GPS Precise Point Positioning as a Method to Evaluate Global TanDEM-X Digital Elevation Model

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Key words: Positioning, GNSS, GPS, Precise Point Positioning

SUMMARY

The **T**erraSAR-X **a**dd-o**n** for **D**igital **E**levation **M**easurements (TanDEM-X) mission of the German Space Agency (DLR) will derive a global digital elevation model (DEM) using satellite SAR interferometry. Two radar satellites (TerraSAR-X and Tandem-X) will map the earth in a resolution and accuracy, which was never possible in earlier missions: an absolute height error of 10m respectively a relative height error of 2m for 90% of the data are aimed for. One method to evaluate the accuracy is the use of GPS measurements. To get a high amount of data kinematic GPS data from all over the world will be used. To reach the required accuracy of around 0.5 m, phase data has to be evaluated, because code solutions will not provide such an accuracy. Since data has to be acquired all over the world, the procedure has to be easy and time and money economizing. This is the reason that first investigations propose the Phase Precise Point Positioning (phase PPP) method that neither need any local reference station nor any regional reference station network. The solutions are independent of these kinds of infrastructure. As explained in this paper precise GPS orbits and clocks, e.g. delivered by the International GNSS service (IGS) are used to deliver coordinates with the required accuracy. These first investigations were concentrated in an area around Munich, Germany. They have been initiated by German Remote Sensing Data Center (DFD) of DLR. FIG Commission 5 has supported the search for kinematic-GPS-data-acquisiteurs all over the world.

The evaluation of the tracks is carried through using the software GIPSY 5.0 of the Jet Propulsion Laboratory (JPL), USA. For comparison a second PPP-solution is generated using the online service of the Natural Resources of Canada named CSRS-PPP. Both results a combined thus defining the final solution. The conditions are rather difficult, since the data are acquired with velocities up to 120 km /h and the tracks show a lot of masking by shadowing trees, buildings and bridges.

First results will be presented in this paper for Europe. These PPP results cover a track from Munich, Germany, to Sao Martinho, Portugal. The final average RMS is 0.48 m and the availability rate is calculated to 59 %. By this way the defined requirements are fulfilled. The tracks will be expanded all over the world. Up to now further tracks are acquired in Europe and South America. Plans for Africa, Ukraine, North America and Australia are on the way.

ZUSAMMENFASSUNG

Die TanDEM-X Mission des DLR wird ein globales digitales Höhenmodell mittels SAR Interferometrie erstellen. Die zwei Radarsatelliten (TerraSAR-X und Tandem-X) werden die Erde mit einer Auflösung und Genauigkeit abbilden, die in früheren Missionen noch nie möglich war: ein absoluter Höhenfehler von 10 m und ein relativer Höhenfehler von 2 m sollen für 90 % der Daten erreicht werden. Eine Möglichkeit zur Genauigkeitsevaluierung ist die Nutzung von GPS Messungen. Um möglichst viele Evaluierungen durchführen zu können, werden weltweit verteilte kinematische Messungen genutzt. Um die notwendige Genauigkeit von 0,5 m zu erreichen, sind Phasendaten auszuwerten, da reine Codedaten diese Genauigkeit nicht erwarten lassen. Da die Daten weltweit erhoben werden müssen, ist die Erfassung einfach und wirtschaftlich zu gestalten. Aus diesem Grund haben erste Studien die Methode „Precise Point Positioning" (PPP) empfohlen, da diese weder eine lokale Referenzstation noch ein regionales Referenzstationsnetz benötigt. Die so erhaltenen Lösungen sind unabhängig von diesen Referenzstationen. Wie im nachfolgenden Paper erklärt werden wird, sind präzise GPS Bahnen und Uhren notwendig, um die geforderte Genauigkeit erreichen zu können. Diese werden zum Beispiel vom International GNSS Service (IGS) zur Verfügung gestellt. Die ersten Untersuchungen waren auf die Umgebung von München in Deutschland konzentriert. Sie wurden vom Deutschen Fernerkundungsdatenzentrum (DFD) des DLR initiiert. Die FIG Commission 5 hat die Suche nach weltweiten Partnern unterstützt.

Die Auswertung der Fahrten wurde mit der Software GIPSY 5.0 des Jet Propulsion Laboratory (JPL), USA durchgeführt. Zum Vergleich wurde eine zweite PPP Lösung generiert. Hierfür wurde der Online Service des Natural Resources of Canada (CSRS-PPP) herangezogen. Beide Lösungen wurden zu einer endgültigen Gesamtlösung zusammengefasst. Die Messbedingungen waren und sind sehr schwierig, da die Daten mit Geschwindigkeiten bis zu 120 km/h erfasst wurden und vielen Abschattungen durch Bäume, Gebäude und Brücken auftreten.

