Global Digital Elevation Model from TanDEM-X and the Calibration/Validation with worldwide kinematic GPS-Tracks

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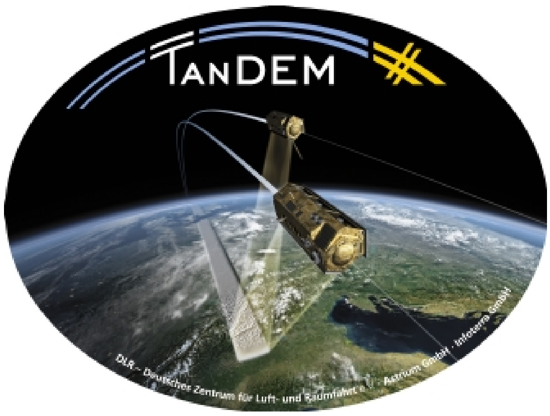
SUMMARY

In the first half of 2010 the second satellite of the system **T**erraSAR-X **a**dd-o**n** for **D**igital **E**levation **M**easurements (TanDEM-X) will be launched from *Baikonur* Cosmodrome, the first one – TerraSAR-X - is already working since more than two years. The TanDEM-X satellite mission will provide a digital elevation model (DEM) from the complete Earth. The relative height accuracy will be approx. 2m, the resolution on ground will be better than 12m.
Four DLR institutes are responsible for the SAR payload, mission control, receiving stations, interferometric SAR (InSAR) processing, product generation and archiving and web interface. The scientific user community can use this web interface to submit their proposals and order DEMs for there test sites. The German company Infoterra will support commercial users.
Four DEM products are planed: Intermediate DEM (2.5 years after launch) with less accuracy, final DEM (4 years after launch) with the required quality, FDEM with a higher ground resolution and HDEM with a better height quality. The paper will also give an overview about this DLR processing chain.
These system- and product accuracy requirements will be guaranteed by different calibration and validation approaches. One important reference source especially for the validation are kinematic GPS tracks with accuracies better than 0.5m. Due to the fact that either local reference station or any regional reference station network is worldwide available Precise Point Positioning was selected as post processing method.
In 2009 several world-wide tracks were measured with this method in Argentina/Chile, Brazil, North America, Central Europe, Northwest Africa, East-West coast track in southern Africa, Russia and Central Asia. Tracks in India and Saudi-Arabia are ordered and will be carried out in spring 2010. More than 50 000km were measured from different teams. This paper will present the organisation, requirements and experiences during the tracks, examples of the products (height-profiles) and first results of these kinematic GPS tracks.
In summer 2008 the Commission 5 published the announcement "Kinematic GNSS for Evaluation of TanDEM-X Digital Elevation Model" to support the German satellite mission “TanDEM-X”.



1. TanDEM-X MISSION

Ten years after the very successful Shuttle Radar Topographic Mapping Mission (SRTM), the TanDEM-X satellite opens a new era in space borne radar remote sensing. Together with the first German radar satellite (TerraSAR-X) a bistatic SAR mission will be operating in space. These two satellites will take interferometric data sets of the complete globe (Zink, 2008). The former SRTM mission had covered only the region between +/- 60 degree latitude.
Using the SAR interferometric approach to generate very precise Digital Elevation Models (HRTI-3) there are strong requirements to the mission, e.g. precise baselines for interferometric acquisition.
The two satellites are flying in a closely controlled formation with typical cross-track distances between 200m and 600m (Fig.1). A minimum safety distance of 150m must be guaranteed. This very complex configuration called HELIX flight formation was never realized before in a space mission.

