HIGH PRECISION MEASUREMENT ON THE ABSOLUTE LOCALIZATION ACCURACY OF TERRASAR-X

Ulrich Balss[1], Xiao Ying Cong[2], Ramon Brcic[1], Moritz Rexer[2], Christian Minet[1], Helko Breit[1], Michael Eineder[1], and Thomas Fritz[1]

[1]Remote Sensing Technology Institute (IMF),
German Aerospace Center (DLR),
D-82230 Wessling, Germany

[2]Technical University Munich (TUM),
D-80333 Munich, Germany

ABSTRACT

The German SAR (synthetic aperture radar) satellites TerraSAR-X (TSX-1) and TanDEM-X (TDX-1), launched in June 2007 and June 2010 respectively, provide an unprecedented geometric accuracy. Previous studies showed an absolute pixel localization for both sensors at the centimeter level [4] [5] [6]. However, recent measurements show that in range, under extraordinary good conditions, a location accuracy of even a few millimeters seems to be attainable. While on a long-term scale, we observed a slow variation of subsequent measurements; on a short-term scale, they coincided to within a few millimeters. The measurement series will be continued. The cause of the long-term variation is the subject of current investigation.

Index Terms— Synthetic aperture radar, TerraSAR-X, absolute localization accuracy, imaging geodesy

1. INTRODUCTION

The German SAR satellites TSX-1 and TDX-1, launched in June 2007 and June 2010 respectively, outperform former civilian space-borne radar sensors in terms of geometric accuracy. Since 2010, each satellite supports the TerraSAR-X mission equally. In contrast, the bistatic interferometric TanDEM-X mission uses both satellites' resources at once. With the high geometric accuracy of both satellites, the geolocation of ground targets has to accurately consider signal propagation effects and geodynamic effects such as solid earth tides and the continental drift which were formerly negligible [1] [2] [3]. Previous studies which took these effects carefully into account showed an absolute pixel localization at the centimeter level for TSX-1 and TDX-1 [4] [5] [6]. However, recent measurements show that in range, under extraordinary good conditions, a location accuracy of just a few millimeters seems to be feasible. Here, we present our measurement results.

2. MEASUREMENT METHOD

Radar systems indirectly measure geometric distances by means of the travelling time of radar pulses from the radar transmitter to ground and back to the radar receiver. Usually, the conversion from travelling time to geometric distance refers to the vacuum velocity of light. However, electrons in the ionosphere, dry air and water vapor in the troposphere introduce additional signal delays which have to be taken into account. At the level of geometric accuracy of the TerraSAR-X mission, geodynamic effects like solid earth tides and continental drift shift the true position of a ground target by several centimeters over the course of a day or years, respectively [1].

In order to verify the pixel localization accuracy of TSX-1 and TDX-1, the radar range and azimuth times of corner

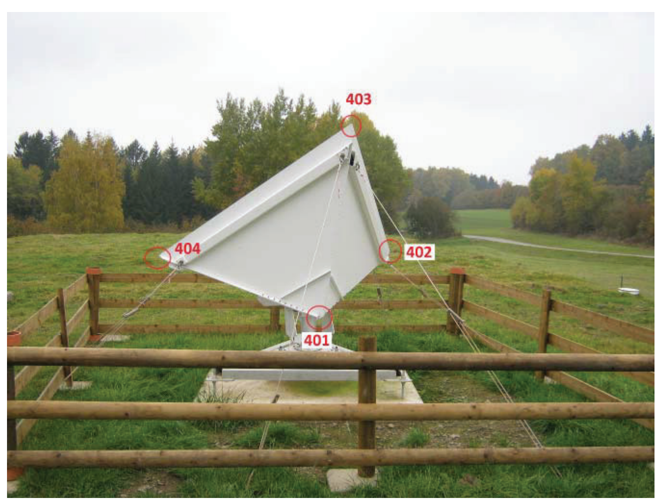

Figure 1: Corner reflector at the geodetic observatory Wettzell, Germany.

