The TerraSAR-X Payload Ground Segment: Pre-Launch Status and Performance

B. Schättler, H. Breit, T. Fritz, M. Eineder, E. Schwarz, H. Damerow, U. Balss, E. Boerner, W. Balzer
Remote Sensing Technology Institute
German Remote Sensing Data Center
German Aerospace Center (DLR)
82234 Weßling, Germany
Birgit.Schaettler@dlr.de

I. Abstract and Introduction

TerraSAR-X, the first national German radar satellite, is scheduled for launch in 2006. It carries an X-band high-resolution synthetic aperture radar instrument featuring imaging modes like StripMap, ScanSAR and, particularly, SpotLight in a variety of different polarization modes [1] [2]. Thus the TerraSAR-X mission will provide both the scientific [3] and commercial [4] user community with a variety of products from advanced SAR modes.

The TerraSAR-X space segment was built by EADS Astrium GmbH, the ground segment by DLR [5].

One central ground element is the payload ground segment (PGS) which is responsible for the reception of the SAR payload data, their archiving and processing and the distribution of the generated SAR basic products to users [6]. It is currently in its final pre-launch integration and test phase.

To test the operational SAR data processing chain under most realistic TerraSAR-X conditions, specific SAR proving grounds have been set up. These are supplemented by a number of test data generation tools and - most important - by a considerable amount of test data generated using the satellite SAR instrument itself and made available for ground segment testing. Thus, an extensive PGS SAR test bed is currently in place and used for both functional and performance end-to-end tests.

This paper depicts the various PGS elements for SAR data reception, transcription and processing and summarizes their functionality and design in terms of hard- and software.

Both the PGS SAR test bed and the performed end-to-end tests are described. Selected test results which characterize the PGS pre-launch performance are reported.

II. TerraSAR-X Imaging and Polarization Modes

Figure 1 and Table 1 below recall the nominal TerraSAR-X imaging modes and their important characteristics.

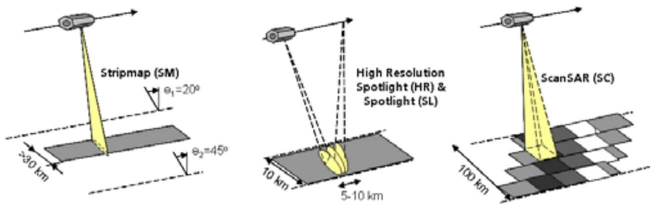

Figure 1: TerraSAR-X Nominal Imaging Modes

	StripMap SM	SpotLight HS, SL	ScanSAR SC
swath width	30 km (single pol.) 15 -30 km (dual pol.)	10 km azimuth extent: 5 / 10 km (HS / SL)	100 km
full performance incidence angle range	20° - 45°	20° - 55°	20° - 45°
azimuth resolution	3 m (single pol.) 6 m (dual pol.)	1 m / 2 m (HS , single / dual pol.) 2 m / 4 m (SL , single / dual pol.)	17 m (1 look, 4 beams)
ground range resolution @ 150 MHz chirp BW	1.7 m - 3.5 m (@ 45°.. 20°)	1.5 m - 3.5 m (@ 55°..20°)	1.7 m - 3.5 m (@ 45°.. 20°)

Table 1: TerraSAR-X Nominal Imaging Modes Characteristics

III. Basic Product Portfolio

A. *Basic Product Types*

The basic product portfolio [7], [8] offered by the ground segment comprises

- single-look slant-range complex SSC
- multi-look ground-range detected MGD
- geocoded ellipsoid corrected GEC
- enhanced ellipsoid corrected EEC

products for all nominal imaging modes provided by the TerraSAR-X instrument

- StripMap SM

- High-Resolution SpotLight HS
- SpotLight SL
- ScanSAR SC

in single and dual polarization. The detected products are available in two flavors, the spatially enhanced (SE) one for an optimum quadratic spatial resolution and the radiometrically enhanced (RE) one for an optimized radiometric resolution.

Note, that for SC no dual polarization data and only the RE variant for the detected products are foreseen. The SSC is regarded as an experimental product.

The ***SSC*** product contains magnitude and phase information. It is kept in the so-called natural pixel spacing governed by the PRF in azimuth and the range sampling rate.

