TerraSAR-X

TerraSAR-X is Germany's first national remote sensing mission being implemented in a public-private partnership between the German Aerospace Centre (DLR) and EADS Astrium GmbH. TerraSAR-X was launched on June 15th, 2007 and is supplying high-quality radar data for purposes of scientific observation of the Earth for a period of at least five years. At the same time it is designed to satisfy the steadily growing demand of the private sector for remote sensing data in the commercial market.

TerraSAR-X is the successor of the scientifically and technologically successful radar missions X-SAR (1994) and SRTM (2000). EADS Astrium GmbH has developed the TerraSAR-X satellite, whereas DLR is responsible for the overall mission and provides the necessary ground segment infrastructure and its operation.

Mission and System

The TerraSAR-X satellite was launched on a Russian DNEPR-1 with a 1.5 m long fairing extension. All launch vehicle elements except for the fairing inter-stage are unmodified components of the original SS-18 intercontinental ballistic missile. The lift capability into the selected orbit is 1350 kg.

For the orbit selection, an altitude range between 475 km and 525 km has been investigated. The sun-synchronous dawn-dusk orbit with an 11-day repeat period showed the best performance with respect to order-to-acquisition and revisit times.

The satellite is being operated by the German Space Operation Centre (GSOC) in Oberpfaffenhofen using two primary ground stations in Germany. Weilheim serves as the telemetry and telecommand station, and Neustrelitz is used as the central receiving station for the X-band downlink of the SAR data. Beyond that, additional Direct Access Stations, commercial partners of Infoterra GmbH, are extending the baseline receiving station concept.

TerraSAR-X carries an advanced high resolution X-band Synthetic Aperture Radar (SAR) based on active phased array technology which allows the operation in Spotlight-, Stripmap- and ScanSAR Mode in various polarisations. It provides the ability to acquire high resolution images for detailed analysis, as well as wide swath images for overview applications.

The X-band SAR instrument operates at a centre frequency of 9.65 GHz and

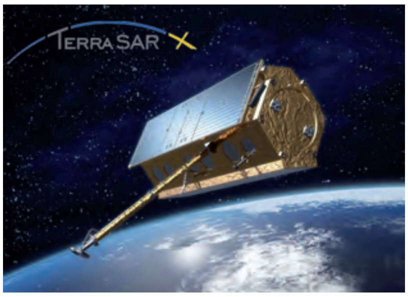


Figure 2-5: Artist's view of the TerraSAR-X spacecraft.

Figure 2-6: TerraSAR-X modes of operation.

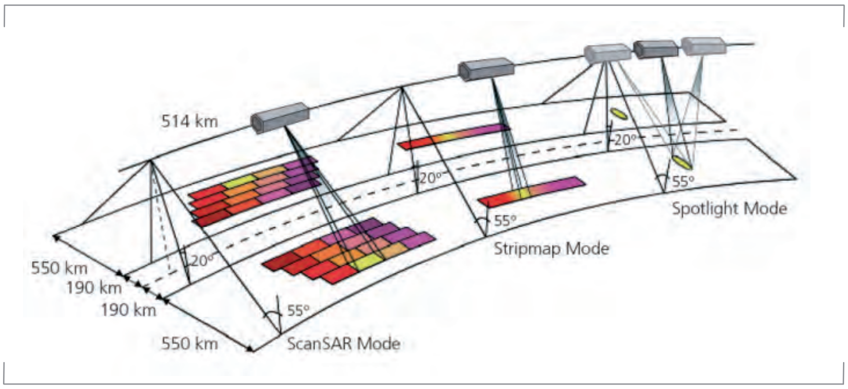


Table 2-2: TerraSAR-X orbit parameters.

