

TERRASAR-X: HOW CAN HIGH RESOLUTION SAR DATA SUPPORT THE OBSERVATION OF URBAN AREAS?

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ABSTRACT:

TerraSAR-X is a new German radar satellite that shall be launched in mid 2006. The expected lifetime is 5 years. It carries a high frequency X-band Synthetic Aperture Radar (SAR) sensor that can be operated in different modes and polarisation. The Spotlight-, Stripmap- and ScanSAR-modes provide high resolution SAR images for detailed analysis as well as wide swath data whenever a larger coverage is required. Imaging will be possible in single, dual and quad-polarisation. TerraSAR-X will be an operational SAR-system for scientific and commercial applications.

Today's space borne SAR systems usually provide 25 m resolution that is suitable to separate built-up areas from other land use and therewith the delineation of the city bodies. The high resolution SAR data of the upcoming new SAR sensors like TerraSAR-X and Radarsat-2 will increase dramatically the level of details visible in the SAR images. The detection and mapping of buildings, city structures and infrastructure like roads and railways will be possible. These features are of interest for mapping and monitoring purposes. The high resolution further enables to derive meaningful texture measures. Polarimetry can be used to separate different backscattering mechanisms and therewith to improve classification results. The very short revisit time together with the all weather capability make TerraSAR-X to a very useful source to assess disaster damage.

SAR interferometry is one of the major applications of today's SAR data and can also be applied to TerraSAR-X data. Here the range differences between the ground targets and the antenna's position during the acquisition are evaluated. Ground motions can be derived by applying differential interferometry and persistent scatterer techniques. A prerequisite for interferometry is the correlation of the radar echoes. The degree of correlation can be estimated from the SAR data and can be utilized for classification and change detection purposes. High resolution, short revisit times and a $\pm 250\text{m}$ repeat orbit service will open new perspectives for the observation of urban areas.

1. INTRODUCTION

The potential of SAR data detect settlements, estimate population sizes, assess the impact of human activities on the environment, map and analyse urban land use patterns, interpret socio-economic characteristics and detect land use changes has been demonstrated (Henderson and Xia, 1998; Jensen, 2000; Xia and Henderson, 1997). Additionally coherence analyses were applied for the delimitation of city bodies (Strozzi & Wegmüller, 1998), to map the degree of sealing (Kuntz, 2001) and to support mapping (Fanelli et al, 2001; Weydahl, 2001). It was also successfully used for the mapping of urban change (Grey et al, 2003). (Ito & Hosokawa, 2002) performed a damage assessment based on the coherence of ERS C-band and JERS L-band data.

SAR interferometry is one of the major applications for today's space borne SAR sensors. Anthropogenic ground displacements in urban centers are commonly due to groundwater or hydrocarbon extraction (e.g. Prince & Galloway, 2003), underground construction (Fruneau & Sarti, 2000) or mining activities (Carnece et al., 1996). Even though urbanized regions do not suffer from temporal de-correlation of the SAR signals to the extent densely vegetated regions do, the short wavelength will unfortunately cause difficulties in interferograms spanning longer time periods. Permanent scatterer (PS) analyses (Ferretti et al., 2001) can overcome this limitation and are particularly applicable in urbanized regions.

TerraSAR-X is a new German radar satellite that shall be launched mid 2006 with the Russian DNJEPR-1 launch vehicle.

The scheduled lifetime is 5 years. The mission's objectives are the provision of high-quality, multi-mode X-band SAR-data for scientific research and applications as well as the establishment of a commercial EO-market and to develop a sustainable EO-service business. TerraSAR-X will provide high resolution SAR data and can be operated in different modes and polarisations.

Within this paper it will be discussed how the innovative features of the satellite can be utilized for the observation of urban areas. The satellite, the imaging modes and polarisations will be presented in sections 2 and 3. Products and operational modes will be described in sections 4 and 5. Afterwards a perspective for the application of TerraSAR-X to the observation of urban areas will be given.

2. TERRASAR-X MISSION

TerraSAR-X is an operational, advanced SAR-satellite system for scientific and commercial applications that shall be launched in mid 2006. The scheduled lifetime is 5 years. It will carry a new high resolution satellite operating in the X-band at 9.65 GHz that can be operated in different modes and polarisation. The SpotLight- (1.3 m), StripMap- (3.3 m) and ScanSAR-modes (14.8 m) provide high resolution SAR images for detailed analysis as well as wide swath data whenever a larger coverage is required. Imaging will be possible in single, dual and quad-polarisation. Beam steering enables observation in different incidence angles. Nominally TerraSAR-X will be a

right looking system. Double side access can be realized by satellite roll maneuvers. The satellite will be positioned in an 11 days repeat orbit.

