TWO YEARS OF TANDEM-X BASELINE DETERMINATION

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Abstract: *The TanDEM-X mission is a German dual satellite formation with the task to acquire a global digital elevation model (DEM) by bistatic interferometric synthetic aperture radar (SAR) data takes. Therefore the two satellites are kept in a close helix-formation with a distance of less than 1 km. In order to reach the intended DEM accuracy, the baseline vector between the two spacecraft needs to be determined with an accuracy of 1 mm. To achieve this goal, both satellites are equipped with high grade dual-frequency GPS receivers.*

The baseline vector between the two satellites is determined by GFZ and the German Space Operations Center (GSOC/DLR) using independent software packages. The GSOC/DLR baseline solution is processed with the FRNS software (Filter for Relative Navigation of Spacecraft). The underlying concept is to achieve a higher accuracy for the relative orbit between two spacecraft by making use of differenced GPS observations, than by simply differencing two independent precise orbit determination (POD) results. The use of single-differenced code and carrier phase observations rigorously eliminates GPS clock offset uncertainties and largely reduces the impact of GPS satellite orbit and phase pattern errors. Double differences are used for the integer ambiguity resolution of the carrier phase observations.

In studies prior to the TanDEM-X mission, comparisons between independent software packages showed biases of a few millimeters. In order to ensure the highest accuracy, a baseline calibration and combination process has been installed. The baseline products are validated by dedicated baseline calibration data takes over test sites, where the DEM is well known. Using those DEMs as a reference, height differences in the TanDEM-X scenes are estimated. Taking into account the incident angle and the height of ambiguity, these height differences can then be used to infer errors of the baseline products.. The resultant offset parameters are then applied in the baseline calibration process. The analyses show that the derived offset parameters are in the range of few millimeters. Finally the different solutions are merged to a combined product.

Keywords: *TanDEM-X, baseline determination, relative navigation, GPS, DEM calibration*

1. Introduction

1.1. The TanDEM-X Mission

The TanDEM-X mission (TerraSAR-X and on for Digital Elevation Measurements) is a German dual satellite formation. It consists of the TSX satellite, which was launched in June 2007 with a Russian Dnepr rocket in Baikonour and the almost identical twin TDX which was launched in June 2010 with the same type of launcher. Both satellites have a hexagonal shape with a length of about 5 m, a diameter of 2.4 m and a weight of more than 1200 kg. They are operated in a sun-synchronous orbit at an orbit height of 515 km and an inclination of 97.44° (see Fig. 1).

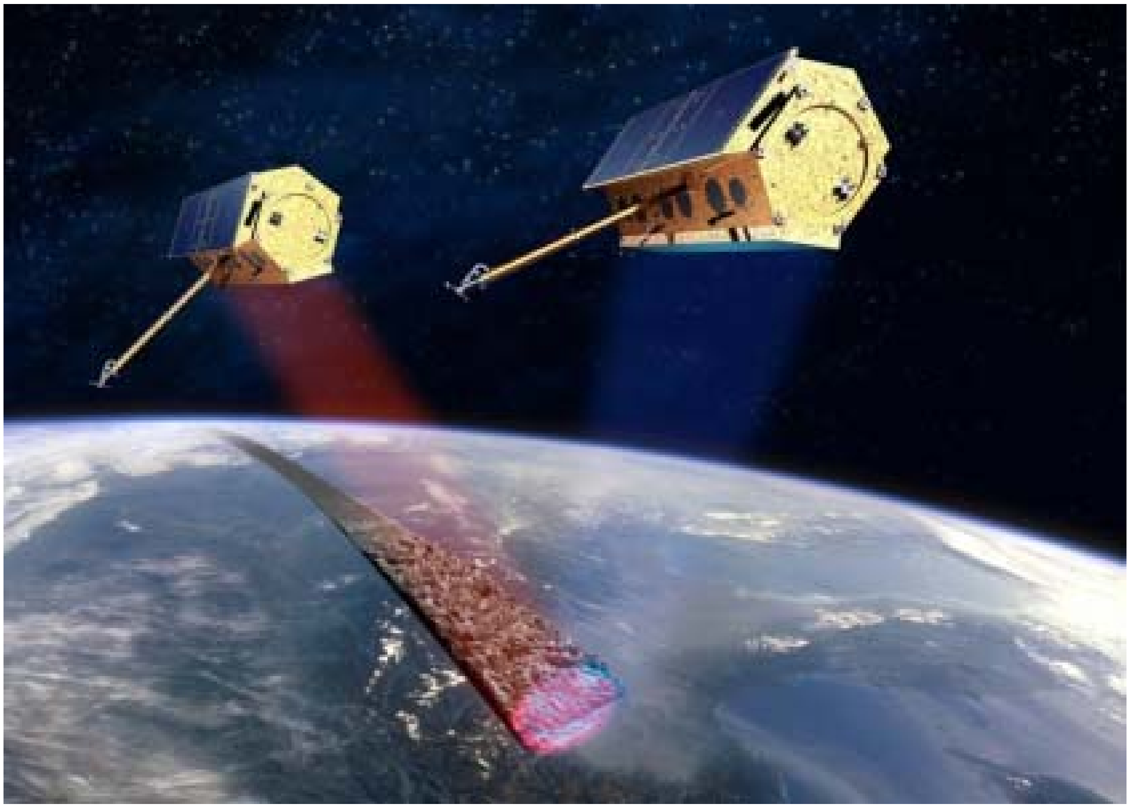

Figure 1. The TanDEM-X mission.

