TERRASAR-X SAR DATA PROCESSING
RESULTS FROM COMMISSIONING AND EARLY OPERATIONAL PHASE

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ABSTRACT

TerraSAR-X, the first national German radar satellite, was launched June 15, 2007. SAR data taking and image generation started as early as four days after launch [i]. The commissioning phase was completed in December 2007 with the basic product release for StripMap and SpotLight mode, ScanSAR product release will follow in February 2008. Since beginning of 2008, basic products from all modes are provided to the scientific and commercial user community.

Due to a comprehensive system validation testing performed pre-launch on ground including both, the ground and space segment, the TerraSAR-X mission experienced an extraordinary smooth transition into the commissioning phase. Thousands of data takes were acquired and provided to the verification team already in the first months.

All level 1b user products are generated with the high-precision phase-preserving TerraSAR Multi-Mode SAR processor TMSP developed by the Remote Sensing Technology Institute of DLR (using a geocoding plug-in component provided by the German Remote Sensing Data Center). This does not hold for the ground segment itself, but also exclusively for the commercial direct access stations. Focus of its commissioning phase check-out was its fitness to deal with TerraSAR-X in-orbit SAR data characteristics which could not be assessed pre-launch on ground, namely the signal Doppler behaviour, calibration pulse processing influences and the resulting range and azimuth focusing quality in low and high contrast scenes. With the help of a detailed Doppler analysis, the correct working of the Total Zero Doppler Steering law applied during attitude control was shown. An observed beam mispointing with respect to the spacecraft attitude reference system was corrected based on Doppler deduced correction values.

A major commissioning phase activity was the qualification and verification of the various SAR basic products for the science and commercial users, a challenging task considering their multitude in terms of complex and detected product types from the various imaging and polarization modes which span a wide range of incidence angles. Specific care was given to their geometrical accuracy and phase-preserving characteristics which promise to support new exciting applications using TerraSAR-X.

The suitability of high-resolution TerraSAR-X data for interferometric processing was shown already in July 2007 as soon as the first repeat-pass data takes were available. Not only standard StripMap, but also SpotLight interferometry – a novelty in spaceborne SAR imaging - was demonstrated using the GENESIS interferometry system developed by and operated at DLR’s Remote Sensing Technology Institute. An example over an urban area is presented.

TERRASAR-X IMAGING MODES AND BASIC PRODUCT PORTFOLIO

The unique flexibility in instrument commanding in combination with the azimuth steering capability of the phased array antenna allows the data taking in a variety of different imaging modes. Baseline for the standard SAR product generation are

- StripMap configuration SM

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- four-beam ScanSAR configuration SC
- two sliding SpotLight configurations SL and HS.

The full performance incidence angle range covers 20º to 45º for SM and SC, 20º to 55º for SL and HS.

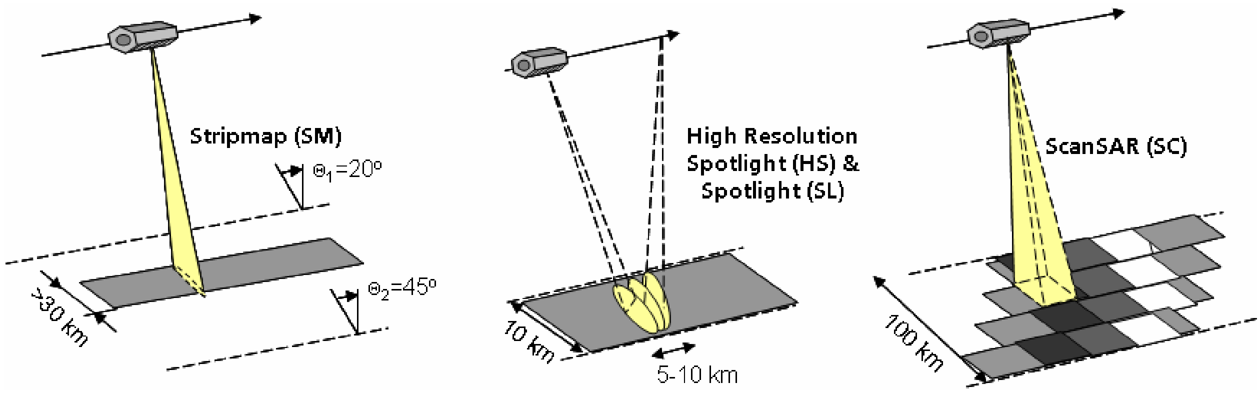

Figure 1: TerraSAR-X Imaging Modes Sketch

In addition to single polarization, data from SM, SL and HS are offered as dual polarization variants, but at cost of a double-sized azimuth resolution and a halved swath with in SM.

The basic products offered from the nominal imaging and polarization modes are specified in [ii] and consist of a

- single-look phase-preserving complex image SSC

and the derived detected multi-look variants

- MGD in ground range projection
- GEC in UTM (UPS) projection and ellipsoid corrected using an average scene height
- EEC in UTM (UPS) projection and ellipsoid corrected using a digital elevation model

The multi-look variants are offered in two flavours, the spatially enhanced SE and the radiometrically enhanced RE (SC products as RE variant only). Whereas the SE variants are essentially kept at their best quadratic resolution, a constant equivalent number of looks is chosen for the RE variants at the cost of reduced spatial but higher radiometric resolution and a considerable reduction in file size.

Detected image data are presented in GeoTIFF format, complex data in the DLR proprietary CoSAR format, parameter annotation is structured XML and thus human readable. Specific care is taken to provide the user with appropriate information to convert between instrument (range and azimuth) times and geographic location on ground.

In addition to basic products from the standard HS mode with its 150 MHz acquisition bandwidth, experimental products stemming from HS acquisitions with 300 MHz in single polarization mode were successfully qualified and characterized in the commissioning phase and are made available as well to the end user (who may use a specific order option).

PAYLOAD GROUND SEGMENT OVERVIEW

A central element in the TerraSAR-X ground segment is the payload ground segment PGS [iii] performing the reception of the SAR payload data, their processing and archiving and the distribution of the generated SAR basic products to users.