Parameter	*Mission Orbit*
Orbit Type	Sun-synchronous repeat orbit
Repeat Period	11 days
Repeat Cycle	167 orbits in the repeat cycle
Orbits per Day	15 2/11
Equatorial Crossing Time	18.00 h ±0.25 h ascending pass
Eccentricity	0.0011 – 0.0012
Inclination	97.443823°
Argument of Perigee	90°
Altitude at Equator	514.8 km
Ground Track Repeatability	within ±250 m per repeat cycle

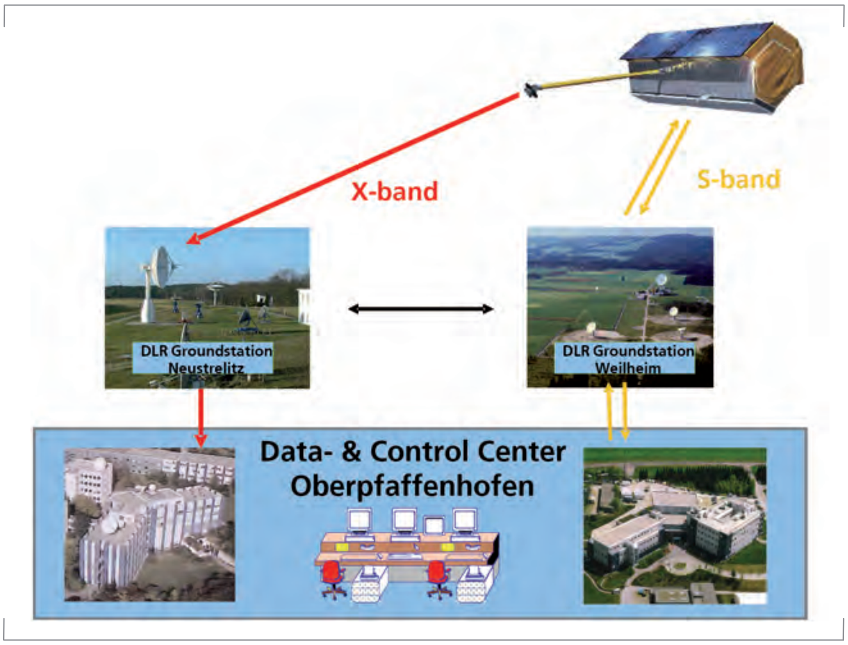


Figure 2-7: TerraSAR-X data flow concept.

with a maximum bandwidth of 300 MHz. The antenna is capable to operate in two polarisations: H and V on transmit as well as on receive and consists of 12 panels with 32 dual polarised slotted waveguide subarrays stacked in elevation. Each sub-array is fed by a dedicated Transmit/Receive Module (TRM). The SAR antenna's approximate dimensions are 4800 mm in length, 800 mm in width and 150 mm in depth. It features electronic beam steering in azimuth (±0.75°) and elevation (±20°). The acquired SAR data are stored in a Solid State Mass Memory Unit (SSMM) of 256 Gbit end-of-life capacity before they are transmitted to ground via a 300 Mbit/s X-band system.

All payload sub-systems are fully redundant, i.e. main and redundant functional chains exist. This allows the utilisation of a new concept that involves activation of both functional chains at the same time, one being the master for timing purposes. As a result operation in an experimental Dual Receive Antenna (DRA) Mode, where the echoes from the azimuth antenna halves can be received separately, becomes possible. This new experimental mode enables interesting new features like Along-Track Interferometry (ATI), fully polarimetric data acquisition and the enhancement of azimuth resolution.

Ground Segment

The TerraSAR-X Ground Segment is the central facility for controlling and operating the TerraSAR-X satellite, for calibrating the SAR instrument, archiving the SAR-data and generating and distributing the basic data products. The overall TerraSAR-X Ground Segment and Service Segment consist of three major parts:

- Ground Segment which is provided by DLR,
- TerraSAR-X Exploitation Infrastructure (TSXX) under the responsibility of Infoterra and
- Science Service Segment coordinated by DLR.

