ON THE EFFECT OF REFERENCE FRAME MOTION ON INSAR DEFORMATION ESTIMATES

Hermann Bähr[1], **Sami Samiei-Esfahany**[2], **and Ramon F. Hanssen**[2]

[1]*Geodetic Institute, Karlsruhe Institute of Technology, Englerstrasse 7, 76131 Karlsruhe, Germany, baehr@kit.edu*
[2]*Department of Remote Sensing, Delft University of Technology, Kluyverweg 1, 2629 HS Delft, The Netherlands, s.samieiesfahany@tudelft.nl, R.F.Hanssen@tudelft.nl*

ABSTRACT

For processing of interferometric synthetic aperture radar (InSAR) data, precise satellite orbits are required. These orbits are given in a reference frame with respect to which tectonic plates perform a relative motion. Neglecting this motion can cause temporally increasing baseline errors that induce large scale error ramps into the interferometric phase. The amount of error depends on the geographical location and is evaluated globally for the ENVISAT orbit. Predicted biases of deformation estimates can reach up to 7 mm/a in some areas. Whereas these biases are not separable from actual deformation signals by spatio-temporal correlation properties, they are well predictable and can easily be accounted for. A most simple correction approach consists in compensating the plate motion by modifying orbital state vectors, assuming a homogeneous velocity for the whole plate. This approach has been tested on Persistent Scatterer Interferometry (PSI) results over the area of Groningen, the Netherlands.

Key words: InSAR; Baseline Error; Reference Frame; ITRF; Plate Tectonics.

1. INTRODUCTION

InSAR deformation analysis is based on comparing the measured interferometric phase of two images with the reference phase computed from acquisition geometry. The latter is deduced from precise orbit ephemerides, which are commonly expressed in the *International Terrestrial Reference Frame* (ITRF). This frame is a realisation of a global coordinate system and defined by a number of geodetic stations close to the earth surface. To account for secular tectonic motion, not only positions but also linear velocities are attributed to the ITRF stations.

A common assumption for InSAR processing is that the reference system of the orbit data does not move with respect to the earth surface. However, due to plate tectonics, this assumption is not valid at the centimetre level. Observing from a viewpoint on a tectonic plate, the coordinate frame of the orbits performs a relative motion in the order of centimetres per year. Neglecting this in InSAR processing is comparable to making an error in the interferometric baseline, the size of which is increasing with the temporal baseline. The effect on the interferometric phase is an almost linear trend in range, suggesting a large scale tilt of the surface. In contrast to temporally uncorrelated ramps caused by orbital errors, this kind of trend is correlated in time and cannot be separated from spatio-temporally correlated deformation signals. Hence, it can mistakenly be interpreted as an actual deformation signal in applications where the signal of interest is a large scale deformation over a long time period, e. g., in monitoring interseismic tectonic motions.

This contribution investigates the effect of neglecting the relative tectonic motion on InSAR deformation estimates, henceforth referred to as the *reference frame effect*. After a brief review on the ITRF and orbit errors in SAR interferometry, the effect will be described in detail and evaluated globally. A simple correction approach will be proposed and applied on ENVISAT PSI results from the Groningen area in the Netherlands.

2. THE ITRF

ITRF station positions and velocities are based on observations from space geodetic techniques like *Very Long Baseline Interferometry* (VLBI), *Satellite Laser Ranging* (SLR), *Global Navigation Satellite Systems* (GNSS) and *Doppler Orbitography and Radiopositioning Integrated by Satellite* (DORIS). Starting with ITRF88, twelve releases have been published to date, continuously improving and refining estimation strategies. The most recent ones are ITRF2000 [1], ITRF2005 [2] and ITRF2008 [3]. The oldest observations date from about 1980, and the number of the respective release approximately specifies the year of the latest observations included. ITRF2008 comprises positions and velocities of 935 stations, i. e., radio telescopes, SLR lasers, GPS antennas and DORIS beacons. For some stations, multiple solutions have been estimated for time spans separated by discontinuities like tectonic events or antenna changes.

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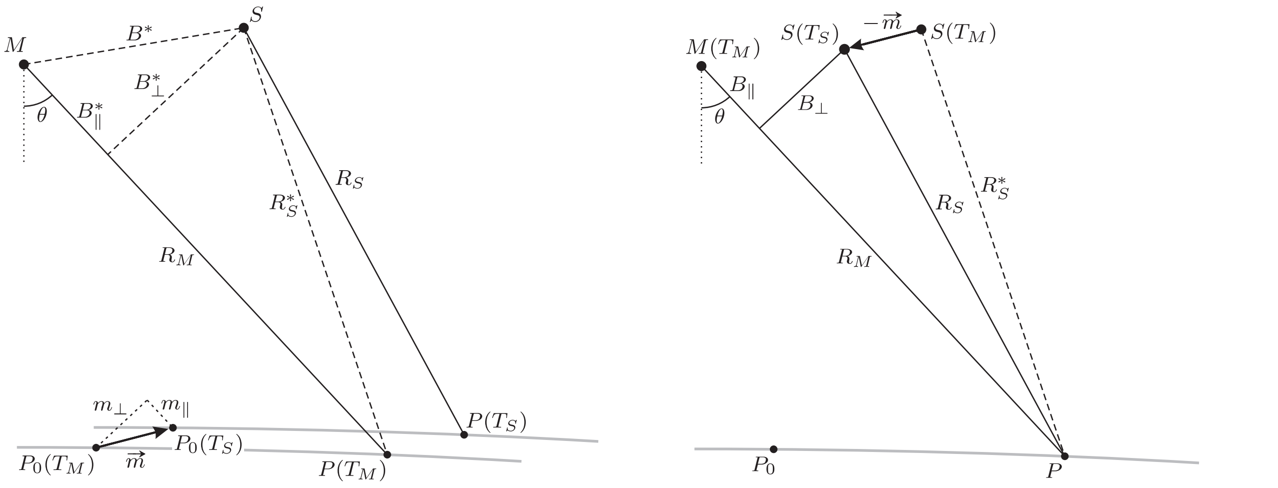


