GPS HIGH PRECISION ORBIT DETERMIANTION SOFTWARE TOOLS (GHOST)

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ABSTRACT

The GHOST "GPS High precision Orbit determination Software Tools" are specifically designed for GPS based orbit determination of LEO (low Earth orbit) satellites and can furthermore process satellite laser ranging measurements for orbit validation purposes. Orbit solutions are based on a dynamical force model comprising Earth gravity, solid-Earth, polar and ocean tides, luni-solar perturbations, atmospheric drag and solar radiation pressure as well as relativistic effects. Remaining imperfections of the force models are compensated by empirical accelerations, which are adjusted along with other parameters in the orbit determination. Both least-squares estimation and Kalman-filtering are supported by dedicated GHOST programs. In addition purely kinematic solutions can also be computed. The GHOST package comprises tools for the analysis of raw GPS observations as well. This allows a detailed performance analysis of spaceborne GPS receivers. The software tools are demonstrated using examples from the TerraSAR-X and TanDEM-X missions.

1. INTRODUCTION

The GPS High precision Orbit determination Software Tools (GHOST) were developed at the German Space Operations Center (DLR/GSOC) in cooperation with TU Delft. They are a set of tools, which share a common library written in C++. The library contains modules for input and output of all common data formats for GPS observations, auxiliary data and physical model parameters. It also provides modules for the mathematical models used in orbit determination and for modelling all physical forces on a satellite.

The tools can be classified in analysis tools and tools for the actual precise orbit determination (POD). Additionally a user can implement new tools based on the library modules.

The user interface of the GHOST tools consists of human readable and structured input files. These files contain all the parameters and data filenames which have to be set by the user.

Although a software package for orbit determination and prediction existed at GSOC, it was decided with the availability of GPS tracking on missions like CHAMP and GRACE, to implement GHOST as a flexible and modular set of tools, which are dedicated to the processing GPS data for LEO orbit determination. GHOST has been used in the orbit determination of numerous missions like CHAMP, GRACE, TerraSAR-X, GIOVE and Proba-2. The newest tool for relative orbit determination between two spacecrafts (FRNS, see section 5.5) was designed using data from the GRACE mission and will be used in the operation of the TanDEM-X, PRISMA and DEOS missions.

Due to its modular design the library offers users a convenient way to create their own tools. As all necessary data formats are supported, tools for handling and organizing data are easily implemented. For example many GPS receivers have their own proprietary data format. Hence for each new satellite mission a tool can be created, which converts the receiver data to the standard RINEX format in order to be compatible with the other tools. This is supported by the library modules.

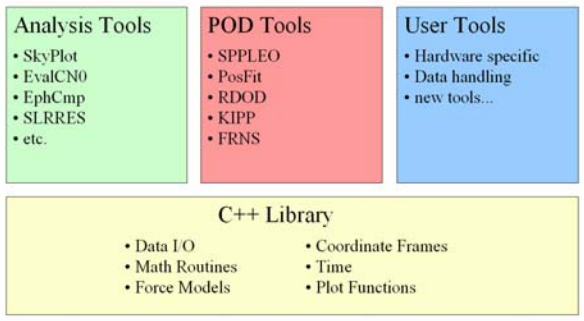

Figure 1: GHOST Software Architecture.

2. THE TERRASAR-X AND TANDEM-X MISSIONS

GHOST has been used and will be used in the preparation and the data processing of numerous satellite missions including the TerraSAR-X and TanDEM-X missions. The examples shown in this paper are taken from actual TerraSAR-X mission data or from simulations done in preparation of the TanDEM-X mission. Hence these two satellite missions are introduced here.

TerraSAR-X is a German synthetic aperture radar (SAR) satellite which was launched in June 2007 from Baikonur on a Dnepr rocket and is operated by GSOC/DLR. Its task is to collect radar images of the Earth's surface. To support the TerraSAR-X navigation needs, the satellite is equipped with two independent GPS receiver systems. While onboard needs as well as orbit determination accuracies for image processing (typically 1m) can be readily met by the MosaicGNSS single-frequency receiver, a decimeter or better positioning accuracy must be achieved for the analysis of repeat-pass interferometry. To support this goal, a high-end dual-frequency IGOR receiver has been contributed by the German GeoForschungsZentrum (GFZ), Potsdam. Since the launch DLR/GSOC is routinely generating precise rapid and science orbit products using the observations of the IGOR receiver.

