TanDEM-X: DEM ACQUISITION IN THE THIRD YEAR ERA

D. Borla Tridon, M. Bachmann, D. Schulze, C. J. Ortega Miguez, M. D. Polimeni, M. Martone

Microwaves and Radar Institute, German Aerospace Center (DLR)
82234 Oberpfaffenhofen, Germany, E-mail: Daniela.BorlaTridon@dlr.de

Abstract: *TanDEM-X (TerraSAR-X add-on for Digital Elevation Measurement) is a space-borne X-band SAR mission designed to derive a Digital Elevation Model (DEM) of the Earth's land surface with an unprecedented relative vertical accuracy of 2 m at a 12 m posting. To achieve this goal, the two satellites fly in close controlled formation with the opportunity to adjust flexible along- and across-track baselines. A combination of multiple acquisitions with different baseline lengths is required to allow stable phase unwrapping and to achieve the high height accuracy.*
This paper provides an overview of the TanDEM-X acquisition plan for the third year over Antarctica, mountainous and deserted areas.
Critical aspects of the areas to be acquired are presented and the acquisition strategy is illustrated. Moreover, the formation flight and the baselines are compared to the ones of the previous years in terms of their impact on the height of ambiguity and on the performance with respect to the interferometric quality.

Keywords: *DEM, height of ambiguity, baseline, DEM acquisition timeline.*

1. Introduction

The TanDEM-X project is realized in a public-private partnership between the German Aerospace Center (DLR) and EADS Astrium GmbH.
The primary goal or the TanDEM-X mission is to deliver a DEM with a relative vertical accuracy of 2 m for terrain slopes less than 20% and 4 m for slopes higher than 20%. Digital elevation models are required for many commercial and scientific applications, such as navigation, cartography and in many geoscience fields. Beyond that, TanDEM -X offers great scientific potential for along-track interferometry as well as for new radar imaging techniques and applications.
The TanDEM-X mission comprises the TerraSAR-X satellite (launched on June 15, 2007) and the almost identical TanDEM-X satellite (launched on June 21, 2010) [1]. Since December 2010 the two satellites are flying as a large single-pass bi-static SAR interferometer in a novel close Helix formation at about 514 km of altitude (mean value across the equator). TerraSAR-X flies in a sun-synchronous dusk-dawn orbit with 97° inclination. This orbit has an 11 days repeat cycle and is maintained for the entire mission within a 250 m toroidal tube around a predefined reference trajectory [10]. TanDEM-X has a relative orbit to TerraSAR-X and together they fly in a precise controlled formation.
Originally designed for a nominal joint operation time of three years, the current status of the satellites resources (primarily fuel) will allow a mission extension of several years. In addition the two satellites serve also for the TerraSAR-X mission, where both

satellites independently provide high-quality SAR products for the science community and commercial purposes.
The baseline between the two satellites during the three years varies according to the global acquisition scenario. The scenario determines the desired height of ambiguity (HoA), which itself influences the final height error accuracy.
The HoA is defined as the height difference equivalent to a complete 2π phase cycle in the interferogram scaled with the perpendicular baseline between both satellites. For the bi-static case it can be expressed as:

$$HoA = \frac{\lambda r \sin\theta_i}{B_\perp} \quad (1)$$

where λ is the radar wavelength, *r* the slant range, θ_i the incidence angle and $B_\perp$ the perpendicular baseline. The relative vertical error can be then expressed as:

$$\Delta h = HoA \frac{\Delta\varphi}{2\pi} \quad (2)$$

defining $\Delta\varphi$ as the point-to-point phase error, normally calculated at the 90% confidence interval [2].
The lower the HoA is, the smaller is the relative height error. In contrast, with a low HoA, the DEMs suffer from phase unwrapping problems over terrain with large slopes, like mountainous regions or forests, impacted by volume decorrelation. To solve this problem a combination of multiple acquisitions with different HoAs is required. In this way a dual baseline phase unwrapping technique [3] can be used to resolve phase unwrapping errors in the DEM. This approach evaluates the height differences in the phase of two scenes and corrects the wrongly wrapped parts of the scene.
In addition, two acquisitions can be combined to reduce the noise like decorrelation errors [4]. For this purpose the acquisitions of the second coverage are shifted by half a swath width compared to the first coverage. By this, the pattern regions with higher antenna gain (better SNR and thus lower height error) are combined with the lower gain regions at the edges of the pattern main lobe from the other coverage. This results in a rather flat height accuracy distribution across the whole access range not achievable with only one acquisition coverage [5].