The main payload of the satellites is an X-band synthetic aperture radar (SAR) instrument. In the frame of the TerraSAR-X mission both satellites can acquire radar images of the Earth's surface. In the frame of the TanDEM-X mission, they work together to acquire bistatic radar data takes in order to generate a global digital elevation model (see [1]). Therefore, they are operated by the German Space Operations Center (GSOC/DLR) in a close helix formation (see [2]) with a separation of less than 500m. In order to keep the tight formation and prevent collisions, the TDX satellite frequently performs formation keeping maneuvers with its cold-gas thrusters.

1.2. Navigation Hardware

For navigation purposes, both satellites are equipped with two GPS receivers: the single-frequency MosaicGNSS receiver and the TOR (Tracking, Occultations and Ranging) instrument. The main task of the MosaicGNSS receiver is to provide robust on-board orbit parameters and time. The TOR instrument consists of the geodetic grade IGOR receiver (Integrated GPS and Occultations Receiver) and a Laser Retro Reflector developed by GFZ (see [3]). The IGOR, provided by GFZ is a heritage of the Black Jack receiver, which was successfully flown on missions like CHAMP and GRACE (see [4] and [5]). It’s main purpose is to provide highly accurate GPS observations for precise orbit determination (POD). Hence 12 of the 16 channels for tracking of GPS satellites are dedicated to navigation and the remaining four are dedicated for occultation observations, which is a secondary mission objective.

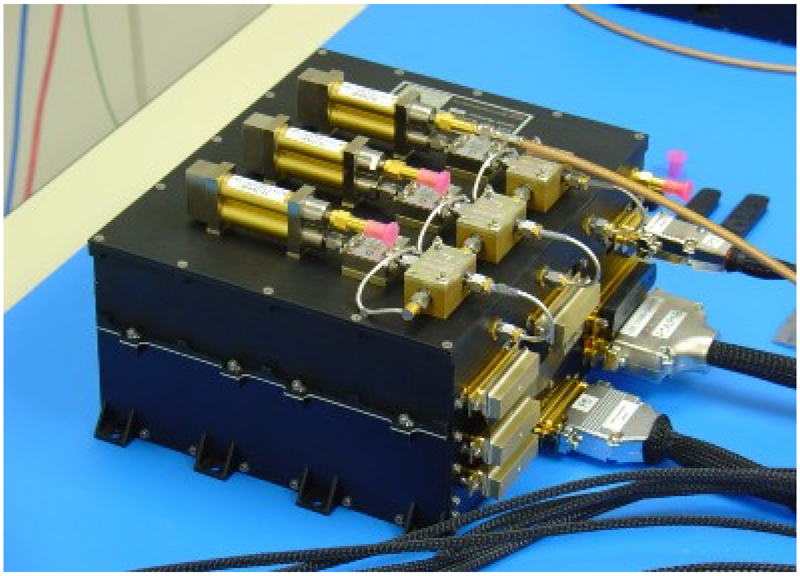

Figure 2. The IGOR (Integrated GPS and Occultation Receiver).

Both IGOR receivers have two redundant boards and are connected to two independent Sensor Systems S67-1575-14 GPS antennas. The antenna series has undergone a pre-flight phase center variation (PCV) calibration at the Institut für Erdmessung of the University Hanover (IfE) (see [6]). In addition, the individual pattern of each of the four antennas was calibrated in-flight using 30 days of GPS observations.

1.3. Accuracy Requirements

The goal of the TanDEM-X mission is to create a global digital elevation model (DEM) with the unprecedented accuracy of 2 m over a horizontal grid of 12 m x 12 m. Therefore the baseline error has to be kept minimal, as a baseline error will not only induce a height error and tilt in the DEM but also a horizontal displacement. The height error Δh which results from a baseline error in line of sight ΔB_{LOS} can be computed by:

$$\Delta h = \frac{h_{amb}}{\lambda} \Delta B_{LOS}, \qquad (1)$$

where λ is the wavelength of the SAR signal and h_{amb}, the height of ambiguity, is a factor depending on the satellite geometry (see [7]):

$$h_{\mathrm{amb}} = \frac{\lambda r_0 \sin\theta}{B_\perp}. \qquad (2)$$

$B_\perp$ is the so-called effective baseline i.e. the vector between the satellites projected on the line of sight, r_0 is the slant range and θ the incidence angle of the data take. At a wavelength of λ = 3.1 cm (X-Band) and a typical h_{amb} = 30 m, a baseline error in line of sight of 1 mm would translate to a DEM height error of 1 m. Furthermore, a baseline error will cause a tilt of the DEM scene, which can be estimated by:

$$\varphi_{\mathrm{tilt}} = \frac{\Delta B_{\mathrm{LOS}}}{B_\perp}. \qquad (3)$$

