How to Update a Global DEM – Acquisition Concepts 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 from space. A first global DEM with unprecedented accuracy was completed in 2016. The satellites are still in good shape despite being over their expected lifetime. With the experience of the last seven years of DEM data acquisition and processing, an update of the global DEM, called "Change DEM", was planned and is currently in acquisition. DLR is also pushing for the time after TanDEM-X. With Tandem-L, a proposal for a similar but more complex satellite-duo operating in L-band was developed. The number and variety of applications to be served besides the DEM is a major difference to TanDEM-X and also one of the great challenges of the new mission. For both missions the acquisition concepts are of crucial importance as they combine the scientific demands with the processing requirements on the data. The paper gives an overview about the actual state of acquisitions on TanDEM-X and an insight in the proposed acquisition plan for Tandem-L.

1 Introduction

1.1 TanDEM-X

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 (DEM) of the land surface of the Earth. Digital elevation models 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. Data acquisition for the global DEM was performed between 2010 and 2014. With these data, the global DEM was generated with 12 m posting. It reaches an unprecedented relative vertical accuracy of 2 m for terrain slopes less than 20% (90% point-to-point error) and 4 m for slopes higher than 20% [2]. The DEM generation was completed in 2016. As the satellites have sufficient resources for several more years of operation left, the acquisition of a further coverage was started in 2017 in order to derive a so called global "Change DEM" indicating the changes compared to the global TanDEM-X DEM.

Already in 2010 DLR started to define a follow-on mission in L-band:

1.2 Tandem-L

Understanding the global dynamics of different earth system processes in the geosphere, biosphere, cryosphere, and hydrosphere is of fundamental importance for various scientific research fields. Tandem-L is the proposal for a unique mission to monitor these processes on earth in order to contribute to urgent questions in earth system dynamics [3]. The mission is 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. Approval for full implementation is expected for 2018 resulting in a potential launch around 2023/24.

Tandem-L shall acquire data on a global basis with high temporal sampling. Certain scientific applications require data with 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 and based on that, the biomass estimates. For applications in the field of the geosphere, products to accurately monitor geologically active areas like volcanoes, seismic deformations, or landslides will be generated. 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.

In the following chapters, the paper first describes the approach for the acquisition of an additional global 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: Update of the Global DEM

2.1 First Global DEM and Lessons Learned

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 of meters [1]. 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 mountainous terrain two additional coverages were acquired from an opposite viewing direction in order to resolve shadow and layover. Until 2016, the data was processed and mosaicked together to generate the final global DEM of all land masses.

Since 2014, dedicated phases concentrating on formations for scientific purposes were flown. Examples for the applications served with data from these scientific phases are:

- Agricultural monitoring of the vegetation growing cycle with very large baseline up to 3.6 km,
- Forest monitoring utilizing the full-polarimetric mode of TerraSAR-X/TanDEM-X.
- Monitoring of glaciers at high latitudes flying in a constellation where the satellites are separated in flight direction by about 76 km.

An additional phase concentrated on the acquisition and demonstration of DEMs with an increased horizontal and vertical resolution (so called High-Resolution DEMs).

During the processing of the global TanDEM-X DEM, a number of disadvantages of the used acquisition strategy were faced. Many of these disadvantages could be reverted by dedicated additional acquisitions. The following list shows some of the lessons learned:

- Data over glaciers or snow-rich mountains explicitly need to be acquired during local winter time, as melting ice or snow shows a very bad SNR performance during summer time.
- The baseline and the corresponding height of ambiguity (HoA) needs to be different for different land types and should be in a well-defined range:
  - Glaciers, mountains or mountainous forests need be acquired with HoAs between 45 m and 90 m.
  - Tropical forests can be acquired year-round but with HoAs larger than 50 m.
  - Sandy deserts need to be acquired with very steep incidence angles to overcome the low backscatter of sand and hence to increase the low signal-to-noise ratio.