SAR System Engineering

SAR System Engineering is the key responsibility of the Microwaves and Radar Institute. It provides the SAR know-how to operate the instrument within the required specifications and to monitor the payload hardware. It also provides support to the ground segment integration and the overall project management.

Examples for major tasks of SAR System Engineering are:

- Specification of TerraSAR-X modes and imaging beams
- Overall SAR system performance control
- Instrument shadow engineering
- Support in instrument acceptance tests
- Technical support for project management decisions

- Algorithm development for Spotlight SAR processing
- Attitude steering definition law for Doppler centroid minimisation

In the following, typical examples of SAR System Engineering tasks are presented in more detail.

Spotlight Processing Algorithms

The Extended Chirp Scaling Algorithm for Steering Spotlight has been enhanced for the processing of TerraSAR-X sliding Spotlight raw data. The enhancement consists more of
a detailed analysis of the sliding Spotlight geometry and raw data signal.

Zero-Doppler Attitude Steering

The Total Zero Doppler Steering developed for TerraSAR-X enables SAR data acquisition with Doppler centroids close to zero independent
of incidence angle and terrain height variation. This is achieved by introducing a slight pitch steering on top of the standard yaw steering to align the satellite attitude to its velocity vector.

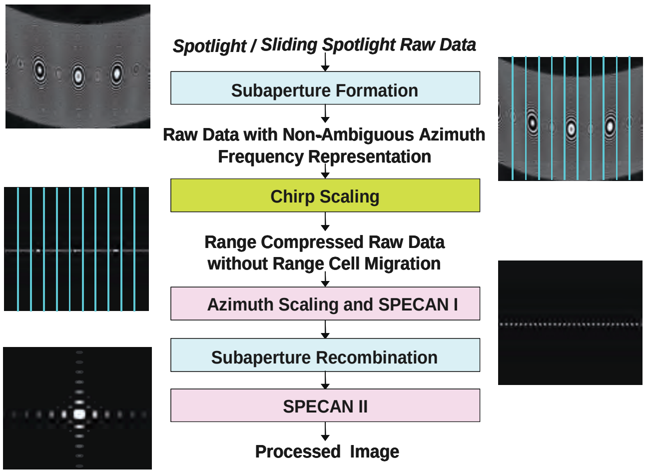


Figure 2-8: Algorithmic steps of Extended Chirp Scaling processor for Sliding Spotlight Mode products.

Figure 2-9: Measured Doppler centroids in Hz at the swath center for all data takes acquired since begin of the operational phase. All TerraSAR-X data pass a systematic screening process which includes Doppler centroid estimation. The results of the screening are provided via a so-called Data Quality Check Product to the Long-Term Data Base of the IOCS system.

