Geometric Calibration and Validation of ASAR Imagery

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ABSTRACT

We describe work conducted to calibrate and then validate the geometry of ENVISAT ASAR products. A systematic error in range location was observed in ASAR products during the commissioning phase. A careful and complete analysis has been performed to establish the precise error. It has been compensated by updating the range gate bias (or sampling window start time bias). Validation of the absolute location accuracy of most ASAR products was performed subsequently.

The location of surveyed targets is predicted using the satellite state vectors and ancillary timing information via the range and Doppler equations. The prediction's accuracy is affected by instrument bias, ionospheric and atmospheric path delay, as well as target survey errors. Transponders are in addition subject to internal delay uncertainty. The positions of the strong transponder and corner reflector targets in the images are measured to sub-sample accuracy by employing large oversampling factors. Initial and residual bias determinations were made using image acquisitions covering transponders and corner reflectors in the Netherlands, Canada, and Switzerland. Using a large number of independent targets helps reduce the influence of their independent survey errors.

The highest resolution slant range single look complex (SLC) products (IMS, APS) were mainly used for testing. In addition, absolute location error was also measured on selected ground range products (IMP, APP, IMM, APM, WSM). Some ground range products also require treatment of multiple slant/ground range polynomials - proper handling is validated. For all test cases processed with precise orbits to date, the residual bias in the slant range direction has been smaller than the size of a single range sample. Predictability of target image location within ASAR image products is very high - better than experience with ERS-1/2, JERS-1, and RADARSAT-1. This result is encouraging, as it opens possibilities for ground control point (GCP) free terrain-geocoding and simplified interferometric processing.

INTRODUCTION

The ENVISAT ASAR sensor can acquire data in a variety of modes: these include (a) the normal imaging mode (**IM**) at a variety of incidence angles, (b) a burst-mode known as alternating polarisation (**AP**) whereby alternate bursts record differing transmit/receive polarisation combinations, and (c) wide swath (**WS**) mode: a ScanSAR mode that cycles through swaths at different incidence angles to allow synthesis of images covering a wider swath (sacrificing resolution). The geometries of two additional modes known as global monitoring (GM) and wave (WV) are not treated here.

In addition to the differing *modes*, there are also a variety of *product types* available from the ASAR ground segment. Data acquired in the IM or AP configurations may be processed to the Single-Look-Complex (SLC) level (**IMS** & **APS**), to a high resolution ground range image analogous to ERS PRI products (**IMP** & **APP**), or to a strip map at medium resolution: (**IMM** & **APM**). The wide swath (WS) mode images are currently available only in medium resolution mode format (**WSM**), although an SLC product (WSS) is currently under development.

Beyond the available acquisition modes and product types, the *orbital state vectors* used during processing (and annotated in all of the above product types) vary in quality from the lowest level (a) flight segment **predicted**, through (b) flight segment **restituted**, (c) DORIS **preliminary**, to the best available (d) DORIS **precise**.

METHOD

Accurate geometric calibration was performed using products with the highest spatial resolution processed using the most accurate orbital state vectors available. IM and AP single look complex (SLC) products (IMS/APS) were therefore selected for initial tests. In addition, the aim of this analysis was also to characterise the full family of ASAR products and to compare the absolute location error between products processed using different orbit types. For this reason, the same acquisition was often processed multiple times, e.g. with predicted, restituted, and precise state vectors. We used the well-surveyed coordinates of relatively easily distinguishable targets such as transponders and corner reflectors to predict their range and azimuth positions in each product, and systematically compared our predictions with the actual location in each product. Large oversampling factors were used in the neighbourhood of the strong targets to measure their actual position at sub-sample levels. Images of ASAR transponders in Flevoland (NL) and the Radarsat transponder in Resolute Bay (Nunavut, Canada), and of corner reflectors outside of Zürich (Switzerland) were used for the study. Image position predictions were made by solving the Doppler and range equations using the target surveyed coordinates together with the provided orbit state vectors and the image timing annotations [8]. Image position measurements were taken via FFT complex oversampling (factor of 50). The location of the maximum was chosen as the target's image position measurement.

The range gate bias (Sampling Window Start Time / SWST bias) was first *calibrated* by measuring range differences between predictions and actual measurements for a set of Single Look Complex (SLC) products processed using precise quality state vectors. The refined SWST bias value was then *validated* by processing new products processed with the new SWST bias value and again measuring the difference between freshly predicted and actual measured image positions.

