TERRASAR-X RAPID AND PRECISE ORBIT DETERMINATION

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ABSTRACT

TerraSAR-X is a German Synthetic Aperture Radar (SAR) satellite that has been placed into orbit in mid 2007 and is since then collecting SAR imagery on a routine basis. To support the TerraSAR-X navigation needs, the satellite is equipped with two independent GPS receiver systems. The German Space Operation Center is providing several orbit products with different latencies and accuracy levels to support the scientific mission goals.

In this paper, the different orbit products provided by GSOC are described and evaluated. The quality is assessed using internal quality checks, external data from satellite laser raging (SLR) and a comparison with orbits computed by the Astronomical Institute of the University of Bern. Furthermore prospects for high accuracy low-latency orbit determination of LEO satellites are discussed based on tests conducted with RETICLE GPS real-time clock data.

1. THE TERRASAR-X MISSION

TerraSAR-X is a German radar satellite mission, which is realized as a public-private partnership between the German Aerospace Center (DLR) and EADS Astrium GmbH. Its observation technique for the acquisition of radar images of the Earth's surface is synthetic aperture radar (SAR). The satellite is controlled by the mission operations segment (MOS) which is located at the German Space Operations Center (GSOC). Among the various tasks of the MOS are the rapid and precise orbit determination (ROD and POD) of the spacecraft.

The satellite was launched on a DNEPR rocket on June 15th 2007 from Baikonur in Kazakhstan and is now more than two years in orbit. The satellite is flying in a sun-synchronous dusk-dawn orbit at an altitude of 514 km and at a near-polar inclination of 97.44°. The orbit has a pre-defined Earth-fixed reference orbit, which closes after a repeat cycle of 167 revolutions in 11 days. It is task of the MOS to maintain the satellite within 250 m in cross-track direction of this reference orbit, in order to enable the precise planning of radar data-takes of certain scenes.

The satellite has a length of 5 m, a diameter of 2.4 m and weighs about 1300 kg. During nominal operations, the SAR antenna is oriented with an angle of 33.8° degrees off the nadir direction looking right of the flight direction. In order to point the radar payload to dedicated target areas on the Earth's surface (e.g. the poles), the satellite has to be occasionally rotated to the so-called "left-looking mode", where the SAR antenna is oriented with an angle of 33.8° off the nadir direction to the left.

Fig. 1 The TerraSAR-X satellite (courtesy by EADS Astrium).

2. ON-BOARD GPS RECEIVERS

TerraSAR-X is equipped with two space-qualified GPS receivers. The MosaicGNSS receiver designed by EADS Astrium is a single-frequency receiver, which fulfils the role of providing onboard timing and a basic orbit determination for attitude and orbit control. The precise orbit determination for scientific use e.g., processing of SAR images is done using the dual-frequency Integrated Geodetic and Occultation Receiver (IGOR). The IGOR receiver was developed by Broad Reach Engineering and JPL, and is a follow-on of the BlackJack GPS receiver. It is part of the Tracking, Occultation and Ranging (TOR) Instrument [1] provided by GFZ Potsdam, which includes an occultation antenna and a laser ranging reflector (LRR) as well.

2.1 <u>The MosaicGNSS Receiver</u>

As shown in Fig. 2, the antennas of the MosaicGNSS receiver are not pointing in zenith direction, but have an angle of 33.8° to the left of the flight direction. This antenna boresight angle results in an asymmetric tracking as illustrated by Fig. 3, as more satellites to the left can be tracked by the antenna. The slanted boresight axis is commanded to the receiver to allow it to track satellites, which would be below the horizon in case of a zenith-oriented antenna mounting. It can also be observed in Fig. 3, that satellites are tracked at lower elevations in the backward sector than in the forward. This is due to the fact, that satellites are often acquired only after they have reached a higher elevation, but are tracked until they descend below horizon.