Erste Auswertungen werden in diesem Beitrag für Europa präsentiert. Diese PPP Ergebnisse umfassen eine Fahrt von München (Deutschland) nach Sao Marthinho (Portugal) und zurück. Die mittlere Standardabweichung hat sich bei einer Verfügbarkeitsrate von 59 % zu 0,48 m ergeben. Die Anforderungen können hiermit als erfüllt gelten. Die Erfassungsfahrten werden weltweit ausgedehnt werden. Bisher sind weitere Fahrten in Europa und Südamerika bereits durchgeführt. Für Afrika, die Ukraine, Nord Amerika und Australien sind Fahrten geplant.

GPS Precise Point Positioning as a Method to Evaluate Global TanDEM-X Digital Elevation Model

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1. MOTIVATION

A new world-wide and highly accurate digital elevation model (DEM) will be generated in the near future. The first mission dealing with this task and using Synthetique Aperture Radar (SAR) technique was the Shuttle Radar Topography Mission (SRTM) in the year 2000. The results were outstanding and the estimated accuracy was approximately 6 to 10 m with a spacing of around 30x30 m (Rodriguez et al., 2005). The next step will be the TanDEM-X mission that will deliver a 2m relative DEM with the help of two SAR satellites using the interferometric approach to reach this high accuracy. This project is a public private partnership cooperation between DLR as the public and scientific partner and Infoterra-Germany as the commercial partner.
For DLR the question arrises, how to evaluate the expected accuracy. There are different methods proposed (Huber et al., 2009). This paper will deal with the evaluation using kinematic GPS tracks. These kinematic tracks have to be more accurate as the DEM, at its best one order of magnitude. On the other hand the evaluation method should not be too expensive, since the kinematic acquisition should carried through world-wide. Consequently the proposed method was kinematic Precise Point Positioning (PPP) that is easy to handle during data acquisition. The evaluation is carried through by University Stuttgart, Institute for Applications of Geodesy to Engineering, for all acquired tracks. In this paper processing for one exemplary track is documented and its results are presented.

It was and it is not easy to find companies or researchers all over the world that are capable to acquire kinematic GPS data with the required carefulness and accuracy. This was the reason to involve FIG Commission 5 "Positioning and Measurement" into the process. In 2008 a flyer was launched indicating the cooperation between DLR and FIG and to advertise for data acquisition all around the world. This call for participation was a success and up to now almost all parts of the world are planned to be covered.

Fig. 1: Header of DLR – FIG Flyer regarding GPS evaluation for TanDEM

2. THE TANDEM-X SATELLITE MISSION

2.1 General Description of the 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 in October 2009. Table 1 provides the system parameters for the TanDEM-X mission.

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 2.

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.

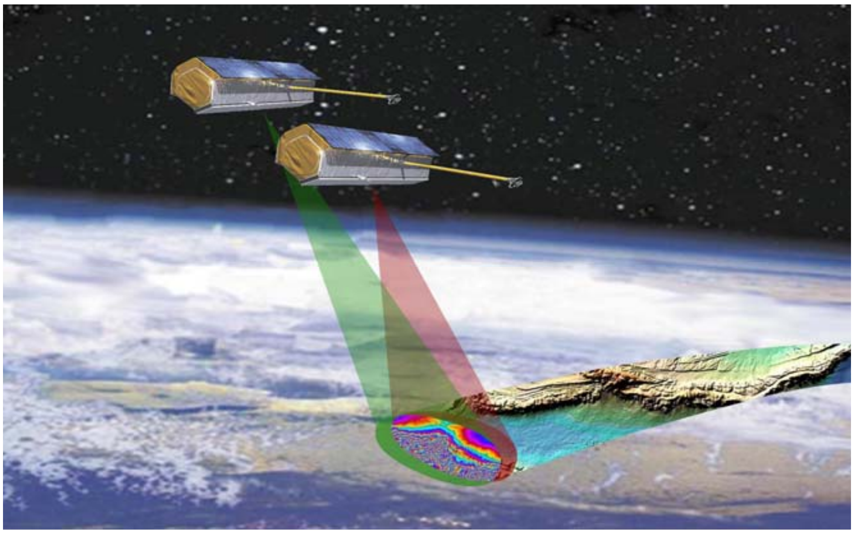

Fig. 2: TanDEM-X helix flight configuration

2.2 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 maximum 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 – Arching.*
The data tracks for the DEM production are a patchwork of single strips around the globe. In the first year of operation it is planned to get coverage with a small baseline (approx. 300m). In the second year of operation the baseline will change to improve the accuracy. In the last year of the 3 year mission period additional data tracks for difficult terrain will be carried out. The mission planning is the task of the German Space Operation Center. Operation of the

ground receiving stations, DEM processing and archiving are tasks of the "Cluster of Applied Remote Sensing"; the science coordination, SAR calibration and system operation is task of the Institute of Radio-frequency, all institutions being institutes of the DLR (German Space Aerospace Centre) located in Oberpfaffenhofen near Munich.