SWST BIAS REFINEMENT

Corner Reflectors in Dübendorf, Switzerland

Evaluation of data from corner reflector campaigns is free of location errors caused by the transponder delay term. Close-ups of the six Dübendorf scenes available with surveyed corner reflectors are shown in Fig. 1 to provide a qualitative indication of the accuracy of the predictions. The image location predicted on the basis of the corner reflector location, the satellite state vectors, and the radar timing parameters is marked with a blue cross. Multiple zoom levels are provided, ranging from 3 range and 15 azimuth looks (387×1935) at the top, through 1 range & 5 azimuth looks (129×645), the native 1×1 single look complex (SLC) image aspect ratio (129×129), and concluding at the bottom with a 3×3 zoom upon the neighbourhood surrounding the prediction location (43×43). The azimuth sample spacing in IMS and APS SLC products is approximately 4m. The slant range sample spacing is approximately 8m (constant over all incidence angles). A constant slant range resolution translates to varying ground resolution depending on the incidence angle of the beam used (IS1-IS7). The SLC sample aspect ratio between slant range and azimuth sample size therefore varies between 3 and 6.

One Dübendorf scene was available processed with precise orbits and the old/new SWST bias values - a qualitative comparison of the three different processing results is shown in Fig. 2. Quantitative differences between predicted and measured corner reflector positions are shown in Table 1 for both the azimuth and range directions in SLC sample units. Note that for the product processed with the new SWST bias value, the prediction corresponds to the measured location to within a single range sample.

A signal to clutter ratio (SCR) value was calculated to give an indication of the strength of the target signal in comparison to the background. The background value is measured by averaging the backscatter values within the oversampled area excluding an area immediately surrounding the maximum. The image clutter is generally higher when using beams with relatively steep incidence angles such as IS1 - terrain backscatter generally decreases at shallower incidence angles.

Transponders in Resolute (Canada) and Flevoland (The Netherlands)

Four ASAR IM acquisitions covering the area surrounding the Radarsat transponder deployed in Resolute, Canada were investigated. Two acquisitions were processed with precise orbits, and both old and new SWST bias values. Two others were only processed with precise orbits and the new SWST bias. The predicted (blue cross) and measured locations are shown in Fig. 3.

Quantitative comparisons of predicted and measured transponder locations are listed in Table 2. Note the good agreement between prediction and measurement for the images processed with the new SWST bias value. For these Resolute images, predictions and measurements correspond uniformly well, to better than 10% of a range sample. As expected, clutter values increase at steeper incidence angles. The spread of azimuth prediction errors is also smaller than for the other test sites.

Based on comparisons of predictions and actual image location measurements of ASAR transponders imaged during orbits 4542, 4549, and 7269 (see Table 2) -- these were the first products available processed with precise-quality state vectors -- a mean SWST bias was calculated. It was found to be consistent across all beams and invariant for ascending/descending viewing directions [9]. The modified SWST bias was later incorporated into the PF-ASAR processing of the same acquisitions - see the discussion in the next section.

