GEOCODING OF TERRASAR-X DATA

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ABSTRACT:

TerraSAR-X is a new German radar satellite that shall be launched in April 2006. The expected lifetime is 5 years. It carries a high frequency X-band 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.

DLR currently develops the TerraSAR-X Ground Segment. One part is the geocoding system that will provide geocoding capability for multi-resolution, multi-polarisation and multi-frequency data. The user can select different products with respect to the geometric processing and quality. Multi-look ground range products as well as ellipsoid and terrain correction capabilities are provided. A new product called Enhanced Ellipsoid Corrected will be offered. It considers Digital Elevation Models (DEM) of a moderately coarser resolution than the 1 up to 3 m resolution of the TerraSAR-X modes. SRTM/X-SAR DEMs with approximately 25 m spacing will be the backbone for this operational and fully automated service. The system design considers the processing of SAR data provided by other sensors as well. High precision terrain correction using high resolution DEMs, tie-pointing and image adjustment will be implemented in an experimental processor.

1. INTRODUCTION

TerraSAR-X is a new German radar satellite that shall be launched in April 2006. The scheduled lifetime is 5 years. It's high frequency X-band SAR sensor 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 and double side access can be realized by satellite roll maneuvers. The satellite will be positioned in an 11 days repeat orbit. 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.

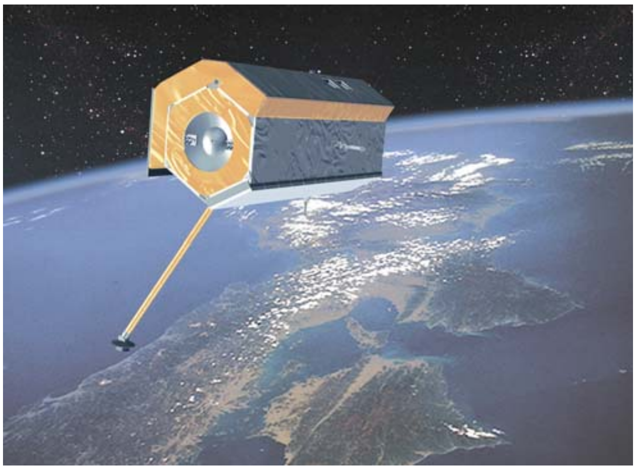

Figure 1. Artist view on TerraSAR-X:

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. Part of the TerraSAR-X Ground Segment is the geocoding system. In order to cover the different features of the TerraSAR-X sensor the system is parameterised with respect to the resolution and the number of layers (polarisation).

The development is based on the experiences and techniques available from the ERS-1/2, SIR-C/X-SAR, SRTM and Envisat-ASAR missions (Roth et al, 1996), (Rabus et al, 2003), (Kosmann et al, 2000). New requirements rose due to the high resolution capability of TerraSAR-X and a higher rate of geocoded products as a global ortho-rectification service will be offered.

The rectification procedure is based on the range-Doppler approach developed by (Meier, 1989) and allows the geocoding of other SAR data as well. SAR inherent distortions in combination with the multi-incidence and left- and right-looking capability require the consideration of terrain information during the geocoding process. SRTM significantly improved the ortho-rectification service as it provides DEMs for almost 80% of the land surface. The corresponding terrain corrected product is called Enhanced Ellipsoid Corrected (EEC). The term "ellipsoid corrected" is used because it considers moderately coarser DEM resolution then the 1 to 3 m resolution of the TerraSAR-X modes.

Complementary to the EEC high precision terrain correction can be performed using high resolution DEMs (e.g. from LIDAR), ground-control points and image adjustment techniques. As both resolutions of the DEM as well as the SAR image are in the same order of magnitude, this product is seen to be the equivalent to the Geocoded Terrain Corrected (GTC) product offered for ERS and SIR-C/X-SAR. A Geocoded layover shadow and Incidence angle Mask (GIM) can be generated as a by-product to GTC and EEC.

2. SAR GEOCODING

2.1 Geometric Distortions in SAR Images

TerraSAR-X is a side-looking synthetic aperture radar (SAR). It transmits pulses in X-Band to the Earth, which will be reflected back to the instrument and received again by the radar. The signal travel time is measured and therewith the range distance between the antenna and the ground target. Due to the side looking geometry of SAR-systems undulated terrain is significantly distorted during the SAR mapping process.
The most important and well known local image distortions are (Schreier, 1993) foreshortening, layover, and **s**hadow. The area on ground is not seen by the radar. But also the range displacement effect needs to be considered that causes elevated features to be mapped in false range positions – namely to closely to near range. These effects as well as the varying ground resolution caused by varying slopes can be corrected using a digital elevation model.

