Observation Strategies for TanDEM-X and Tandem-L

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Abstract

TanDEM-X is a unique mission to derive Digital Elevation Models (DEMs) with two SAR satellites in orbit since 2007 and 2010. The acquisition of the first global DEM was performed until 2014. After a first science phase was performed between 2014 and 2017, an update of the global DEM, called "Change DEM", was acquired between 2017 and 2020. Currently, a second science phase is carried out concentrating on permafrost areas, forests and the major cities of the world. DLR is also pushing for the time after TanDEM-X with Tandem-L, a proposal for a sophisticated satellite-duo operating in L-band, serving a variety of applications. The paper describes the acquisition concepts for both missions which are of crucial importance for delivering high-quality DEM data to scientific and commercial users.

1 Introduction

TanDEM-X is a spaceborne SAR system based on two satellites flying in close formation [1]. Operating as a single-pass interferometer, the mission generates digital elevation models (DEMs) of the global land surface. DEMs are required for many commercial and scientific applications, such as navigation, cartography, and in various geoscience fields. The satellites were launched in 2007 and 2010 respectively. They acquired data for the global DEM between 2010 and 2014. The global DEM generation was completed in 2016 achieving an unprecedented accuracy with e.g. the absolute height error considerably fulfilling its specification of 10 m at 90% confidence level [2]. As the satellites have sufficient resources for several more years of operation left, the acquisition of a further coverage was started in 2017. With the acquired data, a so-called global *Change DEM* indicating the changes compared to the global TanDEM-X DEM is currently derived.

Based on the success of TanDEM-X, the German Aerospace Center started to define a follow-on mission. Tandem-L is the proposal for a unique mission to monitor the global dynamics of different Earth system processes in the geosphere, biosphere, cryosphere, and hydrosphere [3]. The mission will be comprised of two L-band SAR satellites flying in close formation. Digital beam forming capabilities are implemented in the system to allow high-resolution wide-swath imaging. In addition, a reflector antenna is required and used to increase the coverage and the sensitivity of the system. The project is currently in a Phase B. A complex acquisition strategy is derived aiming to fulfil the various scientific demands.

In the following chapters, the paper first describes the approach for the acquisition of an additional global *Change DEM* coverage with TanDEM-X. In the second part, the paper introduces the challenges of the Tandem-L mission, leading to a dedicated concept for the Tandem-L acquisitions.

2 TanDEM-X Acquisitions

2.1 Review of the Global DEM Acquisition

Since 2010, the two satellites TerraSAR-X and TanDEM-X have been flying as a large single-pass bistatic SAR interferometer in a close helix formation. The distance between the two satellites varies from 120 m to several hundred meters [4]. The acquisition of the global TanDEM-X DEM took place until 2014. During this time, at least two global coverages (including Antarctica) were performed. Over difficult terrain like mountainous or deserts additional coverages were acquired. Mountains areas were acquired from an opposite viewing direction, which was performed to resolve shadow and layover. Deserts on the other hand were acquired with steeper incidence angle to increase the signal-to-noise ratio (SNR) for this low-backscatter targets. The data was processed until 2016 and mosaicked together to generate the final global DEM of all land masses.

After the completion of this primary mission goal, dedicated satellite formations and geometries concentrating on data for advanced scientific applications were flown between 2014 and 2017. One example is a formation geometry with very large horizontal baselines of up to 3.6 km to monitor the vegetation growing cycle or to demonstrate High-Resolution DEMs.

During the processing of the global TanDEM-X DEM, a number of challenges of the used acquisition strategy were faced [5]. Many of these could be reverted by dedicated additional acquisitions. An example for the lessons learned is the necessity to acquire glaciers explicitly in local winter time, as melting ice or snow shows a poor SNR performance during summer time. Sandy deserts as another example need to be acquired with very steep incidence angles to overcome the low backscatter and SNR of dry sand.

