ENHANCEMENT OF SATELLITE IMAGE DATA BY DATA CUMULATION

Prof. Dr.-Ing. JÖRG ALBERTZ
Dipl.-Ing. KONSTANTINOS ZELIANEOS
Department of Photogrammetry and Cartography
Technical University of Berlin
Straße des 17.Juni 135
D - 1000 Berlin 12
Federal Republic of Germany

Abstract

The visibility of targets in satellite image data is clearly limited by the spatial resolution of the sensor. This is why many attempts have been made and will be continued to improve the performance of earth observation sensor systems by reducing the size of the instantaneous field of view (IFOV). However, this is not the only way to achieve higher geometrical resolution in satellite imagery as long as additional information, which is available in multiple scene coverage, remains unutilized. Therefore, an approach has been developed which makes use of this type of information by merging the data from several images of the same area. This enhancement technique is called Data Cumulation.

The paper starts with the theory of sampling image data over a scene, discusses the theoretical background of the approach and describes its implementation. Simulated Data Cumulation has been carried out using both artificial targets and satellite image data as well.

The method was proven to be effective if certain requirements are met. The usefulness of the approach as well as its limitations are discussed in the paper.

Introduction

It is generally known, that the visibility of high frequency topographical objects, such as roads, canals, buildings etc., is strictly limited by the spatial resolution of the sensor system. Nevertheless small objects can often be recognized in some images, but they disappear or are only partly visible in others. This is due to the complex interaction between the pixel size (IFOV), the radiometrical contrasts and the orientation of the sampling grid relative to the target features. Let us assume that the same area is imaged several times by the same sensor under the same conditions. Then there will still be a significant difference in the data recorded from high frequency objects because the sampling grid is - from a practical point of view - randomly overlaid over the scene. However, these differences contain additional information on the object, information which mostly remains unutilized in image processing and interpretation.

The purpose of this paper is to discuss the potential use of the additional information on small topographical features which is available from multiple scene coverage. In order to make use of this information a new set of image data is derived by merging multiple image data of the same area. This approach, which improves the visual presentation of the image data and enhances information extraction, is called Data Cumulation. Data from opto-mecanical scanners (MSS, TM), from opto-electronical scanners (SPOT) as well as from CCD-cameras can be subject to this enhancement technique. In order to describe the priniciples of the approach the imaging process should be analysed first.

The imaging process

Every imaging system reproduces the details of objects only within certain limits. These limits depend on the parameters and the performance of the imaging system as well as on the structure and the physical parameters of the objects concerned. It is often distinguished between »geometrical« and »radiometrical« resolution. The first one depends mainly on the pixel size, i.e. the IFOV. The second one depends on the sensor sensibility and the existing contrast. But both of them are interdependent from each other. Thus high frequency details can only be detected in an image if the combination of the geometrical dimensions of the object and its contrast exceeds a certain threshold.

For determining more precisely the limits of reproduction of objects, it is necessary to analyse the imaging process in terms of signal processing and system analysis. The principles can be described in case of a one-dimensional signal.

As a system is considered every transformation, which converts the input function f(x) to the function g(x) through an operator L:

$$g(x) = L(f(x)) \qquad (1)$$

Of particular importance are the linear and shift invariant systems. A system can be characterized as linear, if every linear combination of the inputs $f_i(x)$ leads to the respective linear combination of the outputs for i = 1, 2, 3, ... and any a_i :

$$L(\sum a_i f_i(x)) = \sum a_i L(f_i(x)) = \sum a_i g_i(x) \qquad (2)$$

Shift invariant is a system when a shift of the input causes the same shift of the output:

$$g(x-c) = L(f(x-c)) \qquad (3)$$

The performance of a linear and shift invariant (LSI) system is described by its impulse response h(x). For instance, the impulse response of a photographic system is its point spread function. The function h(x) describes completely the output of the system as a function of the input. The equation (1) will be :

$$g(x) = \int f(a)\, h(x-a)\, da \qquad (4)$$

The operation of equation (4) is called convolution of f(x) and h(x), denoted by (∗) :

$$g(x) = f(x) * h(x) \qquad (5)$$

Furthermore, a system can be analysed in the frequency domain by means of the Fourier transformation [2, p.19]. The outcome of the system is not similar for all frequencies of the input signal. Some systems for instance restrain the high frequencies more than the low ones. This results a low pass filtering (smoothing) of the input, i.e. the output contains no frequencies, which are higher than a cut off frequency f_g. The effect of a LSI system on any frequency results the modulation transfer function (MTF). The MTF is the Fourier transformation H(2πf) of the impulse response h(x) :

$$H(2\pi f) = \int h(x) \exp(-j\, 2\pi x f)\, dx , \qquad j = \sqrt{-1} \qquad (6)$$

