Precise Measurements on the Absolute Localization Accuracy of TerraSAR-X on the Base of Far-Distributed Test Sites

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Abstract

Space-borne SAR is known for its ability to provide weather and time of day independent observation of the earth's surface and measurement of relative shifts based on the carrier phase (SAR interferometry). In contrast, our objective is the absolute pixel localization of a SAR image. Our previous studies demonstrated the unprecedented localization accuracy of the German SAR satellites TerraSAR-X (TSX-1) and TanDEM-X (TDX-1) at the centimeter level on the base of a repeat-pass measurement series. Now, in the next stage of our project, the world-wide reproducibility of these results and possible angular dependencies shall be investigated.

1 Introduction

The German SAR satellites TerraSAR-X (TSX-1) and TanDEM-X (TDX-1), launched in June 2007 and June 2010, respectively, provide an unprecedented localization accuracy at the centimeter level [1][2]. In our previous studies on base of a corner reflector with very precisely known geodetic position which we installed at the Geodetic Observatory at Wettzell, Germany, we found that after thoroughly correcting the measurements for all signal propagation delays and geodynamic effects like tides, loadings and plate movements, the measured location of the corner reflector in repeat-pass datatakes coincides by about 1 centimeter [3][4].

In order to prove the world-wide reproducibility of our measurement results, we setup two further test sites with two and one corner reflectors, respectively, in other parts of the world: GARS O'Higgins at the Antarctic Peninsula and Metsähovi in Finland. In order to investigate also possible angular dependencies, each corner reflector is recorded from up to three neighboring orbit tracks and therefore as much different incidence angles.

2 Location Measurements by SAR

Radar systems indirectly measure geometric distances by means of the two-way travel time of radar pulses from the radar transmitter to ground and back to the radar receiver. Usually, the conversion from travel time to geometric distance refers to the vacuum velocity of light. However, electrons in the ionosphere, dry air and water vapor mainly contained in the troposphere introduce additional signal delays which have to be taken into account. While the amount of the tropospheric delay in TerraSAR-X range measurements lies between 2.5 and 4 meters, the ionospheric delay amounts several centimeters up to a few decimeters.

Moreover, geodynamic effects shift the true position of a ground target. The most prominent effects are solid earth tides and the plate tectonics which cause a shift up to a few decimeters over the course of a day or years, respectively. The atmospheric pressure loading and the ocean tidal loading weigh on the tectonic plate and their variation shifts the target position by several millimeters each. Pole tides are due to the precession of the axis of the earth. Their amount varies also at the millimeter level. Even weaker effects are caused by ocean pole tides and atmospheric tidal loading.

As these effects are likewise relevant for the global navigation satellite system (GNSS), GNSS and the International GNSS Service (IGS) provide local correction values for the atmospheric delays [6][7][8]. The used correction values for the geodynamic effects are based on

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the IERS (International Earth Rotation and Reference Systems Service) conventions [9].

3 Verification of the Pixel Localization Accuracy of SAR

In order to verify the pixel localization accuracy of a SAR system, the range and azimuth times of corner reflectors in the focused SAR images corrected for the estimated propagation delays and geodynamic effects are compared with the expected values obtained from precise on-ground measurements of their positions (see also [10]). The conversion of the spatial geodetic coordinates into radar time coordinates is based on the zero-Doppler equation [11] and the interpolation of the satellite's position.

On July 12, 2011, we set-up our first measurement series based on a 1.5 meters trihedral corner reflector in Wettzell (**Figure 1a**). As we benefit from the very close distance (about 240 m) to the local IGS reference station, the ground position of the reflector is known very precisely (<5 mm) relative to the reference station's coordinates from terrestrial geodetic survey. In order to investigate possible angular dependencies of the measured position offsets, we started a second measurement series of this corner reflector with the same orbit direction (ascending) but moderately different incidence angle (46 instead of 34 degree) at March 2, 2013. As any change in the orientation of the corner reflector would move the position of its phase center and therefore invalidate its precisely measured geodetic coordinates, we left the reflector unchanged and accept a slight reduction in the radar cross section by about 2 dB.