2.2 Change DEM Acquisition

Even more than 13 years after the launch of TerraSAR-X, the satellites are still in good shape and consumables are sufficient for several more years of operation [4]. However, parts of the data used for DEM generation were already more than seven years old in 2017. A lot of changes in the topography of the Earth took place during this time. Thus, the acquisition of a further global coverage in order to update the first global DEM in form of a *Change DEM* product is of great value for the geoscience community.

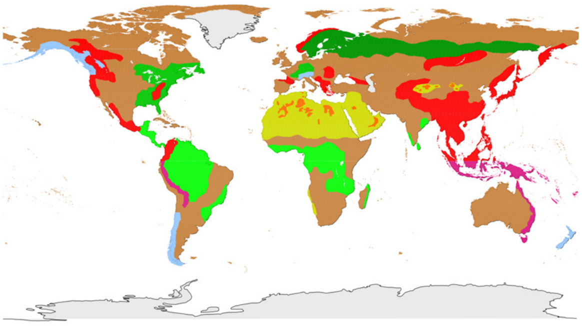

Figure 1: Areas to be acquired with dedicated parameters over forests (green), glaciers (blue), mountains (red/pink) and the rest of the world (brown).

For this purpose and considering the lessons learned mentioned above, the Earth was separated in dedicated acquisition areas according to the dominant land classes and terrain types as shown in **Figure 1**. For each acquisition area certain acquisition constraints were defined. The red areas indicate mountainous terrain and are acquired twice in local summer time, whereas glaciers in light blue are acquired twice in winter. The dark green forest areas are acquired once in summer time. Tropical forests in light green as well as deserts in yellow and the rest of the world in brown are acquired all year round, each only once.

As the focus of the project changed and the satellites are getting older, several new constraints had to be considered for the acquisition planning. The maximal duration of an acquisition is limited to decelerate down the degradation of the batteries. In addition, the number of ground stations was reduced which significantly decreased the contact time per orbit and thus the amount of data that can be acquired. With these inputs the acquisition timeline was derived using the TanDEM-X Acquisition Planner [6], the operational tool used to perform the TanDEM-X acquisitions planning. For this purpose, constraints like the on-board resources, the maximal and average duration of acquisitions, the areas to be acquired, the desired baselines, or the seasons are considered. These inputs are optimized together with the formation of the two satellites in order to maximize the utilization of the system and the quality of the acquisitions. The process delivers a feasible acquisition timeline.

The *Change DEM* acquisitions started in September 2017. The formation flown to acquire the *Change DEM* is shown in **Figure 2**. The graph shows the evolution of the baselines. The horizontal baseline changes from large to small within each winter/summer season in order to acquire the different dominant land types in times with appropriate conditions. The Change DEM phase was completed by a recovery phase in the first half of 2020 to catch up missing acquisitions.

During the acquisition of the *Change DEM*, the mission faced several further challenges. On the one hand, the number of conflicts with commercial and scientific customers increased due to higher utilization of the satellites for acquiring TerraSAR-X products. An agreement with the commercial partner Airbus D&S was elaborated and established to alternate between commercial and *Change DEM* acquisitions every other orbit in case of conflicts. This is the main reason for the stretched acquisition phase in autumn/winter 2019. A semi-automated approach was implemented in the acquisition planning system to easily re-plan the acquisitions. A recovery phase was attached to the initial acquisition timeline in the first half of 2020 for this re-scheduling of acquisitions that were suppressed by high-priority commercial acquisitions. Especially for future acquisitions, the possibility to use the PAZ satellite launched in 2018 is expected to relax the situation for highly-conflicted orbits [7].

Furthermore, in July 2019 the primary transmit chain on the TanDEM-X satellite failed due to a malfunction of the first high power amplifier stage (TUS3). Fortunately, the switch to the redundant chain was successful. The TanDEM-X mission was re-activated after about two months that were necessary to re-adjust the TanDEM-X satellite as well as the TanDEM-X mission [8].