(a) Acquisition geometry in the ITRF datum.

(b) Acquisition geometry in the reference system of a motionless tectonic plate.

Figure 1: Geometry of a master acquisition from orbit M at time T_M and a slave acquisition from orbit S at time T_S. (a) The sensor positions M and S are given in ITRF coordinates, whereas the tectonic plate incorporating the acquired region, performs a relative motion with respect to the ITRF. Assuming a non-deforming plate, this motion can be described by the displacement vector $\vec{m} = (T_S - T_M)\vec{v}$ of a nearby ITRF station P_0. If the motion is neglected for the computation of the reference phase, the biased range R_S^* is used in eq. (1), implying a biased perpendicular baseline $B_\perp^*$. (b) Observing from a viewpoint on the tectonic plate, ITRF coordinates perform a relative motion, which has to be applied to the orbit data to yield an unbiased reference phase.

The ITRF is defined by three-dimensional station positions and velocities (i. e., 6 parameters per station) and has thus 14 degrees of freedom (corresponding to seven parameters of a similarity transformation and their rates of change) to define its datum. The three translations and their rates are defined by the centre of mass of the earth sensed by SLR, and the scale and its rate are fit to the metre convention via SLR and VLBI measurements [3]. The orientation of the frame is basically arbitrary, aligning the three orientation parameters and their rates recursively to preceding ITRF realisations [1, 2, 3]. For ITRF2000 however, the time evolution of the orientation has been explicitly aligned to the geophysical plate kinematic model NNR-NUVEL-1A [1, 4]. Consequently, this alignment applies recursively to the subsequent releases ITRF2005 and ITRF2008.

Satellite orbital state vectors are commonly expressed in the ITRF datum, because the underlying orbit solutions are generally aligned to the ITRF positions and velocities of a number of ground control points from the tracking network.

3. ORBIT ERRORS IN SAR INTERFEROMETRY

In InSAR processing, the reference phase has to be subtracted from an interferogram to reveal a potential deformation signal. It is defined as the theoretical phase measurement that would be obtained in absence of deformation, atmospheric signals and all kinds of errors. It can be computed from the simulated ranges R_M and R_S of master and slave acquisitions, respectively (see fig. 1) [5]:

$$\phi_{\text{ref}} = -\frac{4\pi}{\lambda}(R_M - R_S) \approx -\frac{4\pi}{\lambda}B_\parallel \,, \tag{1}$$

where λ is the radar wavelength, and $B_\parallel$ is the component of the interferometric baseline B in ranging direction. The reference phase is commonly decomposed into separate contributions of the ellipsoid and the superimposed topography. However, this discrimination will not apply to the following considerations.

Errors or residual inaccuracies in orbits may induce an almost linear signal into the interferometric phase (see fig. 2). In this context, only relative errors, i. e., baseline errors, have a significant impact. Parameterising them by the temporally variable baseline components $B_\parallel(t)$ and $B_\perp(t)$ (see fig. 1), it has been concluded in [7] that errors in $B_\parallel$ and $\dot{B}_\perp$ are negligible. Errors in $\dot{B}_\parallel$ induce an almost linear error signal in azimuth, whereas errors in $B_\perp$ induce a similar signal in range. From the differential equation:

$$d\delta\phi_{\text{ref}} = -\frac{4\pi}{\lambda}\,\delta\dot{B}_\parallel dt - \frac{4\pi}{\lambda}\,\delta B_\perp d\theta \,, \tag{2}$$

the relationship between errors $\delta\phi_{\text{ref}}$ in the reference phase and baseline errors δB can be inferred, where θ is the look angle, and $\partial B_\parallel/\partial\theta = B_\perp$. Note that t stands for the acquisition time and actually represents a spatial

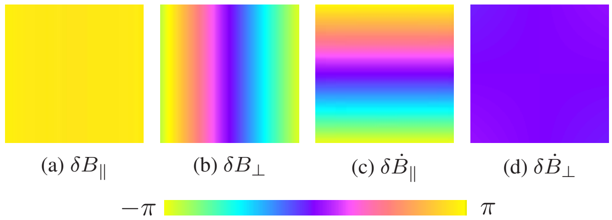


Figure 2: Interferometric error signals induced by errors in particular baseline components, computed for a full ENVISAT scene of 100 × 100 km [7]. (a) $\delta B_{||}$ = 26 cm. (b) $\delta B_{\perp}$ = 26 cm, equivalent to one fringe in range. (c) $\delta \dot{B}_{||}$ = 1.7 mm/s, equivalent to one fringe in azimuth. (d) $\delta \dot{B}_{\perp}$ = 1.7 mm/s.

coordinate, specifying a location along the orbit. In the following, a capital T will stand for another timescale, referencing individual acquisition dates in a long-term context. Derivatives are defined by: $\dot{x} = \partial x/\partial t$ and $x' = \partial x/\partial T$.