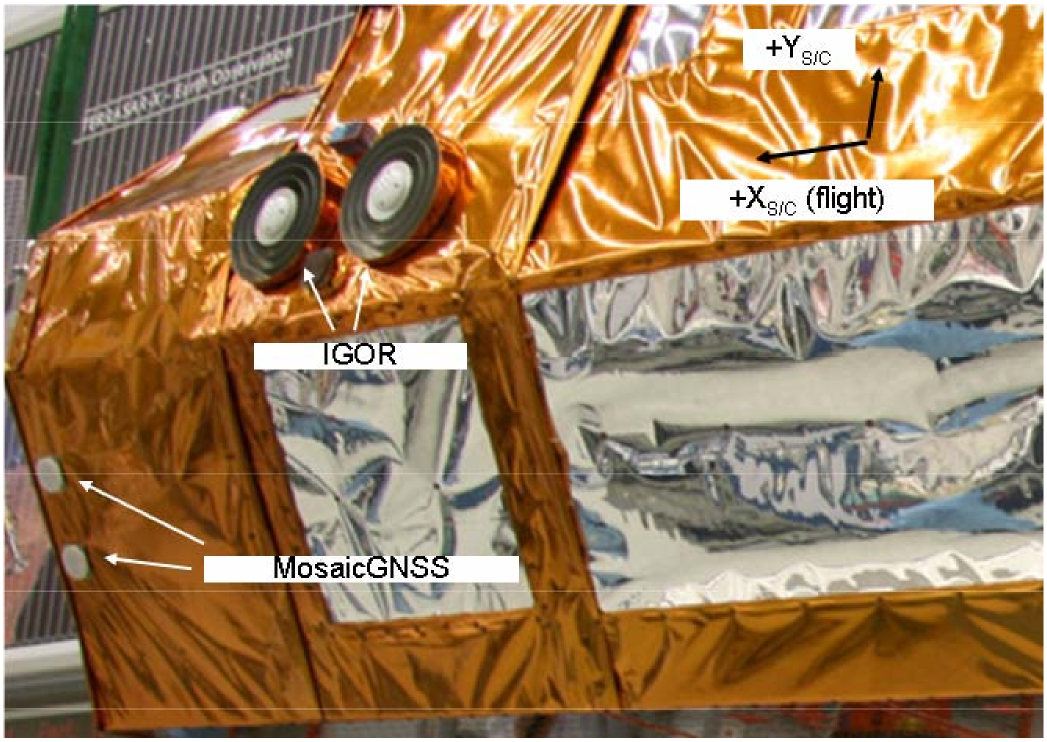

Fig. 2 The TerraSAR-X GPS Antennas (courtesy by EADS Astrium).

The MosaicGNSS receiver has 8 channels for tracking. Fig. 3 shows the distribution of actively tracked satellites over time for July 1st 2009 (which is representative for the whole mission). It can be seen, that more than half of the time 6 satellites are tracked. For more than 99% of the epochs, the necessary minimum number of 4 satellites for point-positioning can be observed. The maximum of 8 satellites is almost never reached.

2.2 <u>The IGOR Receiver</u>

In contrast to the MosaicGNSS receiver, the IGOR receiver is a dual frequency receiver and can track up to 16 satellites. In nominal operations, 12 dual-frequency channels are reserved for navigation purposes, while the remaining channels are available for the tracking of rising and setting occultations. The IGOR antennas are mounted "on top" of the satellite and their boresight is nominally pointing in zenith direction. Hence the pattern of tracked satellites shown in Fig. 4 is more regular than that of the MosaicGNSS receiver (see Fig. 3). It can be seen, that a cut-off elevation of 10° has been set, but in some cases satellites are tracked until they descend below the horizon.

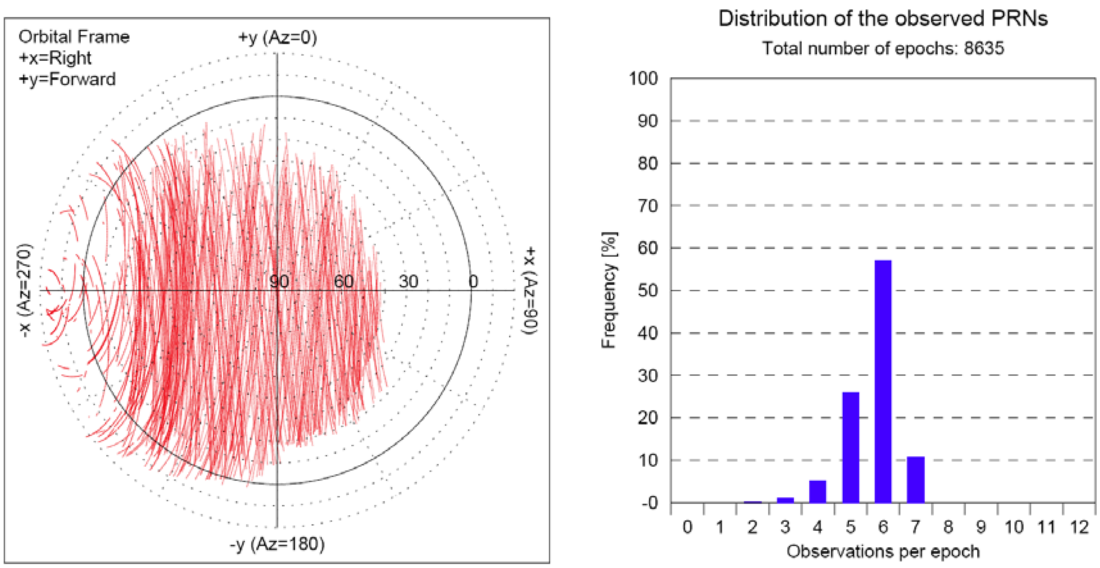

Fig. 3 Skyplot (left) and statistical distribution (right) of satellites tracked by the MosaicGNSS receiver on July 1st 2009.

The distribution of observed satellites shows, that in most cases eight or even more satellites are tracked but only in rare cases all 12 channels allocated for navigation are actually used. In general, the number of observed satellites is significantly larger than that of the MosaicGNSS receiver.

