REMOTE SENSING IMAGE UNDERSTANDING BASED ON PHYSICAL MODEL INVERSION *

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ABSTRACT

The application of computer vision methods for the analysis of remotely sensed images is studied within the framework of the Research Programme "Theory and Applications of Image Processing and Pattern Recognition" of the Austrian Science Foundation ("Fonds zur Förderung der wissenschaftlichen Forschung"). This contribution gives the system overview of a proposed image understanding system based on the inversion of a physical (radiometric) model of image acquisition. The physical model, sufficiently simplified for practical implementation, is formulated and discussed in detail. The image understanding system is devised to perform automatic land use mapping from optical satellite images. The land use categories are defined in terms of their spectral reflectance on the ground and geometric (shape) characteristics.

KURZFASSUNG

Die Anwendung von Computer-Vision-Methoden für die Auswertung von Fernerkundungsbildern wird im Rahmen des Forschungsschwerpunkts "Theory and Applications of Image Processing and Pattern Recognition" des österreichischen Fonds zur Förderung der wissenschaftlichen Forschung untersucht. Dieser Beitrag gibt den Systemüberblick über ein vorgeschlagenes System zum automatischen Bildverstehen, das auf der Inversion eines physikalischen (radiometrischen) Modells der Bildaufnahme beruht. Das physikalische Modell, das für die praktische Ausführung hinreichend vereinfacht ist, wird formuliert und im Detail besprochen. Das Bildanalysesystem ist für die automatische Landnutzungskartierung aus optischen Satellitenbildern konzipiert. Die Landnutzungskategorien sind durch ihre spektrale Reflexion im Gelände und durch geometrische (Form-)Charakteristiken definiert.

1 BASIC IDEA

The following experiences and ideas are the starting point of the project:

- The human interpreter, analysing remotely sensed images visually or interactively on an image processing system, uses knowledge about the physical mechanism of the image generation process. The main advantage of this is the fact that scene-independent knowledge (e.g. on spectral reflectance characteristics of surfaces) can be used in the interpretation process, and that disturbing factors (e.g. atmospheric influences) can be accounted for.

- In automatic analysis, this knowledge up to now is used, if at all, in a very coarse and implicit way only. For example, land use classification of an optical satellite image may be based on the vegetation index being defined as the ratio of an infrared and a red channel. In this case, one makes use of 2 pieces of knowledge: (a) that differences in the terrain vegetation cover can be recognized in terms of differences of the ratio of infrared and red reflectance, and (b) that disturbing multiplicative influences from the atmosphere and from the illumination on uneven terrain cancel out by taking the ratio.

- Fully automatic analysis of remotely sensed image data is highly desirable because of the large earth observation data volumes, the high expenditure in visual or semiautomatic, interactive interpretation and the shortage of expert interpreters.

- The idea suggests itself to formalize the expert knowledge about the physical mechanism of remote sensing image acquisition and to use this knowledge in an automatic analysis procedure. A model of image acquisition transforms a scene in the real world (more exactly: a description of a scene) into an image. Image analysis is nothing else than the reversal of this process: In image analysis, a scene description is derived from an image. The basic idea of this project therefore is to analyse images by inverting a physical model of image acquisition.

- As a byproduct of image analysis, a physical model containing a quantitative description of the radiometry of image acquisition can provide a radiometric calibration of the images, i.e. the exact transformation parameters between pixel values in the images and reflectance values on the ground.