4. THE REFERENCE FRAME EFFECT

4.1. Description

Fig. 1 illustrates how the neglect of relative tectonic motion can bias the computed reference phase. For this purpose, a point P situated in the rigid interior of a tectonic plate is considered. The sensor positions M for the master acquisition at time T_M and S for the slave acquisition at time T_S are given with respect to the ITRF. If P is assumed to maintain its position from T_M in the coordinate frame of the ITRF (fig. 1a), the simulated line of sight (LOS) for the slave acquisition (dashed in the figure) does not reflect the actual range measurement R_S. Using R_S^* in eq. (1) instead of R_S results in a biased baseline B^*.

The most straightforward approach to compute an unbiased reference phase is a datum transformation of the orbital state vectors from the ITRF datum to a frame in which the tectonic plate under consideration is static:

$$\vec{x}_{\text{plate}}(T) = \vec{x}_{\text{ITRF}} - (T - T_0)\vec{v}\ . \tag{3}$$

$\vec{v}$ is the plate velocity expressed in the ITRF, for which the velocity vector of a nearby ITRF station P_0 is an adequate estimate. T_0 is the reference epoch, at which the two frames coincide. Its choice is almost arbitrary, since a homogeneous shift of the state vectors of both acquisitions does not change the baseline. In fig. 1b, $T_0 := T_M$ has been chosen, meaning no change to the master orbit M and a shift of $-\vec{m} = -(T_S - T_M)\vec{v}$ to the slave orbit S. The reference phase computed from the orbit positions $M(T_M)$ and $S(T_S)$ is unbiased, implying the actual perpendicular baseline $B_{\perp}$. Thus, the error $\delta B_{\perp}$ in the perpendicular baseline due to neglecting the reference frame effect can be predicted from the component of $\vec{v}$ perpendicular to the line of sight:

$$\delta B_{\perp}(T) = B_{\perp}^* - B_{\perp}(T) = v_{\perp}(T - T_0)\ . \tag{4}$$

The component $\delta B_{||}$ in ranging direction can be ignored, since it does not affect the interferometric phase in a significant way (see fig. 2). The maximum bias of the reference phase in range can be predicted according to eq. (2):

$$\Delta_{\text{rg}}\delta\phi_{\text{ref}}(T) = -\frac{4\pi}{\lambda}\, v_{\perp}(T - T_0)\,\Delta\theta\ , \tag{5}$$

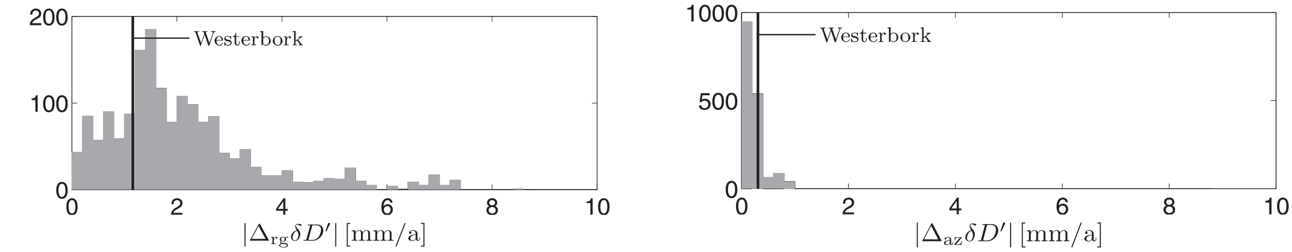
where $\Delta\theta$ is the look angle difference between near range and far range. For instance, $\Delta_{\text{rg}}\delta\phi_{\text{ref}} = 2\pi$ would imply an almost linear error signal of one fringe in range (see fig. 2b). Translating $\Delta_{\text{rg}}\delta\phi_{\text{ref}}$ into an error in the estimated ground displacement rate D' in the line of sight yields:

$$\Delta_{\text{rg}}\delta D' = -v_{\perp}\Delta\theta\ . \tag{6}$$

Here, the sign has been inverted twice with respect to eq. (5). The first change of sign accounts for the fact that the reference phase is subtracted from the measured phase, and the second one re-defines a temporally increasing phase (or range) as negative displacement (subsidence) and a decreasing phase as positive displacement (uplift). Thus, a positive $\Delta_{\text{rg}}\delta D'$ would imply a tilt of the ground towards the sensor and vice versa. However, this apparent interpretation does not reflect the actual cause of the signal, as it is due to a translational motion of the tectonic plate, perpendicular to the line of sight. This translation is misinterpreted as a tilt if the reference frame effect is not corrected for.