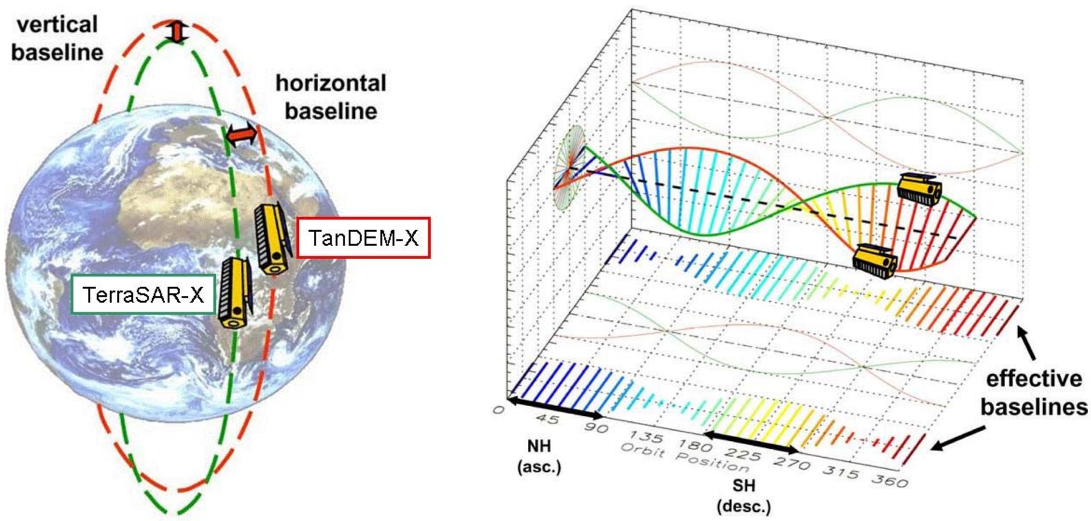


Fig. 1: Orbit and baseline configurations of TerraSAR-X and TanDEM-X (HELIX)

The generation of DEMs is not the only purpose of the mission. TanDEM-X doubles the product availability of civil German SAR mission and gives the scientists the possibility to work for new bi-static applications e.g. polarity or along-track-interferometry.
Examples for the technical progress are additional X-band horn antennas for inter-satellite phase synchronization, the availability of a dual frequency GPS receiver for precise orbit determination, the excellent phase stability of the SAR instrument and PRF synchronization based on GPS as a common time reference. Also manoeuvrable beam pointing and flexible beam shaping is possible.

The TanDEM-X satellite is designed for a nominal lifetime of 5 years and has a planned overlap with TerraSAR-X of 3 years. The instruments on both satellites are advanced high resolution X-band synthetic aperture radars based on active phased array technology, which can be operated in Spotlight, Stripmap and ScanSAR mode with different polarization capabilities. The centre frequency of the instruments is 9.65GHz. The active phased array antenna, which has an overall aperture size of 4.8m x 0.7m, is fixed mounted to the spacecraft body and incorporates 12 panels. The satellites were built by the company Astrium.

Fig. 2: SAR panel of TanDEM-X satellite

The German Aerospace Center (DLR) in Oberpaffenhofen (near Munich) is responsible for the ground segment. Four DLR-institutes are involved in the operation of the ground segment.
The German Space Operation Center is responsible for the mission planning and control.
The Microwaves and Radar Institute develops and manages the SAR sensor and is organizing SAR calibration and validation. This institute also coordinates the science community.
The Institute of Remote Sensing Technology will set up the system for the InSAR processing.
The German Remote Sensing Data Center produces the final DEM products, handles the user interface, operates the DEM archive and the national receiving stations in Inuvik (Canada), Neustrelitz (Germany) and O'Higgins (Antarctica).

The commercial partner in this Public Private Partnership project is the company "Infoterra" from EADS-Astrium located in Friedrichshafen (Germany).

2. DEM GENERATION AND DEM PRODUCTS FROM TanDEM-X

The DEM processing based on the well proved InSAR technique. To acquire sufficient InSAR data the three years joint mission is separated in different operational phases:

- Six months *commissioning phase* for calibration and validation
- *Phase 1*: First year, first global coverage with a short baseline (200m) and a high height ambiguity (~40m) to generate a DEM with a lower accuracy.
- *Phase 2:* Second year, second global coverage with a long baseline (500m) and a smaller height ambiguity (~30m) to generate a high quality DEM data
- *Phase 3*: Six months, additional coverages in difficult areas and gap filling
- *Phase 4:* Continuation of the mission with special requested products, longer baselines.