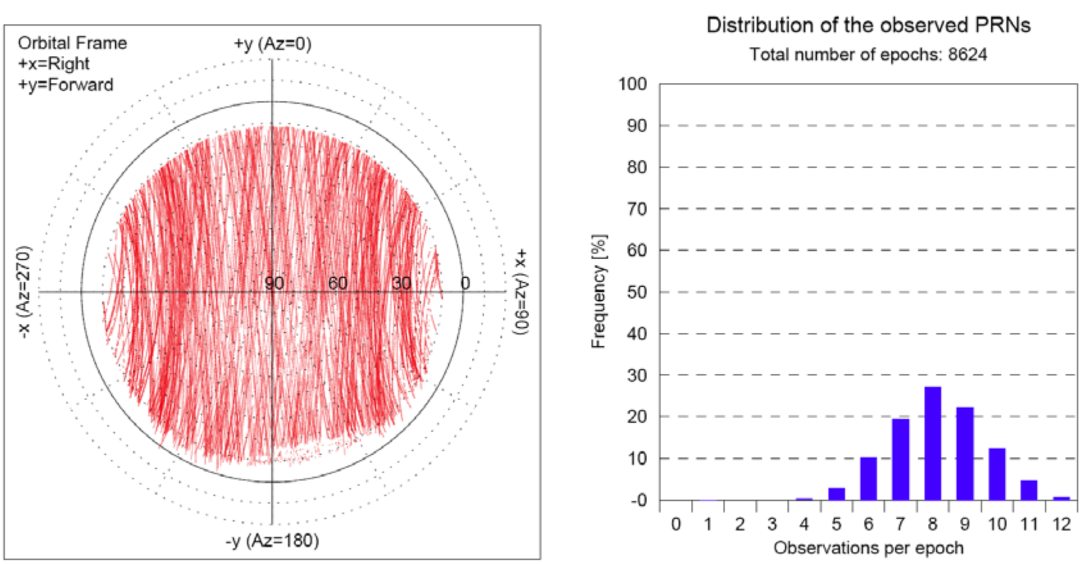

Fig. 4 Skyplot (left) and statistical distribution (right) of satellites tracked by the IGOR receiver on July 1st 2009.

3. ORBIT DETERMINATION

GSOC is nominally providing four different types of orbit products: *quick look* orbits, *predicted* orbits, *rapid* orbits and *science* orbits. The first three are routinely delivered after each ground station contact during which GPS data was dumped, while the latter is computed once for each calendar day with a latency of several days. In addition to those four official orbit products, two further orbit products are computed on a regular basis: a *backup* orbit using observations from the MosaicGNSS receiver and an experimental orbit product using *real-time* GPS ephemerides computed by DLR/GSOC.

The *quick look* orbit is computed immediately after the GPS data dump of a ground station contact has been received. Its purpose is to provide an orbit solution as soon as possible after data reception. Hence the latency of the *quick look* product is only about 15 minutes. The solution is computed on basis of the navigation solution of the IGOR data by GSOC's orbit determination software ODEM [2]. The navigation solution computed onboard is a single frequency solution with an error of about 10 m. This error is mainly caused by an uncorrected ionosphere and the use of broadcast ephemerides. The ODEM software uses the positions of the navigation solution as pseudo-observations and fits them with a dynamic model. By this method, the orbit position error is reduced to about 3 m.

The *predicted* orbit is computed based on the *quick look* orbit by orbit propagation. It covers 24 h into the future, starting from the last GPS observation. This propagated orbit is necessary for a precise planning of maneuvers and radar data-takes (especially timing) and near real-time (NRT) SAR data processing.

The *rapid* orbit is - contrary to the *quick look* orbit - not based on the navigation solution, but on the raw GPS observations of the IGOR receiver. This means, that the GPS observations are reprocessed on ground using precise orbit determination (POD) software GHOST [3] (GPS High Precision Orbit Determination Software Tool). The rapid orbits are used for a preliminary processing of radar data-takes with short latency after the acquisition of the data-take. Therefore the POD software has to collect various auxiliary data, like real-time GPS ephemerides, attitude information from the satellite's star sensors (which are normally down linked during the same ground station contact as the GPS data) and physical model parameters (e.g. Earth rotation parameters or flux data). In order to be able provide the *rapid* orbit products with a latency of about one hour after data reception, JPLs commercial real-time-GPS ephemerides (RTG) are used for the *rapid* orbit determination.

The *science* orbit is processed using the same software and algorithms as the *rapid* orbits, but with two significant differences. *Science* orbit products are computed with a latency of several days over a well defined time span. They are computed for each calendar day including a 3 hour overlap with the previous and the following day. The latency of several days allows the use of high-quality scientific GPS ephemerides provided by the Center for Orbit Determination in Europe (CODE). This has a significant impact on the overall quality of the orbit product. The *science* orbits are used for a final processing of data-takes.

Similar to the *rapid* orbits, a *backup* orbit is computed after each ground station contact using the GPS raw observations from the MosaicGNSS receiver. As it is a single frequency receiver, the ionosphere free GRAPHIC (Group and Phase Ionospheric Correction) combination (½ (C1 + L1)) of code and carrier phase measurements is used as observation. As shown below, the accuracy of these orbits is much lower, than that of the dual-frequency solution obtained using IGOR observations. Hence the product is computed only for monitoring purposes and used as backup for the rare cases of IGOR data gaps.