The multi-look ***MGD*** product is oriented along flight direction and along ground range with an equidistant pixel spacing in range and in azimuth. The same range mapping polynomial is used for all range lines. Thus the geo-referencing is not geometrically precise, however does not suffer from interpolation artifacts.

The multi-look detected geocoded ***GEC*** product is projected and resampled to either UTM or UPS with WGS84 as earth reference model using one average terrain height for the whole underlying scene. The pixel spacing is constant in easting and northing. Thus a homogenous quality reproducible in time and space is achieved. However, the pixel localization accuracy may be off by hundreds of meters depending on the imaged terrain.

For the multi-look detected enhanded ellipsoid corrected product ***EEC***, the projection and resampling to UTM/UPS based on WGS84 is done using a Digital Elevation Model. Thus, terrain induced distortions are corrected and a very precise pixel localiziation accuracy – meter level – is achieved. The achieved accuracy strongly depends on the accuracy of the underlying digital elevation model.

In addition to the basic products, which are the L1b products above acquired in the nominal imaging modes, also experimental products – namely SSC for ScanSAR and products from the twin and quad polarization mode – are generated by PGS and may be operationally distributed later during the mission. Note, that a quad polarization acquisition can only be achieved through the experimental dual-receive antenna configuration which uses the redundant receiver chain in addition to the primary one and thus will be operationally restricted. Products from that mode will only be distributed, if the achieved quality and performance is regarded as sufficient.

B. Product Structure and Format

The product structure and format are discussed in detail in [8].

The products are presented as a set of product components in a hierarchical directory structure which allows the inclusion of further annotation and data sets, e.g. when submitted the basic products to a value adding process. This feature is furthermore supported by using the Extensible Markup Language XML for the product annotation. The binary image data are stored in GeoTIFF format for all detected products and in the DLR proprietary COSAR (*co*mplex *SAR*) format which specifically supports the presentation of complex ScanSAR products.

IV. SAR Data Workflow Of Payload Ground Segment

A. Major Tasks

Major tasks of the Payload Ground Segment ***PGS*** are the generation of the Basic Products to be delivered to users and the reception and long-term archiving of all TerraSAR-X raw data. These two tasks are fulfilled by the so-called SAR Data Workflow [9] of the PGS consisting of the:

- Multi-Mission Neustrelitz Ground Station *NSG*
    - reception of SAR payload data
    - frame synchronization, de-randomizing, Reed-Solomon decoding
    - reconstruction of data take files in instrument source packet format from the downlinks/replays
- Transcription System *TSC*
    - decrypton of data take files
    - data take assembly in case of partial replays and / or data from dual-receive antenna configuration
- Processing System TMSP *PS-TMSP*
    - generation of L0 archive products
    - generation of L1b user products

B. System Layout and Operational Scenarios

Figure 2 below shows a diagram of the PGS SAR Data Workflow.

The TerraSAR-X SAR payload data are received in X-band in the multi-mission receiving station system ***NSG*** which operates several S-/X-band antenna systems. A core element is the X-band Direct Archive System DAS manufactured by MDA, Canada, which performs the recording of the high-speed serial data and their conversion into computer-compatible raw data. In case of TerraSAR-X, these raw data are the still encrypted, but already instrument source packet reconstructed data take files. NSG also supports the TerraSAR-X S-band data reception. All receiving components are connected via matrices which allow a flexible signal routing and device usage. A comprehensive station control software system performs the scheduling as well as the monitoring and control of all data reception activities and devices [10]. Essential planning input are the downlink info files provided by the mission operations segment MOS through which NSG is informed about the satellite contacts and their detailed content (replays, data take files). The received data take files are provided via ftp at a pickup point for further processing by the TSC.

The ***TSC*** essentially performs the decryption of these data takes based on information in the key info files supplied by MOS. In case, that a data take file is down-linked in portions (partial replay) and/or from the dual receive antenna configuration, the TSC gathers the individual file segments and/or channels before providing them as a whole at the pickup point for the subsequent processing by PS-TMSP.