A remote sensing scanning system can be understood as a combination of two sub-systems, the *imaging subsystem* and the *sampling subsystem*. This is schematically sketched in Fig.1 in

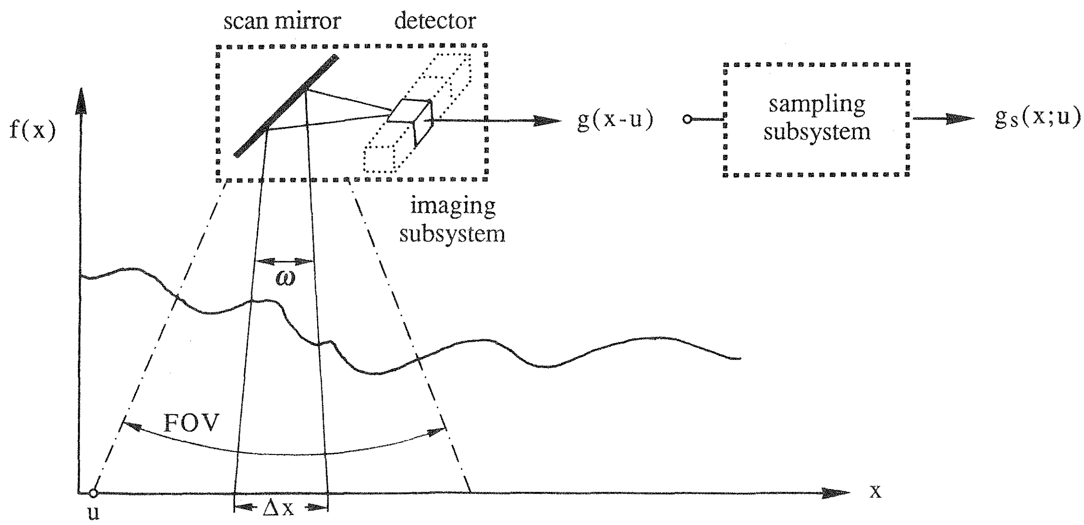

Fig.1 The two subsystems of a remote sensing scanning system

case of an opto-mechanical scanner; however, the principle is the same if other scanning systems, e.g. opto-electronical scanners, are concerned.

a) *The imaging subsystem.* The input signal f(x) is the earth's surface spatial distribution of radiance. The reflected radiation comes from the scanning mirror to the detector through a small aperture and is converted into an electrical signal. The distance Δx on the earth's surface is:

$$\Delta x = 2\, a \tan(\omega / 2) \qquad (7)$$

where a is the flight altitude and the angle ω is the IFOV. The IFOV or the corresponding distance Δx controls the imaging process. In this process an image degradation (image blur) takes place as a result of the fact that the aperture dimension and consequently the distance Δx is large as compared to the high object frequencies (see f(x) in Fig.2). Therefore the output of the imaging subsystem is a smoothed signal (see g(x) in Fig.2). The smoothing characteristics of the imaging subsystem can easily be described in the frequency domain. The impulse response of the first subsystem is a rectangular function (Fig. 3) [3, p.21]:

$$h(x) = \frac{1}{\Delta x}\, \mathrm{rect}(x / \Delta x) \qquad (8)$$

The MTF of the subsystem is the Fourier transformation of h(x) (Fig. 4):

$$H(2\pi f) = \frac{\sin(\pi\, \Delta x\, f)}{\pi\, \Delta x\, f} \qquad (9)$$

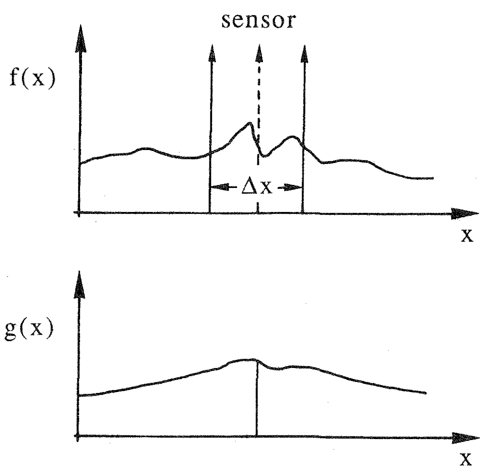

Fig.2 Smoothing effect of the imaging subsystem

It is obvious that the imaging subsystem works as a low pass filter with a cutoff frequency $f_g = 1/\Delta x$. Spatial frequencies higher than f_g cannot be resolved, or can be observed as »false resolution« [2, p.64], [4, p.61]. The larger Δx is, the less high spatial frequencies can be received. The first subsystem is shift invariant, i.e. the output signal is independent from its shift relative to an arbitrarily choosen coordinate origin.

