Integrating NWP products into the analysis of GPS observables

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Abstract

The processing of the Global Positioning System (GPS) observables is regularly performed using some “a priori” standard meteorological values. These can be very unrealistic if only few observations are available since the actual atmospheric conditions over the geodetic network are neglected. This seems to be the case of randomly moving GPS receivers far from continuously observing reference stations, as geodetic coordinates and tropospheric parameters cannot be accurately estimated. More realistic initial values for the troposphere may be obtained from a Numerical Weather Prediction (NWP) model. Thus, the impact of the ingestion of NWP forecasts into the GPS data processing is analyzed for short time series in terms of the geodetic vertical coordinate. The non-hydrostatic MM5 model with boundary and initial conditions given by the ECMWF analysis is used to compute estimates of the zenith wet and dry delays. These modeling simulations are then ingested into the GPS data analysis of the GIPSY software package. First, this approach is applied to GPS data gathered at the UK permanent stations of the COST-716 first benchmark campaign where it is possible to estimate a stable 24 hour reference solution. Here, an improvement of about 60 % in the vertical coordinate bias is found. Still, the absolute accuracy cannot expected to be better than 1 decimeter due to the remaining mismodeling of the troposphere. Then, the modeling approach is applied to a kinematic analysis of GPS buoy data. In this case also a qualitative improvement is noticeable as demonstrated by a comparison with independent satellite radar altimeter data.

1 Introduction

The processing of observables from the GPS system is regularly performed using some "a priori" standard meteorological values (e.g., Leick, 1994). The atmospheric components are the Zenith Hydrostatic Delay (ZHD) and the Zenith Wet Delay (ZWD). The ZHD is the larger term (nominal value of 2300 mm at sea level) but can be accurately modeled if measurements of surface pressure are available (Saastamoinen, 1972). As a consequence, the ZHD strongly depends on the elevation of the GPS site. The ZWD has a smaller value (0-300 mm at sea level) and is associated with the distribution of the water vapor in the atmosphere (Bevis et al., 1994).

In the standard approach of the GPS data processing, the a-priori-values for the ZHD and ZWD variables are assumed independent of the atmospheric conditions over the geodetic network as well as independent of time. This may be a sufficient approximation for the ZHD component, which can be derived from a topographic model if ground pressure measurements are not available (Cucurull et al., 2001). The ZWD term, on the other hand, is very difficult to model because it is highly variable in space and time. Consequently, the use of time independent a-priori-values in the standard procedure may be unrealistic. Such a situation may occur in the processing of kinematic GPS data, where few observations are available and it is not always possible to make use of a close reference station to estimate the troposphere (e.g., Dodson et al., 1999).

The aim of this work is to study the impact of using predictions of NWP models in the GPS data processing instead of the regular a-prioris for short time series (1 hour) and under a stormy meteorological situation. While the GPS-derived estimates of ZHD and ZWD are commonly used to monitor and validate some aspects of NWP models (Cucurull et al., 2000), the simulations carried out with a NWP model can be used to assist in the GPS analysis procedure when not enough data is available to estimate both geodetic coordinates and tropospheric parameters.

In order to study the effect of injecting ZHD and ZWD values derived from an NWP model we firstly utilized GPS data from the COST Action 716 "Exploitation of ground-based GPS for climate and numerical weather prediction applications" benchmark test (e.g., Brockmann et al., 2001). Using ground-based GPS receivers instead of moving platforms facilitates the estimation of a stable solution obtained from a 24 hour data processing to be used as a reference solution when analyzing the short time series results.

The standard GPS processing is compared with the NWP modeling approach in terms of the repeatability of the vertical geodetic coordinates of the GPS stations. By carrying out the static comparison study we can assess the potential of NWP simulations to improve the kinematic analysis. The impact of the ingestion of model forecast into the GPS technique is then exemplified with a moving platform case.

The structure of the paper is as follows: Section 2 describes the experimental set up and the meteorological situation under study. The model simulations are briefly described in Section 3. The treatment of the GPS observations and a discussion of the results are given in Section 4. The main conclusions and future work are drawn in the last section.