The DEM processing itself is separated into following major modules:

- RawDEM Generation,
- Mosaicing of stripes and
- Calibration.
-

With the Bundle Block adjustment the single raw DEMs will be converted into the final mosaiced DEM. In one block adjustment for one continent about 40 000 unknowns and 2 000 000 observations have to be handled. For calibration purposes height information from Laser Airborne DEMs, ICEsat and kinematic GPS profiles will be available.
Besides the final DEM Mosaic, a Height Error Map (HEM) will be provided. The HEM contains information about the height discrepancy between the different data tracks, used tiepoints and calibration information.

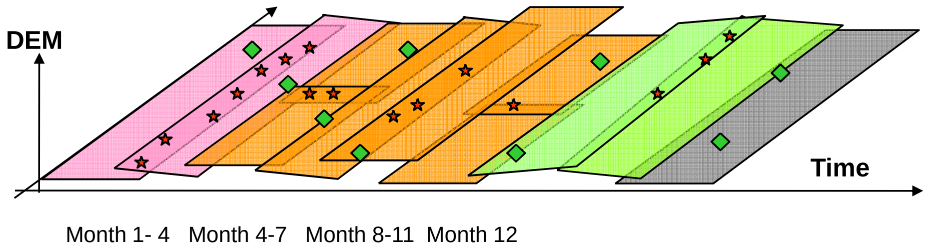

Fig. 3: DEM stripes (RawDEMs of first coverage)

3. KINEMATC GPS TRACKS FOR EVALUATION

3.1 Requirements and Possibilities for Kinematic GPS Positioning

The accuracy values given in table 2 are no standard deviations, as explained in the column "remark". Therefore they have to be transformed to standard deviations as well as to requirements for the kinematic GPS tracks. Details about this operations are provided by Ramm & Schwieger (2007). Table 3 gives requirements using different factors with respect to the TanDEM-X standard deviations. Even if a factor of 10 would be perfect, the actual possibilities regarding GPS accuracy and expense has lead to smaller factors for evaluation.

Tab. 3: Accuracy requirements for reference trajectories (Ramm & Schwieger, 2007)

<table>
<tr><th rowspan="2">Accuracy</th><th colspan="2">TanDEM-X specification</th><th colspan="3">Requirements for reference trajectories</th></tr>
<tr><th>HRTI-3</th><th>Std.dev.</th><th>Std.dev.
factor 3</th><th>Std.dev.
factor 5</th><th>Std.dev.
factor 10</th></tr>
<tr><td>Abs. vertic.</td><td>10 m</td><td>6.10 m</td><td>2.03 m</td><td>1.22 m</td><td>0.61 m</td></tr>
<tr><td>Rel. vertic.</td><td>2 m
(slope < 20 %)</td><td>0.86 m</td><td>0.29 m</td><td>0.17 m</td><td>0.09 m</td></tr>
<tr><td>Horizontal</td><td>10 m</td><td>4.65 m</td><td>1.55 m</td><td>0.93 m</td><td>0.47 m</td></tr>
</table>

Regarding the possibilities of kinematic GPS positioning two accuracy levels were defined.

- **level 1**: standard deviation of 1 m (approx. factor 5) to evaluate the absolute and
- **level 2**: standard deviation of 0.3 m (approx. factor 3-5) to evaluate the relative accuracy of TanDEM-X.

First of all you have to consider the recommended accuracy level and choose an appropriate acquisition an evaluation method: smoothed DGPS, PDGPS, code PPP or phase PPP. The following table gives an overview about the different acquisition and evaluation possibilities.

Tab. 4: Accuracy levels and alternative acquisition methods

	Required Standard Deviation	**Differential GPS**	**Precise Point Positioning**
level 1	1 m (factor 5)	smoothed DGPS	Code PPP
level 2	0.3 m (factor 3)	PDGPS (phase)	Phase PPP

The PPP approach uses a single GPS receiver; the (P)DGPS approach requires the adoption of a reference – rover configuration. Since the latter is a kind of relative GPS positioning, some restrictions to the baseline length were given. Assuming no ionospheric disturbances in the near future, baseline length of approx. 20 km was recommended in mid latitude. For other regions only 10 km baseline length should be considered.

Regarding **resolution** the last line of table 2 has to be considered. According to Ramm & Schwieger (2007) a minimum of three points of the reference trajectory should lay inside one 12 m pixel. This requirement is related to the sampling rate and the velocity while measuring the GPS trajectory. A sampling rate of 10 Hz is recommended. If a lower sampling rate is available only, the velocity has to be reduced so that a minimum of 3 measurements are within the 12 m grid. For 2 Hz this would be approx. 30 km/h, for example. Figure 4 shows the maximum velocity with respect to a given sampling rate.

Fig. 4: Maximum velocity with respect to a given sampling rate (Ramm & Schwieger, 2007)

3.2 Most Efficient Positioning Technique

In general differential GPS methods are very widespread within the GPS user community. There two possibilities to implement this method are:

- setting up a reference station by the user himself or
- using a reference station or a reference station network of a service provider.