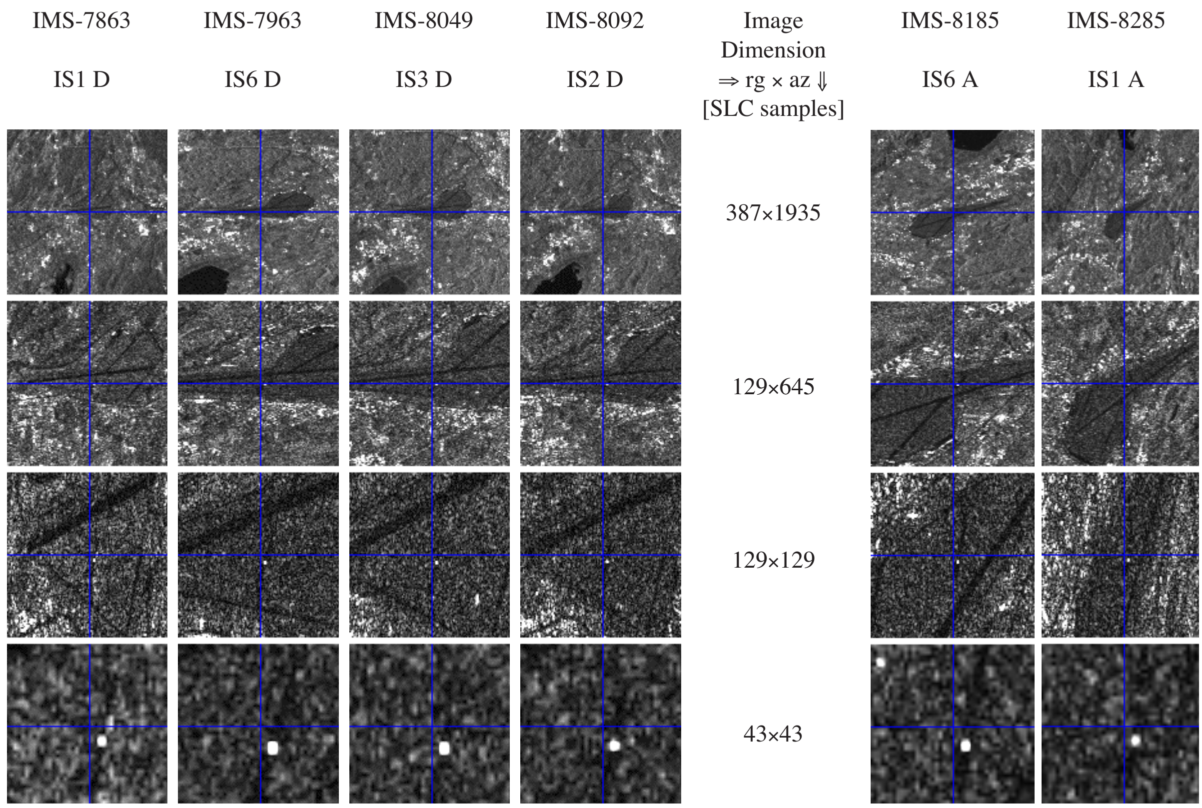


Figure 1: Dübendorf Corner Reflector Measurements vs. Predictions (restituted orbits) -- Left: Descending (D), Right: Ascending (A)

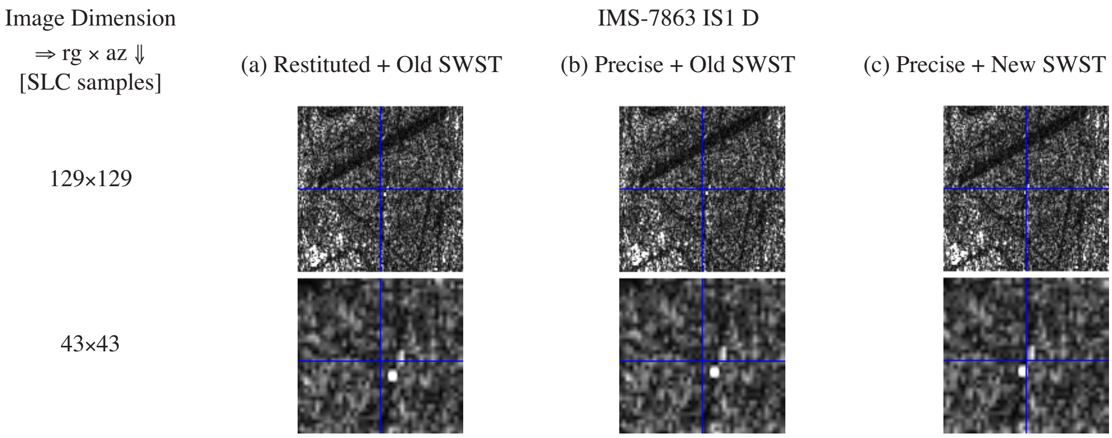


Figure 2: Dübendorf Corner Reflector Location Predictions using (a) restituted, (b) precise / old SWST, (c) precise / new SWST

State Vector Quality	SWST Bias	Prediction - Measurement		SCR
		Azimuth [SLC samples]	Range [SLC samples]	
Restituted	Old	-4.59	-3.13	9.4
Precise	Old	-3.12	-3.12	9.4
Precise	New	-3.12	**0.38**	9.4

Table 1: Dübendorf Corner Reflectors -- Differences between Predictions and Measurements: IMS products from orbit 7863 (IS1 descending acquisition) with restituted, precise & old SWST, and precise & new SWST

APS and APP products from the same Flevoland data take using the same state vectors were terrain geocoded and overlaid, with no shift visible [9]. This indicated that there does not seem to be a systematic shift in PF-ASAR or the terrain geocoding software causing a relative bias between ground range and slant range. For the three Flevoland scenes provided that

