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GEODETIC STEREO SAR WITH SMALL MULTI-DIRECTIONAL RADAR REFLECTORS

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ABSTRACT

This paper evaluates the applicability and achievable SAR accuracy for octahedrons – a combination of eight corner reflectors with a common phase centre. In an experiment at the observatory in Wettzell from July to November 2015 these cost-efficient and mobile radar targets are measured with TerraSAR-X Staring Spotlight and High-Resolution Spotlight. Applying the geodetic stereo SAR concept, octahedrons are very robust for 3D-positioning through their backscattering in multiple directions. Using TBD size Octaeders, we achieve 3σ standard deviations of about 3 cm for east, north and height components. For individual measurements in Staring Spotlight the standard deviation shows 1.4 cm in range and 3.2 cm in azimuth.

Index Terms – radar remote sensing, spaceborne radar, geodesy, synthetic aperture radar, stereo image processing

1. INTRODUCTION

During the last years several publications documented the progress in the accuracy of absolute range and azimuth measurements of high-resolution SAR satellites [1, 2, 3, 4]. In the case of TerraSAR-X and TanDEM-X, the correction of atmospheric delay and geodynamic effects as well as external calibration allows an accuracy of 1.5 cm in range and 2.0 cm in azimuth [5]. Moreover, these observations enable absolute 3D positioning of similar accuracy [5]. These results have been demonstrated by measurements of corner reflectors (CR) with 1.5 m side length at the geodetic observatories Wettzell (Germany) and Metsähovi (Finland). These reflectors offer good Signal to Clutter Ratio (SCR) at resolution of 3 m in X-Band, but they are large and expensive, and the stability against rain and wind makes them heavy and cumbersome for field usage.

In consequence, we have expanded our on-going research at Wettzell geodetic observatory. The aim is to test a different kind of reflector dedicated to positioning and exploiting the very high resolution of TerraSAR-X. The so called octahedrons are a combination of eight ordinary CRs arranged around a common phase centre, cf. Figure 1. Reduced to decimetre size, these octahedrons provide a significantly smaller Radar Cross Section (RCS) than classical CRs, but can offer several advantages by comparison to common CR.

Due to backscattering in multiple directions, the octahedrons can be measured from all available TerraSAR-X satellite passes which leads to a more robust 3D-positioning when using the stereo SAR concept [5]. Moreover, octahedrons are significantly less expensive and much lighter than classical CR and they are very mobile. The ones we used in our test have a dimension of 47 cm, costs of about 40 € and weight less than a kilogram.

This paper discusses the usage of these octahedrons based on a dedicated experiment carried out at the geodetic observatory in Wettzell. In doing so the applicability of octahedrons, their pros and cons and the resulting accuracies for positions as well as measurements shall be tested.

Figure 1: Octahedron reflector placed on a concrete pillar of the local geodetic survey network in Wettzell.

2. EXPERIMENTAL SETUP

In summer 2015, four octahedrons (OT1-OT4) have been installed in Wettzell and measured with the TerraSAR-X satellite. From these four reflectors, two are mounted on geodetic measurement pillars (OT1, OT2, cf. Figure 1) whereas the octahedrons OT3 and OT4 are directly attached to ground. Their reference coordinates have been derived from on-site terrestrial survey within the local geodetic network, and can be considered to be better than 5 mm.

All in all, 12 TerraSAR-X datatakes between July and November 2015 from different satellite orbits and modes are available (Table 1). Four datatakes have been captured in Staring Spotlight mode (ST) with the best possible resolution of 0.22 m in azimuth and 0.60 m in range. The remaining datatakes are High-Resolution Spotlight (HR) datatakes which provide less resolution in azimuth (1.07 m) [6]. Both ascending and descending acquisitions are involved.

Table 1: Overview on the available data acquisitions in Staring Spotlight (ST) and High-Resolution Spotlight (HS) mode.