The ***PS-TMSP*** performs a screening of all incoming data takes. During base screening, high-level annotation (e.g. start and stop UTC times) is generated and calibration and noise data are extracted and stored in separate files for further off-line analysis. For all imaging data takes, the subsequent SAR screening performs SAR data processing to derive a complete set of SAR annotation parameters, quick-look images and map plots. The original input data take is stored together with the derived information and data as L0 archive product in the PGS product library.

This completes the data-driven workflow for the automatic generation and archiving of the L0 product which is only monitored by the PGS production control.

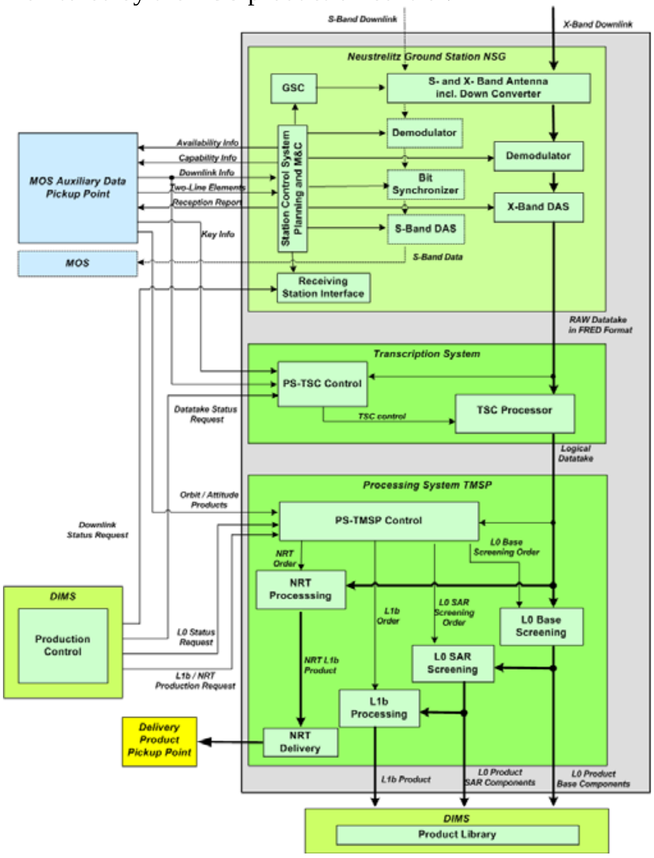

Figure 2: PGS SAR Data Workflow

For L1b processing, the ***PS-TMSP*** obviously needs production requests (sent from PGS production control) which specify the product to be generated. The standard L1b processing is based on a previously generated L0 archive product. The generated product is moved into the PGS Product Library for further delivery to users within 24 hours once all needed input data (specifically the external orbit data) are available. The PS-TMSP also supports a near-real time (NRT) processing scenario. In this case, the processing is directly based on an incoming data take using predicted orbit and reference attitude information. The generated NRT product is directly placed onto the Delivery Product Pickup Point.

C. *TerraSAR-X Mult-Mode SAR Processor TMSP*

Heart of the PGS SAR Data Workflow is the TerraSAR-X Multi-Mode SAR processor TMSP [11]. 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 novum 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 [12], [13], [14].

A digital 10 arc sec reference elevation model is consistently applied throughout the processing chain for the derivation of geolocation information, velocity (B) parameter determination and the radiometric corrections imposed by the projected elevation antenna pattern.

A geometrical Doppler determination is performed based on antenna pointing information derived from the attitude products, the digital elevation model, the beam pointing and orbit info. A fusion of this geometrically determined behavior with the base-band estimates obtained from the signal data is done to derive the Doppler processing parameters (including the PRF ambiguity estimation). Note, that the TerraSAR-X mission applies the DLR developed total zero Doppler steering which reduces the earth rotation induced Doppler frequency very close to zero [15].

D. *Auxiliary Data Interfaces*

In addition to the SAR payload data, external auxiliary data are needed to support the data-driven PGS SAR data workflow for the L0 archive product generation and the request-driven L1b user product generation as listed in Table 2 below.