These operational phases will control the DEM processing schedule. With the first acquisition an intermediate DEM will be computed. All three coverages are used for the final DEM. Four years after launch the DEM should be processed and usable. For calibration purpose an early product access is planned.

2.1 DEM Processing

The ground segment processing is adapted to the phases of the DEM acquisition schedule. In a data driven processing step all data takes are processed to interferometric DEMs - so called raw DEMs - within the interferometric SAR processor. They are already geocoded. These raw DEMs are the basic input for the Mosaicking and Calibration Processor (MCP), which produces the final DEM.

Interferometric Proc.	**Preparation**	**Calibration**	**Mosaicking**
Raw DEMs (Coregistration Phase Unwrapping)	Water body Calibration points	Block adjustment: Estimation of height corrections	Height values Error map Amplitude layer

Fig. 3: DEM Processing

The MCP consists of three processor components – preparation-, calibration- and mosaicking processor. The data driven preparation processor analyzes the raw DEMs regarding height discrepancies e.g. caused by phase unwrapping, carries out a water body detection and extracts calibration points. Calibration points like reference points and tie-points are building the basis for the calibration process. The tie-point detection is done in overlapping areas between the single data takes, which is in minimum 4km wide. The tie-points are not single points, but chips with 100 x 100 pixels. An operator has to initiate the next processing steps the calibration and the mosaicking for selected regions. The calibration processor sets up all necessary information and parameter for the block adjustment (BA) and computes for each data acquisition height correction parameters for relative and absolute height calibration. For the mosaicking all required raw DEMs are transferred from the product library (PL) to the processor. Output layers are: height values, height error map, amplitude layer and masks about water, shadow, and layover (Wessel et al., 2008).

2.2 DEM Products from TanDEM-X

The most important product of the mission is the global DEM. It is an Earth surface model, which is effected by vegetation, buildings etc.. The high quality, precise accuracy and global coverage are the most important improvements regarding other global height data sets.
The improvement of the quality comparing to the SRTM mission is shown in the following simulated InSAR DEM.

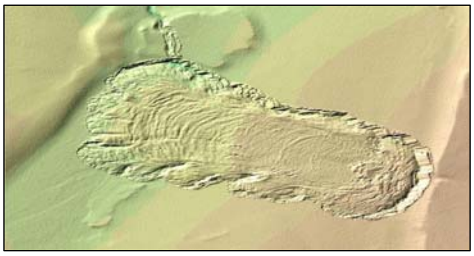



Fig. 4: DEM from SRTM (left) and TanDEM-X (right, simulated)

Tab. 1: DEM product parameter

Parameter	**Value**	**Comment**
Absolute vertical accuracy	10 m	90% linear error
Horizontal accuracy	10 m	90% circular error
Relative vertical accuracy	2 m (slope ≤ 20 degree)	90% linear error
Latitude sampling	0.4”	12.4 m
Longitude sampling	0.4”, between 0-50 degree lat. ... 4.0 ” between 85-90 degree lat.	11.2 m … 5.4 m
Format	GeoTIFF	

TanDEM-X DEM products consist of various layers:
- DEM with height information
- Height Error Mask (HEM) which contains local accuracy information
- Various masks like water body mask, shadow and layover mask
- Amplitude mosaic.

For the verification of the DEMs different approaches and reference information are used like:
- Visual quality inspection
- Height discrepancy relative to e.g. SRTM
- Ground control points (IceSAT, etc)
- Tiepoint statistics
- Height Error Map (HEM)
- Kinematic GPS Tracks.

