Bistatic exploration using spaceborne and airborne SAR sensors: A close collaboration between FGAN, ZESS, and FOMAAS

J. H. G. Ender, J. Klare, I. Walterscheid,
A. R. Brenner, M. Weiß,
C. Kirchner, H. Wilden

FGAN
Research Institute for High Frequency
Physics and Radar Techniques (FHR)
Neuenahrer Str. 20, 53343 Wachtberg, Germany
Email: ender@fgan.de

O. Loffeld[1], A. Kolb[1], W. Wiechert[2],
M. Kalkuhl[2], S. Knedlik[1], U. Gebhardt[1],
H. Nies[1], K. Natroshvili[1], S. Ige[1],
A. Medrano Ortiz[1], A. Amankwah[1]
[1]Center for Sensor Systems (ZESS)
[2]Research Center for Multidisciplinary Analysis
and Applied System Optimization (FOMAAS)
Paul-Bonatz-Str. 9-11, 57068 Siegen, Germany
Email: loffeld@zess.uni-siegen.de

***Abstract*— Following the goals of our cooperation treaty between FGAN and ZESS (University Siegen), we work closely together on the complex research field of bistatic exploration. Single tasks of the overall topic are for instance experimental missions, processing, image formation, position- and attitude estimation, synchronisation, simulation, parameter estimation, and visualization. This paper presents an overview about the common projects of FGAN, ZESS, and FOMAAS.**

I. Bistatic Exploration

The methods of remote sensing, surveillance, and reconnaissance have been fundamentally improved by new developments and applications of synthetic aperture radar (SAR) in the last decades. Large areas on Earth can be imaged with highest resolution independent on weather and time of day.

In a next step, new and promising applications might evolve with the development of bi- and multistatic SAR systems. In comparison with monostatic SAR systems, bistatic SAR can improve the classification of the investigated area by varying the bistatic angle. On the one hand, if the radar cross section of particular features is small in the monostatic case, one might find bistatic angles, with an enhanced RCS in the bistatic case, which would make these features visible. On the other hand, the di- and polyhedral effect (especially in urban areas), which outshines details in monostatic images, can be reduced by using bistatic SAR.

With the choice of a proper geometry, one could even image in flight direction or backwards, which is impossible with usual monostatic SAR systems. This might result in new applications in aviation by imaging obstacles (e.g. mountains) in flight direction which are covered by fog, rain or clouds. With such future systems, one might even improve the safety of landing airplanes by imaging the runway in dirty weather conditions.

Another advantage of bistatic SAR systems is the cost reduction. One could use small, inexpensive, and passive receive-only-systems which don't need expensive an heavy transmit electronics. Additionally, this leads to a lowering of energy consumption for the passive systems and allows for instance the implementation of receive-only SAR systems in small UAVs (Unmanned Aerial Vehicle).

Moreover, the use of monostatic SAR systems in conflict areas is only suitable to a limited extent because of the active illumination of the scene. With bistatic SAR one can deploy the transmitter on a satellite or a high flying airplane while the receiver can be used close to the operational area.

In summary, with the progress in the development of new bistatic SAR systems and algorithms, many new applications might evolve.

II. Collaboration between FGAN, ZESS, and FOMAAS

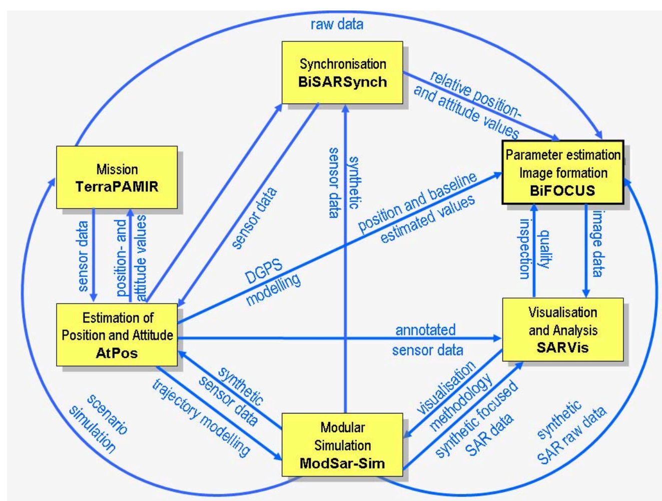

Fig. 1. Interplay between the six topics of the 'bistatic exploration' project.

The common project 'bistatic exploration' of FGAN, ZESS, and FOMAAS is supported by the German Research Foundation (DFG) and displays an important exploratory focus in North Rhine-Westphalia. The overall topic is subdivided into several parts (Figure 1). Scientific teams at all three institutes work closely together in order to cover many aspects of this complex working field. Sophisticated bistatic SAR experiments as well as the development of new algorithms to focus bistatic SAR images in a high quality are the main topics of the whole project in conjunction with synchronisation, position and attitude estimation, simulation, and visualisation. Already several publications within the context of bistatic SAR were published by the institutes (e.g.: [1]–[28]). The overall project 'bistatic exploration' is intended to last about four years, starting in summer 2006.