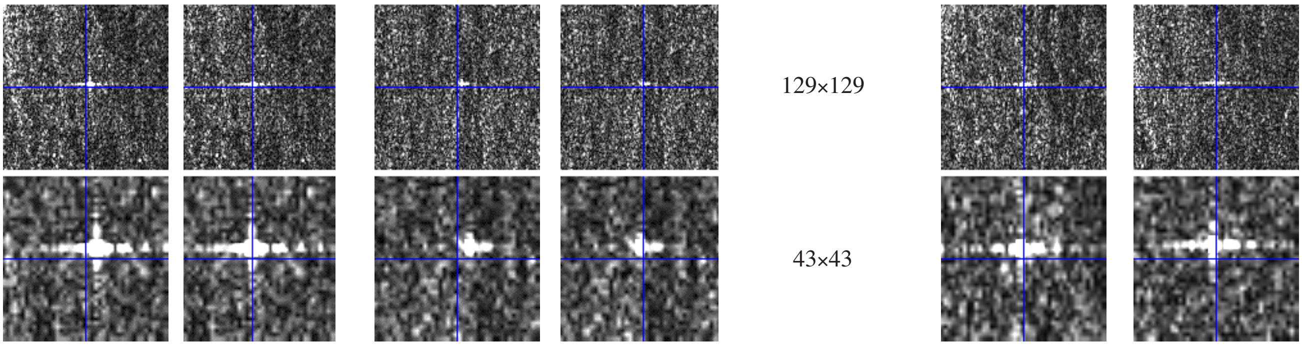
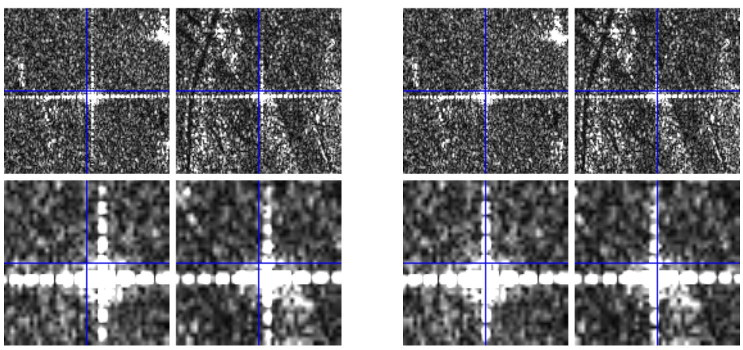


Figure 3: Resolute Transponder Measurements vs. Predictions made using precise orbit state vectors

Transponder Name	Orbit	Beam	State Vector Quality	Prediction - Measurement [SLC samples] Azimuth		Range		SCR
				Old SWST	New SWST	Old SWST	New SWST	
Resolute	5755	IS4 A	Precise	2.51	2.49	-3.54	**-0.01**	141
	7272	IS1 A		1.62	1.60	-3.53	**-0.01**	50
	7172	IS3 A		N.A.	1.58	N.A.	**-0.05**	54
	8260	IS4 A		N.A.	2.81	N.A.	**0.09**	140
Resolute Mean and Standard Deviation (1 transponder)				2.07±0.63	2.12±0.63	-3.54±0.01	**0.01±0.06**	[Samples]
				8.1±2.5	8.0±2.8	-27.6±0.06	0.04±0.5	[m]
Zwolle	4542	IS7 D	Precise	-7.49	-7.53	-3.28	0.22	135
Swifterbant				-5.29	-5.35	-4.08	-0.58	202
Zwolle	4549	IS1 A		2.58	-1.13	-3.35	0.17	133
Swifterbant				2.11	-1.57	-4.04	-0.52	77
Edam	7269	IS7 A		-3.18	-3.19	-3.84	-0.34	461
Aalsmeer				-3.58	-3.64	-3.11	0.39	385
Flevoland Mean and Standard Deviation (4 transponders)				-2.48±4.03	-3.65±2.09	-3.62±0.42	**-0.14±0.46**	[Samples]
				-7.4±13.7	-12.1±6.4	-28.2±3.3	-1.09±3.6	[m]

Table 2: Resolute and Flevoland Transponder Differences between Predictions and Measurements



Transponder	Edam	Aalsmeer	Edam	Aalsmeer
Azimuth Offset [SLC Samples]	-3.18	-3.58	-3.19	-3.64
Range Offset [SLC Samples]	-3.84	-3.11	-0.34	0.39
SCR	517	416	539	436

Figure 4: Comparison of Flevoland transponder (left: Edam, right: Aalsmeer) location predictions using (a) precise orbit state vectors and old SWST value, (b) precise orbit state vectors and new SWST value

had been processed with precise orbit state vectors and the modified/new SWST bias, the prediction and measurement agreed to within one range sample. This was true for ascending and descending geometries and for IS1 and IS7 swaths. Clutter is increased at steep incidence angles (IS1) compared to shallow ones (IS7). In the case of transponders, a further amplification to the target return at far incidence angles is caused by the fact that range spreading loss only applies along one path. While the radar equation's range-induced dampening applies to all terrain returns, transponder "echoes" are only weakened by R^2 on the return path.