In order to demonstrate the *near real-time* capability of the POD system, an experimental orbit has been generated as well. A data arc of 12 hours has been utilized and the POD process has been started every 90 minutes, which closely corresponds to the orbit period of TerraSAR-X. The GPS ephemerides used for the experimental orbit stem from GSOC's Real-Time Clock Estimation (RETICLE) system, which provides clock offset estimates based on GPS orbit predictions [4]. The GPS observations processed by RETICLE's Kalman-Filter originate from a global tracking network with approximately 35 stations, most of them are part of the official IGS tracking network. All stations transmit their measurements in real-time via NTRIP with a latency of 2-3 seconds. RETICLE then computes clock offset estimations with an update rate of 10 seconds. The results are disseminated online via data streams with a total latency of about 5-6 seconds for real-time users. Additionally, the products are provided on an ftp-server with a latency of 5 minutes for near real-time applications like precise satellite orbit determination. The orbit determination procedure of the experimental orbit has been implemented as an offline process for this analysis. However, it could also be performed in near real-time, provided that the GPS observations from the IGOR receiver are dumped once per orbit to a downlink station at high latitudes.

Table 1 Overview of different Orbit Products

Product	Data	Frequency	Latency	Coverage
quick-look	IGOR navigation (Mosaic GNSS nav. as backup)	3-5 times a day	15 min	~ 6 hours
predicted	quick-look	3-5 times a day	30 min	24 hours (future)
rapid	IGOR raw	3-5 times a day	1 hour	> 12 hours
science	IGOR raw	once per day	5 days	30 hours
backup	MosaicGNSS raw	3-5 times a day	1 hour	> 12 hours
near real-time	IGOR raw	once per revolution	1 hour	12 hours

The POD processed with the GHOST software [3] - for the computation of *rapid* and *science* orbits as well as *backup* and near *real-time* products – is executed in three steps:

- First a coarse single point positioning is derived with the SPPLEO tool. It computes kinematic positions from pseudorange observations without need for a priori orbit information. This results in an orbit solution containing data gaps and relatively large position noise.
- Hence in the second step a least-squares adjustment of a dynamic trajectory is computed from the single point positions by the PosFit tool. The result is a smooth and continuous trajectory which serves as a priori input for the final step.
- The final step is the reduced dynamic orbit determination (RDOD) with a batch least squares estimator. The a priori orbit generated by PosFit is used for data editing. The process estimates the initial state vector and parameters of force models like drag or solar radiation pressure. In addition to those model parameters, empirical accelerations over constant intervals are estimated in order to allow for a better fit to the data.

The TerraSAR-X satellite has an active orbit control. In order to stay within 250 m from the reference orbit, frequent orbit maneuvers are necessary. During the first two years of the mission, one maneuver was necessary every 2-3 weeks [5], but in times of higher solar activity one maneuver per 1-2 days could become necessary. Those maneuvers have a significant impact on the trajectory, and the GHOST software is able to take them into account and estimate the velocity change.

All orbit products must pass a quality check prior to delivery. The only external data source, that could be used for orbit verification are satellite laser ranging (SLR) observations. But as they are only available wit a latency of up to one day, they cannot be used to verify *rapid* orbit products prior to their delivery. Hence only internal quality checks can be applied. One important criterion are GPS residuals. If the carrier phase residual RMS for IGOR observations exceeds 25 mm for *rapid* or 10 mm for *science* orbits, the product is not delivered.

4. QUALITY ASSESSMENT

As mentioned in Sec. 3, satellite laser ranging (SLR) observations are the only independent way to assess the quality of an orbit product. However their significance is limited, as the SLR stations are sparsely and irregularly distributed over the Earth, and the observations individual SLR stations have an inhomogeneous quality. Hence some internal quality checks like GPS residuals, overlap analysis and comparisons between the different product types are presented here.

4.1 GPS residuals

The GPS residuals are the difference between the GPS observations and the computed orbit. They show how well the actual observations fit to the estimated orbit. For the products computed from IGOR raw observations (*rapid*, *science* and *near real-time*) the residuals can be computed for the ionosphere-free combinations of pseudorange and carrier phases. The residuals are shown in Fig. 5 exemplarily for the *science* product on July 1st 2009. For the *backup* product computed using MosaicGNSS observations the residuals are computed for the GRAPHIC combination (see Fig. 6).

Table 2 lists the RMS error of all residuals computed over the whole July 2009. It can be seen, that the GRAPHIC observations from the MosaicGNSS receiver have by far larger residuals than the IGOR pseudorange and carrier phase observations. Hence the MosaicGNSS receiver is only used as *backup*. The residuals of the *science* product are smallest – which was expected, as the most effort went into the preparation of auxiliary data – especially the GPS ephemerides. It can be seen as well, that the carrier phase residuals of the experimental *near real-time* product are smaller than those of the *rapid* product. This suggests the use of the employed RETICLE GPS ephemerides also for the generation of the *rapid* product.

