VALIDATION OF CENTIMETER-LEVEL SAR GEOLOCATION ACCURACY AFTER CORRECTION FOR ATMOSPHERIC DELAY USING ECMWF WEATHER DATA

Xiaoying Cong[1], M. Eineder[2], R. Brcic[2], N. Adam[2], and C. Minet[2]

[1]*Remote Sensing Technology, TUM, 80333 Munich, Germany*
[2]*Remote Sensing Technology Institute, DLR, Münchner Strasse 20 82234 Oberpfaffenhofen-Wessling, Germany*

ABSTRACT

In this paper, an alternative method to effectively compensate for the atmospheric delay in SAR images using 3D weather data is presented. Based on the absolute ranging method reported in Eineder et al. [1], we could also achieve centimeter-level pixel localization accuracy without having to rely on total zenith path delay (ZPD) information from the GPS station.

Key words: Electromagnetic refraction, tropospheric delay, geodesy, pixel localization accuracy, TerraSAR-X, SAR.

1. INTRODUCTION

As reported in Eineder et al. [1], absolute ranging with centimetre level accuracy can be achieved in TerraSAR-X images after correcting for 1) solid earth and ionospheric delay, both in the centimeter range and the 2) atmospheric delay of about 3 m in slant range due to wet air refractivity. The latter could be compensated for directly by using the total zenith path delay (ZPD) provided by the Regional Reference Frame Sub-Commission for Europe (EUREF) permanent GPS network. Unfortunately, this GPS network is quite sparse and in some regions, such as Africa and South America, not present. In order to accurately correct for atmospheric delay on a global scale another solution is needed.

To solve this problem, we have used the 3D global weather data available from the European Centre for Medium-Range Weather Forecasts (ECMWF) which is sampled every 6 hours and has 60 vertical layers (85 km). Since the atmospheric refractivity can be modeled as a function of temperature, air pressure and water vapor pressure provided by the atmospheric model Hanssen [2], the total ZPD can be found by integrating the atmospheric refractivity in each vertical layer from the bottom to the top of the atmosphere.

In order to validate the accuracy of the total ZPD obtained by using ECMWF data, a comparison was made with respect to that obtained from three GPS stations selected from the EUREF network with different climate conditions: 1) Bad Koetzting (WTZR) in Germany; 2) Borkum (BORJ) in Germany; 3) Kangerlussuaq (KELY) in Greenland. Over two years ECMWF entries were collected. The weather data was interpolated to the GPS location and the surface pressure was adjusted to GPS height. After integration along the zenith path, we compared the ECMWF ZPD with the EUREF GPS ZPD measurements taken at the nearest sample time. The ZPD obtained using the ECMWF atmospheric model hence shows good agreement with GPS ZPD measurements which is discussed in Section 3.

Afterwards, we repeated the experiments carried out at Fogo, Azores Portugal and in Venice, Italy as described in Eineder et al. [1], where the slant range delay (SPD) in the SAR image was obtained as described above using data from GPS stations. The ionospheric delay was also updated using freely available global ionospheric models CODE [3]. In this paper, instead of using the angle corrected ZPD from the GPS network, the range delay at the corner reflector was obtained by integrating along the line of sight to the sensor the refractivity obtained from the 3D atmospheric model. The validation results are discussed in Section 4.

2. INTEGRATION OF ATMOSPHERIC DELAY USING ECMWF WEATHER MODEL DATA

2.1. Atmospheric Propagation Delay

In the following equation (1), the zenith path delay L can be expressed as the integral of the air refractivity from Earth surface z_0 to the upper limit of the atmosphere z_{atmo}, as given in Hanssen [2] and Doin et al. [4]. The ionospheric delay effect and the cloud water content part are not discussed in this paper.

$$L = 10^{-6} \int_{z_0}^{z_{atmo}} \left(k_1 \frac{P}{T} + (k_2 - k_1) \frac{e}{T} + k_3 \frac{e}{T^2} \right) dz, \quad (1)$$

where P_d is the partial pressure of dry air in Pa, e is the partial pressure of water vapor in Pa, T is the ab-

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solute temperature in Kelvin. The constants are $k_1 = 0.776 KPa^{-1}$, $k_2 = 0.716 KPa^{-1}$, $k_3 = 3.75 \times 10^3 K^2 Pa^{-1}$.