2 Available GPS data and meteorological situation

From the entire GPS data set from the COST Action 716 which encompasses 47 stations, the fourteen stations of the United Kingdom were chosen (see Fig. 1). These coincide with stations of the national network of continuously operating GPS receivers for the UK (Dodson et al., 2000). All stations are equipped with either Ashtech Z-XII or Trimble 4000SSI dual frequency geodetic receivers and with choke ring antennas (cf. Table 1). The "raw" data are recorded at a 30 sec epoch rate and downloaded on a daily basis. The data are then archived in RINEX format (Dodson et al., 2000).

The actual benchmark test period was from 9 to 23 June 2000 (Brockmann et al., 2001). From this period the time span 10-14 June was selected in order to test the ingestion approach. The selection is due to the synoptic situation during these days. A frontal system crossed the GPS network during the campaign at around 12-14 June. The synoptic regime corresponding to this frontal passage can be observed in Fig. 2. A low pressure system seen in the North Atlantic on 12 June 2000 at 12 UTC moves eastward overpassing the area of interest on the following day. This low pressure system advected moist air as it approached the coast and the front brought steady precipitation to the area of the experiment, with heavy rain on 13 June.

3 NWP simulation

The NCAR/Penn State MM5 Modeling System [Anthes and Warner (1978); Dudhia (1993); Grell et al. (1994)] is used to simulate the ZHD and ZWD variables for the same region and time period. The MM5 is a primitive equation, finite-difference based non-hydrostatic mesoscale model.

We set up two (2-way nested) domains with grid distance ranging from 54 km down to 18 km. At the finest domain the grid dimensions are 70 grid points in the north-south direction, 61 in the east-west direction, and 24 vertical levels. The physical options used are the high-resolution Blackadar parameterization of the planetary boundary layer (PBL), multi-layer soil model, the simple scheme of Dudhia (1993) for explicit moisture parameterization, the USGS (U.S. Geological Survey) topography and land-use sources of 10 min, and the clouds are solved with the Grell scheme.

The initial and boundary conditions are provided by the ECMWF (European Center for Medium Range Weather Forecasts) analysis at 00 UTC from 10 to 14 June 2000 and all simulations are integrated for a 24 hour period. ZHD and ZWD values are calculated (15 min interval) at every GPS site.

The hydrostatic contribution is estimated from surface pressure modeling. We have used the bilinear interpolation in the horizontal direction to interpolate the ground pressure values from the grid points of the domain to the location of the GPS sites. A more accurate treatment is needed for the interpolation in the vertical in order to avoid a bias between the ZHD measured at the ground-based receiver and the modeled ZHD value caused by orographic effects. This is because the surface pressure strongly depends on the height of the GPS sites and these are not modeled correctly as is shown in Table 1. The table shows the elevation of the ground-based receivers and the corresponding values used in MM5. The differences are as large as 180 m which corresponds to around 4 cm of ZHD.

To interpolate vertically the pressure field from the model topography to the height of each GPS station, we have assumed an exponential dependence for pressure as a function of height. The method that we used yields average errors of the order of 1.0 to 1.5 hPa, which converts to around 3 mm of ZHD [De Pondeca et al. (2001); Cucurull (2001)].

The ZWD is obtained from the vertical integration of the specific humidity. Bilinear interpolation from the four closest grid point values is used in the horizontal. The resulting error associated to the ZWD varies from 1 to 2 cm.

4 GPS data processing and preliminary results

The GPS data were processed with the GIPSY (GPS Inferred Positioning SYstem) software package (Webb and Zumberge, 1993) using the precise point positioning approach (Zumberge et al., 1997). Three different strategies we employed in order to analyze the undifferenced dual-frequency carrier-phase and pseudo-range measurements (cf. Table 2).

In all three solutions the necessary estimates of the satellite clock corrections and orbits as well as consistent earth-rotation parameters were provided by JPL (Jet Propulsion Laboratory). The cut-off elevation angle was chosen to 10° and the estimation interval to 15 min. In case of estimating tropospheric parameters the Niell (1996) mapping function was used.