2. Acquisition concept

The nominal SAR image acquisition (TerraSAR-X mission) as well as the derivation of the global DEM (TanDEM-X mission) share the same satellite resources. Therefore a joint acquisition concept has been elaborated in order to ensure both missions goals. TanDEM-X DEM data takes are summarized in the so-called DEM acquisition timeline.
In order to fulfill the requirements of the height error of the DEM, since the HoA is changing with beam and latitude, the Helices are optimized accordingly with respect to each region that has to be mapped. TerraSAR-X mission data takes are then planned around the calculated TanDEM-X acquisition timeline.

2.1 TanDEM-X acquisition timeline

Based on the concept above, the TanDEM-X acquisition timeline is derived. The acquisition strategy is furthermore constrained by the following factors:

- TerraSAR-X reference orbit.
- Radar geometry with look angles and beam information (each beam overlap with the adjacent one for 4 km).
- Mapping strategy: the nominal strategy is to record data during ascending orbit in the Northern Hemisphere and during descending orbit in the Southern one. Due to the fact that the distance between two adjacent ground projected tracks is decreasing with increasing latitude, a smaller number of swaths is required with increasing latitude.
- Target HoA.
- Acquisition time per orbit: a mean orbit usage of 180 s is considered.
- On-board solid-state mass memory (SSMM): the storage capacity of TanDEM-X is 768 GBit, while the one of TerraSAR-X is 384 GBit. Therefore the mass memory of the latter must be dumped firstly.
- Ground station network and downlink capacity: the network used for the downlink of the TanDEM-X mission includes stations in Kiruna, Inuvik and O'Higgins.

Once decided the area to be acquired, the calculation of vertical (radial track) and horizontal (cross track) baselines is then performed for each repeat cycle of 11 days. According to the acquisition strategy, the algorithm is created so that the baseline will get smaller along the time, consequently the HoA for the same beam will increase. Based on these assumptions and constraints, the timeline is derived. It includes all the data takes to be acquired with their start/stop times and their relative acquisition parameters, like PRF or duty cycle [11], [12].

3. Current acquisitions status

In the first two years of operations two global coverages of the Earth's land masses, excluding Antarctica, have been acquired. All the acquisitions have been carried out in the nominal right-looking observation mode. In order to avoid that the satellites illuminate each other and get irreparably damaged, exclusion zones have been defined. They constraint the orbit part in which the acquisitions may be executed: during ascending orbits in the northern hemisphere and during descending orbits in the southern hemisphere.

The acquisition of the first global coverage was finished in March 2012. In this first year the target HoA was set to 50 m. Since the HoA depends on the incidence angle and the Helix changing with the latitude on Earth, the formation in terms of horizontal and vertical distance between the satellites has to be changed accordingly to keep a stable HoA, as close as possible to the target HoA. One can see this in Figure 1, where the formation parameters are adapted along the mission time; the vertical and the horizontal distances decrease progressively during the two global acquisitions (first and second year).

It can be seen that within the two main acquisition phases, the helix has been slightly reconfigured several times in order to achieve different HoA margins. One example can be seen on April 2011, in which the minimal HoA was re-set from 40 m to 45 m over forested areas, in order to deal with the strong volume decorrelation over these regions.
In addition, already during this phase additional acquisitions were performed over the rain forest in the south eastern Asia, or over mountainous regions. These included acquisitions with even higher HoA in the order of 60 m to 80 m, which require very small baselines. This can be seen in Figure 1 starting from October 2011, where also the HoA has a greater variation.
The acquisitions of the second global coverage started in March 2012 and lasted until April 2013. According to the acquisition strategy the target for the HoA was reduced from 50 m to 35 m in this second coverage. The decrease of the HoA by a factor 0.7 has been found optimal in order to combine the two acquisitions to resolve phase unwrapping errors [6] and to improve the relative height error.
In Figure 1, the transition from the first to the second year is clearly visible in the sudden jump of the formation and a consequent decrease of the HoA.
In addition, during the whole time of the DEM acquisitions, supplementary science acquisitions are performed in order to explore the great potential for interferometric applications.