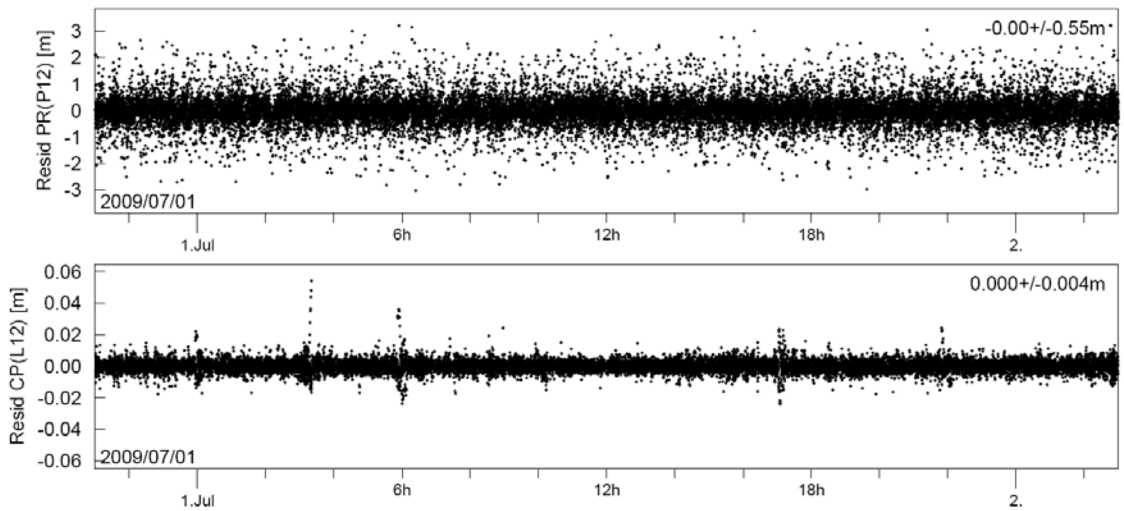

Fig. 5 Ionosphere Free Pseudorange and Carrier Phase Residuals of the *science* product on July 1st 2009.

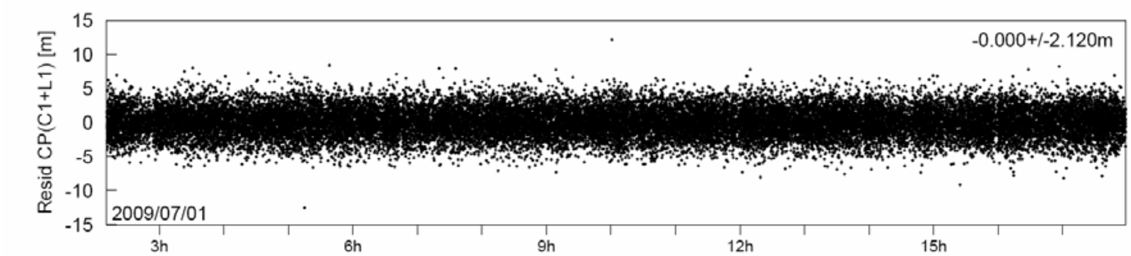

Fig. 6 GRAPHIC residuals of the *backup* product for the MosaicGNSS receiver on July 1st 2009.

Table 2 GPS residuals of the different orbit products.

Product	Pseudorange (P1/P2)	Carrier Phase (L1/L2)	GRAPHIC (L1/P1)
rapid	0.611 m	16.6 mm	
science	0.555 m	3.9 mm	
backup			2.136 m
near real-time	0.614 m	6.3 mm	

4.2 Overlap Analysis

All precise orbits are generally computed with an overlap of at least three hours to the previous orbit. A comparison of the overlap period of two consecutive orbits yields a good consistency check, which allows the detection of severe processing errors. Additionally it can be used as an internal measure of the orbit quality. In order to remove edge effects, always the first and last hour of the overlap period is neglected. A daily *science* orbit arc for example, is always computed over 30 hours from 21:00 of the previous day to 3:00 of the following day. This results in an overlap period of 6 hours, of which only 4 hours are considered in the overlap analysis. Fig. 7 shows the overlap between 22:00 on July 1st 2009 and 2:00 on July

2nd 2009 in radial – along-track – cross-track coordinate system. It shows that the difference stays well below 1cm in each component.

Table 3 lists a statistic of all overlap periods of all products in July 2009. The numbers are not an absolute quality measure, but rather an indicator of internal consistency. It can be assumed, that an orbit type with better internal consistency has a higher absolute accuracy. All orbits derived with IGOR observations reach an internal consistency of better than 1cm, while the *backup* orbit derived from MosaicGNSS observations reaches only 70cm. Here again, the *science* orbits show the best results followed closely by the *near real-time* product.