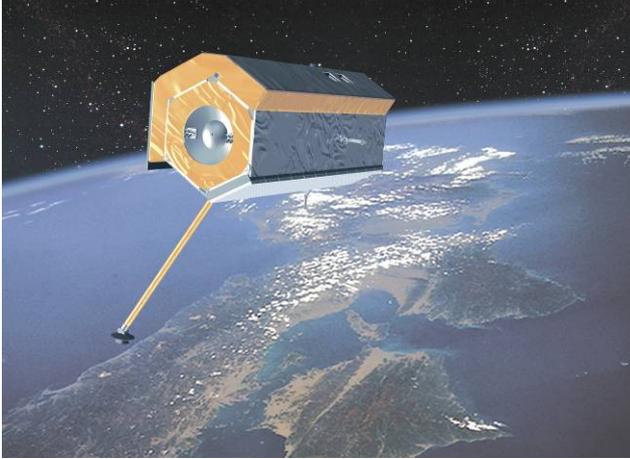


Figure 1. Artist view on TerraSAR-X:

Figure 1 shows some details of TerraSAR-X satellite. The solar panel is mounted on top of the satellite bus. The SAR antenna is visible on the bottom side. The X-band downlink antenna is mounted on a small boom in order to avoid interference with the SAR-antenna.

TerraSAR-X is realised in a close co-operation between the German Aerospace Centre (DLR) and the EADS Astrium GmbH. The German Aerospace Center (DLR) currently implements the satellite control system and the payload ground segment for receiving, processing, archiving and distribution of the X-band SAR data. DLR is also responsible for the instrument's operation and calibration, the 5 years of operation and the scientific use of the TerraSAR-X data. EADS Astrium currently develops builds and will launch the satellite under DLR contract. The Infoterra GmbH, a subsidiary of EADS Astrium, is setting up a distribution system for the commercial use of the TerraSAR-X data and products on its own cost. The commercial data distribution and value adding will be the task of the Infoterra GmbH.

3. TERRASAR-X IMAGING MODES AND POLARIZATION

This section summarises the main features of the TerraSAR-X imaging modes. (Roth, 2003) provides more details.

3.1 SpotLight (SL) and High Resolution SpotLight Mode (HS)

TerraSAR-X achieves the highest geometrical resolution in the SpotLight modes. During the observation of a particular ground scene the radar beam is steered like a spotlight so that the area of interest is illuminated longer and hence the synthetic aperture becomes larger. The maximum azimuth steering angle range is $\pm 0.75^\circ$. The size of the observed area on ground is smaller than the one in all other modes. HS and SL modes are very similar. In SL mode the geometric azimuth resolution is reduced in order to increase the azimuth scene coverage. Characteristic parameters of the SpotLight and High Resolution SpotLight modes are listed in Table 1.

Parameter	Value HS	Value SL
Scene extension (azimuth x ground range)	5 km x 10 km	10 km x 10 km
Incidence angle range (full performance)	20° - 55°	20° - 55°
Azimuth resolution	1 m	2 m
Ground range resolution (55°-20° incidence angle)	1.5 m - 3.5 m	1.5 m - 3.5 m

Table 1: Parameters of SpotLight and High Resolution SpotLight Modes

3.2 StripMap Mode (SM)

In StripMap Mode the ground swath is illuminated with a continuous sequence of pulses while the antenna beam is fixed in elevation and azimuth. This results in an image strip with continuous image quality in azimuth. The corresponding parameters are listed in Table 2.

3.3 ScanSAR Mode (SC)

The ScanSAR mode provides a large area coverage. The wider swath is achieved by scanning several adjacent ground sub-swaths with simultaneous beams, each with a different incidence angle. Due to the reduced azimuth bandwidth the azimuth resolution of a ScanSAR product is lower than in StripMap mode. The ScanSAR beams will be composed from the calibrated StripMap beams. The corresponding parameters are listed in Table 2.

Parameter	Value SM	Value SC
Number of sub-swaths	na	4
Swath width (ground range)	30km (polarimetric mode: 15–30 km)	100 km
Acquisition length	≤ 1650 km	≤ 1650 km
Incidence angle range	20° - 45°	20° - 45°
Azimuth resolution	3 m	16 m
Ground range resolution (45°-20° incidence angle)	1.7 m - 3.5 m	1.7 m - 3.5 m

Table 2: Parameters of StripMap and ScanSAR Modes

3.4 Polarisation

Each pulse can be transmitted either vertically (V) or horizontally (H) polarised. The back-scattered signal can be received with either vertical or horizontal polarisation, independent from the transmit polarisation. The resulting product will consist of one polarimetric channel in one of the combinations HH, HV, VH or VV.