System	Needed Information	From	Name
NSG	downlink planning information like start and stop time of downlink event	MOS Mission Planning	downlink info file
	orbital data for receive antenna tracking	MOS Flight Dynamics	two-line elements
TSC	replay planning information for decryption	MOS Mission Planning	downlink and key info file
TMSP	orbit product with state vector information	MOS Flight Dynamics	predicted quicklook rapid science
	attitude product with SAR antenna pointing information	MOS FD	reference standard
	instrument characterisation and calibration parameters	IOCS	IOCS auxiliary product

Table 2: Auxiliary Data Interfaces Overview

E. Processing Storage and Hardware Environment

The TSC and PS-TMSP processing systems are hosted by a TerraSAR-X specific storage and hardware environment. The processing is done on six SUN V890 computers, each equipped with 8 double core CPUs (1.5 GHz each). A storage area network SAN enables a fast data access from all nodes. The SAN is controlled by two SUN V440 controller nodes which also host the PS-TMSP control software responsible for the scheduling and load balancing of the processing nodes.

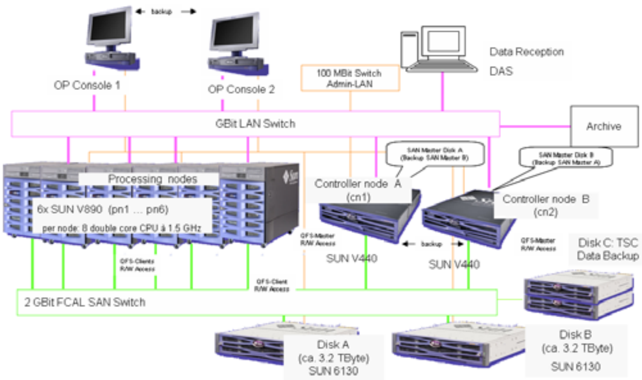

Figure 3: Processing Storage and Hardware Environment

V. SAR DATA WORKFLOW TEST BED

The pre-launch testing of the integrated PGS SAR data workflow is a challenging task, since no TerraSAR-X like data are available from other space-borne SAR sensors, particularly due to the operational SpotLight technique and its high spatial resolution. Furthermore, the NSG and TSC systems have to cope with a number of TerraSAR-X specific downlink scenarios like partial replays, data encryption, etc.

Therefore, special attention has been paid to the development of test tools which support the generation of suitable test data and their application at various stages within the SAR data workflow. These test tools have been defined such, that they are not only operated “stand-alone” for specific subsystems and test purposes, but also run interactively “in chain” to allow a closed loop testing. Since various test data sets from the TerraSAR-X instrument itself (stemming from the Astrium on-ground test program) were available at a very early stage, the original concept to simulate data take files in instrument source packet structure was abandoned in favor of a consistent inclusion of these Astrium test data throughout the whole PGS integration phase.

Furthermore, the TMSP processor was adjusted such, that it is able to directly process the Astrium supplied data without any further manipulation to L0 and even L1b products despite the fact, that only noise is available instead of SAR echo data. Thus, a thorough TMSP testing is enabled by a two-fold test approach. The algorithms and generated products are verified based on simulated SAR echo data with TerraSAR-X characteristics for a very limited number of data takes (essentially one representative per imaging and polarization mode). Its throughput, robustness and operational behavior is tested using a high number of various data takes as acquired and recorded in the Astrium on-ground test environment.

The SAR data workflow test environment consists essentially of the following tools, see middle column in Figure 4 below.

The *ISP Header Dump* extracts the header data from the Astrium supplied data takes in instrument source packet format and provides ASCII dumps of them. An off-line evaluation of such a header dump provides the details of the acquired data take with respect to acquisition parameters (modes, beams, scene times) and its configuration (e.g. presence of cal and noise data). These parameters are an essential input for the DLR *SAR Point Scatterer and Doppler Noise Simulator*. Together with information retrieved from the IOCS auxiliary product (beam info, antenna patterns) and reference orbit and attitude information supplied by MOS Flight Dynamics, the point scatterer characteristics (e.g. Doppler, B-parameter, antenna pattern weighting) are determined. Thus, SAR echo data consistent to the supplied data take files are simulated.

The *ISP Data Exchanger* reads the Astrium supplied data take files and replaces their SAR echo data (noise during on-ground testing) with the DLR simulated SAR echo data while the instrument source packet structure including all calibration and noise data remains unchanged. If necessary, administration parameters like the replay and data take file numbers can be changed. These data takes can be directly submitted to the Processing System TMSP via the TSC – TMSP pickup point and processed.