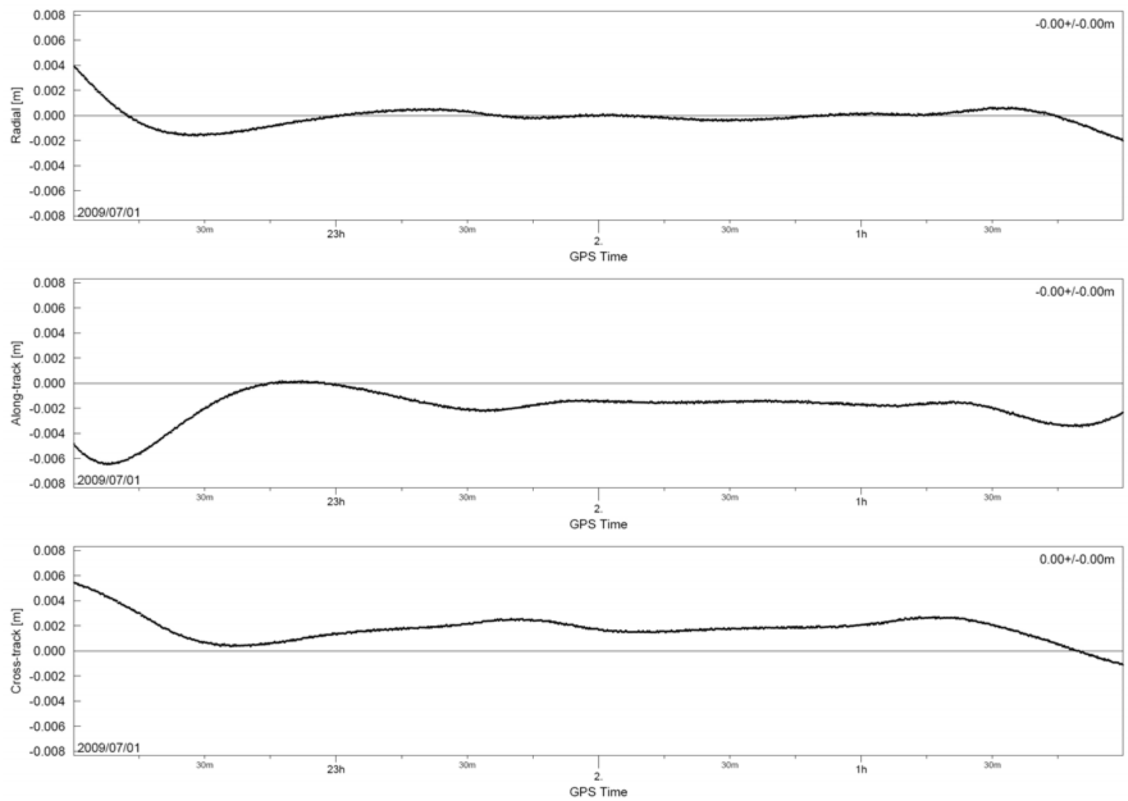

Fig. 7 Overlap between *science* orbits of July 1st and 2nd 2009 in RTN system.

Table 3 Overlap statistics for different orbit types in July 2009.

Product	Radial	Along-Track	Cross-Track	3D-RMS
rapid	3.7 mm	6.3 mm	4.8 mm	8.8 mm
science	1.0 mm	2.8 mm	1.6 mm	3.4 mm
backup	245 mm	604 mm	234 mm	693 mm
near real-time	1.5 mm	4.0 mm	1.5 mm	4.5 mm

4.3 Comparisons with respect to Science Orbit

In order to compare the quality of the two orbit products – *rapid* and *near real-time* – with short latency, they are compared against the *science* orbit. The *science* orbit is supposed to be more accurate than *rapid* and *near real-time* orbits due to the use of highly accurate GPS ephemerides. Hence it can serve as quality measure to evaluate the other orbit products.

Each dot in Fig. 8 shows the RMS difference between one *rapid* (blue) or *near real-time* orbit solution and the corresponding *science* orbit. It becomes clear, that on the one hand the *near real-time* orbit matches the *science* orbit significantly better than the *rapid* orbit. But on the other hand the *near real-time* orbit shows two large gaps in which the RETICLE GPS products were not operationally available.

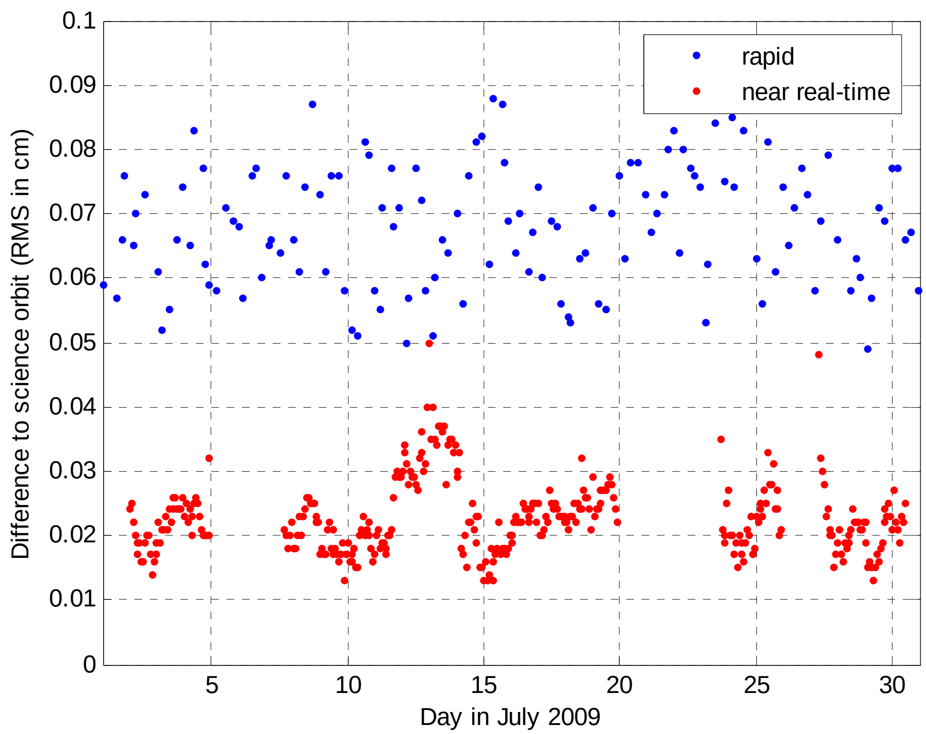

Fig. 8 Comparison of *rapid* and *near real-time* with *science* orbit (RMS in cm).