For the reference solution REFSOL the tropospheric delay was modeled as a random walk ($\sigma^2 = d^2 \cdot t$) with a drift rate of $d = 6$ mm/$\sqrt{\text{h}}$. The a-priori-values for the ZHD and ZWD correspond to the standard values of the GIPSY processing. In the solution GIPSOL hourly batches were solved for station coordinate and clock parameters, whereas the tropospheric parameters were not estimated, but rather taken as the GIPSY standard a-priori-values: the ZHD is alloted a value derived from a simple height dependent model, the ZWD a-priori is always set to 0.1 m. The solution MM5SOL, in turn, uses the 15 min tropospheric parameter time series derived from MM5 as tropospheric information. Again no tropospheric estimation is performed.

Fig. 3 shows the radial geodetic coordinate component estimated by the three different GPS data processing strategies for four arbitrarily chosen stations. The dotted line corresponds to solution GIPSOL, whereas the dash-dotted line depicts the radial coordinate estimated with the ingestion of NWP products (MM5SOL). The continuous line represents the reference solution REFSOL. The average (four days) biases and root-mean-square (rms) values of the differences between the radial geodetic coordinates using the two different approaches and the REFSOL solution are summarized in Table 3 for all 14 stations.

Using hourly batches in the solution strategy (GIPSOL, MM5SOL), the time series of the site elevation shows a high variability. The variability is less pronounced with the ingestion of MM5 derived ZHD and ZWD values (MM5SOL). The reference solution for the heights of the GPS sites (REFSOL) is derived from 24 hour processing. Here the impact of using or not using a-prioris from a NWP model is negligible as the number of observations is sufficient to resolve both geodetic coordinates and tropospheric parameters. (A test run with GIPSY including the MM5 derived ZHD and ZWD values in the 24 hour processing, yielded identical results as REFSOL.)

The average absolute bias of the hourly solution w.r.t. REFSOL decreases significantly (about 60%) when modeled values of ZHD and ZWD are included in the data processing. In general, the rms values also slightly reduce from the GIPSOL to the MM5SOL solution. The station Aberdeen (ABER) shows unrealistic high rms values (exceeding 5 m); single differences of the hourly solutions w.r.t. REFSOL obtain values as large as 40 m. Because the problem does not show up in the daily processing, there appears to be a problem with the hourly data processing.

The ZTD value increases for denser atmospheres and longer trajectories of the signal between the GPS satellite and the receiver. Thus, for an atmospheric profile denser than the one assumed in the a-priori-value of ZTD (for instance, due to a stormy episode associated with a large amount of moisture in the atmosphere) the estimate of the radial geodetic coordinate should intuitively be smaller in order to increase the trajectory and reproduce the observations. However we find from the table the opposite situation: MM5SOL is always (except Aberdeen) lower with respect to REFSOL, while GIPSOL is always higher with respect to REFSOL. The reason is that the above argument only holds true if the station clocks were perfect. As the receiver clocks need to be modeled as well, an increase in ZTD is absorbed both in the clock correction and in the radial coordinate component.

In order to better understand the nature of the error correlation of the tropospheric delay with the errors committed in the estimation of the radial coordinate component and the clock correction, we follow a simple model that was proposed by Claflin and Resch (1980). Their functional model states that the sum of the three error components vanishes:

$$\begin{aligned} \Delta\varrho(\mathrm{h}) + \Delta\varrho(\mathrm{clock}) + \Delta\varrho(\mathrm{trop}) &= 0 \\ -\Delta\mathrm{h} \times \sin\varepsilon + \Delta\varrho(\mathrm{clock}) + \Delta\mathrm{ZTD}/\sin\varepsilon &= 0 \end{aligned}$$

The model should be understood as a rough approximation that is based on the $1/\sin\varepsilon$ mapping function and thus degrades for low elevation angles ε. Rearranging the terms and introducing the variables $A = -\Delta\varrho(\mathrm{clock})/\Delta\mathrm{ZTD}$ and $B = \Delta\mathrm{h}/\Delta\mathrm{ZTD}$, yields the following equation:

$$A + B \times \sin\varepsilon = 1/\sin\varepsilon\ .$$

Fitting the two similar functions of the left and right hand side of the equation in a least squares sense, furnishes estimates for the variables A and B providing the sought for functional relationship.

