction was used—let us believe that this technique is very promising in the context of AGNES.

It is interesting to note that Wanninger (1999) concludes that procedures including the estimation of (what we call) stochastic ionosphere parameters (and what he calls ambiguity resolution strategies for long baselines) have to be recommended even when using ionosphere-corrected RINEX data (corresponding to a virtual reference station). We come to similar conclusions. For ambiguity resolution on baselines longer than about 20 km, this option seems to be almost mandatory.

6 Modeling the Atmosphere Over a Ground Network

Which fraction of the *tropospheric* zenith correction and of the satellite-specific *ionospheric* delay can be absorbed by linear models in latitude β, longitude λ, and height h? Let us consider the two effects separately.

6.1 Modeling Troposphere Parameters

We analyze the station-specific troposphere parameters for the 1998 data set as they were gener-

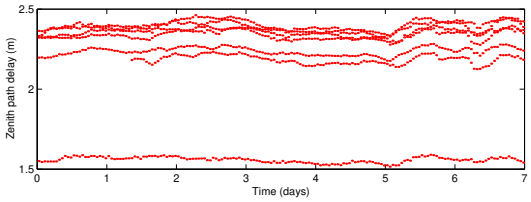

Figure 4. Hourly tropospheric zenith path delay estimates

ated by a network solution of type (1).

Figure 4 shows estimated zenith path delays for all stations and for every hour. The individual curves in Figure 4 correspond to the AGNES sites. The offsets are related to the station heights, the lowest curve corresponds to the highest, the Jungfraujoch site, the highest curve to the lowest site (Muttenz).

We have to address two issues:

- Question 1: What are the independent parameters? Obviously, we should use latitude β, longitude λ, *and* height h. We are sure, however, that we do not have enough stations to model the height dependency in an adequate way.
- Question 2: What quantity do we model as a function of our independent arguments? We decided to analyze

$$q = \frac{\Delta\rho_{trop}}{\Delta\rho_{trop,0}(h)} \qquad (2)$$

where $\Delta\rho_{trop,0}(h)$ are a-priori values stemming from an atmosphere model.

Our model reads as:

$$q = c_0 + c_\beta \cdot \Delta\beta + c_\lambda \cdot \Delta\lambda + c_h \cdot \Delta h + c_{h^2} \cdot \Delta h^2 \quad (3)$$

Table 2 characterizes the results of our tests. n_{par} is the number of parameters, f the degree of freedom (of an individual determination). The standard deviation σ_q of the quantity q is dimensionless. When multiplying this value with an average value for $\Delta\rho_0 \approx 2.2$ m we get an impression of the rms of the fit of the original zenith path delays.

From Table 2 we conclude that in the present realization phase of AGNES either a model of 3 or 4 parameters seems to be an optimum and that a fit on the 1-cm level, leading to height RMS errors of about 3 cm are achievable. Figures 5 and 6 show the estimated terms c_0 and c_β

Table 2. Solution types fitting the zenith path delay estimates

n_{par}	f	σ_q (1)/(mm)	Parameters
1	6	0.0085/17.8	c_0
2	5	0.0083/17.3	c_0, c_h
3	4	0.0076/15.9	c_0, c_β, c_λ
4	3	0.0056/11.7	c_0, c_β, c_λ, c_h
5	2	0.0041/ 8.5	c_0, c_β, c_λ, c_h, c_{h^2}

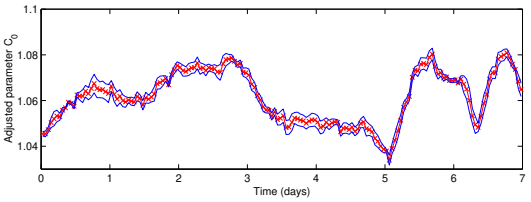

Figure 5. Estimated constant term c_0

(together with the associated rms band). They underline that a significant fraction of the tropospheric zenith delays may be absorbed by our models.

6.2 Modeling Ionospheric Refraction

After having reduced the ionospheric delay using global ionosphere maps (based on procedures developed by Schaer (1999)) the residual ionospheric (slant) delay must be analyzed separately for each satellite and for each epoch. This prevents us from modeling the entire ionosphere over the area of the network and allows us to consider at each epoch only a small portion of the ionosphere above the ground network. Thinking in terms of a single layer, we only have to consider an area of the size of the network in the ionospheric layer.

We made tests with the following linear model:

$$\Delta\rho_{ion} = c_0 + c_\beta \cdot \Delta\beta + c_\lambda \cdot \Delta\lambda \qquad (4)$$

where $\Delta\rho_{ion}$ is the ionospheric observable and c_0, c_β, and c_λ are the model parameters established separately for each epoch and each satellite.

First attempts estimating ionospheric gradient parameters c_β and c_λ showed that these parameters may absorb a significant part of the satellite- and epoch-specific biases. Nevertheless,

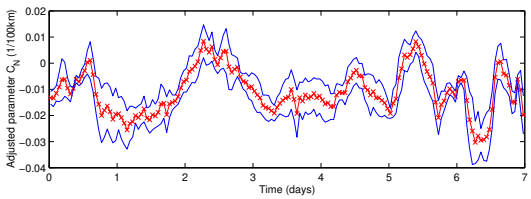

Figure 6. Estimated (North-South) gradient c_β

our investigation also revealed that the approach does not remove the entire signal. The WADGPS user thus cannot be advised to use solely the L1 observations (and to use L2 only for ambiguity resolution).

The result reported here is consistent with those given by other authors, e. g., Wanninger (1999).

7 Summary and Outlook

Two small portions of the observations stemming from the AGNES were analyzed. We studied the impact of atmospheric and orbit biases (a) on network solutions to be produced by the AGNES operator and (b) on the results a WADGPS user may expect from the AGNES.

We have seen that, despite the disappointing fact that the quality of code observations did not allow for an ambiguity resolution using the Melbourne-Wübbena LC, the wide-lane ambiguities can be safely resolved provided ionosphere maps are considered.

For narrow-lane ambiguity resolution, the orbit quality is a critical issue. Neither the broadcast nor the IGS predicted orbits are at present of sufficient quality for that purpose. We have argued that this problem will be resolved as soon as IGS orbits based on a sub-daily turnaround cycle will become available. We have also shown that simple orbit improvement schemes applied are well suited to cure the orbit problem.

For the AGNES user, tropospheric refraction is the ultimate accuracy limiting factor. Our study indicates that under normal conditions it should be possible, even in a mountainous environment, to model the tropospheric zenith path delay on the 1-cm level in real time. This would imply (sub-)cm accuracy in horizontal baseline components and 3–5-cm accuracy for the height estimates.

For ambiguity resolution using short data pieces, ionospheric refraction is the crucial element. The approach using pseudo-stochastic parameters is very promising. It remains to be seen by how much the ambiguity resolution performance is improved, if the information derived from the satellite- and epoch-specific models is used in the ambiguity resolution procedure.

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