In mid 2010 the TanDEM-X satellite is scheduled for launch. It is an almost identical twin of the TerraSAR-X satellite. Both satellites will fly in a close formation to acquire a digital elevation model (DEM) of the Earth's surface by stereo radar data takes. Therefore the baseline vector between the two satellites has to be known with an accuracy of 1 mm. In preparation of the TanDEM-X mission, GHOST has been extended to support high precision baseline determination using single or dual-frequency GPS measurements.

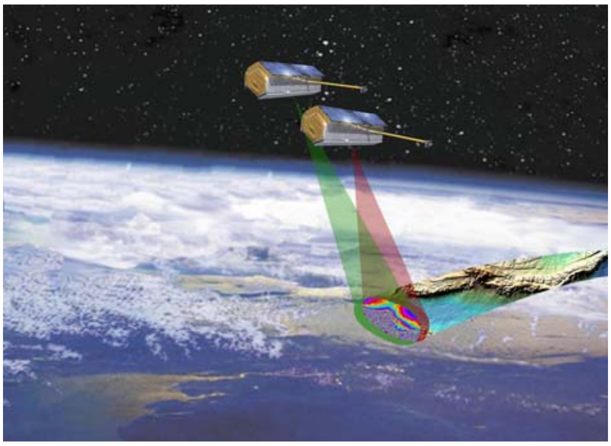

Figure 2: The TanDEM-X mission. (Image: EADS Astrium)

3. THE GHOST LIBRARY

The GHOST library is written in C++ and fully object-oriented. All data objects are mapped into classes and each module contains one class. Classes are provided for data I/O, mathematical routines, physical force models, coordinate frames and transformations, time frames and plot functions.

All data formats necessary for POD are supported by the library. Most important are the format for orbit trajectories SP3-c [1] and the 'Receiver Independent Exchange Format' RINEX [2] for GPS observations. The SP3 format is used for the input of GPS ephemerides (as those files are usually provided in SP3-c format) and for the output of the POD results. The raw GPS observations are provided in the RINEX format. At the moment the upgrade from RINEX version 2.20 to version 3.00 is ongoing to allow for the use of multi-constellation and multi-antenna files. Other data formats, which are supported, are the Antenna Exchange Format ANTEX [3] containing antenna phase center offsets and variations and the Consolidated Prediction Format CPF [4] used for the prediction of satellite trajectories to network stations. The Consolidated Laser Ranging Data Format CRD [5] which will replace the old Normal Point Data Format is currently being implemented.

The library provides basic mathematical functions needed for orbit determination like a module for matrix and vector operations, statistical functions and quaternion algebra. As numerical integration plays a fundamental role in orbit determination, several numerical integration methods for ordinary differential equations are implemented, like the 4th-order Runge-Kutta method and the variable order variable stepsize multistep method of Shampine & Gordon [6].

Forces acting on the satellite are computed by physical models including the Earth's harmonic gravity field, gravitational perturbations of the Sun and Moon, solid Earth and ocean tides, solar radiation pressure, atmospheric drag and relativistic effects.

In orbit determination several coordinate frames are used. Most important are the inertial frame, the Earth fixed frame, the orbital frame and the spacecraft frame. The transformation between inertial and Earth fixed frame is quite complex as numerous geophysical terms like the Earth orientation parameters are involved. The orbital frame is defined by the position and velocity vectors of a satellite. The axes are oriented radial, tangential (along-track) and normal to the other axes and often denoted as R-T-N. The spacecraft frame is fixed to the mechanical structure of a satellite and used to express instrument coordinates (e.g. the GPS antenna coordinates). It is connect to the other frames via attitude information. The GHOST library contains transformations between all involved frames.

Similar to reference frames, also several time scales like UTC and GPS time are involved in orbit determination. A module provides conversions between different time scales.

In order to visualize results of the analysis tools or POD results like orbit differences or residuals, the library contains a module dedicated to the generation of post script plots.

