REMOTE SENSING APPROACH FOR DIGITAL AERIAL IMAGERY

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ABSTRACT:

Typical but distinct application fields have traditionally been established for satellite-based remote sensing as well as for airborne photogrammetry. However, within recent years new technological developments have caused a slow disappearance of these divergences and the formerly clear separated application areas are gradually starting to converge. In the area of aerial image acquisition one of the most important steps towards the expansion of traditional application fields which has been made within the last few years is the development of digital photogrammetric cameras and their introduction to the market. As a result it was possible to combine the extremely high geometric resolution and accuracy with the excellent radiometric and spectral characteristics of digital image sensors. Our contribution features the results of some selected projects and discusses the experiences made during practical operations. An investigation will be presented in which both the DMC and a film-based photogrammetric camera LMK (Zeiss) were used to take images of the same area, thus comparing geometric features of the images from both cameras. The results show the outstanding geometric features of the DMC and prove that the DMC is suitable for traditional photogrammetric tasks under operational conditions. The second part of the presentation focuses on the new, in comparison to film-based cameras, significantly improved spectral and radiometric features, and first results of the application of automated classification procedures as well as classification results derived from combined data sets containing DMC images and other digital remote sensing data are presented.

KURZFASSUNG:

Traditionell haben sich für die Satellitenfernerkundung einerseits und für die flugzeugbasierte Photogrammetrie andererseits jeweils typische und deutlich voneinander abgegrenzte Anwendungsgebiete etabliert. Neue technologische Entwicklungen haben in den letzten Jahren jedoch dazu geführt, dass sich diese Grenzen langsam auflösen und die vorher relativ eindeutig voneinander abgegrenzten Anwendungsgebiete mehr und mehr beginnen, ineinander überzugehen. Von Seiten der Luftbildaufnahmetechnologie war die Entwicklung und Markteinführung digitaler photogrammetrischer Kamerasysteme in den letzten Jahren einer der entscheidenden Schritte zur Erweiterung der traditionellen Anwendungspalette. Damit konnten bei Beibehaltung der extrem hohen geometrischen Auflösung und Abbildungstreue gleichzeitig die von digitalen Fernerkundungssensoren bekannten ausgezeichneten spektralen und radiometrischen Eigenschaften realisiert werden. Im Beitrag werden Ergebnisse aus ausgewählten Projekten gezeigt und dabei über Erfahrungen aus dem Routinebetrieb berichtet. Dabei wird eine vergleichende Untersuchung vorgestellt, die auf einer Doppelkammerbefliegung basiert und dadurch einen direkten Vergleich der Ergebnisse der DMC mit einer parallel dazu eingesetzten filmbasierten Luftbildkamera vom Typ LMK (Zeiss) ermöglicht. Die gezeigten Ergebnisse belegen die hervorragenden geometrischen Eigenschaften der DMC und weisen deren volle Eignung für traditionelle photogrammetrische Aufgabenstellungen nach. Im zweiten Teil des Beitrages wird auf die neuen, gegenüber filmbasierten Kamerasystemen deutlich verbesserten radiometrischen Eigenschaften eingegangen und erste Ergebnisse der Anwendung automatischer Klassifizierungsverfahren sowie auch Klassifizierungsergebnisse von kombinierten Datensätzen der DMC mit anderen digitalen Fernerkundungssensoren gezeigt.

1. INTRODUCTION

With the introduction of the digital airborne photogrammetric cameras the expectations of the photogrammetric and remote sensing user community have grown. The primary focus of the users' expectations includes the implementation of an excellent photogrammetric quality for the digital airborne imagery together with a high level of operational workflow, which can be seen as a pre-condition for the replacement of the film-based airborne cameras (Reulke 2003). Moreover, a significant improvement of the radiometric features due to the digital sensor technology is expected. A better spectral and radiometric quality of airborne images could make possible the use of several computer-based processing methods, which have been developed for thematic applications and analysis. Until now these methods have been used mainly in satellite-based remote sensing, but with the expected improvement of the radiometric quality they could also be used in the field of airborne image data and thus enlarge their application possibilities.

ILV-Fernerkundung GmbH decided in 2003 to start with the digital airborne data acquisition with the Digital Mapping Camera DMC by Z/I Imaging. This decision was based on long-term experience which has been gathered in the field of airborne photogrammetric image acquisition with film-based airborne photogrammetric cameras from Carl Zeiss and more than ten years of work in ortho-photo processing and interpretation. Since the beginning of the operational use in January 2004, more than 60.000 digital aerial images were acquired with the DMC in the course of several practical projects.

The following presentation is based on the practical experiences gathered while operating the DMC and aims to compare these practical experiences with the expected improvements. Special emphasis will be put on the geometric accuracy in order to evaluate the possibilities of replacing the film-based airborne cameras for photogrammetric purposes, and on the radiometric features of the DMC, which are especially important for thematic application of the image data and therefore determine the Remote Sensing approach to digital aerial imagery.

2. THE DIGITAL PHOTOGRAMMETRIC CAMERA DMC

The DMC (Digital Mapping Camera) of Z/I Imaging is the first digital photogrammetric camera with the CCD frame (matrix) sensor technology. The concepts, developments and solutions implemented in the DMC have been discussed and published in many presentations and publications; examples can be found in Tang et al. 2000, Heier 2001, Hinz et al. 2001, Dörstel 2003. Therefore, below only a short description of the DMC will be given. The CCD matrix sensor concept offers a number of advantages in comparison to line-based airborne sensor systems. First of all, the stable, rigid image geometry has to be mentioned, which ensures a high quality of the image geometry even under difficult flight conditions and is comparable to the precision of film-based aerial cameras. Because of the two-dimensional area sensors, the image data shows a well known and precise geometry in the X- and in the Y- direction. This allows an image orientation and the generation of ortho-photos, even when the quality of the GPS data is limited. In contrast, a line based digital airborne camera, for example, needs the direct orientation data for each image line. Moreover, the electronic compensation of the aircraft's forward flight move (Forward Motion Compensation FMC) during the sensor exposure time improves the spatial resolution and the geometric accuracy.

The DMC is equipped with four high-resolution panchromatic camera modules with a 7k x 4k image sensor chip. Each module is an autonomous unit with its own optical systems. An electronic matching process combines the four individual images into a resulting high resolution panchromatic image. This process is performed automatically and as a result produces a panchromatic airborne image with a size of 7680 x 13824 pixels.

Figure 1. DMC Camera head unit

Another four separate camera modules with separate sensor chips of 3k x 2k pixels are equipped with spectral filters for the blue, green and red colours and also for the near infrared (NIR) band. In this way, together with the high resolution panchromatic image, a multi-spectral image data set with four bands will be obtained. From this image data the typical image types for the conventional airborne image interpretation - Colour, CIR, and Panchromatic - can be generated with one single flight. This makes repeated flights obsolete.

In order to generate a high resolution colour image or CIR image, an automatic merging of the corresponding 3 multi-spectral bands and the high resolution panchromatic band is performed. The final resulting image has the same resolution as the panchromatic image (7680 x 13824 pixels).

The eight camera modules are equipped with separate lens systems, which have been especially designed and developed in close partnership with Carl Zeiss. Since separate lenses are used for each of the eight camera heads, a higher optical performance could be achieved, which is not possible with a single, large-diameter lens. The panchromatic channels contain lenses with 120-mm focal length at a maximum aperture of f/4, the multi-spectral channels have wide-angle lenses with the same aperture and 25-mm focal length.