b) *The sampling subsystem.* From the continuous function g(x) a sequence of discrete values $g_s(x)$ is derived by the sampling subsystem (Fig.5). The sampling rate, i.e. the number of samples (pixels) per IFOV or sampling frequency, is not the same for all remote sensing scanning systems. However, in most cases the sampling rate is about 1. Thus the spatial sampling frequency f_s equals $1/\Delta x$. The sampling theorem (SHANNON) proves that a sampled signal contains no frequencies which are higher than $f_s/2$, where f_s is the sampling frequency [2, p.44].

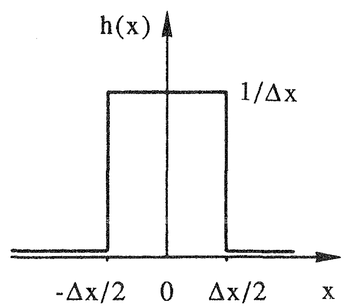

Fig.3 Impulse response of a scanner

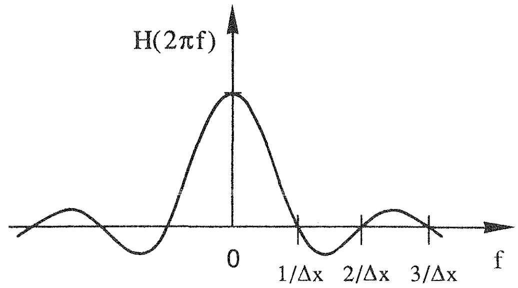

Fig.4 Fourier transform of the impulse response

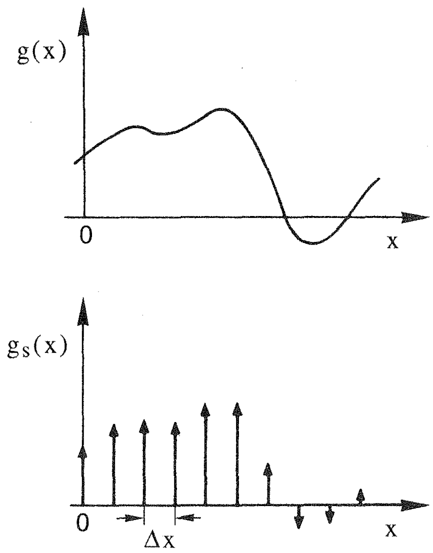

Fig.5 Sampling with sampling frequency $f_s = 1/\Delta x$

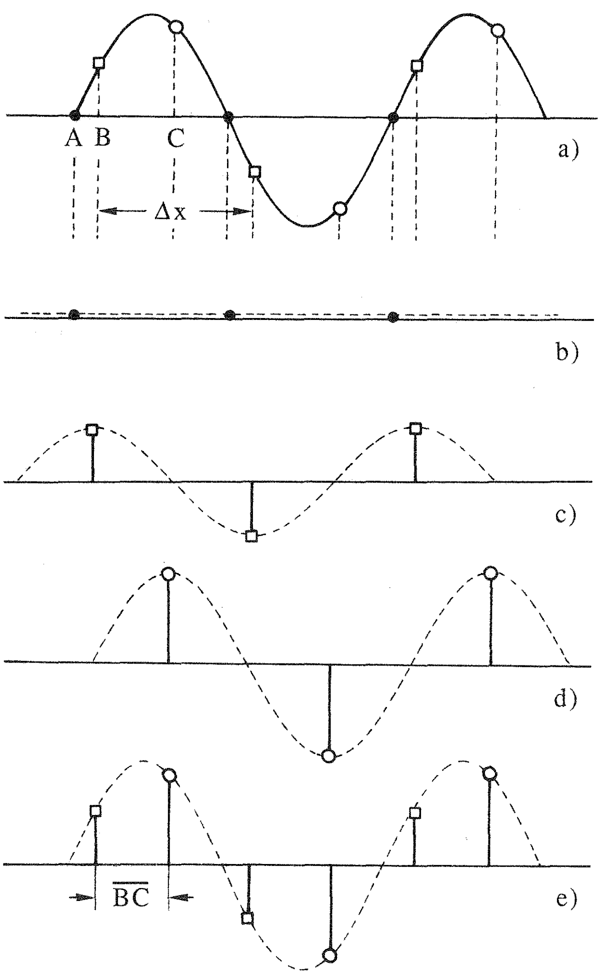

Fig.6 Principle of Data Cumulation

Therefore, the output g(x) of the imaging subsystem cannot be fully reconstructed through the sampled values $g_S(x)$, in any case it is only an approximation. The resulting error is called sampling or aliasing error. By increasing the sampling frequency, the number of sampled values is also increased and the sampling error decreases. However, with regard to Data Cumulation it is important, that the sampling process is not shift invariant. Through shifting the subsystem produces a completely different sample sequence (see Fig.6).

