Possibilities of Combining Images from a Synthetic Aperture Radar with Digital Maps and Other Geolocated Images

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ABSTRACT
The present study describes main features of the joint use of Radar Images (RI) and high-resolution digital maps and other geo-referenced images of the terrain. The main ways to implement the combination of images are described and the major factors affecting the accuracy of image alignment using the parameters of the navigation system and radar are estimated. A method for the automatic alignment of image data and processing of the results to refine the alignment and correction of parameters for the source location is proposed. Each of the stages of the proposed methodology is closely analysed: The formation of reference images, dispelling geometric distortions, filtering, segmentation and delineation of radar image and the implementation of the search reference images on processed radar images. The results of the implementation of the proposed algorithms using radar and optical images of the terrain are presented. The formulas for the correction of the parameters of the navigation system by measuring the discrepancy between the prior and posterior position of reference images based on a series of measurements are given.

Key words: Digital image processing, combining images of different spectral bands, radar images, synthetic aperture radar, correlation-extremal navigation systems, digital terrain maps

INTRODUCTION
Today Synthetic Aperture Radars (SAR) are widely used in aviation in reviewing the earth's surface. The synthetic aperture antenna is one of the most promising areas of the radar. The main advantage of this trend is repeated increase (by 1000 times or more) in the angular resolution of a conventional radar due to the formation of an artificial antenna aperture as a result of the in-phase summation of the electromagnetic wave incident on a real antenna when moving the SAR platform. In this case, the SAR provides high resolution and obtains detailed radar images of the observed surface and objects regardless of weather conditions and time of the day (Kondratenkov and Frolov, 2005). However, errors in the determination of the navigation parameters and parameters of the SAR can lead to significant errors when combining SAR radar images and maps of the area which greatly complicates the analysis of the shared information.
There are currently a large number of image processing methods of various physical natures (Gonzalez and Woods, 2006; Baltasavias, 2004). Highly detailed radar images (and as a consequence, a large number of pixels of reference image objects) allow the use of correlation methods for solving problems by assessing the correlations between the following objects:

- Radar image and Digital Terrain Maps (DTM)
- Radar image and optical image
- Current and reference radar image
- Radar images obtained at different times

The following problems of the field can be resolved with correlation methods:

- Evaluation of flight navigation parameters of the SAR carrier
- Implementation of the correction for Inertial Navigation Systems (INS) (discrete-continuous, using the Kalman filter)
- Detection and identification of lumped and distributed objects
- Combination of SAR images with digital maps and other geo-referenced images of areas with high accuracy

The purpose of this study is to develop a uniform methodology for co-processing images of different physical natures (SAR and digital map images) to determine the position of objects on them, implement the results in visualisation problems and clarify the parameters of the location of aircrafts with the SAR based on advanced image processing techniques.

MATERIALS AND METHODS

The combination of digital maps with radar images can be used for navigation and information problems, as well as to increase the information in the systems of air-based review of the earth’s surface (Li, 2014). In this case, the indicator combines radar image with a digital terrain map or landforms. This allows the crew, if necessary, carry out flight on a route without the use of ground-based navigation aids and visual examination of the area under the aircraft. When radar image and the DTM are combined it facilitates the determination of compliance between features on radar images and objects on the map. Data display is performed in real time.

The combination of digital maps with radar images can be realised in three ways: Navigation, automatic and manual (Kondratenkov et al., 2007). The easiest way to implement is the navigation method. Its implementation is also the primary step in the functioning of other methods. When using it, there is a ‘superposition’ of radar images to DTM in a single projection (the same coordinate systems and scale) in the parameters of the navigation system. In the case of the low accuracy of the navigation systems of the aircraft the disadvantage of this method is low accuracy of image alignment.

Higher accuracy is obtained using the manual method of implementation. In this method, the operator on the alignment of radar image and DTM parameters in navigation manually assigns landmarks and the refinement of the parameters is performed for them. The simple linear shift of radar images relative to the map is possible as well as its re-conversion, eliminating non-linear distortion between images.
The automatic refinement of combining does not require an operator, since the matching of search points in the images is performed by software. The main difficulties in the creation of automatic alignment algorithms are primarily differences in the physical principles of obtaining an optical (topographic) and radar images. Furthermore, RI of most objects essentially depends on the season (due to the presence of leaves, snow, etc.) and the coating condition (humidity). RI of objects (especially small-scale) contain random components—in particular there is large influence of speckle noise. Therefore, for the practical implementation of the algorithm of automatical radar images and DTM combining it is necessary to provide reference points with stable performance of reflection, or to produce records of their condition. The practical difficulty of combining DTM with radar images is mainly caused by the instability of the radar contrast field and the complexity of building a reference field.