Applying the above model to the elevation angle range $10^\circ \leq \varepsilon \leq 90^\circ$ in steps of 1° the following relationships are derived:

$$\begin{aligned} \Delta\varrho(\mathrm{clock}) &= -3.4 \times \Delta\mathrm{ZTD} \qquad \text{and} \\ \Delta\mathrm{h} &= -2.5 \times \Delta\mathrm{ZTD}\ . \end{aligned}$$

Accordingly, an error of 1 cm in ZTD corresponds to an error of -3.4 cm in the clock correction respectively

-2.5 cm in the height estimate, i.e., both the clock bias error and the station height error have the opposite sign w.r.t. the ZTD error.

In the case of fixing the tropospheric parameters to given values (GIPSOL and MM5SOL), the difference between the two ZTDs propagates into the height and the clock bias estimates according to the above given factors. For the case at hand, the average difference in ZTD roughly amounts to -0.16 m (GIPSOL–MM5SOL). The average difference between the height estimates (cf. Table 3) is about 0.44 m (GIPSOL–MM5SOL). This is in good agreement with the value of -2.5×-0.16 m $= 0.40$ m derived from the error model.

The average bias (four days) of MM5SOL w.r.t. REFSOL over all stations with the station Aberdeen being excluded amounts to about -0.132 m (cf. Table 3). Thus, the error that is caused by a mismodeling of the troposphere is in the range of 10 to 20 cm. Kinematic applications using NWP products as source for the tropospheric information can, thus, hardly be better than 10 cm.

In order to show an application of the ingestion of NWP products into the GPS data processing in a moving platform we focus on the processing of GPS data from a light-weight GPS buoy located in the Mediterranean Sea on 17 September 2000 (Cardellach et al., 2000) at 80 km from the nearest ground reference station.

Fig. 4 shows the sea surface height above the ellipsoid by using the standard a-prioris in the GPS data processing (dots) and the value given by the ingestion of the MM5 products (continuous line). In the standard approach, the tropospheric parameters are estimated as a random walk process with 1 hour intervals between updates. The vertical geodetic coordinate is estimated at 15 sec interval in both cases.

We note from the figure that the use of MM5 modeling simulations results in an improvement of the solution by around 0.17 m, when it is compared to the value obtained from the ERS altimeter (triangle) at 21.9 UTC. In the standard GPS data processing, there is not enough data to estimate correctly both the vertical coordinate and troposheric parameters and is useful to make use of better a-priori-values (e.g. NWP forecasts).

5 Conclusions and future work

We have used the ZHD and ZWD values modeled with the MM5 model to evaluate the impact of using NWP forecasts into the short time series analysis of the GPS observables. While in the standard procedure the a-priori-value of the ZWD is fixed in time, the use of a NWP model to provide this variable provides information on the small spatial and short temporal scales of variation of the atmospheric water vapor. This is of special interest for stormy meteorological events and for situations where few data is available and it may not be possible to estimate adequately the tropospheric parameters. The interpolation of the modeled ZHD to the location of the GPS sites also improves the values of this variable into the GPS data analysis.

We have selected fourteen stations of the COST-716 first benchmarch campaign (9-23 June 2000) due to the large amount of precipitation accumulated over the network during part of this period. This ground-based receivers analysis allows to compute a 24 hour reference solution. In addition, the impact of the ingestion of meteorological products into the GPS data processing is tested for a GPS buoy located in the Mediterranean Sea at 80 km from the nearest ground reference station.

Significant improvement (about 60 %) is found in the estimate of the vertical coordinate for 1 hour of GPS data processing when compared to the approach where the a-prioris are assumed to be time independent.

For the GPS buoy case, when fixing the troposphere to the NWP forecast, first results indicate an improvement of 10-20 cm in the vertical coordinate.

These are initial results of the application of NWP forecasts in the processing of the GPS observables based on a limited amount of data sets. Future work should extend the analysis to more study cases in order to be able to draw general conclusions on the impact of ingesting NWP products into kinematic GPS evaluation.

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Tables

Table 1. Continuously operating GPS stations for the UK (Calais and Ge, 2001) [Key: Z-XII3 (Ashtech Z-XII3), 4000SSI (Trimble 4000SSI), ASH (Ashtech ASH701945B_M), TRM (Trimble TRM29659.00)] and height values for the GPS stations [Key: h_GPS = ellipsoidal height of GPS station, H_GPS = orthometric height of GPS station, H_MM5 = orthometric height of MM5's 10 min topographic model]. Unit: metres.