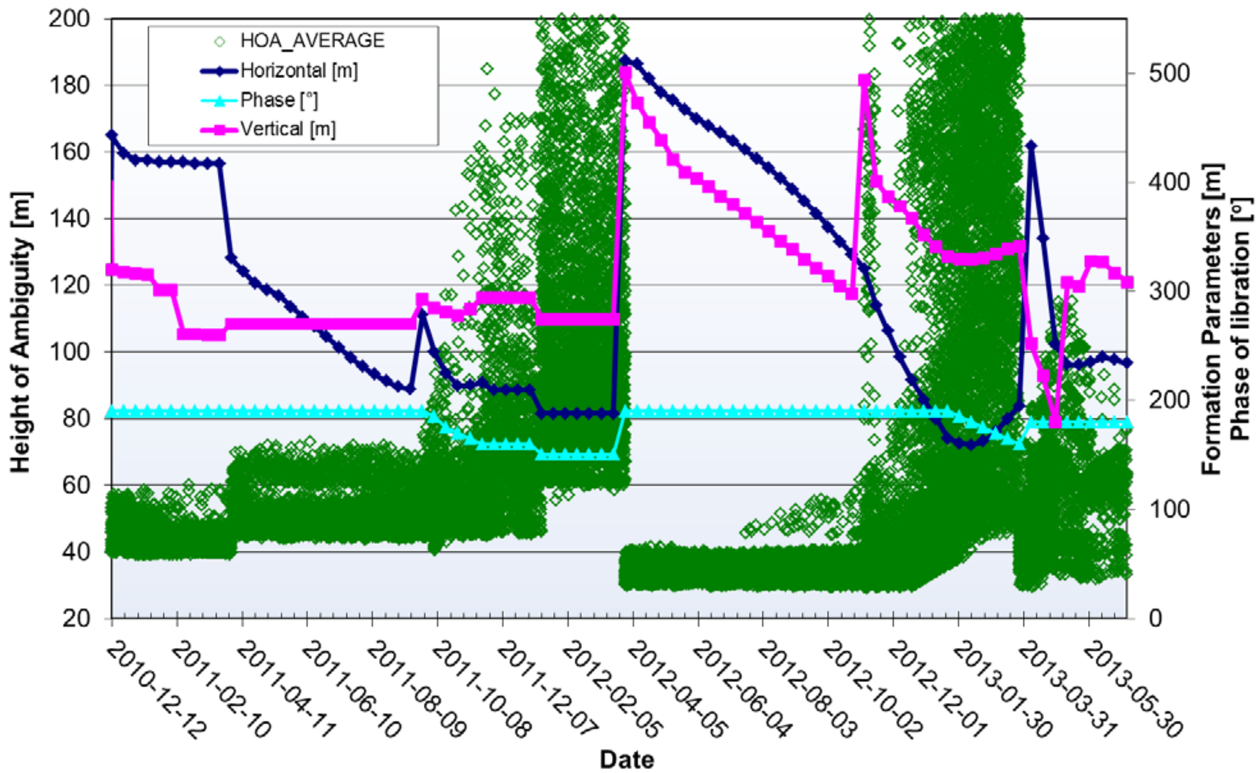

Figure 1. Formation parameters evolution over time and corresponding “HoA”.

4. Third year acquisitions

Main goal of the third year is to acquire additional coverages over difficult terrain, such as mountainous regions affected by unwrapping problems, as well as deserted areas, where performance is suffering from very low SNR.
Also, in the third year it is planned to acquire the Antarctica for the first time with a space-borne X-band sensor.
Both goals required preliminary studies in terms of performance, appropriate formation and optimal use of satellites resources. Starting chronologically the main challenges and results for these acquisitions are presented below.