A. Bistatic spaceborne/airborne SAR experiments

An announcement of opportunity was opened for the scientific use of the TerraSAR-X satellite by the carrier DLR in June 2005. The proposal of FGAN/FHR (department ARB) to conduct hybrid spaceborne/airborne bistatic SAR experiments between TerraSAR-X and PAMIR is one of the selected projects (Figure 2).

Fig. 2. Artist impression of the planned hybrid bistatic spaceborne/airborne SAR experiments between TerraSAR-X and PAMIR.

TerraSAR-X is a new German radar satellite developed in a public/private partnership by EADS-Astrium und DLR. The satellite will be launched at the end of 2006. It will be operated in a 515 km high orbit and has a scheduled lifetime of at least 5 years. The technical outstanding instrument is the active, high-resolution X-band SAR system, with the operational modes Strip-Map, Spotlight, and Scan-SAR. It will be possible to obtain an image resolution down to 1 m.

PAMIR is a state-of-the-art airborne experimental X-band SAR system which was developed and built by FHR/FGAN. This system combines multi-mode ability with highest resolution. Basic operational modes are Strip-Map, Spotlight, Sliding Spotlight, 3D-IfSAR, Scan MTI, and ISAR. An image resolution in the sub-dm range is possible.

FGAN/FHR gained already much experience with conduction bistatic airborne/airborne SAR experiments using PAMIR and its precursor AER-II (Figure 3). Data of these experiments were used to process high resolution bistatic SAR images.

Following our proposal mentioned above, FGAN/FHR will carry out several hybrid bistatic SAR experiments within the years 2007 and 2008. First experiments will be conducted with a special prepared test site to demonstrate the feasibility of this technique. In subsequent experiments, the complexity of the imaged scene will be enhanced in combination with different and more sophisticated flight geometries.

Fig. 3. Bistatic airborne/airborne SAR experiment with PAMIR and its precursor AER-II.

The flight velocity of TerraSAR-X will be 7,6 km/s, resulting in about 15 revolutions around the Earth per day. This high satellite velocity results in a very short illumination (just seconds) of the scene to be imaged. Thus, the space-time synchronization of the antenna footprints will be a methodical and technological challenge. To reach this aim, a high precision knowledge of the TerraSAR-X trajectory is necessary. Beside information provided by the carrier DLR, this task will be supported by the FHR tracking and imaging radar TIRA. The determination of the trajectory of the airborne platform will be done using DGPS and INS.

Since the overlap of both antenna footprints will last just seconds, another challenge will be the optimization of different flight geometries in order to maximize the time of data acquisition in conjunction with a high image quality.

The multi-channel SAR system PAMIR allows to use one channel for the reflected radar echoes and another one for the direct TerraSAR-X signal. The direct signal enables to trigger the data acquisition and to calibrate the bistatic SAR data in post-processing.

B. Parameter estimation and Image Formation

The acquired raw data of the bistatic hybrid SAR experiments will be processed in parallel at FGAN and ZESS. Both institutes have already gained experience in focussing bistatic SAR data from a bistatic airborne SAR experiment (Figure 3) [3], [13], [17], [24]. FGAN and ZESS have developed two different approaches to focus bistatic SAR data. Now, it has to be proven if both algorithms are suitable to process also data from an extreme bistatic constellation like the proposed experiment between a satellite and an airplane. Beside these algorithms, also other focussing approaches will be investigated. The knowledge of some particular processing parameters is essential for the focussing task. One of the most important information is the precise knowledge of the attitudes and flight trajectories of TerraSAR-X and PAMIR during the acquisition time. Then it will be possible to implement a motion compensation algorithm in the software processor which will improve the focussing results significantly.

An additional calibration of the total system will further improve the image quality. This can be done by internal and external calibration methods with active and passive calibration targets. The aim of the calibration tasks will be to find a transfer function of an inverse filter, which will equalize the received signal as much as possible.

As indicated earlier, bistatic focussing, especially for such extreme constellations, as the hybrid spaceborne/airborne experiment will constitute, cannot be accomplished with monostatic approaches. The exact analytic solution of the bistatic focussing problem does not seem to be available, hence approximate or purely numerical solutions come into the focus. Both approaches of FHR and ZESS use the principle of stationary phase to derive a bistatic processor. While FHR determines the point of stationary phase and all successive functions in a numerical way, ZESS uses a Taylor series decomposition to determine the bistatic point of stationary phase in an approximate, but nevertheless analytical way. Theoretical limits of the validity have been formulated in [13], but nevertheless have to be verified in this challenging experiment. On the other hand, it will be very interesting to find out, how the purely numerical solution will be capable of handling the range and azimuth varying nature of the bistatic focussing task.

In order to achieve sufficient azimuth scene extension and at the same time sufficient azimuth bandwidth, TerraSAR-X will be operated in sliding spotlight mode during the experiment and PAMIR will operate in some accelerated strip mode, chasing TerraSAR-X's antenna footprint. This will, however, create rather non trivial focussing parameters such as (e.g.) a time varying Doppler centroid between plus/minus 3 kHz over the azimuth scene. This is only one example for the massive time varying nature of the processing parameters.