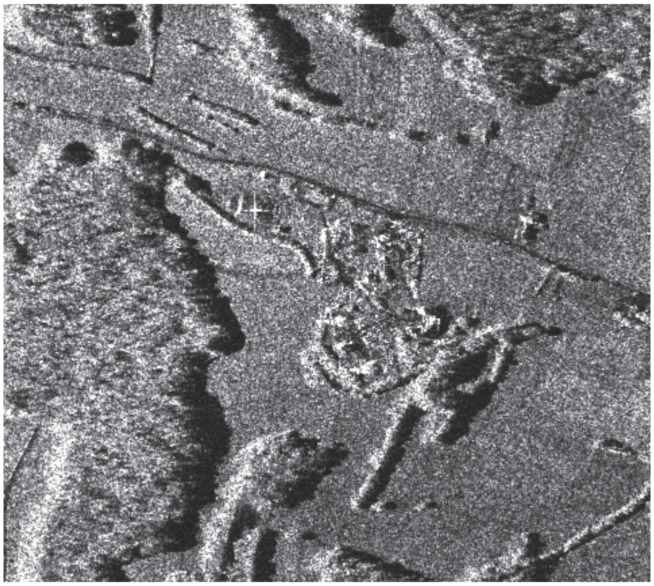

Figure 2: Close-up of the Wettzell corner reflector imaged by TerraSAR-X.

reflectors in focused SAR images are compared with their expected values obtained from precise GPS measurements of their positions and estimated propagation delays. The conversion of the spatial GPS coordinates into expected radar time coordinates is based on zero Doppler equations [7] and orbit interpolation of the satellite's position during acquisition.

Our recent measurement series is based on a trihedral corner reflector with 1.5 meters edge length which we installed at the geodetic observatory at Wettzell, Germany (see Figure 1 and Figure 2). Thus, we benefit from the very close distance (about 240 meters) to the local EUREF [8] GPS reference station. The ground position of the corner reflector which is defined by its phase center (see Figure 1, point number 401), is known very precisely (<1 cm) relative to the reference station from terrestrial geodetic measurement methods. The transformation of the position, given in the local station reference system, into ITRF 2008 (International Terrestrial Reference Frame) positions at TerraSAR-X measurements epochs, which are needed in order to retrieve the expected radar time coordinates, takes station movements and solid earth tides into account. Here, official ITRF station velocities provided for the geodetic observatory in Wettzell and state of the art earth tide models [9] are used.

Further, the GPS station provides precisely measured values of the zenith path atmosphere delay at the station height hourly [10]. We just have to project the measured zenith path delay onto slant range. In contrast, a corner reflector which is far away from the station would necessitate additional information from weather model data in order to estimate the tropospheric delay in slant range at the position of the corner reflector [6].

The ionosphere was modeled as a shell concentrated at a height of 400 kilometers. Using orbit information, the geographic coordinates of the ionospheric pierce point, the point at which the line of sight connecting the sensor to a point within the scene intersects with the shell, was determined. This was done for a 10×10 grid spaced uniformly over the scene. For each grid point the TEC (Total Electron Content) was retrieved by interpolating the freely available TEC maps from CODE (Center for Orbit Determination Europe) [11]. The TEC values were then converted to slant range by multiplication with the ionospheric mapping function $M=1/\cos(\theta_{inc})$ where θ_{inc} is the incidence angle with the ionosphere. Finally, the grid of STEC values was interpolated at the known position of the corner reflector within the scene and converted to a delay in meters using the formula $40.28 m^3/s^2 \times STEC / f^2$ with f being the radar carrier frequency.

Since the ionosphere is actually distributed between approximately 100-1000 kilometers, the TEC seen by a radar signal is less than that calculated above. Using the IRI-2007 model (International Reference Ionosphere) [12] which describes the electron density versus height, the fraction of the ionosphere below TSX-1's orbit height of 514 kilometers was found to be somewhat less than 80%. A regression analysis of the estimated ionospheric delay against the range measurements after correction for all other factors yielded a best fitting weight of a little more than 75%. A weighting factor of 75% was used here.