4. ANALYSIS TOOLS

The GHOST package comprises tools for the analysis of raw GPS observations and POD results. This allows a detailed performance analysis of spaceborne GPS receivers in terms of signal strength, signal quality, statistical distribution of observed satellites and hardware dependent biases. The tools can be used either to characterize the flight hardware already prior to the mission or to analyze the performance of in flight data during the mission. An introduction to the most important tools is given here.

4.1. EphCmp

One of the most basic but most versatile tools is the ephemeris comparison tool EphCmp. It simply compares an orbit trajectory with a reference orbit and displays the differences graphically (see Fig. 3). The coordinate frame in which the difference is expressed can be selected. In addition a statistic of the differences is given. It can be used to visualize orbit differences in various scenarios like the comparison of different orbit solutions, the comparison of overlapping orbit arcs or the evaluation of predicted orbits or navigation solutions against precise orbits.

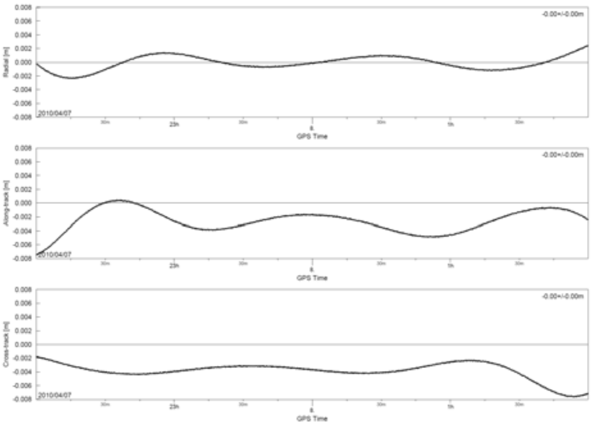

Figure 3: Comparison of two overlapping orbit arcs from TerraSAR-X POD.

4.2. SkyPlot

SkyPlot is a tool to visualize the geometrical distribution of observed GPS satellites in the spacecraft frame. A histogram and a timeline of the number of simultaneously tracked satellites are given as well. Hence the tool can be used to detect outages in the tracking.

Fig. 4 shows the output of SkyPlot for the MosaicGNSS single-frequency receiver on TerraSAR-X on 2010/04/05. The antenna of the MosaicGNSS receiver is mounted with a tilt of 33° from the zenith direction. This is very well reflected in the geometrical distribution (upper left) of the observed GPS satellites. It can be seen, that mainly satellites in the left hemisphere have been tracked. The histogram (upper right) shows, that – although the receiver has 8 channels – most of the time only 6 satellites (or less) were tracked. The lower plot in Fig 4. shows the number of observed satellites as timeline. It can be seen, that there was a short outage of GPS tracking around 11h. This is useful information for the evaluation of GPS data and the quality of POD results.

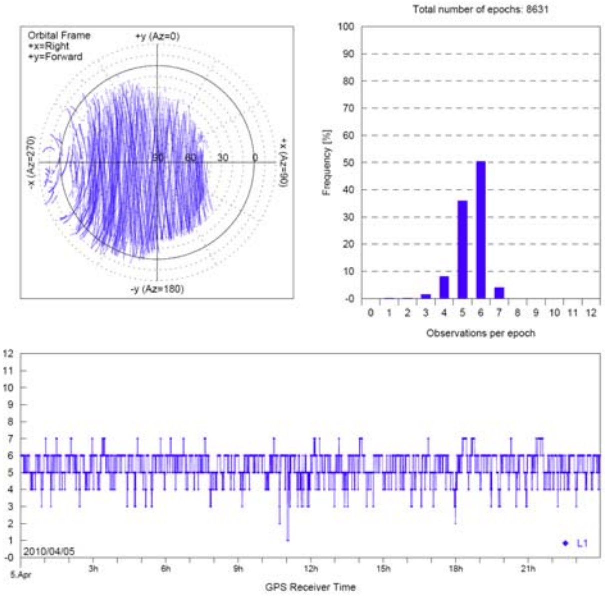

Figure 4: Distribution of tracked satellites by the MosaicGNSS receiver on TerraSAR-X.

4.3. EvalCN0

The tool EvalCN0 is used to analyze the tracking sensitivity of GPS receivers. It plots the carrier-to-noise ratio (C/N$_0$) in dependence of elevation.