Three approaches can be applied to geocode SAR images and will be discussed in the following chapters. Common to all cases is the backward geocoding also denoted as object-to-image approach.

2.2 Rigorous Range Doppler Approach

For each output pixel, which defines a co-ordinate triple (easting, northing, height) in the output map projection, the corresponding azimuth and range positions in the input image have to be determined. This is based on the Range-Doppler (1) and range equations (2) applicable to SAR images. Due to the dynamic imaging principle of SAR this is an iterative and hence time consuming search procedure. The orbit position is varied until the range and Doppler equations are simultaneously fulfilled (Meier et al, 1993).

$$(1) \quad F_1(i,j) = f_{DC} - \frac{2 \cdot (\vec{p}-\vec{s}) \cdot (\vec{p}-\dot{\vec{s}})}{\lambda \cdot |\vec{p}-\vec{s}|} = 0$$

$$(2) \quad F_2(i,j) = r_0 + m_r \cdot j - |\vec{p}-\vec{s}|$$

(i,i) are the pixel co-ordinates where i are the azimuth and j the range positions. f_{DC} is the Doppler reference function applied during the SAR processing. p and s are the earth surface point and sensor position vectors, λ is the SAR sensor wave length and r_0 and m_r the slant range offset and the pixel spacing.

2.3 3D Interpolative Approach

The principle of this approach is to perform the rigorous transformation for grid points and using an interpolation to fill the grid cells (Raggam, 1988). The radar image range and time co-ordinates are determined by interpolating between anchor points. At first a three-dimensional grid of points (co-ordinates in easting, northing, height) is generated and the corresponding pixel co-ordinates (in azimuth and range) of the input image are determined using the rigorous Range-Doppler approach. The grid covers the output area and its height extension spans the entire elevation range of the underlying DEM. Starting from the azimuth and range co-ordinates at a reference elevation correction terms in azimuth and range are interpolated using the individual height values from the DEM. In order to correct non-linear terrain effects a quadratic term for height interpolation is considered.

The main purpose of the interpolative approach is to reduce the computing time for generating a terrain corrected geocoded product. Tests showed that the throughput can be improved by at least a factor of 5 compared to the rigorous geocoding. Geometric degradation strongly depends on the grid size. (Raggam & Gutjahr, 2003) showed that the interpolative approach is precise from the geometric point of view if the mesh sizes is less or equivalent to 1000 m on ground. In comparison errors caused by accuracy deficiencies of e.g. the DEM and the sensor model parameters cause significantly larger location errors.

2.4 Interpolative Ellipsoid Correction

The ellipsoid correction is a special case of the 3d interpolation approach. A net of points is transformed applying the rigorous range-Doppler-approach. As only constant elevation values need to be considered the grid cells are filled using a bilinear interpolation (Roth et al, 1993).

2.5 Implementation Issues

Rigorous, 3d- and interpolative ellipsoid correction are parameteric geocoding approaches. They are independent from the radar wavelength and can be applied to other space- or airborne SAR data as well. The current version of the geocoding system supports input from Envisat-ASAR, ERS, J-ERS, Radarsat-1, SIR-C / X-SAR and DLR's airborne system ESAR. The pixel spacing of the in- and output data as well as the Doppler reference function are parameterised and are stored in configuration files. Even though most SAR processors refer to zero-Doppler the geocoding system is able to consider other reference functions. Multi-polarised data are considered as multi-layer images.

3. TERRASAR-X IMAGING MODES AND POLARIZATION

This chapter 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 ±0.75°. 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 GEOCODED PRODUCTS

4.1 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 terrain induced SAR specific distortions will not be corrected and significant differences can appear in particular for strong relief and steep incidence angles. The GEC is generated by applying the interpolative ellipsoid correction approach (s. chapter 2.4).
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.

4.2 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 then the TerraSAR-X products. For this purpose the 3D-interpolation described in chapter 2.3 will be applied. 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.