4.1 Antarctica acquisitions

Due to the inclination of the orbit, Antarctica cannot be acquired entirely with the standard configuration of the satellites. In fact the central part of Antarctica (over a radius of 1300 km) is not seen in the right-looking imaging mode and with the TanDEM-X nominal beams.
Left-looking observations with large incidence angles are therefore required over the central region. The outer part of Antarctica can in contrast be acquired in the nominal right-looking mode. The acquisition of the complete Antarctica is planned during the winter period in the Southern Hemisphere in order to have a better image quality and not to be affected by low signals reflected due to surface melting. On the counter part, in this period the satellites are passing through eclipse for up to about 20 minutes/orbit, therefore lower energy resources are available during this time and have to be taken into account in the planning.
Antarctica presents mountainous regions up to 3000 m high as well as very flat regions, all covered by ice and snow.
Since no data with sufficient high quality is available in this area, a priori performance study and some test acquisitions were performed.
The very central part can only be acquired with incidence angles larger than 60^o (over a radius of about 200 km) and about 50^o (over a radius between 200 and 400 km). For such large angles, azimuth and range ambiguities are impacting image and interferometric performance [13].
A performance study showed that in order to reduce range ambiguities a pulse repetition frequency (PRF) smaller than the nominal one of about 3200 Hz is required. In addition the PRF should be larger than 2000 Hz in order to reduce azimuth ambiguities. An optimal PRF of around 2300 Hz is therefore selected for incidence angles of 60^o.
The desired HoA for the first acquisition of this area has been chosen between 50 m in the outer region and 90 m in the central region, in order to avoid phase unwrapping problems. Consequently a formation geometry has been determined and it is shown in Figure 1, represented by the last six points in the plot, from 29^{th} of April to 4^{th} of July 2013. A constant phase of libration of 180^o has been set and relative constant and homogeneous vertical and horizontal distances have been found. For the TanDEM-X

Helix, the phase of libration is defined as the difference between the relative ascending node and the relative perigee [9], [10].

In Figure 2, the HoA versus the argument of latitude is shown for different beams for a formation flight with 300/230 m vertical/horizontal distances and 180^{o} phase of libration. In the case of the very central region of the Antarctica, where the beam with highest incidence angle is used the HoA cannot be lower than 90 m.

The central part of the Antarctica is acquired in May 2013 for a total number of three repeat cycles (33 days in total) and the outer part in June, also for three cycles.

In addition to the nominal constraints mentioned above, additional constraints related to the power resources of the satellites have been taken into account for planning the acquisitions over Antarctica. From May to July the satellites pass through an eclipse zone, where the batteries are not charged. Therefore less energy power is available. In addition the solar panels are not all the time oriented towards the Sun during the left-looking positions.

A simulation during the maximum of the eclipse (middle June to middle July) has been carried out in order check if the acquisitions are feasible. The results of the simulation are shown in Figure 3, where one can see the battery discharge level for both satellites (TanDEM-X and TerraSAR-X) when operating in left-looking mode. The level 0% represents the lower limit of the permitted discharge. At this level no further acquisitions can be planned.

The results show a maximum use of 50% of the allowed battery discharge by both satellites used. However, because of the exclusion zone, for each left-looking acquisition only the TanDEM-X satellite can be the active satellite. Hence the TanDEM -X satellite is more affected satellite by the battery discharge, while the TerraSAR-X satellite consumes much less resources.

Compared to the nominal right-looking acquisition for the same period, the left-looking acquisition creates an average increase of 3% in the battery discharge.

