Evaluation of the TanDEM-X Digital Elevation Model by PPP GPS - Analysis and Intermediate Results -

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SUMMARY

From mission **T**erraSAR-X **a**dd-o**n** for **D**igital **E**levation **M**easurements (TanDEM-X) of the German Space Agency (DLR) a global digital elevation model (DEM) will be derived using satellite SAR interferometry. Two radar satellites (TerraSAR-X and Tandem-X) are going to map the earth in such a resolution and accuracy that was not possible in any earlier missions: the aim is an absolute height error of 10m or a relative height error of 2m respectively for 90% of the data. One method to evaluate the accuracy is the use of kinematic Precise Point Positioning (PPP) GPS measurements. The required accuracy is around 0.5 m.

The evaluation of the tracks is carried out using the software GIPSY 5.0 of the Jet Propulsion Laboratory (JPL), USA, as well as using the online service of the Natural Resources of Canada named CSRS-PPP. Both results are combined, thus defining the final solution.

After the presentation of results for the first track from Munich, Germany, to Sao Martinho, Portugal in 2009, the intermediate results of five tracks located in Europe, China and South America are described and analyzed in this paper. The final average RMS is calculated to 0.49m and the availability rate is determined to 61%. These values justify the characteristics of the first drive and fulfill the requirements. A second focus of the paper is the analysis of the standard deviations provided by the software packages used for this purpose and the processing services respectively. The authors will show that these numerical values are indicators for the actual accuracy, but not in a reliable way.

One track in Africa has been processed recently. For the future further tracks should be acquired and processed for India, Russia, North America and Australia.

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1. MOTIVATION

A new world-wide and highly accurate digital elevation model (DEM) will be generated in the near future, since the second satellite of the TanDEM-X mission is now expected to be in the orbit, thus allowing to determine a 2m relative DEM. In contrast to the first mission dealing with this task and using Synthetique Aperture Radar (SAR) technique the Shuttle Radar Topography Mission (SRTM mission) in the year 2000 is a big step forward The SRTM-results were outstanding and the estimated accuracy was approximately 6 to 10 m with a resolution of around 30x30 m or 90x90 m respectively (Rodriguez et al., 2005).

The question arising for DLR, is how to evaluate the expected accuracy. Different methods have been proposed (Huber et al., 2009). Kosmann et al. (2010) provide background information regarding the TanDEM-X mission, the resulting Digital Elevation Model (DEM) and the different elevation methods. This paper will deal with the evaluation using kinematic GPS tracks. Due to the more accurate TanDEM-X DEM, the accuracy level of the GPS tracks has to be higher, too. In Schwieger et al. (2009), the decision to use Precise Point Positioning (PPP) as a kinematic evaluation method was justified. First results were presented as well. This paper focuses on the processing of the first five of the world-wide distributed kinematic GPS tracks. Through these intermediate results the authors hope to confirm the first accuracy and availability patterns for the first track.

2. THE TANDEM-X SATELLITE MISSION

The most important task of the TanDEM-X mission is the generation of a precise worldwide digital elevation model. Recent SAR missions are working as repeat-pass interferometry systems. This technique is well proofed and established since many years. The loss of coherence between the two data tracks of the repeat pass approach causes severe problems in the processing and reduces the accuracy. The SRTM mission in the year 2000 was the first single pass interferometric mission. The results were so excellent, that a new bistatic SAR mission will be realized in 2009 – TanDEM-X. It is a Public Private Partnership cooperation between DLR und Infoterra-Germany.

The space segment consists of two nearly identical satellites. The first satellite TerraSAR-X (TSX) was launched in 2007 and operated since the end of the calibration phase very well. More than 40 000 data sets were already taken. The second spacecraft (TDX) will be launched end of 2009. Table 1 provides the system parameters for the TanDEM-X mission, which are identical with TerraSAR-X

Tab. 1: TanDEM-X system parameters

Frequency	9.65 GHz
Bandwidth	up to 300MHz
Incidence Angle	20- 55 degree
Polarization	single, dual, quad
SAR modes	Spotlight (1m), Stripmap (3m), ScanSAR (15m)

A helix configuration for both satellites as flight formation is planned. A minimum safety distance of 150m between the two spacecrafts will be kept. Baselines in cross- and along track between 200m and 10km are possible. Data tracks for DEM processing will have a variable baseline in the range of 300m to 500m. In this flight-configuration one satellite illuminates the scene on ground and both satellites receive and measure the backscatter. This is shown in figure 1.

Besides the DEM standard SAR products, which are well-known from TerraSAR-X, will be available for the worldwide user community. With the second SAR satellite the temporal resolution of these radar products will increase.