In dual polarisation mode the radar toggles the transmit and/or receive polarisation on a pulse to pulse basis. The effective PRF in each polarimetric channel is half of the total PRF, which means that the azimuth resolution is slightly reduced. The product consists of two layers that can be selected out of the possible combinations.

Single and dual polarisation will be available for all image modes.

Quad polarisation is possible in the experimental dual receive antenna mode as the signal can be received simultaneously in H and V polarisation. By sending alternating H and V pulses, the full polarimetric matrix can be obtained. The corresponding experimental product consists of four layers. Currently quad-polarisation is not operationally foreseen.

4. TERRASAR-X PRODUCTS

4.1 Single Look Slant Range Complex (SSC)

This product is the basic single look product of the focused radar signal. The pixels are spaced equidistant in azimuth (according to the pulse repetition interval $PRI=1/PRF$) and in slant range (according to the range sampling frequency) and the data are represented as complex numbers. Each image pixel is processed to zero Doppler coordinates, i.e. perpendicular to the flight track.

The SSC product is intended for scientific applications that require the full bandwidth and the phase information, e.g. SAR interferometry and interferometric polarimetry.

4.2 Multi Look Ground Range Detected (MGD)

This product is a detected multi look product with reduced speckle and approximately square resolution cells. The image coordinates are oriented along flight direction and along ground range. The pixel spacing is equidistant in azimuth and in ground range. A simple polynomial slant to ground projection is performed in range using a WGS84 ellipsoid and an average, constant terrain height parameter.

4.3 Geocoded Ellipsoid Corrected (GEC)

The GEC product is a multi-look detected product. It is projected and re-sampled to either UTM or UPS in polar regions. WGS84 is used as geodetic reference assuming one average terrain height. As the ellipsoid correction does not consider a DEM, the pixel location accuracy varies due to the terrain.

The GEC is the recommended product for marine and coastal applications where topography doesn't effect the location accuracy. The orbit precision will be the main factor for the achieved location accuracy. Depending on the time delay between acquisition and processing either quick-look (± 10 m), rapid (± 2 m) or science orbits (± 20 cm) will be used for the geocoding.

4.4 Enhanced Ellipsoid Corrected (EEC)

Like the GEC, the EEC is a multi-look detected product provided in UTM or UPS projection. WGS84 will be used as the geodetic datum. Terrain induced distortions are corrected considering a DEM of a moderately coarser resolution than the TerraSAR-X products. The pixel location accuracy in these products is highly accurate. The geometric quality depends on the height accuracy and resolution of the DEM in combination with the type of terrain and the incidence angle. DEMs from SRTM (C-band and X-SAR), ERS-derived elevation models and GLOBE provide a global basis for a terrain correction service.

It is expected that the EEC will become the standard geocoded product of TerraSAR-X. Like the GEC the EEC is generated automatically. No operator interactions are required.

4.5 Geocoded Layover Shadow and Incidence Angle Mask (GIM)

The GIM product is generated as an optional add-on to the EEC product. It provides information about the local incidence angle for each pixel of the geocoded SAR scene and about presence of layover and shadow areas (Meier et al, 1993). The local

incidence angle is the angle between the radar beam and a line perpendicular to the slope at the point of incidence.

The GIM product shows the same cartographic properties like the geocoded output image with regard to output projection and cartographic framing. The content is basically the local terrain incidence angle and additional flags indicate whether a pixel is affected by shadow and/or layover or not.

5. TERRASAR-X OPERATIONAL FEATURES

5.1 Repeat Cycle and Coverage

TerraSAR-X will have a rather short repeat cycle of 11 days. This means that every 11 days a ground target can be imaged with the same geometry. As the antenna is electronically steered a certain area can be observed more frequently with different incidence angles.

Table 3 lists the different observation possibilities for the Oberpfaffenhofen test field (49° latitude) within one orbit cycle. This particular site can be imaged 12 times within 11 days. An interferometric pair is available within 12 days and even 12 interferometric pairs within 22 days (Eineder, 2003).