From eq. (5) can be seen that the error signal is a linear function of time, which is remarkable, since orbit errors can generally be considered random for subsequent acquisitions and are thus uncorrelated in time. This correlation property is commonly exploited to separate orbital errors from deformation signals in time series analyses. As both the reference frame effect and deformation signals are correlated in time, a distinction by spatio-temporal properties is impossible.

In contrast to deformation signals, the reference frame effect is well predictable in many cases. Thus, the most straightforward way to prevent biased deformation estimates is to correct for it. This can be achieved by modifying orbital state vectors for the reference phase computation by subtracting the relative motion of a nearby ITRF station as demonstrated in fig. 1b. The approach works well in the quasi-rigid interior of a tectonic plate, where the tectonic motion can be considered homogeneous for a whole radar scene. It fails in deforming zones close to plate boundaries, where different orbit modifications would have to be applied to compute the reference phase



(a) Relative LOS displacement biases in range that are induced by the reference frame effect and can be removed with the correction in eq. (3).

(b) Relative LOS displacement biases in azimuth that are induced due to approximation errors of the correction model (3).

Figure 3: Global evaluation of trends that would result from a correction of the reference frame effect following eq. (3), predicted for 100×100 km^2 ENVISAT frames from one ascending and one descending track at 840 ITRF2008 stations.

for different subregions. Such a procedure would require detailed knowledge about the local velocity field.

Baseline errors due to the reference frame effect induce primarily fringes in range. Fringes in azimuth are related to errors in $\dot{B}_\parallel$ (see fig. 2c) and can only result if the relative velocities $\vec{v}$ would vary in their LOS component $v_\parallel$ for different azimuth times. By analogy to eq. (6), the maximum bias of the estimated ground displacement rate would be:

$$\Delta_{\mathrm{az}}\delta D' = -\dot{v}_\parallel \Delta t = -\Delta v_\parallel \tag{7}$$

where Δt is the total acquisition time of the scene. In principle, no large variations of the plate motion are expected within the rigid interior of a tectonic plate. However, the correction approach in eq. (3) involves a minor model inaccuracy, since the motion of a plate on a spherical body is approximated by a velocity vector that is constant in a 3D Euclidean space. As the lines of sight of the radar are not collinear for different azimuth times at constant ranges due to the curvature of the earth, $v_\parallel$ may vary even if $\vec{v}$ is constant. Thus, an error signal in azimuth is additionally induced when intentionally an error signal in range is corrected for. But as long as only a single SAR frame of 100 km length is processed, the bias in azimuth is generally much smaller than the reference frame effect in range (see fig. 3). Hence, the benefit of the correction outweighs its model error.

The accuracy of the correction model (3) could be enhanced by describing the relative motion of a tectonic plate with a spherical angular velocity and an associated rotation axis. The parameters could be taken directly from a plate kinematic model that is given in the same datum as the ITRF. This approach would complicate the processing though, because different modifications would have to be applied to orbital state vectors for individual pixels in an interferogram.

4.2. Global Evaluation

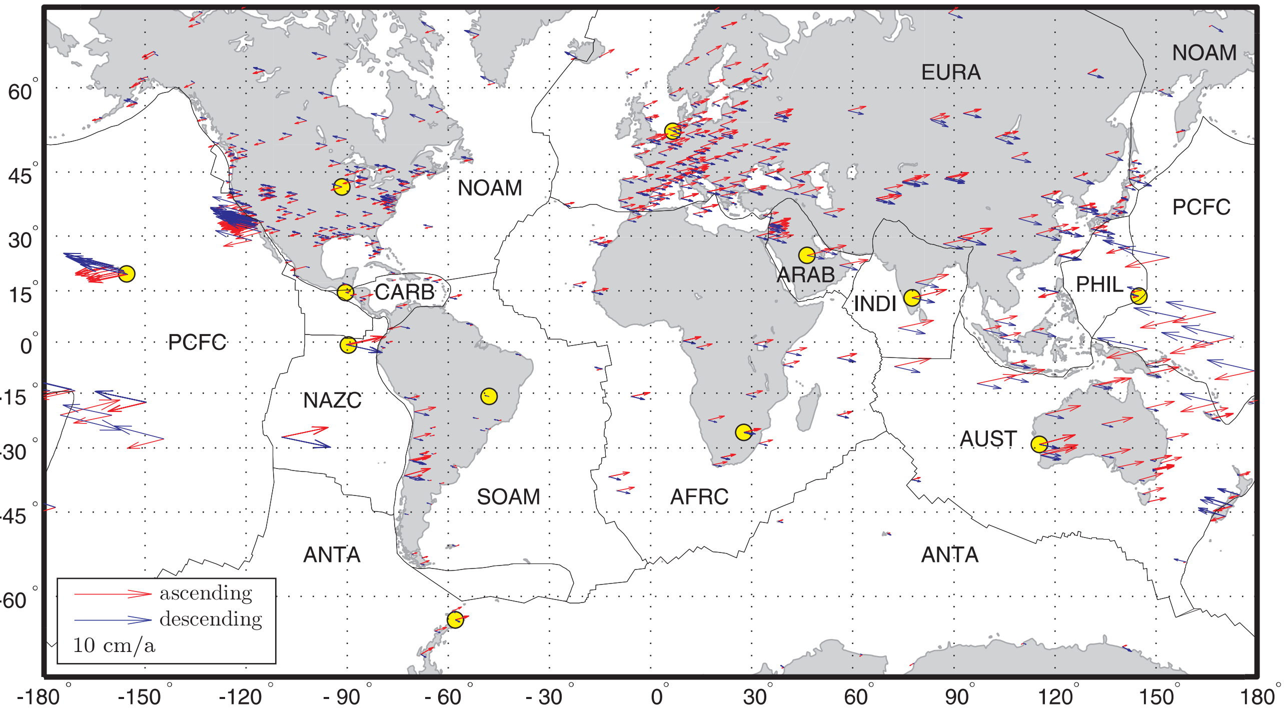
To get a global picture of the reference frame effect, the associated baseline error rate $\delta B'_\perp = v_\perp$ has been predicted for 840 of the 935 ITRF2008 stations that qualify by a high-quality velocity estimate, preferably representative for a long timespan. 95 stations have been disregarded, because their observation data spans less than a year or the standard deviation of their 3D velocity $|\vec{v}|$ exceeds 1 mm/a. For stations with multiple solutions, referring to different time spans separated by tectonic events or antenna changes, always the solution with the longest observation time has been selected.