The *Replay Constructor* is a UNIX tool which just attaches individual data takes to one replay, the *Encryption Tool* encrypts those replays.

The *Downlink Generator* takes a number of encrypted replays, generates the transfer frame format and finally the serial raw data stream applying all requested data transformations steps like Reed-Solomon encoding and randomization.

The *Downlink Simulator* records the serial raw data stream and plays it back with the required clock speed and stability for further direct ingestion into the NSG DAS system or alternatively into the test modulator and via a fiber optic link into the receiving antenna system.

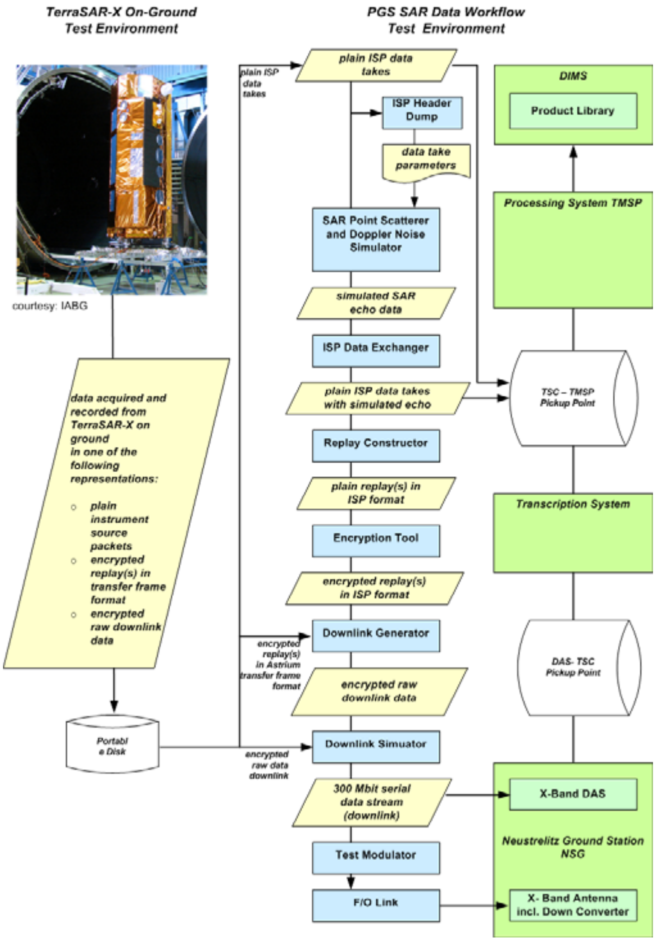

Figure 4: PGS SAR Data Workflow Test Environment

The left column in Figure 4 represents the important test data source being TerraSAR-X itself. The serial raw data stream of the downlink are captured by the data evaluation unit of the check-out equipment which is able to reconstruct them into either transfer frame or even instrument source packet structure including data decryption. The recorded test data are stored on portable disks for their transport to PGS. Depending on the level of reconstruction already done at Astrium side, they have to be ingested into the appropriate module of the SAR data workflow test bed.

The PGS tests are further supported through the provision of appropriate orbit and attitude information by MOS Flight Dynamics and the IOCS auxiliary product by the Instrument and Operations Calibration Segment IOCS.

With start of the ground segment integration phase, a consistent reference orbit (TerraSAR-X flies a 11-day repeat orbit) was established throughout the ground segment in all entities dealing with orbit information (e.g. MOS Mission Planning, IOCS and PGS TMSP). Orbit products for arbitrary time spans are derived from this reference orbit. In addition, an 11-day reference attitude product (one for right- and one for left-looking) was established which incorporates the total zero-Doppler steering conditions. Again, reference products for arbitrary time spans are generated based on this reference attitude.

VI. Test Data Sets, Scenarios and Results

Various test data sets were generated and used throughout the PGS SAR data workflow integration and test phase in a number of different test scenarios.

A. Downlink Scenarios for NSG and TSC

A first set of plain ISP data takes generated in the frame of the space segment instrument functional tests was used to construct four downlinks with various replays incorporating all operational downlink scenarios to be dealt with by NSG and TSC (plain versus encrypted, complete versus partial, DRA).