To validate the delay effect using weather model data with SAR acquisitions, instead of the zenith integration path z, the slant range integration path for the acquisition geometry can be formulated by using the slant range $\vec{r} = [\cos t \sin\theta, -\sin t \sin\theta, \cos\theta]^T$ (θ: incidence angle, t: heading angle).

$$L_S = 10^{-6} \int_{r_0}^{r_n} \left(k_1 \frac{P}{T} + (k_2 - k_1)\frac{e}{T} + k_3 \frac{e}{T^2} \right) dr. \quad (2)$$

2.2. ECMWF Weather Model Data

For integration of atmospheric delay, the weather data from ERA-Interim re-analysis project has been used. ERA-Interim is the latest ECWMF global atmospheric reanalysis with several improvements Dee et al. [5]. This project will cover the period from 1989 to 2013. The internal data are defined as spherical harmonics with triangular truncation at wave number 255 (TL255) or as Gaussian data on a Quasi-regular N128 Gaussian grid which represents a horizontal resolution of about 80 km. 3-D weather data are generated four times per day at 0, 6, 12 and 18 h in 60 hybrid η-levels. The observation levels are based on the surface pressure field on the lowest level. The advantage of this representation is that the measurements follow the topography of the Earth surface, as represented in the numerical model. The temperature and the specific humidity are assimilated with weather model analysis on each level. The geopotential and pressure are defined in hybrid model based on the surface level Trenberth et al. [6].

For the validation with GPS ZPD measurements and with SAR acquisitions, it is necessary to interpolate these magnitudes. Horizontally, all weather parameters are interpolated to the 3-arc resolution (ca. 90m grid) of the Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) using a kriging method. Vertically, the parameters are interpolated on the external layer or at a given location with a certain height.

2.3. Cross-Validation Concept

In this paper, we use three independent data sources to generate the atmospheric delay, either in zenith direction or in slant range. SAR range measurements are similar to the GPS range measurement which also uses electromagnetic wave. So, the atmosphere, according to the equation (1), has the same delay effect on both range measurements. In this paper, we concentrate on the validation of atmospheric delay correction using numerical weather model data. The GPS ZPD measurements from the EUREF GNSS permanent network are treated

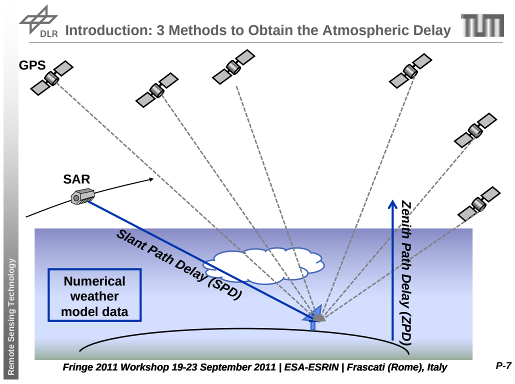


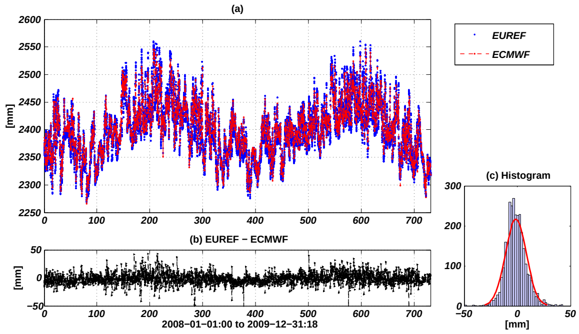
Figure 1. Cross-validation concept using GPS, SAR and numerical weather model data

as ”true” values. The first comparison is carried out between GPS ZPD and the ECMWF ZPD on the selected GPS station. Based on the absolute ranging technique reported in Eineder et al. [1], the atmospheric delay can be derived for a TerraSAR-X image by correcting effects such as solid Earth tides (SET) and ionospheric delay (ID). In the second comparison, two experiments using the TerraSAR-X stacks in Eineder et al. [1] are repeated with the ECMWF SPD.