During the 35 day repeat cycle of ENVISAT, each station is covered by several swaths. The evaluation of the reference frame effect has been performed for one ascending and one descending track in IS2 mode, for each of which the station is closest to the middle of the swath. For both, the error rate $\delta B'_\perp = v_\perp$ in the perpendicular baseline has been predicted from the ITRF velocity vector $\vec{v}$, where the decomposition into $v_\parallel$ and $v_\perp$ is defined by the line of sight to the middle of the swath.

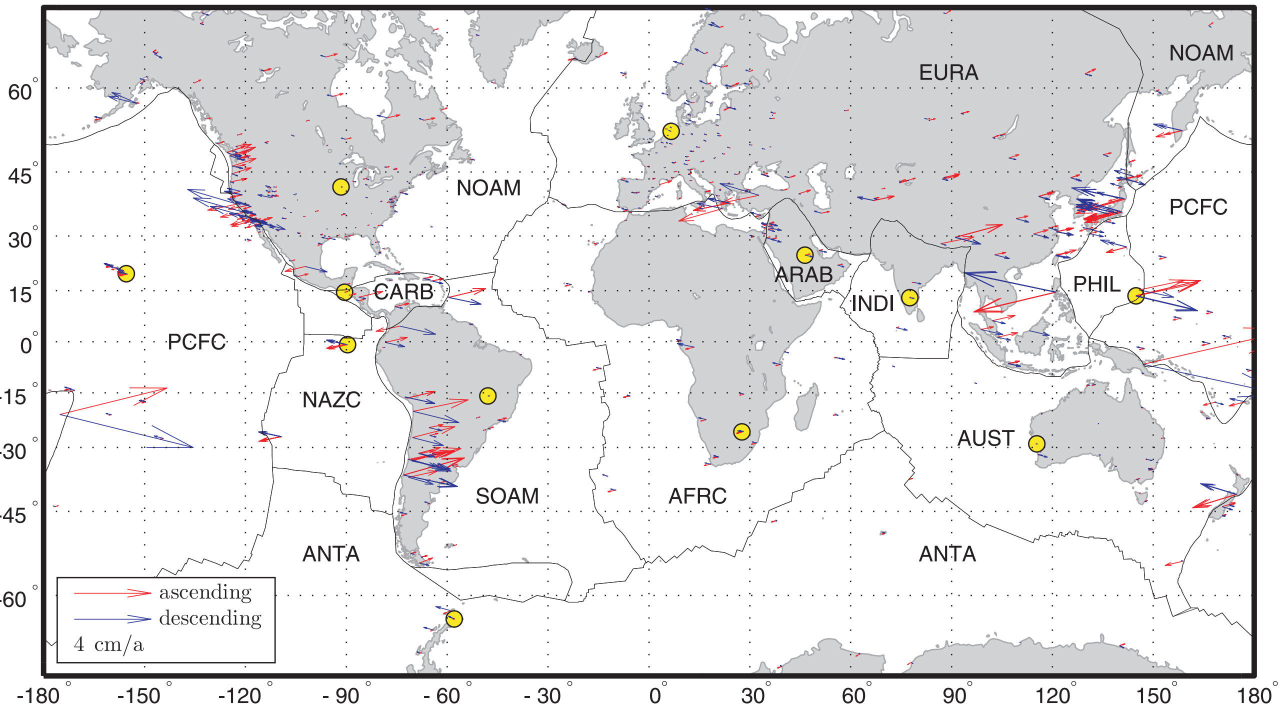
Fig. 4a and tab. 1 give an overview of the predicted baseline error rates. For most plates the effect behaves largely homogeneous, in some cases undergoing smooth variations due to rotational plate motion, for instance on the Australian plate. Only in deforming zones like the Andes or Japan, the rates follow a distinctly different pattern or appear even arbitrary. Hence, except for some regions, a prediction of the reference frame effect is expected to perform well with the velocity vector of the closest ITRF station.

