Selected Annotated Bibliographies for Image Mapping: Geometric Registration, Resampling, Contrast Enhancement, Spatial Filtering, and Color Calibration

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Department of the Interior
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Selected Annotated Bibliographies for Image Mapping: Geometric Registration, Resampling, Contrast Enhancement, Spatial Filtering, and Color Calibration

By B.K. Quirk, L.S. Kalman, D.D. Judd, M.E. Richards, and J.W. Feuquay*

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*Technicolor Government Services, Inc. Authors.
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PREFACE

Many articles have been published in the image processing areas associated with image mapping, but no document has combined these references in a single publication. Image mapping is a new and dynamic field and a baseline document reviewing past research in the image processing areas associated with it needs to be provided. A collection of annotated bibliographies provides a source for that background information.

Image maps are part of an experimental U.S. Geological Survey National Mapping Division (NMD) program. The image map base is generally derived from satellite data. Currently, Landsat multispectral scanner (MSS) or thematic mapper (TM) data are used. Eventually, data from other remote sensing systems and their associated derivative products will be used as image map bases. Advanced Very High Resolution Radiometer (AVHRR), synthetic aperture radar (SAR), and digitized National High Altitude Photography (NHAP) images are examples of the other types of remotely sensed data that might be used for image map bases. An example of derivative products could be the use of digital elevation model (DEM) data to produce shaded-relief or perspective image map bases. The maps are published at various scales, such as 1:250,000 or 1:100,000, and may have the topography of the area printed on the reverse side. Image maps are designed for general-purpose use rather than for any particular application or academic discipline.

During the production of an image map within NMD, several image processing steps are involved. The first step is to select the image or images that cover the area of interest. Depending on the quality of the image(s), it may be necessary to perform a preprocessing step to remove noise in the data (such as striping in Landsat data caused by sensor miscalibration).

Next, the data are registered to a map projection. This is performed by selecting ground control points (GCP's) that are distinguishable on both a map and the imagery. These GCP's allow a transformation to be generated that converts the pixels to a map projection. An nth-order polynomial warping function is generally used in this step. Part of the registration step is resampling, the calculation of a new brightness or density level for each pixel. The common resampling techniques are: nearest neighbor, bilinear interpolation, cubic convolution, parametric cubic convolution, and restoration. The choice of resampling technique is based on the project requirements, quality of the input data, geographic location of the data, cost, etc. If more than one image is needed to cover the area of the map, each image is registered and the images are digitally mosaicked.

Contrast enhancement is performed after geometric registration. In this step, an attempt is made to make better use of the available density range in the data by increasing the contrast and removing any variations caused by geographic features or date of acquisition. For example, although Landsat data is provided in an 8-bit format (256 density levels), it generally does not make full use of this range of values primarily because of the way it is acquired. Landsat scenes with a wide range of geographical features or scenes that were obtained at different times of the year or during different years can be enhanced to make a more appealing image that reduces large variations in contrast over the entire scene while preserving detail and contrast at the local level.

The next digital step in producing an image map base is spatial filtering, or more specifically, edge enhancement. This sharpens the image by enhancing the boundaries between edge features where an edge is defined as a sharp transition in brightness or density levels (for example, agricultural fields).

Each of the three sensor bands that comprise the image map base are represented as a red, green, or blue (RGB) channel on a color monitor. The final digital processing step is to transform the data for the image map base to photographic separations. In this step, each of the RGB components is recorded as a black and white separate by a laser beam recorder (LBR). These film separates are sent to the U.S. Geological Survey in Reston, Virginia, for final lithographic processing. Color calibration in the production of image maps allows for monitoring and modeling of the color changes between the digital, photographic, and lithographic processes.

Each of the following five sections is arranged alphabetically. In most cases, each paper's abstract was used as the annotation. Several of the papers were not published in their symposia's proceedings, but were thought important enough to be included in this bibliography.

CONTENTS

ABSTRACT

Annotated bibliographies have been prepared which contain citations from technical reports, journal articles, government publications, and other publications in five areas of interest that relate to the production of image maps. Image mapping is the process of applying remotely sensed data, primarily satellite data, to a map base by performing a series of digital and analog processing steps. Particular emphasis is on utilizing Landsat data in image maps, but Advanced Very High Resolution Radiometer (AVHRR) and other remotely sensed data and derivative products, such as digital elevation models, are being used. The five topics related to image mapping for which citations appear are: (1) geometric registration, (2) resampling, (3) contrast enhancement, (4) spatial filtering, and (5) color calibration.

The annotated bibliographies contain 164 citations to selected publications from 1955 to 1984. The articles and books were published in English and are available through symposia proceedings, U.S. Government agencies, the National Technical Information Service (NTIS), and the cited publishing companies.