Multisampling

Sampling causes an information loss. This loss concerns the phase and amplitude for any frequency. As a result of it, the complete reconstruction of the sampled signal through its sample values is not any more possible. This may be illustrated by a small theoretical example. Let the signal be a harmonic function (Fig.6a) which is sampled three times (Fig.6b, 6c, 6d). The starting points A, B and C are randomly distributed and generally not identical. The sampled values represent the original signal in different ways. In one case (Fig.6b) it gets even completely lost. Obviously the original signal cannot be reconstructed on the basis of the values of one single sample. However, it is evident that the entirety of data sets contains more information than each individual one. In order to make use of these fact additional information is necessary. This is the phase difference between the samples, i.e. the distances $\overline{AB}$, $\overline{BC}$ or $\overline{AC}$. For our idealized example two samples, for instance B and C, and the shift distance $\overline{BC}$ between them are sufficient for the complete reconstruction of the original signal (Fig.6e).

Thus, the basic idea of Data Cumulation is to reconstruct the output signal of the sensor as good as possible out of the various sample sets available, and then to resample with a higher sampling rate. In the case of image data this process is carried out two-dimensionally.

Multitemporal Imagery and Data Cumulation

The multisampling of a signal can be compared with the acquisition of multitemporal image data. The imaging system measures the reflected radiation f(x,y,I) reaching the sensor. The radiation quantity depends on the reflection factor of surfaces (i.e. on the position x,y) and the irradiance I (power density). Furthermore the radiation arriving at the sensor is influenced by the sun elevation and the atmospheric conditions. The Data Cumulation approach assumes that all the parameters involved remain invariant for all the image data. This supposition can be accepted in so far as invariant topographical features are concerned. If we assume, that the irradiance remains also constant, the output signal of the imaging subsystem, which will be sampled, is identical for all multitemporal images:

$$g(x-u_i, y-v_i) = f(x-u_i, y-v_i) * h(x,y) \qquad (11)$$

where u_i, v_i are offset coordinates from an arbitrary origin for any image $i = 1, 2, 3 ...$; $h(x,y)$ is the two-dimensional rectangular response function. Nevertheless, the sample sequences are different for every single image. Through Data Cumulation the image function $g(x-u_i, y-v_i)$ can be locally approximated by a third degree surface function:

$$\hat{g}(x',y') = a_0+a_1x'+a_2y'+a_3x'y'+a_4x'^2+a_5y'^2+a_6x'y'^2+a_7y'x'^2+a_8x'^3+a_9y'^3 \qquad (12)$$

where the coefficients a_i are determined by a local LSQ adjustment. After this, resampling of the locally approximated image function $g(x,y)$ can be carried out for the choosen sampling frequency. For this procedure of Data Cumulation sampling with double frequency as compared to the original data is appropriate. By higher sampling rates no additional information can be restored.

The newly generated image has four times the number of pixels and a better resolution than each one of the original images. The enhancement causes the gain of spatial frequencies, which have a period of about two pixels (Fig.6).