3. INSTALLATION OF THE DMC AT ILV

The ILV-Fernerkundung GmbH first installed this camera in a two-engine aircraft, Cessna 404 Titan. This aircraft is equipped with two camera holes (Fig. 2). Thus, for tests and comparison purposes, simultaneous image data acquisition with two cameras, a digital DMC and a film-based photogrammetric camera, were made possible.

Figure 2. ILV's twin-engine aircraft Cessna 404 Titan

In addition to the DMC camera unit the following components belong to the DMC flight system installed in the aircraft:

- ASMS – Airborne Sensor Management System, including the
  - Camera Interface
  - GPS Receiver
  - IMU Control
  - Video Camera System
- Pilot display
- T-AS gyro stabilized camera suspension mount
- Sensor control module for the DMC
- MDR Flight Data Storage (3 units, each with 288 GB disk space for 2,200 images total)

After development of the necessary interface, for the DMC installation a link was incorporated to connect the DMC control to the flight navigation system CCNS4/AeroControl (IGI) already existing in the aircraft. The usage of this navigation system, installed in the ILV aircrafts for a number of years especially for photo flights with film-based photogrammetric cameras, has brought excellent results. Flight navigation is carried out by the CCNS4; every 0.1-sec the D-GPS data is collected with a Trimble 5700. The combination of the digital camera DMC and the Aerocontrol for the DGPS/INS–data collection is an innovative solution and at this time unique.

First experiences with the operational flight campaigns indicated that the storage units MDR needed to be replaced by the newer, improved systems FDS (Flight Data Storage). Thus, the stability during flight operation was also improved and data security was increased.

Figures 3 and 4 show the DMC camera module as installed in the ILV aircraft Cessna 404 Titan ready for photo flights. In autumn 2004 a second aircraft of ILV, in this case a two-engine Cessna 441 Conquest with turbo-prop engines and a pressurized cabin, which also was equipped and used in particular for remote sensing purposes, was prepared to be equipped with the DMC. This second aircraft offers the possibility to perform photo-flights in very high altitudes producing images with a pixel size up to 50 cm, thus approaching the resolution of satellite images.

Figure 3. Installation of the DMC in the ILV aircraft

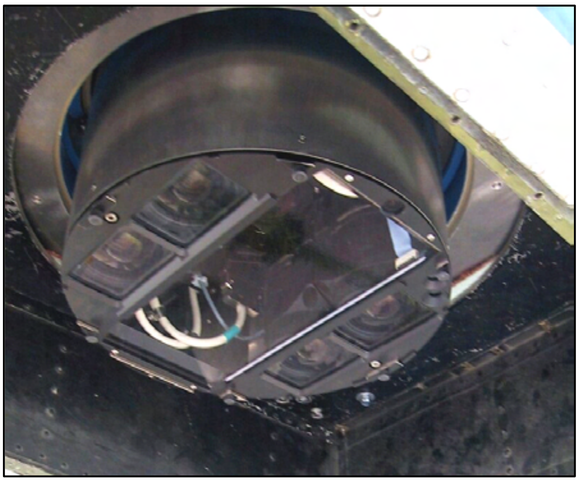

Figure 4. View from bottom to the DMC camera module with the separate objectives

4. OPERATIONAL EXPERIENCE WHILE USING THE DMC

During operational use digital aerial cameras showed a number of known advantages, which can contribute to the limitation and optimisation of the costs of photo flight projects. First of all, the elimination of time-consuming and labour-intensive processing steps like scanning and film processing will save time and money. Operational costs can also be reduced because material, such as aerial film and developer, will no longer be needed. However, a large number of digital storage media (CD/DVD, Hard-discs) for processing, storing and archiving of the digital airborne images will be necessary.

A significant advantage of the operational use of the DMC proved to be the direct digital data stream ranging from image acquisition to usage and delivery. Because of this completely digital process, logistical problems associated with film development, scanning as well as a possible loss of quality during these processes can be reduced or eliminated. First images can even be presented within some hours after finishing the photo-flight. In particular for projects abroad, transportation of the original film material beyond a country's border can be difficult or even impossible for a variety of reasons. This results in problems finding high quality film processing and scanning laboratories and facilities. Such problems can be avoided with the completely digital data stream of the DMC. Fig. 5 shows a scheme of the complete digital data stream of the DMC.

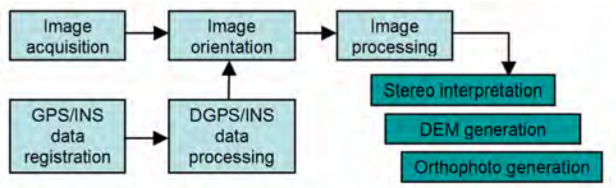

Figure 5. Digital processing chain of the DMC

For routine operation of airborne cameras like the DMC in regard to commercial projects, the safety of the initially acquired data, together with the image quality, is of utmost importance. The replacement of the MDR by the better FDS as mentioned before was one of the measures undertaken to improve the data safety during the flight itself. Another measure is the generation of a back-up copy of the primary data immediately after the photo-flight. This is performed in connection with the transfer of the acquired image data to the central airborne image data server of ILV.

After processing of the navigation data and their implementation on the image processing computers the post-processing of the acquired image data begins. Depending on the size of the data sets, first results (processed airborne images) can be expected already after 30 minutes. During the post-processing the type and parameters of the resulting image (high or medium resolution, 8- or 12 bit radiometric resolution, the included spectral bands to generate a Colour, CIR or panchromatic image) can be determined. After the post-processing, the images are ready for the further digital photogrammetric processing as is usual for airborne stereo images.

Here again the advantage can be seen that the digital airborne images of the DMC have the same image geometry as is already known of the conventional, film-based airborne imagery; which has been established as standard in the photogrammetry for more than 100 years. Therefore, the DMC images may in principle be further processed on all existing digital photogrammetric workstations.

5. THE GEOMETRIC ACCURACY

A key factor for photogrammetric image quality is geometric accuracy. According to the manufacturer, the specially developed optical system of the DMC and the integration of eight camera modules with separate CCD-area sensors into one digital camera system make it possible to achieve maximum resolution with minimum distortion. The geometric resolution on the ground is supposed to be as small as 5 cm, depending on the flight altitude. By employing a CCD matrix sensor with its rigid image geometry and stable pixel positions one can expect a minimum of geometric distortions.

Corresponding investigations by the manufacturer, performed and published for instance by Dörstel 2003, resulted in an accuracy of the position of signalised reference points after bundle adjustment to the order of 0.5 pixel. Assuming a nominal ground resolution of 5 - 10 cm, it would be possible to reach a mapping scale of 1 : 500.

Direct investigations concerning the geometrical accuracy of the DMC images, based on calibration targets for geometrical distortion and resolution under normative conditions, could not be performed by ILV because of missing technical preconditions for such work. However, in order to evaluate the definitive geometric quality of the DMC images, a special photo flight for test purposes was performed simultaneously using two aerial cameras: the digital DMC in the first camera hole and a film-based photogrammetric camera ZEISS - LKM in the second camera hole.

This photo-flight was performed in March 2004 at an altitude of about 800 m. The images were taken over an area in the vicinity of Schöneiche in Brandenburg. The resulting image scale for the DMC was 1 : 6,500. To make sure that the results of both cameras could be compared as accurately as possible, the LMK was equipped during this test flight with a wide-angle optics (c_k = 150 mm). The original image scale thus was nearly 1 : 5,000. A panchromatic airborne film of type PAN 200 (AGFA) was used to ensure a maximal geometric resolution.