GEOMETRIC REGISTRATION BIBLIOGRAPHY

Algazi, V. R., Ford, G. E., and Meyer, D. I., 1979, Geometric correction of satellite data using curvilinear features and virtual control points, in International Symposium on Remote Sensing of Environment, 13th, Ann Arbor, Michigan, 1979, Proceedings: Ann Arbor, Michigan, Environmental Research Institute of Michigan, v. III, p. 1377-1383.

In this paper, we describe a simple, yet effective procedure for the geometric correction of partial Landsat scenes. The procedure is based on the acquisition of actual and virtual control points from the line printer output of enhanced curvilinear features. The accuracy of this method compares favorably with that of the conventional approach in which an interactive image display system is employed.

Anderson, J. E., 1983, Landsat scene-to-scene registration accuracy assessment: Quarterly Report, January 22 to April 21, 1983: NSTL Station, Mississippi, NASA/NSTL/Earth Resources Laboratory, 7 p.

This report documents initial results obtained from the registration of Landsat-4 MSS data to Landsat-2 MSS data. A comparison is made with results obtained from a Landsat-2 MSS to Landsat-2 MSS scene-to-scene registration (using the same Landsat-2 MSS data as the "base" data set in both procedures). RMS errors calculated on the control points used in the establishment of scene-to-scene mapping equations are compared to errors computed from independently chosen verification points. Models developed to estimate actual scene-to-scene registration accuracy based on the use of electrostatic plots are also presented. This project will include analyses of TM data at a later date, and both SCROUNGE and TIPS era products will be evaluated. Analysis or results obtained indicates a statistically significant difference in the RMS errors for the element contribution. Scan line errors were not significantly different. It appears from analysis that a modification to the Landsat-4 MSS scan mirror coefficients is required to correct the situation.

Anuta, P. E., 1970, Spatial registration of multispectral and multitemporal digital imagery using fast Fourier transform techniques, in Bernstein, R., ed., 1978, Digital image processing for remote sensing: New York, John Wiley, p. 122-137.

A system for spatial registration of digitized multispectral and multitemporal imagery is described. Multispectral imagery can be obtained from sources such as multilens cameras, multichannel optical-mechanical line scanners, or multiple vidicon systems which employ filters or other spectral separation techniques to sense selected portions of the spectrum. Spatial registration is required so that multidimensional analysis can be performed on contextually similar image elements from different wavelength bands and at different times. The general registration problem is discussed first; then the fast Fourier transform (FFT) technique for cross correlation of misregistered imagery to determine spatial distances is discussed in detail. A method of achieving translational, rotational, and scaling corrections between images is described. Results of correlation analysis of multispectral scanner imagery and digitized satellite photography is presented. Use of the system for registration of multispectral airborne linescanner imagery and space photography is described. Application of the techniques to preprocessing of earth resources satellite imagery from systems such as the Earth Resources Technology Satellite (ERTS) scanner and vidicon system is discussed in conclusion.

Barnea, D. I., and Silverman, H. F., 1972, A class of algorithms for fast digital image registration, in Bernstein, R., ed., 1978, Digital image processing for remote sensing: New York, John Wiley, p. 138-145.

The automatic determination of local similarity between two structured data sets is fundamental to the disciplines of pattern recognition and image processing. A class of algorithms, which may be used to determine similarity in a far more efficient manner than methods currently in use, is introduced in this paper. There may be a saving of computation time of two orders of magnitude or more by adopting this new approach. The problem of translational image registration, used as an example throughout, is discussed and the problems with the most widely used method of correlation are explained. Simple implementations of the new algorithms are introduced to convey the basic idea of their structure. Data from ITOS-1 satellites are presented to give meaningful empirical justification for theoretical predictions.

Benny, A. H., 1981, Automatic relocation of ground control points in Landsat imagery, in Matching Remote Sensing Technologies and Their Applications, London, England, 1981, Proceedings: London, England, Remote Sensing Society, p. 307-315.

Images obtained from the Landsat multispectral scanner are not provided in any normally recognized map projection system, so it is often necessary for a transformation to be made. This is usually done with the aid of ground control points, whose locations on the ground (or on a map) are accurately known and which can be accurately located within Landsat images. The initial selection and location of such ground control points is usually performed manually. For multitemporal imagery, the same ground control points can be used. The positions of these points can be located within the repeat image either manually or, as described in this paper, by an almost entirely automatic computer process. The semi-automated process has been found to work speedily and effectively on many repeat images of Britain, usually giving accurate location of well over 90 percent of ground control points. The process has been developed for use with images of Britain, but it could readily be adapted for worldwide use.