Assuming a typical $B_\perp$ of 300 m, a baseline error in line of sight of 1 mm would cause a tilt of 0.0002°. This would cause a height variation of 0.1 m over a DEM scene with a swath width of 30 km.

When a raw DEM containing a height error and tilt is geocoded using overlapping raw DEMs and DEMs from former missions (like the Shuttle Radar Topography Mission SRTM), the errors cause a displacement of the DEM (see Fig. 3). The displacement can be estimated by:

$$\Delta x = \frac{1}{\tan\theta} \Delta h, \qquad (4)$$

where θ is the incidence angle (the angle from which the line of sight deviates from the nadir direction). This means, that e.g. during a near range data take under an incidence angle of 27°, the displacement Δx is twice the height error Δh. Hence already a baseline error of 3 mm would cause a height error of 3 m, which could again cause a displacement of 6 m. With a DEM pixel size of 12 m this shift of more than half a pixel would cause the wrong pixels in two raw DEMs to be matched. Therefore, a requirement for the baseline accuracy of 1 mm RMS in 1D was raised.

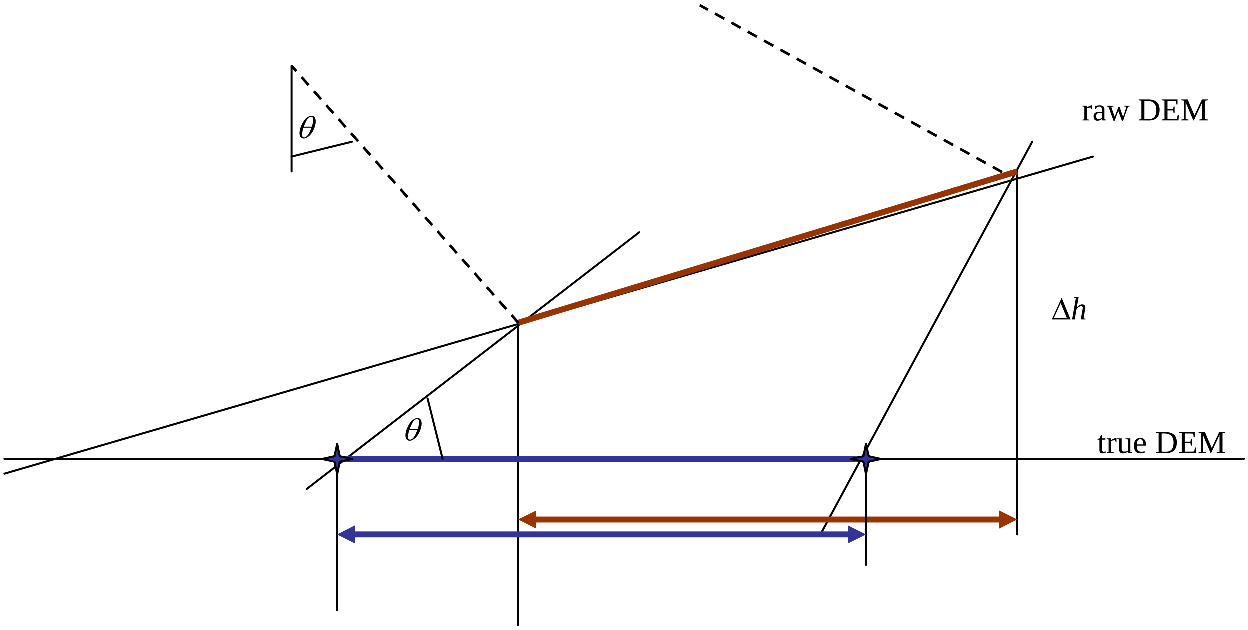

Figure 3. Displacement of a raw DEM due to Height Error and Tilt.

2. Baseline Determination Results

2.1. The Filter for Relative Navigation of Spacecraft (FRNS)

The GSOC/DLR baseline solution is processed with the FRNS software (Filter for Relative Navigation of Spacecraft) developed in cooperation of TU Delft and GSOC/DLR. It is designed to perform a relative orbit determination based on a Kalman filter approach (see [8]). The underlying concept of the FRNS software is to achieve a higher accuracy for the relative orbit between two spacecraft by making use of differenced GPS observations, than by simply differencing two independent precise orbit determination (POD) results. The use of single-differenced code and carrier phase observations rigorously eliminates GPS clock offset uncertainties and largely reduces the impact of GPS satellite orbit and phase pattern errors. Double differences are used for integer ambiguity resolution, which effectively converts the ambiguous carrier phase observations into highly accurate distance measurements.