2 SYSTEM OVERVIEW

A description of a remotely sensed scene is a thematic map consisting of cartographic objects such as regions, line objects, point objects etc. In the project reported here, the attention is restricted to regions as the most frequent objects. The task of image analysis is simplified considerably if regions can be identified in the image in a segmentation process before the physical model of image acquisition is applied. The overall information flow in an analysis system with a separated segmentation process is illustrated in Fig. 1

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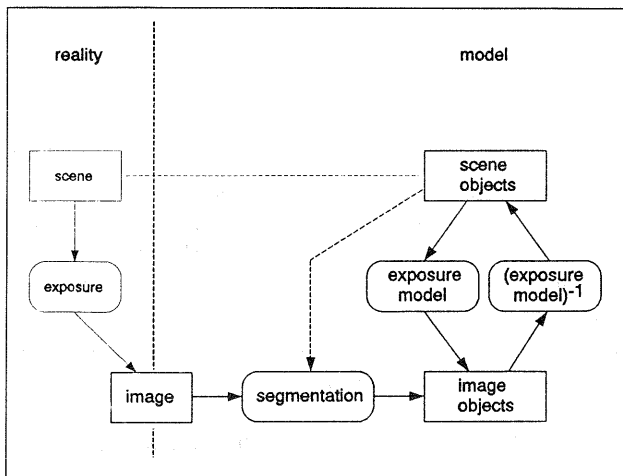
Figure 1: Information flow in the proposed image understanding system: Subdivision of the problem into segmentation and physical model application

[Schneider, Bartl, 1995].

Starting from the image, image objects are identified by segmentation according to homogeneity criteria. The advantage of this approach is twofold:

1. The amount of information to be processed in the following analysis is reduced so that it becomes managable, and

2. the mixed-pixel-problem can be brought under control: A high percentage of the pixels of a satellite image are mixed pixels containing radiometric information of more than one surface category at an unknown mixing ratio. If the segmentation is performed employing spatial subpixel analysis [Schneider, 1993, Steinwendner, 1996], objects with pure spectral signatures can be obtained even in the case of a very high percentage of mixed pixels in the original image.

The physical model of image acquisition transforms the reflectance characteristics ρ_{ki} of objects i (regions on the terrain surface) in spectral bands k, to pixel values d_{ki} in the image. This transformation is influenced by global parameters $\vec{p}_A$, describing the various absorption and scattering processes in the atmosphere, and by sensor parameters $\vec{p}_I$. The parameters $\vec{p}_A$ usually are unknown.

The image understanding problem is to assign every region object i to one surface category C_i. The set of possible surface categories is defined a priori by the (mean) reflectance values ρ'_{kC} of the categories C in the spectral bands k. For certain categories C, other properties (geometrical parameters such as shape or size descriptors of the regions belonging to these categories) may be characteristic. The mean values of these geometrical parameters for categoty C are denoted g'_{jC}, where j is an index defining the parameter. g_{ji} is the geometrical parameter j for object i as determined from the image. The image understanding problem can now be formulated in the following way: Given are

- the physical model

$$d_{ki} = d_k(\rho_{ki}, \vec{p}_A, \vec{p}_I) \qquad (1)$$

- the sensor parameters $\vec{p}_I$,
- the (mean) pixel values d_{ki} of the objects,
- the (mean) reflectance values ρ'_{kC} of the surface categories to be identified, and
- the (mean) geometrical parameter g'_{jC} of the surface categories to be identified.

The problem is to find the global parameters $\vec{p}_A$ and the category C_i of every object in such a way that

$$\sum_{k,i} a_k \cdot (\rho_{ki} - \rho'_{kC_i})^2 + \sum_{j,i} b_j \cdot (g_{ji} - g'_{jC_i})^2 \to Min. \qquad (2)$$

The quantities a_k and b_j here are the weights of the different spectral bands and geometrical parameters. These weights also determine the relative importance of the geometrical parameters as compared to the spectral characteristics.

Reference information ("ground truth data") can be used in this image understanding scheme: "Radiometric control points" (reference surfaces on the terrain with given reflectance data) may provide input values for ρ_{ki}, and "thematic control points" (regions with known land use) may provide input values for C_i.

3 PHYSICAL MODEL

Object reflectance, radiance and irradiance quantities as well as atmospheric absorption and scattering are expressed as integral quantities for the individual discrete spectral bands of the sensor. Assuming a sensor with linear radiometric response, the pixel value d_{ki} is related to the radiance L_{Iki} incident on the sensor instrument I by

$$d_{ki} = m_k L_{Iki} + a_k. \qquad (3)$$

m_k and a_k are the multiplicative factor and the additive term, respectively, characterizing the response of the sensor to incident radiation in the spectral band k.