Berlioz, G., 1980, An interactive rectification system for remote sensing image, in American Society of Photogrammetry Fall Technical Meeting, Niagara Falls, New York, 1980, Proceedings: Falls Church, Virginia, American Society of Photogrammetry, p. 361-370.

CAP GEMINI SOGETI, a European computer service company, under contract to CNES (French Space Research Center), is involved in applied research and in development of techniques and systems for digital image processing. One requirement of this contract was the conception, development, and implementation of an interactive rectification system using ground control points (GCP's) in the image processing system of CNES. The hardware configuration is composed of a general-purpose CII French computer, a graphic display Tektronix 4014, and an interactive high-resolution color display MULTTTRIM CIT ALCATEL.

The software system has two functional modules:

- The determination of the polynomial deformation (degree 1 to 5) (forward and backward) between the raw picture and a reference element (picture or map).

- The processing of the corrected image with one of the previous deformation models.

For all these operations, the user has systems items for GCP and deformation models, and all parameters are defined interactively. Particular to the system are the conversational language, the algorithms for segmentation, and the ability to rectify pictures with any content of distortion, any extent of rotation, and local scale factors between 1 to 10.

Bernstein, R., 1978, Digital image processing of earth observation sensor data, in Bernstein, R., ed., 1978, Digital image processing for remote sensing: New York, John Wiley, p. 55-72.

This paper describes image processing techniques that were developed to precisely correct Landsat multispectral Earth observation data and gives results achieved, e.g., geometric corrections with an error of less than one picture element, a relative error of one-fourth picture element, and no radiometric error effect. Techniques for enhancing the sensor data, digitally mosaicking multiple scenes, and extracting information are also illustrated.

Bernstein, R., and Silverman, H. F., 1978, Digital techniques for earth resource image data processing, in Bernstein, R., ed., 1978, Digital image processing for remote sensing: New York, John Wiley, p. 107-120.

The growing availability of faster and more versatile digital hardware, along with the development of more efficient processing algorithms has brought about an improvement in the ability of digital systems to process high-resolution imagery. In this paper, techniques for implementing image corrections are described, and the results of image processing experiments are presented. The techniques include methods for automatically locating reseau marks and reference ground-control points, and for computing and applying both geometric and radiometric image corrections. A fast method of correlation (based on a class of sequential-similarity-detection algorithms) which solves the problem in digital image processing of correlating the working image to a reference image is also presented.

Bernstein, R., and Ferneyhough, D. G., 1975, Digital image processing: Photogrammetric Engineering and Remote Sensing, v. 41, no. 12, p. 1465-1476.

The use of digital sensors in earth resources applications appears to be well-established. The signals sent to the ground from the Landsat (previously known as the Earth Resources Technology Satellite, ERTS) multispectral scanner (MSS) are digitized prior to transmission. For future earth-observation programs, both the sensor outputs and the ground processing will be digital. If such sensors are to serve a useful role in the surveying and management of the Earth's resources, efficient methods for correcting and extracting information from the sensor outputs must be developed. The Federal Systems Division of IBM has developed an image processing facility to experimentally process, view, and record digital image data. This facility has been used to support Landsat digital image processing investigations an advanced image processing research and development. A brief description of the facility is presented, some techniques that have been developed to correct the image data are discussed, and some results obtained by users of the facility are described.

Brown, R. J., Bernier, M., and Fedosejevs, G., 1982, Geometrical and atmospheric considerations of NOAA AVHRR imagery, in International Symposium of Machine Processing of Remotely Sensed Data, 8th, West Lafayette, Indiana, 1982, Proceedings: West Lafayette, Indiana, Purdue University, p. 374-381.

The Advanced Very High Resolution Radiometers (AVHRR) on the National Oceanic and Atmospheric Administration (NOAA) satellites NOAA-6 and NOAA-7 have good potential for use in the area of crop monitoring. Channels 1 and 2 of the sensor are, spectrally, very close to bands 5 and 7 of the Landsat multispectral scanner (MSS). The daily global coverage which can be obtained from these satellites makes this monitoring role feasible. However, the 1.1 km resolution and large scan angle (approximately +/- 56 degree from nadir) lead to some data interpretation problems. Within this paper the effect of large scan angles and the subsequent effects of the atmosphere are investigated. It was found that there are substantial day-to-day variations in the data that are not related to crop condition. Procedures using intra-scene radiances have been developed to remove these radiance variations, which are caused by the illumination/view geometry and atmospheric path radiance.

Caron, R. H., 1975, Evaluation of full-scene registered ERTS MSS imagery using a multitemporal/multispectral Bayes supervised classifier, in Annual Remote Sensing of Earth Resources Conference, 4th, Tullahoma, Tennessee, 1975, Proceedings: Tullahoma, Tennessee, University of Tennessee Space Institute, p. 783-806.