In addition to a dual-frequency solution the software is as well able to compute single-frequency solutions. Due to the small separation of the two spacecraft, ionospheric path delays are almost identical and are thus eliminated to a large extent by differencing. The single-frequency solution – despite being potentially less accurate than the dual frequency solution – is more robust against ambiguity resolution problems and erroneous GPS observations. Hence it is employed as quality check in the outlier detection during the routine processing of the dual-frequency solution.

2.2. Data and Results

Since the launch of the TDX satellite, both satellites tracked an average of 8.5 satellites per epoch, but in average only 8.1 satellites were tracked simultaneously by both satellites. Figure 4 shows a high dispersion of the daily average, but also a high long-term stability. Nevertheless this is still more, than the 6.5 common observations that were available for GRACE baseline determination.

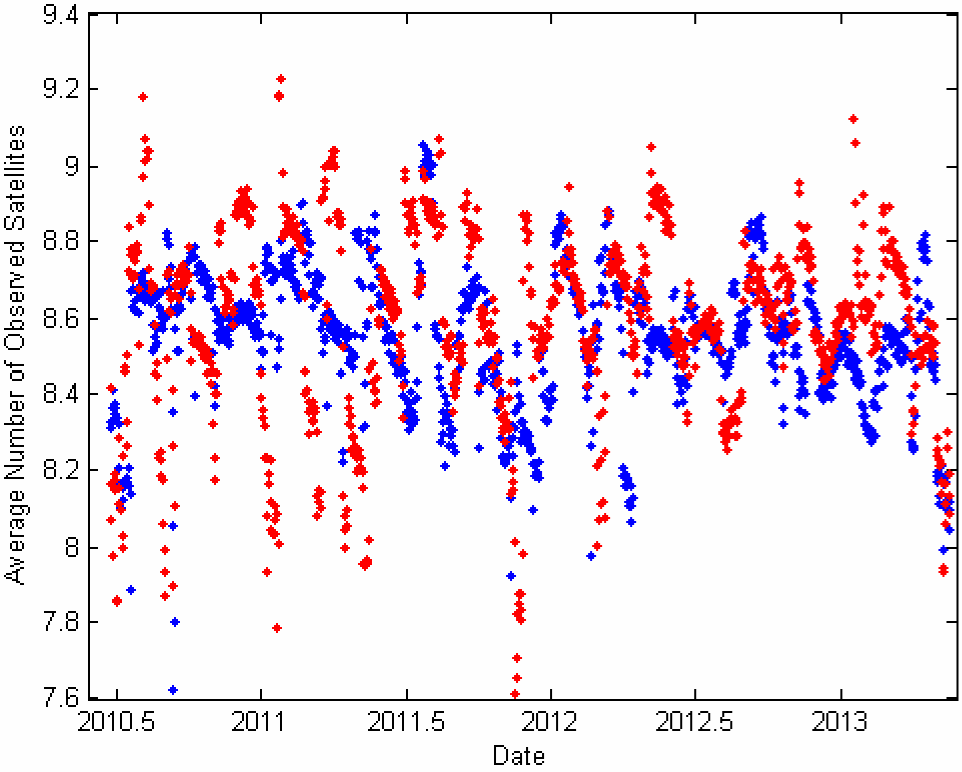

Figure 4. Daily average of number of observed satellites (TSX blue, TDX red).

In order to analyze the quality of the differential GPS measurements, the GPS residuals after the baseline determination are analyzed. After removal of outliers, the pseudorange observations residuals have an RMS of 21 cm on each of the two frequencies. The L1 carrier phase residuals have an RMS of 1.0 mm and the L2 residuals have an RMS of 0.7 mm. A residual plot for DOY 301 is shown in Fig. 6. The carrier phase residuals achieved with data from the GRACE mission (0.9 mm for L1 and 0.7 mm for L2) are slightly better, than those of TanDEM-X. This could be attributed to the fact, that unlike for GRACE, the TanDEM-X receivers are not connected to an ultra-stable oscillator.

The two spacecraft were brought into a wide formation with 20 km separation for commissioning of the radar instrument shortly after the launch of the TDX satellite. During this phase a single-frequency solution was possible, but it showed differences to the dual-frequency solution of 3.5mm (3D-RMS). After the two spacecraft were brought into a close formation with a separation of less than 500 m, the difference was reduced to 2.1 mm (3D-RMS), clearly demonstrating the effect of the differential ionosphere.

In case of maneuvers there are typically differences of up to 10 mm in the along-track and radial components between single- and dual-frequency solutions. Figure 5 contains two pairs of cold gas maneuvers, which are typical for formation control. The first pair occurs between 22:00 h and 24:00 h on 2010/10/27 and the second between 20:00 h and 22:00 h on 2010/10/28. This demonstrates that the handling of maneuvers is difficult for the baseline determination.