Date	Mode	Geometry	Incidence angle
2015 07 23	ST	descending	54°
2015 08 03	ST	descending	54°
2015 08 14	ST	descending	54°
2015 08 16	ST	ascending	34°
2015 08 25	HS	descending	54°
2015 09 05	HS	descending	54°
2015 09 16	HS	descending	54°
2015 09 27	HS	descending	54°
2015 10 08	HS	descending	54°
2015 10 19	HS	descending	54°
2015 10 30	HS	descending	54°
2015 11 04	HS	descending	45°

3. STEREO SAR PROCESSING

The data processing follows our concept named geodetic stereo SAR which yields global coordinates directly in the International Terrestrial Reference Frame (ITRF) 2008 and is described in full detail in [5]. Based on the TerraSAR-X L1B image products [7] the 2D-coordinates range and azimuth of the octahedrons are extracted from the radar images focused to zero-Doppler geometry by applying point target analysis (PTA). These raw measurements are corrected for atmospheric delay and geodynamic effects to enable accurate SAR positioning. Our correction scheme follows the conventions of the International Earth Rotation Service (IERS) [8] and can be found in [5]. Finally, the reflector coordinates are retrieved by solving the fully-linearized Range-Doppler equation system and using the corrected observations along with the TerraSAR-X Science orbit product. This geodetic least squares approach allows the combination of all observations in one single estimate and additional variance component estimation provides estimated standard deviations for range and azimuth in ST and HR. This is important, because the octahedrons show a higher noise in HR due to the smaller Signal to Clutter Ratio which results from the resolution.

These observation standard deviations, the standard deviation of the coordinate solution as well as the differences to reference coordinates provide the basis of our analysis. To simplify interpretation, the positioning results are transferred to a local North-East-Height (NEH) system.

For the available satellite passes of Wettzell given in Table 1, the three geometries combined in the joint-processing are visualized in Figure 2. Classical CR are limited to either ascending or descending satellite passes, while octahedrons remain visible in all available data acquisitions, cf. Figure 2. Thus octahedrons enable a better intersection geometry which directly affects the 3D position accuracy.

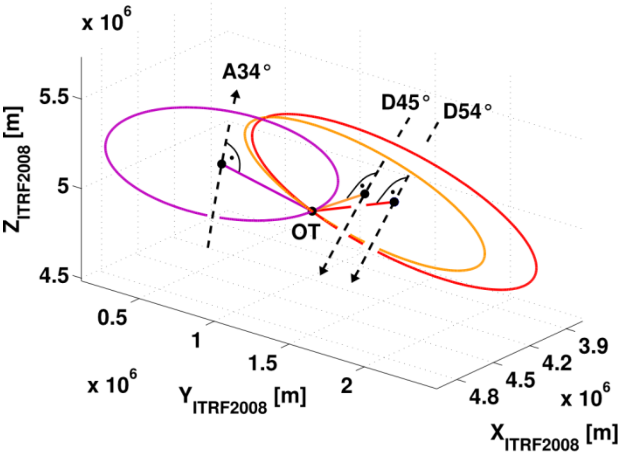

Figure 2: Visualization of available TerraSAR-X passes in Wettzell. Satellite zero-Doppler positions (black dots) and the measurements (range, azimuth) define oriented circles which intersect at the reflector position (OT).

4. RESULTS

The differences to the reference coordinates are visible in Table 2. They account for up to ±1.7 cm in horizontal direction but have a constant offset in height of circa 5 cm. The cause is not yet detected and could result from the satellite orbit, the

Table 2: Octahedron positioning results in ITRF2008. ΔN, ΔE and ΔH are the differences to the reference coordinates, and σ_N, σ_E, σ_H are the standard deviations (3σ) of the estimated positions. The values are given in north, east and height.

	ΔN [cm]	ΔE [cm]	ΔH [cm]	σ_N [±cm]	σ_O [±cm]	σ_H [±cm]
OT1	-0.88	0.81	5.20	2.76	2.52	2.82
OT2	0.41	-1.72	5.56	3.06	2.49	2.76
OT3	1.72	-0.08	4.56	3.09	2.79	3.09
OT4	-0.19	0.24	4.39	2.85	2.25	2.67

scattering of the octahedron itself or the geometrical calibration. For further offset analysing first of all a new satellite orbit will be tested, because the revised version of the orbit affects the orbit calculation as well as the transformation of the satellite's mass centre to the phase centre of the antenna.