The Earth Resources Technology Satellite (ERTS) passes over the same region of the Earth's surface every 18 days. In general, however, the multispectral scanner imagery from one pass are not spatially registered to the imagery from any other pass. Thus, the success of change detection analyses and multitemporal/multispectral classifications depends upon the degree to which scenes from different passes can be made to overlay one another. A technique for precision registration (and simultaneous rectification) of entire ERTS scenes has been developed which yields misregistrations smaller than one picture element throughout an image. A comprehensive study to evaluate this registered imagery as a data base for multispectral signature analysis has been undertaken. Initial results show that for some land use signatures an 8- to 12-percent improvement in classifier performance obtains when patterns are derived from registered multi-pass as opposed to single-pass imagery. Delineation of urban land use in the metropolitan Washington area according to four categories--livelihood, residential, mostly open space and water--has been achieved with an average of 88 percent classification accuracy.

Cox, C. W., 1982, Computer-aided image registration: Los Alamos, New Mexico, Report LA-9507-MS, Los Alamos National Laboratory, 13 p.

Correlation techniques applied to highly processed digitized images can accurately register similar images.

Crombie, M. A., 1980, Errors in automatic pass point mensuration using digital techniques: Fort Belvoir, Virginia, Report ETL-0232, U.S. Army Engineer Topographic Laboratories, 19 p.

A technique for automatically measuring pass points from digital stereo images is evaluated. Numerical estimates of x- and y-parallax for a specific stereopair of images is presented as a function of terrain relief.

Derouchie, W. F., and Edmond, J. J., 1970, Techniques for registration of ERTS multispectral television images, in American Society of Photogrammetry Annual Meeting, 36th, Washington, D.C., 1970, Proceedings: Falls Church, Virginia, American Society of Photogrammetry, 7 p.

The images that will be received from the return beam vidicon (RBV) imaging system of the Earth Resources Technology Satellite (ERTS) will be unavoidably geometrically distorted. These are high-resolution images covering 100-mile-square areas of the Earth's surface that have been simultaneously exposed in three spectral bands. Relative geometric distortion (registration error) between the three images must be removed for the production of color-composite images. Absolute distortion must be removed for mapping purposes, and for precise overlay comparisons of successive coverage. A study was made of the distortion problem, and two methods for correcting image misregistration were considered, including a direct approach based on automatic image correlation, and an indirect approach based on image-reseau measurements. The reseau measurement method showed the most promise, and an analytical image distortion and registration investigation was made, based on this method. Distortion parameters derived from the RBV data were used to calculate distortion within the image format. The study evaluated the effectiveness of a number of different geometric transformations that could be implemented with various processing systems.

Emmert, R. A., and McGillem, C. D., 1973, Multitemporal geometric distortion correction utilizing the affine transformation, in Bernstein, R., ed., 1978, Digital image processing for remote sensing: New York, John Wiley, p. 153-161.

In the analysis of multitemporal remotely sensed imagery, it is necessary to register the data sets. To do this, the data are divided into subimages, and the misregistration between the data subsets is modelled by an affine transformation. The properties of the Fourier transform of a two-dimensional function under the affine transformation are given, and examples of these relations between the spatial and spatial frequency domains are shown. Techniques for the estimation of the coefficients of the distortion model using the spatial frequency information are developed, and an example of the use of this method for the correction of line scanner imagery is given.

Forster, B. C., 1980, Urban control for Landsat data: Photogrammetric Engineering and Remote Sensing v. 46, no. 4, p. 539-545.

The importance of accurate registration of ground truth areas to equivalent Landsat digital data in urban areas must be stressed, if detailed classification is to be achieved. A stepwise polynomial transformation of 100 ground control points over the Sydney Metropolitan area produced transformation parameters which achieved standard errors of approximately 30 m. The least-squares polynomial transformation was computed using a standard multiple-regression statistical package. Shade prints and character prints of typical ground control points were generated to illustrate a small-feature selection method. The effect of the ultimate transformation on the control points was examined visually on a plot of the residuals.

Friedmann, D. E., Friedel, J. P., Magnussen, K. L., Kwok, R., and Richardson, S., 1983, Multiple scene precision rectification of spaceborne imagery with very few ground control points: Photogrammetric Engineering and Remote Sensing, v. 49, no. 12, p. 1657-1667.

The success of the Landsat series of satellites has greatly advanced remote sensing and its applications. However, the utility of the imagery data has been limited in application areas requiring high precision due to the expensive and time-consuming process of precision geometric correction. Present correction methods require for each scene the identification of an average of 15 features whose geographic location is known. This paper discusses a method which reduces the number of features which must be identified by more than an order of magnitude. Results presented here show that ten scenes can be rectified by identifying only four features. This method, in combination with the latest resampling technology, will make the operational production of geocoded precision imagery products feasible and economical even in poorly mapped areas.