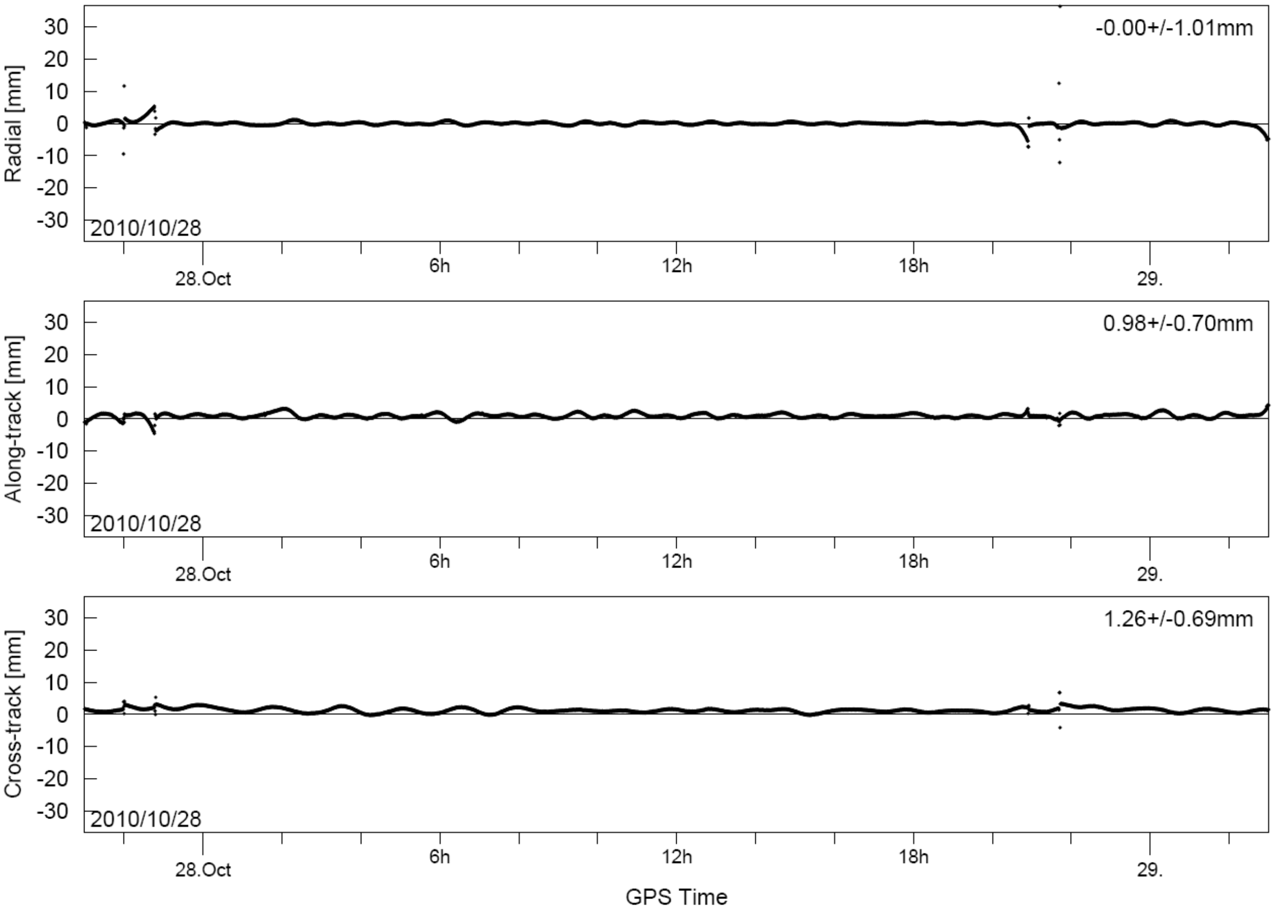

Figure 5. Comparison between single- and dual-frequency solutions for DOY 310/2010.

3. Baseline Calibration and Combination

3.1. Motivation

The FRNS software was developed using data from the GRACE mission as it was the only available data source of a dual-satellite formation with high quality GPS data. In addition the GRACE mission operates a K-band ranging instrument to determine the distance between the two spacecraft with an accuracy that is at least one order of magnitude higher than any GPS-based ranging. Hence the K-band measurements were used to asses the quality of the relative navigation results and an accuracy of 0.7 mm was achieved (see [9]). This verification method has two drawbacks. First, the K-band instrument of GRACE is only sensitive in the along-track direction. This is the least important direction for the TanDEM-X mission, which is only sensitive to errors in the radial and normal direction. Second, the GRACE K-band observations are inflicted with an ambiguity and thus measures only range-changes, but not absolute ranges.