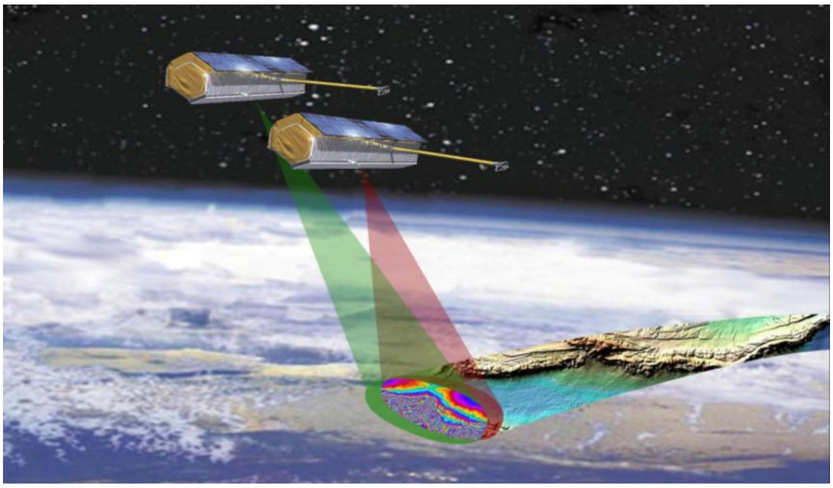

Fig. 1: TanDEM-X helix flight configuration

2.1 Characteristics and Accuracy of Global Digital Elevation Model

TanDEM-X is designed the produce a high accurate world wide elevation model. The specifications are given in table 2.

Tab. 2: DEM accuracy parameters

Parameter	**Error**	**Remark**
absolute vertical accuracy	10 m	90% linear error
horizontal accuracy	10 m	90 % circular error
relative vertical accuracy	2 m (slope < 20%) 4 m (slope > 20%)	90% linear error
spatial sampling / resolution	0.4’’ (~12m)	independent pixels

The best accuracy is 2 m; being specified for the relative vertical component. The spatial sampling will increase from 0.4’’ up to 4” in areas between 85 – 90 degree latitude.

The generation of the worldwide DEM is the pre-final step of the processing chain given and described in the following: *mission planning - data receiving – SAR interferometric processing – DEM generation – Archiving.* Four years after start of the operational data acquisition the final DEMs should be availability. After the first worldwide aquisition an intermediate DEM product with a lower accuracy will be available. Additional special products with a higher accuracy or higher resolution on ground will be available in selected and suitable areas. The scientific user community will get access to the DEMs of selected areas via an online web interface

3. PRECISE POINT POSITIONING

Precise Point Positioning (PPP) was chosen as the most efficient positioning technique, and it fulfills the requirements for reference trajectories for the TANDEM-X Project described in Ramm & Schwieger (2007).

In general, PPP is a stand-alone precise point positioning method on the basis of un-differenced dual-frequency code and carrier phase observations, along with precise orbit information on the cm-level accuracy. In contrast to differential GPS where the position can be estimated relative to one or more reference stations and by this way common satellite and receiver errors will be minimized or eliminated, here the satellite and receiver errors fully affect the positioning. Thus there is a need for precise correction models. In the following, the most important facts and constraints concerning PPP are described.

3.1 Characteristics of Precise Point Positioning

The uncertainty of satellite ephemeris and clocks is the main reason in single station observation for non-accurate positioning. With regard to this, the International GNSS Service (IGS) offers a number of orbit and clock products with a better accuracy than the broadcast ephemeris shown in table 3.

Tab. 3: Extract from IGS Products; broadcast included for comparison (IGS, 2009)

		Accuracy	**Latency**	**Sample Interval**
Broadcast	*Orbits*	*~100 cm*	*Real time*	*Daily*
	Sat. clocks	*~2.5ns SDev*		
Ultra-Rapid (predicted half)	Orbits	~5cm	Real Time	15 min
	Sat. clocks	1.5ns SDev		
Rapid	Orbits	2.5cm	17-41 hours	15 min
	Sat. clocks	25ps SDev		5min
Final	Orbits	2.5 cm	12 – 18 days	15 min
	Sat. clocks	~20ps SDev		30s

In real time, the ultra rapid orbits can be used with an increased accuracy in contrast to the broadcast orbits (improvement from 100cm to 5cm). However to achieve the highest accuracy for positioning, there is a demand for final orbits and clocks. This is only possible in post-processing, as this product is available only 12 days after observation time.