No	Orbit Time [UTC]	Ascending / Descending	Look angle [°]	Look Direction
1	day 1, 16:19:54	A	30.9	left
2	day 2, 05:19:32	D	37.4	right
3	day 2, 16:01:01	A	47.1	left
4	day 5, 05:19:32	D	42.7	left
5	day 6, 05:37:35	D	23.0	left
6	day 6, 16:56:53	A	47.4	right
7	day 7, 16:00:02	A	25.2	left
8	day 7, 16:37:54	A	30.6	right
9	day 8, 04:59:42	D	32.5	right
10	day 8, 15:41:08	A	43.9	left
11	day 9, 04:40:42	D	48.4	right
12	day 11, 05:36:36	D	46.0	left

Table 3: TerraSAR-X coverage simulation for Oberpfaffenhofen (Eineder et al, 2003)

Please note that the nominal antenna look direction is to the right. Left looking is also possible but has some operational deficiencies and will be used in high priority situations.

5.2 Orbit

Depending on the time delay between acquisition and processing orbits of different accuracies will be used. The quick-look orbit (± 10 m) will be available for near real time applications. Usually rapid (± 2 m) and science orbits (± 20 cm) will be used for the data processing. The science orbit accuracy will be achieved whenever the standard single frequency GPS receiver plus an additional dual-frequency GPS flown as an experimental payload will be operated in parallel.

In order to support interferometric applications it is investigated to maintain small baselines over the mission. This would be performed by keeping the orbit in a ± 250 m tube with respect to a reference orbit (Eineder et al, 2003).

6. DISCUSSION OF THE OBSERVATION POTENTIAL

The all weather and day and night observation capability of SAR systems ensure to observe urban areas at regular and predefined times. Both are outstanding features for mapping and monitoring purposes. The very short revisit times of TerraSAR-X will even improve the observation possibilities. Additional to these features fast visibility is required for disaster management and damage assessment.

The location accuracy of TerraSAR-X products is mainly determined by the orbit precision (s. section 5.2). The EEC product (s. section 4.4) comprises an ortho-rectification based on the SRTM elevation models and therewith also corrects terrain induced distortions. (Roth et, 2004) provides more information on the geocoding service.

6.1 Resolution

Spatial resolution is a much more critical issue for mapping and monitoring of urban areas than for agricultural or forested regions. Today's space borne SAR systems mainly provide 10-25 m resolution that is suitable to separate build-up areas from other land use and therewith the delineation of the city bodies. However the detection and mapping of buildings, city structures and infrastructure like roads and railways requires high resolution SAR data. Several studies have indicated a significant increase in the classification accuracy when textural information is considered. E.g. (Esch & Roth, 2004) showed, that an automated analysis of high resolution X-band data based on textural and context-related features allows for an accurate detection of built-up areas. Figure 2 presents a subset of ERS data (upper image), simulated TerraSAR-X data, derived from DLR's airborne system ESAR (middle) and a corresponding classification result of an urban area in Germany. The subset covers a sub-urban area with single houses and gardens (upper part) and an industrial area with big warehouses and administration buildings (lower part). The red square in the ERS image indicates the location of the ESAR sub-image.

Nevertheless the application of high-resolution SAR data in urban areas is complicated. Typical SAR imaging phenomena like foreshortening, layover, and shadowing and the strong dependence of backscatter on the geometric characteristics and topology of the illuminated objects need to be considered. Particularly in dense urban areas these effects may occur very commonly, adversely affecting the appearance and ability to detect buildings and roads. Layover and double-bounce scattering effects displace the building footprint and features in the radar image. (Soergel et al., 2003) showed that the limitations related to the SAR sensor principle can be partly remedied by combining data acquired at different aspect and viewing angles. Thus, the left- and right-looking capability of TerraSAR-X and the range of possible incidence angles may prove to be important in resolving geometrical issues in urban settings.



Figure 2: Comparison of ERS-data (upper), TerraSAR-X like data derived from DLR's E-SAR (middle) and ESAR-derived classification (lower) of Ludwigshafen, Germany

6.2 Polarimetry

Relatively few studies have been carried out regarding the value of fully polarimetric SAR data for urban applications. Generally polarimetry can be used to separate different backscattering mechanisms and therewith to improve classification results. E.g. In a recent study (Pellizzeri, 2003) analyzed the benefit of polarimetric parameters derived by the eigenvector decomposition theorem for the classification of suburban areas using C- and L-band. (Dong et al, 1997) examined the dominant backscattering mechanisms and their relative contributions to the backscatter. Full polarized data were then used to decompose the backscatter into components caused by single, double and triple bounce. The data for these investigations were acquired by NASA/JPL's AIRSAR system.

6.3 Interferometry

Usually urbanized regions do not suffer from temporal de-correlation of the SAR signals to the extent densely vegetated regions do. However it can be expected that due to the short wavelength of TerraSAR-X interferograms spanning longer time periods will be affected by de-correlation.