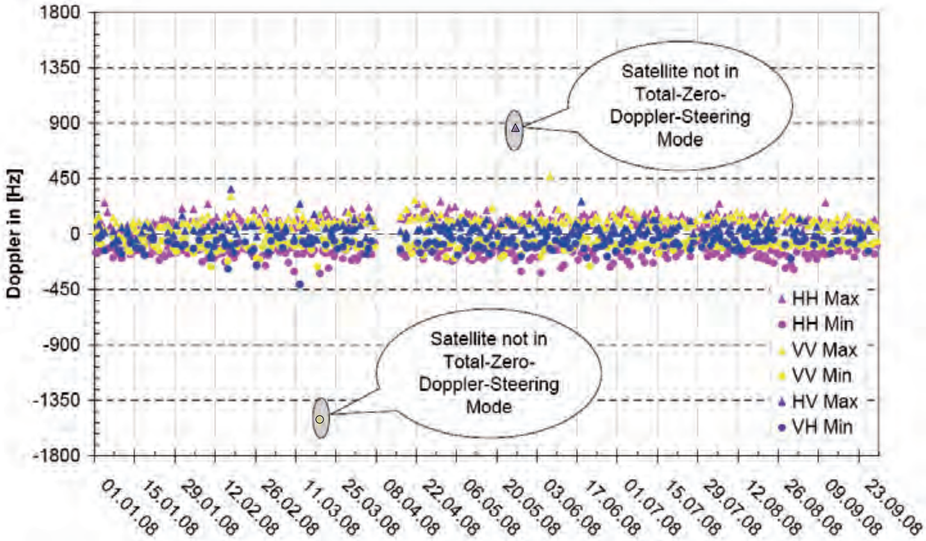


Figure 2-10: This 150 MHz TerraSAR-X Spotlight image of Amsterdam and its many canals was taken on December 9, 2008.

The implementation in TerraSAR-X is based on a look-up table with a step width of two degrees in argument of latitude and linear interpolation in-between. The look-up table implementation and satellite pointing errors result in a residual Doppler centroid below 250 Hz for left and right looking geometries.

Operationalisation of 300 MHz Spotlight Products

Use of the full 300 MHz bandwidth was originally limited for experimental modes only. A strong demand from the commercial customers triggered the inclusion of 300 MHz spotlight products into the standard product portfolio. It required an optimisation of the acquisition parameters and a corresponding upgrade of the commanding chain as well as adaptations of the SAR processor. The 300 MHz option became operational already\ during the Commissioning Phase and is since then being heavily used for high-resolution imaging.

Special Instrument Commanding

Our *System Command Generator* enables the exploitation of the full flexibility of the TerraSAR-X SAR instrument by providing tools for commanding data

Figure 2-11: 300 MHz Spotlight image of Venice/Italy taken by TerraSAR-X on October 3, 2008.

takes with special instrument settings. This feature of the Instrument Operations and Calibration System is being regularly used to command special data takes, for example:

- Aperture switching mode for along-track interferometry applications (e.g. traffic monitoring): for this mode either the forward or backward half of the antenna is activated on receive for sub-sequent pulses.
- Special beams using for example notch patterns for antenna pointing calibration.
- Special nadir data takes for investigations on the nadir interference.
- Split-bandwidth operation for delta-k interferometry.
- TOPSAR data takes for large area acquisitions with improved quality w. r. t. ScanSAR.

TOPSAR Demonstration

TOPSAR is a new and promising mode of operation for future SAR satellite missions. It overcomes the inherent SNR variations in standard ScanSAR (scalloping) by an additional azimuth scanning during the burst acquisition. Future sensors like Sentinel-1 will primarily rely on this mode. The active phased array antenna on TerraSAR-X does allow for electronic scanning in both range and azimuth direction. This feature is already being used for ScanSAR and Spotlight acquisitions. Using the *System Command Generator*, the required combined range and azimuth scanning can be achieved. The first spaceborne demonstration of TOPSAR operation was successfully achieved early in the Commissioning Phase.

The Instrument Operations and Calibration Segment

TerraSAR-X is the first mission to implement the novel concept of a dedicated ground segment facility

Figure 2-12: Image over the Amazon rain forest acquired with a notch beam pattern. The gamma profiles derived from such images show a well established drop around the position of the pattern null. Using fitting techniques this position and hence the antenna beam pointing can be determined with milli-degree accuracy.