Beside the higher accuracy of the the final orbits and clocks, the higher sample interval of the satellite clock corrections contributes to a better accuracy. To get a satellite position and a clock correction for every epoch interpolation between the provided values is required. Because of the bad short-term stability of satellite clocks, the interpolation provides better results, when the sample interval is smaller. The sample interval improves from 15 min (ultra rapid) over 5 min (rapid) to 30 sec (final). As described in Heßelbarth (2009), the interpolation error is reduced by factor 5 when using satellite clock corrections with a sample interval of 30 sec instead of a sample interval of 5 min. The effect on height can reach an rms of 6.4 cm when using 5 min in contrast to 3.1 cm when using 30sec data after a convergence time of 100 min in kinematic mode. Heßelbarth (2009) also shows that when using 30 sec data, there can be reached the same accuracy already after a convergence time of about 40 min, whereas with 5 min data there can be reached this accuracy only after 100 min.

In addition to the “standard” correction models, e.g. the atmospheric corrections (ionosphere and troposphere) even used for pseudo range positioning, further effects have to be considered. As mentioned in Kouba & Héroux (2000), there are effects on positioning which are divided into satellite attitude effects and site displacement effects. Regarding an overview of different corrections, the authors refer to Schwieger et al. (2009) or even Heßelbarth (2009). In addition to the correction models another important fact regarding PPP evaluation is the convergence of the results. The so-called convergence time is 30 minutes for cm level in static mode (Kouba & Héroux, 2000). In kinematic mode (Bisnath & Gao, 2008) there can be reached an RMS of 8.5cm for the same convergence time.

3.2 Processing Procedure

The raw data provided in several Receiver-independent Exchange Format (RINEX) files are processed with the GPS-Inferred Positioning SYstem and Orbit Analysis SImulation Software

(GIPSY-OASIS (GOA II)) from the Jet Propulsion Laboratory (JPL), USA and with the Canadian Spatial Reference System (CSRS) PPP Online service (CSRS, 2009) from the Natural Resources Canada (NRCan). In addition, an evaluation of the final result is realised by using PDGPS. Therefore a reference station near the track has to be chosen and the points within a radius of 20km have to be evaluated and used for the PPP solution (Ramm & Schwieger, 2007).

3.2.1 GIPSY 5.0

At the moment the authors are using GIPSY version 5.0 which runs on Fedora 10, an open source Red Hat distribution. GIPSY is a free source command line based software, which supports among others the PPP evaluation, using final orbits and clocks as well as the correction models mentioned in table 4, however, not all of them are necessary for the required accuracy. For detailed information on the processing procedure with GIPSY 5.0, the authors refer to Schwieger et al 2009

3.2.2 CSRS-PPP Online Service

The CSRS-PPP Online Service is very easy to use. The raw data in RINEX format is uploaded at the web interface. Options like the reference system can be selected and a choice between kinematic or static processing can be made. The links to the results including positions, residuals and processing overview are provided via email after approximately five to ten minutes. For details regarding the implemenetd models, corrections, and processing strategies the authors refer to Kouba & Héroux (2000).

3.2.3 Combination of the two results

The processing results from both systems are merged. Only those are selected where the height difference between GIPSY results and CSRS results is less than 1m. With this process an accurate and reliable solution is provided, whereas the availability is reduced. The other data is rejected. Finally, the final result is the mean value of coordinates from GIPSY and CSRS. In figure 2 an overview of the whole evaluation process is given.