The first being non-efficient, since time and staff is needed to built up a reference station every 40 kms. The second being available in some countries around the world only. Since a uniform evaluation has to be assured for the whole world, the decision was made to evaluate the positions using PPP. With respect to table 4, obviously code PPP and phase PPP are available for level 1 respectively level 2 processing. Since code and phase data can be acquired at the same time, if geodetic-class 2-frequency receivers are used, it was decided to directly use only one solution: the **kinematic phase PPP solution**. 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.

4. PRECISE POINT POSITIONING

Differential GPS is a very effective processing mode in geodetic point positioning and has received a widespread acceptance. The position can be estimated relative to one or more reference stations, using differenced carrier phase observations and a baseline or network estimation approach. Here common satellite and receiver errors will be minimized or eliminated. One drawback is the fact, that simultaneous observations at reference stations have to be made and the distance between reference station and rover should not be too large, here shorter than 20 km. Single station positioning method PPP can do positioning without reference station and achieves under certain constraints almost the same accuracy as differential GPS. Though there is a need for precise correction models because common satellite and receiver errors fully affect the positioning. In the following the most important facts and constraints about PPP are described.

4.1 Characteristics of Precise Point Positioning

The uncertainly of satellite ephemeris and clocks are the main reason in single station observation for non-accurate positioning. Regarding 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 5.

Tab. 5: 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 (prdicted half)	Orbits	~5cm	Real Time	15 min
	Sat. Clocks	1.5ns SDev		
Rapid	Orbits	2.5cm	17-41 hours	15 min
	Sat. & Stn clocks	25ps SDev		5min
Final	Orbits	2.5 cm	12 – 18 days	15 min
	Sat. & Stn clocks	~20ps SDev		Sat. 30s Stn.:5min

In real time the ultra rapid orbits can be used with an increased accuracy in contrast to the broadcast orbits (improvement from 100 cm to 5 cm). But to achieve the highest accuracy for positioning the need for final orbits and clocks is given. This is only possible in post-processing, because this product is available only 12 days after observation time.
In addition to the “standard” correction models, e.g. the atmospheric corrections (ionosphere and troposphere) even used for pseudo range positioning, additional 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. In table 6 there is an overview given over the additional correction models necessary for PPP.

Tab. 6: PPP correction models (Heßelbarth, 2009)

	Description	Correction	Impact on positioning
1. Satellite antenna offsets (satellite attitude effect)	Difference between the satellite center of mass and the phase center of its antenna	Correction of satellite coordinates	height: up to 10 cm position: several cm
2. Phase wind-Up (satellite attitude effect)	Rotation of satellite antenna around its bore axis will change the carrier phase	Correction of carrier phase observation	height: several mm
3. Solid earth tides (site displacement effect)	Deformation of the earth caused by gravity of the sun and the moon	Correction of station coordinates	height: several dm position: several cm
4. Ocean Loading (site displacement effect)	Deformation of the earth caused by ocean loading	Correction of stations near the coasts	height: several cm
5. Earth rotation parameters (ERP) (site displacement effect)	Shift of the axis of the earth to the earth's crust: - pole position - time correction dUT1	Correction of Station coordinates (Not necessary, if ITRF is used)	height: several cm position: several cm

Besides the correction models another important fact about PPP Evaluation is the convergence (time). At initial epoch the solution relies entirely on the pseudorange observations. As time passes and phase observation are added to the solution, the ionospheric free ambiguities and station position components (in static mode) converge to constant values. In Kouba & Héroux (2000) there is described that cm level in static mode is reached after 30 min using high rate orbit and clock products mentioned in table 6. In kinematic mode the accuracy at the same convergence time is a little bit worse than static. In Bisnath & Gao (2008) there is reached after 30 min convergence time an RMS of 1.5 cm in static mode and 8.5 cm in kinematic mode.

The evaluation of PPP is based on the following ionospheric-free pseudorange (P) and carrier-phase observation (ϕ) equations:

$$\ell_P = \rho + c(dt\text{-}dT) + T_r + \varepsilon_P \qquad (1)$$
$$\ell_\Phi = \rho + c(dt\text{-}dT) + T_r + N\lambda + \varepsilon_\Phi$$

The geometric range ρ is computed as a function of satellite (X_S,Y_S,Z_S) and station (x,y,z) coordinates.

$$\rho = \sqrt{(X_S - x)^2 + (Y_S - y)^2 + (Z_S - z)^2} \qquad (2)$$

The parameter c is the vacuum speed of light, dT and dt describes the satellite or receiver station clock offset from GPS time. The parameter T_r is the signal path delay due to the neutral-atmosphere and is a function of the zenith path delay (zpd). The parameters N and λ are the ambiguities with the associated wavelength and ε_P, ε_Φ are the relevant measurement noise components, including multipath.

The solution of the adjustment is a vector with the unknown parameters: the station position *x,y,z*, the station receiver clock offset *dt*, the zenith path delay *zpd* and the ambiguities *N*. In kinematic mode the station coordinates x,y,z have to be estimated every epoch in contradiction to the static mode where the station coordinates are invariant. For detailed information see Kouba & Héroux (2000).
In summary one can say that PPP is an economical GPS- respectively GNSS-evaluation technique with a high potential. Under certain circumstances accuracy of the PDGPS level can be reached.