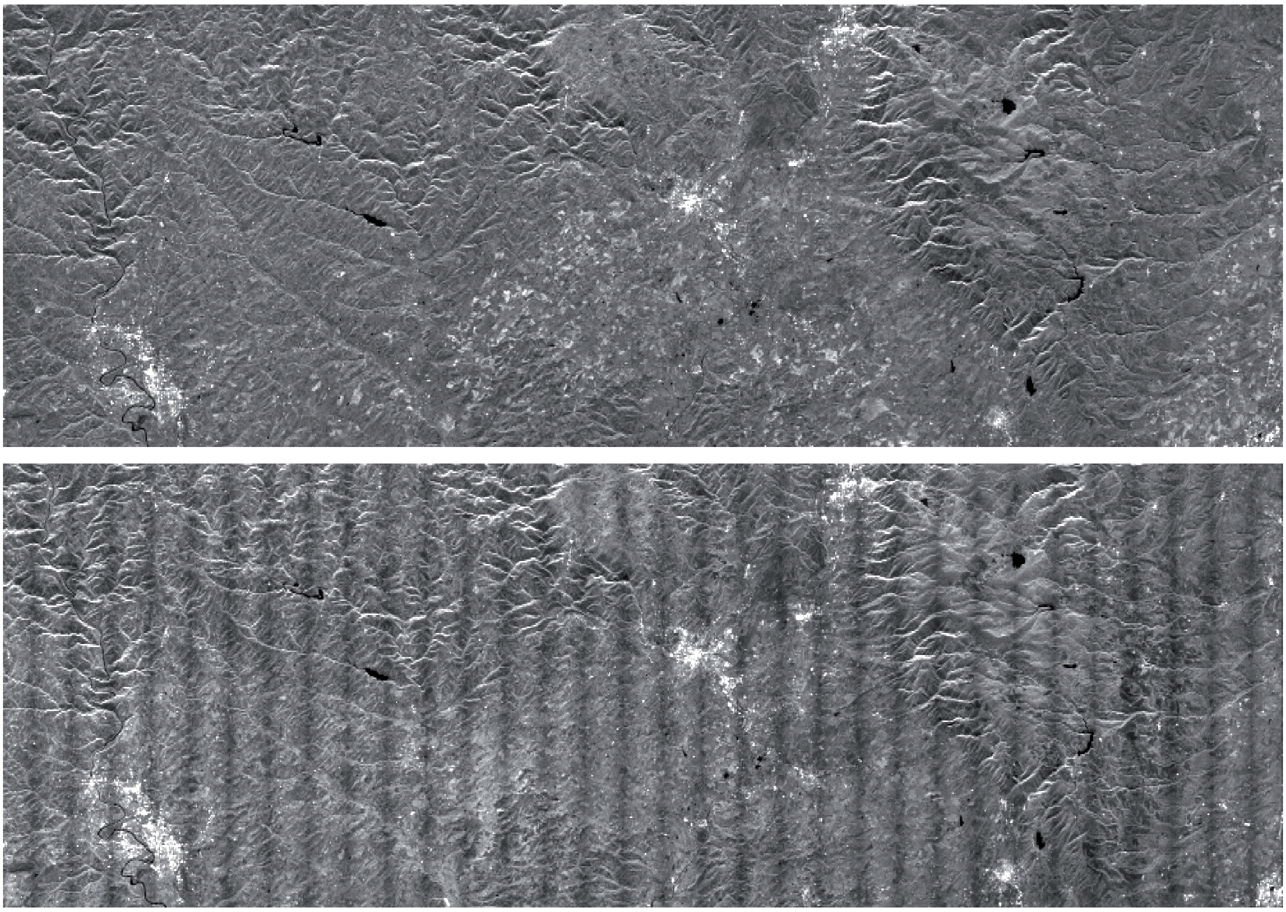


Figure 2-13: TOPSAR (top) and ScanSAR (bottom) comparison. The first subswath of data takes acquired over Toulouse has been processed. No scalloping correction has been performed. The measured scalloping in the ScanSAR image is around 1.2 dB, compared to 0.3 dB in the TOPSAR image. Thirty-three ScanSAR bursts were necessary in contrast to only nine required by the two TOPSAR modes. The advantage in using the TOPSAR technique in terms of scalloping and therefore signal-to-noise ratio is clearly visible.