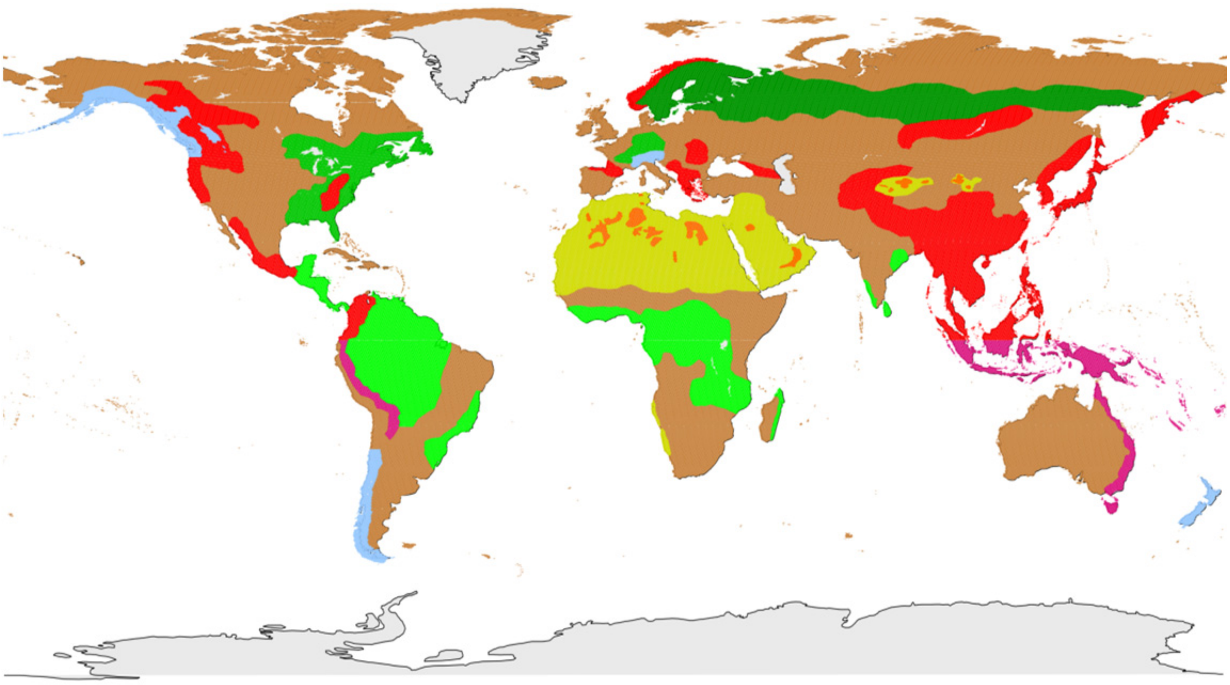

Figure 1: Areas to be acquired with dedicated parameters, colours as defined in Table 1.

2.2 Update of the Global DEM

The generated DEM was successfully sold by the commercial partner (Airbus D&S) and great scientific interest was raised with the scientific release of the DEM data in late 2017. However, a part of the data used for DEM generation is already more than seven years old. Hence, a lot of changes in the topography of the Earth took place during this time. On the other hand, the satellites are still in good shape and there are sufficient consumables for several more years of operation left [4]. Thus, the mission decided to acquire a further global coverage in order to update the first global digital elevation model in form of a self-contained "Change DEM" product.

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 listed in **Table 1** and indicated by the same colour need to be observed.

In addition, several constraints had to be considered for the acquisition planning:

- The maximal duration of a data take is limited to avoid too fast degradation of the battery.
- The reduction of the number of ground station significantly reduced the contact time per orbit and thus the amount of data that can be acquired.
- Small but more and more regular hick-ups in the system lead to more effort for the operations team and the need to re-plan acquisitions.