Graham, M. H., and Luebbe, R., 1981, An evaluation of MSS P-format data registration: NSTL Station, Mississippi, NASA/NSTL Report NSTL/ERL-197, NASA/NSTL/Earth Resources Laboratories, 57 p.

Twelve Landsat scenes of the P-format were analyzed for registration accuracy based on the Hotine Oblique Mercator (HOM) tick marks contained in the annotation record. Independently chosen ground control points were used to evaluate each scene. The results indicate that 8 out of the 12 showed either good or fairly good registration and that the registration information provided with the MSS data can be used as a starting point from which to make a more precise registration.

Hall, E. L., Davies, D. L., and Casey, M. E., 1980, The selection of critical subsets for signal, image, and scene matching: IEEE Transactions on Pattern Analysis and Machine Intelligence, v. PAMI-2, no. 4, p. 313-322.

A basic matching problem consists of locating a reference subset in a larger set of data subject to a given criterion. Variations of the problem include template matching for object recognition, matched filtering for signal detection, image registration, change detection, cartography feature location, correlation guidance, and scene matching. In the general case the data sets may be made by completely different sensors at different geometrical orientations. A data set in N dimensions can be considered as a function in N-space. The critical subset selection problem arises when one is given a function and must select some subset of the function to match the original. In some cases uniqueness is a key feature of the best subset. Uniqueness may be measured by the number and relative magnitudes of the peaks in the cross-correlation function of the original and subset functions. For a unique subset, another desirable characteristic is lack of ambiguity. This characteristic may be measured using the correlation length or 50 percent width of the main correlation peak. The smaller the correlation length, the greater the certainty one has in detecting the correct match position. In this paper a method is presented for selecting the "best" subset of a scene where best is defined in terms of the minimum correlation length. The best solution is shown to be a function of the entire scene, i.e., an improper subset. A solution is also obtained for the restriction to a proper subset with minimum mean-square error deviation from the ideal as the criterion. An analysis is presented for the one-dimensional case which generalizes to the two-, three-, and higher dimensional problems. The analysis is extended to the discrete case in which the results may be computed with the fast Fourier transform (FFT) algorithm. Examples and pictorial results are presented which illustrate that the structure of the "best" regions for natural scenes is closely related to edge information in the scene.

Kiss, P., Arnold, P., and Goldstine, J., 1981, Image registration system in the Landsat-D production environment, in International Symposium of Machine Processing of Remotely Sensed Data, 7th, West Lafayette, Indiana, 1981, Proceedings: West Lafayette, Indiana, Purdue University, p. 621-625.

An effort is underway to develop an automated image registration system for the Landsat-D ground segment. This system will be capable of providing accurate control point (CP) location errors in imagery that has been corrected using system models. A part of this effort consisted of studying various image enhancement techniques, correlation techniques and subpixel registration methods. Presented here is an overview of the registration system developed, along with the study results that led to the choices of techniques incorporated. Although much previous work exists in this area, it is believed that some of the methods and findings are new. It is also hoped that the extensive testing results along with the constraints of a very-high-speed production environment will be of value to the remote sensing community.

Lavine, D., Lambird, B. A., and Kanal, L. N., 1981, Analysis and simulation of discrete digital image matching: Fort Belvoir, Virginia, Report ETL-0278, U.S. Army Engineering Topographic Laboratories, 82 p.

This report evaluates procedures for the approximate registration of digital images to maps and other images. It emphasizes point features and vectors derived from point features for image registration labeling and other means of adding definiteness to feature identification are promoted as ways to speed up registration. Clustering algorithms, distribution and type of features, hierarchical matching techniques, and other procedures are investigated with scene and map simulations.

Levine, I., 1983, The geometric correction of Landsat-type imagery using perturbation techniques: IEEE Transactions on Geoscience and Remote Sensing, v. GE-21, no. 2, p. 175-179.

A method for geometric correction data calculation is based on decomposition of image distortions into nominal distortions and perturbations, caused by deviations from the nominal spacecraft motion and sensor pointing. The maximal errors of the method are of the order of 5 m, and the average errors are less than 0.6 m (sigma).

Masry, S. E., 1981, Digital mapping using entities: A new concept: Photogrammetric Engineering and Remote Sensing, v. 48, no. 11, p. 1561-1565.