**Accuracy of the initial alignment:** Specification of the accuracy of initial alignment of radar images and DTM were considered. The main factors that cause registration errors are the following:

- Error in determining the height of the plane $H$ causes the error of combining equal to:

$$
\sigma_H = \frac{H}{\sqrt{D^2 - H^2}}
$$

where, $D$ is distance to the formed frame of the radar image. The effect of this value is significant for the formation of radar images on small distances at high altitude of the radar carrier.

- Accuracy and attention to detail of digital maps in use. At a resolution of radar images of 10 m a map of scale better than 1:25000 is required in order to perform the alignment. Better resolution requires more accurate site plans (5 m:1:10000).

- Error in determining the boundaries of the frame of radar images. This is primarily determined by the accuracy of the angle sensor of the antenna and may be the value of several minutes. The maximum error due to alignment error increases linearly with distance.

- Error in determining the course of the radar carrier. The dependence of the linear error when combining is similar to the error in determining the boundaries of the frame of radar images and equals the product of range and the error in the determination of the course. Standard Deviation (SD) of the definition of the course of the aircraft is determined by the parameters of the navigation system of the aircraft and increases with increasing flight time.

- Position errors in the ground coordinate system. The presence of errors in determining of the coordinates leads to a linear displacement by this amount of the radar images with respect to the DTM.

The total value of the error of the initial alignment of DTM and radar images, arising from the measurement errors of navigation parameters equals:

$$
\sigma_x = \sqrt{\left(\frac{\sigma_x H}{D^2 - H^2}\right)^2 + (\Delta \sigma_x)^2 + (\Delta \sigma_y)^2 + \Delta \sigma_x^2}
$$
Fig. 1: Functional diagram of the automatic alignment of radar images and DTM

Depending on the conditions of RI the dominance of various components in the given expression is possible. A characteristic mode when combining radar images with the DTM is an overview of the earth’s surface at considerable distances at which altimetry error is minimised. In addition, the accuracy of the location of the aircraft with the use of modern satellite navigation systems is measured in tens of meters. Therefore, the main contribution to the error when determining the location of the radar image on the DTM is introduced by the error in determining the azimuthal direction when forming the frames of radar images.

The implementation of correlation binding methodology allows automatic registration of radar images with digital maps and optical images of areas and ensures the accuracy of the potential mutual binding to the resolution element of radar images. Accuracy depends on many factors: The quality of the formed SAR images, processing procedure parameters, reliability and availability of the DTM and the presence of informative objects on it and fatal geometric distortion between RI and DTM. The accuracy of the order of three bins (Kondratenkov et al., 2007) was obtained in a number of pieces of practical work.

**Algorithms for automatic alignment of radar images with the DTM:** The logic of the automated method of combining radar images with the DTM is shown in Fig. 1. The required reference image of DTM and radar images of the area (the object) is formed on the basis of the parameters of the navigation system.

The main steps in the automatic combination of radar images with MTD include:

- Formation of radar reference images of DTM and their pre-treatment
- Conversion of radar images, taking into account the geometry of the resulting radar image
- Processing of radar images in order to define the area’s objects
- Conducting search of reference images on radar images
- Combination of radar images with a map on the display, or the formation of corrections for navigational coordinates. Furthermore, it is possible to form data for removing the distortion of RI compared to DTM (shown in phantom) based on the results of the reference images search

If the results of search for reference images are only used for the correction of parameters of the navigation system (without indication), then the scheme is a system of autonomous correction of navigation parameters. Each stage was discussed new.
Formation of radar reference images: This step is carried out by the operator or automatically based on the knowledge of the intended flight zone and special reflection properties of objects which can be divided into two groups. The first group includes point objects having a high radar contrast: Power lines, towers, buildings, etc. Allocation of a single reference point is not as efficient as the special arrangement of a number of 'bright' objects, a so-called constellation. The advantages of the algorithm when using point objects is a highly accurate correction equal to the resolution of radar images and the relative ease of implementation. However, the lack of detail in digital maps and high chance of point radiators’ reflection in most cases do not allow to reliably determine the bright point objects on radar images via DTM in advance.

