Geometric, Radiometric, Polarimetric and Along-Track Interferometric Calibration of the new F-SAR system of DLR in X-Band.

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Abstract

Since November 2006, DLR operates F-SAR - a new airborne SAR sensor beside its experimental airborne SAR sensor E-SAR. F-SAR is a totally new development utilizing most modern hardware. It is presently operated in X-band and has been supplemented recently being fully polarimetric. F-SAR already accomplished several flights and acquired SAR data in different operation modes, amongst others in along-track-interferometric and full polarimetric mode. Several data takes were acquired at the Kaufbeuren calibration site where eleven permanently deployed corner reflectors are used for calibration. The paper describes the X-band subsystem calibration of F-SAR in geometric, radiometric and polarimetric terms and for along-track interferometry.

1 Introduction

In the last decades, Synthetic Aperture Radars have demonstrated already that they can keep up with optical sensors not only in supplying brilliant images, gray scaled or even colored. They are measurement instruments primarily and, hence, they must be calibrated in order to provide reliable results [1]. The range of applications for SAR instruments is evolving fast. According to its origin from RADAR (radio detection and ranging), SAR measures the distances to objects on ground and also their radar brightness. The geometric calibration of SAR systems ensures that all objects on ground are imaged at the expected position in the SAR image. Via radiometric calibration it is verified that the SAR system images radar brightness to an extent expected from theory according to the radar equation [2]. Furthermore, modern SAR instruments measure more than traditional radars. For example polarimetric channels enrich possible applications for SAR instruments. Properly relating and balancing the polarimetric channels amongst each other is called polarimetric calibration. It minimizes imbalance and crosstalk between polarimetric channels. Another SAR application is for interferometric measurements which can be done across-track (XTI) or along-track (ATI). F-SAR, the new airborne SAR operated by DLR [3], has so far only been used for along-track interferometry. Calibrating the system for ATI measurements is crucial in having success using ATI based detection techniques.

2 F-SAR X-Band Calibration

2.1 F-SAR Data Processing

Two SAR processors for F-SAR are presently maintained at the DLR Microwaves and Radar Institute, Oberpfaffenhofen. One is the new F-SAR processor currently under developement in C++ language for large data volumes and fast throughput. The other one is the long-serving, approved E-SAR processor adapted to the new data format, new features and requirements and new possibilities that F-SAR data offer. This two-sided approach allows us to quickly verify the proper functioning of the new system and its new processor but also to calibrate the new system on one hand and to create a new, faster processor at the same time for coping with the high data volume and being future-proof.

2.2 Geometric Calibration

The first important step in calibrating F-SAR was the verification that GPS time and radar data synchronization works well. It allowed us applying motion compensation to F-SAR data such that fully focused F-SAR images could be processed right from the first data acquisition. The GPS time synchronization, moreover, determines the SAR image position in a georeferenced coordinate system in along-track direction. The determination of locations imaged in the SAR data in the across-track direction depends on the topography and the exact knowledge of all signal delays: range delay and chirp delay (being adjusted by the radar operator) and internal delays which are unknown a priori. We used eleven permanently deployed trihedral corner reflectors of sizes between 0.70m to 1.50m spread across range at Kaufbeuren airfield, our new calibration site near Oberpfaffenhofen, for measuring the unknown constants. They depend on the signal transmit and receive paths inside the F-SAR X-band subsystem, the signal bandwidth and the system temperature. Assuming that the system temperature is constant after warm-up, we determine internal delays in fixed operation modes for all bandwidths being used in that mode. The following calibration relevant modes have been operated so far:

- *SingleChannel mode (VV)*
- *FullPolarimetric mode (HH-HV-VV-VH)*

- *ATI Pseudo4Channel mode (VV1-VV2-VV3-VV4)*
- *ATI Real2Channel mode (VV1-VV2)*
- *TerraSARListenOnly mode (H1-H2)*

Each operation mode is characterized by the set of used transmit and receive paths inside the X-band subsystem (identified via IDs), the transmit and receive antennae (also identified via IDs), and the used chirp bandwidth which is presently 100, 200 or 300 MHz.