The aerial images of both the DMC and the LMK were processed using the procedures typical for each camera. For the digital airborne images the processing software, which was specially developed by Z/I Imaging and INPHO for the DMC image data, was applied. The basic processing steps were mentioned above. After bundle adjustment, an ortho-rectification was performed.

After the photographic development, the LMK – images were scanned with a photogrammetric scanner SCAI (Carl Zeiss), the geometric resolution was selected to be 14 µm. The following processing also included the triangulation and ortho-photo generation. In both cases identical ground control points (GCP) and DGPS/INS – data, collected during the data acquisition by the aircraft navigation system CCNS4/Aerocontrol, were used.

By comparing the accuracy of the image orientation the after bundle adjustment the results shown in the following Table 1 were found. Of course, the comparison included a much larger number of points, so that the numbers shown in Table 1 are only examples of some selected individual points. Although the LMK – equipped with a lens of 150 mm focal length - has a slightly higher focal length than the DMC (120 mm), the results show a higher point position accuracy of the DMC. The corresponding sigma-values of 2.02 µm for the DMC and 6.60 µm for the LMK represent an average of some hundreds or even some thousands of points (depending on the number of images used in the bundle adjustment). The results found in our investigation are comparable to that published by Madani et al. 2004.

By using a graphical representation of the error ellipses for the comparison of both bundle adjustment results, the differences can be clearly seen (Fig. 6). In addition, the graphic representation makes obvious that the automatic bundle adjustment process found and used significantly more tie points for the DMC images (lower image in Fig. 6) in comparison to the scanned images of the film-based LMK.

LMK c_k=15 (film-based airborne camera)
Mean photo scale: 5.09
RESULTS OF ADJUSTMENT SIGMA$_0$ = 6.60 (1/1000)
*
* Control point residuals for graphical output
*

<Point_No>	< Vx >	< Vy >	< Vz >	Key
981802008	-23.	-23.	8.	CKP
981802018	27.	-4.	11.	CKP
981802001	1.	-3.	22.	XYZ
981802004	-19.	-27.	-20.	XYZ
981802005	-45.	61.	-76.	XYZ
981802007	3.	-51.	75.	XYZ
981802009	43.	82.	2.	XYZ
981802011	17.	-10.	-58.	XYZ
981802014	-24.	-23.	-1.	XYZ
981802015	10.	-11.	0.	XYZ
981802016	-4.	-8.	29.	XYZ
981802017	18.	-9.	27.	XYZ

DMC c_k=12 (digital airborne camera)
Mean photo scale: 6.50
RESULTS OF ADJUSTMENT SIGMA$_0$ = 2.02 (1/1000)
*
* Control point residuals for graphical output
*

*<Point_No>	< Vx >	< Vy >	< Vz >	Key
981802008	4.	2.	1.	CKP
981802018	16.	11.	3.	CKP
981802001	-17.	10.	3.	XYZ
981802004	-10.	-9.	5.	XYZ
981802005	-14.	-7.	7.	XYZ
981802007	-3.	12.	-1.	XYZ
981802009	5.	-4.	-6.	XYZ
981802011	5.	-2.	1.	XYZ
981802014	20.	-11	-15.	XYZ
981802015	-1.	18.	1.	XYZ
981802016	3.	-8.	1.	XYZ
981802017	12.	1.	2.	XYZ

Table 1. Results of comparison of the image orientation accuracy: LMK (above) and DMC (below)

Another possibility to check the geometric quality of the image data could be done by investigating the coincidence of points and lines in multi-datasets. Such combinations of data from different sources are often used within ILV projects. One example is the combination of DMC data with a multi-temporal airborne SAR dataset in the course of a research project, which will be presented under thematic aspects in more detail later on. Another example is the combination of DMC image data with vector data coming from existing GIS databases. In all situations within our different projects a good coincidence of single points or lines within the data of these different sources could be observed and no systematic distortions could be found. Remaining differences in the object position or geometry were on average much smaller than in previous projects with film-based cameras. In all cases these differences could be explained by the derived Digital Terrain Model, used for the ortho-photo generation.

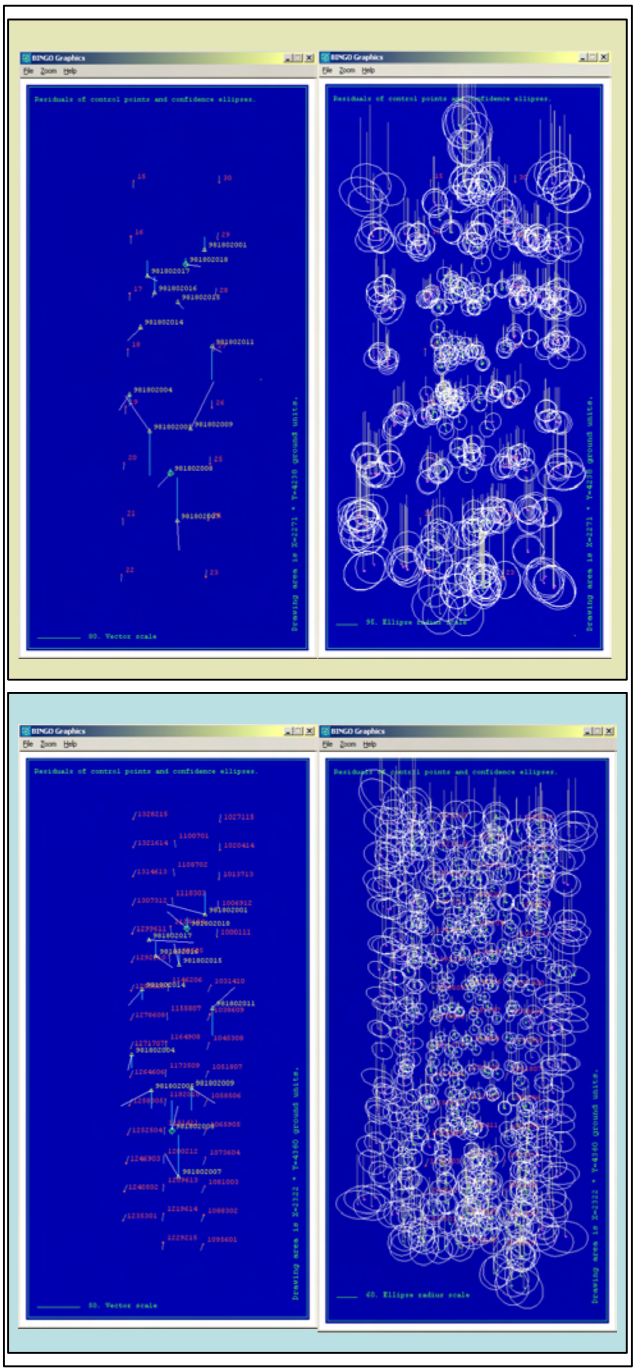

Figure 6. Results of comparison of the image orientation accuracy: LMK (above) and DMC (below)

6. THE RADIOMETRIC ACCURACY

After having discussed geometric accuracy and the operational feasibility of the DMC, the main focus will now be placed on radiometric features. Schiewe et al. 2004 emphasise the great importance of the radiometric features of a digital remote sensing system, together with the geometrical resolution, for the overall information content. This includes the multi-spectral capabilities, such as the number and the spectral position of the different bands, as well as the radiometric quality of the data such as radiometric resolution, accuracy and stability of the entire image area.