Generally, the identification of linear features such as roads, railways, etc., can be easier than that of individual points. This is particularly the case with high-altitude and satellite imagery and photography. Moreover, well-defined linear features can be comparable in precision to point features. However, individual points rather than the wealth of points of linear features have been, so far, used for control. A new concept to utilize linear features in lieu of or to supplement conventional control, is presented. The concept is based on entity-to-entity correspondence; an entity being part or the whole of a feature. Points on an "observed" entity need not correspond to points on a "control" entity. The concept has potential in a digital environment. Digital rectification of a satellite image and testing the precision of digital maps are example applications. The concept was successfully implemented in analytical absolute orientation of a stereomodel and analytical resection of a photograph.

McGillem, C. D., and Svedlow, M., 1978, Image registration error variance as a measure of overlay quality, in Bernstein, R., ed., 1978, Digital image processing for remote sensing: New York, John Wiley, p. 168-173.

When one image (the signal) is to be registered with a second image (the signal plus noise) of the same scene, one would like to know the accuracy possible for this registration. This paper derives an estimate of the variance of the registration error that can be expected via two approaches. The solution in each instance is found to be a function of the effective bandwidth of the signal and the noise, and the signal-to-noise ratio. Application of these results to Landsat-1 data indicates that for most cases registration variances will be significantly less than one picture element.

McGlone, C., and Mikhail, E. M., 1982, Geometric constraints in multispectral scanner data, in American Society of Photogrammetry Annual Meeting, 48th, Washington, D.C., 1982, Proceedings: Falls Church, Virginia, American Society of Photogrammetry, p. 563-572.

Sidelapping aircraft multispectral scanner (MSS) data can be reduced using block adjustment techniques similar to those used with aerial photographs. The accuracy of the elevations thus determined is normally lower than that obtained for planimetry. The incorporation of object space (terrain) geometric constraints, such as points lying on straight lines, improved the accuracy of both planimetry and heights. The mathematical basis for the use of such constraints is developed, and their application in block adjustment of aircraft MSS data outlined.

Murai, S., Okuda, T., and Akiyama, M., 1980, Digital mosaic of color aerial photographs, in International Archives of Photogrammetry, 14th, Hamburg, Federal Republic of Germany, 1980, Proceedings: Hamburg, Federal Republic of Germany, Committee of the 14th Congress for Photogrammetry, v. 23, p. 570-578.

A color orthophoto map with scale of 1:50,000 or 1:25,000 is produced by mosaicking of several pieces of color orthophotographs. While black and white mosaics of aerial photographs involve less distinctive seams at their boundaries, color mosaics of color aerial photographs or color orthophotographs involve more discontinuities of color tones. The objective of this study is to remove the discontinuous seams from color mosaics using digital image processing techniques. As the results of this study, digital mosaics of color orthophotographs with continuously varied tones, that is, seamless mosaics, can be produced by the methodology which has been developed by the authors.

Niblack, W., 1981, The control point library building system: Photogrammetric Engineering and Remote Sensing, v. 47, no. 12, p. 1709-1715.

The Earth Resources Observation System (EROS) Data Center in Sioux Falls, South Dakota distributes precision-corrected Landsat MSS and RBV data. These data are derived from master data tapes produced by the Master Data Processor (MDP), NASA's system for computing and applying corrections to the data. Included in the MDP is the Control Point Library Building System (CPLBS), an interactive menu-driven system which permits a user to build and maintain libraries of control points. The control points are required to achieve the high geometric accuracy desired in the output MSS and RBV data. This paper describes the processing performed by CPLBS, the accuracy of the system, and the host computer and special image viewing equipment employed.

Orti, F., 1981, Optimal distribution of control points to minimize Landsat image registration errors: Photogrammetric Engineering and Remote Sensing, v. 47, no. 1, p. 101-110.

To precisely correct a Landsat MSS image, ground control points are necessary because of the inaccuracy of the satellite's attitude and altitude measurements. If the attitude and altitude are assumed to be described by time-dependent polynomials, the corresponding coefficients can be estimated from the set of ground control points (GCP's), and their estimated error can be propagated to obtain an average registration error over the whole image as a function of the GCP's coordinates. Minimization of this error leads to the result that GCP's should be chosen around certain locations on the left and right edges of the image. Some experiments are run to assess the practical value of this result.

Paderes, F. C., and Mikhail, E. M., 1983, Photogrammetric aspects of satellite imageries, in American Society of Photogrammetry Fall Meeting, Salt Lake City, Utah, 1983, Proceedings: Falls Church, Virginia, American Society of Photogrammetry, p. 626-635.

A comprehensive geometric model for satellite images is derived. This model is used for simulation and for image rectification. Both synthetic and real data are used for investigating the geometry of the imaging process and the accuracy potential of rectifying such images. All satellite-position and sensor-attitude parameters are recovered during rectification. Rectification accuracy improves marginally when using more than 25 control points, and is highly sensitive to errors in image point identification.