Site name	Code	Receiver	Antenna	h_GPS	H_GPS	H_MM5
Aberdeen	ABER	Z-XII3	ASH	53.4513	3.1333	17.5
Aberystwyth	ABYW	Z-XII3	ASH	98.9817	44.5547	217.0
Barking	BARK	4000SSI	TRM	104.1528	58.3968	62.8
Cambourne	CAMB	Z-XII3	ASH	139.5708	86.2278	2.3
Dunkeswell	DUNK	Z-XII3	ASH	303.5625	252.3085	103.7
Hemsby	HEMS	Z-XII3	ASH	61.5884	16.9894	7.8
Lerwick	LERW	Z-XII3	ASH	131.3004	81.6304	20.4
Liverpool	LIVE	Z-XII3	ASH	66.0273	13.4683	22.3
Lowestoft	LOVE	Z-XII3	ASH	53.8260	9.1890	6.2
Newlyn	NEWL	Z-XII3	ASH	64.5499	11.0809	2.7
Nottingham	NOTT	Z-XII3	ASH	98.4324	49.3804	87.8
Teddingdon	NPLB	Z-XII3	ASH	74.2353	28.1443	67.5
Sheerness	SHEE	4000SSI	TRM	53.2823	8.1423	22.3
Sunbury	SUNB	4000SSI	TRM	65.1602	19.0142	66.7

Table 2. Analysis strategies used in the GPS data processing.

Solution	Characteristics
REFSOL	24 hour solution, estimation of troposphere
GIPSOL	1 hour solution, no estimation of troposphere, ZHD and ZWD as a-priori-values of GIPSY
MM5SOL	1 hour solution, no estimation of troposphere, ZHD and ZWD as derived from MM5

Table 3. Average (four days) bias and rms values of the vertical geodetic coordinates of the solutions MM5SOL and GIPSOL with respect to the reference solution REFSOL. Unit: metres.

Site name	MM5SOL		GIPSOL	
	bias	rms	bias	rms
Aberdeen	0.394	5.118	0.551	5.293
Aberystwyth	−0.038	0.131	0.316	0.163
Barking	−0.059	0.180	0.288	0.165
Cambourne	−0.145	0.139	0.321	0.192
Dunkeswell	−0.199	0.142	0.339	0.233
Hemsby	−0.139	0.136	0.298	0.208
Lerwick	−0.097	0.099	0.017	0.113
Liverpool	−0.172	0.188	0.329	0.199
Lowestoft	−0.175	0.173	0.347	0.209
Newlyn	−0.207	0.133	0.356	0.193
Nottingham	−0.126	0.127	0.392	0.220
Teddingdon	−0.206	0.132	0.393	0.233
Sheerness	−0.120	0.395	0.239	0.275
Sunbury	−0.037	0.213	0.301	0.197

Figure Captions

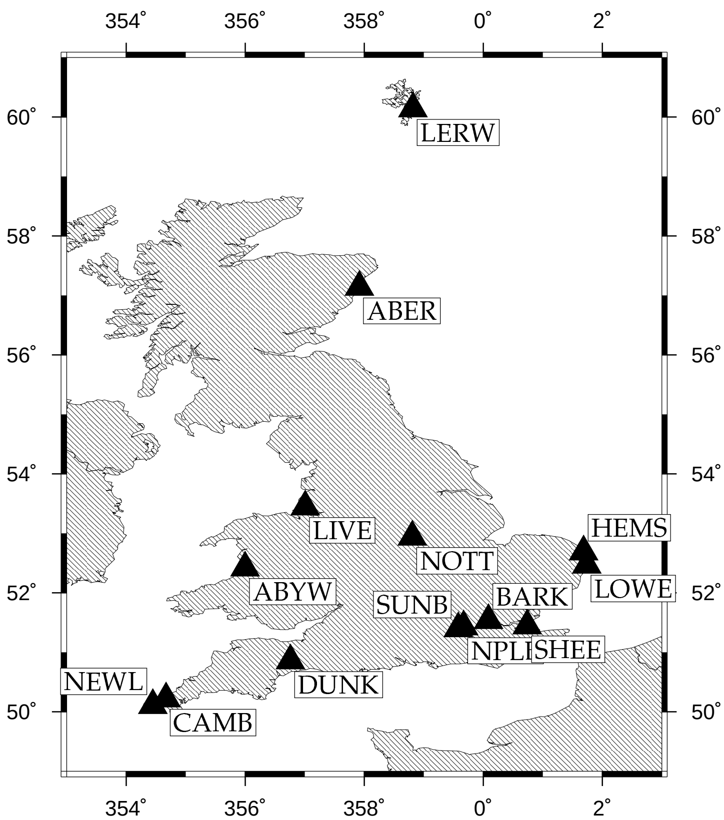
Fig. 1. Selected sites of the national network of continuously operating GPS receivers for the UK.