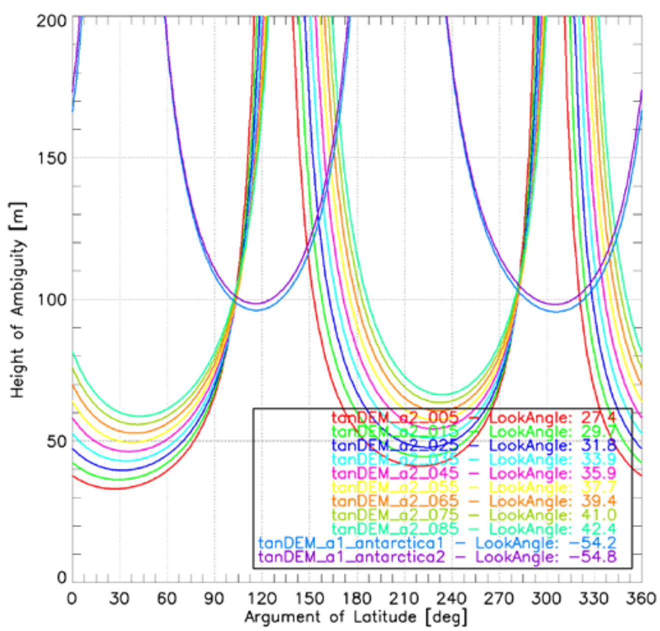

Figure 2. HoA versus argument of latitude.

The left-looking acquisition over Antarctica is starting on the 29th of April 2013 and hence performed at the beginning of the eclipse. Therefore the batteries are discharged much less than assumed in the worst-case scenario analyzed before.

Another constraint taken into account during the planning was related to the SSMM and the downlink of the data. One of the downlink stations is located in O'Higgins, on the Antarctic Peninsula. Since the downlink of the data can only be performed in right-looking position, around 30% of the contact time between the station and the satellites is lost and cannot be used for downlink during the Antarctica left-looking acquisition. The turn time into left looking mode or back is about 4 minutes. To overcome this problem and reduce the dead time, the left-looking acquisitions are performed in ascending, while the right-looking ones in descending mode. In addition, in order to cope with the limited SSMM capacity, the mean satellite orbit usage for the TanDEM-X mission has been set to about 160 s, in contrast to the nominal 180 s.

A second acquisition over Antarctica is planned one year after the first one, in May-June 2014 with a smaller HoA, again in order to combine the two acquisitions.

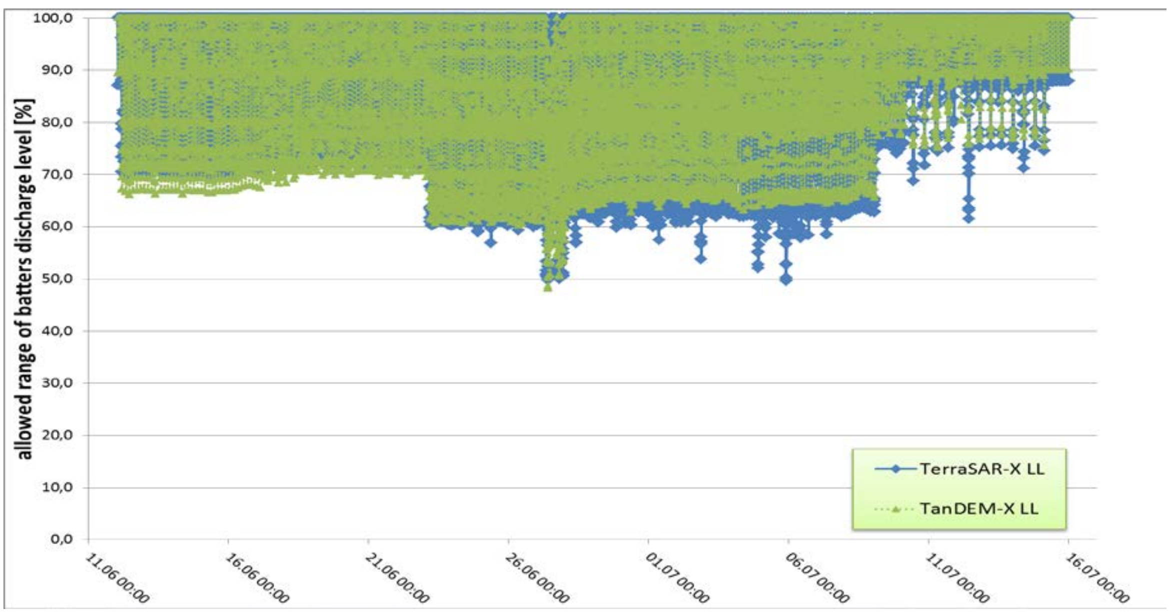

Figure 3. Battery profile discharge during maximum of the eclipse for left-looking mode.