L_{Iki} can be traced back to ρ_{ki} with the use of a computer-coded numeric model such as LOWTRAN7:

$$L_{Iki} = L_{Ik}(\vec{p}_A, \rho_{ki}). \qquad (4)$$

This method is very general and fairly accurate, but computationally expensive. One has to bear in mind that numerous evaluations of (4) are necessary to solve (2).

In an attempt to formulate the problem analytically to facilitate computation, L_{Iki} can be regarded as a sum of 3 terms (Fig. 2): of the radiance reflected by the terrain surface, $L_{\rho ki}$ (i.e. the signal proper), attenuated by the transmission of the atmosphere for a vertical path $\vartheta = 0$, τ_{0k}, the radiance of solar radiation scattered by the atmosphere directly to the sensor, L_{Auk} (u stands for upwards), and the radiance reflected by the terrain surface and scattered afterwards by the atmosphere to the sensor, $L_{\rho uki}$:

$$L_{Iki} = L_{\rho ki}\tau_{0k} + L_{Auk} + L_{\rho uki} \qquad (5)$$

Assuming a terrain surface with Lambertian reflectance characteristics, the reflected radiance is

$$L_{\rho ki} = \frac{1}{\pi} E_{Gki} \cdot \rho_{ki} \qquad (6)$$

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where E_{Gk} denotes the global irradiance of the surface in band k. This quantity again is the sum of 3 terms: of the direct solar irradiance, of the diffuse sky irradiance due to solar radiation scattered by the atmosphere downwards to the earth, and of the diffuse sky irradiance due to the radiation reflected by the terrain surface and scattered back by the atmosphere:

$$E_{Gki} = E_{Sk}\tau_{0k}^{1/\cos\vartheta}\cos\vartheta + \pi L_{Adk} + b_k\pi L_{\rho ki} \qquad (7)$$

E_{Sk} here is the solar irradiance of a plane perpendicular to the incident radiation at the upper edge of the atmosphere, ϑ is the zenit angle of the solar radiation path, L_{Adk} is the solar radiation scattered by the atmosphere downwards, and b_k is the "reflectance" of the atmosphere due to backscattering for radiation reflected by the terrain surface.

Similar to the quantity b_k describing the backscattering characteristics of the atmosphere, a forward scattering coefficient f_k can be defined, yielding an expression for the quantity $L_{\rho uk}$ introduced in equation 5 :

$$L_{\rho uki} = f_k \cdot L_{\rho ki} \qquad (8)$$

Combining all these equations, one obtains the following relationship between the terrain reflectance values ρ_k and the pixel values d_k in the image:

$$d_{ki} = m_k \cdot$$

$$\left[\left(E_{Sk}\tau_{0k}^{1/\cos\vartheta}\cos\vartheta + \pi L_{Adk}\right)\frac{1}{\pi}\rho_{ki}\frac{\tau_{0k} + f_k}{1 - b_k\rho_{ki}} + L_{Auk}\right]$$

$$+a_k \qquad (9)$$

In this equation, some of the quantities are constant and known, such as E_{Sk} from satellite observations of the solar radiation, and ϑ from the exact time of image acquisition. The sensor parameters m_k and a_k are known in principle from preflight or inflight calibration procedures. These parameters may change with time, however, so that it might be of interest to introduce them as unknown variables in the image understanding problem, or at least to allow small corrections of the given values. The atmospheric parameters τ_{0k}, L_{Adk}, L_{Auk}, f_k and b_k are unknown. They depend mainly on a large number of parameters of aerosole properties and aerosole concentration distribution and thus are interrelated in a complicated manner described by intricate atmospheric models. It must be noted that these atmospheric influences can be quite pronounced and must not be neglected in the calculations, as the disturbing quantities L_{Auk} and $L_{\rho uk}$ sometimes exeed the signal quantities $L_{\rho k}\tau_{0k}$. One way to handle these atmospheric parameters in the image understanding procedure is to work with a limited number (e.g. 2 to 4) "standard atmospheres" with constant aerosole types (e.g. "rural atmosphere", "urban atmosphere") and to use one additional continuous parameter (e.g. atmospheric extinction, or horizontal visibility V_h) to describe the atmospheric situation at the time of image acquisition. The atmospheric quantities in the physical model equation can then be reduced to the 2 unknown variables M (discrete, denoting the standard atmosphere model category), and V_h.