The example shown in Fig. 5 is taken from a pre-flight test of the IGOR receiver on the TanDEM-X satellite. The test was carried out with a GPS signal simulator connected to the satellite in the assembly hall [7]. It can be seen, that under the given test-setup, the IGOR receiver achieves a peak carrier-to-noise density ratio (C/N$_0$) of about 54 dB-Hz in the direct tracking of the L1 C/A code. The C/N$_0$ decreases gradually at lower elevations but is still above 35 dB-Hz near the cut-off elevation of 10°.

For the semi-codeless tracking of the encrypted P-code, the C/N$_0$ values S1 and S2 reported by the IGOR receiver on the L$_1$ and L$_2$ frequency show an even stronger decrease towards the lower elevations. The signal strength of the L$_2$ frequency is about 3dB-Hz lower than that for the L_1 frequency. To evaluate the semi-codeless tracking quality, the size of the S1-SA and S2-SA difference is shown in the right plot of Fig. 5. Both frequencies show an expected almost linear variation compared to SA. The degradation of the signal due to semi-codeless squaring losses increases with lower elevation.

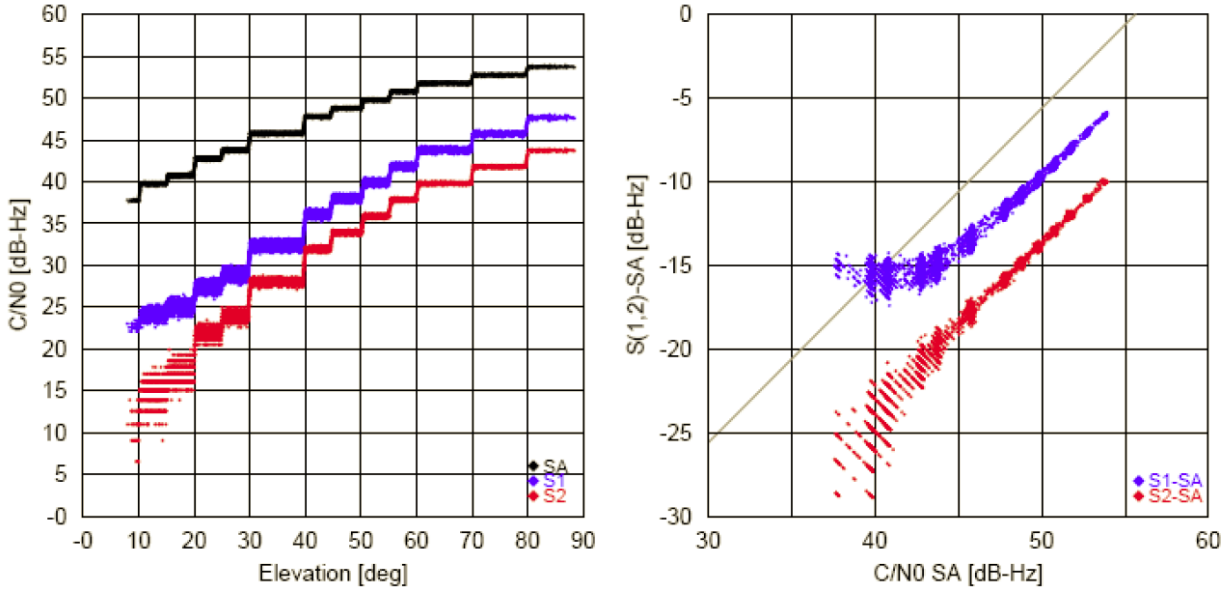

Figure 5: Variation of C/N_0 with the elevation of the tracked satellite (left) and semi-codeless tracking losses (right) for the pre-flight test of the IGOR receiver on TanDEM-X.

4.4. SLRRES

Satellite Laser Ranging (SLR) is an important tool for the evaluation of the quality of GPS-based precise satellite orbits. It is often the only independent source of observations available, with an accuracy good enough to draw conclusions about the accuracy of the precise GPS orbits.

SLRRES computes the residual of the observed distance between satellite and laser station versus the computed distance. The residuals are displayed in a plot (see Fig. 6). As output daily statistic, station-wide statistics and an overall RMS residual are given.