Fig. 2. Surface analysis (from The Met. Office, UK) of atmospheric flow for 06 UTC 13 June 2000.

Fig. 3. Time series of the radial coordinate component for four arbitrarily chosen stations derived from the different solution strategies: REFSOL (continuous line), GIPSOL (dotted line), MM5SOL (dash-dotted line). The corresponding calendar dates of the time series range between 10 and 14 June 2000.

Fig. 4. Sea surface height obtained by means of a GPS buoy and processed by using the standard a-prioris (dots) and the MM5 simulations (continuous line). The solution obtained from the ERS altimeter is shown as a triangle. Unit: meters above the WGS84 reference ellipsoid.

Figures



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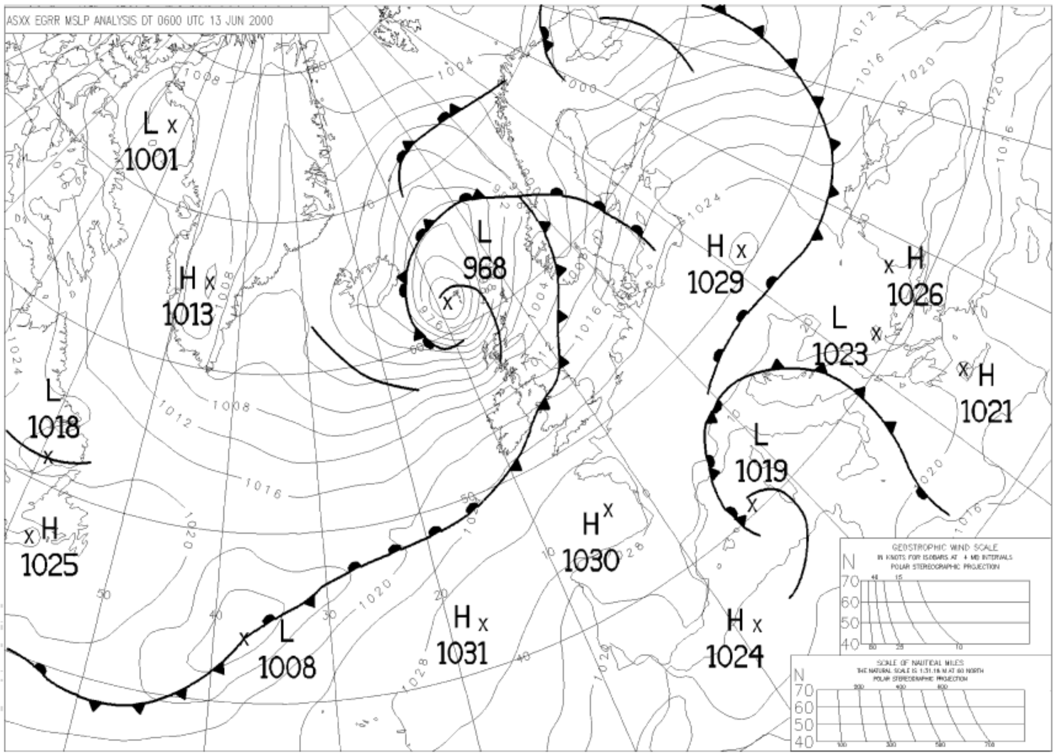