The multi-spectral capability of the DMC is based on the four integrated special digital camera modules as described above. The spectral windows of these four bands have been chosen, as is common for most of the recent digital sensors, to be sensitive for the blue, green, red, and near infrared spectral region. The nominal wavelength for each band is shown in Table 2, the corresponding sensitivity function is shown in Fig. 7. For a large number of applications, in particular thematic investigations and analysis, the significant increase of the feature space is of basic importance. The geometric resolution is about four times lower than for the panchromatic image, as mentioned above.

Spektral Band	Wavelength Region
Blue	400 – 580 nm
Green	500 – 650 nm
Red	590 – 675 nm
NIR	675 – 850 nm
NIR (alternatively)	740 – 850 nm

Table 2. Spectral sensitivity of the DMC multi-spectral bands

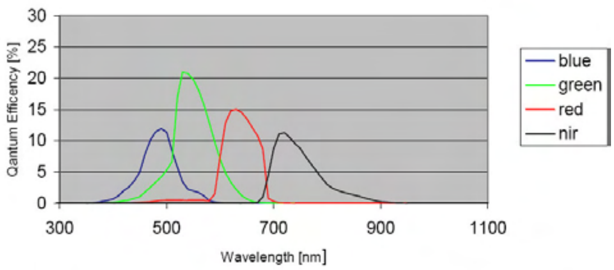

Figure 7. Sensitivity of the DMC multi-spectral bands (© Z/I Imaging, 19.02.2004)

Increased multi-spectral capabilities are considered to be a great advantage in comparison to film-based aerial cameras; however, they are common for digital remote sensing systems and thus only a necessary precondition for the remote sensing approach to the aerial imagery. In particular, also the radiometric quality of the images is of great importance. Therefore, it should be discussed in the following, whether the high expectations concerning radiometric stability, radiometric sensitivity and homogeneity can really be fulfilled. As a rule, digital sensors like the DMC in comparison to film-based aerial cameras have the advantage that all the multi-spectral image data – and in the case of multi-resolution sensors, together with the high resolution panchromatic images – are acquired simultaneously in one single photo-flight. Therefore, these data should offer much more stable and comparable radiometric features, a quality, which can not be guaranteed for the multi-spectral image data set when using different cameras and films in a

dual–camera photo-flight, or even worse, in dual photo-flights at different times.
In this context, the camera developer and manufacturer Z/I Imaging points out a number of camera features and parameters, which are considered as essential for the good radiometric quality of the DMC images. These features are in particular:

- The high sensitivity of the CCD – matrix sensor elements with a very high and linear dynamic range,
- The outstanding optical parameters of the specially developed lens system with a large aperture (f/4) and a corresponding high optical performance,
- The high radiometric resolution of 12 bit.

Due to these optical and radiometric features the DMC should be able to acquire image data even under difficult optical conditions, thus increasing the possibilities and the time frame for performing photo-flights.

An analysis of the image histograms of real aerial images acquired during different photo-flight projects of ILV shows an average use of about 2,800 gray levels within the 12-bit data space. An example of typical image histograms for the green, red and NIR bands is presented in Fig. 8. The analysis of the gray value distribution in the histogram indicates that, depending on the corresponding spectral band, only about 30 – 60% of the full 12 bit range is covered by more than 99% of the image pixels, the remaining gray values are represented by only a few pixels. This, however, is not a specific problem of the DMC, but is typical for practically all of the digital remote sensing systems that provide either less (8-bit) or higher (16 bit) radiometric resolution. Although the 12 bit range with its 4,096 possible gray values is not completely used, the radiometric resolution of the DMC images is still about five to ten times higher than the resolution of 8-bit digitized images of a film-based airborne camera.

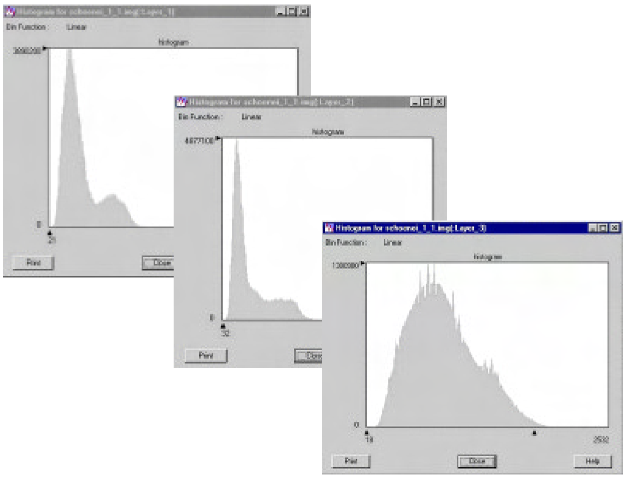

Figure 8. Histograms of the 3 Bands of a DMC CIR image

Again the double-camera photo-flight mentioned above was used for a first practical comparison of the radiometric image quality of the DMC with film-based images. Due to the better radiometric resolution it was expected to achieve a significant improvement of the reconnaissance of details in particular in very bright or in very dark image areas. Fig. 9 shows a subset of an identical region taken with the film-based LMK (image above) and the digital DMC (image below), which demonstrates this difference. Details of the bright roof, not visible in the LMK image subset, can be clearly identified in the DMC image below.

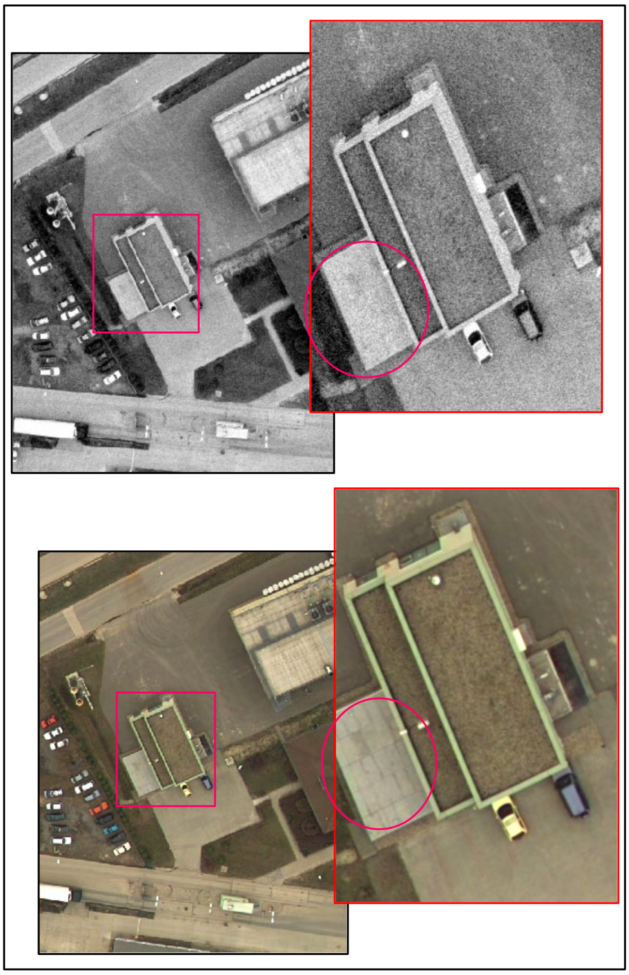

Figure 9. Comparison of LMK (above) and DMC (below)

Beside the radiometric resolution for the application of automatic classification procedures the radiometric stability and homogeneity of the images are of great importance. It is mainly in this area that the major problems with film-based scanned airborne images can be observed. In particular radiometric in-homogeneities, such as the decrease of brightness which is dependent on the distance from the image centre, are the main reasons that the application of thematically oriented digital image processing methods like, for instance, a classification on the basis of pixel values or object signatures is in most cases very difficult or even impossible in practice.