On the one hand, we now have the precise ground position of the corner reflector and we precisely know the signal propagation delays. Based on this, we can compute the expected radar time coordinates. On the other hand, we also have to precisely measure the actual radar position of the corner reflector in the focused SSC (single-look, slant-range complex) SAR images with sub-pixel accuracy. Here, we use a two-stage measurement method. In the first stage, we select a measurement patch around the imaged corner reflector, oversample it in both dimensions, azimuth and range, by spectral zero-padding by a factor of 32 and detect the integer position of the intensity maximum in the oversampled patch. In the second stage, we select 3×3 pixels from the oversampled patch and based on them, we apply a 2-D parabola interpolation in order to refine the sub-pixel position measurement. The measured sub-pixel coordinates can be easily transformed to radar time coordinates based on the TerraSAR-X product annotation [13].

The accuracy of the proposed two-stage method was estimated by a series of measurements performed with increasing oversampling of 8, 16, 32 … 512 in the first stage. We observed consistent location results differing by less than 1/10000 pixel if the oversampling is at least 32. Even a coarse oversampling of 8 or 16 results in a difference of less than 1/1000 pixel compared to more exact

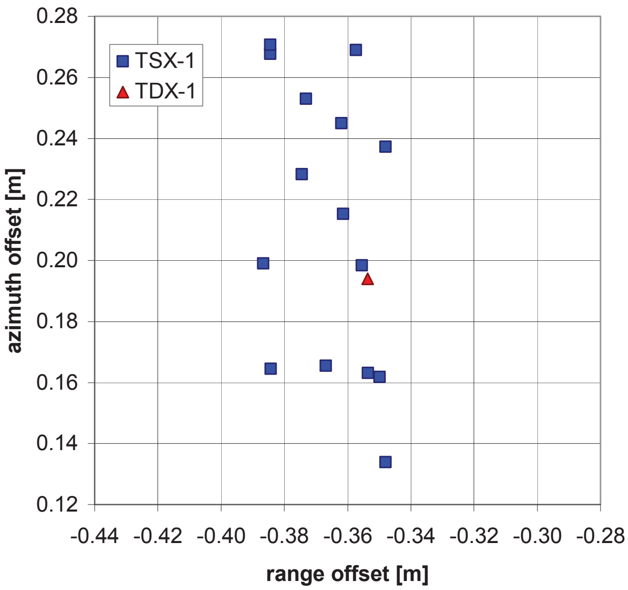

Figure 3: Pixel localization error of TerraSAR-X based on the Wettzell corner reflector.

measurements. Thus, we conclude that oversampling by 32 is sufficient in combination with the second stage 2-D parabola interpolation which actually boosts the accuracy. Aiming at such high resolution by pure oversampling would be barely manageable due to its huge memory requirements and computational effort.

3. MEASUREMENT RESULTS

Up to now, the measurement series is based on 16 TerraSAR-X datatakes of the Wettzell test site which were recorded between July 12, 2011 and May 4, 2012. 15 datatakes were acquired by TSX-1 but only one by TDX-1. In the first stage of this project, we intentionally focused on only one sensor to avoid possible unknown systematic differences. Nevertheless, Figure 3 shows the measurement results for both satellites.

The geodynamic effects and signal propagation delays, which we compensated for in the measurement, are characterized by their statistical parameters which are listed in Table 1. With regard to its absolute value, the tropospheric signal propagation delay is by far the dominant effect. In average, it amounts about 2.70 meters, while the mean values of the other effects in consideration are below one decimeter. A predominant part of the tropospheric delay is attributed to the dry air at average air pressure while the variation in delay caused by varying air humidity and varying air pressure is much lower.