The second group includes extended objects with distinctive shapes, such as hydrography (rivers, lakes and shorelines), roads and settlements. These objects allow an adequate model of radar images to be obtained, based on knowledge of their reflective properties, for further searches on the map. Image is then presented in a binary state, as it is impossible to determine in advance the value of the power of reflection and only about its character can be considered. If the simultaneous use of multiple objects with different reflectivity as reference images is assumed, it is possible to form multi-level reference images, where each level corresponds to the different type of object. Figure 2a and 2b show the allocation of the binary image of the river from the DTM. The position of the reference images in the DTM formed image is assigned according to the form of the auto-correlation function or manually.

In addition to the use of the objects in the formation of the DTM reference images it is also possible to take into account the terrain and to form areas of radio shadows. This factor is especially important in the formation of radar images in areas with significant altitude changes and when the carrier flies at low altitudes. However, when during the implementation one should consider that unlike the images of objects, the formation of the reference images of radio shadow should be made for specific camera angles and altitudes.

Elimination of geometric distortion in RI: Formation of the DTM and RI is implemented in different surfaces in the space, whereby the object images are subjected to significant geometric
distortions. These include rotation, different scales (tension/compression) or perspective distortion. It is thereby necessary to align the images. In general, the mutual deformation is described by projective transformations that are associated with displaying three-dimensional visual information on the two-dimensional surface (Gruzman et al., 2003). To bring the current images to a reference (or vice versa) only a non-linear conversion function can be used, so polynomial approximation function is usually used. Transformation parameters (polynomial coefficients) are calculated by pairs of mutually corresponding points in the images by minimising the mean square error of approximation of actually observed coordinates in the polynomial evaluation. Mutual position of points on the DTM and radar images is computed using the navigation parameters of the aircraft, as well as the parameters of the radar field of view.

Coordinate vectors of reference points of the converted image are based on the calculated or spaced k frames (their number should not be less than 6):

\[ X_{RI} = (x_{R1}, x_{R2}, \ldots, x_{Rk})^T \]
\[ Y_{RI} = (y_{R1}, y_{R2}, \ldots, y_{Rk})^T \]

as well as a special matrix of control points of the reference (mapping) of the image R:

\[
R = \begin{bmatrix}
1 & x_{a1} & y_{a1} & x_{a1}^2 & x_{a1}y_{a1} & y_{a1}^2 \\
1 & x_{a2} & y_{a2} & x_{a2}^2 & x_{a2}y_{a2} & y_{a2}^2 \\
1 & x_{a3} & y_{a3} & x_{a3}^2 & x_{a3}y_{a3} & y_{a3}^2 \\
\vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
1 & x_{ak} & y_{ak} & x_{ak}^2 & x_{ak}y_{ak} & y_{ak}^2 \\
\end{bmatrix}
\]

Transformation parameters (coefficients of polynoms) \( A = (a_0, a_1, \ldots, a_6)^T \), \( B = (b_0, b_1, \ldots, b_6)^T \) are calculated as:

\[
A = (R^T R)^{-1} R^T X_{RI}
\]
\[
B = (R^T R)^{-1} R^T Y_{RI}
\]

where, the superscript T denotes the transpose of the matrix.

Further enumeration calculates the corresponding point of the transformed image for each screen pixel by the equation:

\[
i = a_0 + a_1 r + a_2 c + a_3 r^2 + a_4 r c + a_5 c^2
\]
\[
 j = b_0 + b_1 r + b_2 c + b_3 r^2 + b_4 r c + b_5 c^2
\]

where \( r, c \) are the coordinates of the formed image and \( i, j \) are corresponding coordinates of the initial image. If the values of \( i, j \) fall outside the original images to be converted, default values (e.g., 0-black or 255-white) are assigned to them.