4.2 Processing Procedure

Commonly the data acquisition was carried through with dual frequency receiver (e.g. Leica GX1230) on a normal passenger car with a maximum velocity of 120 km/h. The data was provided in several RINEX files with a data rate of 10 Hz. So the point density of minimum 3 points per 12 meter is warranted. This raw data referring to the report Schwieger & Schwieger (2008) is 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 20 km have to be evaluated and used for the PPP solution (Ramm & Schwieger, 2009).

4.2.1 GIPSY 5.0

At the moment the authors use GIPSY version 5.0 which runs on Fedora 10 an open source Red Hat distribution (Schweitzer & Schwieger, 2008). GIPSY is a free open source commando-line based software, which supports among others the PPP evaluation using final orbits and clocks as well as the correction models mentioned in table 6, though not all of them are necessary for the required accuracy.
Each RINEX file is firstly processed by the GIPSY module “ninja” which edits and decimates the data and converts it into a quick measurement (qm) -file. This qm-file can be processed afterwards by the “gd2p.pl” (GPS Data to Position) GIPSY batch-script, a more or less automatic procedure. The last step in GIPSY processing is the transformation from the geocentric, cartesian coordinate system (XYZ) to the geographic coordinate system (latitude, longitude, ellipsoidal height).
The processing strategy for kinematic PPP measurements is slightly different. It was estimated that points at the end of tracks, which are longer than 10 km show unrealistic values. The reason of this effect is not absolutely clear. It seems to be that tropospheric parameters, orbit computations, clock parameters and height value play a role. Additionally it seems to be that the linear adjustment model implmented in the GIPSY software is not suited for kinematic tracks, since the approximate vaules for the adjustment are not valid for the whole track. This shouldn’t be a problem, if the iterative adjustment procedure would work in as indicated in the manual. But the described iterative procedure is not working properly.

Several tests to change processing parameters in GIPSY like the "Troposphere Parameter Estimation Settings", "Filter/Smoother options", number of iterations, etc. failed. So the authors have chosen the most easy method to solve this problem. Every single track is divided into several shorter tracks and every short track is processed for its own. This method is not theory-founded but effective (Wang 2009).

4.2.2 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 refrence system can be selected and the 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).

4.2.3 Combination of the two results

The processing results from both systems are merged together. Only the data is 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, although the availability is reduced. The other data is deleted. Finally the final result is the mean value of coordinates from GIPSY and CSRS. In figure 5 an overview of the whole evaluation process is given.

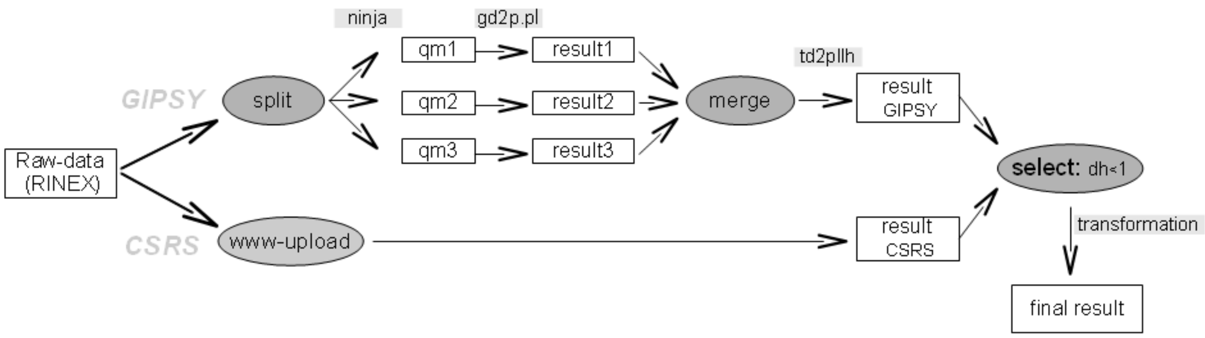

Fig. 5: Overview of the PPP evaluation process

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 refer both to ITRF2005 current epoch. So the coordinates have to be transformed from ITRF2005 current epoch to ITRF2005 epoch 2010.0. The data, this article is based on, has been acquired between May 2008 and June 2008. The shift between epoch 2008.5 and epoch 2010.0 in Europe amounts 3 cm (Schweitzer & Schwieger, 2008). For further data acquisitions (after 2008) the shift gets smaller and can be neglected. Thus the final result is a file with three dimensional coordinates (latitude, longitude and ellipsoidal height) in ITRF2005 epoch 2010.0.