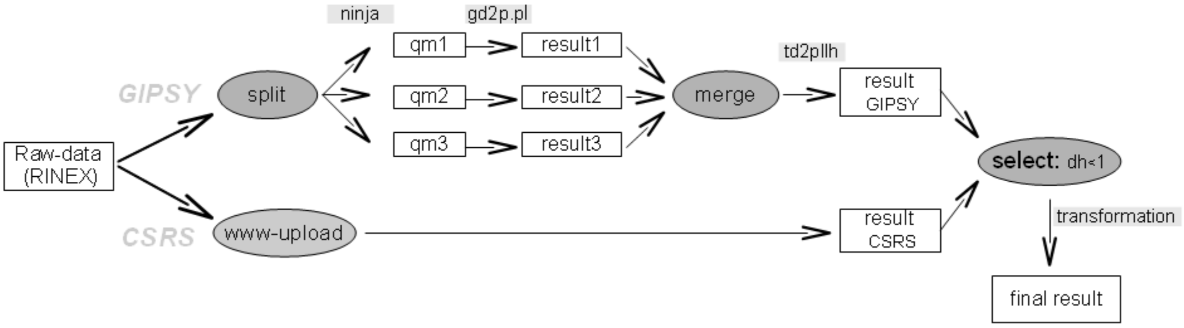

Fig. 2: Overview of the PPP evaluation process

The reference frame for the coordinates which will be used for the TanDEM-X project, is ITRF2005 (International Reference Frame 2005) epoch 2010.0. The coordinates resulting from GIPSY and CSRS-PPP both refer to ITRF2005 current epoch. So the coordinates have to be transformed from ITRF2005 current epoch to ITRF2005 epoch 2010.0. The data, upon which this article is based on, have been acquired between May 2008 and June 2008. The shift between epoch 2008.5 and epoch 2010.0 in Europe amounts 3cm. For further data acquisitions (after 2008) the shift gets smaller. Thus the final result is a file with three dimensional coordinates (latitude, longitude and ellipsoidal height) in ITRF2005 epoch 2010.0.

4. DATA ACQUISITION AND ANALYSIS

Up to now, there are already five evaluated tracks for the TanDEM-X mission. The whole data acquisition was carried out in 2008. The figure below shows an overview of the processed tracks.

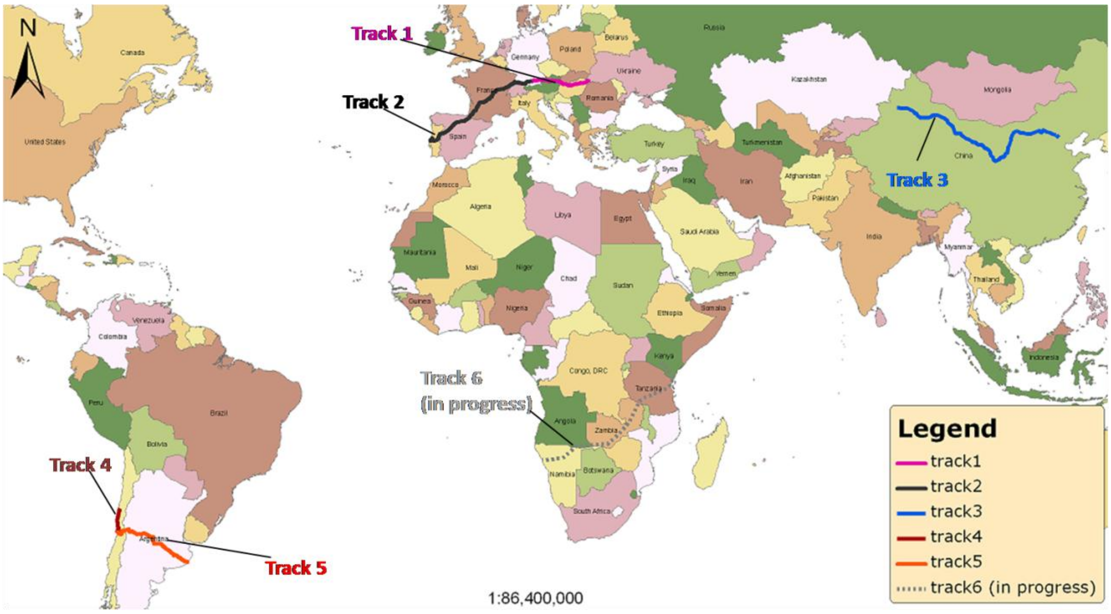

Fig. 3: Overview of the five evaluated tracks for TanDEM-X mission

The first two tracks were driven in Europe, the third one is in Asia and the last two tracks are located in South America. In this chapter we will describe the evaluation of these tracks and present the results of post-processing.

4.1 Current Status of Data Acquisition

The first track (track 1 in figure 3) is from Munich to the border of Ukraine and Hungary. The data acquisition was carried out from May 13th to May 17th. The whole track has a length of about 1000km (see figure 4) and is divided into 9 separated track parts covering a time period of 60 to 140 minutes each. For example, one RINEX file of 100 minutes has about 60000 measurements.

The second track (track 2 in figure 3) is from Munich to Sao Matinho. The data acquisition was carried out from June 9th to June 28th. This track has a one way length of about 2400km and is divided into 22 separate track parts. All the track parts cover time periods of 60 to 240 minutes each.

The third track (track 3 in figure 3) is located in North China. To acquire data a car was driven from Beijing to Gaoquan. The data acquisition was carried out from October 4th to October 11th. The whole track has a one way length of about 4000km and is divided into 42 separate tracks covering time periods of 27 to 125 minutes each.