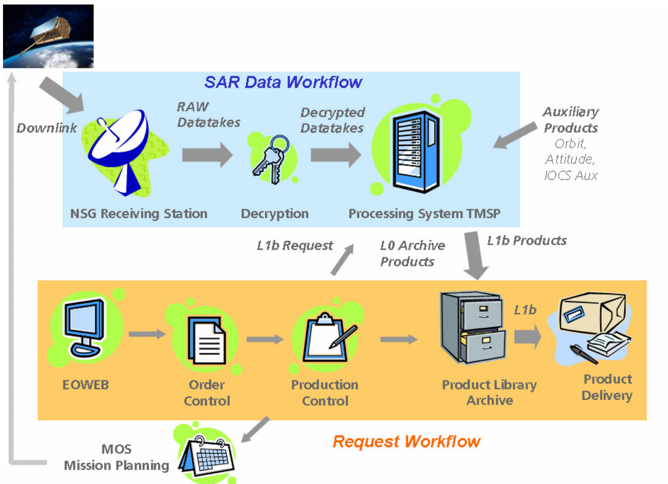

Figure 2: Schematic Payload Ground Segment Workflow Overview (courtesy: W. Balzer)

The user places a TerraSAR-X basic product order via EOWEB into the system. This order is further processed by the PGS ordering and production control and submitted to the mission planning entity from the mission operations segment MOS. Following successful planning, commanding and acquisition of the data take, the data are down-linked to DLR's ground station in Neustrelitz where they are decrypted and processed into L0 archival products by the Processing System TMSP. This process is data-driven and thus stimulated by data arrival only, i.e. the downlink followed later by orbit and attitude data provided off-line from MOS Flight Dynamics. The request for the L1b product to be generated is sent by the production control to the Processing TMSP as soon as commanding of a data take is confirmed by mission planning and thus well in advance of the downlink itself. The L1b product is generated by the TMSP, transferred into the product library (short-term archiving only) and delivered from there to the user. Both L0 and L1b processing use SAR instrument and calibration information from the auxiliary product provided by the instrument and calibration segment IOCS.

TERRASAR-X MULTI-MODE SAR PROCESSOR TMSP

Heart of the PGS SAR Data Workflow is the TerraSAR-X Multi-Mode SAR processor TMSP [iv], an in-house development of DLR's Remote Sensing Technology Institute (geocoding plug-in by German Remote Sensing Data Center). It's most prominent challenge is the consistent generation of phase-preserving products from all different imaging and polarization modes at varying incidence angles with a considerable throughput. Specifically the operational space-borne SpotLight constellation represents a novelty in that sense.

Whereas many conventional SAR processors are built and optimized for one of the imaging modes StripMap, ScanSAR and SpotLight, the TMSP uses a "one fits all" approach, i.e. the core SAR correlator module provides phase-preserving single-look slant-range complex data sets for all imaging modes. This is achieved through a hybrid focusing kernel based on the chirp-scaling algorithm variants as developed at DLR [v], [vi]. Derivation of multi-look detected products is consistently based on SSCs as an interim production stage.

In a "one fits all" sense, the TMSP is also used exclusively at the direct access stations of the commercial service segment. This will ensure that the same high basic product quality standards as set by the ground segment are met throughout the mission life time.

PRE-LAUNCH ON-GROUND TESTING AND TRANSITION INTO COMMISSIONING PHASE

Pre-launch integration testing of the PGS SAR data workflow was a challenging task, since no TerraSAR-X like data were available from other space-borne sensors, particularly due to the SpotLight technique with its high spatial resolution. Furthermore, the system had to cope with a number of

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TerraSAR-X specific downlinks scenarios like partial replays and data encryption. In collaboration with the space segment supplier Astrium and the ground segment instrument operations team, test data from the TerraSAR-X instrument itself in various presentations (instrument source packets, transfer frames and raw binary stream) were recorded and used both for subsystem integration and verification as well as validation tests spanning the whole PGS SAR data workflow up to the delivery of L1b products [vii].

In the end, a ground validation test starting with user orders and ending with the delivery of the generated L1b product was conducted. As far as we know, this type of end-to-end validation testing including not only real-time spacecraft operation from the mission control room, but also the real-time payload data acquisition, recording and specifically further processing by the payload ground segment (interrupted only by the time needed to physically transport the data on portable disk from spacecraft to the Neustrelitz ground station) is a novel approach in ground segment validation testing.

The vast exercising of the operational workflows needed in the commissioning phase enabled the successful switch-on of the ground segment directly following the launch with the activation of the first thousand order requests from the verification team. The first imaging data take was acquired on mission day 5 at 15:03:19 UTC and down-linked to Neustrelitz at 15:03:57. Its processing with the operational system required no processing parameter adjustment and no manual intervention at all, the generated quick-look could be printed "as is" and presented to the mission team at 16:00 UTC.

Figure 3: First TerraSAR-X Image Acquired and Processed at June 19, 2007. Scene: Novopetrovskiy near Volgograd in Russia, Tsimlyansk Reservoir / river Don. Mode: SM in HH polarization, beam 19 at an incidence angle of 51º. The zoom on the right hand side shows a train off the track. The image is also influenced by rain clouds as seen on the upper left side.

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COMMISSIONING PHASE OVERVIEW

The major activities in the commissioning phase comprised the

- characterization and verification of the SAR instrument
- overall SAR system performance characterization
- orbit and attitude product accuracy assessment and verification
- geometric and radiometric SAR calibration
- SAR product verification and characterization
- commercial direct access station check-out support
- operational load tests including the commercial service segment

For detailed results refer to [viii], [ix], [x], [xi] and [xii]. The commissioning phase was completed according to plan. From mid November on, data takes are acquired in their final operational setting with respect to instrument commanding and parameter setting, the built-up of the catalogue for external users started accordingly.

TERRASAR-X MULTI-MODE SAR PROCESSOR CHECK-OUT

The check-out out of the TMSP SAR processor served two purposes: On one hand, the fitness of the SAR processor to deal with the TerraSAR-X in-orbit data had to be proven. On the other hand, it was only through SAR processing itself that a number of in-orbit data characteristics can be assessed and if necessary fine-tuned [xi], [xiii].