3. CALIBRATION AND VALIDATION WITH KINEMATIC GPS-TRACKS

TanDEM-X is a global mission and therefore a global calibration- and validation-procedure as well as a global data set is necessary. As DEM calibration reference points from IceSAT-mission are worldwide available, but for the validation of the DEM accuracy independent data sets are needed (Huber et al., 2009). Kinematic GPS tracks are such a suited data set. They fulfil the accuracy requirements for calibration and validation datasets, to have height accuracy better than 0.5m and a sampling about 3m on ground.

NASA has used kinematic GPS Tracks for the SRTM Mission in the year 2000. These tracks are not available and there is no information about their accuracy. Therefore the DLR decided to order the measurements of worldwide kinematic GPS-tracks.

The standard precise GPS methods (DGPS, PDGPS, etc) are very expensive or will not fulfil the accuracy requirements in any case (Schwieger & Schweitzer, 2008). GPS correction services like SAPOS (http://www.sapos.de) in Germany are only available in a limited area and the differential approach to derive these GPS tracks is too expensive and needs too much infrastructure in the countries. The Precise Point Positioning is a suitable alternative (Ramm & Schwieger, 2007). The realization in countries around the world is technical relatively easy. The major problems are customs and national restrictions. The post-processing which is the major part can be done in the home office.

3.1 FIG Support and Data Access

The DLR had no network of partners who can organise and carry out the measurements. On the other hand the result of the TanDEM-X mission will be a very interesting research object for FIG members. In summer 2008 FIG Commission 5 published in the newsletter an announcement of ”Kinematic GNSS for Evaluation of TanDEM-X Digital Elevation Model” to support the German satellite mission TanDEM-X. It offers the possibility of cooperation between DLR and FIG members. More than twenty-five groups from all continents were interested to carry out measurements for DLR. Some were interested to work as a contractor; some are also interested to use the acquired data for their own research.

Interested FIG-members, who carried out measurements, can request TanDEM-X products, e.g. DEMs for calibration and validation projects in the framework of the science coordination (http://www.dlr.de/hr). Also other science topics will be supported with data.

3.2 Worldwide GPS-Tracks

For the validation of the achieved height accuracy of the TanDEM-X DEM it is desirable to have validation data on each continent.

The location and configuration depends on following conditions:

- Direction should be perpendicular to the tracks of the satellites to validate height errors between neighboured DEM acquisitions
- At least one track in each continent or landmass
- Limitation of the PPP approach, e.g. number of points for the processing
- Reduction of personal risk for the staff.