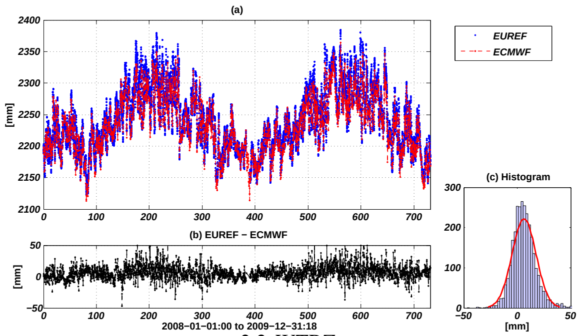
3. VALIDATION OF ECMWF ZPD USING GPS ZPD MEASUREMENTS

First, two GPS stations BORJ and WTZR from Germany are selected. BORJ station is installed on the sland of Borkum in the North Sea which is dominated by a oceanic climate. WTZR station is installed at the geodetic observatory and fundamental station Wettzell. The third, KELY, is installed in Greenland. The two-year atmospheric delays from 2008-1-1 to 2009-12-31 have been used for validation which are available in 30 min intervals. The GPS ZPD measurements are generated by the Federal Agency for Cartography and Geodesy (BKG) in Germany and the Center for Orbit Determination in Europe (CODE) in Switzerland. ECMWF weather data from the same period are collected and interpolated at each station location. The ECMWF ZPD are integrated from the station height to the upper limit of weather data. For comparison, the GPS ZPD are temporally interpolated to the ECMWF Interim analysis time. The comparison results are shown in *Figure 2*.

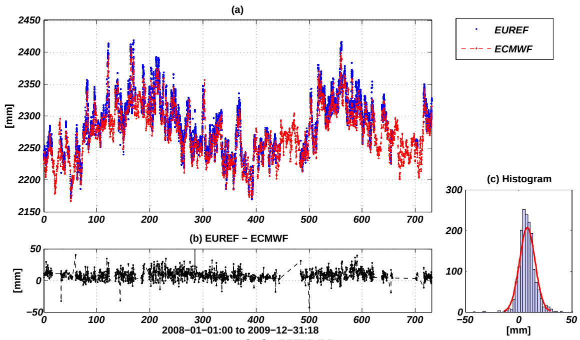
The ECMWF ZPD shows a good agreement with the GPS ZPD. According to the ECMWF integrations the mean ZPD of three stations varies from 2.23 m to 2.40 m and the total variation from 40.1 mm to 47.4 mm (see Table 3). Since the surface pressure and temperature decreases exponentially with the height see equation (1), the smallest ZPD of 2.23 m is measured at WTZR which has the highest elevation (666.0 m) compared with KELY (229.8 m) and BORJ (48.3 m). At BORJ the ECMWF ZPD has the largest variation due to the oceanic climate. In Table 3, the maximum standard deviation of the residual ZPD difference is about 12.7 mm at WTZR in summer



2.1 BORJ



2.2 WTRZ



2.3 KELY

Figure 2. Zenith path delay validation results of three GPS stations: (a) comparison of integrated ZPD from ECMWF weather data (red) with GPS ZPD from EUREF (blue); (b) difference between both ZPDs; (c) histogram of the ZPD differences.

time (2009). The minimum is 5.6 mm at KELY in winter time (2008). The average standard deviation of the three stations is about 8.9 mm, in summer 10.4 mm and in winter 7.5 mm. At KELY, several gaps of the GPS ZPD measurements have been observed. In this situation, the ECMWF ZPD can be used to obtain the atmospheric delay.

4. VALIDATION OF ECMWF SPD USING REPEAT-PASS RADAR IMAGES

In Eineder et al. [1], two experiments with TerraSAR-X acquisitions were presented. In the paper, the tropospheric delay (TD) was corrected by means of the GPS ZPD measurements from a nearby GPS station. In this section, we reprocess the two stacks of TerraSAR-X data by updating the atmospheric corrections using ECMWF weather model data.

Table 1. Mean value and standard deviation of ZPD measurements from ECMWF ZPD and GPS ZPD in millimeters.

	ECMWF ZPD		GPS ZPD	
Station	Mean	STD	Mean	STD
WTZR	2231.9	44.9	2238.9	47.6
BORJ	2399.6	47.4	2398.6	49.5
KELY	2272.5	40.1	2286.8	42.2

Table 2. Standard deviation of ZPD differences between ECMWF ZPD and GPS ZPD in 2008 W (winter), 2008 S (summer), 2009 W (winter), 2009 S (summer) in millimeters.