5. FIRST RESULTS

5.1 Test Tracks near Munich

Since PPP and PDGPS were proposed as evaluation methods, DLR carried through five test drives near to Munich, The drives were carried through using 2-frequencs Leica receivers with a sampling rate of 10 Hz. Figure 6 gives an overview about the location of the tracks.
For comparisons different strategies and evaluations were followed. The authors carried through PPP using the GIPSY version 4.04 and CSRS. The meanwhile out-dated GIPSY version 4.04 did not show the possibility to evaluate 10 Hz data and some bugs that could be fixed in the version 5.0 (compare sections 4.2 and 5.2). Additionally PDGPS was carried through with the software packages GIPSY and Leica Geo Office. Since a PDGPS service provider was available in Germany, the set up of an own reference station could be disregarded. The authors use the data of one reference station of the service provider as well as so-called virtual reference stations (VRS) that may be understood a s a sort of network solution. The final RMS as an indicator for accuracy was estimated using the double differences between the Leica Geo Office PDGPS and the CSRS PPP solution, since the GIPSY PPP solutions did not show any reliable result. Especially the availability was very weak: 39 % in average. Additionally one has to mention that this already bad value did not account for the two test tracks that are completely excluded from the analysis.

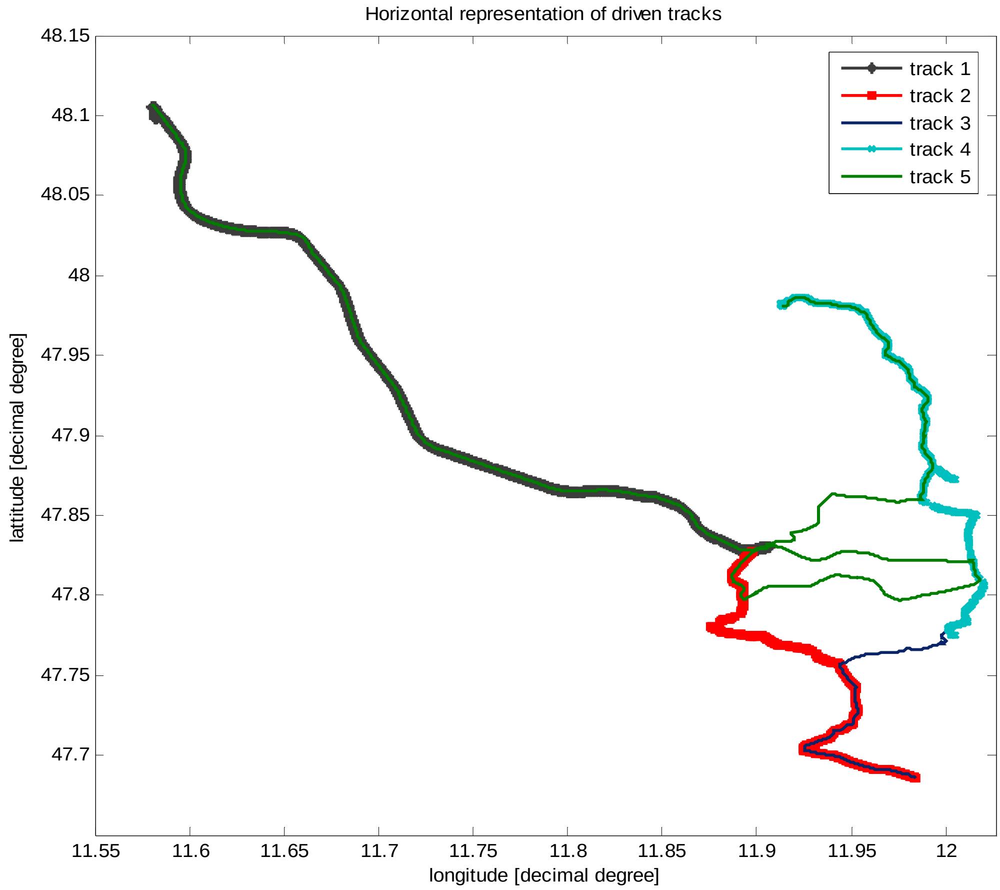

Fig. 6: Munich test drives (Schwieger & Schwieger, 2008)

The general result shows that the availability of the positions during kinematic data acquisition, the reference solutions for PDGPS and phase PPP deliver reasonable results. The Leica PDGPS solution provides 74.4 % for virtual reference stations and 70.70 % for the Rosenheim reference station and the CRPS-PPP 90.5 %. The availability of CRPS-PPP is superior to any other solution. The authors point out that the availability is computed using if the respective solution only, meaning without comparison between two solution (in contradiction to section 4.2), so that the values are higher but less realistic than in the following section 5.2.
The RMS was estimated to an average of 0.68 m for both solutions, if periods of bad quality are excluded and virtual reference stations for PDGPS are introduced. For the fixed reference station Rosenheim 0.85 m was reached (Schwieger & Schwieger, 2008). Both values exceed the limit of 0.30 m defined in Ramm & Schwieger (2007). It was assumed that a more careful data acquisition would lead to better results. In any case the reached accuracy level was sufficient to evaluate the TanDEM-X digital height model, so the standard-evaluation was started. As described in sections 4.2 and 5.2 GIPSY version 5.0 improved the processing conditions and special processing strategy was developed. These two circumstances allowed the evaluation using GIPSY PPP.