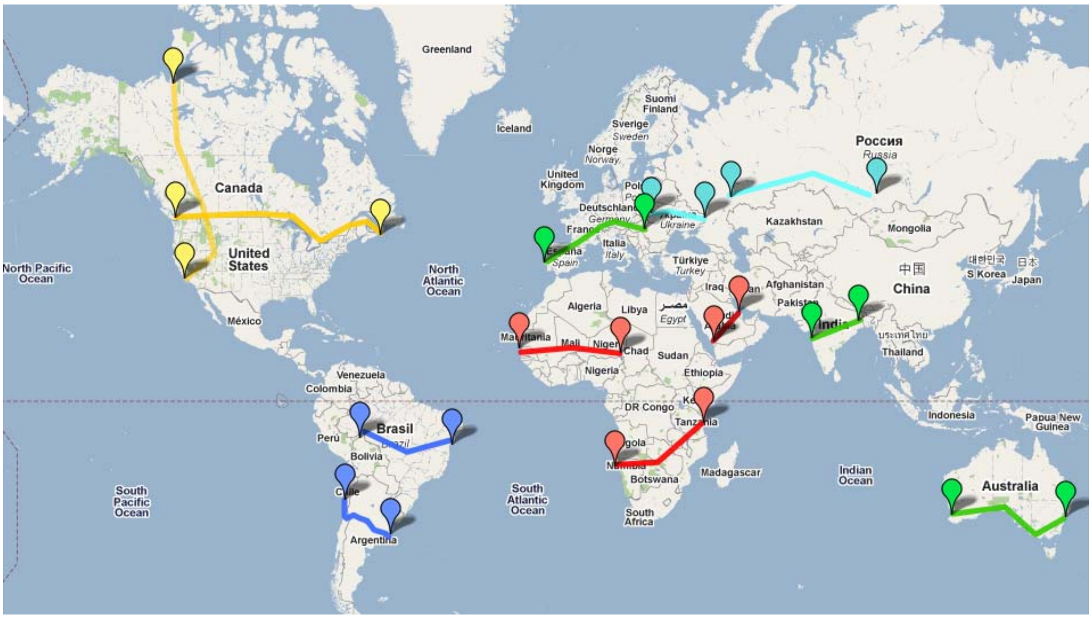


Fig. 5: Worldwide GPS-Tracks

3.3 Requirements for the measurements, post processing

Different GPS receiver, measurement vehicles and software were used by different staff of the partners. A standardisation of measurement to guarantee the anticipated accuracy and to make the post processing as easy as possible is absolute necessary.

To realize this accuracy the following conditions must be guaranteed:

- Dual frequency receiver (code and phase observations)
- Data rate 10 Hz
- Leica GPS1200 is preferred as GPS
- GPS antenna high as possible
- Speed maximum 100km/h
- Exact height of the antenna over ground
- Output format RINEX
- Planning regarding visibility of GPS satellites
- Cut off elevation angle 0 – 10 degree
- Satellite visibility check
- PPP initialization at start (30 minutes)
- Data recording only in dynamic mode
- Track section length of 2 hours
- Maximum single acquisition 2 hours (30 minutes initialization, 90 min. kinematic measurement of raw data)
- Continuous kinematic measurement during acquisition phase
- No power down during the measurement
- 30 minutes static measurements at the end of the day
- Online data quality check

- The track should be in east-west or vice versa direction
- Measurement of 2 large intersections (if possible)
- Integration of available international GPS reference stations with well-known coordinates (International GNNS Service sites) in a distance of maximal 20km. Driving with a reduced speed or a stop near the station of about 10 minutes.

These requirements are the results of studies from the University of Stuttgart (Ramm & Schwieger, 2007). The university is also responsible for the processing of this large amount of data.

3.4 Integration into the Mosaicking and Calibration Processor

For the mosaicking and calibration of TanDEM-X DEM different heterogeneous reference DEM are used, e.g. SRTM, laser scan, other high resolution DEMs, etc. All these data are stored in a DEM database called W42. It is a scalable spatial database system capable of holding, extracting, mosaicking, and fusing all these spatial data (Habermeyer et al., 2009). The GPS tracks are stored in the W42 database as well. At the send of the DEM generation process these data will be stored in the W42 database as well. At the end of the DEM generation process these data will be exported to verify the height accuracy of parts of the adjusted DEM tiles. Furthermore, dedicated DEM validation studies will be carried out in conjunction with the FIG partners to prove the achieved height accuracy.
Tracks are stored in the directory with geographic coordinates as reference. This structure is expanded by:

- A file holding a unique number for assignment of new tracks during the import process
- A list of tracks situated in the specific tile, containing the unique identifier, the file name plus attributes that can be searched for
- A zipped file for each track. Tracks are not further referenced and are identified by their unique identifier, which is part of the filename.

Different in- and output tools are available, also it is possible to convert the height information between different reference systems, to generate either input tom the MCP or integrate TanDEM-X DEMs into the data base.

4. RESULTS

The measurements for the project are mostly complete, only the track in Saudi Arabia is not finished yet. More than 50 000 km were measured covering all continents. This distance includes round-trips in Europe, South America and partially in North America. The other tracks are only one-way tracks. In central Africa the track was driven with two vehicles, each equipped with one GPS-receiver (Fernandes, 2010).
To reduce the post processing effort of the University Stuttgart in a first version only the result in one direction is computed. The roundtrips will be used for validation and further research. Besides the roundtrips for European tracks for a part of the South America the roundtrip data were already compared. Here the mean height difference is 0.3 m.