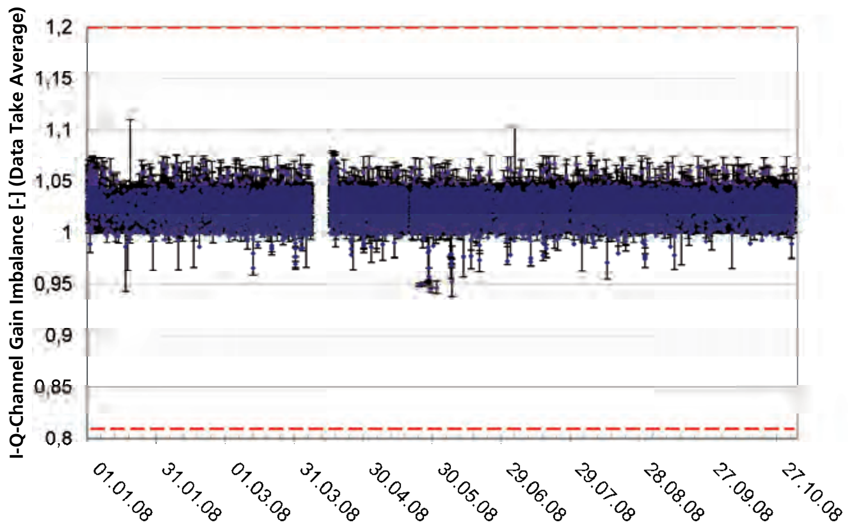
comprising all the tools for instrument operations, performance monitoring as well as system and product calibration and verification.

The Instrument Operations Section has the function to operate the SAR instrument in its different operational SAR modes Stripmap, ScanSAR, Spotlight and in the experimental modes. The main tasks are to:

- generate, maintain, archive and distribute all required instrument tables for use on-board and on-ground, generate radar parameters and command information for each SAR data acquisition,
- generate flight procedures with respect to the SAR instrument for nominal and contingency operations,
- provide and maintain a Long Term Data Base (LTDB) for archiving all relevant instrument information throughout the whole mission,
- provide auxiliary products with all calibration and instrument information required in the SAR data processing.

A key element of the IOCS is the LTDB. The central role of this archive is to provide all required data for system performance prediction and execution of corrective measures throughout the whole mission lifetime. In previous SAR missions, this information was often distributed over different locations. With the LTDB architecture, all mission data relevant for SAR system performance assessment are brought together and can be accessed by calibration, characterisation, monitoring, and verification tools. These tools are able to quickly provide a more complete picture of the whole TerraSAR-X system and its performance in shorter time. The effort for contingency analysis and the identification of counter-measures can be reduced. Under long-term system monitoring aspects, it is possible to detect performance degradations with more anticipation and to provide more room for degradation mitigation.

Figure 2-14: ***Above*****: Imbalance statistic of the complex raw data recorded by TSX-1. The data of all nominal images is checked automatically against its limits (red lines): The raw data imbalance is well below its limit. The gap in April 2008 is the result of a maintenance phase where no images were acquired.** ***Below*****: Typical examples of long-term system monitoring showing the performance of the on-board start time correction since begin of the operational phase.**