C. Position and Alignment Estimation and Synchronisation

Bistatic radar systems demand a highly accurate synchronisation in space and time. To produce high quality SAR images, a precise position and alignment estimation of both platforms is essential. The needed accuracy has to be an eighth of the wavelength, meaning about 3.8 mm in X-band. The aim of the project BiSARSynch is, to realise a dedicated navigation unit which will be able to provide the relative platform position and orientation of the receiver in relation to the transmitter in realtime. For this, a navigation unit with 4 subunits will be installed on each platform. Due to the slightly different travel time between the navigation subunits (Figure 4) the position and alignment of the platforms can be estimated [28].

In remote sensing applications using bistatic SAR it is a big challenge to determine the platform position and attitude with a small time delay in order to guarantee an antenna footprint overlap despite the different platform trajectories and velocity vectors. A solution of this problem will be given within the AtPos project by considering a data fusion approach that is based on dynamic modeling. Raw data derived from a network of GPS receivers, gyroscopes, and accelerometers as well as other redundant position and attitude information (e.g., from baseline measurements, other GNSS and appropriate services) will be integrated. The focus of AtPos is positioning and attitude determination with the required accuracy, reliability, and near real-time capability at low cost.

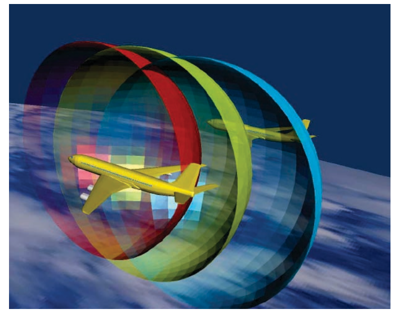

Fig. 4. Artist impression of BiSARSynch

D. Simulation and Visualisation

To support the evolution of new signal processing algorithms, mission planning as well as further tasks for bi- and multistatic SAR missions a suitable flexible and powerful simulation tool is fundamental. The basic philosophy of the simulator [8] is to provide a freely configurable framework to simulate user-defined SAR scenarios with less expense (Figure 5). Complex bi- and multistatic SAR missions take place in corporation of several satellites and/or airplanes. In every SAR scenario reusable modules are found (e.g. carrier platform, SAR devices, GPS, star tracker, laser ranger, etc.). This leads to the idea of a set of building blocks to flexibly assemble a wide variety of different scenarios. The simulator framework consists of three main components: The Computing and Control Unit includes all mathematical models of the satellite trajectories, antenna pointing strategies and position

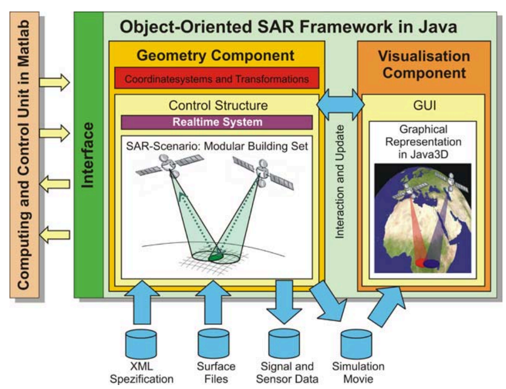

Fig. 5. Architecture of the modular SAR-framework

estimators. Additionally this unit assumes the control of the simulator. The autonomous Geometry Component contains the modular representation of all physical objects in the system respectively in the scenario and administrates all issues concerning geometrical attributes. The Visualization Component is used to visualize the simulation results, for debugging and to illustrate the scenario and all significant parameters.

Another important aspect will be the visualization of SAR data. SAR images possess some specific properties, that make an interactive visualization a non-trivial task. Especially the high dynamic range in combination with significant speckle noise is very challanging for real-time visualization.

The adoption of modern graphic cards allows to shift complex image processing and visualisation algorithms from the CPU to the GPU (Graphics Processing Unit). Utilizing so-called *data streaming approaches* in combination with pre-computed meta-data aims to efficiently perform local operations to enhance and explore SAR images (see Figure 6). The final goal is an visualisation that allows the user to navigate through the SAR images in real-time. Additionally, the user will have the possibility to adapt various visualisation parameters, e.g. to improve specific data ranges or to conduct quantitative evaluations on the data, in an interactive manner.

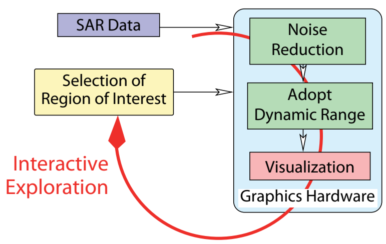

Fig. 6. Conceptual SAR data processing on the GPU

III. Conclusions

The ambitious field of bistatic exploration opens new horizons for various remote sensing applications in the future. The close cooperation between FGAN, ZESS, and FOMAAS covers many important aspects which are needed to accomplish the demanding methodological and technological deviances.

IV. Acknowledgments

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