In regard to the investigation of the homogeneity of the gray value distribution we have to distinguish between internal and external influences. Variation of the gray values resulting from internal influences in digital airborne cameras is not only due to different degrees of sensitivity of the CCD sensor elements, but is also caused by the lens and aperture. However, contrary to film-based airborne cameras, these internal influences could be almost completely corrected for the DMC images. Diener et al. 2000 discussed and demonstrated this radiometric correction of the internal DMC influences and the normalisation of the gray levels.

Yet external influences are mainly caused by the atmosphere and by the objects on the earth's surface itself. Effects that depend on different angles as well as different optical distances at various image locations cause these differences. The external influences are not a specific problem of the DMC but affect all remote sensing image acquisition systems, digital sensors as well as film-based cameras.

Contrary to the correction of the practically constant internal influences, the correction of these external, angle-dependent influences is much more difficult. Beside the atmosphere the radiometric signature of many natural and man-made objects is considerably affected by the direction of the incoming radiation and the viewing direction. This is a well-known fact, and the problem cannot be solved simply by employing some unique correction values. Investigations concerning these angle-dependent signatures as well as foundations and possibilities for the correction of atmospheric influences have been carried out for many decades, and a great number of different methods have been developed and published.

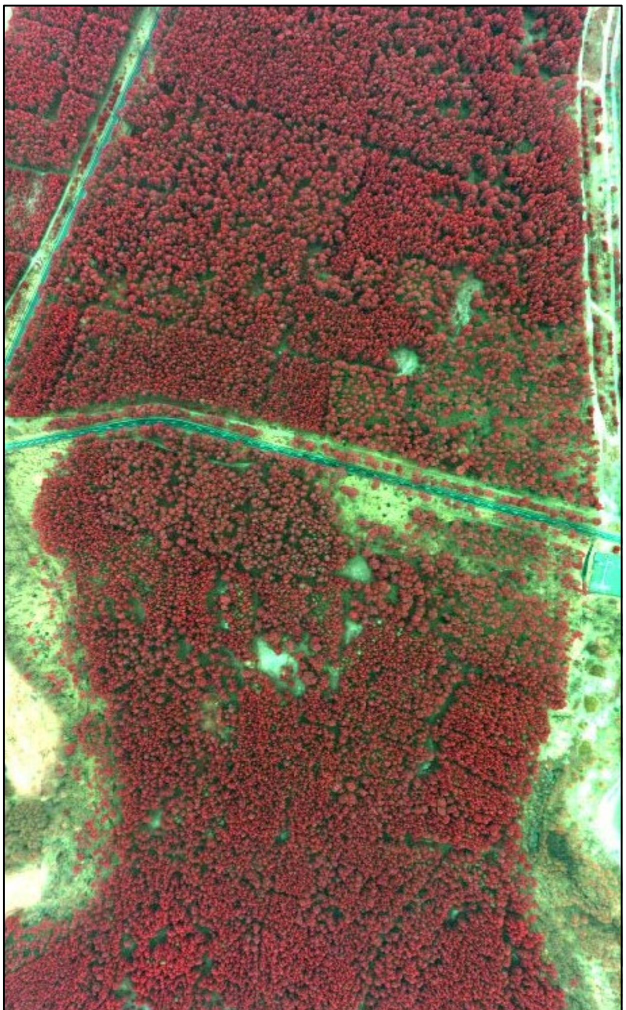

Figure 10. Example of a DMC image, used for the investigation of the radiometric stability and homogeneity

In this regard, the viewing angle of the lens has become an important parameter of the DMC. The DMC with a 120 mm focal length - an image size of 92.160 mm x 165.888 mm - was given a coverage angle of 69.3° (across track) and 42° (along track). Compared to other digital airborne and in particular satellite based image sensors this field angle is relatively large, and it can be expected that the angle-dependent influences will become noticeable.

In order to perform a practical evaluation of the radiometric homogeneity of the DMC-images, a number of different images from several ILV projects have been selected which contain almost completely one single homogeneous object. After several tests, images with large and homogeneous forest areas have been selected. The reason for the exceptional suitability of the forest areas for this test is that - apparently because of the statistical orientation of the small leaves in the tree canopy - the angle-dependence has been found to be less than it is with other objects. An example for an image used in these investigations is presented in Fig. 10. In this case, the photo-flight was carried out under an overcast sky with nearly homogenous and closed cloud coverage. Therefore, shadows do not appear, and effects caused by a dominating direction of the incoming radiation are almost not recognisable. The processing included the image pre-processing, bundle adjustment, ortho-photo generation, and the resolution merge of the panchromatic band with the green, red and NIR band to produce a high-resolution CIR image.

For the investigation tracks were established from the image centre to the image border, and the average signature of test plots with a size of 10 x 10 m² along these tracks was calculated and compared taking into account its distance from the image centre. The results of the comparison show a slightly higher dependency of the average gray value from the distance of the control plot for the green band in comparison with the red and NIR band.

This expected performance can be explained by a higher sensitivity to atmospheric influences in the blue and green spectral region. However, the gray level differences were less than expected for these examples. Table 3 presents the measured values of the three investigated spectral bands of the image shown in Fig. 10, Fig. 11 shows a graphical presentation for the red and the NIR band. These two bands are of special importance for the calculation of spectral vegetation indices like the commonly used NDVI, as will be discussed later on.

Test plot	Average green	Average red	Average NIR
1	284	143	517
2	278	136	514
3	276	138	511
4	273	132	507
5	273	136	499
6	271	133	496
7	274	134	501
8	271	134	491
9	277	142	497
10	272	134	493
11	273	131	498
12	276	133	505
13	276	135	507
14	279	137	513
15	283	139	518

Table 3. Average gray values of the radiometric test plots of Fig. 10

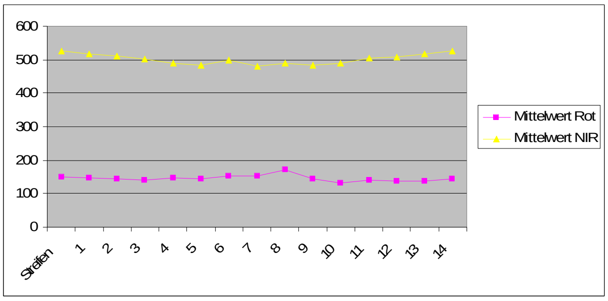

Figure 11. Spectral values (R and NIR bands) for 15 image fragments of a homogenous forest area, distributed over the whole image area

Figure 12. Example of a DMC image of the City of Stuttgart.

These results allow us to conclude that the internal radiometric correction and normalisation of the DMC works satisfactorily, and that the remaining changes and differences are caused by external influences. In a rural atmosphere with a low amount of aerosol and dust, as it was true for the example above, these influences are minor; under difficult atmospheric conditions, however, they could create significant radiometric problems. An example for such conditions is given in the next images, acquired during a photo-flight project of the city of Stuttgart. The atmospheric conditions during the data acquisition time were very difficult, with many dust and aerosol particles especially over the inner parts of the city of Stuttgart. Fig. 12 shows an example of a DMC – image of the central part of Stuttgart.