In December 2013, we installed a second 1.5 meter trihedral corner reflector at Wettzell. Oriented for descending orbits and regularly imaged with 33, 45 and 54 degrees incidence angle, it enlarges the variability of acquisition geometries at this test site. While the datatake acquisition immediately started, the determination of its geodetic ground coordinates is still in progress.

Since March 2013, there are two 0.7 meters trihedral corner reflectors at our second test site, near to DLR's receiving and research station GARS O'Higgins (**Figure 1b**). The either one is imaged from 3 neighboring ascending orbits with 30, 38 and 45 degree incidence angle, respectively. In contrast, the other one is imaged from descending orbits (with 35 and 42 degree incidence angle, respectively). The datatake acquisition started on March 27, 2013. Like Wettzell, there is also an IGS reference station at GARS O'Higgins, and therefore the geodetic coordinates of the corner reflectors' phase centers shall be determined in the same manner and as precise as in Wettzell. This is scheduled to take place together with the renewal of the local ties. Originally, the geodetic survey was planned for early 2014 but unfortunately, it had to be delayed by another year.

At our third test site, Metsähovi, (**Figure 1c**), one 1.5 meters trihedral corner reflector oriented for descending orbits (35 degrees, but also visible from the neighboring orbit tracks with 27 and 46 degree incidence angle) was installed in October 2013 and the ground position of its phase center was determined relative to the coordinates of the local IGS reference station by terrestrial geodetic survey. The regular datatake acquisition of this test site started on November 4, 2013.

4 Measurement Results

At the Wettzell test site, both satellites, TSX-1 and TDX-1, acquired up to now 52 datatakes of the first corner reflector (in both ascending geometries) and 27 datatake of the second corner reflector (in all descending geometries). **Figure 2** shows the offset between measured and expected radar coordinates of the first reflector after the correction for the signal propagation delays and geodynamic effects. For convenience, the radar times are converted to spatial distances. As already discussed in [3] and [4], there is a bias of about 31

Figure 1: Our test sites: **a**: Wettzell (Germany), **b**: GARS O'Higgins (Antarctic Peninsula), **c**: Metsähovi (Finland)

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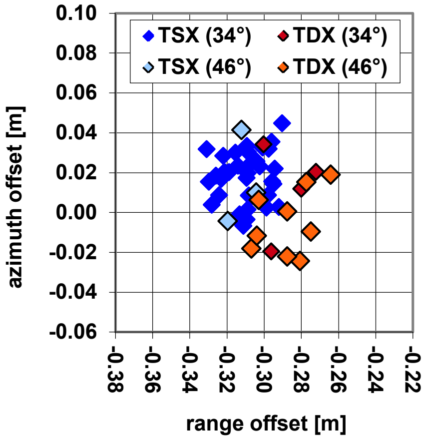

Figure 2: Difference between SAR and GNSS coordinates at the Wettzell test site in radar geometry

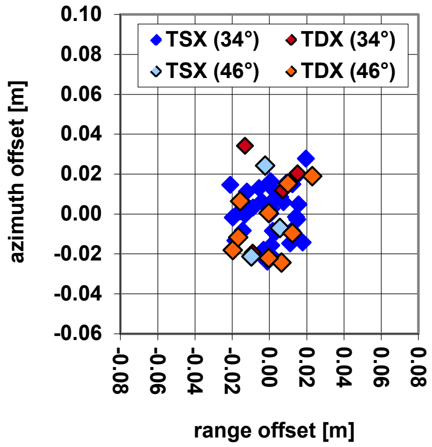

Figure 3: dto. after redetermination of the geometric calibration constants

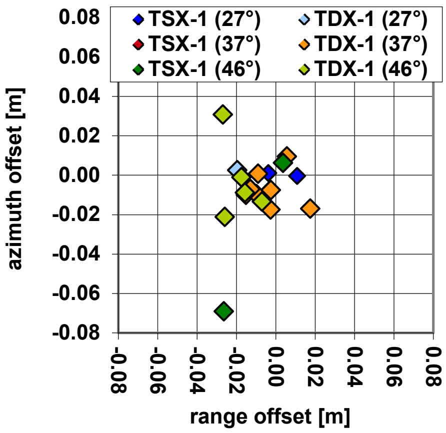

Figure 4: Difference between SAR and GNSS coordinates at the Metsähovi test site in radar geometry