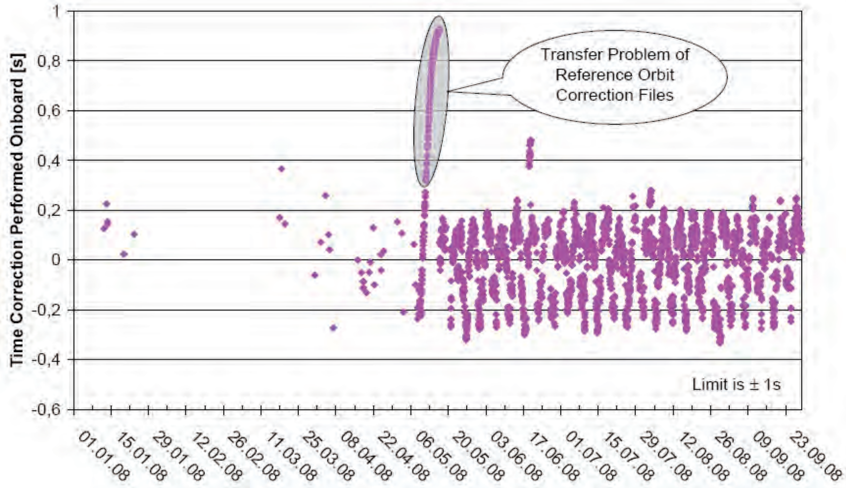
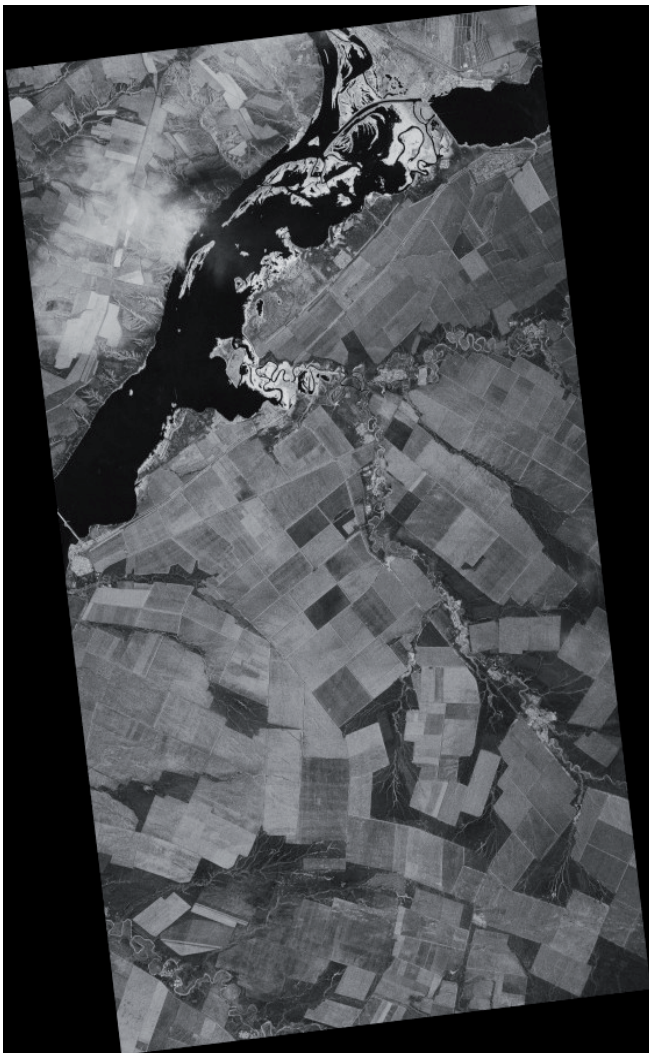


Figure 2-15: First TerraSAR-X image, Tsimlyanskoye reservoir, taken on 19 June 2007, 15:03:24 UTC. During this acquisition, a thick cloud cover prevailed. Nevertheless, radar satellites such as TerraSAR-X offer imaging capability even in case of cloudy skies and at night. However, exceptional strong precipitation events like heavy thunderstorms may influence even radar imaging. Such an event can be seen at the upper left part of the radar image as a bright veil.



The Verification Section ensures the correct in-orbit operation of the entire SAR system from data take instrument command generation to ground processing and has to technically release the SAR products. The complete SAR system verification is performed during the commissioning phase and at regular intervals during the mission. Specific verification activities can be triggered by faults and failures for trouble shooting. Typical tasks performed by this section are: data take verification, long-term SAR system monitoring, and instrument health monitoring.

The Calibration Section comprises all the analysis tools necessary for the internal and external calibration, antenna pattern determination including optimisation of beam coefficients, control of ground equipment, and noise characterisation. Further details on the TerraSAR-X calibration concept and its implementation are described in *Chapter Microwave Systems*.