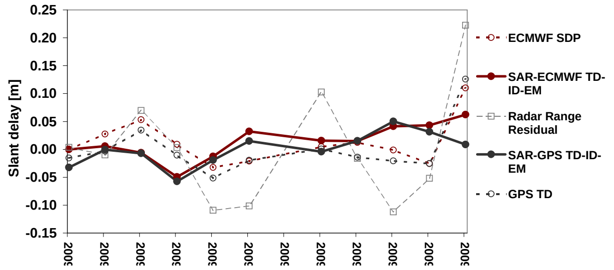
Station	2008 W	2008 S	2009 W	2009 S
WTZR	8.9	12.2	7.9	12.7
BORJ	7.9	11.7	8.1	10.4
KELY	6.4	7.9	5.6	7.7

4.1. Test site: Fogo, Azores

For this test site, two corner reflectors were installed in Fogo Volcano, Azores Island, Portugal during April to August 2009. 11 TerraSAR-X Stripmap datatakes were acquired. The absolute range offset was retrieved by means of the precise GPS location. In Eineder et al. [1], an accuracy of 2.6 cm has been achieved by applying the corrections of SET, ID and TD. Instead of using the TD from GPS ZPD, the slant range delay is integrated along the observation direction using ECMWF weather data. Both results are presented in *Figure 3*. The standard deviation of range offset using ECMWF SPD correction is 3.1 cm which is slightly worse than using the GPS ZPD correction. The GPS station PDEL in Ponta Delgada (Portugal), used for TD correction, is only 16.8 km away from installed corner reflector. Nevertheless the GPS ZPD measurements with 30 min interval are close to the acquisition time in comparison with the 6 h interval of ECMWF weather data.

4.2. Test site: Venice, Italy

For estimation of the relative range offsets, 22 TS-X High Resolution Spotlight (HS) datatakes during May 2008 to September 2009 were used in Eineder et al. [1]. The atmospheric delay is corrected with ZPD from the GPS station in Rovereto which is 114 km away. Therefore the atmospheric condition at the GPS station differs from the test site. After the corrections the standard deviation of the SAR slant range measurements is 3.8 cm in range. The atmospheric slant range delays are calculated for the center point of the scene from numerical weather model data. The standard deviation is reduced from 3.8 cm to



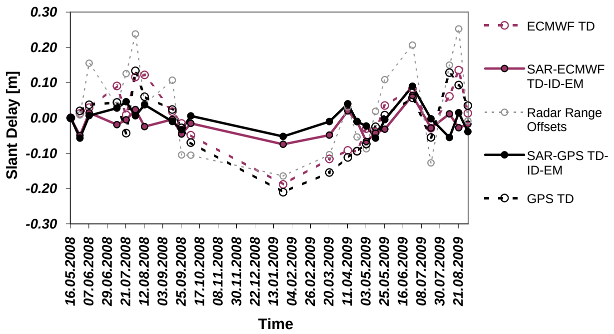


Figure 4. Cross-validation concept using GPS, SAR and numerical weather model data

3.2 cm by using the ECMWF SPD as well as the corrections of SET and ID. Furthermore, the outliers on 2009-05-14 and 2009-06-27 are reduced from -5.7 cm to -4.3 cm and from 9.0 cm to 6.4 cm (see *Figure 4*).

5. CONCLUSION

In this paper, we presented two independent ways to validate the atmospheric delay using ECMWF weather model data. Firstly, the GPS ZPD from EUREF permanent GNSS network was used as reference data. Three GPS stations with different climate conditions were selected as test sites. The comparison was carried out by using two-year entries from ECMWF weather data from 2008 to 2009. Total average discrepancy of three stations between two measurements is 8.9 mm, in winter is 7.5 mm and in summer 10.4 mm. Secondly, the atmospheric delays in the radar signal have been corrected for two stacks of TerraSAR-X acquisitions. A range accuracy of 3.2 cm was achieved at our test sites.

The atmospheric delay for a SAR image can be estimated using numerical weather model data which is useful for SAR geocoding, as well as for SAR interferometry in mountainous areas. However, the weather data is available only every 6 hours and at a coarse spatial resolution. As an improvement, a mesoscale weather model could be used to generate the real-time high resolution weather data with the help of assimilation methods.

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