$$L_{Adk} = L_{Adk}(M, V_h), \qquad L_{Auk} = L_{Auk}(M, V_h),$$
$$\tau_{0k} = \tau_{0k}(M, V_h),$$
$$f_k = f_k(M, V_h), \qquad b_k = b_k(M, V_h)$$
$$\qquad (10)$$

Fig. 3 illustrates the quantity L_{Auk} as calculated with LOW-TRAN7 for LANDSAT TM bands k=1,2,3,4,5,7, for a standard midlatitude summer atmosphere M with a standard rural aerosole profile, and for 3 values of V_h (5km, 23km, 50km).

Polynomial regression can be used to describe this dependence of L_{Auk} and of the other atmospheric parameters of equation 10 on V_h for a given M.

4 APPLICATION OF THE MODEL TO REAL DATA

Data sets of LANDSAT TM data for experiments with the physical model were obtained by manual selection of test objects on a conventional image processing system. The reflectance data for different surface materials such as water of different degree of pollution, soil, forest (different tree species) and meadow were taken from field measurements and from the literature. Using these data, the basic validity of the model could be proved. The reflectance data (defined a priori) produced the observed pixel values for plausible values of the atmospheric parameters.

Solving the image understanding problem by global optimization techniques is being studied at present. In particular, simulated annealing and genetic algorithms are being tested.