Sampling Window Start Time (SWST) Bias Validation with IMS/APS Products

The SWST bias estimates calculated by comparing predicted and measured image locations are subject to a number of error sources, including errors in target surveying, transponder delay, and atmospheric path delays. East-west oriented survey errors should show opposite signs for ascending/descending scenes, and can be controlled to some extent by ensuring inclusion of both geometries. Preliminary tests at RSL indicate that ionospheric path delay produces a worst case one-way shift of 1-2m for ASAR (fraction of a range sample) [4]. This presents a further limitation (or need for modelling) in predicting a target's image location. The size of the uncertainty increases for systems with longer wavelengths, and will become significant even at shorter wavelengths for future systems with higher range resolutions.

The new SWST bias used during later processing was derived by averaging bias estimates (using precise orbits and the old SWST value) based on APS-4542 & 4549 products over Flevoland (The Netherlands) together with the corner reflector measurement from Dübendorf (Switzerland). To *validate* use of the improved values, six independently surveyed corner reflectors and transponders were used: four Flevoland transponders, one Resolute transponder, and one Dübendorf corner reflector (minimising systematic survey biases). For all six targets tested using data processed with precise orbit state vectors and the new SWST bias, all range predictions were within one range sample of the measurement, as shown in Table 3. The average remaining bias calculated on the basis of all nine measurements is -0.04 range samples (~-0.3m), or 0.01 samples (~0.1m) if one excludes the data sets (4542, 4549, 7863 / shaded in table) originally used to refine the SWST bias value. This exclusion reduces the number of measurements, but ensures an independent test of validity. Additional scenes processed with precise orbits will be examined for a more geographically robust validation. Based on the results of this validation exercise, the initial SWST bias (3.2775×10^{-7} s) was replaced by the new value (5.0995×10^{-7} s) on Dec. 12, 2003. The SWST bias is included in an auxiliary data file (ASA_INS_AX) used by the ESA processor, available to users interested in processing ASAR data. The ASA_INS_AX file was updated with the new SWST bias value on Dec. 12, 2003 and all ASAR products generated by ESA since Dec. 13, 2003 use the new value.

Location	Target	Product Type	Orbit	Beam	Prediction - Measurement	
					Azimuth [SLC samples]	Slant Range [SLC samples]
Dübendorf	Corner Reflector	IMS	7863	IS1 D	-3.12	0.38
Resolute	Transponder	IMS	5755	IS4 A	2.49	-0.01
			7172	IS3 A	1.58	-0.05
			7272	IS1 A	1.60	-0.01
			8260	IS4 A	2.81	0.09
Edam	Transponder	IMS	7269	IS7 A	-3.19	-0.34
Aalsmeer					-3.64	0.39
Zwolle	Transponder	APS	4542	IS7 D	-7.53	0.22
			4549	IS1 A	-1.13	0.17
Swifterbant			4542	IS7 D	-5.35	-0.58
			4549	IS1 A	-1.57	-0.52
Mean and Standard Deviation (all scenes included)					-1.5±3.25	**-0.04**±0.36
Mean and Standard Deviation (excluding orbits 4542, 4549, 7863 originally used to refine SWST value)					0.3±2.9	**0.01**±0.24

Table 3: Corner reflector and Transponder SWST *Validation* Measurements (precise state vectors and new SWST used throughout)

GROUND RANGE PRODUCT VALIDATION

Image Mode and Alternating Polarisation Mode Products: IMP, IMM, APP, APM

The ASAR slant range products IMS and APS are the highest resolution product types available, and were therefore used to refine and validate the SWST bias estimate. The remaining ground segment product types considered here are all pro-