One downlink was modified to carry bit error characteristics (in dependence of the elevation angle) as derived from the link budget.

The NSG and TSC correctly handle all downlink scenarios. The data of one downlink are provided by NSG at the DAS-TSC pickup point within a few minutes after a downlink is finished. The TSC decrypts the data with an approximate rate of 0.75 GByte per minute and thus provides a complete downlink within 30 minutes at the TSC – TMSP pickup point for further TMSP processing.

B. TMSP Product Scenarios

The next set of data takes was acquired by the instrument based on command sets by the Instrument Operations and Calibration Segment IOCS team. These data takes represent actual data acquisitions over scenes on earth and are thus consistent in all SAR header parameters (specifically timing). A representative for each imaging and polarization mode was chosen by the TMSP team, SAR echo data were simulated and thus a comprehensive acceptance test data set was constructed specifically for the off-line TMSP algorithm and product verification .Some selected test results:

- A formed StripMap eigen interferogram (CEOS offset test) showed a phase noise below 2 degrees.
- The spatial resolution is well within specification.

- The measured pixel location accuracy is well below 0.1 pixel.
- The processor normalization throughout all imaging modes is verified.

C. *TMSP Throughput and Robustness*

The remaining data takes from the set described in B were used unaltered for TMSP throughput and robustness tests. The data variety comprised all imaging and polarization modes, left- and right-looking, ascending and descending orbits, northern and southern hemisphere as well as regions close to north pole and south pole, see the map plots of selected L0 products as archived in the PGS Product Library in Figure 5.

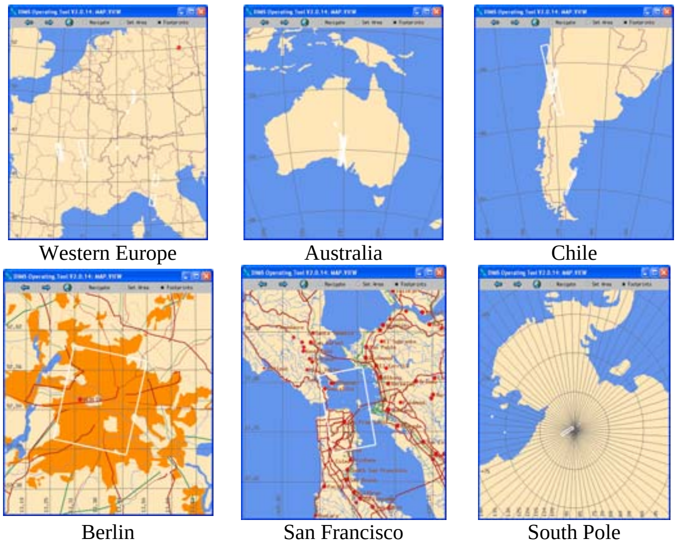

Figure 5: Map Plots of Selected L0 Products

This time the TMSP integrated into the PGS SAR data workflow was used. Some selected throughput results:

Using five processing nodes (one is reserved for TSC operations), 120 GByte of raw data (mixture of all imaging and polarization modes) were processed into L0 products and archived within 8 hours. This corresponds to a screening rate of 0.25 GByte per minute. Note, that the SAR screening implicitly contains a SAR SSC focusing step for the generation of the quick-looks and that the PGS is required to screen 90 GByte per day.

The L1b throughput considerably depends on the product type to be generated and the underlying imaging and polarization condition. The SSC generation time e.g. varies between 8 Minutes (SM single pol) and 25 minutes (HS dual pol). The generation of a MGD RE product typically takes between 17 minutes (SM single pol), 30 minutes (HS dual pol) and 55 minutes (SC). PGS is required to process and deliver 15% of all incoming data takes within 24 hours once all input data (specifically the delayed orbit information) is available. With the current hardware configuration, it should be possible to process about 45 GByte of raw data per day into L1b products.

D. *First Ground Segment Validation Test and Complete Test Data Set*

Once the PGS test bed was in place and it was proven, that the complete PGS SAR data workflow can be tested end-to-end based on data takes as acquired and recorded at the space segment, this test concept was put forward onto ground segment level.