In order to compute the distance between satellite and laser station, the orbit position of the satellite has to be corrected for the offset of the satellites laser retro reflector (LRR) from the center of mass using attitude information. The coordinates of the laser station are taken from a catalogue and have to be transformed to the epoch of the laser observation. This is done by applying corrections for ocean loading, tides, and plate tectonics. Finally the path of the laser beam has to be modelled considering atmospheric refractions and relativistic effects.

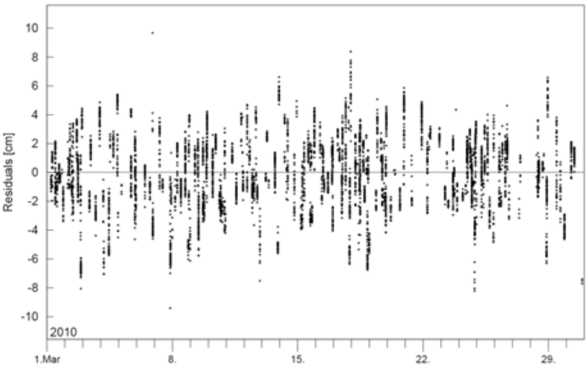

Figure 6: SLR Residuals of TerraSAR-X POD for March 2010.

5. PRECISE ORBIT DETERMINATION TOOLS

The POD tools comprise two different fundamental methods of orbit determination. A reduced-dynamic orbit determination is computed by the RDOD tool, while KIPP produces a kinematic orbit solution. Both tools process the carrier phase GPS observations. They need a reference solution to start with. This is provided by the tools SPPLEO and PosFit.

SPPLEO generates a coarse navigation solution by processing the pseudorange GPS observations. The satellite position and receiver clock offset are determined in a least squares adjustment. Next PosFit is run to determine a solution in case of data gaps and to smoothen the SPPLEO solution by taking the satellite dynamics into account.

5.1. SPPLEO

SPPLEO (Single Point Positioning for LEO satellites) is a kinematic least squares estimator for LEO satellites processing pseudorange GPS observations. The program produces a first navigation solution, with data gaps still present. For each epoch, the satellite position and receiver clock offset are determined in a least-squares adjustment.

The tool is able to handle both single and dual-frequency observations. In case of single frequency observations, the C1 code is used without ionosphere correction. In case of dual-frequency observations, the ionosphere free linear combination of P1 and P2 code observations is applied. In case range-rate observations are available, it is also possible to estimate velocities.

Before the adjustment, the data is screened and edited. Hence the user can choose hard editing limits for the signal to noise ratio of the observation, the elevation and the difference between code and carrier phase observation. In case of the violation of one limit, the observation is rejected. If the number of observations for one epoch is below the limit set by the user, the whole epoch is rejected. After the adjustment the PDOP is computed, and if it exceeds a limit, the epoch is rejected as well. If the a posteriori RMS of the residuals exceeds the threshold set by the user, the observation yielding the highest value is rejected. This is repeated until the RMS is below the threshold or the number of observations is below the limit.

The resulting orbit usually contains data gaps and relatively large errors compared to dynamic orbit solutions. Hence the gaps have to be closed and the orbit has to be smoothed by the dynamic filter tool PosFit.

5.2. PosFit

PosFit is a dynamic ephemeris filter for processing navigation solutions as those produced by SPPLEO. This is done by an iterated weighted batch least squares estimator with a priori information. The batch filter estimates the initial state vector, drag and solar radiation coefficients. In addition to those model parameters, empirical accelerations are estimated. One empirical parameter is determined for each of the three orthogonal components of the orbital frame (radial, along-track and cross-track) for an interval set by the user. The parameters are assumed to be uncorrelated over those intervals.

The positions of the input navigation solution are introduced as pseudo-observations. The filter is fitting an integrated orbit to the positions of the input orbit in an iterative process. In order to obtain initial values for the first iteration, Keplerian elements are computed from the first two positions of the input orbit. All forces that act on the satellite (like atmospheric drag, solar radiation pressure, tides, maneuvers…) are modelled and applied in the integration. Due to imperfections in the force models, the empirical accelerations are introduced, to give the integrated orbit more degrees of freedom, to fit to the observations. The empirical acceleration parameters are estimated in the least squares adjustment together with the initial state vector and model parameters. The partial derivatives of the observations w.r.t. the unknown parameters are obtained by integration of the variational equations along the orbit (for details see [8]). The result of PosFit is a continuous and smooth orbit without data gaps in SP3-c format. It can serve as reference orbit for RDOD and KIPP.