Permanent scatterer (PS) analyses (Ferretti et al., 2001) can overcome this limitation and are particularly applicable in urbanized regions. For example, (Worawattanamateekul et al. 2003) studied subsidence related to groundwater withdrawal in Bangkok, Thailand using PS. (Walter et al, 2004) applied the PS technique to interferometric ERS SAR observations to analyze surface subsidence caused by hard coal mining activities in the densely populated Ruhr area in Germany.

The higher resolution and the higher frequency of TerraSAR-X will improve the signal to noise ratio and therewith reduce the interferometric phase error by a factor of 6.4 (Eineder, 2003). It is expected that the sensitivity to estimate subsidence can be increased by a factor of 10 compared to today's C-band sensors with 25 m resolution.

As mentioned previously the consideration of coherence information significantly improved classification results and can also be used for change detection purposes. The coherence is a statistical measure of the correlation properties of the radar echoes. It is estimated from the SAR data themselves by determining the complex correlation coefficient from a number of neighboring pixels (>64 for ERS). Consequently the resolution of the resulting coherence map is lower than the one of the SAR image.

The coherence reflects the degree of de-correlation which can be separated into temporal, spatial and thermal components (Zebker & Villasenor, 1992). In other words the de-correlation is not only caused by the ground targets properties but also by the imaging geometry and the SAR instrument and processing. The geometry part can be separated into a terrain slope dependent and a baseline induced component. The slope can be considered using a DEM. Baseline effects were reduced by selecting data sets acquired with smaller baselines (< 300m). It can be expected that this limitation will not be a concern for TerraSAR-X due to the high bandwidth and the operational ± 250 m orbital tube.

(Hoffmann et al, 2004) demonstrated the potential of coherence analyses for damage assessment purposes after the Bam earthquake on December 26, 2003. A damage map of the city of Bam in Iran was produced by evaluating the coherence change index derived from acquisitions before and after the earthquake.

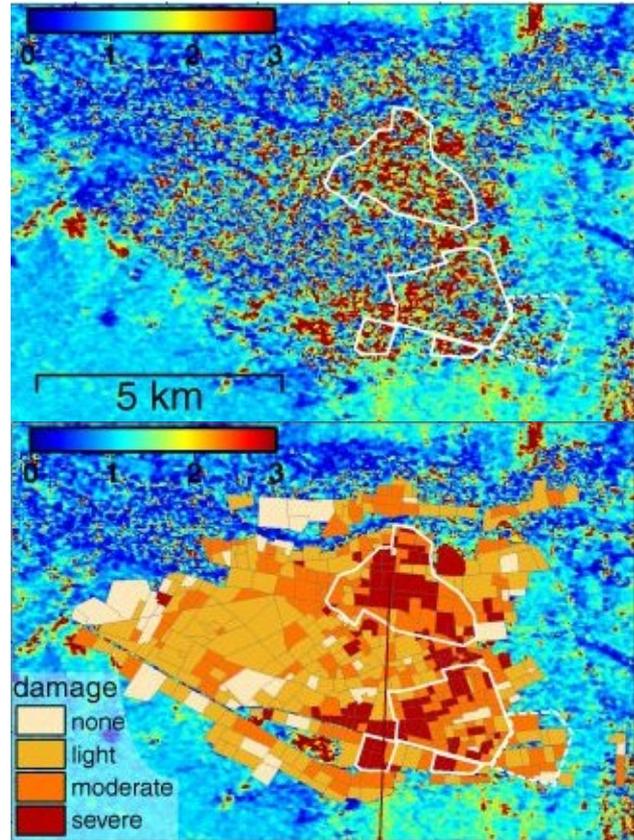


Figure 3: Coherence change index in the city of Bam (left) and derived damage mapping (right) (Hoffmann et al, 2004)

Figure 3 compares the resulting coherence analysis (upper) and a map derived from aerial observations (lower image). The coherence change index is displayed in the upper left corner. Blue indicates areas where no changes appeared while brown areas are affected by significant changes. The coherence change index is highly correlated with a visual delineation of heavily damaged zones (white line in Figure 3), that was derived from an Ikonos image acquired over Bam immediately after the earthquake (Hoffmann et al, 2004).

7. CONCLUSION

TerraSAR-X will provide new features that will improve the Earth observation potential. Beside the typical advantages of SAR systems like all weather as well as day and night observation capability special mission services support the monitoring and mapping also of urban areas. This includes short revisit times, the ± 250 m orbital tube and an operational ortho-rectification service. High resolution data will enable very detailed studies, the consideration of texture measures and will open new perspectives also to SAR interferometry. Polarimetric data can be used to distinguish between different backscatter mechanisms on ground.

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