Pratt, W. K., 1978, Correlation techniques of image registration, in Bernstein, R., ed., 1978, Digital image processing for remote sensing: New York, John Wiley, p. 162-167.

An extension to the basic concept of correlation detection as a means of image registration is developed. The technique involves linear spatial preprocessing of the images to be registered prior to the application of a correlation measure. This preprocessing operation utilizes the spatial correlation within each image and greatly improves the detectability of image misregistration. An analysis of the computational aspects of the algorithm is given. Also, results of a computer simulation to evaluate the technique are given.

Price, K., and Reddy, R., 1979, Matching segments of images: IEEE Transactions on Pattern Analysis and Machine Intelligence, v. PAMI-1, no. 1, p. 110-116.

This correspondence describes research in the development of symbolic registration techniques directed toward the comparison of pairs of images of the same scene to ultimately generate descriptions of the changes in the scene. Unlike most earlier work in image registration, all the matching and analysis will be performed at a symbolic level rather than a signal level. We have applied this registration procedure on several different types of scenes and the system appears to work well both on pairs of images which may be analyzed in part by signal-based systems and those which cannot be so analyzed.

Rifman, S. S., Monuki, A. T., and Shortwell, C. P., 1979, Multi-sensor Landsat MSS registration, in International Symposium on Remote Sensing of Environment, 13th, Ann Arbor, Michigan, 1979, Proceedings: Ann Arbor, Michigan, Environmental Research Institute of Michigan, v. I, p. 245-258.

An account is given of the methods developed for precision registration of full-scene MSS data obtained from different Landsat spacecraft. Results are presented for Landsat 1/2 scene registration as well as multitemporal registration of data from the same satellite. Direct cross correlation measurements show registration accuracies approximately 1/3 pixel for Landsat 1/2.

Schowengerdt, R. A., 1980, Reconstruction of multispatial, multispectral image data using spatial frequency content: Photogrammetric Engineering and Remote Sensing, v. 46, no. 10, p. 1325-1334.

A data compression technique that utilizes a mixture of spatial resolutions (multispatial) for a multispectral scanner is described. The complementary reconstruction procedure that extrapolates edge information from the high resolution band(s) to the low resolution bands is also discussed. Examples of Landsat MSS imagery that have been compressed and reconstructed to the original resolution are presented. Error rates are calculated for two types of scenes, one containing prominent topographic effects, the other of an agricultural area. Improvement in radiometric quality of up to 40 percent is achieved by applications of the reconstruction procedure to the compressed data.

Seidel, K., Ade, F., and Lichtenegger, D., 1983, Augmenting Landsat MSS data with topographic information for enhanced registration and classification: IEEE Transactions on Geoscience and Remote Sensing, v. GE-21, no. 3, p. 252-258.

This paper deals with problems arising in the classification of Landsat MSS data from rugged terrain. A digital terrain model (DTM) was found to be useful in several ways. For registration by cross-correlation, mountain ridges were extracted from both a synthetic image based on the DTM and a Landsat image. Information from the DTM, from thematic maps, and meteorological data were all used as ancillary data to aid in rapid snow cover determination without direct ground control in a large catchment area. In addition it is shown that the use of the DTM not only allows the assessment of relative and absolute snow distribution within given elevation zones, but also permits the extrapolation of snow cover into areas partly covered with clouds.

Simon, K. W., 1975, Digital image reconstruction and resampling for geometric manipulation, in International Symposium of Machine Processing of Remotely Sensed Data, 1st, West Lafayette, Indiana, 1975, Proceedings: West Lafayette, Indiana, Purdue University, p. 3A-1-3A-11.

The problems of digital image registration and geometric correction can be subdivided into two parts: 1) determination of the warping function which will transform the geometry of the scene to the desired geometric coordinate system; and 2) processing of the digital image intensity samples, given the warping function, to produce image samples on the desired coordinate grid. The latter process, called "resampling", is a subset of the problems of image reconstruction, i.e., determination of the continuous (analog) image form a set of samples of the image, and is the subject of this paper. This paper defines the process of image resampling in more detail in terms of general image system models, the requirements of digital image geometric manipulation and constraints of available digital processing systems. The problem is then formulated as a constrained linear estimation problem with suitable image models and optimization criteria. The resulting reconstruction filters are compared to more heuristic approaches, such as nearest neighbor, bilinear interpolation, Lagrange interpolation, and cubic convolution (cubic and quartic spline interpolators). Finally, the various resampling techniques are compared against theoretical image models, synthetically generated imagery, and actual ERTS MSS data. Nearest neighbor, bilinear, and Lagrange interpolation resamplers are shown to give significantly poorer reconstruction accuracy than TRW Cubic Convolution and the optimal constrained linear estimator.