The largest baseline error rates of 6 cm/a are predicted for descending tracks on Hawaii. If the effect is not corrected for, this would cause a phase ramp in range equivalent to a relative difference of 7 mm/a in the displacement rates observed at near range and far range. For a temporal baseline of four years, the error signal would already amount to one fringe. Other regions where the effect is very large are Baja California (Mexico), southern California (USA), the Indian plate and western Australia. The predicted baseline error rate is also considerable for some smaller Islands in the Pacific Ocean, but the associated error signal would be less pronounced due to the limited extension of land masses.

Whereas ITRF velocities reflect the recent plate motion, they are only available at discrete points. Even though they may be representative for a larger region, a suitable



(a) Baseline error rates predicted from ITRF velocities.



(b) Bias of the baseline error rates due to approximation of the ITRF2008 velocities by NNR-NUVEL-1A velocities. Mind the enlarged scale.

Figure 4: Prediction of the baseline error rate $\delta B'_\perp = v_\perp$ due to the reference frame effect for ENVISAT interferograms, evaluated at 840 ITRF2008 stations. The arrows are aligned to the horizontal projection of the respective radar line of sight. Numerical values for the twelve encircled stations can be found in tab. 1.

Table 1: Prediction of the reference frame effect observed with ENVISAT for one sample ITRF station per tectonic plate, fig. 4a giving information on their representativeness. Each station has a unique "DOMES" identifier and may have multiple solutions for different time spans separated by tectonic events or antenna changes. $v_\perp$ is the baseline error rate, computed from ITRF2008 and NNR-NUVEL-1A velocities, respectively. $\Delta_{\mathrm{rg}}\delta D'$ is the bias of the relative LOS displacement rate between near range and far range, computed with $\Delta\theta = 6.2°$. The last column gives the temporal baseline $B_{T,\mathrm{fringe}} = |\lambda/(2\delta D')|$ that is required to induce an error signal of one fringe in range. All values are given for both ascending and descending orbits.

Plate	Site name	DOMES no.	Solution no.	$v_\perp$				$\Delta_{\mathrm{rg}}\delta D'$		$B_{T,\mathrm{fringe}}$	
				ITRF2008		NUVEL-1A		ITRF2008		ITRF2008	
				[mm/a]		[mm/a]		[mm/a]		[a/fringe]	
				asc.	desc.	asc.	desc.	asc.	desc.	asc.	desc.
AFRC	Hartebeesthoek (ZA)	`30302S001`	1 (1986-2008)	20	-12	23	-14	-2.2	1.3	13	22
ARAB	Riyadh (SA)	`20101S001`	1 (2001-2008)	36	-23	33	-19	-3.9	2.4	7	12
ANTA	O'Higgins (–)	`66008S001`	1 (1993-2008)	17	-6	18	-9	-1.8	0.7	15	41
AUST	Yarragadee (AU)	`50107M001`	1 (1982-2008)	48	-25	48	-25	-5.2	2.7	5	10
CARB	Guatemala City (GT)	`40901S001`	1 (2000-2009)	6	-4	4	-4	-0.6	0.4	46	63
EURA	Westerbork (NL)	`13506M005`	1 (1997-2009)	21	-10	21	-12	-2.2	1.1	13	25
INDI	Bangalore (IN)	`22306M002`	1 (1996-2005)	46	-30	46	-28	-5.0	3.2	6	9
NAZC	San Cristobal (EC)	`42004S001`	1 (1993-2005)	49	-45	59	-55	-5.3	4.8	5	6
NOAM	North Liberty (US)	`40465S001`	1 (1992-2008)	-15	13	-15	14	1.6	-1.4	18	20
PCFC	Maunakea (US)	`40477S001`	1 (1993-2008)	-50	61	-46	58	5.4	-6.6	5	4
PHIL	Guam (US)	`50501S001`	1 (1993-2002)	-7	10	-42	42	0.8	-1.1	35	26
SOAM	Brasilia (BR)	`41606M001`	1 (1996-2007)	-1	6	-2	6	0.1	-0.6	352	45

reference station has to be selected with care to correct for the reference frame effect. Alternatively, the usage of plate kinematic models may be considered. These models have the advantage that they provide velocities for any point on the earth surface. However, they are sometimes partly or fully based on geological data reflecting the average motion from a few million years ago to date, which is not necessarily representative for the era of remote sensing. They also provide only horizontal velocities, which is an adequate approximation though, because the vertical component is in general relatively small. Furthermore, it is important to assure that the model velocities are given in (or transformed to) the same datum as the orbit reference frame, i. e., the ITRF.

This last requirement is definitely satisfied for the solely geological model NNR-NUVEL-1A [4], because the ITRF2000 and later releases have adopted its datum (see sect. 2). Fig. 4b shows the biases of the baseline error rates at the ITRF2008 stations that occur if the reference frame effect is corrected using NNR-NUVEL-1A velocities. For most stations, the deviation is in the order of few mm/a and thus insignificant. Apart from singular outliers close to plate boundaries, significant deviations occur only at the west coast of America and in south east Asia. An only marginally better approximation can be yielded using models based on geodetic observations only [8, 9].