4.2 Mountainous and deserted areas acquisitions

In the third year of acquisition, after the Antarctica campaign, it is planned to acquire difficult terrain from the opposite viewing geometry. Difficult regions mainly include mountainous, but also deserted areas, which will be acquired at steeper incidence angles

Performance over sandy desert is in general affected by weak backscatter signal from sand, with low signal-to-noise ratio (SNR) and consequently low coherence, leading to

high relative height uncertainties. Studies show that a SNR is about 3 dB higher for an incidence angle of 32° than for 48°. At the same time the coherence improvement is about 60% [7], [8]. Rocky deserts, like the ones in North-West China present instead topography which my lead to shadow effects.
Deserts have been already acquired in the first and second year with nominal incidence angles between 30° and 48°. They will therefore be reacquired with lower incidence angles (between 14° and 27°) in order to increase the signal to noise ratio and to minimize the performance loss. Deserts with topography are instead planned to be reacquired also from different geometry, which is explained below in the paragraph concerning the mountainous regions.

Mountainous regions present a pronounced topography. Steep and irregular surfaces are particularly affected by phase unwrapping errors. Steep slopes facing the radar illumination result in layover effects, i.e. the signal from mountain summit is reflected earlier than the one from valley in front of the mountain, generating artefacts in the DEM. Slopes facing away the radar line of sight are not illuminated at all and are therefore in shadow.
Therefore a different acquisition geometry is foreseen for mountainous regions: North-descending and South-ascending acquisitions will be performed, enabled by a shift in the phase of libration of about 180°, in order to acquire slopes from the other side.

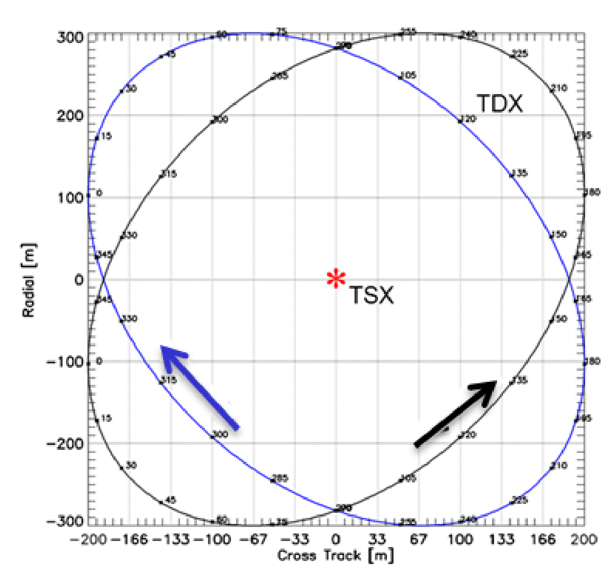

Figure 4. Radial vector versus cross track vector for phase of libration=200° in blue and 20° in black.

The inverted acquisition mode is required because of the shadow and layover effects visible in the mountainous regions. In addition, the shift in the phase of libration is also required to shift the exclusion zones by 90° to enable acquisitions with both satellites as transmitter. Figure 4 shows what happens when the phase of libration is changed: the star in the middle represents the TerraSAR-X satellite moving perpendicular to the radial/cross-track plane toward the reader. The TanDEM-X satellite rotating around the

TerraSAR-X is represented by the blue ellipse for a phase of libration of 200^o (clockwise) and by the black one for 20^o (anti-clockwise).

Regions affected by shadow and layover effects are mainly the mountainous regions on the entire West coast of America, South-East Asia and South Europa. In Figure 5, these areas are shown in red.
Here, a height of ambiguity even higher than 85 m is desired. This implies a challenge for the system since the baseline between the two satellites needs to be even shorter than for the additional acquisitions.
During analyses prior to the mission, a minimum satellite distance of 150 m was found appropriate to ensure the safety of the satellites, i.e. to minimize the risk of collision and mutual illumination between the two satellites. From the analysis of the first two years it is shown that the formation flight and the maintenance of the formation is very stable. Therefore new lower limits on the baselines can be set: 250 m for the vertical distance and 120 m for the horizontal one.