A first validation test was conducted which started with the user product ordering at PGS. The acquisition requests were planned and the instrument command data take sets were derived by MOS Mission Planning and IOCS. Command files were produced and “uplinked” (i.e. sent via ISDN connection) by MOS from the TerraSAR-X control room at DLR’s German Space Operations Center to the spacecraft during a real-time training session. The commands were executed at the spacecraft and lead to the acquisition of 52 data takes “downlinked” during NSG contact times, i.e. being recorded as serial raw data stream by the Astrium check-out equipment. They were transported on a portable disk to Neustrelitz for ingestion into the downlink simulator and thus into the PGS SAR data workflow.

The PGS requested auxiliary data as listed in Table 2 were consistently generated and provided for the recorded data takes as well.

The serial raw data stream was ingested into the NSG receiving antenna following the exact time sequence of events (real contact times). The complete data-driven PGS SAR data workflow was run exactly as will be done later during the commissioning phase when processing the first real TerraSAR-X data. Also the provision of the auxiliary data followed the exact time sequence of events.

As far as we know, this type of end-to-end validation testing including not only a 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 the spacecraft to the Neustrelitz ground station) is a novel approach in ground segment validation testing. It is a direct consequence of the comprehensive ground segment – space segment integration and verification program conducted for TerraSAR-X, which aims at testing and exercising the various TerraSAR-X modes and features relevant for a smooth mission operation including specifically the IOCS system calibration, verification and long-term system monitoring tasks. These pre-launch test shall help to complete the commissioning phase in the foreseen time frame despite the vast operational TerraSAR-X capabilities.

This first ground segment validation test lead to a first complete and consistent ground segment SAR test data set which specifically enabled the end-to-end testing of the complete PGS SAR data workflow including L1b basic product generation.

Figure 6 below shows a screen shot of the EOWEB order placed for a high-resolution spotlight product over downtown San Francisco in comparison to the map plot of the generated L1b SSC product.

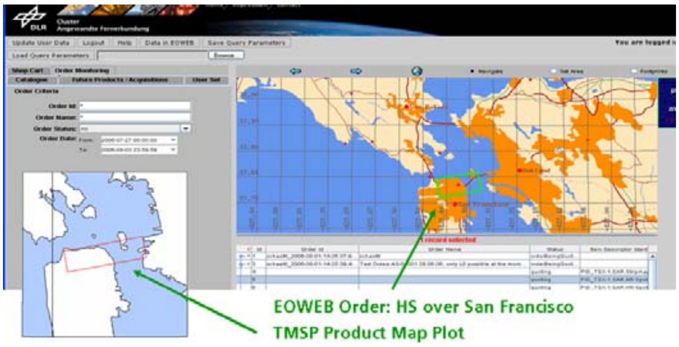

Figure 6: EOWEB order versus L1b product map plot

E. Complete PGS SAR Data Workflow

Using the test data as introduced in B, C and mainly D, a 48-hour operational validation test of the complete PGS SAR data workflow was successfully conducted. The L1b basic product requests were ingested using the off-line XML request interface of the PS-TMSP control. Otherwise, the SAR data workflow was operated in the nominal data-driven way including all system parts.

38 GByte of raw data were received, transcribed and screened on the first operations day, 21 GByte on the second. This lead to a total of 91 archived L0 products. A high-number of basic product requests was activated to keep the PS-TMSP under permanent processing load. In total 551 L1b products were generated and archived within the 48 hours.

Five NRT products were generated stemming from two different NRT data takes. After successful generation they were successfully uploaded onto the delivery product pickup point within one hour after data reception start.

VII. CONCLUSION AND OUTLOOK

The PGS SAR Data Workflow is fully integrated at DLR's Neustrelitz Ground Station and ready for the commissioning phase operation.

The DLR approach for performing a comprehensive on-ground testing starting with a product order placement by the user and ending with the archiving of the generated product including not only the real-time instrument commanding and data acquisition at the space segment, but also the payload ground segment operation for data processing was successfully demonstrated. Such extended on-ground validation tests promise a reduction of the in-orbit verification activities and may thus reduce the duration of commissioning phases.

ACKNOWLEDGMENT

We particularly thank R. Metzig, U. Steinbrecher, D. Schulze from the DLR instrument team and A. Schwab, C. Giese from the TerraSAR-X team at EADS Astrium, Germany, for their never ending enthusiasm and support in providing appropriate instrument test data sets.