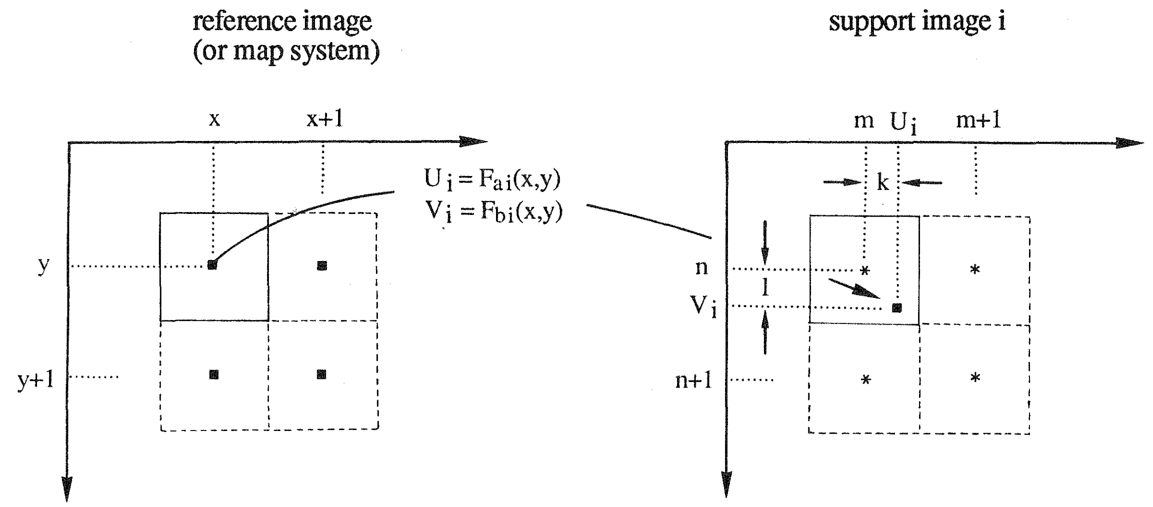

Fig.7 Registration between the reference image and the support images

Implementation of the method

a) Reference image and mapping polynomials

The Data Cumulation procedure requires the availability of several sets of image data. It is assumed that no significant changes in the object reflectivity occurred between the dates of data acquisition. Furthermore, the geometrical offsets between the data sets are supposed to be random values (as it is practically the case for satellite image data). From all provided images, one is choosen as *reference image*. The rest of them are called *support images*. In order to achieve registration between the support images and the reference image, mapping functions are calculated by means of control points. The procedure can be handled in the same way as in any other process of geometrical correction. The mapping functions for any support image i = 1, 2, 3, ... are polynomials of second or third degree:

$$U_i = Fa_i\,(x,y) = a_0+a_1x+a_2y+a_3xy+a_4x^2+a_5y^2$$
$$V_i = Fb_i\,(x,y) = b_0+b_1x+b_2y+b_3xy+b_4x^2+b_5y^2 \qquad (13)$$

where (x,y) and (U,V) are image coordinates, i.e. coordinates on the system, that defines the columns and rows of the pixel grid of the reference and support image respectively. The fractions (k,l) of (U_i,V_i), where $-0.5 < (k,l) < 0.5$ give the local shift, i.e. the phase difference, between the reference and support image (Fig.7). This is the additional information, which is necessary for the reconstruction of the image function.

If the final result of the procedure is expected to be registered to a map coordinate system, this system has to be choosen as a reference. In this case all images involved are registered by mapping functions, and the Data Cumulation process yields a geometrically corrected image.

b) Definition of the sampling grid

The sampling locations grid is identical to the image system of the output image. In order to resample with double frequency as compared to the original data, the distance between the grid points must be half a pixel of the input images. The placing of the sampling grid on the image system of the reference image is arbitrary. For practical reasons the grid is defined as it is sketched in Fig.8.

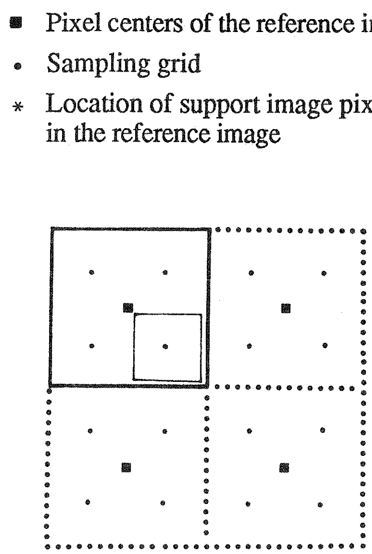

Fig. 8 Sampling grid

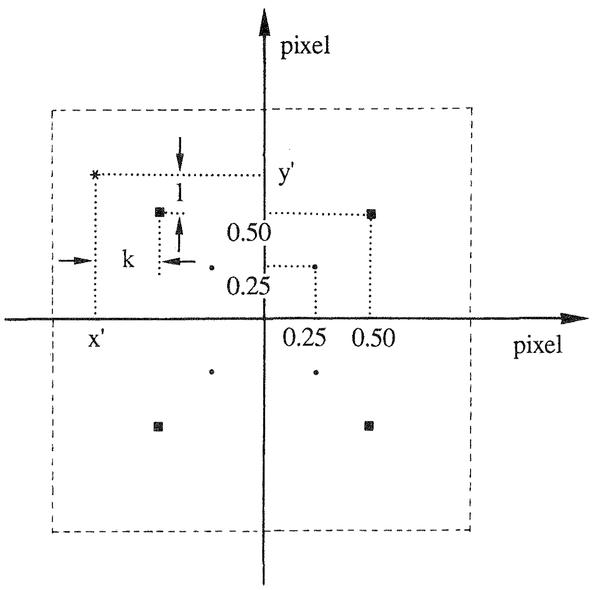

Fig.9 Local approximation coordinate system

c) Local Approximation of g(x,y)

The function $\hat{g}(x',y')$ approximates g(x,y) in a small area of 2·2 pixels, defined on the reference image. The coordinates (x',y') refer to a local system, shown in Fig.9. All four pixels of the reference image, i.e their coordinates and their gray values as well as the corresponding pixels on the support images, are used in the calculation of $\hat{g}(x',y')$.