Figure 7 displays the graphical output of PosFit. The three upper graphs show the residuals after the adjustment in the three components of the orbital frame. In this example, which is taken from a 30h POD arc of the TerraSAR-X mission, the RMS of the residuals lies between 0.5m and 1.5m. This mainly shows the dispersion of positions of the SPPLEO solution. The three lower graphs show the estimated empirical accelerations in the three components of the orbital frame.

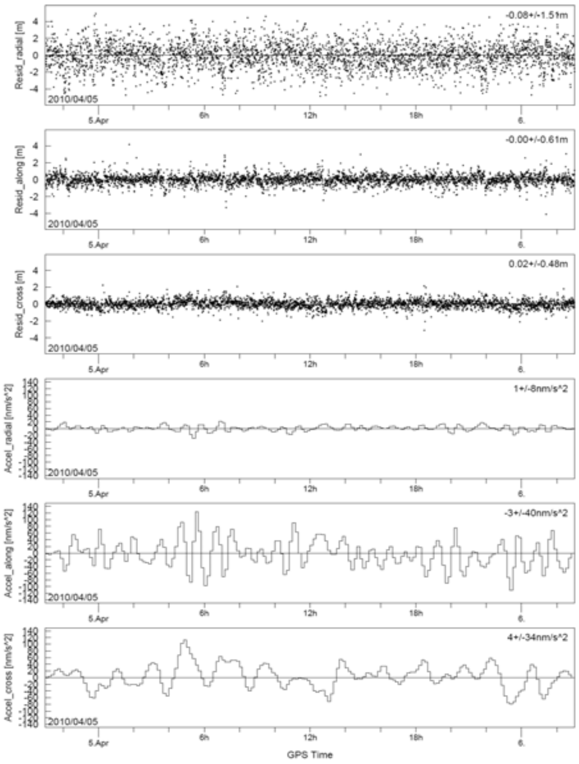

Figure 7: Graphical output of PosFit Tool for TerraSAR-X POD.

5.3. RDOD

RDOD is a reduced dynamic orbit determination tool for LEO satellites processing carrier phase GPS observations. This is also done by an iterated weighted batch least squares estimator with a priori information. Similar to PosFit, RDOD estimates the initial state vector, drag and solar radiation coefficients and empirical accelerations. Contrary to PosFit, where the positions of a reference orbit are used as pseude-observations, RDOD directly uses the GPS pseudorange and carrier phase observations. Nevertheless a continuous reference orbit – normally computed by PosFit – is required by RDOD for data editing and for obtaining initial conditions for the first iteration.

The tool is able to handle both single and dual-frequency data. In case of single frequency observations, the GRAPHIC (Group and Phase Ionospheric Correction) combination of C/A code and L_1 carrier-phase is used as observation. In case of dual-frequency observations, the ionosphere free linear combination of L_1 and L_2 carrier phase observations is applied.

The data editing is crucial to the quality of the results. Hence the data is also screened and edited by RDOD using limits specified by the user. If the signal-to-noise ratio of the observation exceeds the limit, or the elevation is below a cut-off elevation, the observation is rejected. This is done if no GPS ephemerides and clock information is available for that observation. Next outliers in the code and carrier-phase observations are detected. This is done comparing the observations to modelled observations using the reference orbit.

The RDOD filter is fitting an integrated orbit to the carrier-phase observations. This is done in a similar way as in PosFit, considering all forces on the satellite and estimating empirical acceleration parameters. But while PosFit uses absolute positions as observations, the carrier-phase observations used in RDOD contain an unknown ambiguity. The ambiguity is considered to be constant over one pass – the time span in which a GPS satellite is tracked continuously. Hence one unknown ambiguity parameter per pass is added to the adjustment.