5.2 First track in Western Europe

One of the first track evaluated, is located in Western Europe and leads from Munich in Germany to Sao Martinho in Portugal (see figure 7). The data acquisition was carried through from June the 9th to June the 28th 2008 using a LEICA GX 1230 receiver (dual frequency) and an AX 1202 antenna. The whole track has a one way length of about 2400 km and is divided into 22 separated tracks. This is necessary to make the handling and the processing with the software easier. Because of the high data rate (10Hz) the whole track in one way has about 1.3 million points to evaluate.

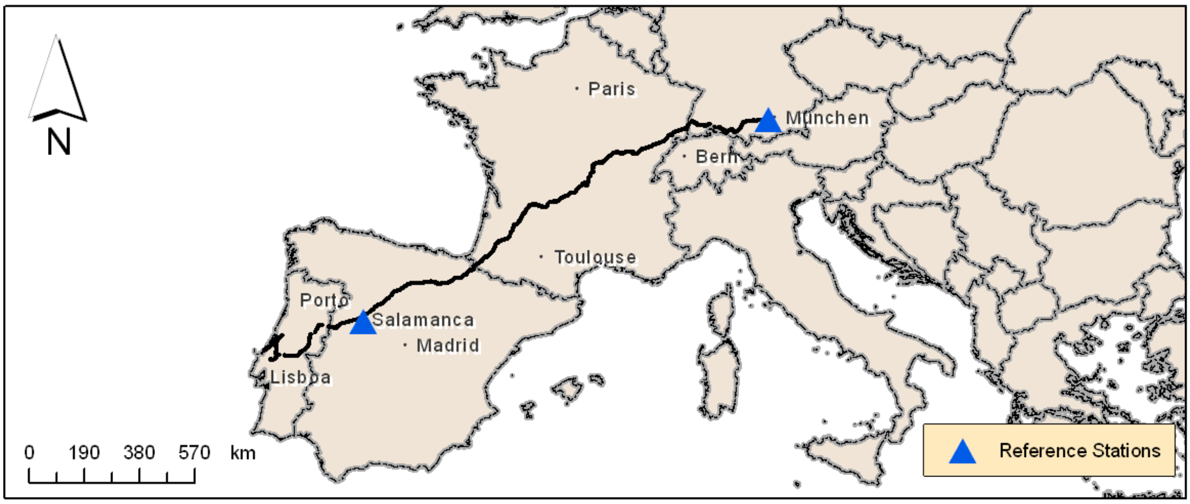

Fig. 7: Track from Munich to Sao Martinho

To rate the results and make them comparable some statistical values are computed. In table 7 the statistical values are shown for forward and backward way.

Tab. 7: Statistical values of the result

direction	epochs	availability	RMS_{dh} [m]	length [km]	point density [1/km]
forward	772685	60 %	0.48	2343	330
backward	774775	58 %	0.48	2570	301

The number of epochs is defined as the estimated positions resulting from the whole evaluation process (after editing and rejecting). The availability is the relation between the epochs after evaluation process and epochs in raw data in percent (before evaluation process). The RMS_{dh} ist the root mean square of the height differences between GIPSY and CSRS. The length of the forward and backward way is not match exactly, because the routes driven in forward and backward way are not always exactly equal. The point density is a value which results from all the epochs divided through the length of the track. The point density is a mean value for the whole track. That means that there are parts with clearly more than 300 positions/km, especially when the velocity is small and there are parts where the track has gaps and there are no positions at all. As assumed the availability is reduced and the accuracy is improved with respect to the processing in section 5.1. Still the required 0.3 m RMS are not reached, but in any case the numerical value is sufficient to evaluate the future TanDEM-X DEM model.

If you zoom into the track of figure 7, one can see a lot of these data gaps in the track. These gaps occur if no GPS satellites are available. This may be caused by tunnels, bridges, etc. or even from bad data quality caused e.g. by shadowing trees or other cars leading to temporal multipath or shadowing, so that the height difference dh between GIPSY and CSRS exceeds the threshold of 1m.
In particular behind large or even small structures like bridges or traffic signs which cause signal losses, the gap can be get very large, since the time needed until the precise solution is computed again may reach up to 10 seconds. In figure 8 there is shown a signal loss after a drive under a small bridge. A reliable position is estimable after about 200 m.

Fig. 8: Signal loss behind bridge

To increase the reliability an evaluation method using PDGPS with Leica Geo Office is done. For this track 2 IGS reference station were found. The first station is OBE3 in

Oberpfaffenhofen near Munich, Germany and the second one is called SALA located in Salamanca, Spain. The two reference stations are shown in figure 7.
The RINEX files of the reference stations are taken from the official The Crustal Dynamics Data Information System (CDDIS, 2009) and the GNSS Data Center (GDC, 2009) homepage. The maximum data rate available on these sites is 30 s. That's why only 67 position comparisons between points computed with PDGPS and points computed with PPP are provided. The results of this comparison are shown in table 9.