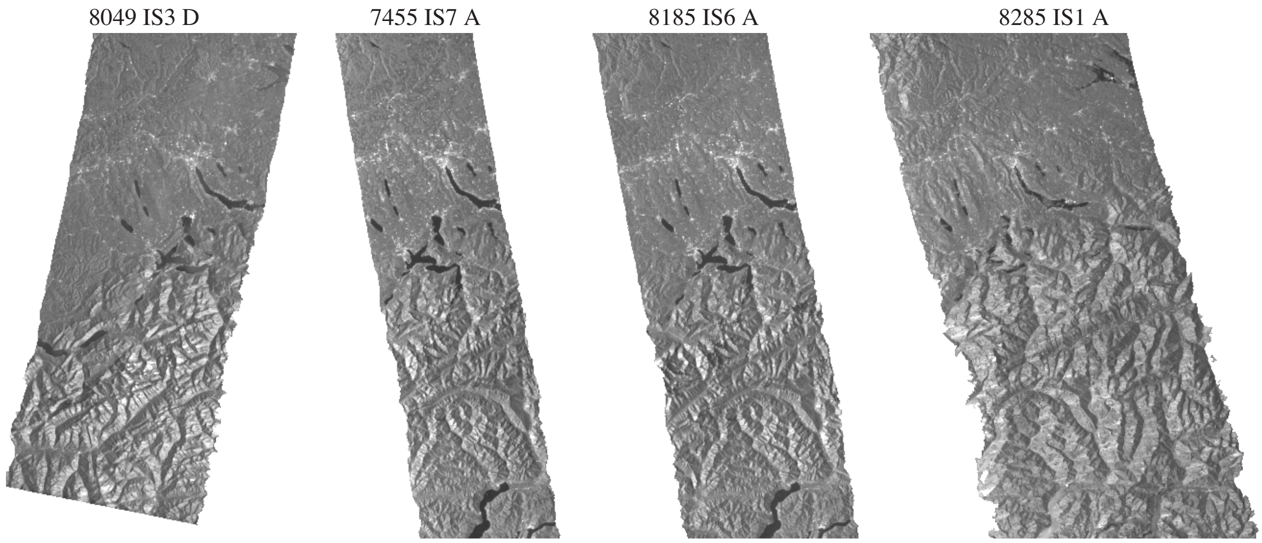
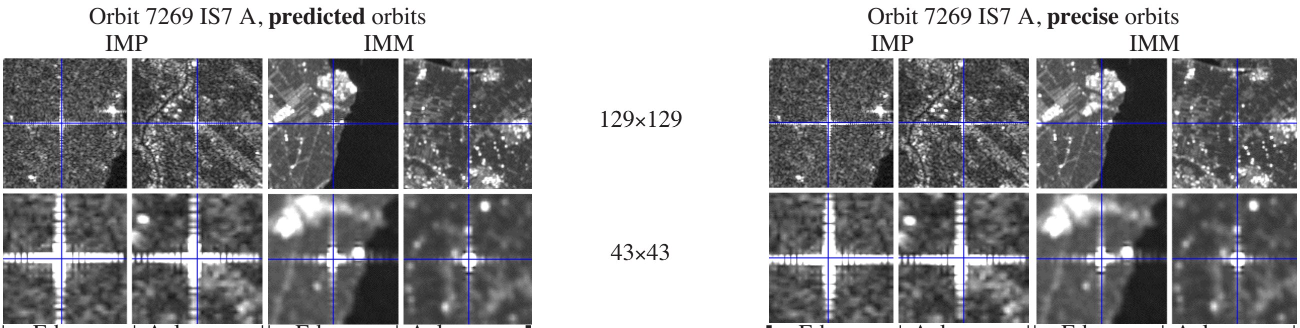
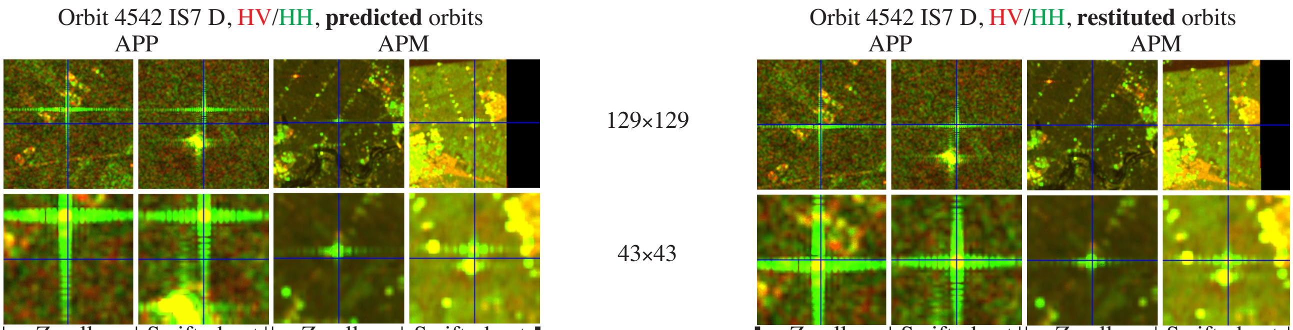


Figure 5: Automatic Medium Resolution IMM Product Terrain Geocoding - Zürich, Switzerland



Edam	Aalsmeer	Edam	Aalsmeer		Edam	Aalsmeer	Edam	Aalsmeer
-0.23	-0.31	-0.08	-0.13	**Az Offset** [Samples]	-0.98	-1.02	-0.20	-0.27
-0.05	0.93	-0.21	-0.08	**Rg Offset** [Samples]	-0.46	0.49	-0.31	-0.15
249	181	43	30	**SCR**	257	182	43	30

Figure 6: Geometry Validation for IMP and IMM Products - Prediction vs. Measurement for Flevoland Transponders



Zwolle	Swifterbant	Zwolle	Swifterbant		Zwolle	Swifterbant	Zwolle	Swifterbant
13.67	14.10	2.21	2.32	**Az Offset** [Samples]	-1.53	-1.10	-0.30	-0.24
0.07	-0.67	0.16	-0.01	**Rg Offset** [Samples]	0.30	-0.38	0.17	-0.01
203	144	40	35	**SCR**	201	128	40	35