The graphical output of RDOD shows the residuals of the code and carrier phase observations (see Fig. 8). This is an important tool for a fast quality analysis and for detecting systematic errors.

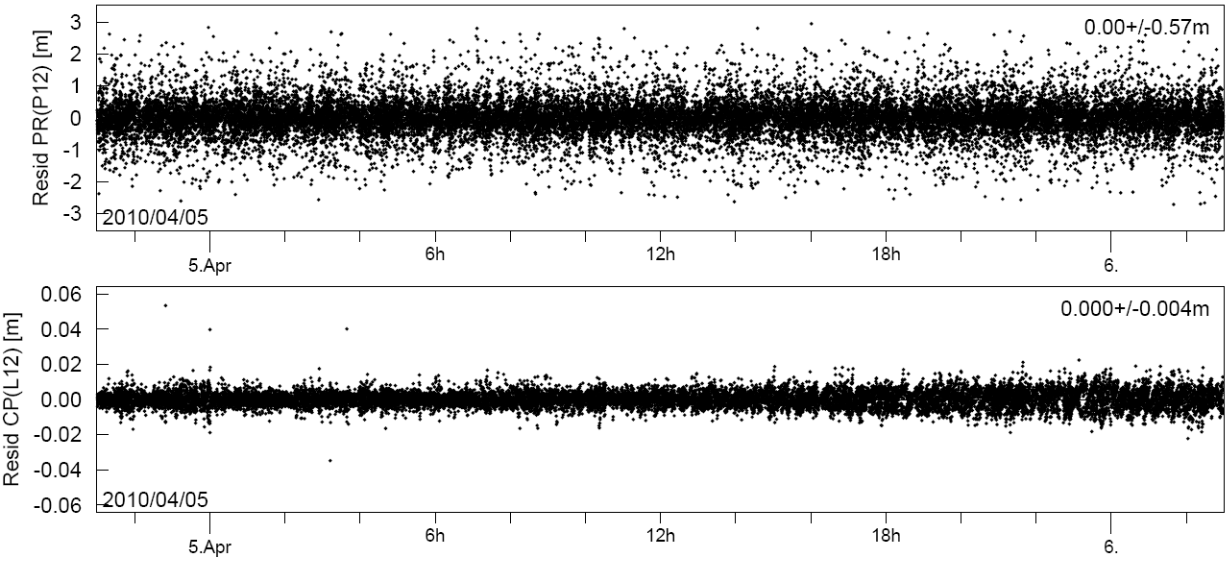

Figure 8: Output of RDOD tool for TerraSAR-X POD.

Both the antennas of the GPS satellites and the GPS antennas of spaceborne receivers show variations of the phase center dependent on azimuth and elevation of the signal path. It is necessary to model those variations in order to obtain POD results with highest quality. GHOST does not only offer the possibility to use phase center variation maps given in ANTEX format. It also offers the possibility to estimate such phase center variation patterns, and thus can be employed for the in-flight calibration of flight hardware. This was done for the GPS on TerraSAR-X as shown in Fig. 9. The figure shows the phase center variation pattern for the main POD antenna of the IGOR receiver on TerraSAR-X. It was estimated from 30 days of flight data and needs to be applied to carrier phase observations in addition to a pattern which was determined for the antenna type by ground tests (for details cf. [9]).

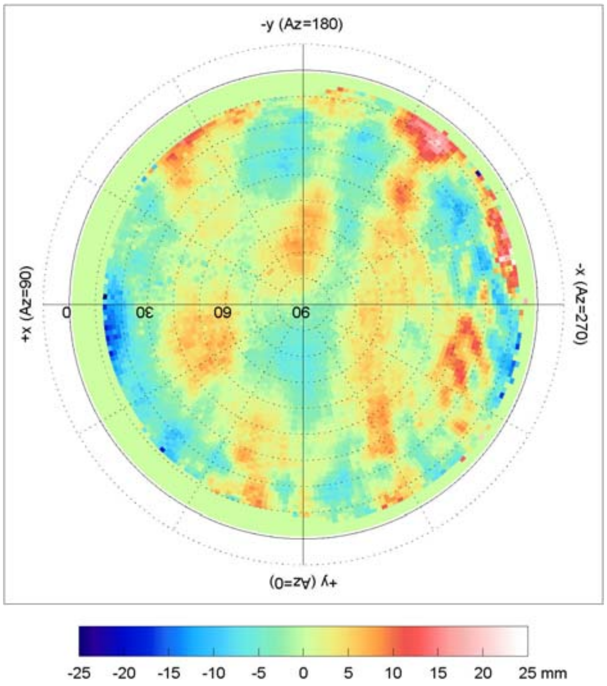

Figure 9: Phase Center Variation Pattern for the Main POD Antenna on TerraSAR-X.