In order to get a better prediction of what level of accuracy can be expected, a comparison with an independent software package, the Bernese GPS software developed at the Astronomical Institute of the University Bern (AIUB) was performed (see [10]). This led to the conclusion, that biases of several mm per component can be expected between independent solutions. Hence the requirements for TanDEM-X would have been violated. In order to compensate that deficiency, a baseline calibration and combination process was installed.

3.2 Baseline calibration

As mentioned in section 1.3, an error in the baseline vector causes an error in the DEM model. The baseline calibration process is based on the idea that by acquisition of calibration data takes over test sites where accurate height information is already available conclusions on the baseline error can be drawn. Equation 1 shows, that there is a direct relation between the baseline error in line of sight and the DEM height error. When the test sites are covered by several data takes under different incident angles, a separation between baseline errors in radial and normal components is possible. This method is not suitable to detect baseline errors in the tangential component, as data takes are always acquired perpendicular to the flight direction. But for the same reason, the DEM generation is not sensitive to baseline errors in the tangential component.

For the operational baseline calibration, test sites distributed over the whole Earth have been selected carefully. In order to avoid the coupling of ground range displacements with height errors, test sites of extremely flat regions with little vegetation have been selected. Furthermore in these regions a sufficient number of height points from the ICESat mission were available. Over these test sites several hundred calibration data takes were acquired and processed with highest priority. The data takes were taken continuously in order to detect a variation in the baseline errors. For the GSOC baseline computed with the FRNS software a bias of 1.9mm with a standard deviation of 1.1mm in radial direction and a bias of -1.9mm with a standard deviation of 1.3 mm in normal direction was detected (see Fig. 6). The biases seem to be very stable over the whole mission. For a detailed description of the calibration process see [11].

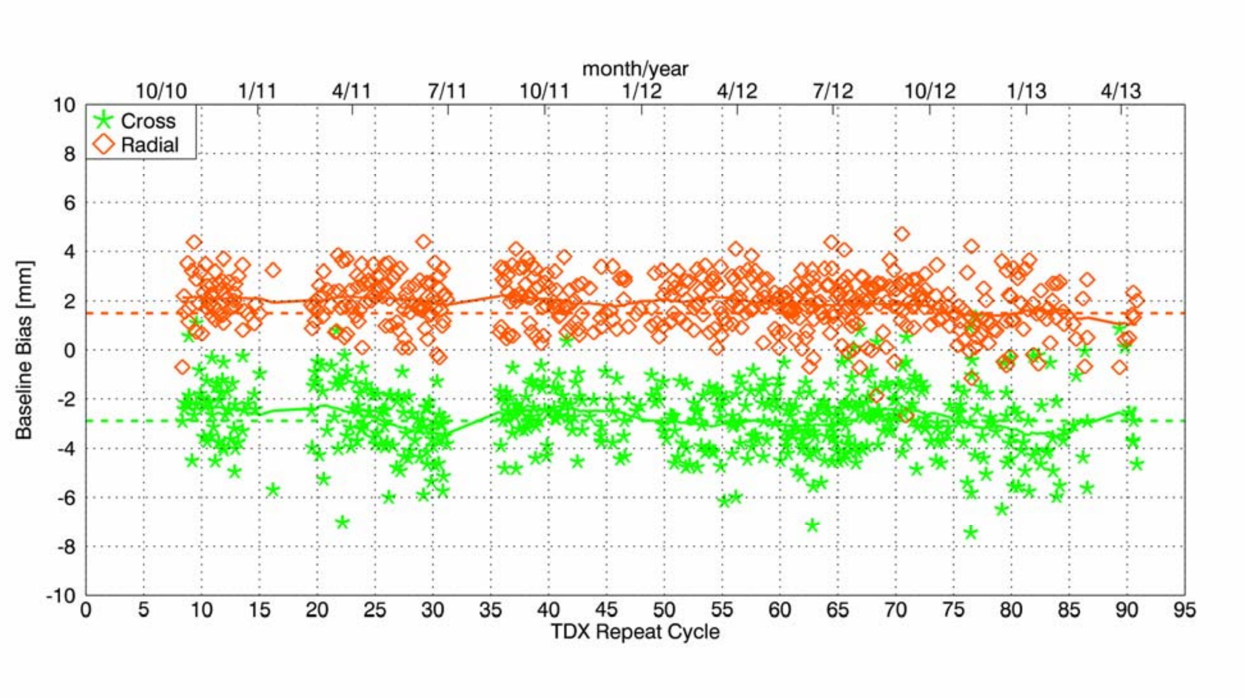

Figure 6. Development of the FRNS baseline bias.