All predictions from this section also apply to the *European Remote Sensing Satellites* (ERS), which followed the same orbit as ENVISAT. For other sensors, similar results are expected. The most determining factor is the orientation of the perpendicular component $B_\perp$ of the interferometric baseline, which is defined by orthogonality with respect to both the satellite trajectory and the line of sight. As SAR satellites commonly have a sun-synchronous orbit with an inclination around 98°, all have similar local headings. More variable is the respective line of sight, since the look angle typically varies between 15° and 60°. As plate motions are dominated by their horizontal component, the reference frame effect is expected to be stronger for steep looking beam modes, for which the orientation of $B_\perp$ is rather horizontal than vertical. Finally, the bias of deformation estimates due to baseline errors increases with the swath width, which is owed to the ramp-like characteristic of the error signal. This is a meaningful conclusion in view of the planned mission Sentinel, where the *Interferometric Wide Swath Mode* is designed with a swath width of 250 km.

4.3. Orbits based on different ITRF Solutions

Although subsequent ITRF releases basically describe the same reference system, station positions and velocities are subject to small changes due to improved estimation strategies. Every time a new release is published, it has to be decided how to proceed with operationally processed orbit solutions. A switch in the processing strategy to the new frame may be considered as well as a complete reprocessing of older mission phases [6]. Keeping the old frame as reference would avoid discontinuities in the data, but on the other hand no benefit could be drawn from the enhanced frame consistency.

Even though it is advisable to always use homogeneous datasets for processing, the choice of the ITRF release can be assessed to affect orbit solutions only on the millimetre level. This can be seen from tab. 2, where estimated parameters of similarity transformations between

Table 2: Estimated transformation parameters (translations T_x, T_y, T_z, differential scale D, rotation angles R_x, R_y, R_z and their rates of change) between recent ITRF realisations [1, 2, 3]. Scale and rotation parameters have been multiplied by a mean earth radius R_{E} = 6371 km to depict the impact on station coordinates. Note that there is no strict analytical relation between two ITRF releases; the estimated parameters rather provide a rough idea of the actual datum shift.

from	to	T_x	T_y	T_z	$R_{\mathrm{E}}D$	$R_{\mathrm{E}}R_x$	$R_{\mathrm{E}}R_y$	$R_{\mathrm{E}}R_z$	T'_x	T'_y	T'_z	$R_{\mathrm{E}}D'$	$R_{\mathrm{E}}R'_x$	$R_{\mathrm{E}}R'_y$	$R_{\mathrm{E}}R'_z$
		[mm]							[mm/a]						
ITRF2008	ITRF2005	-0.5	-0.9	-4.7	6.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0
ITRF2005	ITRF2000	0.1	-0.8	-5.8	2.5	0.0	0.0	0.0	-0.2	0.1	-1.8	0.5	0.0	0.0	0.0
ITRF2000	ITRF97	6.7	6.1	-18.5	9.9	0.0	0.0	0.0	0.0	-0.6	-1.4	0.3	0.4	0.4	0.4

recent ITRF solutions provide a rough idea of the actual datum shift. Only a translation in direction of the perpendicular baseline has a significant effect on InSAR processing. Even for the most pessimistic circumstances, where the perpendicular baseline is collinear with the z-axis of the global frame and the temporal baseline is very long, the effect on $\delta B_\perp$ cannot exceed a few centimetres. Hence, the choice of the correct ITRF release is not of primary importance for the correction of the reference frame effect.

5. VALIDATION

To validate the predictions from the last section, a correction for the reference frame effect has been applied to a persistent scatterer time series analysis of the Dutch province Groningen. The region has been and still is subject to InSAR deformation monitoring, measuring ground subsidence due to gas extraction [10]. Fig. 5a shows the deformation signal estimated from a stack of 68 ENVISAT images (track 380, descending orbit) spanning 6.7 years from 2003 to 2010. For the reference phase computation, the precise orbit solution distributed by the *European Space Agency* (ESA) and processed by the French *Centre National d'Etudes Spatiales* (CNES) has been used.

Apart from a local subsidence signal, the estimated velocity exposes a large trend in range direction of 13.8 mm/a from near range (east) to far range (west). This trend is not likely to be due to orbit errors, because these are not expected to be correlated in time, and thus their effects would average out. Ketelaar [10] has thoroughly analysed a number of conceivable causes, finding no plausible explanation for this large trend.

The reference frame effect for this scene can be adequately predicted with the ITRF velocity of the GPS station Westerbork (WSRT), which is situated in the southern part of the scene (see fig. 5a). As the Netherlands are not subject to significant tectonic processes, this velocity is considered representative for the relative movement of the whole region. The ESA orbit solution is based on ITRF2000 until April 2008 [6], which covers the major part of the time series. Hence, it is appropriate to use the ITRF2000 velocity $|\vec{v}| = 23$ mm/a. The component in direction of the perpendicular baseline is $v_\perp = -13$ mm/a and would cause a difference of 1.4 mm/a in the displacement rate between near and far range. Note that this number does not deviate significantly from the prediction based on ITRF2008 in tab. 1.