5.4. KIPP

KIPP (Kinematic Point Positioning) is a kinematic least squares estimator for LEO satellites. Similar to RDOD carrier phase observations are processed. But in contrast to RDOD no dynamic models are employed, and only the GPS observations are used for orbit determination. For each epoch, the satellite position and receiver clock offset are determined in a weighted least squares adjustment. KIPP also requires a continuous reference orbit, as that computed by PosFit.

Like RDOD, the KIPP tool is able to handle both single and dual-frequency data. In case of single frequency observations, the GRAPHIC (Group and Phase Ionospheric Correction) combination of C/A code and L_1 carrier-phase is used as observation. In case of dual-frequency observations, the ionosphere free linear combination of L_1 and L_2 carrier phase observations is applied.

5.5. FRNS

The Filter for Relative Navigation of Satellites (FRNS) is designed to perform relative orbit determination between two LEO spacecrafts. This is done using an extended Kalman filter described in [10]. The concept is to achieve a higher accuracy for the relative orbit between two spacecrafts by making use of differenced GPS observations, than by simply differencing two independent POD results. FRNS requires a continuous reference orbit for both spacecrafts, such as computed by RDOD. It then keeps the orbit of one spacecraft fixed, determines the relative orbit between the two spacecrafts and adds it to the positions of the first spacecraft. As result a SP3-c file containing the orbit of both spacecrafts is obtained. The tool is able to process both single and dual-frequency observations.

The FRNS tool was developed using data from the GRACE mission and will be applied on a routine basis for the TanDEM-X mission. In contrast to TanDEM-X, GRACE consists of two spacecrafts, which follow each other on a similar orbit with about 200 km distance. The distance between the two spacecrafts is measured by a K-band link, which is considered to be at least one order of magnitude more accurate than GPS observations. Hence the K-band observations can be used to assess the accuracy of the relative navigation results – with the limitation, that the K-band observations only reflect the along-track component, and contain an unknown bias. The differences between a GRACE relative navigation solution and K-band observations are shown in Fig. 10. The standard deviation is about 0.7 mm. As the TanDEM-X mission uses GPS receivers which are follow-on models of those used on GRACE, and the distance between the spacecrafts is less than 1 km, one can expect that the quality of the relative orbit determination will be on the same level of accuracy or even better.

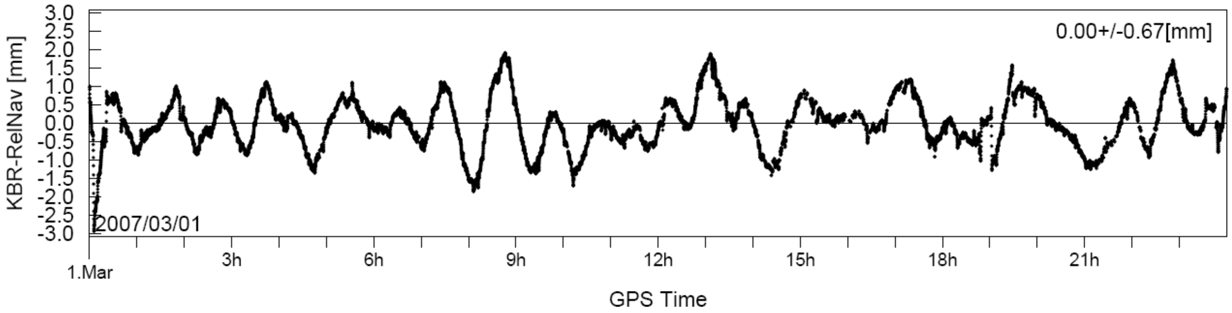

Figure 10: Comparison of GRACE relative navigation solution with K-band observations.

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