The definition of the corresponding pixels and its coordinates in the local coordinates system will be realized through the mapping polynomials. The value of $\hat{g}(x',y')$ at the sampling point yields the pixel value of the output image. Four pixels will be calculated through one local approximation of g(x,y).

d) Correlation Grid

The success of the Data Cumulation approach highly depends on the geometric accuracy achieved before merging of the data sets. The accuracy required is theoretically ± 0.1 of pixel. Therefore a high precision geometrical correction is necessary. For this purpose a correction grid is calculated with the grid points determined through digital correlation by means of a LSQ algorithm. The approximate values required by this algorithm are the coordinates defined from the polynomials. The accuracy of the LSQ correlation according to ACKERMANN [1] lies beyond 0.1 pixel. These results have been confirmed by the calculations during this study.

e) The Radiometric Correction

The Data Cumulation approach assumes that all multitemporal image data involved are samples of the same continuous signal g(x,y). However, the illumination of the terrain, atmospheric influences, sensor performance etc. do not remain constant. Therefore, a radiometric adjustment of the multitemporal data is necessary. The discrepancies between the various data sets can be determined through the comparison of its histograms. Image data, which are derived from the same g(x,y), give similar histograms. Therefore a relative matching of the histograms is used for radiometric correction.

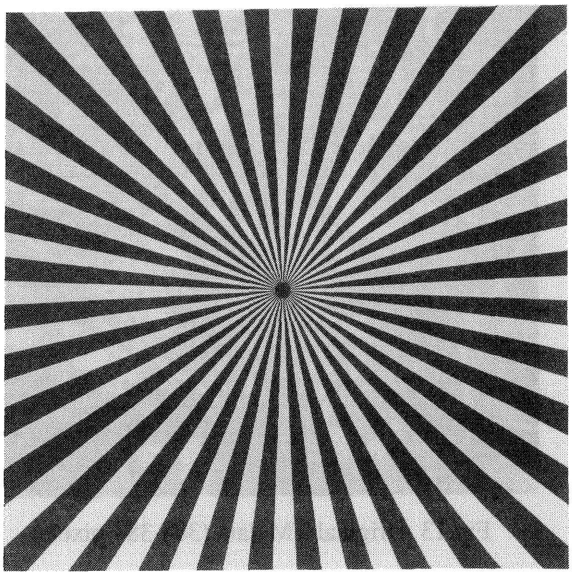

Fig.10 Test target

Experiments with Simulated and Real Image Data

Cumulation of image data has been carried out using data from an artifical target and simulated satellite image data as well as real satellite image data.