Range and Azimuth Focusing Quality

Instrument internal calibration pulses provide the reference function for range focusing as well as instrument gain and phase drifts over an acquisition. A major commissioning activity performed by the instrument calibration and the TMSP team was the fine-tuning of the calibration pulse commanding and the introduction of a dedicated range reference chirp sequence at the beginning of the data take. Finally the originally proposed range reference function modelling by a polynomial was replaced by the application of a digitized replica.

The range and azimuth spectral weightings were also changed with respect to its original specification to achieve better side-lobe suppression, specifically important in imaging urban and industrial areas where the high spatial resolution of the system exposes high numbers of strong scatters leading to high image contrasts. As well, the level of azimuth ambiguities is decreased. By enlarging the azimuth processing bandwidth and the azimuth steering angles in SpotLight mode, the resulting impulse response broadening could be compensated. However, due to the fixed range bandwidth, the range resolution values are slightly worsened with respect to the original product specification. The updated performance values are found in the basic product specification [ii].

Doppler Analysis

The assessment of the in-orbit Doppler behaviour and an accurate knowledge of the beam pointing are an important prerequisite for processing and product verification.

The Doppler centroid is estimated from the signal data itself (baseband Doppler) and in addition derived from the attitude information (geometric Doppler). Fusion of both Doppler estimates leads to the Doppler used during processing.

Comparing the baseband signal estimates with the geometrically derived Doppler values revealed a mispointing with respect to the attitude reference frame. After alignment of on-board coordinate systems, the baseband signal estimates and the geometrically derived Doppler show a good consistency. In addition, the margins expected from the Total Zero Doppler Steering [xiv] are met as

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well and thus the suitability of the applied steering law is proven. The remaining absolute Doppler offset is found to be within +/- 120 Hz.

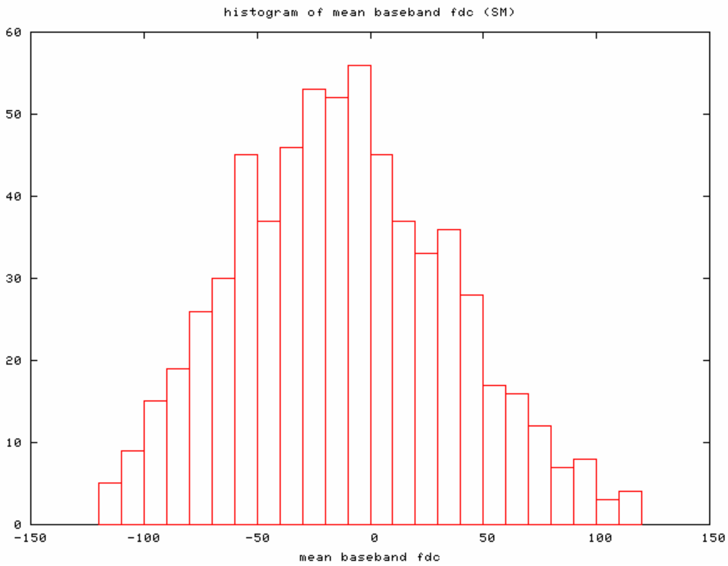

Figure 4: Mean Base-Band Doppler Measured in Operational SM Data Takes From Early Operational Phase

BASIC PRODUCT VERIFICATION AND CHARACTERIZATION RESULTS

Major results from the basic product verification and characterization activity performed in the commissioning phase are presented:

Spatial Resolution

The spatial resolution in the *SSC* products is governed by the SAR system performance and instrument commanding as well as the processing bandwidth and windowing applied during processing. The sampling rates, azimuth and range, of StripMap SSC products is kept to the same rates as on acquisition. In the case of a change of the pulse repetition frequency PRF within a StripMap data take the SSC product is resampled in azimuth accordingly to the highest PRF. Resampling in azimuth is inherent to the processing of ScanSAR and SpotLight data.

The following table lists the nominal SSC slant range and azimuth spatial resolution for the basic imaging and polarization product variants [ii]:

Imaging and Polarisation Mode	slant range resolution [m]	azimuth resolution [m]
SM 100 MHz single (far beams)	1.8	3.3
SM 150 MHz single (near beams)	1.2	3.3
SM 100 MHz dual (far beams)	1.8	6.6
SM 150 MHz dual (near beams)	1.2	6.6
SL 150 MHz single	1.2	1.7
SL 150 MHz dual	1.2	3.4
HS 150 MHz single	1.2	1.1
HS 150 MHz dual	1.2	2.2
HS 300 MHz single	0.6	1.1

For the detected product types *MGD*, *GEC* and *EEC* in the *spatially enhanced resolution variant SE*, the best quadratic spatial resolution on ground is principally taken as design criterion. This means that in general the better resolution value is broadened to the worse one, allowing for radiometric looks in some cases, specifically at higher incidence angles. Exceptions are e.g. HS acquisitions in 150 MHz for which the better azimuth resolution is kept. Figure 5 gives an example of the measured spatial resolution for a 150 MHz HS acquisition in SSC, MGD and EEC SE products.