The fourth track (track 4 in figure 3) and the fifth track (track 5 in figure 3) were driven in South America. The data acquisition of track 4 was carried out November 21th to November 24th in Chile. This track from Laguna Verde to Punta de Choros has a one way length of about 622km and is divided into 7 separate track parts covering time periods of 66 to 157 minutes each. The data acquisition of track 5 was carried out from November 24th to December 9th. The whole track from Vina Del Mar to Mar Del Plata has a one way length of about 1812km and is divided into 12 separate track parts covering time periods of 52 to 230 minutes each.
In the table below an overview of the tracks in chronological order including the date of the measurements, the length and the type of receivers is given.

Tab. 4: Overview of the five tracks (forward and backward)

Track	Position	Direction	Start date	End date	Length [km]	Receiver
1	Munich – Ukraine	Forward	05/13/08	05/15/08	997	Leica GX1230
		Backward	05/15/08	05/17/08	1004	Leica GX1230
2	Munich – Sao Martinho	Forward	06/09/08	06/13/08	2343	Leica GX1230
		Backward	06/15/08	06/28/08	2573	Leica GX1230
3	Beijing – Gauquan	Forward	10/04/08	10/11/08	3903	Leica GX1230
4	Laguna Verde – Punta De Choros	Forward	11/21/08	11/23/08	622	Leica GX1230
		Backward	11/23/08	11/24/08	556	Leica GX1230
5	Vina Del Mar – Mar Del Plata	Forward	11/24/08	11/28/08	1715	Leica GX1230
		Backward	12/01/08	12/09/08	1811	Leica GX1230

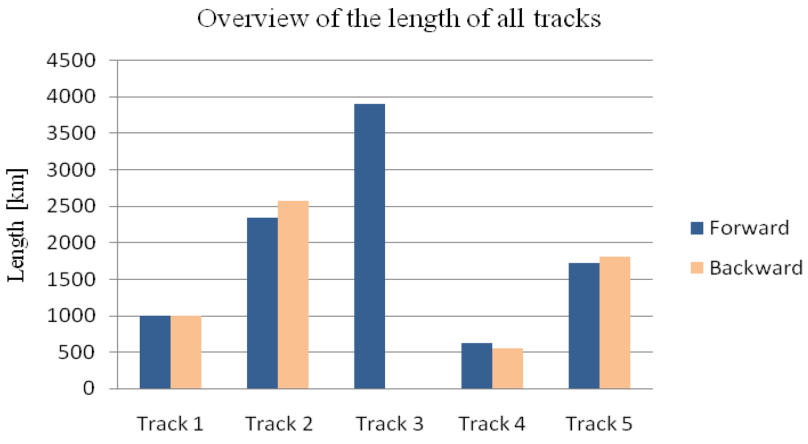

Fig. 4: Length of the tracks

Excepting track 3 all other tracks have a forward way and a backward way. A LEICA GX 1230 receiver (dual frequency) and an AX 1202 antenna were used for all tracks for the data acquisition. The data of each track was provided in several RINEX files with a data rate of 10 Hz. The data acquisition of track 6 was carried out from June 14th to June 24th 2009. This track is located in South Africa and has a length of about 5230km. A TPS HIPER_GGD receiver (dual frequency) and a TPSPG_A1 were used for the data acquisition.

4.2 Results of Post-Processing

In this chapter, some statistical values of the final results of the whole evaluation is resented. Track 6 is still in progress. Therefore just the results of the first five tracks are presented. To compare and combine the evaluation results from GIPSY and CSRS-PPP only measurements with height differences between GIPSY and CSRS-PPP less than 1m are selected. The other measurements are rejected. Afterwards the positions and the heights of the selected measurements are averaged. In the following table you see some characteristic values of the results, originating from GIPSY and CSRS-PPP combined positions.

Tab. 5: Statistic values of the results (forward and backward)

Track	**Position**	**Direction**	**Epochs**	**Duration [Hour]**	**Availability**	**RMS_{dh} [m]**	**Point density [1/km]**
1	Numich - Ukraine	Forward	375046	16.5	65%	0.45	376
		Backward	350577	18.4	57%	0.44	349
2	Munich – Sao Martinho	Forward	772685	36.2	60%	0.48	330
		Backward	774775	39.1	58%	0.48	301
3	Beijing - Gauquan	Forward	1788140	68.0	71%	0.48	458
4	Laguna Verde - Punta De Choros	Forward	288296	13.8	59%	0.50	464
		Backward	260881	12.0	58%	0.49	469
5	Vina Del Mar – Mar Del Plata	Forward	497312	28.9	46%	0.57	290
		Backward	519377	31.2	47%	0.51	287
Weighted mean					61%	0.49	