Mission Status

Only four days after launch the first SAR image was processed successfully. An 30 km x 60 km area in Russia, west of Wolgograd has been imaged in the stripmap mode, HH polarisation at a resolution of 15 m. The successful processing of the first image demonstrated the functional capability of the satellite on one hand and the operability of the ground segment on the other hand. The entire processing chain including order input, scheduling, commanding, data acquisition, on ground data reception, SAR processing, and archiving of the images has been verified. This result was also the consequence of a comprehensive pre-launch testing program including numerous space-to-ground segment tests.

The commissioning phase was finished right on schedule after 5.5 month and the goal was attained to ensure optimum SAR product quality and to accomplish the full operational readiness of the space and ground segment in December 2007. The TerraSAR-X team executed a very comprehensive program involving tasks such as calibration, characterisation and verification of the SAR instrument and overall SAR system performance, and verification of the final image products. During the commissioning phase 12000 data takes were executed and all imaging modes were tested and verified. In most cases the obtained results even exceeded the initial specifications. Consequently, TerraSAR-X turned out to be a very stable precision instrument for radar imaging.

On January 7th, 2008 the operational phase was kicked off and the image production for scientific and commercial users is running extremely satisfactory since then.

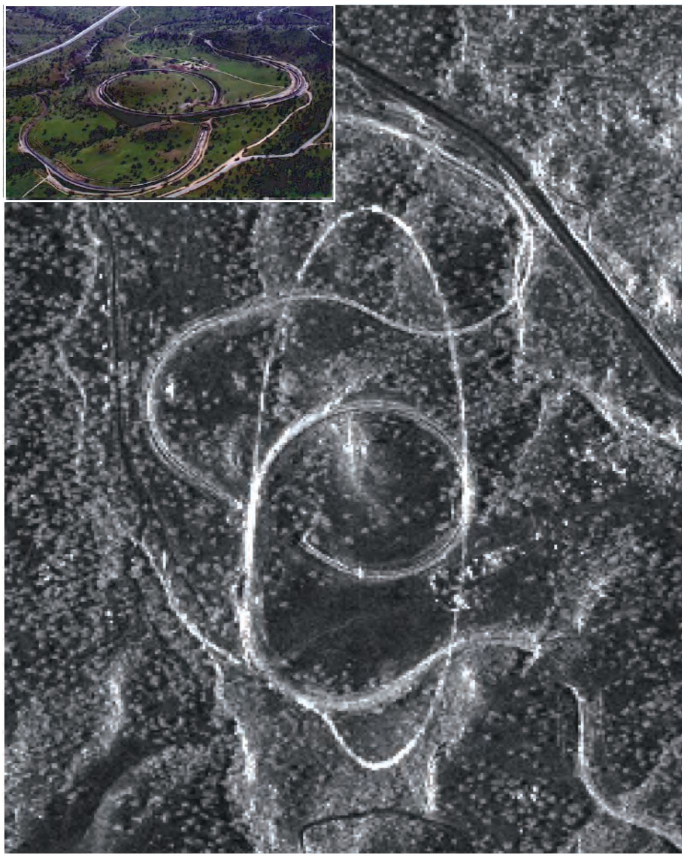


Figure 2-16: Trainspotting with TerraSAR-X: This image shows a valley located approx. 100 km north of Los Angeles, California. It contains the highway 58 (dark line) and a railway (bright line) connecting Bakersfield to Mojave, crossing the Tehachapi Pass. The Tahachapi Loop was build to reduce the slope and can be recognised as the bright circle in the center of the image. The bright circle is the railway track; the ellipse touching the circle is a very long, running train which appears displaced from the tracks. The displacement between the train and the rails in azimuth direction is a SAR effect for objects moving in range direction. For this imaging geometry, the speed of the train can be estimated from the azimuth displacement of 360m to 25 km/h.