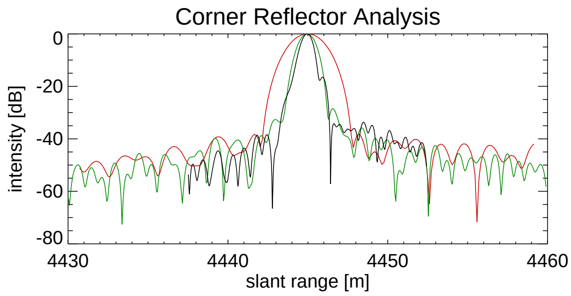

Figure 1: *Performance check at a corner reflector. Achieved resolutions: 2.10m, 1.05m and 0.70m with 100 MHz, 200 MHz and 300 MHz Hamming weighted spectra (red,green,black). The used chirp replica for 300 MHz is not yet reliable.*

The *SingleChannel* mode is purely monostatic, it transmits and receives with a V-polarized antenna, the *FullPolarimetric* mode transmits and receives with two H/V-polarized antennae. The ATI modes transmit via a separate transmit antenna and receive the signal via two receive paths in two receive channels (*Real2Channel*) or from four antennae in two receive channels via switching from pulse to pulse (*Pseudo4Channel*). The *TerraSARListenOnly* mode must also be calibrated for balancing the two receive channels in terms of absolute and differential delays, receive antenna patterns and channel phase differences.

	100 MHz	200 MHz	300 MHz
SingleChannel	1.340	34.129	3.842
Pseudo4Channel	-1.328	31.294	n/a
Real2Channel	tbd	n/a	n/a
FullPolMode	-9.084	23.213	-5.937
TerraSARListen	tbd	n/a	n/a

Table 1: *Internal delays [nsec] for several F-SAR operation modes, required for proper image localization in geographic coordinate systems.*

In total, we require so far the determination of 5 overall internal delays, one for each mode (**Table 1**). Also required are differential delays between channels such that all channels are exactly co-registered to each other: Additionally 3 differential internal delays for the *FullPolarimetric* mode, 3 for the *Pseudo4Channel* mode, 1 for the *Real2Channel* mode and 1 for the *TerraSARListenOnly* mode. With 3 different chirp bandwidths, the overall internal calibration task adds up to the determination of 39 delay constants for the above mentioned modes. Note that for the determination of one internal delay more than one data take should be processed to confirm the estimated value. Exemplarily, we list the determined differential delays for the *FullPolarimetric* mode in **Table 2**. They are used for fine coregistration among the polarimetric channels. Note, that due to the different transmit-receive path combinations there is obviously a shorter path for HH than for VV.

	100 MHz	200 MHz	300 MHz
X-HH	-1.42651	-1.328	-1.328
X-HV	0.	-0.011	0.027
X-VV	1.06724	1.102	1.298
X-VH	0.	-0.068	0.001

Table 2: *Determined differential internal delays [nsec] for the FullPolarimetric mode, required for fine channel coregistration*

2.3 Chirp Replica

When calibrating a SAR system, especially for coregistering different channels to each other, it is crucial to achieve the best possible SAR focusing. Focusing with a nominal chirp function instead of using the actually transmitted chirp is not enough here any more. Due to amplitude variations and a non-ideal phase history of the chirp signals, there might be imbalances on the individual scatterer sidelobes (**Figure 2**).

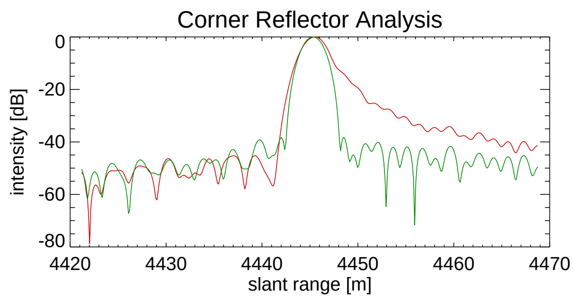

Figure 2: *Processing with nominal chirp (red) and chirp replica (green), resolution: 2.10m (100 MHz)*

For that reason we measured and prepared chirp replicas especially adapted to the different chirp bandwidths and transmit-receive paths in the laboratory. As a result of that, the sidelobes are now balanced, thus better suppressed and a better focusing is achieved.

2.4 Radiometric Calibration

The internal calibration of a SAR system requires retracing all signal amplifications and attenuations in the SAR system such that the amount of backscatter of known objects (such as corner reflectors) can be exactly predicted from system settings. External calibration (e.g. corner reflectors) can be used to calibrate the system: We adjusted the system radiometrically such that the acquired data can already be used in miscellaneous studies amongst others also for velocity measurements in ATI modes. Furthermore, we remove antenna patterns varying with the aircraft roll angle from the data. By that we verified that the elevation antenna patterns measured in the laboratory are correct and can be used (**Figure 3**) for radiometric calibration.