Tab.9: Results of PDGPS comparison

Reference station	Num. of comparisions	$MEAN_{ds}$ [m]	$MEAN_{dh}$ [m]	RMS_{dh} [m]
OBE3	29	0.3	0.21	0.50
SALA	35	0.38	0.18	0.37

The characteristic values like the $MEAN_{ds}$, which describes the mean distance between two comparable points, $MEAN_{dh}$ and RMS_{dh} show satisfying results. The RMS_{dh} shows the same values like the RMS_{dh} in table 7, by this way reflecting that the evaluation procedure described in section 4,2 and carried through in section 5.2 obtains reasonable values and may be understood as an external accuracy measure.

6. CONCLUSIONS AND OUTLOOK

This paper presents one evaluation method of the future TanDEM-X digital evaluation model that should have a maximum relative height accuracy of 2 m 90% linear error. The proposed, analysed and proposed method is PPP processing of kinematic GPS tracks. This is an efficient and sufficiently accurate method for the world-wide evaluation of the DEM. The test results were not 100% satisfying, but the first track from central to south-west Europe delivers a height RMS of better than 0.5 m as well for the comparison between GIPSY and CSRS as for the evaluation with PDGPS and an availability rate of around 60 %, if reliable solutions were used only. A combined GIPSY 5.0 and CSRS solution was calculated. Both values make the use of the trajectories for future evaluation possible and even a very good opportunity.
For the future tracks all over the world have to be processed respectively to be carried through and processed. Future reports will be given to the scientific and the user community.

REFERENCES

BISNATH S., GAO Y.: Current State of Precise Point Positioning and Future Prospects and Limitations. International Association of Geodesy Symposia, Vol. 133 pp. 615-623, 2008.

CDDIS: The Crustal Dynamics Data Information System. http://cddis.gsfc.nasa.gov/. last acces April 2009.

CSRS: Canadian Spatial Reference System. http://www.geod.nrcan.gc.ca/index_e.php, last access August 2009.

GDC: GNSS Data Center. http://igs.bkg.bund.de, last acces April 2009.

HÉROUX, P., GAO, Y., KOUBA, J., LAHAYE, F., MIREAULT, Y., COLLINS, P., MACLEOD, K., TÉTREAULT, P., CHEN, K.: Products and Applications for Precise Point Positioning – Moving Towards Real-Time. Proceedings of ION GNSS 2004, Long Beach, CA, pp. 1832-1843, 2004.

HEßELBARTH, A.: GNSS-Auswertung mittels Precise Point Positioning (PPP). Beitrag zum 83. DVW-Seminar "GNSS 2009: Systeme, Dienste, Anwendungen", 18.-19.03.2009, Dresden. DVW-Schriftenreihe, Band 57/2009, Wißner-Verlag, Augsburg, S. 187-202, 2009.

HUBER, M., WESSEL, B., KOSMANN, D., FELBIER, A., SCHWIEGER, V., HABERMAYER, M., WENDLEDER, A., ROTH, A.: Ensuring globally the TanDEM-X height accuracy: Analysis of the reference data sets ICESat, SRTM and KGPS-Tracks. International Geo Science and Remote Sensing Symposium, Kapstadt, Südafrika, 12.07.-17.07.2009.

IGS: IGS Products. http://igscb.jpl.nasa.gov/components/prods.html, last access July 2009.

KOUBA, J., HÉROUX, P.: Precise Point Positioning Using IGS Orbits and Clock Products, Vol. 5, No. 2, 12-28, DOI 10.1007/PL00012883.

KJØRSVIK, N. S., GJEVESTAD, J. G. O., ØVSTEDAL, O.: Handling of the Tropospheric Delay in Kinematic Precise Point Positioning. Proceedings of ION GNSS 2006, Fort Worth, TX, pp. 2279-2285, 2006.

RAMM, K., SCHWIEGER, V.: Requirements on Kinematic GPS-Measurements for the Evaluation of Height Accuracy within the TanDEM-X Project, DLR TanDEM-X Ground Segment Document TD-PGS-TN-3061, 2007.

RODRIGUEZ, E., Morris, C.S. Belz, J.E., Chapin, E.C., Martin, J.M., Daffer, W., Hensley, S.: An assessment of the SRTM topographic products, Technical Report JPL D-31639, Jet Propulsion Laboratory, Pasadena, California, 2005.

SCHWEITZER, J., SCHWIEGER, V.: Kinematic GPS proessing of the Track Munich-Ukraine, 2008.

SCHWIEGER, V., SCHWIEGER, I.: Evaluation of Exemplary Kinematic GPS-Measurements Using Different Methods, DLR TanDEM-X Ground Segment Document TD-PGS-TN-3097, 2008.

WANG, R.: Investigation on Precise Point Positioning for Kinematic GPS Tracks, Master Thesis, University Stuttgart, 2009 (unpublished).

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