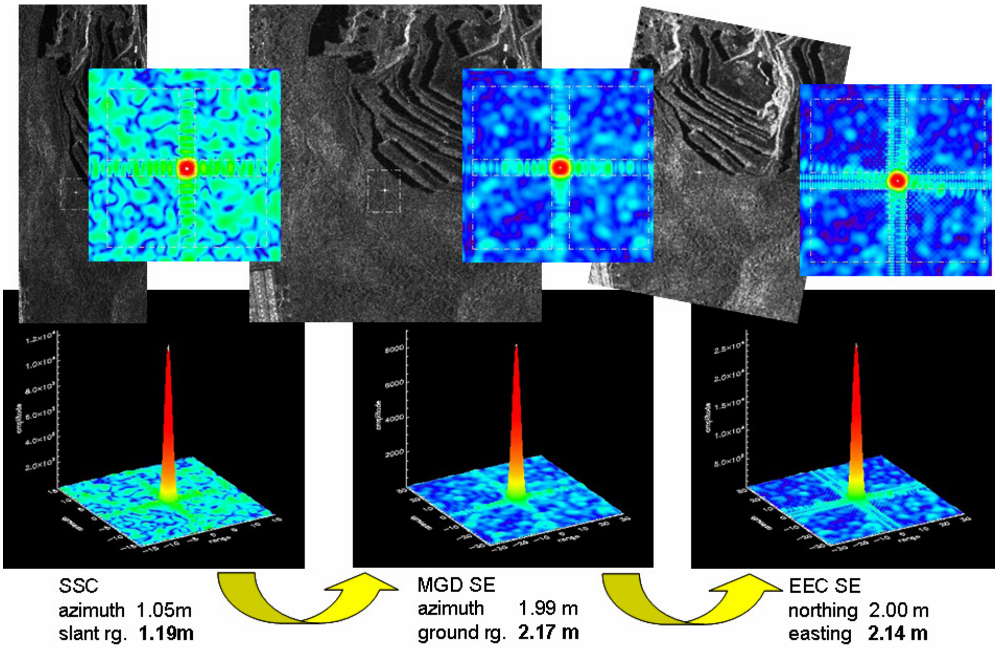

Figure 5: Comparison of Measured Impulse Response Function of Barcelona Corner in HS 150 MHz Product Variants at 34º Incidence Angle

Figure 6 and Figure 7 illustrate the expected detected spatial resolutions for all imaging and polarization modes in dependence of the incidence angle range. The sphere diameter is proportional to the resolution. Figure 8 shows measured HS spatial resolution values in comparison to the specified ones taken from the original product specification.

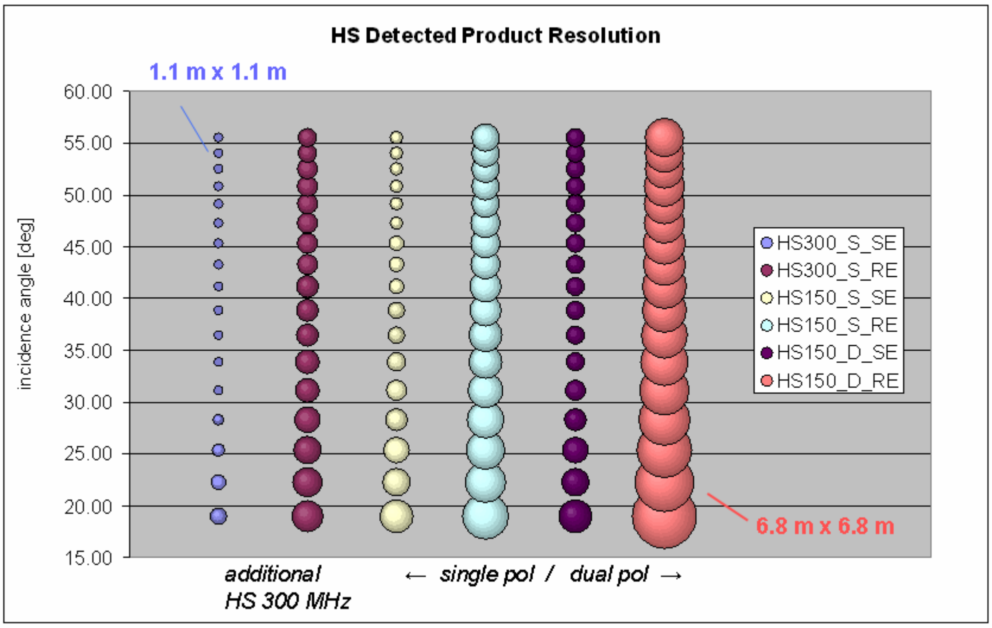

Figure 6: Specified Spatial Resolution for Detected Products from HS 150 MHz / 300 MHz Modes

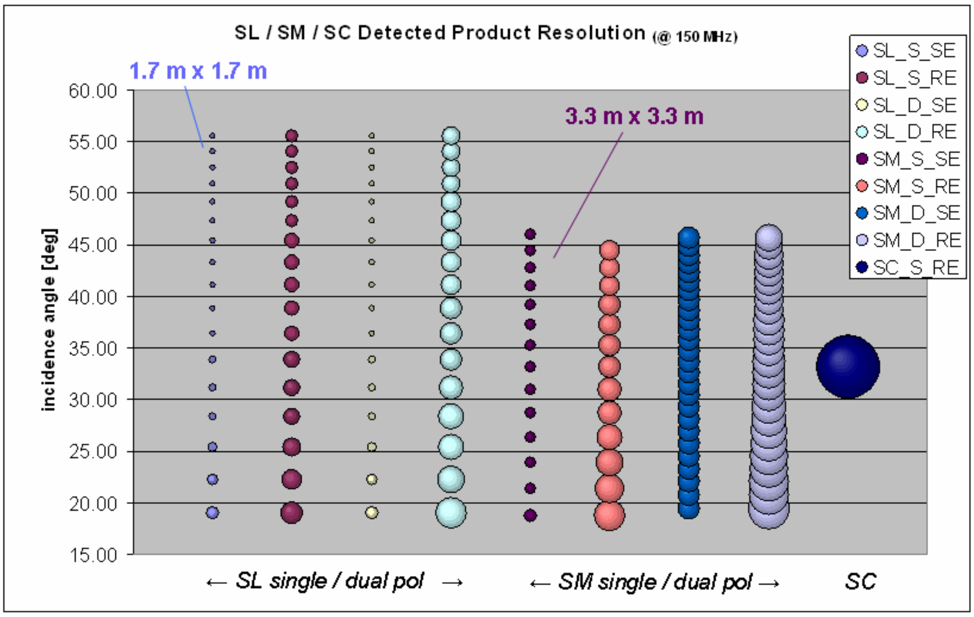

Figure 7: Specified Spatial Resolution for Detected Products from SL, SM and SC Modes