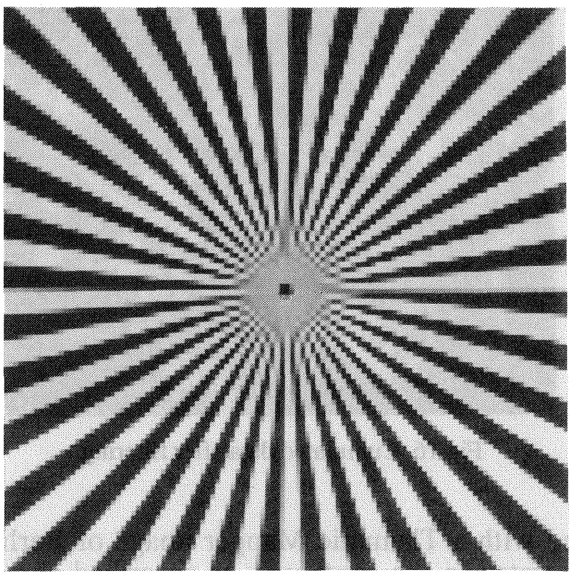

Fig.11 Low-resolution image of test target

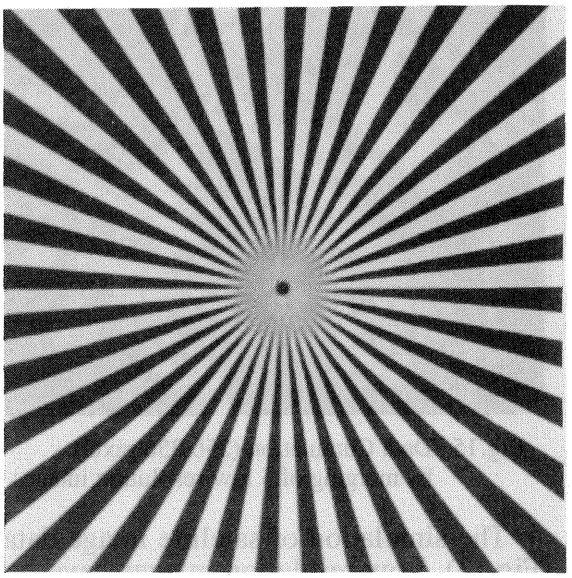

Fig.12 Cumulated target image

The target of Fig.10 served as an ideal test object to study the correct implementation and the effectiveness of the Data Cumulation approach. After digitization of the image simulated low-resolution image data (Fig.11) were generated by averageing 3·3 submatrices. The offsets between the simulated samples were choosen randomly. In this case the additional information about the shift of the pixel grids, which is required for carrying out Data Cumulation, was known *a priori* and error-free. For the generation of the cumulated target image (Fig.12) five low-resolution images were combined.

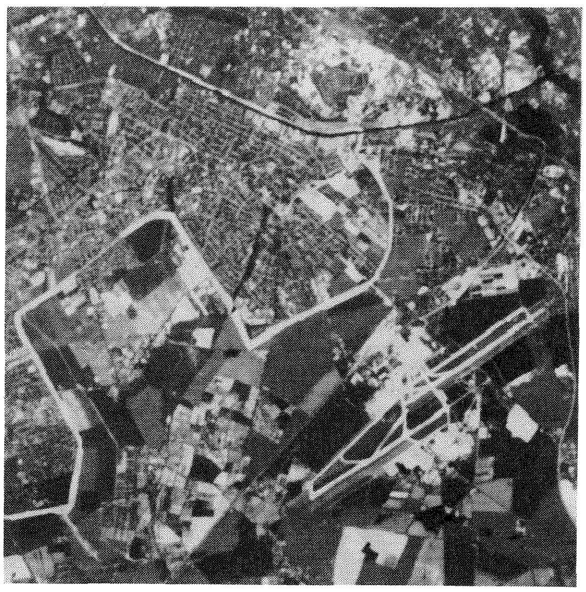

Fig.13 Original TM data (384·384 pixels)

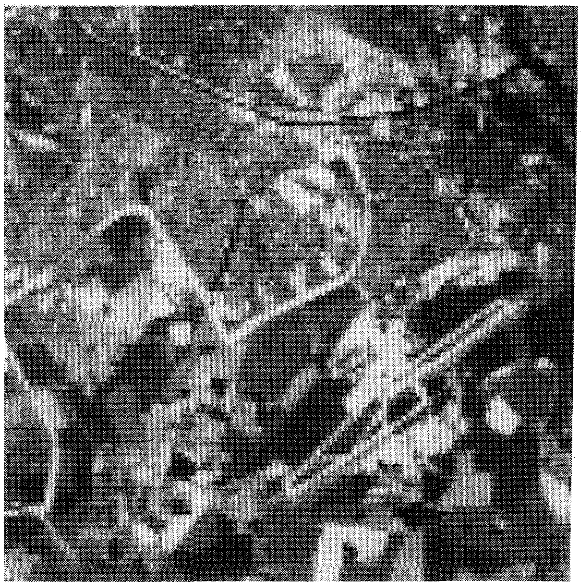

Fig.14 Simulated low resolution data (128·128 p.)