Tab.2: Measured Tracks

Europe	Munich - Ukraine
Europe	Munich - Sao Marinho (Portugal)
Asia	Beijing – Gaoquan (China)
South America	Vina Del Mar - Mar Del Plata (Chile-Argentina
South America	Laguna Verde - Punta de Choros (Chile)
Russland	Krasnojarsk – Belgorod (Russia)
Ukraine	Dovzhanck - Tissa
South Africa	Dar es Salaam - Skeleton Coast (Namibia)
West Africa	Conakry - Ife (Niger)
Brazil	Recife – Porto Veiho
USA/Canada	Los Angeles – Inuvik (Canada)
Canada	Vancouver – Nova Scotia (Canada)
Australia	Sydney - Perth
India	Kolkata -Surat
Saudi-Arabia	Dammam – Khamis Mushayt

An independent quality check is done with available reference station from the IGS global system of satellite tracking stations. With these stations a PDGPS evaluation was realized (Tab.3). The mean height error fulfils the requirements.

Tab. 3: GPS-Track height accuracies at IGS Station

Reference Station	**Mean dh (m)**	**RMS dh(m)**
URUM (China)	-0.03	0.39
SANT (Chile)	0.37	0.79 (large dist. to station)
NVSK (Russia)	0.39	0.15
OBE3 (Germany)	0.21	0.5
SALA (Spain)	0.18	0.37

Due to the lack of more IGS stations or other reference data and to fulfil the accuracy requirements for the TanDEM-X references the processing is done with two independent approaches – the online service of the National Resources Canada (CSRS, 2010) and the software GIPSY. The height discrepancies in same points between these two solutions have to be smaller 0.5m. If this limit is not achieved, this point is not used for further DEM validation and the length of suitable track is reduced. Tab. 4 gives an overview about the amount of usable track points (Schwieger et al., 2009).

Tab. 4: Percentage of valid GPS-Track length

Track	Track Length (km)	Valid track
Vina Del Mar - Mar Del Plata	1714	47 %
Laguna Verde - Punta de Choros	621	59%
Punta de Choros - Laguna Verde	566	58%
Beijing – Gaoquan	3991	71%
Munich - Ukraine	900	61%
Munich - Sao Martinho	2400	59%
Krasnojarsk – Belgorod	4585	59%

The percentage of valid tracks is not directly correlated with rough topography or vegetation. In very difficult terrain like the Andean mountains (Fig. 6) the results are very good, but in flat farmland (Fig. 7) areas the discrepancies between the two solutions are too large and the points are not suitable for evaluation, even in areas where more than eight GPS-satellites visible. This is caused by different velocities. Looking at the serpentines in the Andean mountains the driver have to drive slow and the receiver has no problems regarding satellite tracking. The flat terrain was driven with a much higher velocity.

Fig. 6: Track in the Andean mountains

Fig. 7: Gaps in flat terrain

Fig. 8: Quality check with a roundabout

Additional internal data checks are possible. Special road feature like crossings and roundabouts are feasible. Fig. 8 shows an example of a test for a roundabout. In this test for both accuracies – location and height – were checked through driving the roundabout two times.

The processing at University Stuttgart supports by a protocol dataset for each track (Fig. 9a-f), which can be used by further investigations either in the PPP-technique or the validation control of the TanDEM-X height values (Schwieger et al., 2009).