3.3 Baseline combination

In order to further reduce the baseline error, three different solutions from independent software packages are computed and combined to a final product. Two solutions are computed by the primary baseline provider GFZ with the EPOS (see [12]) and Bernese (see [13]) software packages and one is computed by GSOC/DLR with the FRNS software. According to the law of error propagation, the noise should be reduced by the factor $\sqrt{N}$, where N is the number of combined solutions, in case the solutions are completely independent. An internal study using GRACE data showed that the combination of two products reduced the error by a factor of 1.25. This shows that the solutions are not completely independent as the same input data is used. Nevertheless a significant improvement of the final solution can be achieved, especially with three solutions.

In addition to an error reduction, the availability of three independent solutions provides an outlier detection mechanism. The baseline calibration process operated at GFZ compares all three solutions. If the differences between three solutions are within a certain threshold, all three solutions contribute to the final product. If one solution differs from the other two, it is rejected from the combination. In case all three solutions differ, operators are informed in order to re-evaluate the solutions. In the figures 7-9, the daily comparisons of the products from the start of the close formation are shown. It can be seen, that the biases between the solutions can be considered constant at the level of a few mm over the whole mission. The statistics of this comparison are given in Tab. 1.

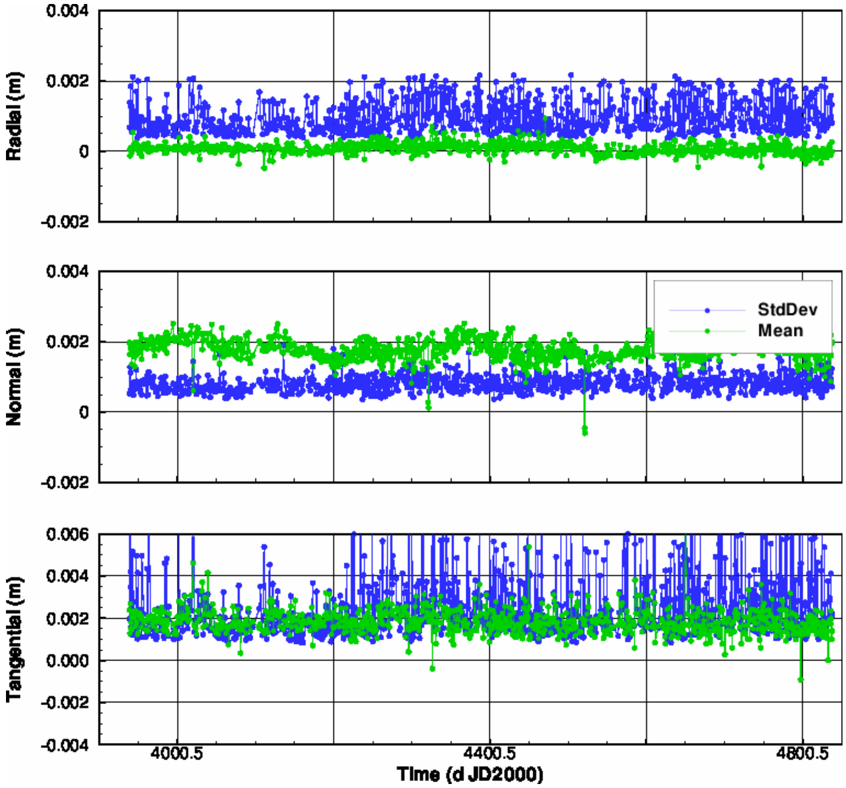

Figure 7. Comparison between EPOS (GFZ) and FRNS (GSOC).