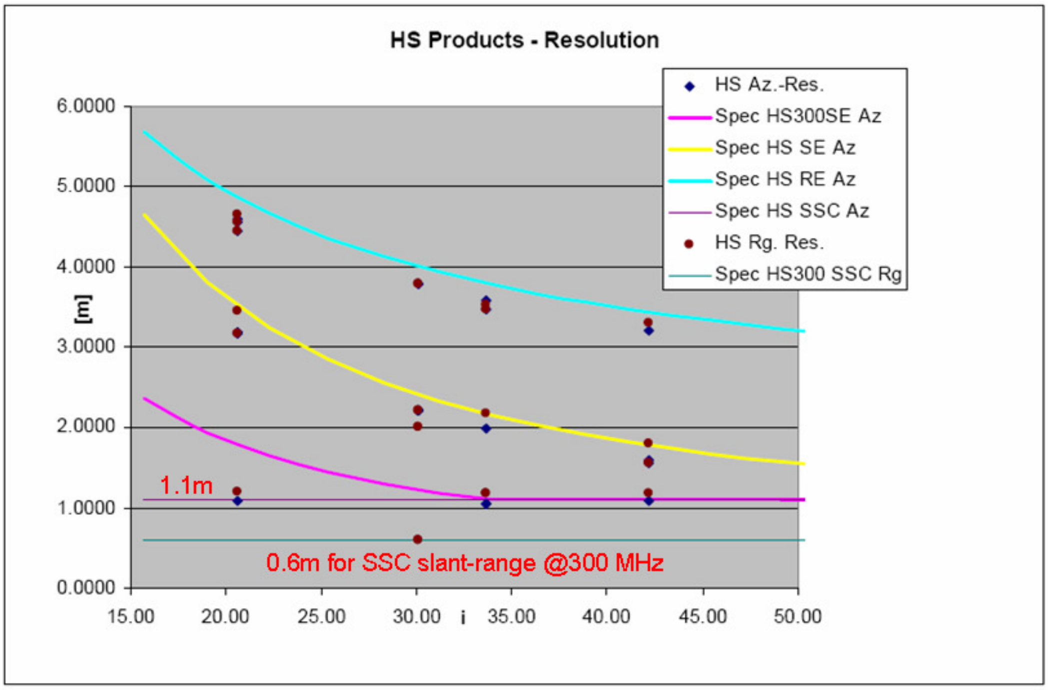

Figure 8: Measured vs. Specified Spatial Resolution In Dependence Of Incidence Angle

Detected products represented in the *radiometrically enhanced resolution variant RE* are designed such, that the equivalent number of looks is kept close to a value of 6.5 to achieve uniform radiometry.

Relative Geometric Accuracy

A *relative geometric accuracy* on sub-pixel level was already observed in the early commissioning phase after TerraSAR-X had reached its final reference orbit. This was further confirmed by the early interferometric processings and finally confirmed as part of the geometric calibration campaign. Multi-temporal "blind" overlays of GEC or EEC images are obtained using the geometrical product annotation only. This is e.g. shown by the multi-temporal overlay of radiometrically cali-

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brated GEC SE images of three Sydney acquisitions in HS 300 MHz mode as shown in Figure 9. The white pixels impressively demonstrate the “intrinsic” co-registration of the geometrically calibrated L1b products.

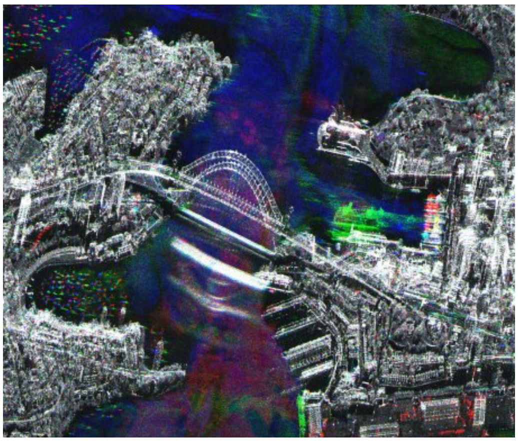

Figure 9: Zoom into Harbour Bridge Area of Multi-Temporal GEC SE Overlay Built From Three HS 300 MHz Acquisitions. The relative accuracy is in the subpixel range

Absolute Geometric Accuracy

The absolute geometric accuracy obtained in SAR products is determined by a number of influencing parameters, namely the

- a most accurate knowledge and application of the orbit position and velocity
- a most exact knowledge and application of instrument internal range time delays
- an assessment of the atmosphere induced range delay
- an assessment of possible further systematic range and / or azimuth time shifts not being accountable to known instrument effects

The accuracy assessment of the most precise orbit information – the science orbit – was performed by the MOS Flight Dynamics team based on satellite laser ranging measurements. A three-dimensional accuracy of better than 10 cm (1 σ) in the RMS (root mean square) sense was reported.

A number of reference targets (corner reflectors) were deployed and their location measured with GPS by the calibration team in the frame of the geometrical calibration campaign, then evaluated together with the TMSP team in the SSC products. This resulted in a fine-tuning of the instrument related time delays to be accounted for during SAR processing and the annotation of a systematic azimuth time shift.

The resulting ***absolute pixel location accuracy*** in SSC products is **within 1 m** and thus well below the originally required 2 m margin. The range delay induced by the atmosphere as well as the systematic azimuth time shift are annotated in the geo reference grid for the L1b products and are taken into account when transforming from the SAR range and azimuth time into geographical location information as done for each grid point.

The geometric accuracy of the detected products in cartographic UTM (UPS) projection strongly depends on the accuracy of the height information used during map projection. Since the GEC only uses an average height, its geometrical accuracy is limited and deviations in the range of tens of meters may be observed. The accuracy of the EEC directly depends on the accuracy of the under-lying DEM (currently SRTM C-Band 1 arc sec at best) used during projection since the height error directly translates into a geographical location error.

Product Location Accuracy and Extent

When ordering a scene from SpotLight mode, a user is guaranteed that the delivered product covers at least 10 km x 10 km in SL and 5 km x 5 km in HS mode around the ordered scene centre coordinates. As for all SAR data acquisitions, the Doppler centroid and its variations strongly influence the raw data azimuth start and stop times. Whereas the duration of data taking in StripMap or ScanSAR configuration can be quite easily extended by considerable margins, the situation is by far more complex for the SpotLight mode due to the azimuth beam steering. The automatic TMSP check of the deviations between the ordered and the processed scene confirms that the SL and HS products are within their specified extent and location accuracy. Note that the 300 MHz HS products show a reduced range extent (still centred around the ordered scene centre) due to the on-board echo buffer limitations, in some cases also a shortened azimuth length.