Figure 3 shows that all necessary acquisitions were performed and that the Change DEM is completed. However, there are about 20 acquisition (state 2021-01-28) that will be re-acquired in order to achieve an improved performance when the formation is suitable during the current science phase. In addition, as the processing of the *Change DEM* acquisitions is currently on-going, there might be acquisitions showing an insufficient performance and thus have to be re-acquired. The according re-planning of those acquisitions will be executed as soon as the information is available.

The processing of the acquisitions is performed exploiting a new processing approach [9]. This approach is based on a reference DEM generated from the global TanDEM-X DEM. Therefore, the TanDEM-X DEM has been edited in order to allow an accurate and consistent processing [10]. The two main goals of this DEM editing are void filling and water flattening. The filling of voids is needed to eliminate areas where no or inconsistent data is present in the global TanDEM-X DEM.

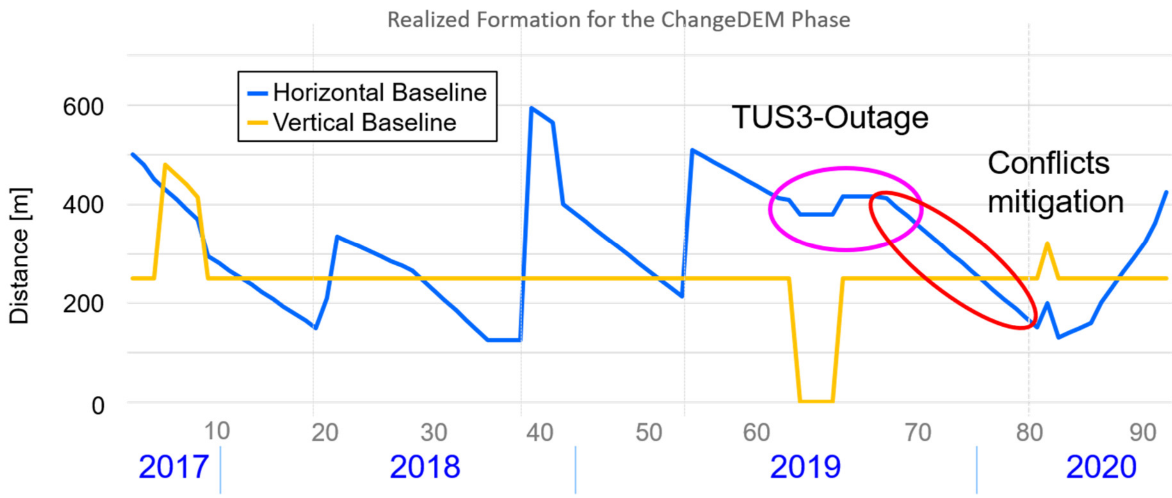

Figure 2: Formations flow during the *Change DEM* phase

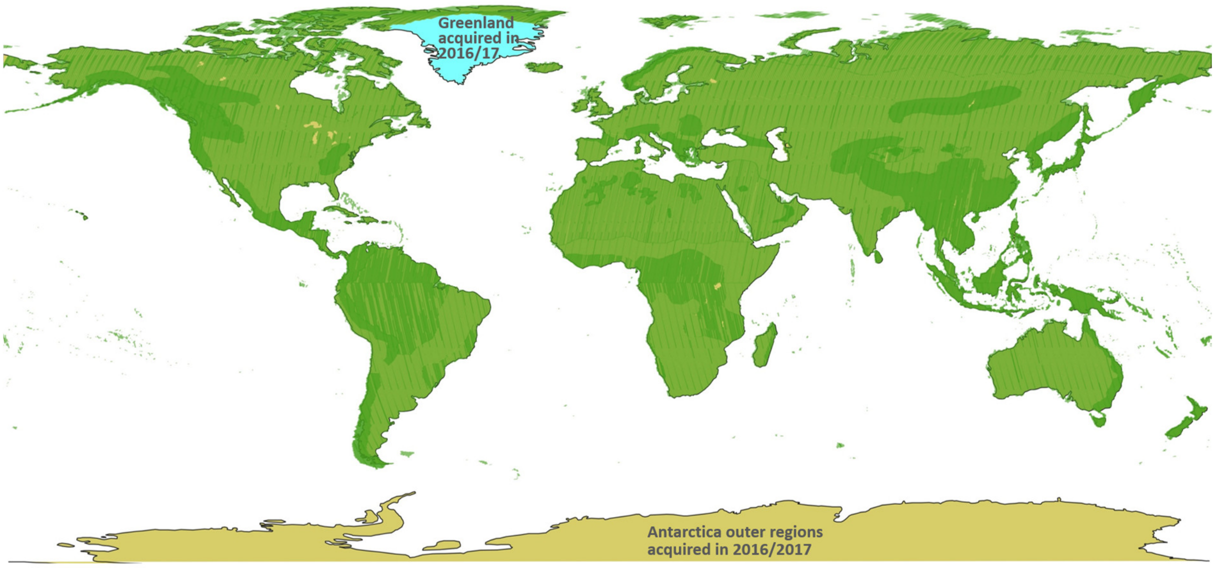

Figure 3: Areas acquired between 2017 and summer 2020 in green. Light green indicates one coverage, darker green two coverages. Greenland (cyan region) and the outer regions of Antarctica were acquired in 2016/2017.