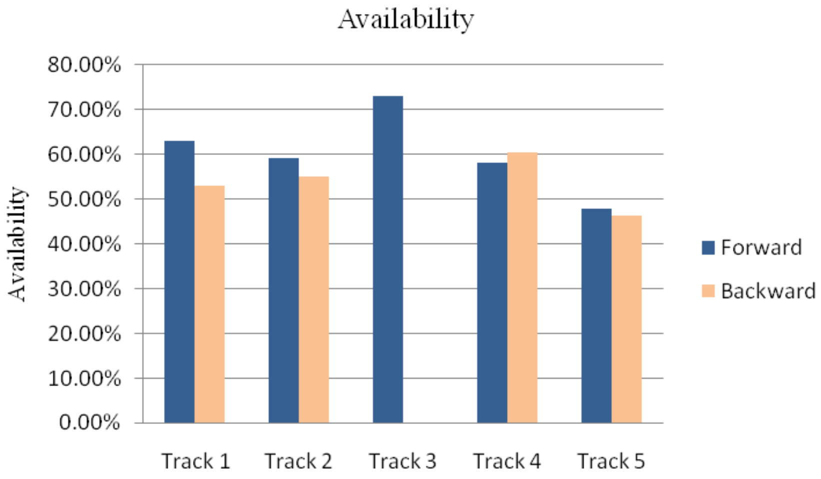

Fig. 5: Availability of the measurements

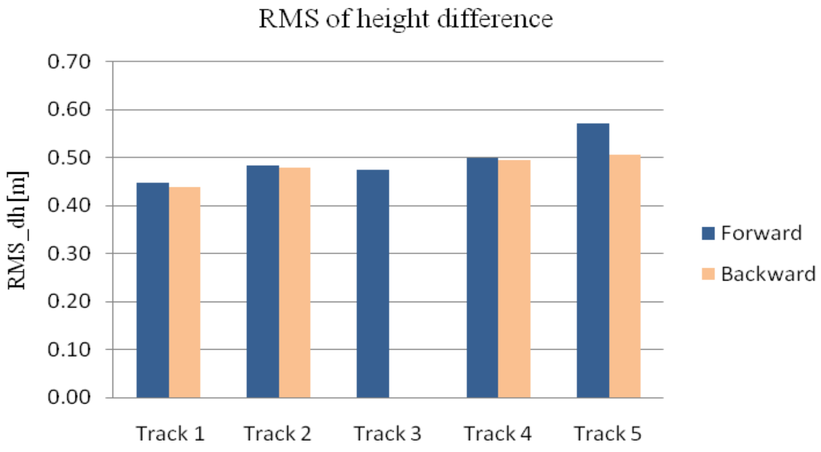

Fig. 6: Root Mean Square of the height difference

The columns in tabel 6 are explained in the following.

$$Availability = \frac{Epoch}{Duration}, \text{ with} \qquad (1)$$

”Epoch” - number of positions after data editing and position rejection of each track,
”Duration” – all-over duration of each track.
”RMS_{dh}” indocates the Root Mean Square of the height differences between GIPSY and CSRS-PPP.

$$Point\ density = \frac{Epoch}{Length} \qquad (2)$$

shows how many points per kilometer in average are provided for a track. This value characterizes the spatial distribution of the positions.

In comparison to the other tracks the results of track 3 show the best availability (see figure 5). A mean availability of 71% is reached. This can be explained by the fact that the route leads through weakly populated areas without any tunnels, bridges etc. Furthermore, the topology of North China is more or less planar. There are no high mountains, except the plateau of Inner Mongolia. In contrast to this the results of track 5 show the worst availability. A mean availability of just 47% is reached. The mean RMS of height differences is 0.54m (average between forwards and backwards, compare figure 6). The complex topology at the boundaries between Chile and Argentina are the Andes, they are the world's longest exposed mountain range and lie along the western coast of South America. Due to this topology, the accuracy and availability of the measurements are degraded by error effects like shadowing, multipath effects etc.. The two tracks in Europe have roughly the same mean availability of 61% and 59%. In comparison to all other tracks, track 1 has the best mean RMS of 0.445m.

The solutions generated for relative phase GPS (PDGPS) with fixed reference stations are produced using Leica Geo Office. The results of the evaluation are only to validate the PPP results. To guarantee the required accuracy, a baseline length of 20 km is not to be exceeded (Ramm & Schwieger, 2007).