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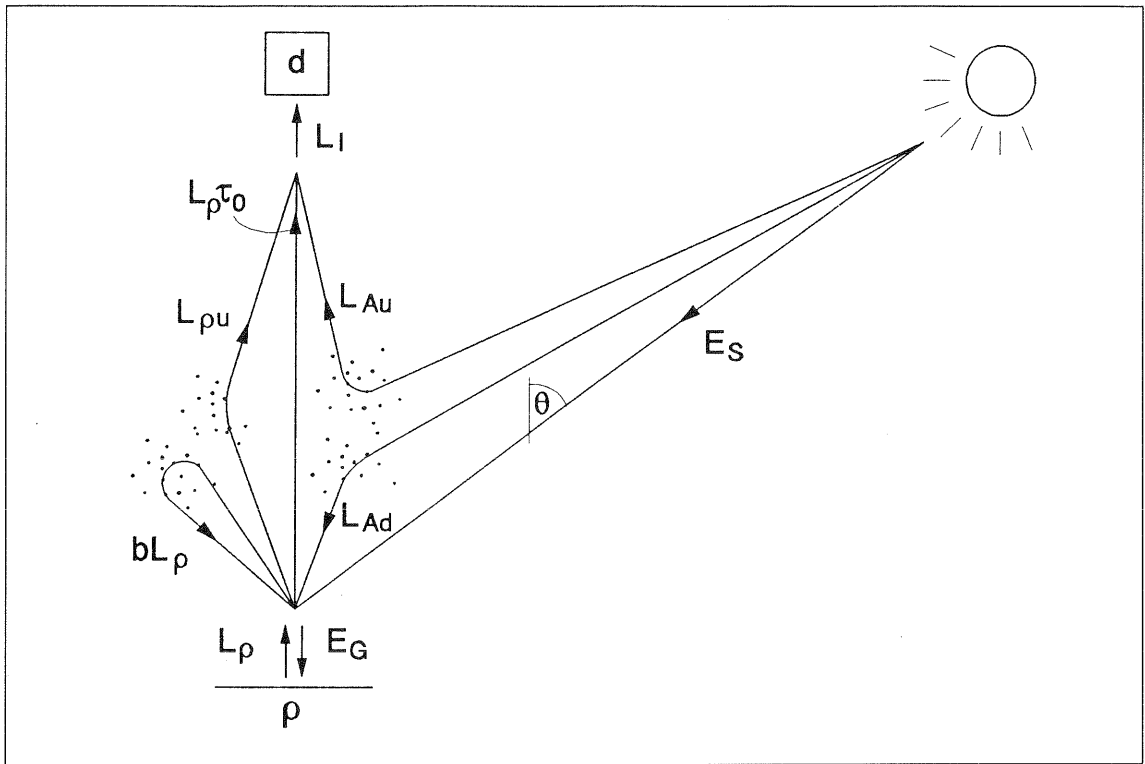
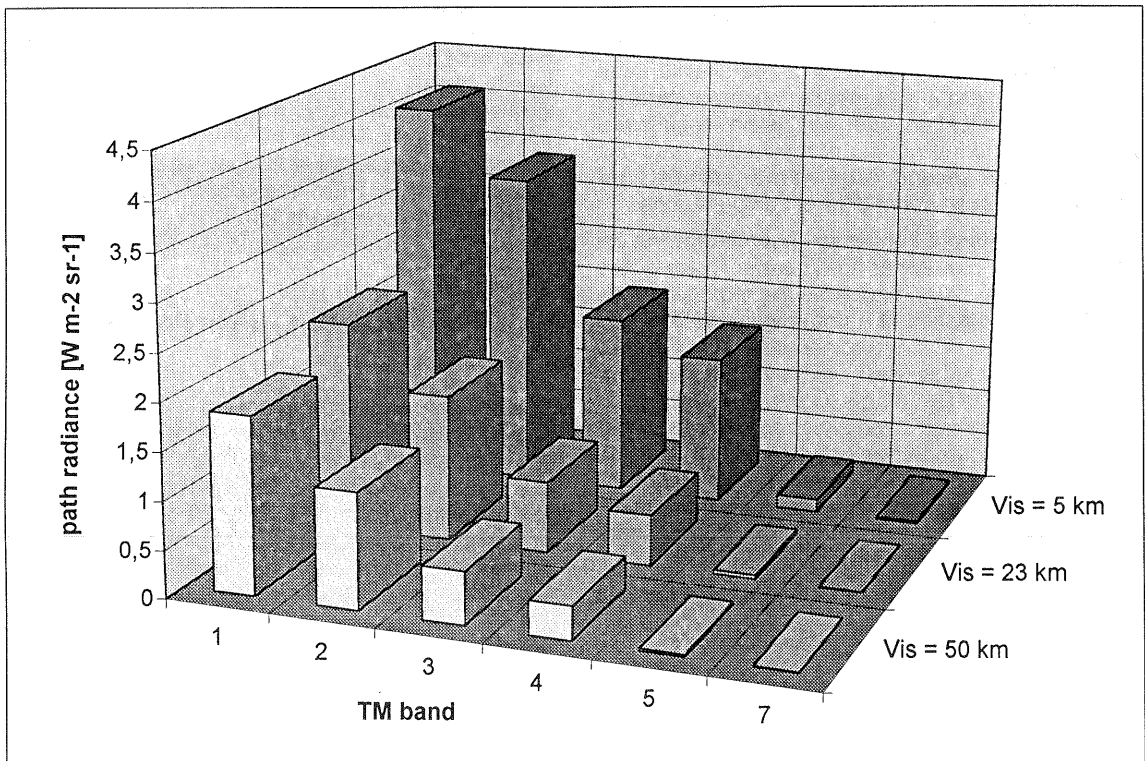Figure 2: Radiation paths in remote sensing image acquisition

Figure 3: Path radiance in LANDSAT TM spectral bands for a standard midlatitude summer atmosphere with standard rural aerosole distribution for 3 values of horizontal visibility, as calculated by LOWTRAN7

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