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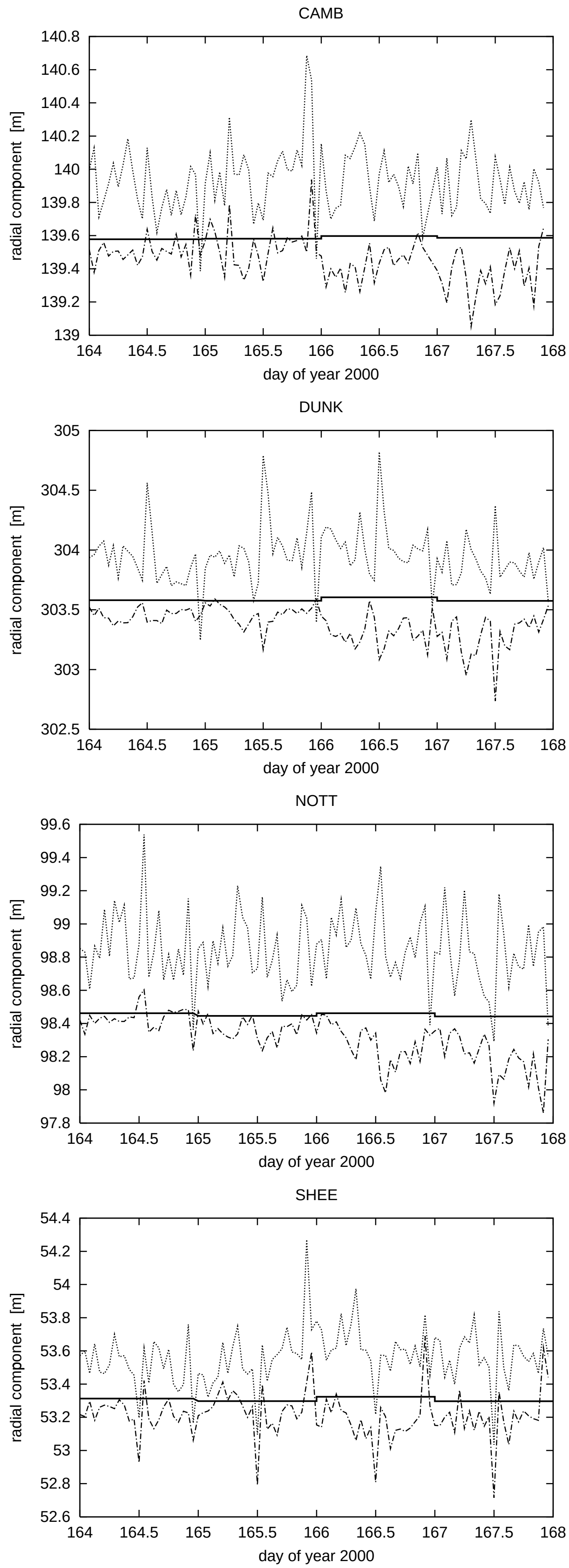

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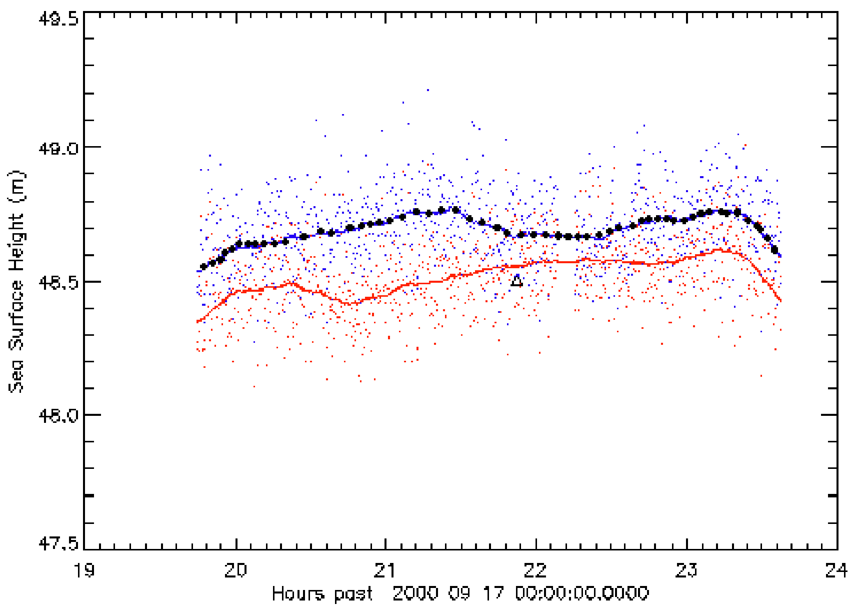

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