4.4 SLR Residuals

The TerraSAR-X satellite is equipped with a laser ranging reflector as part of the TOR instrument [1]. The satellite is tracked by satellite-laser-ranging stations. SLR residuals are the difference between the observed distance and the computed distance between the satellite and the laser ranging station. Fig. 9 shows the residuals for the *science* orbit in July 2009. Over the whole month only 4849 usable SLR observations were made, as the satellite is only tracked during a few passes per day. In addition the observation is only one-dimensional in direction of the line of sight.

It is common to compute SLR residuals with a cutoff elevation of 10° and 50°. With a cutoff elevation of 10° generally more observations are taken into account, making the result more robust. As a downside observations with lower elevations have normally larger errors (due to atmospheric disturbances), which degrades the result. Choosing a cutoff elevation of 50°, one will only take observations into account, which are near the radial direction. This allows – at least to some extent – to separate the radial orbit error from the other components.

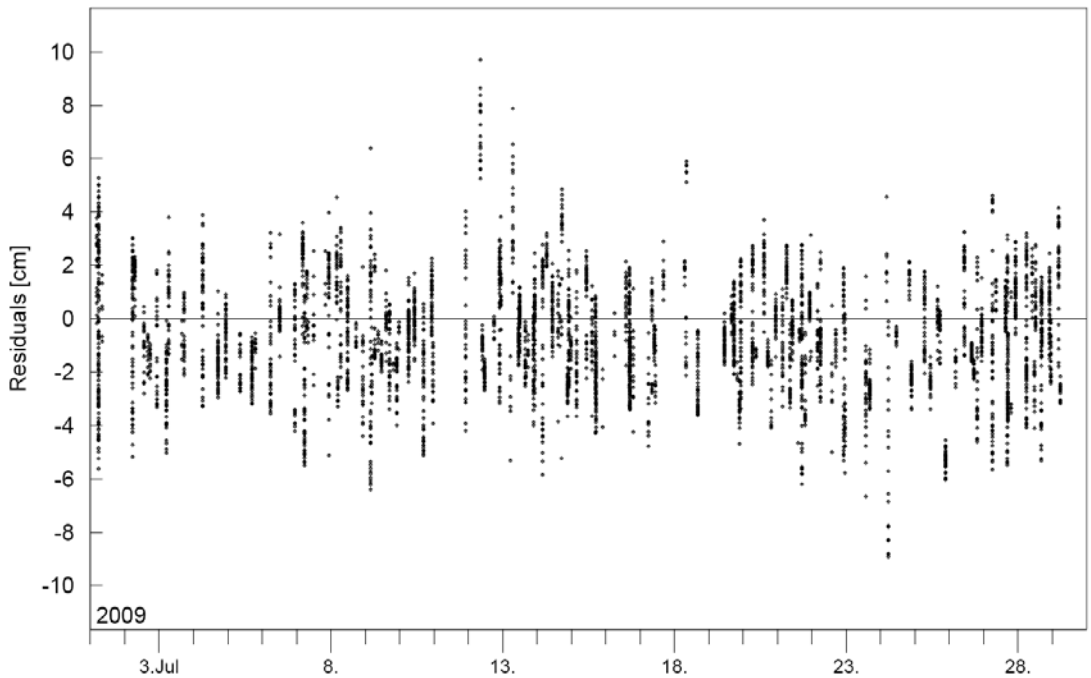

Fig. 9 SLR residuals for *science* orbit in July 2009 – 4849 points.

Table 4 lists the SLR residuals for the different orbit products over July 2009. As mentioned above, these values are the RMS errors of a one-dimensional measurement. In order to estimate the overall 3D-accuracy in a conservative guess, one can multiply the listed values by the square root of 3. Hence one can state, that the accuracy of *science* orbits is about 5cm, the accuracy of *rapid* orbits 10cm and that of *backup* orbits about 1m. Here again the residuals of the *near real-time* orbit come close to those the *science* orbit.

Table 4 SLR residuals over July 2009.

Product	**10° elevation**	**50° elevation**
rapid	4.6 cm	3.1 cm
science	2.2 cm	2.1 cm
backup	49.2 cm	43.2 cm
near real-time	2.4 cm	2.1 cm

4.5 Inter-Agency comparison

The *science* orbit product is validated against an independent solution computed by the Astronomical Institute of the University of Bern (AIUB) using the *Bernese GPS Software* [6]. The test comprises 11 days in late 2007 (Sep. 27th to Oct. 7th). The overall RMS difference between the two solutions is 2.5 cm. This result shows a good agreement between the two independent software packages and confirms the results of the quality assessment above. In Fig. 10, the difference is displayed in radial, along-track and cross-track components for one exemplary day. It can be seen, that there is an offset of about 1cm in all three components. This offset is yet unexplained but might origin in a different treatment of systematic effects in the two software packages.