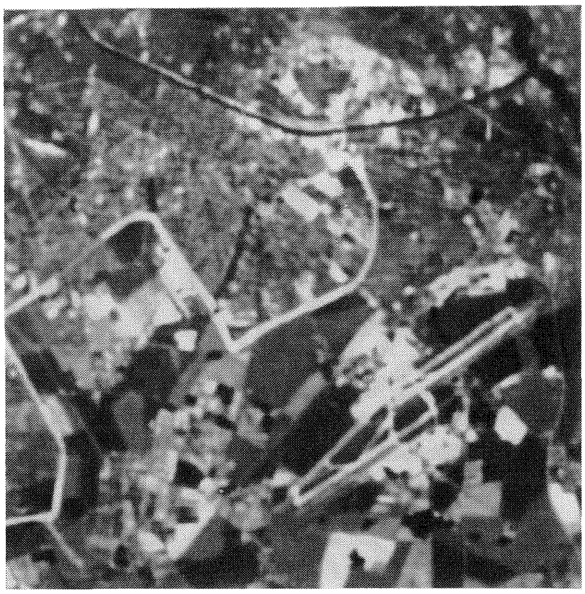

Fig.15 Data Cumulation (256·256 pixel) by merging of 5 low-resolution images

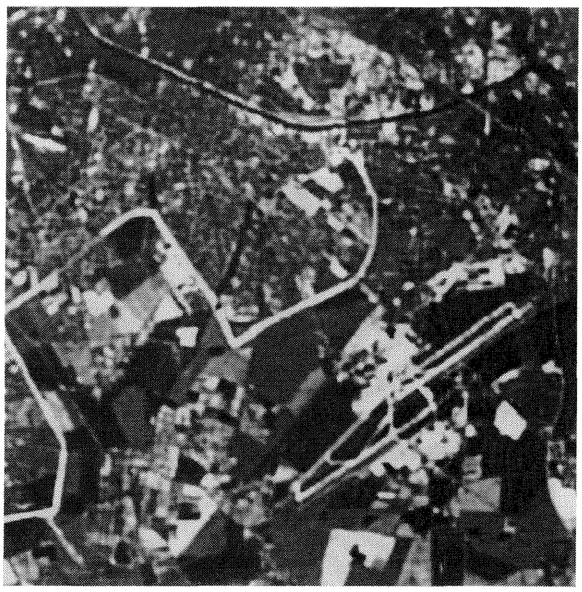

Fig.16 Cumulated data after filtering

The simulation of satellite image data started with a Thematic Mapper image of Berlin (Fig.13). Low-resolution images have been generated in the same way as described above (Fig.14). However, in this case the *a priori* known error-free phase information was not used for the cumulation process. The mapping polynomials were calculated by means of digitally

Fig.17 Part of a NOAA-AVHRR image from an area in Greece

Fig.18 Enhanced NOAA-AVHRR image after cumulation of 5 data sets and filtering

correlated control points, and Data Cumulation was applied. The procedure yields a blurred image (Fig.15) as one would expect, because of the fact, that the imaging subsystem reduces the amplitudes of the recovered high frequencies more than the lower ones. Therefore highpass filtering can enhance the image significantly (Fig.16).

For a test with real multitemporal image data five subsets of images from the NOAA - AVHRR (Advanced Very High Resolution Radiometer) in Band 4 (10.3 - 11.3 micrometers) have been used. The dates of acquisition of the images were 21.07., 07.08., 09.08., 10.08., 26.08.1987. Figure 17 shows the image of 09.08.1987 which has been chosen as the reference image. Figure 18 is the Data Cumulation image (after filtering) showing improved resolution.

Limitations of the Approach

The application of the Data Cumulation approach can only be successful if certain requirements are met:

a) Several sets of image data from the same sensor type must be available. According to the test results five images are sufficient, four images could be considered as a minimum.

b) The Data Cumulation approach presumes, that no significant object changes occurred during data acquisition. Consequently, multitemporal images showing large seasonal differences or other large-scale variations can not be applied.

c) The accuracy requirements with regard to the geometrical transformations are very high. Misregistrations are disturbing the effect of Data Cumulation. Therefore high precision techniques have to be applied.

Conclusions

The method of Data Cumulation was proven to be effective under simulation and real data conditions. Each cumulated image appears visually better than any one of the input images.

Tests with an artificial target clearly demonstrate the improvement, concerning spatial frequencies which are about equal to the cutoff frequency of the imaging system. Furthermore aliasing effects can be completely removed and the stepwise appearence of edges is reduced.

Similar enhancement was achieved by cumulating simulated satellite data. Linear and small topographic features can be recognized, even though they were not visible at one of the input images. Comparison with the original data proves that these structures correspond to real objects.

The experiment concerning real data (NOAA-AVHRR) is only a preliminary one. The image data used were of low contrast and with little variety of patterns. Nevertheless, the application of the method was successful. The result image, like all other examples, shows improved visibility of edges and other features.

However, the application of Data Cumulation is restricted by some practical limitations and also by the computer time required. It will therefore be appropriate for special applications, where for some reasons the optimum interpretability of image data is desired.

References

[1] ACKERMANN. F.: High precision digital image correlation. 39th Photogrammetric Week 1983, Stuttgart 1983, pp. 231-243.

[2] LÜKE, H.D.: Signalübertragung, Springer Verlag, Berlin, Heidelberg, New York 1979.

[3] NOWAK, P.: Bildverbesserung an multispektralen Scanneraufnahmen mit Hilfe digitaler Filterverfahren. Dissertation, Wien 1979.

[4] RÖHLER, R.: Informationstheorie in der Optik, Wissenschaftliche Verlagsgesellschaft mbh, Stuttgart 1967.

Acknowledgement

The NOAA data have been made available from the Meteorological Institute of the Free University of Berlin. This cooperation is gratefully acknowledged.