The regions shown in red in Figure 5, together with deserts will be reacquired twice with decreasing HoA starting from August 2013 till spring 2014.

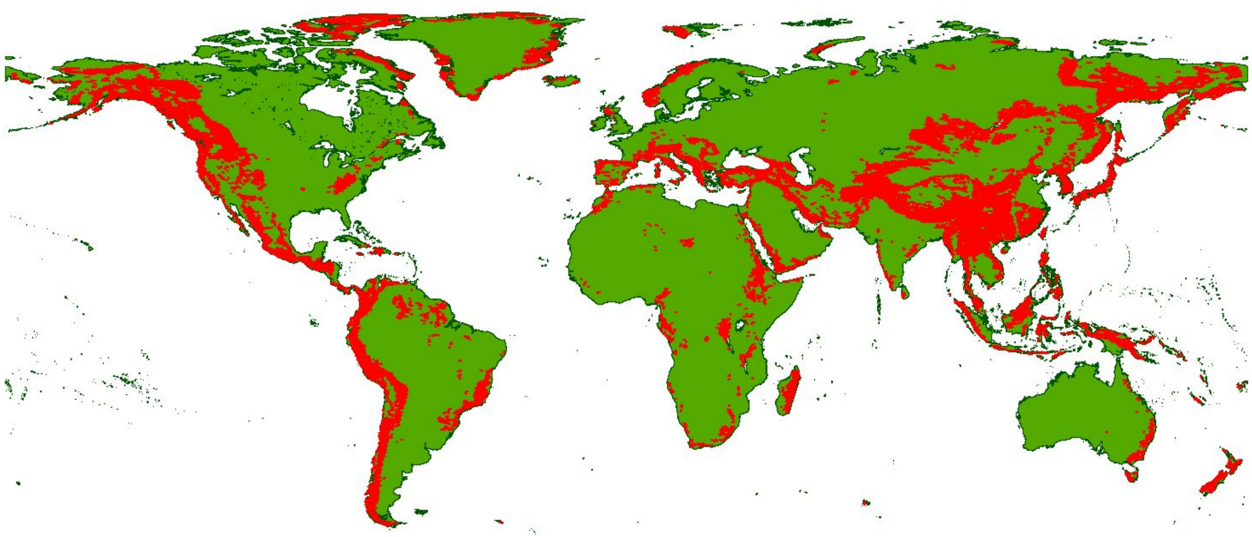

Figure 5. Regions affected by shadow and layover effects in red.

5. Conclusions

The TanDEM-X mission will deliver a global and consistent Digital Elevation Model with unprecedented accuracy. The acquisition of the first coverage has been completed in March 2012 and the acquisition of the second one has been finished in April 2013. The third phase of the acquisition, starting from May 2013, includes for the first time the acquisition over Antarctica and further acquisitions of difficult terrain such as deserts and mountainous regions. Performance has been studied in order to derive a consistent and appropriate acquisition strategy over these areas.

Left-looking imaging mode is required for the acquisitions over inner Antarctica, while North-descending and South-ascending acquisition mode, with a shift of 180^o in the phase of libration is planned for the difficult terrain and in the outer rim of Antarctica.

6. Acknowledgements

The TanDEM-X project is partially funded by the German Federal Ministry of Economics and Technology (Förderkennzeichen 50EE 1035) and realized in a public-private partnership between German Aerospace Center (DLR) and EADS Astrium GmbH.

7. References

[1] Krieger, G. and Moreira, A. and Fiedler, H. and Hajnsek, I. and Werner, M. and Younis, M. and Zink, M. "TanDEM-X: A Satellite Formation for High Resolution SAR Interferometry," IEEE Transactions on Geoscience and Remote Sensing, vol. 45, no. 11, pp. 3317-3341, 2007.