Clear changes of the image brightness as well as of the colour (as representation of the spectral signature) can be observed between the northern image part and the southern part. The previously described and used method to investigate large homogenous objects as proof for the radiometric features was not suited to be used here; therefore, identical objects in images of different but overlapping stripes were selected and compared. Fig. 13 presents two examples of subsets prepared for this investigation. Such identical areas located at different positions in the images of different flight passes were compared concerning their radiometric features for the whole subset (averaged gray values of the subset), for selected areas integrating a number of objects of nearly identical features (i.e. roofs of the same material), and for single objects or part of objects.

The observed results show clear differences in the averaged values over larger areas as well as over single objects. Table 4 gives the numerical results of the two subsets shown in Fig. 13.

Figure 13. Two examples of subsets prepared for the investigation of the radiometric quality of the DMC images of Stuttgart

Nr. of subset	Location of subset	Red	Green	Blue
1	north	414	432	427
	centre	338	342	338
	south	311	312	324
2	north	585	590	592
	centre	449	450	450
	south	383	384	385

Table 4. Average gray values of selected subsets of identical location at different image positions

The observed differences in the gray values are nearly identical for all spectral bands. The changes are monotonous from north to south for all investigated examples, this means, neither maxima nor minima can be observed within the image centre; and they are not linear. In particular, they are much higher, if the comparison is made between the location in the northern image part and the centre than between the southern part and the centre. The investigation of single objects shows very different results, which reflects the additional influence of the orientation and the optical features of the material (i.e. directional reflectivity). Taking into account the direction of the sun during the image acquisition, all these are clear indicators that the radiometric changes are caused by angle-dependent atmospheric influences of aerosol and dust.

Concerning the acquired image data, the correction of such externally caused radiometric distortions is very difficult. The best way is to avoid such problems by increasing the degree of overlapping and choosing a flight direction according to the sun's azimuth so that sensitive directions do not coincide with the larger viewing angel in the across-track direction.

Changes of the spectral signatures due to radiometric influences are also of particular importance for the calculation of such spectral indices, which are commonly used i.e. for the investigation of the vitality and the state of vegetation, special features of the soil or other objects. The normalisation connected with the calculation of such indices can certainly eliminate disturbing influences, i.e. spectral independent factors can be removed for the NDVI, but additive influences from the atmosphere and especially different spectral changes remain or can even increase. As a result, for scanned images of film-based cameras a strong systematic dependency of the resulting NDVI value from the distance to the image centre could be observed.

In order to evaluate the DMC-images for their suitability to compute spectral indices, again representative images from different projects had been selected and investigated. As a result, the previous conclusions concerning the good homogeneity and stability of the gray values in case of normal or good atmospheric conditions could be confirmed. Fig. 14 shows a – in this case not normalised – relative computation result of the NDVI for a DMC-image taken of a forest site under good atmospheric conditions. It is obvious that in the particular forest area the computed values for the NDVI can be seen as almost stable over the whole image; a dependency on the distance from the image centre can not be observed.

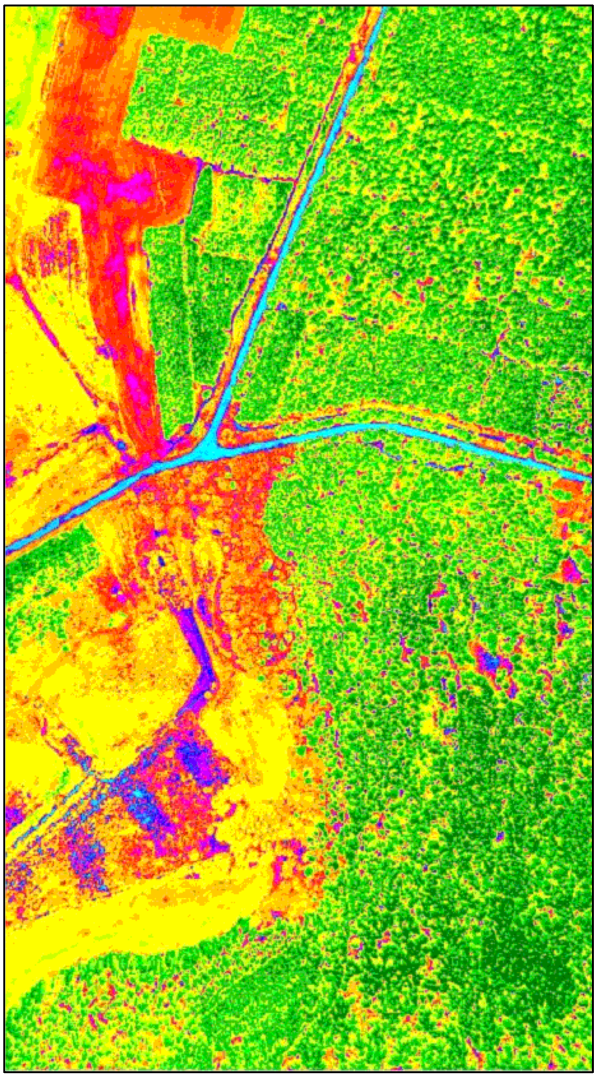

Figure 14. NDVI of a DMC - Ortho-photo

The next step was to investigate the stability of the radiometric and spectral features for more than one single image. In a test similar to that done on images with forest sites the gray values as well as the NDVI for an image mosaic were calculated and investigated with regard to their stability. As a result of this investigation similar conclusions could be made for image mosaics just as they have been made for single images. For example, Fig. 15 shows single ortho-images of a project carried out in Baden-Württemberg, and the corresponding NDVI, derived from the ortho-image mosaic. Again, these images show the good radiometric homogeneity of the DMC images under good atmospheric conditions during the data acquisition.

The observed radiometric stability and homogeneity is a fundamental pre-condition concerning the usage of airborne images for thematic investigations and applications on the basis of thematically oriented digital image processing technology, as it was developed and used for satellite-based digital remote sensing image data already for some decades. It can be expected, that these valuable methodological tools will be used for digital airborne images more and more in the next few years.

In this regard, the automatic classification procedures play an important role. The radiometric quality determines the result especially of classification processes. It is, together with the geometric resolution, the main indicator for the information content of the image. Unambiguity and stability of the spectral signatures are primary preconditions necessary to automatically assign this spectral signature to a certain class. This is true both for pixel-based classification models as well as for object-oriented, segmentation-based classification approaches.

A special problem for a computer-based analysis and classification of the DMC–image data appears to be the merging of the high-resolution panchromatic bands with the medium-resolution multi-spectral bands; if the merged bands are used as input data for the processing. The merging process itself changes the spectral signature of an object in an unpredictable way. Therefore, if it is not possible to use the original multi-spectral bands for the classification, i.e. with a multi-resolution classification approach together with the panchromatic band, a precise monitoring of the merging process is necessary. The conservation of the specific spectral signature of the objects is to a large extent most important. Investigations concerning such merging procedures can be found in Ehlers et al. 2004 among others. A technological solution based on a modified IHS transformation with a differential substitution to avoid changes of the spectral feature space is already described in Knorr et al. 1999.