Important TerraSAR-X system features set the base for this high location accuracy achieved in SpotLight data taking: The *antenna look direction* is accurately measured with star trackers and thus reduces the pointing error on ground to less than 20 m. The attitude is actively controlled by the *Total Zero Doppler Steering* law which reduces the Doppler offset to less than 120 Hz. Based on GPS measurements, a *data take start time correction* value is determined and applied on-board with respect to the assumed predicted value which effectively shifts the acquired scene towards the ordered location.

Nominal scene extents and product location accuracies have been also confirmed for the SM and SC products.

Radiometric Performance

A relative radiometric accuracy of 0.31 dB is and an absolute radiometric accuracy of 0.6 dB (taking a conservative margin for the long-term instrument stability) is reported by the calibration team [x]. Since the TMSP performs the antenna pattern correction based on digital elevation model information, this radiometric performance is essentially passed through into the user products.

INTERFEROMETRIC PROCESSING AND PERSISTENT SCATTERER POTENTIAL

Interferometric processing using the DLR developed GENESIS system was started very early in the commissioning phase in order to assess the phase stability of the instrument itself and the phase-preserving characteristics of both the TMSP and its generated complex SSC products. Specifically the first *spotlight interferogram* has been generated already in July 2007, right after the first repeat pass image pairs were available from DLR's major interferometric test site Las Vegas [xv], [xvi], [xvii].

Already these first interferograms impressively demonstrate the potential of the TerraSAR-X system with its short wave length combined with the 11-day repeat pass orbit (with a maximum allowed deviation of +/- 250 m with respect to its defined reference orbit), specifically over man-made structures [xvi] and urban areas [xv], when compared to the current C-band sensor with their higher wavelength and longer repeat cycles.

Since a series of high-resolution spotlight scenes over Tokyo was acquired as part of the direct access station check-out support given to the commercial service segment, spotlight interferometry was e.g. exercised over the urban area of Tokyo.

Figure 10: Tokyo, Amplitude Image, HS 150 MHz, Single Polarization HH, Beam spot_058, Incidence Angle 42º

Besides a 150 MHz pair, five 300 MHz acquisitions were available and interferometrically processed. Figure 11 below shows one of the obtained phase images.

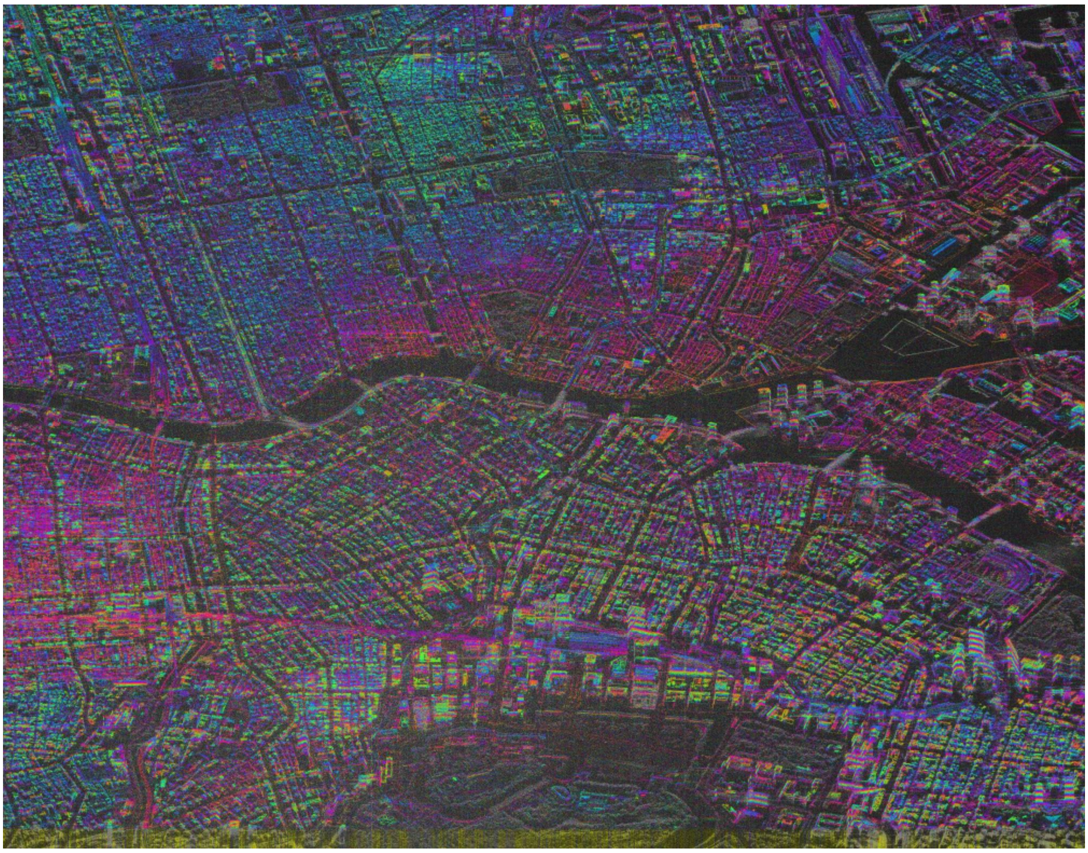

Figure 11: Tokyo 300 MHZ HS Phase Image From (05-OCT-2007 / 16-OCT-2007 Interferogram. The baseline is 158 m and the fringe frequency 43.8 m.

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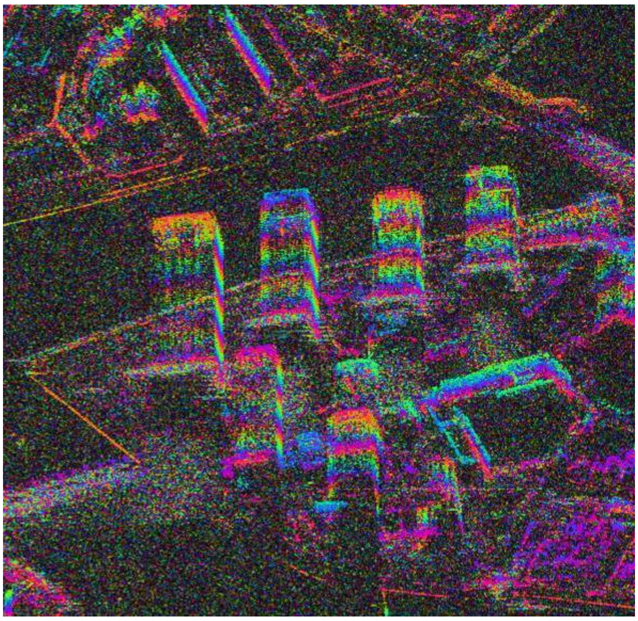

Figure 12: Zoom Into Tokyo Phase Image of 05-OCT-2007 / 16-OCT-2007 Interferogram

Even by analysing a series of amplitude images only one gets a good hint how TerraSAR-X interferometry will revolutionize the persistent scatterer techniques. We zoom into the lower middle part of the Tokyo scene showing the Tokyo River Island (image rotated by 90º to the left to “raise” the high-rise buildings). Of particular interest is the St. Luke’s Tower clearly visible in the lower image part in the middle.