[2] Rizzoli, P. and Bräutigam, B. and Kraus, T. and Martone, M. and Krieger, G. (2012) Relative height error analysis of TanDEM-X elevation data. ISPRS Journal of Photogrammetry and Remote Sensing, 73, pp. 30-38. Elsevier B.V. . DOI: 10.1016/j.isprsjprs.2012.06.004. ISSN 0924-2716.

[3] Fritz, T. and Rossi, C. and Yague-Martinez, N. and Rodriguez Gonzalez, F. and Lachaise, M. and Breit, H. (2011) Interferometric Processing of TanDEM-X Data. in IEEE: International Geoscience And Remote Sensing Symposium, Vancouver, Canada.

[4] Bräutigam, B. and Rizzoli, P. and Martone, M. and Bachmann, M. and Krieger, G. (2012) InSAR and DEM Quality Monitoring of TanDEM-X. IEEE: International Geoscience And Remote Sensing Symposium, Munich, Germany.

[5] Bachmann, M. and Schulze, D. and Ortega-Miguez, C.J. and Polimeni, M.D. and Böer, J. and Hueso Gonzalez, J. and Walter Antony, J. and Krieger, G. and Bräutigam, B. and Schwerdt, M. and Zink, M. (2012) TanDEM-X Acquisition Status and Calibration of the Interferometric System. In: Proceedings of the IEEE International Geoscience and Remote Sensing Symposium (IGARSS), pp. 1-4. IEEE. IEEE International Geoscience and Remote Sensing Symposium (IGARSS), 2012-07-22 - 2012-07-27, Munich, Germany.

[6] Lachaise, M. and Fritz, T. and Balss, U. and Bamler, R. and Eineder, M. (2012) Phase unwrapping correction with dual-baseline data for the TanDEM-X mission. IGARSS 2012, 22-27 July 2012, Munich, Germany. ISBN 978-1-4673-1160-1. ISSN 2153-6996

[7] Martone, M. and Bräutigam, B. and Rizzoli, P. and Gonzalez, C. and Bachmann, M. and Krieger, G. (2012) Coherence Evaluation of TanDEM-X Interferometric Data.

ISPRS Journal of Photogrammetry and Remote Sensing, 73, pp. 21-29. DOI: 10.1016/j.isprsjprs.2012.06.006. ISSN 0924-2716.

[8] Martone, M. and Rizzoli, P. and Bräutigam, B. and Krieger, G. (2013) First two years of TanDEM-X mission: interferometric performance overview. Radio Science. (Submitted)

[9] Ardaens, J.S. and D'Amico, S. and Kazeminejad, B. and Montenbruck, O. and Gill, E. (2007) Spaceborne Autonomous and Ground Based Relative Orbit Control for the TerraSAR-X/TanDEM-X Formation. 20th International Symposium on Space Flight Dynamics, 2007-09-24 - 2007-09-28, Annapolis.

[10] D'Amico, Simone and Montenbruck, Oliver (2004) Proximity Operations of Formation Flying Spacecraft using an Eccentricity/Inclination Vector Separation. Journal of Guidance, Control, and Dynamics, 29 (3). AIAA.

[11] Ortega-Miguez, C.J. and Schulze, D. and Polimeni, M.D. and Böer, J. and Rizzoli, P. and Bachmann, M. (2012) TanDEM-X Acquisition Planner. European Conference on Synthetic Aperture Radar (EUSAR), 2012-04-23 - 2012-04-26, Nuremberg, Germany.

[12] Fiedler, H. and Krieger, G. and Zink, M. and Geyer, M. and Jäger, J. (2008) The TanDEM-X Acquisition Timeline and Mission Plan. In: Proceedings of the European Conference on Synthetic Aperture Radar (EUSAR), p. 4. European Conference on Synthetic Aperture Radar (EUSAR), 2008-06-02 - 2008-06-05, Friedrichshafen, Germany.

[13] Li, F.K. and Jonson, W.T.K. (1983) Ambiguities in Spaceborne Synthetic Aperture Radar Systems. In: IEEE Trans. Aerosp. Electron. Syst. , Vol. 19, S. 389-397