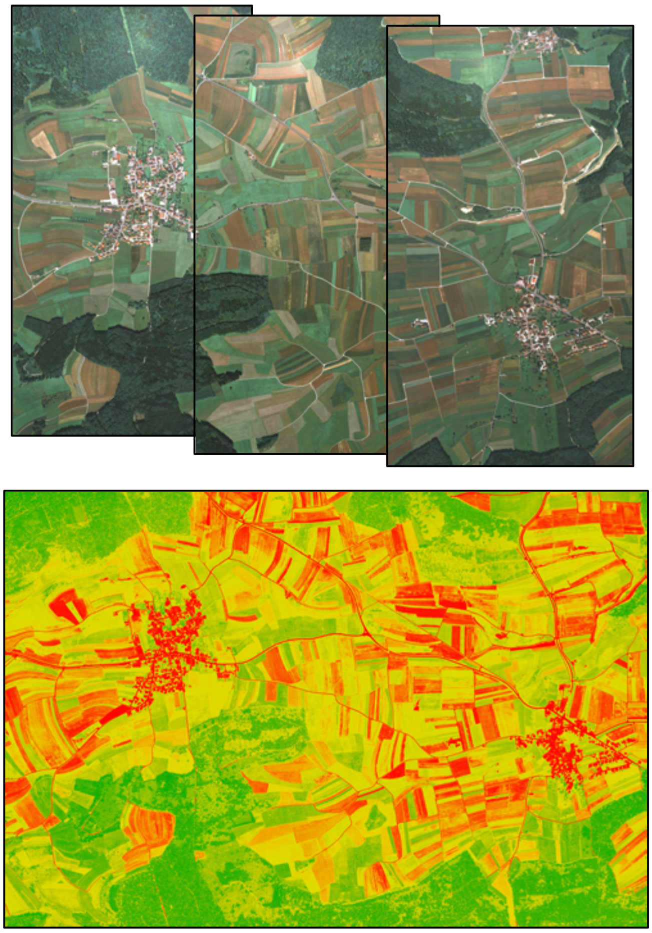

Figure 15: Ortho-images (RGB, above) and NDVI computed from the CIR - ortho-image mosaic (below). Red: low NDVI – Green: High NDVI

In general, for the classification of airborne images due to the very high geometric ground resolution and therefore the higher information content of the images in comparison with images from satellites, a better object differentiation and therefore a higher amount of classes as well as higher classification accuracy could be expected. Nevertheless, the high geometric resolution requires a high standard of investigational methods and processing technology, because the lower level of generalisation and the higher level of detail will increase the amount of radiometric and spectral variances of the objects in the image. Depending on the task, even a decrease of the classification quality or, at least, higher processing expenses for the control of the object variances could be necessary.

Former internal investigations for example have shown that for the classification of trees a generalisation within an area of 0.5 - 2 m² is necessary in order to get stable results; for grassland and corn, however, due to the significantly smaller structure, already 10 – 20 cm² are enough for a statistically stable generalisation of the local variances within the object signature. Additional problems concerning the row structure occur for root crops like beets or potatoes. Most difficulties in finding an optimal generalisation level concern the classification of urban areas because very different single objects blend with structures of different size. In general, the required geometric resolution and the generalisation depend on the task and the necessary object differentiation.

Another problem for automatic classification procedures is the treatment of the shadows cast by higher objects. This problem is increased by the high geometric resolution of the airborne images in comparison with satellite image data up to now mainly used for automatic object classification procedures. For instance, in the neighbourhood of tree alleys in arable land, and in particular in urban areas, strong changes of the radiometric values can be observed which are caused by the shadow of the higher objects in the neighbourhood. A number of different approaches aim at a minimisation of these effects, i.e. the suppression of the brightness information of the object signature by using special band combinations, which emphasize especially the spectral differences of the objects and therefore are less influenced by the brightness differences due to the shadows. Another approach is the derivation and implementation of a high-resolution digital terrain model into the classification procedure and, based on this DTM, the computation of potential areas with shadow influences within the image. Then, these areas can be investigated and classified separately from the image areas which are not influenced by shadows.

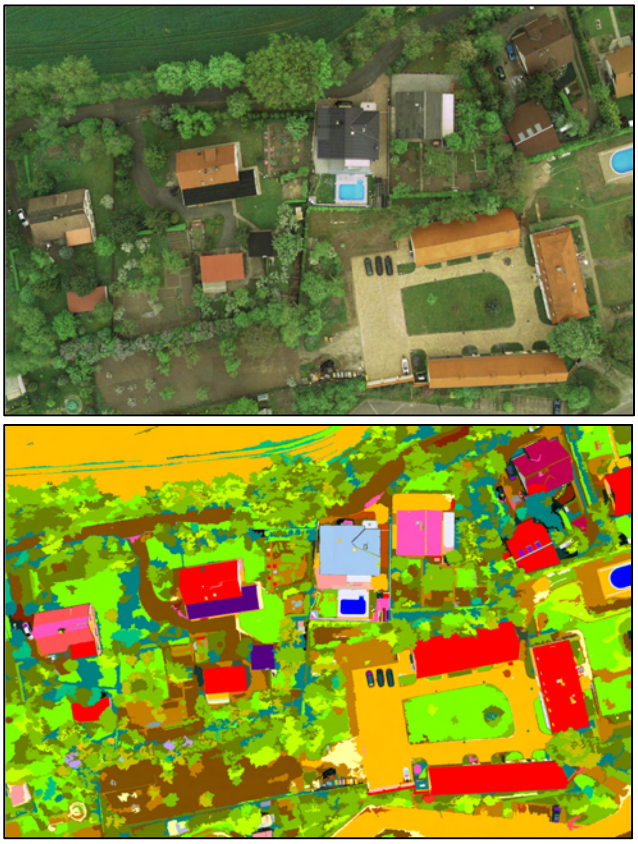

Figure 16: Classification of a multispectral DMC image.

For example, Fig. 16 presents a first classification attempt of a small test site near the city of Groitzsch, featuring the main office of the ILV. The major goal of this first attempt was to test and to show the potential of the digital DMC image data for classification purposes and to attain an object differentiation as precise as possible but with stable, homogenous results in the whole small subset of the image. The classification of the different object types within the image, like, for instance, the different material of the buildings' roofs or the different tree species, is clearly recognisable. The trees in particular show the problems with a very low generalisation level, caused by the extremely high geometrical resolution. However, it can also be seen that the class assignment is almost stable over the whole image subset, which is an indicator for the stable radiometry within this subset.

Figure 17 shows the stability of this feature not only in small subsets but also in larger areas, in whole images and even in mosaics of several images.

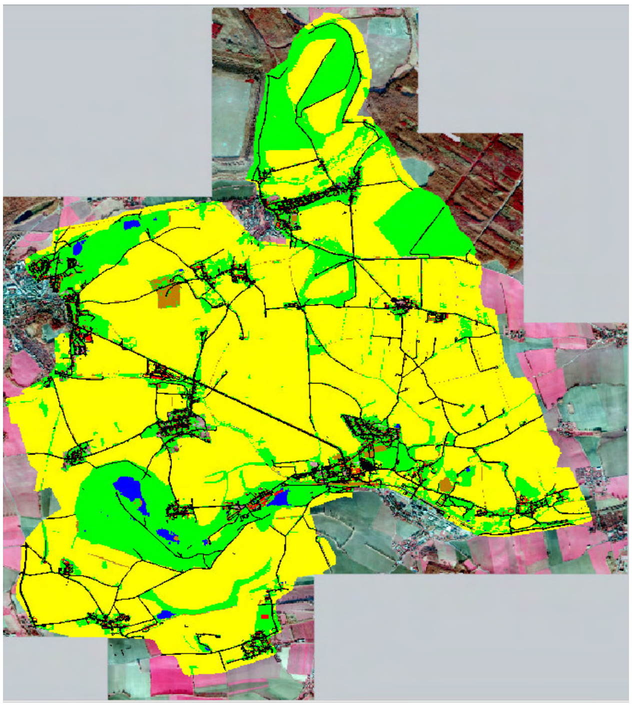

Figure 17: Classification of an ortho-image mosaic generated from digital airborne Images of the DMC