The estimated standard deviations (3σ) account for about 3 cm and represent the 95% confidence interval of all measurements (Table 2). Through the acquisition geometry (cf. Figure 2) the confidence ellipsoid for all four octahedrons is almost similar to a sphere. For classical CR the estimated standard deviations are always dominated by an uncertainty in the coordinate orthogonal to range and azimuth [5].

The 2D standard deviations give the mean error of the solved positions to the measurements itself (cf. Table 3). The ST standard deviation for all octahedrons is about 1.3 cm and therefore 2-3 times better than in HR. In azimuth one is able to accomplish about 3.2 cm in ST and 4.0 cm in HR mode. All in all the four octahedrons show similar behaviour, only OT4 differs with its surprisingly good range precision in High Resolution mode. For ST the achieved accuracy for these measurements is even similar to given SAR accuracy for corner reflectors of 1.5 m side length as used at the observatory in Wettzell.

Table 3: Results of the variance component estimation. Standard deviations of range σ_R and azimuth σ_A in Staring Spotlight (ST) and High-Resolution Spotlight (HR).

CR	ST		HR	
	σ_R [±cm]	σ_A [±cm]	σ_R [±cm]	σ_A [±cm]
OT1	1.32	2.97	2.91	3.79
OT2	1.27	3.34	3.33	4.15
OT3	1.44	3.53	3.44	4.10
OT4	1.29	2.89	1.79	4.12

In comparison to results from classical CR [2, 4, 5] octahedrons contain a significant noise resulting from the background clutter. Based on the Radar Cross Section (RCS) of the octahedrons the SCR and the theoretical localization accuracy are calculated [9, 10]. Table 4 shows these accuracies when using TerraSAR-X and a background scattering of -8dB. The better resolution in ST compared to HR leads to a higher SCR and a bigger weight in the estimation of ITRF2008 positions.

Table 4: Theoretical localization accuracy (noise) for octahedrons solely derived from the SCR. Values for TerraSAR-X with a background scatter of -8dB.

	$\sigma_{R,\ \mathrm{OCTAHEDRON}}$ [±cm]	$\sigma_{A,\ \mathrm{OCTAHEDRON}}$ [±cm]
HS	3.03	5.40
ST	1.37	0.50

Even more detailed information is given in Figure 3 where the residuals of all measurements to the estimated values are shown. While the four ST acquisitions reveal a very high correlation among each other, the results differ for the HR datatakes. The high correlation in ST indicates that measurement errors in this mode do not primarily result from the reflectors. The higher noise for HR (cf. Table 3, 4) is clearly visible in Figure 3 for both range and azimuth.

When utilizing the four ST measurements only for 3D positioning, the 3σ precisions amount already for about 4 cm in average. The adding of eight HR measurements has only a relatively small effect to the estimated precisions.

5. CONCLUSIONS

The presented results clearly show that SAR positioning with off sthe shelf TBD cm size octahedrons is possible in Staring Spotlight and High Resolution Spotlight with TerraSAR-X. Because of the small size, background clutter dominates the positioning error in HR which makes ST first choice for the high-precision measurements. To use octahedrons more effectively with HR the dimension should be increased.

For available measurements the 2D standard deviation for ST accounts for 1.3 cm in range and 3.2 cm in azimuth. The 3σ standard deviations account for about 3 cm in north, east and height

Figure 3: Observation residuals for the four octahedrons for azimuth (above) and range (below). The first four values are from the Staring Spotlight (ST) acquisitions, the following from High Resolution (HR). The different signs symbolize the associated geometry.

component, but the reason for height offset to reference coordinates is not yet detected.

Octahedrons show practical advantages due to small weight and size as well as robust 3D positioning. Compared to stereo imaging of CRs with 1.5 m side length, the double-sided measurement geometry in ST is even able to compensate the noise of octahedrons due to their smaller SCR. The high correlation in the residuals of range and azimuth for Staring Spotlight makes the data promising for differential evaluation.

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