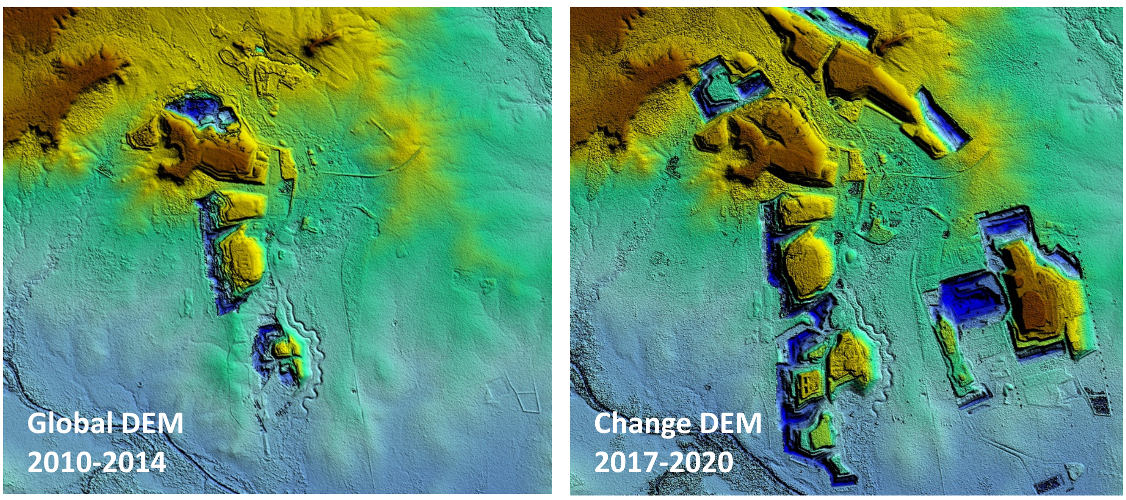

Figure 4: *Change DEM* example of Millenium Coal Mine, Queensland, Australia

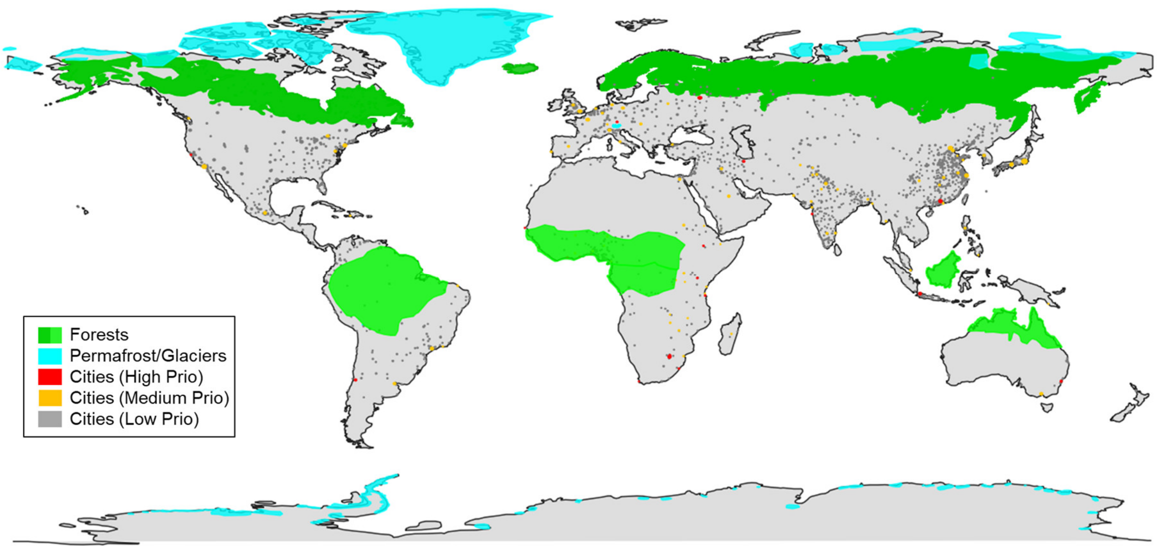

Figure 5: Regions of interest for the Science Phase 2020-2022

The flattening of water bodies on the other side is required as water areas are quite noisy and often appear as ramps or inconsistent data in the DEM. Based on this edited DEM, the processing of the *Change DEM* scenes started in autumn 2020 and will last approximately three years until the mosaicked *Change DEM* is generated.

Figure 4 shows an example of the *Change DEM* (right side) in comparison to the global DEM acquired between 2010 and 2014 (left side). It demonstrates the large changes that take place in mining areas within a few years only and the scientific and commercial potential of the *Change DEM* product.

2.3 Science Phase 2020-2022

The acquisition of the *Change DEM* coverage was completed in June 2020 and it was followed by a second phase dedicated to scientific acquisitions. Based on the experience and results gained from the continuous science acquisitions and the science phase 2014-2016, the focus of this phase is put on the permafrost and arctic regions [11] and on forested areas. In addition, the largest cities of the world are mapped with different baselines in order to allow 3-D city monitoring [12] and a possible update of the global urban footprint [13]. The designated regions are shown in **Figure 5**.

3 Tandem-L Observation Strategy

3.1 Motivation

Tandem-L is the proposal for a global mapping mission, covering dynamic processes on the Earth surface. The mission shall acquire data on a global basis with high temporal sampling. Certain scientific applications require data providing about one global coverage per week. The mission will generate higher level data products (Level-2 and above) for selected scientific applications and make them available to the scientific community. These products will, for example, provide global forest heights and structure maps which are used to determine the biomass estimates [14]. The generation of such products is based on tomography and requires a multitude of acquisitions with different baselines to perform tomography. In the field of the geosphere, products to accurately monitor geologically active areas like volcanoes, seismic deformations, or landslides with mm accuracy will be generated [15]. Further important scientific topics that will be served with Level-1 SAR data are agricultural, soil moisture mapping, ice and glacier observation, and ocean monitoring.

Due to this multitude of required products the Tandem-L mission is much more complex than TanDEM-X. In addition, the partly contradicting product requirements and different demands on the product resolution and on the polarization need to be accounted for in areas with overlapping regions of interest. The combination of these applications and the derivation of a consistent, feasible plan is the goal for the Tandem-L observation concept.