This is a representation of an ortho-photo mosaic with an area covering about 70 km². For the mosaic generation more than 130 single digital airborne images had been used. For the classification the following basic classes were to be distinguished:

- open water bodies
- forest
- agricultural used areas
- urban areas, settlements
- transportation (streets, tracks, railroads)

The subset shown in Fig. 18 demonstrates that in many cases, in particular in the agricultural fields, a significantly deeper and

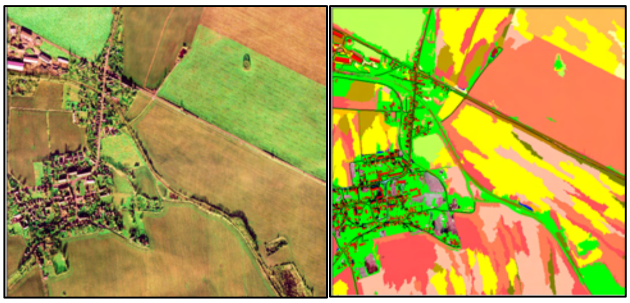

Figure 18: Subset of the ortho-image mosaik, showing a deeper differentiation in the agricultural areas

more detailed object differentiation would be possible, showing the much higher potential for object recognition within these images.

The last example presented in this contribution will show a first result of a multi-sensor approach. For this purpose digital airborne images of the DMC were combined with airborne SAR (Synthetic Aperture Radar) data, collected in a previous airborne data acquisition during a research project. This research project ERLEN was supported by the BMBF (German Ministry of Research and Development) and carried out within the ProSmart–II project for the development of application examples for the future German SAR satellite TerraSAR. The classification was again focused on the differentiation of the main land use classes, with an emphasis on the distinction between agricultural areas and grassland. The test site was located in the vicinity of the city of Ehingen in Baden-Württemberg, parts of the test site have already been shown in Fig. 15.

The classification was carried out with an object-oriented approach, using the classification software eCognition made by Definiens. The first step was to mask off unwanted image parts, such as forest areas, urban areas and water, using an object mask that had been automatically derived from the multi-temporal SAR data. Fig. 19 shows such a multi-temporal SAR data set.

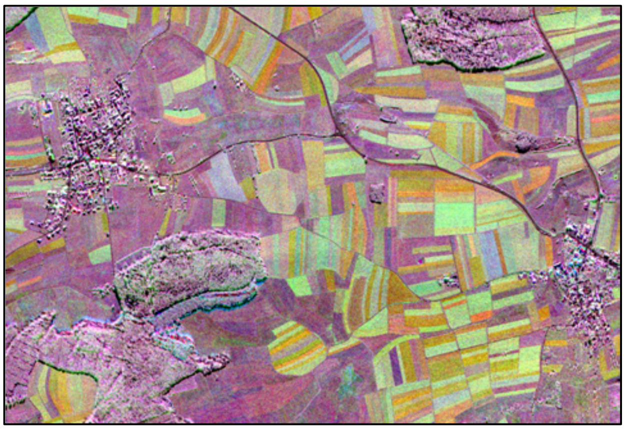

Figure 19: Multi-temporal SAR image (subset) of the test site Ehingen (ProSmart II project ERLEN)

The result of the classification on the basis of these multi-temporal SAR data is shown in Fig. 20a. The inclusion of the digital airborne DMC images could, on the one hand, emphasize the multi-temporal approach (because of the significant later date of the data acquisition of the DMC images, extending the time period of the overall investigation); on the other hand, it was possible to carry out the main task concerning the distinction between agricultural fields and grassland with a higher amount of accuracy. By employing the DMC images, the class assignment for 19 plots within the test area, which were classified as grassland on the basis of the multi-temporal SAR data only, could be corrected. Fig. 20b shows the result of this multi-sensor classification including the DMC image data. The differences of the grassland classifications are coloured in red so that they can be more easily distinguished. During the airborne DMC data acquisition, which was performed later than the SAR image data acquisition, these plots were not covered with grassland.

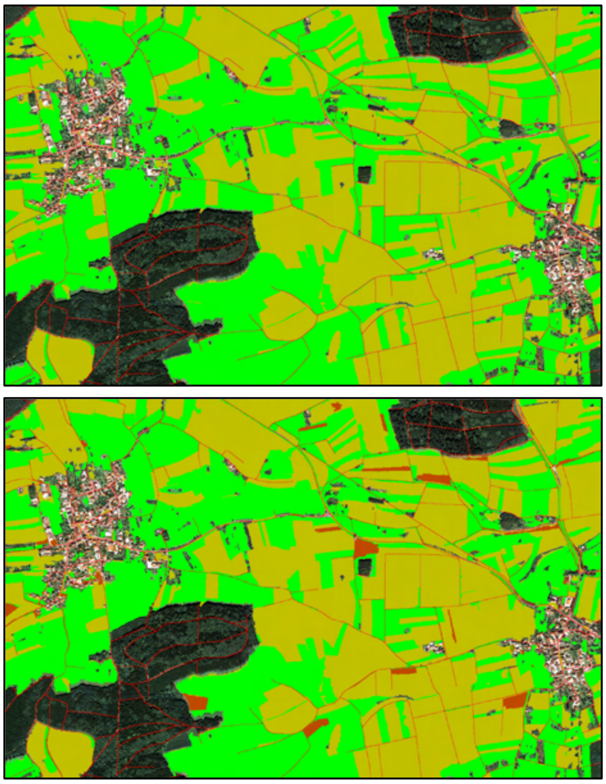

Figure 20: Classification result for the differentiation of agricultural land and grassland, based on a) multi-temporal SAR data only (above), b) a multi-sensor approach using SAR data and digital DMC images (below).

7. CONCLUSIONS

Of course, within this paper it was not possible to discuss and present all details, experiences and results of the operational work with the DMC made by ILV during the last 15 month. But summarizing all results and practical experiences it can be clearly stated that our expectations were fulfilled in practically every significant respect. Especially the geometric quality is excellent and fulfils all demands of the classical and modern photogrammetric work. The operational workflow saves a lot of time and cost. Of course, the adaptation of this new technological process requires a number of changes of structures and processes or even the establishment of new structures within a company dealing so far with film-based airborne data acquisition.

Although there is a significant improvement for the radiometric resolution of DMC images compared with film-based scanned airborne images, we found some remaining problems in the DMC-radiometric and multi-spectral image quality. These are, however, not sensor-inherent but are mainly due to external influences and distortions. Furthermore, the wide viewing angle of the camera is partly involved in these radiometric problems, however, a wide viewing angle is necessary for the operationality and cost effectiveness. Several technological solutions have been studied:

- the selection of the flight direction in dependence of the sun's azimuth
- a higher degree of overlapping for special tasks.

These techniques should be used for sensitive radiometric demands or in difficult atmospheric conditions. Further investigations concerning such technological solutions as well as further improvements of the digital image processing software are necessary for the ongoing improvement of the DMC image application results.

The new possibilities due to improved radiometric and geometric resolution have to be analysed with respect to their application potential for client specific demands. This includes also the application of more sophisticated classification methods. The higher geometrical and radiometric resolution allows a higher differentiation and provides more detailed signature information. This requires adaptive classification strategies using segmentation algorithms, textural analysis and hierarchical classification methods, which are not applied so far when using conventional optical satellite data. Moreover, a radiometric calibration has to be provided in order to guarantee the accuracy and stability for multi-temporal data acquisitions and analysis.

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