For all tracks except track 4, reference stations could be used. The individual names of the stations and the quality parameters can be found in table 6. In contradiction to all other tracks there is no IGS reference station available for track 4. The nearest station is SANT. However, the shortest distance between the track points and the reference station is already more than 100km. The distance dependent errors can corrupt the evaluation results, so it was decided to leave the PDGPS evaluation out.

The RINEX files of the reference stations are taken from the official homepage "The Crustal Dynamics Data Information System (CDDIS, 2009)" and the homepage "GNSS Data Center (GDC, 2009)". The station coordinates at the respective epoch are taken from the SINEX file taken from the same CDDIS homepage. In the table below the mean values of the differences in height as well as the RMS_{dh} are shown.

Tab. 6: Results of PDGPS

Track	**Ref. Station**	**Num. of comparisions**	**MEAN$_{dh}$ [m]**	**RMS$_{dh}$ [m]**
1	LINZ	7	0.21	0.26
	OBE3	3	-0.51	0.53
2	OBE3	29	0.21	0.5
	SALA	35	0.18	0.37
3	URUM	99	-0.03	0.39
4	No ref. Station			
5	Sant	97	0.37	0.79

The characteristic values $MEAN_{dh}$ and RMS_{dh} show satisfying results. $MEAN_{dh}$ and RMS_{dh} of track 5 show the worst results. Again this can be explained as written before, by the complex topology at the boundaries between Chile and Argentina. For all tracks, the evaluation shows accuracy parameter values that correspond to the determination using the PPP procedure, briefly described in section 3.2.

4.3 Analysis of Accuracy-Height Difference Correlation

In this chapter, the internal accuracy of the two software systems GIPSY and CSRS-PPP is analyzed. Each software provides a position accuracy for each epoch called σ_{3D}, which should represent the accuracy of the measurement. Not to confuse with the RMS_{dh}, mentioned in chapter 4.2 which describes the rms of the height difference between GIPSY and CSRS. In this chapter the correlation between the internal accuracies and the height differences of GIPSY and CSRS is evaluated. Final positions as described in section 3.2.3 are only calculated for the epochs for which the height differences are below 1 m. These epochs are named filtered in the following. The other positions which are eliminated from the final result are called rejected.

In table 7 the average σ_{3D}, and the respective standard deviation (stdv) are shown, divided into filtered results and rejected results of both software systems. So, if a correlation exists, the rejected results should have a worse internal accuracy than the filtered ones.

Tab. 7: Internal accuracies of GIPSY and CSRS

in cm		**GIPSY filtered**		**GIPSY rejected**		**CSRS filtered**		**CSRS rejected**		
track	**subtrack**	**MEAN$_{\sigma3D}$**	***stdv$_{\sigma3D}$***	**MEAN$_{\sigma3D}$**	***stdv$_{\sigma3D}$***	**MEAN$_{\sigma3D}$**	***stdv$_{\sigma3D}$***	**MEAN$_{\sigma3D}$**	***stdv$_{\sigma3D}$***	**avail.**
3	01	13	*6*	19	*28*	10	*5*	13	*20*	71%
	02	10	*4*	11	*5*	8	*3*	10	*6*	84%
	03	12	*7*	27	*40*	21	*17*	46	*70*	69%
	04	8	*4*	11	*10*	6	*4*	7	*5*	55%
	05	4	*1*	5	*5*	6	*1*	7	*3*	65%
	06	6	*3*	28	*24*	11	*8*	108	*50*	80%
2	01	19	*10*	148	*130*	25	*13*	55	*43*	45%
	02	24	*12*	28	*25*	81	*75*	258	*270*	48%
	03	23	*13*	31	*29*	43	*34*	95	*109*	53%
	04	21	*12*	29	*32*	36	*29*	105	*204*	74%
	05	14	*13*	27	*47*	20	*50*	54	*246*	70%
	06	21	*12*	41	*45*	33	*20*	73	*83*	57%

As expected, the rejected epochs generally show a worse rms and standard deviation of σ_{3D} than the filtered epochs. It is also visible that track 3 shows a better accuracy than track 2 which corresponds to the statement of table 5 in which track 3 has an availability of 71 % in contrast to 59% of track2. That means that in track 3 there are more epochs showing a height difference smaller than 1 m.

The difference between filtered and rejected is not always significant. One example in subtracks 02 and 05 of track3 the difference between filtered and rejected is only 1cm, in contrast to the subtracks 1 and 2 of the track2, where the difference is more than 1m.
The trend is obvious, but the correlation between the internal accuracies and the height difference is not always given.