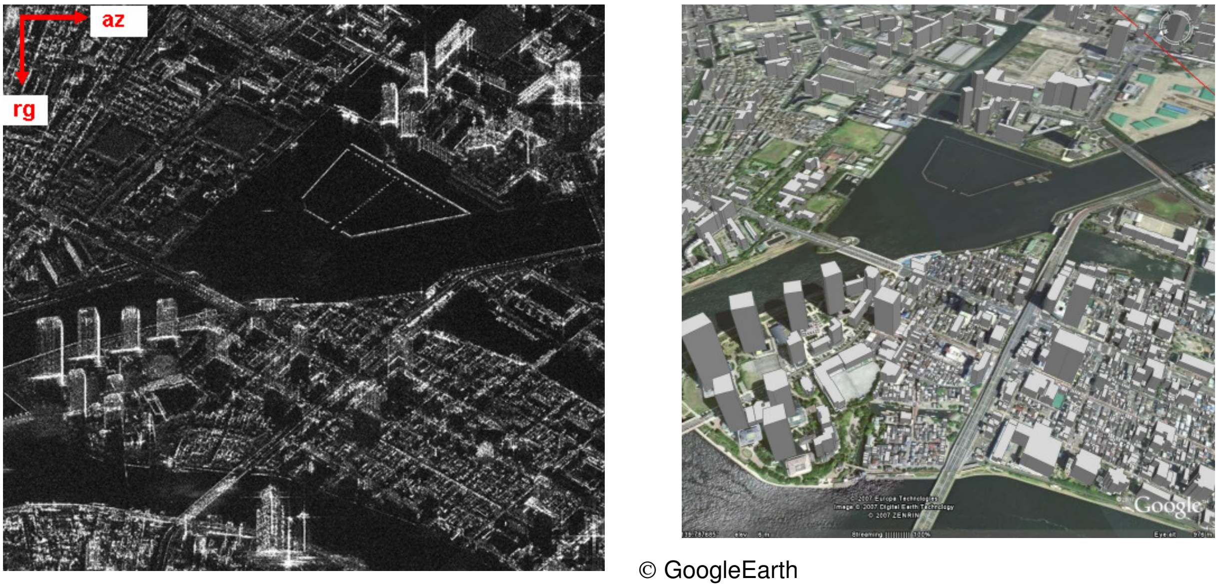

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Figure 13: Part of Tokyo Scene: Tokyo River Island

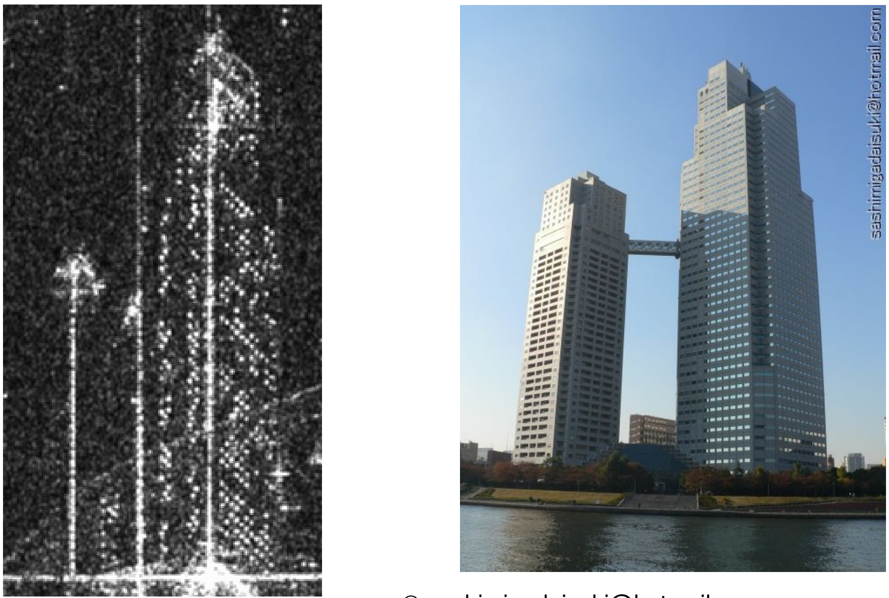

Figure 14: St. Luke's Tower in Tokyo: Amplitude Image (300 MHz HS from 02-SEP-2007) vs. Photography

A regular pattern of points is clearly identified and indicates the presence of a multitude of persistent scatterers stemming from one building only, an assumption which is supported analysing a series of images and identifying the white pixels in the multi-temporal RGB image overlay as shown in Figure 15.

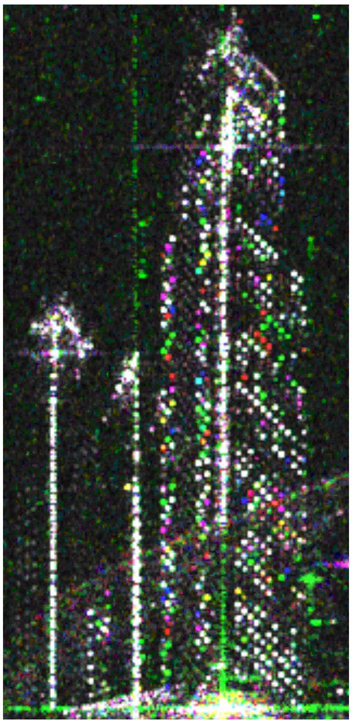

Figure 15: St. Luke's Tower in Tokyo: Multi-Temporal Amplitude Image Overlay (red: 05-OCT-2007, green: 02-SEP-2007, blue: 16-OCT-2007)

Persistent scatterer candidates may be identified as the bright pixels in an image representing each resolution cell in terms of its expected signal clutter ratio. This is obtained by temporal power averaging over all scenes in an interferometric stack. The images below are taken from a five

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scenes Tokyo stack acquired in HS 300 MHz configuration. Figure 16 shows the River Island area with thousands of candidates. The colour coding from green to red indicates the quality of the scatterers with red marking the best ones.