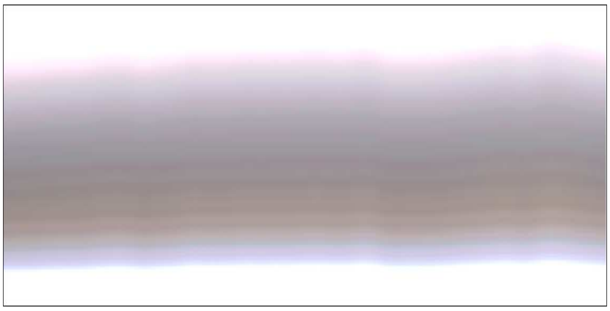

Figure 3: *Antenna pattern, range trend and constant gain offset correction matrix (azimuth: left to right, near range: below) in three ATI channels (red=VV1, green=VV3, blue=VV4)*

2.5 Polarimetric Calibration

The polarimetric calibration of a SAR system aims for minimizing crosstalk between H and V polarizations as well as minimizing the channel imbalances in amplitude and phase. For that, it is necessary to solve an equation system to obtain a solution for 6 (complex valued) unknowns from polarimetric SAR measurements: two imbalance components and four crosstalk components [1]. Once determined, the solution is then used to turn observed scattering matrices into calibrated scattering matrices.

	Before	**After**
$abs(r_{VV}t_{HH}/r_{HH}t_{VV})$	0.978765	0.999905
$arg(r_{VV}t_{HH}/r_{HH}t_{VV})$	-14.85°	0.008399°
$abs(r_{VH}/r_{HH})$	-32.57 [dB]	-36.80 [dB]
$abs(t_{VH}/t_{VV})$	-26.57 [dB]	-36.68 [dB]
$abs(r_{HV}/r_{VV})$	-26.57 [dB]	-36.69 [dB]
$abs(t_{HV}/t_{HH})$	-32.57 [dB]	-36.79 [dB]

Table 3: *Determined polarimetric calibration values, t=transmit, r=receive. For detailed explanations see [4].*

Usually, the equation system cannot be solved straight forward but a number of assumptions must be made in order to solve the system unambiguously. The iterative approach in [4], however, only requires the assumption of symmetry between HV and VH channel - which applies to F-SAR. Then the system can be solved in order to retrieve 5 unknowns, the sixth unknown (total imbalance between HH and VV) is determined on a trihedral corner reflector. **Table 3** lists the measured entities together with the result of their application to the same data set for calibration. As can be seen in the table, there is nearly no crosstalk before calibration and the transmit/receive imbalance is small in amplitude. It is worth, however, compensating the phase imbalance of nearly 15 degrees. Furthermore, we remove differential phase variations in range between the polarimetric channels. Those would be very disturbing in any polarimetric analysis. They are an implication of multipath effects at the aircraft body. **Figure 4** shows the equivalent effect in differential ATI channels. Channels HV,VV, and VH are phase corrected using the differential phase curves of (HH/VV)/2, HH/VV, (HH/VV)/2, respectively. In general, the F-SAR system appears stable in amplitude and phase from near to far range with amplitude imbalances of no more than +/-1 [dB] and phase imbalances of +/-8 [deg]. This could be verified at the deployed corner reflectors. **Figure 6** shows details of a first full polarimetric F-SAR image.

2.6 ATI Mode Calibration

Along-track-interferometry (ATI) allows measuring ground velocity fields or ground moving target indication (GMTI) [5] and velocity estimation [6] within the constraints of SAR system design, ATI calibration, and dedicated interferometric SAR processing. An ATI interferometer is realized by mounting at least two antennae at different positions along the flight track at the aircraft body. F-SAR presently uses four receive antennae equidistantly mounted at the aircraft body in flight direction. The last antenna is optionally mounted at a larger distance (3cm) in order to additionally resolve ambiguities.

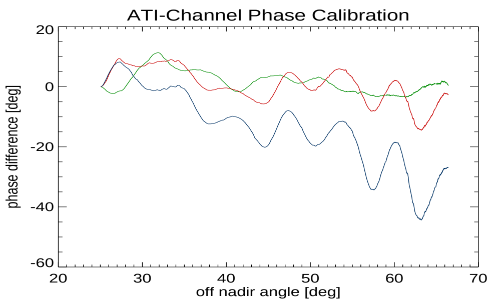

Figure 4: *A priori phase differences in F-SAR ATI channels: red=VV1-VV2, green=VV1-VV3, blue=VV1-VV4, varying with range.*