An example of conversion of radar images (Fig. 3a) in the surface of the digital map (Fig. 2a) is shown in Fig. 3b.
Fig. 3(a-b): (a) Initial radar image and (b) RI converted into DTM surface

**Processing of the radar image:** It is inefficient to search for binary reference sites on the radar images obtained due to the large number of objects on the ground and the presence of a significant noise component. Therefore, the search phase is preceded by the operation of contouring of the desired object in radar images. The main methods that allow the performance of this operation are segmentation and contouring of images. Both methods have a large number of algorithms which differ in the complexity of implementation and efficiency of objects contouring. In addition, to reduce the dependence of the results of image processing on random distorting noise components, image filtering (mask, median, frequency, etc.) must be performed first.

Image segmentation refers to the process of splitting the object into parts according to the similar properties of their points. There are several basic methods of segmentation (variance, building areas, etc.) (Yang et al., 2014; Zhang et al., 2012) but in practice threshold methods are most easily applicable modifications. The main problem in carrying out such processing is thresholding definition which would be adaptive to the characteristics of image. Comparison of the brightness of the original image with the thresholding allows the value of the output image to be determined at each point. In order to improve the segmentation it is possible to additionally apply
the operations of mathematical morphology for binary images. It allows for allocation of the specified objects based on the analysis of the image structure, or changing their shape to enhance the effectiveness of the subsequent operations of the correlation search (Yang and Ouchi, 2012). An example of delineation for reference DTM and radar images after the segmentation is shown in Fig. 4.

**Search for reference images location on radar images:** Algorithms for similarities definition in their basic versions are to some extent related to the stochastic characteristics of the relationship of the image fragments to be compared. All of algorithms are based on the ideas of correlation and the spectral theory of signals. Correlation method implies the search for the correlation coefficient’s maximum for the processed binary radar images with the reference image (Zhang et al., 2011):

$$
\hat{r}(k,l) = \frac{\sum_{x} \sum_{y} \tilde{u}_b(x,y) \tilde{u}(x,y)}{\left( \sum_{x} \sum_{y} [\tilde{u}(x,y)]^2 \sum_{x} \sum_{y} [\tilde{u}_b(x,y)]^2 \right)^{1/2}}
$$

where, \( \tilde{u}_b \) and \( \tilde{u} \) are centered intensity values of the reference image and binary radar images. Centering operation serves to remove the dependence of the values of the correlation coefficient on energy (brightness) of the zones.

To ensure the reliability of the binding values it is necessary to exceed the ratio of the level of the main maximum and the rest of threshold. Typically, the performance criteria of identification procedures are alignment accuracy similarity for fragments and the probability of false binding when the extremum of the functional similarity significantly shifts from the true position.
Fig. 5: Combined image of radar images and DTM

Calculation of the relationship of the reference and the image can be performed based on the spectral analysis of the signals. In fact, this method also performs the formation of the correlation integral but in frequency domain. In this case, the use of the FFT algorithms significantly reduces the computational cost for the algorithms.

**Combination of radar images with map:** After determining the relative displacement of radar images respectively to the DTM via reference images, the problem reduces to the joint indication with the calculated corrections. An example of the combination result is shown in Fig. 5.

When combining radar images and optical images the direct selection of reference objects is usually performed by the operator. All the rest of the operation of automatic alignment is identical. Figure 6b shows the result of the search of radar images for the object present in the optical image formed from the reference (Fig. 6a).

**Correction of parameters of the navigation system:** The long-term autonomous flight of the aircraft without the use of external navigation segments results in accumulating aircraft position errors which may reach hundreds of meters or more. In this case, correction may be performed through identifying the location of objects on radar images and the DTM. INS allows the following navigation parameters to be obtained: Location, speed and acceleration of the carrier, its position in the air (orientation) and angular velocities. Binding of RI and DTM allows the location, orientation and velocity of the carrier to be determined. Run time of INS correction depends on the accumulated error and conditions of radar images reception (the time of forming the frame and the availability of informative objects in the area).
Fig. 6(a-b): (a) Appointment of a reference binary image formed from an optical image and (b) Search results on reference image binary RI