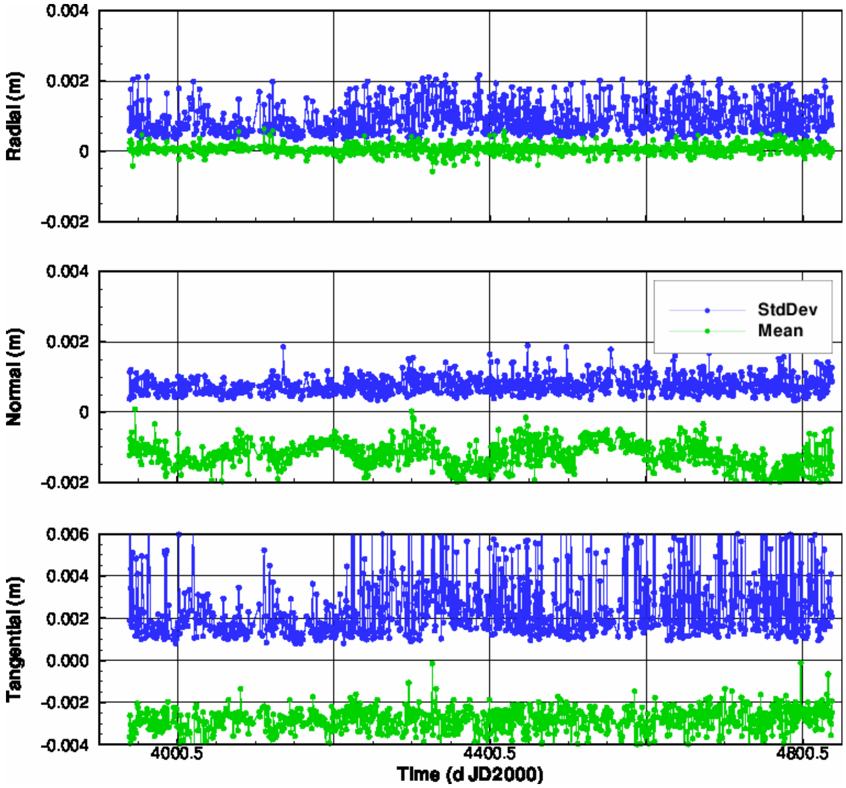

Figure 8. Comparison between Bernese (GFZ) and EPOS (GFZ).

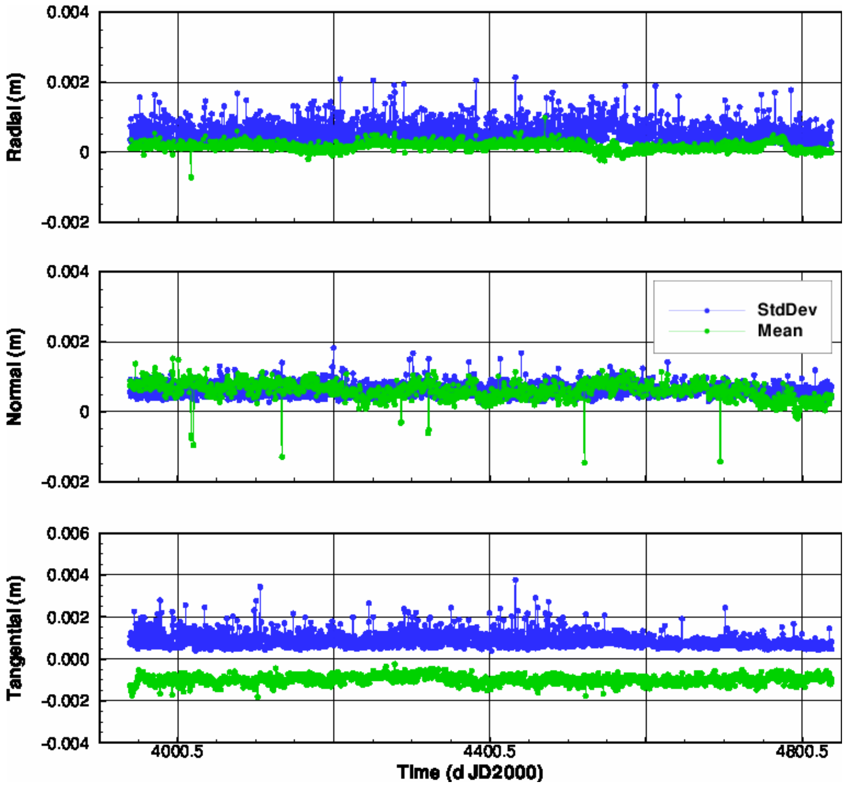

Figure 9. Comparison between Bernese (GFZ) and FRNS (GSOC).

Table 1. Statistics of the Baseline Comparison.

	Radial [mm]	**Normal [mm]**	**Tangential [mm]**	**Samples**
FRNS – EPOS	+0.1 ± 1.1	+1.8 ± 0.9	1.8 ± 3.4	41,204,128
EPOS – Bernese	+0.1 ± 1.0	-1.2 ± 0.8	-2.8 ± 3.4	41,226,133
FRNS - Bernese	+0.2 ± 0.7	+0.6 ± 0.7	-1.0 ± 1.0	74,593,680

4. Conclusion

Prior to the mission, it was not sure, if the requirements on baseline accuracy of 1 mm, 1D-sigma, can be met. It was shown, that the GPS data quality remains constantly on a high level. The routine baseline comparison has helped to assess the precision of the three individual baseline products and to identify systematic offsets between them. Since all baseline products employ identical GPS data sets, these offsets are mainly attributed to different processing concepts (such as ambiguity resolution and reduced dynamic vs. dynamic trajectory models) in the employed software packages. Systematic biases of at most 2 mm can be observed in cross-track direction, while biases in radial direction are about ten times lower. Compared to use of a single baseline product, the combination of multiple baseline solutions has, furthermore, helped to reduce the overall noise and to identify erroneous contributions. On the other hand, the GPS-derived baseline can at best deliver accurate information on the relative position of the two spacecraft but is insensitive to potential errors in the adopted SAR antenna phase centers or uncalibrated differential delays between the two instruments. SAR calibration data takes have therefore been used to determine the effective biases of baseline products and instrumental effects in the SAR processing chain. While it is still not possible to exactly quantify the accuracy of the final calibrated baseline products, its use in DEM-processing has proven, that it is of fully acceptable quality to reach the demanding mission goal.

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