centimeters in range which is due to the fact that in contrast to our measurement series the original geometric instrument calibration constants were determined on the base of a simplified model for the atmospheric delays and therefore still contain some atmospheric information. In order to overcome this incompatibility, we determined new calibration constants based on solely this corner reflector and apply them to all of our measurements at all of our test sites. Doing so, there results the plot in **Figure 3** for the first Wettzell reflector. On the base of both acquisition geometries and both sensors, we obtained a localization accuracy (1σ) of about 15 millimeters in azimuth and 12 millimeters in range.

The world-wide reproducibility of the obtained results and in particular the global validity of our redetermined geometric calibration constants shall be proven on the base of our other test sites. Because Metsähovi is at present the only test site outside Wettzell where we have independent ground coordinates from geodetic survey, the focus of our current analysis has to be on this test site. Up to now, 19 datatake were recorded in the different acquisition geometries and by both satellites. The distribution of the position offset between measured and expected position of the corner reflector is plotted in **Figure 4**. As can be seen, there is no coarse difference to the Wettzell measurement results. The absolute bias between the measurement series from both test sites is at the millimeter level: 7 millimeters in azimuth and 9 millimeters in range. However, one has to consider that even the measurement accuracy of the geodetic reference coordinates is limited to the millimeter level so that it may significantly contribute to the measured position offset. The standard deviation of the Metsähovi measurement series amounts to 19 millimeters in azimuth and 13 millimeters in range.

In GARS O'Higgins, 116 datatakes were acquired up to now. As we have no geodetically determined ground coordinates of the local corner reflectors as yet, we currently use an intermediate workaround for first analyses. On the base of a subset of our SAR acquisitions, we determined preliminary reflector coordinates by Stereo SAR. We described this method in [12]. Even if this approach provides no information on the absolute bias between the Wettzell and GARS O'Higgins measurement series since we use our datatakes for both, coordinate determination and verification, we already get evidence on the spread of the measurement results at GARS O'Higgins. On the base of this preliminary analysis, the obtained standard deviation for all datatake of both local corner reflectors amounts to 26 millimeters in azimuth and 16 millimeters in range.

Table 1 summarizes the obtained position offsets from all of our test sites. The biggest standard deviations occur for those corner reflectors where we have as yet only preliminary ground coordinates. But even there, it amounts to less than 2 centimeters in range and less than 3 centimeters in azimuth.

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Test site	Orbit direction	Azimuth offset [mm]	Range offset [mm]
Wettzell	Asc	**0 ± 15**	**0 ± 12**
	Dsc	*-14 ± 29*	*-7 ± 12*
GARS O'Higgins	Asc	*-18 ± 22*	*-10 ± 16*
	Dsc	*+8 ± 25*	*-1 ± 15*
Metsähovi	Dsc	**-7 ± 19**	**-9 ± 13**

Table 1: Obtained offset between measured and expected positions of the different corner reflectors. Results on base of geodetically determined reference coordinates are printed in **bold** while preliminary results, where the reference coordinates are based on StereoSAR, are *italicized*.

5 Conclusions

With the setup of two further test sites as far away from Wettzell as GARS O'Higgins and Metsähovi, we established a far-distributed test network to verify the worldwide reproducibility of our previous measurement results [3][4]. The vicinity of all of our test sites to local IGS reference stations allows us the very precise determination of the corner reflectors' reference coordinates relative to the respective station ties by terrestrial geodetic survey. While this is already done for the first Wettzell corner reflector and at the Metsähovi test site, a geodetic survey at GARS O'Higgins is still scheduled. Thereafter, also the location accuracy of our GARS O'Higgins datatakes will be analyzed on the base of the by then geodetically determined ground position of the local corner reflectors.

Once the world-wide reproducibility of the Wettzell measurement results is proven, the geometric instrument calibration of SAR sensors shall substantially benefit from the usage of high precision test sites like the ones on hand which leads to a new class of calibration accuracy.

6 Acknownledgments

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