Clutter suppression techniques like DPCA and STAP only work well if any phase and magnitude imbalances between the receiving channels are removed a priori. Thus, phase and amplitude differences must be determined in ATI calibration (**Figure 4**) such that they can be removed with ATI processing. A feasible technique for digital channel calibration has been proposed by Ender [5]. This technique is named adaptive 2D-calibration and it operates in the wavenumber domain. The complex images acquired with different channels are iteratively adapted to a reference image, for example to the image of channel 1. As input images for the calibration procedure fully focused SAR images as well as range compressed images can be used (see **Figure 5a**). Moving target signals become visible after clutter suppression. Their phases are preserved and so motion parameter and position estimators can be applied successfully. In general it is not possible to fully suppress scattered signals of strong stationary targets (see **Figure 5b**). An overlay of the range compressed DPCA image on a common SAR image is shown in **Figure 5c**. Strong stationary target signals (such as corner reflectors) might cause false detections. However, these false detections can partially be removed during the parameter estimation steps where also plausibility checks are performed. **Figure 5d** shows three moving cars detected in the VV1-VV2 difference channel automatically re-placed to their original position. The cars were part of a dedicated GMTI campaign but no auxiliary knowledge has been used here for positioning the cars. The positions are estimated from zero-crossings of a non-coregistrated DPCA-ATI phase ramp.

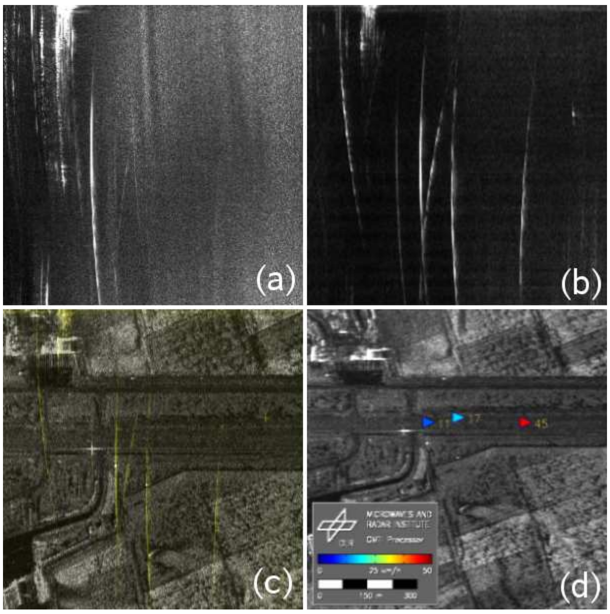

Figure 5: *(a) Range compressed data of a single channel (strong target is a corner reflector), (b) Clutter suppressed DPCA data after adaptive 2D-calibration, (c) DPCA data overlayed (yellow) on a SAR image and (d) Moving targets re-placed to their original position, color coded velocities of 11, 17 and 45 km/h.*

3 Conclusions and Outlook

The paper summarizes all F-SAR calibration efforts so far. We verified raw data burst to GPS time synchronization, determined internal delays and differential internal delays for the co-registration of channels, measured antenna patterns and removed them successfully from the radar data. Chirp replica have also been measured and prepared for processing. Their application helped balancing point scatterers sidelobes. However, F-SAR calibration can still be improved. It will be completed in connection with internal calibration work which will provide the required parameters in an automated way. The internal calibration must be verified, inter-channel coregistration can be improved further, chirp replica have some potential for improvement and some internal delays must still be determined.

4 Acknowledgements

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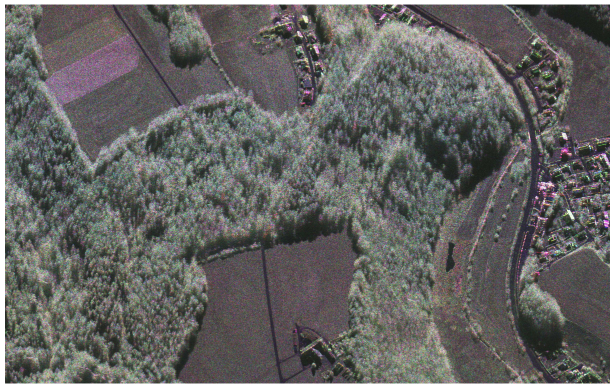

Figure 6: *Calibrated fully polarimetric F-SAR image (detail), X-band, channel sequence RGB = HH-HV-VV, multi-look resolution* 1.00×0.60 *m (az × rg), looks* 4×1 *(az × rg), bandwidth 300 MHz Hamming weighted*

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