However, a thorough consideration of the varying amount of all geodynamic effects and signal propagation delays significantly decreases the spread of results in a localization measurement series [4]. In this respect, the standard deviation of the effect under consideration

Table 1: Statistics of the applied geodynamic and signal propagation corrections in meters. The abbreviations mean: corr.: kind of correction, CD: continental drift, SET: solid earth tides, TD: tropospheric delay, ID: ionospheric delay, Σ: sum of all corrections, dim.: dimension, az: azimuth, rng: range.

corr.	dim.	min	max	mean	σ
CD	az	0.0000	0.0094	0.0049	0.0030
	rng	0.0000	0.0099	0.0052	0.0032
SET	az	-0.0453	0.0064	-0.0110	0.0174
	rng	-0.0438	0.1458	0.0780	0.0556
TD	rng	2.6285	2.8019	2.6986	0.0588
ID	rng	0.0278	0.1088	0.0686	0.0234
Σ	az	-0.0453	0.0158	-0.0061	0.0198
	rng	2.6125	3.0663	2.8518	0.1372

determines the relevance of the respective correction. Here, the range effect of solid earth tides is on par with the tropospheric delay. Both are the most prominent effects, each with about 5-6 centimeters standard deviation. However, the standard deviations of the ionospheric delay in range and of the solid earth tides in azimuth are also at the centimeter level.

Within the duration of the hitherto existing measurement series, the continental drift has had the least effect on the measurement result, causing a shift of about 1 centimeter in both azimuth and range. However, while all other effects taken into account vary around a certain mean value, continental drift is the only effect that increases linearly with time and will eventually become the dominant effect.

With the very accurate measured values of the signal propagation delays and exact knowledge of the ground position of the corner reflector, we obtain a pixel localization accuracy (1σ) for TSX-1 of 46 millimeters in azimuth and 14.3 millimeters in range. However, there is a strong temporal correlation between the measured range location errors as can be seen in Figure 4. A visual inspection of the temporal progression reveals that a good portion of the standard deviation results from a slow variation, perhaps due to seasonal variation of the measured range offset. Its development will be followed with continuation of the measurement series. In contrast, almost all immediately neighboring measurement values typically differ by millimeters. Thus, on a short-term scale, our recent measurements point to a much better localization accuracy for TerraSAR-X than is known from our previous investigations [4] [6].

Based on the visual impression of Figure 4, one might subdivide the plotted values into three clusters. The first one encompasses datatakes from the beginning of the measurement series until the end of September 2011. The

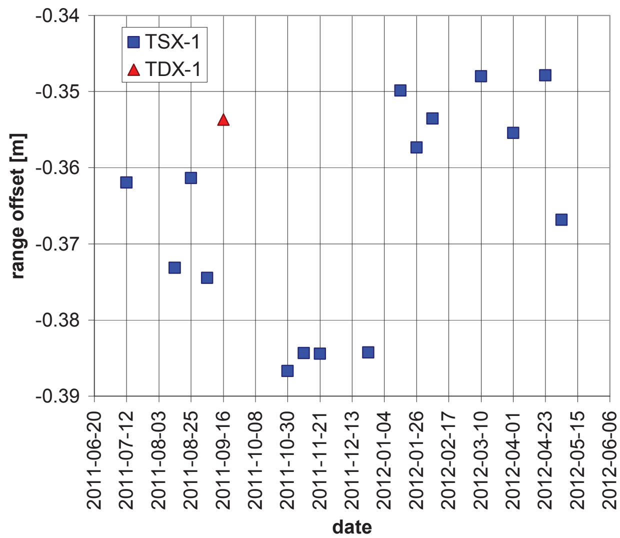

Figure 4: Temporal progression of the pixel localization error in range direction. The axis of ordinate is plotted on a scale of 1:1.

second cluster continues till the end of 2011 while the remaining datatakes belong to the third one. Performing a separate statistical analysis for each cluster in turn gives a standard deviation in the range offset of just 7.0, 1.2, and 6.7 millimeters for the first, second and third cluster, respectively.

4. CONCLUSIONS

The measurement series started on July 12, 2011 will be continued in order to verify the recent measurement results of the localization accuracy. The cause of the observed long-term variation in the measurement results has to be studied. Moreover, the stability of the instrument, the orbit accuracy and applied atmospheric correction values will be investigated. The worldwide reproducibility of the achieved performance may depend on unknown orbit accuracy variations. This will be analyzed by setup of comparable high precision test sites in the world. Geometric instrument calibration will substantially benefit from including such measurements which leads to a new class of calibration accuracy.

5. ACKNOWLEDGMENTS

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