Figure 7: Geometry Validation for APP and APM Products - Prediction vs. Measurement for Flevoland Transponders

vided in a ground range geometry, either with a precision processing (IMP and APP), or as a medium resolution strip-line product (IMM, APM). The latter products may have long swaths with multiple slant/ground range polynomials that must be properly treated during terrain geocoding to ensure accurate results. Automatically terrain-geocoded IMM images of the Swiss Alps are shown in Fig. 5. Note that the foreshortened/layover areas appear to be properly stretched, giving qualitative evidence that the multiple polynomials were correctly interpreted. To cross-validate the IMM and APM products, IMP/IMM and APP/APM product pairs of Flevoland were processed using the same state vectors. Predicted and measured transponder positions are juxtaposed in Fig. 6 for IMP/IMM and Fig. 7 for APP/APM. Note the consistently good predictions for both product types. The IMP and APP product types always include only a single slant/ground range polynomial transformation. Errors are not significantly larger for the IMM and APM product types - the actual image position measurement is noisier due to the lower resolution, also reducing their signal to clutter ratio. Large azimuth errors occurred (as expected) when the poorest quality state vectors (flight segment predicted) were used (see Fig. 7). Measured shifts scale roughly by the relative processed image resolution (APM ~75m vs. APP ~12.5m). Overlaying images acquired in differing modes would require radiometric normalisation, including compensation for terrain-induced variability of local illuminated area and elevation antenna gain pattern (AGP) [10].

Wide Swath Mode (WSM)

Multiple ground/slant range polynomials are present in WSM products (as also in IMM and APM products): they appear to be correctly interpreted by RSL's terrain geocoding software, as illustrated by the proper streching of layover regions in the Alps visible in Fig. 8.

The location of the ASAR transponders was predicted for two WSM products acquired over the Netherlands - see Fig. 9. The Aalsmeer transponder was outside the acquired area during orbit 9330, and Swifterbant appears not to have responded during either data take. The visible transponders could all be predicted to within two sample accuracy despite the poor quality of the state vectors (flight segment predicted).

CONCLUSIONS

Terrain geocoding has been tested on all ESA ASAR product types (slant and ground range), aside from global monitoring (GM) and browse products. Image mode (IMS, IMP, IMM), alternating polarisation (APS, APP, APM), and wide swath (WSM) images have all been validated. The standard ellipsoid geocoded products (IMG, APG) were not treated here - earlier results [8] show errors broadly consistent with those of IMS products from the same acquisition. The WS-SLC (WSS) product currently under development [2] is yet to be tested. For the medium resolution ground range products (IMM, APM, WSM), it was necessary to integrate knowledge of azimuth dependent ground/slant range polynomials into the SAR terrain geocoding software. Concerning the ASAR geometry, all test products received to date processed using precise orbit state vectors and the new sampling window start time (SWST) value have shown differences between image location measurement and prediction of less than a single range sample.

Investigations of possible systematic azimuth biases are ongoing. Since the SWST bias correction was integrated in production (PDS) on Dec. 12, 2003, range prediction is routinely accurate to the sub-pixel level. Predictability of target image location within ASAR image products is very high - better than experience with other radar sensors. This result is encouraging, as it opens possibilities for ground control point (GCP) free terrain-geocoding and simplified interferometric processing.

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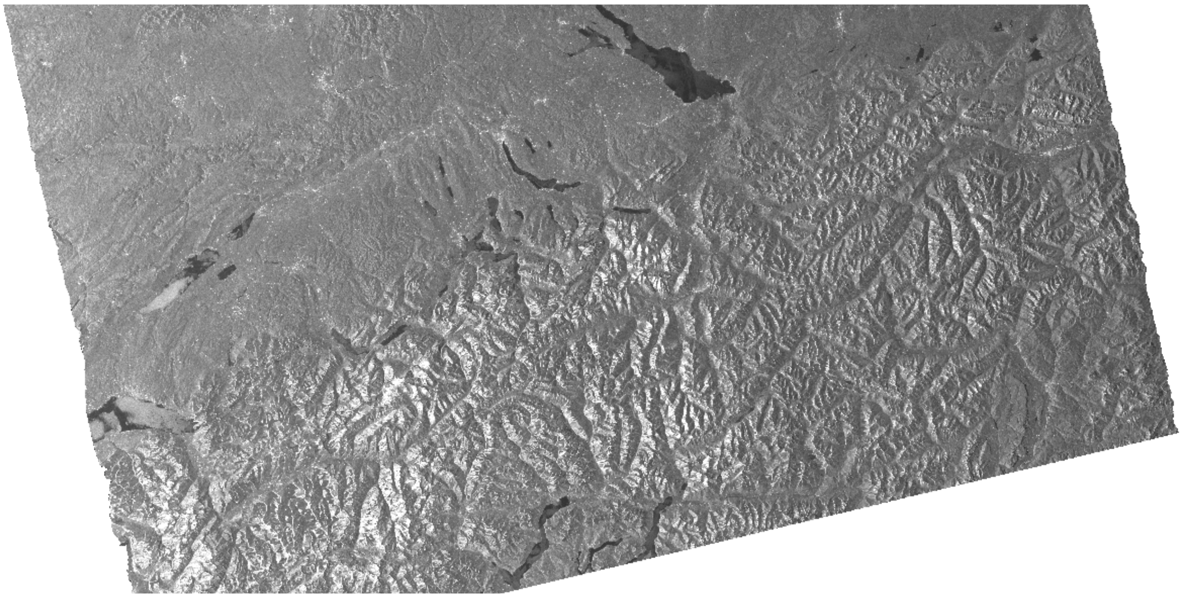