Region	Cover-ages	Season	Height of Ambiguity	Inc. Angle Range
Mountains with Forest	2	Local summer	55 - 75 m (1st) 45 - 53 m (2nd)	27 - 49 deg
Glaciers	2	Local winter	55 - 75 m (1st) 45 - 53 m (2nd)	29 - 47 deg
Tropical forest	1	Year round	50 - 60 m	27 - 49 deg
Temperate & boreal forest	1	Local summer	50 - 55 m	27 - 49 deg
Deserts with Mountains	2	Year round	55 - 75 m (1st) 45 - 55 m (2nd)	27 - 49 deg
Deserts	1	Year round	23 - 45 m	14 - 38 deg
Permafrost area	1	Local winter	35 - 45 m	29 - 47 deg
Rest of the world	1	Year round	35 - 45 m	27 - 49 deg

Table 1: Acquisition parameters for the Change DEM Product.

With this input the planning process was executed. An acquisition timeline was derived using the TanDEM-X Acquisition Planner [5]. With this operational tool the planning of the TanDEM-X acquisitions is performed. 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. The process delivers a feasible acquisition timeline in form of data takes and the corresponding acquisition parameters. The resulting acquisitions were started in September 2017 and are expected to last until the end of 2019.

3 Tandem-L: Variety of scientific applications and acquisition constraints

3.1 Motivation

TanDEM-X was very demanding as it was the first single-pass interferometric mission. In contrast, the Tandem-L mission is even more complex due to the demands of the various scientific applications defined by the different research fields, and their partly contradicting requirements.

Table 2 shows an overview about the major research fields (applications) addressed by Tandem-L and the major challenges with respect to an observation concept.

Applications in the area of geology, like monitoring of seismic deformations or volcanoes, require the measurement of deformations in three dimensions of millimeter range over large areas [6]. This is only possible by combining as many acquisitions as possible from at least three different viewing angles, i.e. in ascending and descending direction and in right- and left looking. In contrast, the derivation of a global digital elevation model and applications for forest science demand bistatic acquisitions and hence a close formation of the two satellites. For forest structure and forest height determination, several of these acquisitions with different baselines are needed to discriminate the different vegetation layers by means of tomography [7].

For applications like agriculture or ocean currents and wind speed, a high temporal sampling is important. For this purpose and to increase the number of acquisitions for deformation measurements, the close formation will be dissolved regularly about once every two years and the satellites will be transferred into a constellation with a phasing of 2+14 days or 7+9 days. Finally, potential observations in case of emergency requests in the frame of the international carter for space and major disasters demand a fast response time of the system.

Research field	Major challenge
Deformation/Geosphere: Plate tectonics, deformation, volcanic activities	High number of acquisitions from three different viewing geometries
Global/local digital elevation models	Consistent elevation models of the whole earth and temporally of local hot spots (like glaciers)
Global land cover	Full-polarimetric global land mapping
Forest/Biosphere: Global forest structure for biomass determination	Varying baselines for tomography, high data volume driven by polarimetric SAR interferometry
Agriculture: Monitoring of the growing period	Tight temporal coverage especially during growing season
Soil moisture	Bi-weekly coverage with high spatial resolution
Ice dynamics: Land ice and sea ice change and structure, permafrost regions	Large baselines close to the poles which are difficult to adjust due to formation constraints
Oceanography: Ocean currents and surface waves, wind speed	High number of acquisitions at all coast lines
Emergency observations	Quick response time in case of emergencies/hazards

Table 2: Research fields and their major challenges driving the observation concept.

In addition, different demands on the product resolution and on the polarisation need to be accounted for in such areas where regions of interest overlap. The combination of these applications and the derivation of a consistent, feasible plan is the goal described in the following. As the project is still in an early phase, there is yet a high variability in terms of requirements and importance of the individual applications and their constraints.

3.2 Mission Constraints

An observation concept for Tandem-L has to take into account certain constraints driven by the radar instruments and the whole mission concept.

The orbit and the instruments are designed to cover a swath width of 350 km on ground in single- and dual-polarimetric mode, and 175 km in full-polarimetric mode. The repeat cycle in this orbit is 16 days.