4.3 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), (Raggam & Gutjahr, 2004).
The local incidence angle is the angle between the radar beam and a line perpendicular to the slope at the point of incidence. For its determination it is necessary to know the slant range vector and the local surface normal vector.
Areas of SAR shadow are determined via the off-nadir angle, which in general increases for a scan line from near to far range. Shadow occurs as soon as the off-nadir angle reaches a turning point and decreases when tracking a scan-line from near to far range until the off-nadir angle reaches that value again, which it had at the turning point.
Areas of SAR layover are determined via the slant range distance, which in general increases for a scan line from near to far range. Layover occurs as soon as the slant range reaches a turning point and decreases when tracking a scan-line from near to far range. In order to separate active and passive layover a two step procedure scanning from near to far and back is required.
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 ERROR BUDGET ANALYSIS

(Frey et al, 2003) analysed the TerraSAR-X error budget for geocoded products. The error sources orbit, radar and processing parameters, cartography and geodesy, atmosphere and relief were investigated and published in (Frey et al, 2004). Assuming that the Sampling Window Start Time bias (SWST) will be determined very precise during the commissioning phase and the consideration of zero Doppler instead of the Doppler Centroid as the reference function the main error sources are the availability and accuracy of the DEM, the orbit and - to some extent - the atmospheric path delay.

The estimated error contribution of the orbit is slightly less then the specified accuracy of the different orbit products quick-look (±10 m), rapid (±2 m) and science (±20 cm), e.g. up to 1.9 m in range in case of rapid orbit and an error in cross track direction.

The height accuracy and resolution of the DEM in combination with the type of terrain and the incidence angle determine the error contribution of the elevation model. For steep incidence angles (<23º) a height errors converts with a factor of 2.4 into a location error. For 45º the factors goes down to 1.

The ionospheric path delay will be modelled and considered during the SAR processing (Jehle et al, 2004).

6. PROCESSING ENVIRONMENT

DLR's German Remote Sensing Data Center operates a satellite ground station in Neustrelitz which will serve as the main ground station for TerraSAR-X. Beside data reception the payload ground segment will comprise screening and processing as well as archiving capability. Screening, processing and geocoding will be performed by the TerraSAR-X Multimode SAR Processor (TMSP). Annotated level 0 data will be generated from every acquired TerraSAR-X data set and will be stored within DLR's long-term archive.

6.1 TerraSAR-X Multimode SAR Processor (TMSP)

The TMSP will be integrated and operated in DLR's ground receiving station in Neustrelitz to routinely screen and archive all received TerraSAR-X data. On request the data will be further processed. The system design foresees the CEOS Level 1b processing of 70 scenes from TerraSAR-X per day mainly acquired in SpotLight and StripMap modes. This corresponds to a data volume of approximately 13.5 GBytes of raw data. Level 1b comprises Single Look Slant Range Complex (SSC), Multi look Ground range Detected (MGD), GEC and EEC products.

This amount of data will be handled by a multi-node processor. The target hardware are multi-processor Unix computers. Beside screening the TMSP will comprise the focussing of the radar data, the geocoding and product formatting. The GEC and EEC generation as well as the elevation data base will be integrated as separate components into TMSP.

6.2 GEC & EEC Generation

The ellipsoid correction and the terrain correction using a coarse elevation model will be implemented in one component. Both procedures geocode the input SAR image block by block. In case of the enhanced ellipsoid correction a DEM is provided in geographic co-ordinates from the DEM data base in the best available spacing. During the block-processing the DEM is transformed into the output map projection and the required pixel spacing by a bilinear interpolation. Then the SAR image is transformed by applying the 3d interpolation approach. Optionally the incidence angle is calculated. Utilising the multi-processor environment the individual blocks are processed in parallel. Finally layover and shadow conditions are determined and flagged in the GIM if required. The GEC processing is similar but simplified as no DEM needs to be considered.

The SAR processing of TMSP will provide the SAR data, the orbit, geometry and order parameters to the geocoding modules. After geocoding the "GEC/EEC generation" component delivers the geocoded image and annotation data to the product formatting component of TMSP.