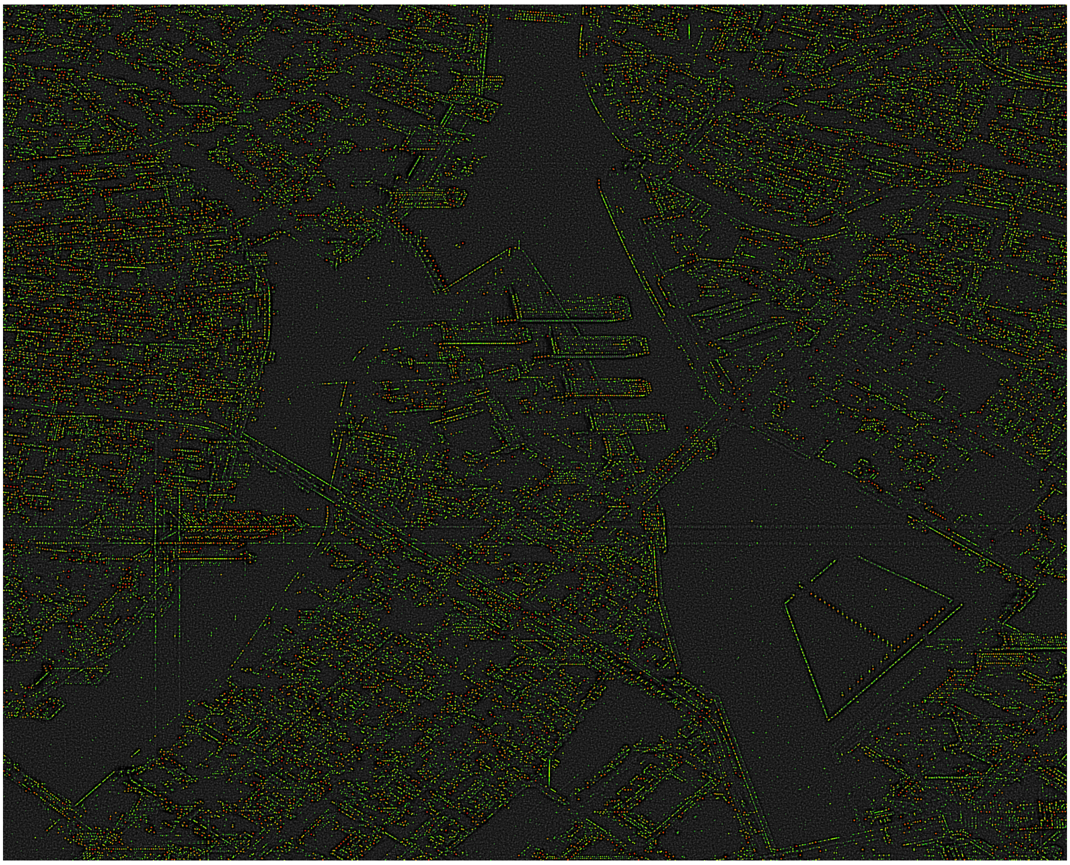

Figure 16: SCR Image of Tokyo River Island

A remarkable building with a most regular red scatterer pattern is located in the left part of the Tokyo, just south of the Imperial Palace Garden:

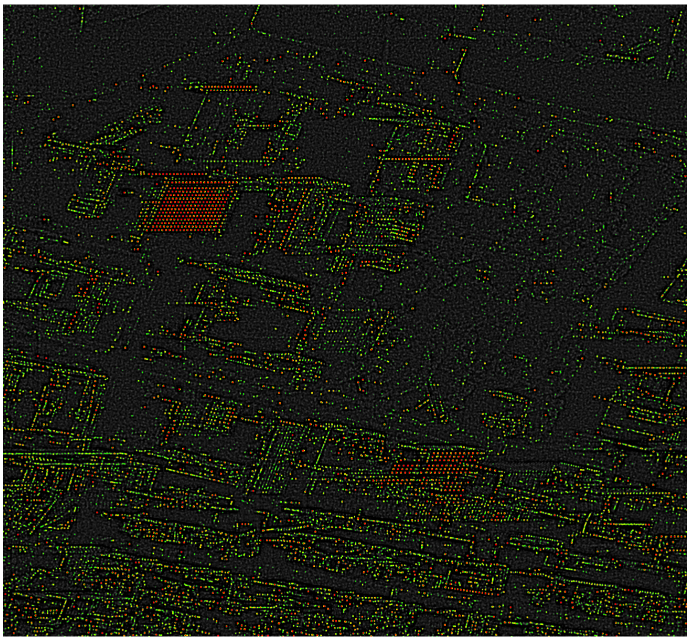

Figure 17: SCR Image of Region South of Imperial Palace Garden in Tokyo

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As shown in [xv], the persistent scatterer density obviously improves significantly in comparison to previous C-band sensors like ERS, ENVISAT/ASAR and Radarsat-1. The TerraSAR-X wave length of 3.1 cm leads to a doubling of the sensitivity for displacement measurements (1.5 cm per cycle). The frequent acquisition opportunities (11-day repeat cycle) allow a fast measurement stack built-up. An individual building may show hundreds of persistent scatterers allowing the measurement of building structural stress and a better assessment of displacement effects.

CONCLUSIONS

The payload ground segment, specifically the TerraSAR-X Multi-Mode SAR Processor TMSP, has proven its fitness to generate and distribute high quality products. After their successful commissioning, TerraSAR-X basic products are now available for science and commercial users. Both the spatial resolution and the absolute geometric location accuracy in the one meter range mark the beginning of a new era of space-borne SAR imaging exploitable by the scientific user community. This specifically holds for interferometric evaluations.

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