The used acquisition modes also determine the data volume that can be acquired. For Tandem-L, five ground stations are foreseen to downlink the data in Ka-band. With this ground station network, a data volume of 64 Tbit/day can be dumped. On the other hand, the on-board memory is limited to 12 Tbit at the end of life. Thus, the acquisitions have to be planned properly to meet these limits.

Finally, 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).

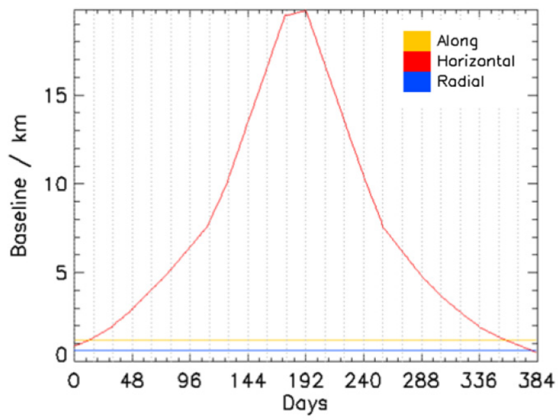

Figure 2: Tandem-L formation over one year

3.3 Formation

Tandem-L consists of two independent SAR satellites. The satellites fly a controlled helix formation [8] similar to the one successfully exploited for TanDEM-X. For Tandem-L however, the formation will be changed by setting slightly different inclination vectors for the orbits of the two satellites [9], [1]. In this way, the natural drift of the orbits is used to slowly increase the horizontal distance at the equator over time.

Certain scientific applications like forest height and structure estimation require dedicated baselines. Therefore, the inclination difference is selected such that the horizontal baseline at the equator increases (or decreases) from 600 m up to around 20 km during six months as shown in **Fig. 2**. In this way, suitable baselines are generated over the whole latitude range.

3.4 Resulting Acquisition Timeline

3.4.1 Planning Concept

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 [5], 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.

3.4.2 Acquired Data Volume

Figure 3 shows the data volume acquired for the different applications for the resulting timeline. Different applications require different resolutions, different number of polarisation channels and hence different acquisitions modes. Acquisitions for forest (green) as an example are acquired in single-pass interferometric quad-polarisation mode. Acquisitions for deformation (red), on the other hand, are acquired mono-statically in a single-polarisation mode, which results in a data volume which is about three quarter lower than for forest. This is reflected in Fig. 3, where the forest acquisitions are the main driver in terms of data volume. In case that acquisitions for different applications (with different modes) need to cover the same area of interest, the mode with the highest data rate is chosen.

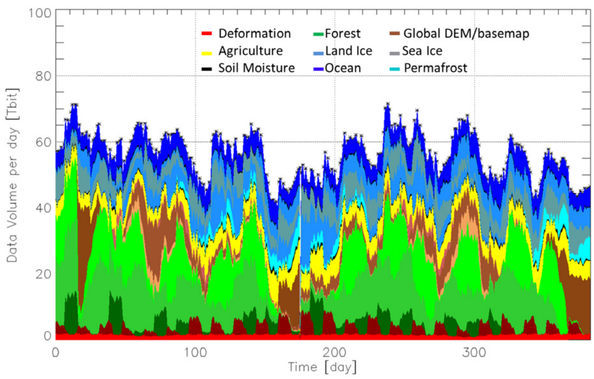

Figure 3: Daily data volume acquired for the different application areas over one year like tropical forest (light green), temperate forest (normal green) and boreal forest (dark green) or the global DEM (light and dark brown)

4 Conclusion

The acquisition of the global DEM being the primary goal of the TanDEM-X mission has been achieved in 2014. The data processing was completed in 2016. The current focus is on the acquisition of an additional global coverage in order to generate global Change DEM. 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. It shows the feasibility of the mission in terms of the fulfilment of the scientific requirements and in observing the constraints of the satellites, the instruments, and the downlink concept.

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