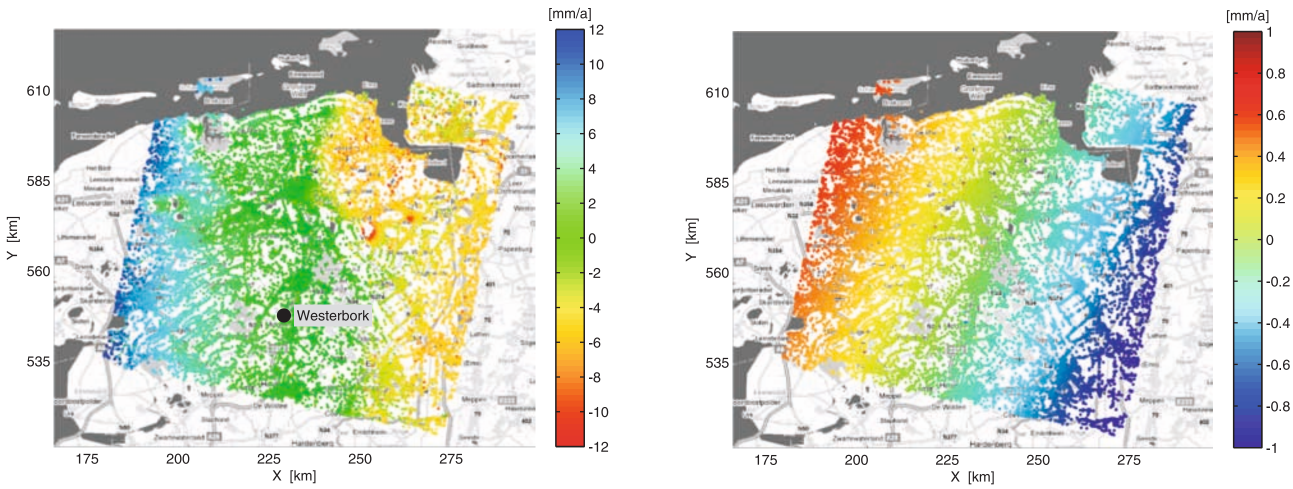
To validate the prediction, processing of the Groningen data has been performed a second time under consideration of the reference frame effect. For this, the reference phase has been computed with modified state vectors following eq. (3). The bias due to neglecting the reference frame effect is shown in fig. 5b, where PS velocities obtained with corrected state vectors have been subtracted from the original estimates (fig. 5a). The signal is dominated by a trend of 1.3 mm/a in range, which matches the prediction very well. There is also a trend component of -0.3 mm/a in azimuth, which can be explained by the variation of look directions due to the curvature of the earth. The LOS component of the Westerbork ITRF velocity increases by $\Delta v_\parallel = 0.3$ mm/a between early azimuth (north) and late azimuth (south) and can be translated into a change in the displacement rate of $\delta D' = -0.3$ mm/a according to eq. (7).

The azimuth trend is an artefact due to approximation errors of the correction model (3) as addressed in sect. 4.1. Whereas its insignificance is not apparent for the sample data at hand, it is still distinctly smaller than the trend in range to be corrected for so that the benefit of the correction outweighs its bias. Fig. 3 illustrates that this conclusion can be generalised. It is even more meaningful for those regions where the reference frame effect is most pronounced.

6. CONCLUSIONS

Relative motion between the earth surface and the coordinate frame in which satellite orbits are expressed is is in the order of few centimetres per year and generally neglected in InSAR processing. This induces a trend into the interferograms that is almost linear in range and can bias ENVISAT deformation rates by up to 7 mm/a. The bias of an estimated relative displacement depends on the geographical location as well as on the separation of two measurements in both time and range. In contrast to orbital ramps, this *reference frame effect* is correlated in time and thus not separable from an actual deformation signal.

Numerical predictions of the reference frame effect have been validated for a PSI time series of the Dutch province



(a) PS velocities obtained without accounting for the reference frame effect.

(b) Bias of PS velocities due to neglecting the reference frame effect.

Figure 5: Results from PSI deformation analysis of the Dutch province Groningen based on ENVISAT acquisitions spanning 6.7 years. As the platform follows a descending orbit, the sensor is looking on the scene from the east. (a) A subsidence bowl due to gas extraction is clearly distinguishable in the north-eastern quarter. In addition, there is a large trend of 13.8 mm/a in range, for which no explanation has been found yet. (b) To compute the bias due to neglecting the reference frame effect, the result of a second processing, in which the effect has been accounted for following eq. (3), has been subtracted from the PS velocities. A trend of 1.4 mm/a in range and -0.3 mm/a in azimuth can be observed. The effect is significantly smaller compared to the originally observed trend (mind the different colour scale).

Groningen. The effect itself could not be observed though. A rigorous validation is difficult due to other, interfering signals. It might be achievable in a region where the predicted bias is more pronounced.

Being negligible for local phenomena, correcting for the reference frame effect may be considered whenever large scale deformation is subject to InSAR analysis. The most straightforward approach is applying a translational shift to the orbit data prior to processing. As the motion of a tectonic plate is homogeneous rather on a spherical body than in 3D space, this approach is only an approximation, but considered adequate for the standard case. A more rigorous correction would involve different orbit modifications for individual pixels, which is by far more complicated. The same applies to deformation zones, where the surface velocity field is inhomogeneous.

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