6.3 Digital Elevation Model Data Base

The task of the Digital Elevation Model Data Base (DEM-DB) is the storage and provision of elevation information for the ortho-rectification process and geometric calculations. The DEM-DB supports multiple resolutions and keeps the elevation data in tiles. The data files are stored on disk via the conventional Unix file system. The data base organisation as well as the elevation data representation is in geographic co-ordinates. DEMs of different sources can be organised in separate projects. Within each project a tree structure from North to South is created in 1° steps. Beneath this directory the next level is sorted from East to West, again in 1 degree increments. At this level DEMs are stored provided in 1" resolution or lower (e.g. 3"). One tile completely covers 1°x1°. Areas where no elevation information is available are masked. Each tile contains an overlap of 30" to the south and the west to the adjacent tiles. Higher resolution DEMs lead to 0,01° cells below the 1°- level. The finest resolution supported is 0,01".

Different elevation models like the SRTM C-band and the SRTM X-band derived elevation products are stored in different projects. This enables the separation of different qualities, DEM sources and the minimisation of disk space.

The DEM data base itself consists of the file configuration and management system and two levels of software modules for file access and data manipulation.

The utility level provides all functions for data access and data base maintenance based on a predefined geographic area. An "import" function for example creates the directory structure, splits the DEM file into the corresponding tiles and inserts those tiles. The "get" function supplies the DEM tiles of a geographic area on local disk.

The application level provides further processing capability like transformations into different map projections and geodetic datum, merging and mosaicking of different resolutions and qualities (Roth et al, 2002) as well as DEM colour shading and visualisation (Knöpfle & Dech, 1999).

The operational EEC generation will utilise DEMs in

- DTED level 2 (SRTM X-band globally, C-band for the US, regionally ERS-derived),
- DTED-1 (SRTM/C-band globally, regionally other DTED-products),
- DTED-0 (GLOBE) where no other DEM information is available.

6.4 Experimental GTC Processor

The standard geocoding does not consider high resolution elevation models. The TerraSAR-X ground segment service focuses on an automated and therewith cost efficient processing.

Furthermore very high resolution DEMs are rarely available and expensive. Nevertheless a geocoding processor will be implemented that will generate SAR products with higher geometric accuracy on an experimental basis. It considers high resolution elevation data, tie-pointing and image adjustment as well as correction capabilities of the atmospheric in particular the tropospheric path delay (Jehle et al, 2004). The corresponding output will be a Geocoded Terrain Corrected (GTC) product.

6.4.1 Geocoded Terrain Corrected (GTC)

The experimental GTC processor will produce a multi-look detected product supporting at least the same cartographic and geodetic references as the EEC (UTM/UPS and WGS84). The image distortions caused by varying terrain height are corrected using an external high resolution DEM. Ground control point measurement and image adjustment ensure that the image geometry will be of sufficient quality even for quick-look and rapid orbit input. The rigorous geocoding approach will be applied (s. chapter 2.2). Optionally the GIM is generated.

The experimental GTC processor supports input of the TerraSAR-X basic products in single look complex and multi-look ground range geometry. Additionally the so called enumeration files can be generated.

6.4.2 Enumeration Files

The enumeration files are an alternative geocoded product, which provides the ground co-ordinates along with the input SAR scene. Thus geo-referencing can be performed by the end-user without the need for image interpolation. To deliver this information two image layers are attached to the SAR image. They contain the ground co-ordinates for each input image pixel in Easting and Northing, respectively.

The enumeration files generation is based on the object-to-image approach. For each pixel in the output domain the corresponding position in the input SAR image is determined. As this step provides a irregular spaced grid it is in a subsequent step resampled to a regular spacing in azimuth and range.

7. CONCLUSION

TerraSAR-X is a new German radar satellite. Its high frequency X-band SAR sensor can be operated in different modes and polarisation ranging from SpotLight-, StripMap- to ScanSAR-modes. Single and dual polarisation will be available operationally, quad-polarised data on an experimental basis.

Geocoded ellipsoid corrected will be available as well as an enhanced ellipsoid corrected product that considers DEMs of a moderately coarser resolution than the TerraSAR-X modes. SRTM will serve as backbone for this global ortho-rectification service. The geocoding sub-system will be integrated into the SAR processor TMSP and will be operated on a multi-processor Unix computers directly at the receiving station in Neustrelitz.

An experimental GTC-processor will be implemented that enables the high precision geocoding using high using resolution DEMs, tie-pointing and image adjustment.

Three geocoding approaches will be applied to produce the GEC, EEC and GTC. The rigorous approach is the most accurate. The 3d interpolative approach provides comparable results but with higher throughput. The interpolative ellipsoid correction does not consider a DEM contrary to rigorous and 3d interpolative geocoding.

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