REFERENCES

[1] M. Suess, S. Riegger, W. Pitz, R. Werninghaus, "TerraSAR-X – Design and Performance", Proc. of 4 th European Conference on Synthetic Aperture Radar, Köln, Germany, 2002

[2] W. Pitz, "The TerraSAR-X Satellite", Proc. of 6 th European Conference on Synthetic Aperture Radar, Dresden, Germany, May 16–18, 2006

[3] A. Roth, R Werninghaus, "Status of the TerraSAR-X Mission", Proc of the IEEE International Geoscience and Remote Sensing Symposium, July 31 – August 4, Denver, Colorado

[4] J. Hermann, N. Faller, A. Kern, M. Weber, "Infoterra GmbH Initiates Commercial Exploitation of TerraSAR-X", Proc of the IEEE International Geoscience and Remote Sensing Symposium, July 25 – 29, 2005, Seoul, Korea

[5] R. Werninghaus, W. Balzer, S. Buckreuss, J. Mittermayer, W. Pitz, „The TerraSAR-X Mission", Proceedings of 5 th European Conference on Synthetic Aperture Radar, Ulm, Germany, May 25-27, 2004

[6] B. Schättler, M. Eineder, H. Breit, E. Boerner, E. Mikusch, "Preliminary Design of the TerraSAR-X Payload Ground Segment", Advanced SAR and CEOS WGCV SAR Workshop 2003, St. Hubert, Canada, June 2003

[7] M. Eineder, B. Schättler, H. Breit, T. Fritz, A. Roth, "TerraSAR-X SAR Products and Processing Algorithms", Proc of the IEEE International Geoscience and Remote Sensing Symposium, July 25 – 29, 2005, Seoul, Korea

[8] T. Fritz, M. Eineder, H. Breit, B. Schättler, "The TerraSAR-X Basic Products – Format and Expected Performance", Proc. of 6 th European Conference on Synthetic Aperture Radar, Dresden, Germany, May 16–18, 2006

[9] B. Schättler, M. Wolfmüller, R. Reissig, H. Damerow, H. Breit, E. Diedrich, "A Description of the Data-Driven SAR Data Workflow in the TerraSAR-X Payload Ground Segment", Proc of the IEEE International Geoscience and Remote Sensing Symposium, September 20 – 24, 2004, Anchorage, Alaska

[10] H. Damerow, H.-J. Pannowitsch, J. Richter, J. Schwarz, H. Maass, "Ausbau der Multimission Bodenstation Neustrelitz für TerraSAR-X", Deutscher Luft- und Raumfahrtkongreß 2006, November 6-9, 2006, Braunschweig, Germany

[11] H. Breit, E. Boerner, J. Mittermayer, J. Holzner, M. Eineder, "The TerraSAR-X Multi-Mode SAR Processor – Algorithms and Design", Proc. of 5th European Conference on Synthetic Aperture Radar, May 25-27, 2004, Ulm, Germany

[12] R. K. Raney, H. Runge, R. Bamler, I. G. Cumming, F. H. Wong, "Precision SAR Processing using Chirp Scaling", IEEE Trans. on Geoscience and Remote Sensing, Vol. 32, No. 4, pp. 786 – 799, July 1994

[13] A. Moreira, J. Mittermayer and R. Scheiber, "Extended Chirp Scaling Algorithm for Air- and Spaceborne SAR Data Processing in StripMap and ScanSAR Imaging Modes", IEEE Transact. on Geoscience and Remote Sensing, Vol. 34, No. 5, pp. 1123 – 1136, September 1996

[14] J. Mittermayer, R. Lord, E. Boerner, "Sliding Spotlight SAR Processing for TerraSAR-X Using a New Formulation of the Extended Chirp Scaling Algorithm", Proc. of IEEE International Geoscience and Remote Sensing Symposium, July 21 – 25, 2003, Toulouse, France

[15] H. Fiedler, E. Boerner, J. Mittermayer, G. Krieger, "Total Zero Doppler Steering", Proc. of 5th European Conference on Synthetic Aperture Radar, May 25-27, 2004, Ulm, Germany