3.2 Mission Constraints and Formation

This observation concept has to consider certain constraints driven by the radar instruments and the whole mission concept. The swath coverage on ground is 350 km and 175 km in single/dual and full-polarimetric mode, respectively, with an orbit repeat cycle of 16 days. A Ka-band ground station network is foreseen to dump a data volume of 64 Tbit/day.

Tandem-L consists of two independent SAR satellites. The satellites will fly a controlled helix formation [1] similar to the one successfully exploited for TanDEM-X. For Tandem-L however, the formation will be varied by setting slightly different inclination vectors for the orbits of the two satellites [16], [17]. In this way, the natural drift of the orbits is used to slowly increase the horizontal distance at the equator over time. By properly selecting this inclination difference, the horizontal baseline at the equator increases (or decreases) from 600 m up to around 20 km within six months. This is required to provide suitable baselines for the tomographic applications.

3.3 Resulting Acquisition Timeline

The different scientific applications require different acquisitions frequencies and seasons. Acquisitions for deformation, as an example, need to be acquired from different angles as often as possible. Forest structure and height acquisitions on the other hand need to be acquired with four to six different baselines during one season (maximum half a year).

The planning of the acquisition timeline is performed using a Tandem-L acquisition planning tool. It is based on the operational TanDEM-X Acquisition Planner [6], but extended to the special purpose of Tandem-L. These adaptations consider changes in the formation flying concept, the acquired swaths/beams, and the downlink scenario. In addition, the acquisition concept is changed, e.g. coverages of latitudes in the far north/south shall be acquired as often as possible. And also the season is considered for certain applications.

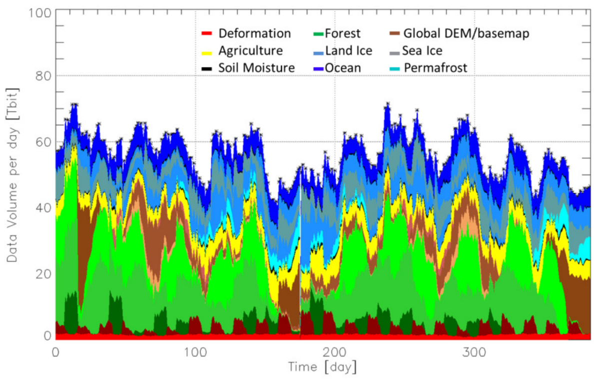

Figure 6: Daily data volume acquired for the different application areas over one year like tropical forest (light green), temperate forest (normal green) and boreal forest (dark green) or the global DEM (light and dark brown)

Figure 6 shows the data volume acquired for the different applications for the resulting timeline. Different applications require different resolutions, different number of polarization channels and hence different acquisitions modes. Acquisitions for forest (green) are acquired in single-pass interferometric quad-polarization mode. Acquisitions for deformation (red), on the other hand, are acquired mono-statically in a single-polarization mode, which results in a data volume that is about three quarters lower than for forest. This is reflected in Fig. 6, where the forest acquisitions are the main driver in terms of data volume. The resulting acquisition timeline is steadily refined and adapted to new findings for the scientific product requirements.

4 Conclusion

The TanDEM-X mission lately acquired an additional global coverage in order to generate a so-called *Change DEM* and deliver a valuable, up-to-date product for terrain applications. The acquisitions for the *Change DEM* were completed until 2020 and the processing is currently ongoing. At this time, the mission is is dedicated to perform scientific acquisitions with focus on permafrost areas, forests and cities. With the generation of various DEM products with outstanding accuracies and the successful conduction of the first science phase, TanDEM-X has demonstrated the feasibility of an interferometric radar mission with close formation flight and innovative SAR technologies. It delivers an important contribution for the conception and design of future SAR missions, such as Tandem-L. The paper therefore also presented a preliminary observation concept for the Tandem-L mission.

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