This statement is also emphasized by the two figures below. The upper chart of figure 7 shows an extract of subtrack01 of track2 for the height difference dh and the corresponding internal accuracies of GIPSY and CSRS. Here the correlation of the internal accuracies and the dh is obviously visible. In contrast to the lower chart of figure 7 where the height difference dh increases constantly from 0.4m to 1.6m, the internal accuracies remain constant at a value of 0.05m respectively 0.1m. So the upper chart exemplary shows that the internal accuracy measure may be an indicator for an actual accuracy change. The lower chart does not support this idea.

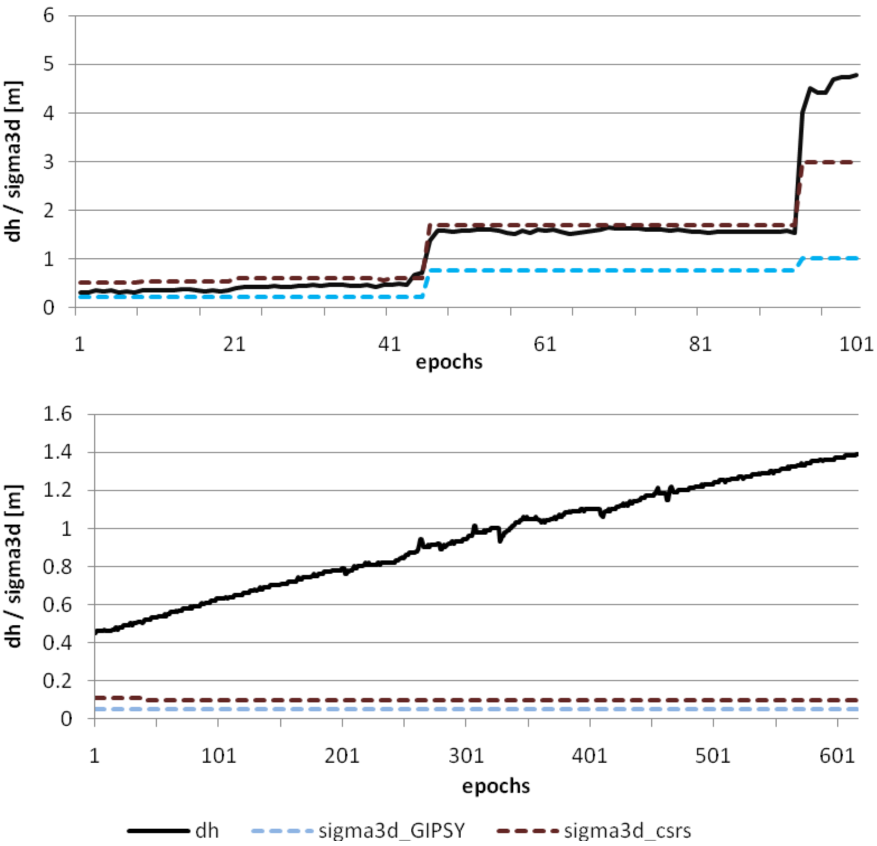

Fig. 7: Correlation between height difference and internal accuracies

Finally it can be said that the internal accuracies cannot be used as filtering criteria. The values are too optimistic, for example the $MEAN_{\sigma 3D}$ of track3 reaches about 10cm for GIPSY and about 11cm for CSRS. In contrast the height difference RMS between the two tracks is 0.48m. This clearly shows that the internal accuracy measures do not correspond to reality.

5. CONCLUSIONS AND OUTLOOK

In this paper, intermediate results for the TanDEM-X evaluation method "kinematic GPS tracks have been presented. They are based on the processing of the first five tracks. The average standard deviation reaches 0.49m and the average availability is 61%. These values empirically justify the values reached in Schwieger et al. (2009). In general, the results are homogeneous for the different tracks on different continents, even the worse results in mountainous areas are within the required levels.

The results as well as the processing procedure itself are proven by PDGPS processing of IGS stations nearby. The resulting accuracy values are on the same level as the final PPP accuracies; this is true for each track individually.
Besides, the authors have analyzed, whether there exists any relationship between internal accuracy measures that are delivered by the processing packages GIPSY or CSRS respectively, and the height differences between the two results used to eliminate "bad data" exist. The correlation was obvious, but not stringent for all data. So, indirectly the chosen post-processing procedure was proven to lead to reliable and accurate results.

One track in Africa has been processed recently. For the future, further tracks should be acquired and processed for India, Russia, North America and Australia. In future the final results of all tracks will be presented. The authors are optimistic that the accuracy and availability values will not change significantly, and therefore the requirements will still be maintained in the future. If the complete acquisition and processing is carried out, the future DEM will be evaluated globally in a reliable way.

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