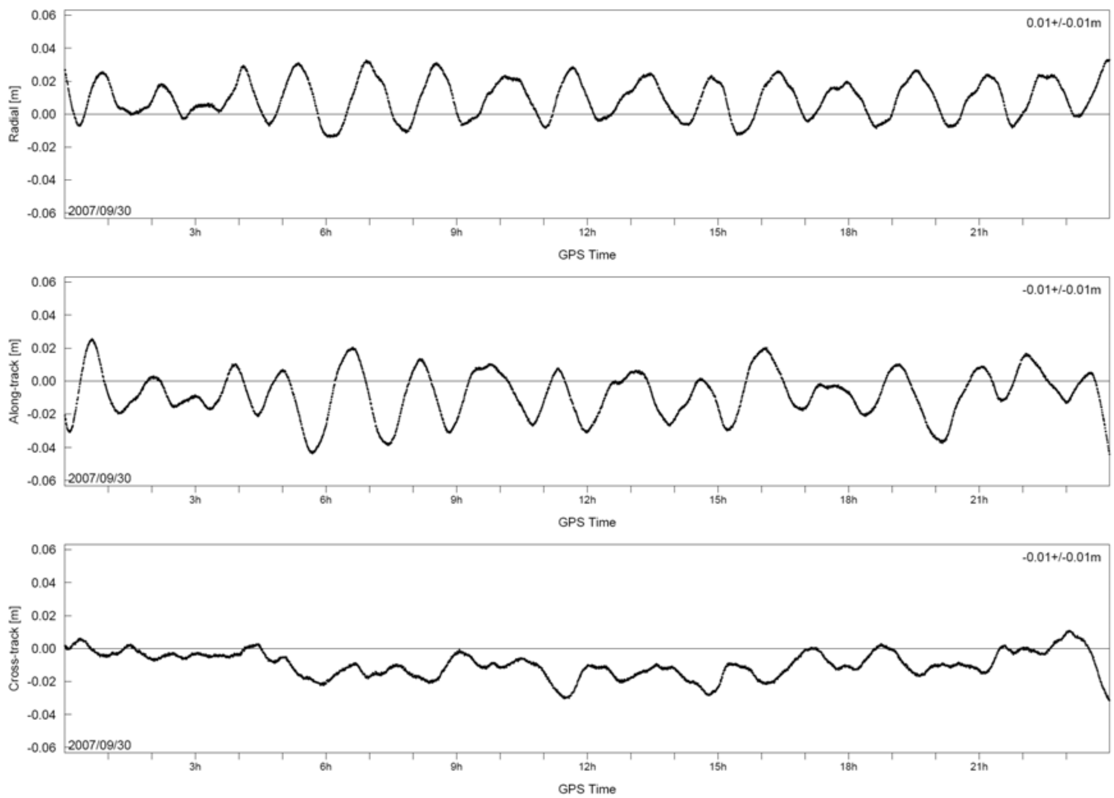

Fig. 10 Difference between GSOC and AIUB orbit solution on Sep. 30th 2007.

5. OUTLOOK

5.1 Near Real-Time Processing

As shown in Sec. 4, the use of RETICLE GPS ephemerides yields very good results considering their availability in real-time. This suggests their use for the generation of the *rapid* orbit product on a routine basis. For this purpose, the redundancy of the system will be improved to eliminate possible single point failures along the complete processing chain from the real-time GPS station via the clock estimation filter to the end user of the products. Setting up two clock estimation processes in parallel, for example, prevents interruptions in the clock estimation which are caused by reconfigurations of RETICLE.

The offline analysis for the near real-time products provided in this paper has demonstrated the capabilities of the POD software system for this task. What remained untested is the downlink GPS receiver's raw data and timely delivery of the pre-processed observations to the POD facility. For testing this part of the processing chain as well, the employment of a ground station close to the polar region is necessary. This would allow a contact during each revolution followed by the immediate processing of the down-linked GPS data.

5.2 TanDEM-X

For the end of 2009, the launch of TanDEM-X (TerraSAR add-on for digital elevation models) is scheduled. The TanDEM-X satellite is an almost identical twin of TerraSAR-X. Both satellites will fly in close formation with distances of less than 1km, with the goal to acquire a global digital elevation model by stereo radar data takes.

This means, that GSOC will provide the same orbit products for TanDEM-X as well. In addition, the processing of stereo data takes with highest precision requires the baseline between the two SAR antennas to be known as precisely as possible. In order to keep the height error of the DEM below 1m, the error of the baseline projected on the line of sight should not exceed 1mm (1D-RMS). The baseline product will be independently delivered by GFZ Potsdam and by GSOC.

GSOC's software for relative navigation FRNS, has so far been only tested on data from the GRACE mission. This test shows that the accuracy of 1mm can be reached, but unknown biases remain. The GRACE satellites are separated by more than 200km, while TerraSAR-X and TanDEM-X will fly much closer. This suggests that systematic errors will be reduced and the accuracy improved. Nevertheless relative navigation with unprecedented accuracy requirements will remain a challenge.

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