Figure 8: Terrain-geocoded Wide Swath (WSM) Product - Southern Germany, Austria & Switzerland (2003.01.15)

(a) WSM - Orbit 9330, predicted-quality state vectors (b) WSM - Orbit 9373, predicted-quality state vectors

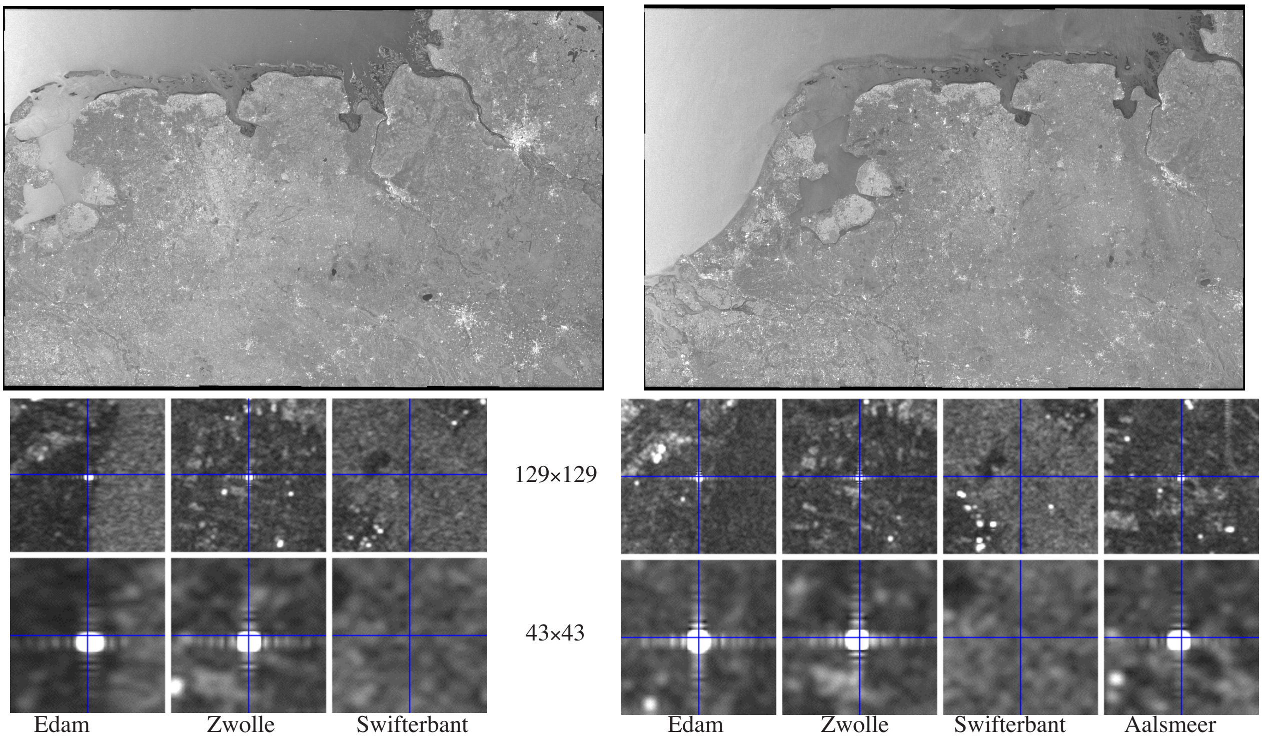

Figure 9: WSM Transponder Predictions vs. Measurements: Flevoland, The Netherlands - (a) Orbit 9330, (b) Orbit 9373