Implementation of an error correction system for navigation radar images requires informative radar-contrast areas along the route of movement (correction zones). Correction of navigation parameters is performed according to the results of radar images and DTM binding. In this case, the discrepancy in the coordinates is calculated as the difference between the reference position and the position of the maximum of the correlation function. It serves as a base for the definition of the value error in the carrier's coordinates ($\Delta x$, $\Delta y$) and the error in determining the angular position of the axis of the review ($\Delta \phi$) which caused the displacement of the resulting radar image with respect to the reference. When using $N$ points of correspondence in the reference ($x_{\text{ref}}, y_{\text{ref}}$) and the resulting radar image ($x_{\text{ref}}, y_{\text{ref}}$):

$$\Delta \phi = \arctan \left( \frac{A - B - x_{\text{ref}}y_{\text{ref}} + y_{\text{ref}}x_{\text{ref}}}{C + D - x_{\text{ref}}y_{\text{ref}} + y_{\text{ref}}x_{\text{ref}}} \right)$$

$$\Delta x = x_{\text{ref}} - x_{\text{ref}} \cos (\Delta \phi) - y_{\text{ref}} \sin (\Delta \phi)$$

$$\Delta y = y_{\text{ref}} + x_{\text{ref}} \sin (\Delta \phi) - y_{\text{ref}} \cos (\Delta \phi)$$

Where:

$$x_{\text{ref}} = \frac{1}{N} \sum_{i=1}^{N} x_i, \quad y_{\text{ref}} = \frac{1}{N} \sum_{i=1}^{N} y_i, \quad x_{\text{ref}} = \frac{1}{N} \sum_{i=1}^{N} x_{\text{ref}}, \quad y_{\text{ref}} = \frac{1}{N} \sum_{i=1}^{N} y_{\text{ref}}$$

$$y_{\text{ref}} = \frac{1}{N} \sum_{i=1}^{N} y_i, \quad A = \frac{1}{N} \sum_{i=1}^{N} x_i y_i, \quad B = \frac{1}{N} \sum_{i=1}^{N} y_i x_i$$

$$C = \frac{1}{N} \sum_{i=1}^{N} x_i x_i, \quad D = \frac{1}{N} \sum_{i=1}^{N} y_i y_i$$
The advantage of this method is the all-weather capability, the use at any time, the possibility of formation of reference images based on different initial information and the possibility of applying the method to the terrain with a minimum drop in height values.

Navigational errors correction according to radiovision data requires the preparation phase of reference images before the flight or in operational mode. The difficulty in constructing a reference field is mostly due to strong dependence of the received signal strength on the viewing conditions and the characteristics of the SAR.

RESULTS

The combination of SAR images and DTM imply the following:

- Coordination binding of detected objects to radar images
- Interpretation of radar images areas by sharing information about the composition of the DTM object
- Identification of alignment errors and clarification of binding of radar images and objects to the base map

In addition, the implementation of correlation methods of binding SAR images and DTM enables the autonomous and automatic correction of navigation parameters. Potential location accuracy can be measured in items of radar resolution cell.

DISCUSSION

In most current published papers performance indicators of the proposed methods are evaluated on the test images, often not corresponding to the real SAR images (Baltsavias, 2004; Li, 2014). Application of the proposed procedures often reveals itself ineffective when using real images. In addition, the authors tend to pay attention to one aspect of image processing (e.g., only edge extraction or only impulse noise reduction in the image) (Yang et al., 2014; Zhang et al., 2012). However, in reality it is necessary to perform a comprehensive approach and the use of certain methods may impair the final result, despite the apparent separate effectiveness.

Unlike analogues the paper presents a uniform methodology for co-processing images of different physical natures (SAR and digital map images) to determine the position of objects on them, implement the results in visualisation problems and clarify the parameters of the location of aircrafts with the SAR based on advanced image processing techniques.

The method of automatic alignment of radar images and DTM proposed in the paper can significantly improve the accuracy of the joint presentation of these images. The technique can be used by radar operator on the aircraft board for the analysis of radar images while on mission and by unmanned systems to automate the search for objects and location correction. Furthermore, the application of the technology in terrestrial conditions can facilitate the operation of terrestrial operators that analyse flight images.

Further research will imply approbation of the proposed method on a large number of real radar images obtained by different SARs in different modes and conditions of operation. In addition, the step of selecting the parameters of image processing procedures is required for each radar type and mode to ensure their effective use when searching for references. There are plans to develop a methodology for automating the selection of parameters for the formation of reference images and processing of radar images according to the type and mode of SAR and possibly the type of ground surface.
During the formation of references, especially for use at low altitudes, it is planned to use digital maps of the terrain in order to create radar shadow zones. This will allow such zones to be more effectively placed with a low radar contrast in the reference images which should increase the accuracy of the generated reference images.

REFERENCES