Fig. 9a: Track location

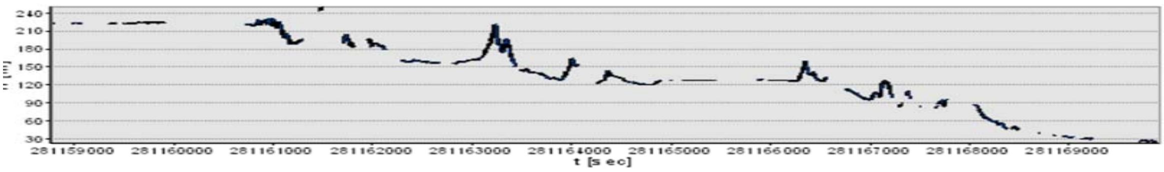


Fig. 9b: Track height profile

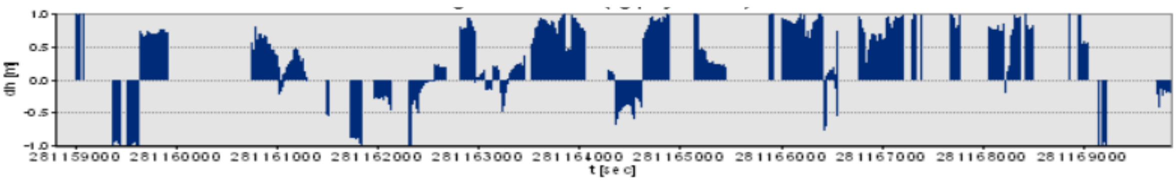


Fig. 9c: Height differences (GIPSY- CSRS)

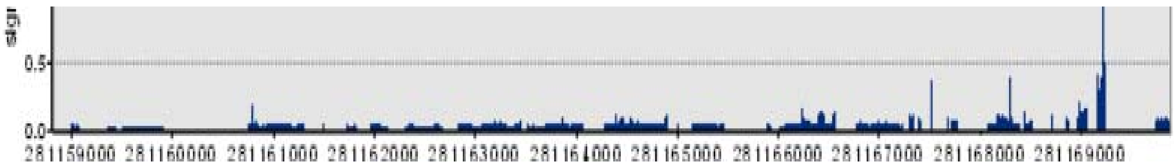


Fig. 9d: Accuracy

Fig. 9e: Number of visible GPS satellites

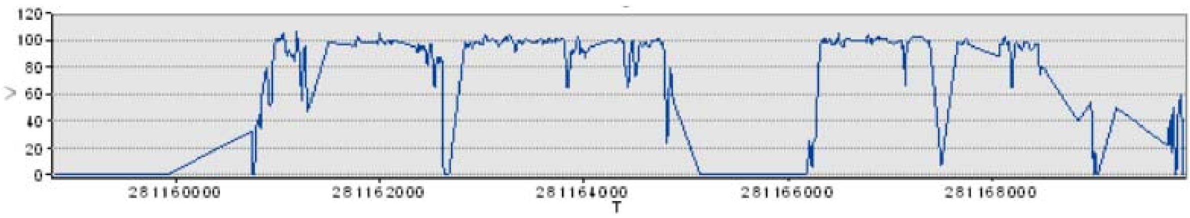


Fig. 9f: Velocity of vehicle

5. CONCLUSIONS AND OUTLOOK

The TanDEM-X mission will provide a worldwide DEM to scientific and commercial users. The maximum relative height error will be 2m (90% linear error), 10m absolute height error and 10 m horizontal error with a spacing of about 12 m.
The calibration/validation of this DEM will be done using various reference data. One important data set for calibration/validation are worldwide kinematic GPS tracks. The post processing approach with Precise Point Positioning (PPP) fulfil the requirements for height accuracy of reference data of about 0.5m, if the conditions for driving, visibility of satellites etc were kept (Heroux et al., 2004; Ramm & Schwieger, 2007). Worldwide approx. 50000km tracks were measured and about 30 000km were processed until January 2010.
In cooperation with FIG members these GPS datasets can be used for further studies regarding TanDEM-X, GPS instruments or post-processing software.
Scientific user will also get access to the DEM for scientific projects in the framework of the TanDEM-X science team (Hajnsek et al., 2009).

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