Simpson, B., 1982, A new method to image registration on a minicomputer: Journal of Applied Photographic Engineering, v. 8, no. 1, p. 68-70.

A new method for rectification and registration of raster maps is described. This method requires reformatting the map files from records consisting of lines of pixels to records consisting of square regions of pixels. By using both forward and reverse transformations, the method for rectification and registration of raster maps is efficient in terms of computational time and computer input/output (I/O). Maps of any size can be handled on a minicomputer. Scale changes have little limitation, and any degree of rotation can be made.

Stockman, G., Kopstein, S., and Benett, S., 1982, Matching images to models for registration and object detection via clustering: IEEE Transactions on Pattern Analysis and Machine Intelligence, v. PAMI-4, no. 3, p. 229-241.

A new technique is presented for matching image features to maps or models. The technique forms all possible pairs of image features and model features which match on the basis of local evidence alone. For each possible pair of matching features the parameters of a rotation, scaling, and translation (RST) transformation are derived. Clustering in the space of all possible RST parameter sets reveals a good global transformation which matches many image features to many model features. Results with a variety of data sets are presented which demonstrate that the technique does not require sophisticated feature detection and is robust with respect to changes of image orientation and content. Examples in both cartography and object detection are given.

Sun, H., 1981, Image registration by combining feature matching and gray level correlation: Fort Belvoir, Virginia, Report TR-1091, U.S. Army Night Vision Laboratory, 10 p.

A method of image registration based on matching patterns of local features was described in an earlier report. This note describes the use of gray-level correlation to handle cases in which feature matching gives ambiguous results. Substantial improvement in matching performance can be achieved at little additional computational cost.

Szorenyi, J. A., 1979, Point identification problems using Landsat images, in AustralAsian Remote Sensing Conference, 1st, Sydney, Australia, 1979, Proceedings: Sydney, Australia, Western Australian Institute of Technology, p. 418-445.

The author analyzes two basic approaches: (1) Data extraction by computers, (2) Image co-ordinate measurement by photogrammetric instruments to determine and identify control points for precision processing of Landsat images. The argument is based on the inherent image formation problems with scanner type of sensors. Automated interpretation problems are also discussed.

Tsuchiya, K., and Arai, K., 1981, Some effects on the GCP success rate, in Canadian Symposium on Remote Sensing, 7th, Winnipeg, Manitoba, Canada, 1981, Proceedings: Ottawa, Ontario, Canada, Canadian Aeronautics and Space Institute, p. 497-502.

Removal of geometric errors in Landsat MSS images in precision processing is made using ground control points (GCP's); thus, selection of GCP's affects the geometric accuracy of the processed images. Based on 2-years of Landsat MSS data, both the effects of the features used for GCP matching and cross correlation between registered images were studied together with the relationship between time lapse between images and the success rate of GCP matching. It was found that the best GCP's in manual matching were breakwaters, highway intersections, and wharfs. Furthermore, it was also found that breakwaters and wharfs produce high cross correlation coefficients in automatic GCP matching. There was a periodic tendency in the success rate of GCP matching with the prevailing period of 21 months. Image pairs separated by 8 to 17 months displayed a symmetric tendency in the GCP matching success rate, with the maximum at 12 months.

Tsuchiya, K., and Yamaura, Y., 1981, Investigation of attitude determination program for Landsat image processing, in Canadian Symposium on Remote Sensing, 7th, Winnipeg, Manitoba, Canada, 1981, Proceedings: Ottawa, Ontario, Canada, Canadian Aeronautics and Space Institute, p. 471-479.

The investigation of Landsat multispectral scanner (MSS) bulk-processed images using well-defined ground control points (GCP's) indicates distortion, both across- and along-track, in addition to skew distortion. It is also found that the magnitude and the direction of distortion vary seasonally. Analysis reveals that the distortion is mainly attributable to inaccuracy in the spacecraft attitude determination program. Among seasonal factors influencing spacecraft attitude determination, the infrared (IR) horizon model and yaw angle determination equation are of vital importance. To obtain accurate spacecraft attitude, the present IR model defined as a function of latitude and date should be revised to include an observed stratospheric temperature distribution. A few experiments were made to improve the currently used yaw-angle determination equation proposed by NASA, however no simple method was obtained. A simple method to adjust the values of Attitude Measurement Sensor (AMS) alignments based on the history of time variation of distortion is found effective to correct the distortion. This method to reduce geometric distortion is applicable to an area where only a few GCP's are selected or can be used.

Webber, W. F., 1973, Techniques for image registration, in Bernstein, R., ed., 1978, Digital image processing for remote sensing: New York, John Wiley, p. 146-152.

Techniques are developed for determining spatial or geometric distortions between two images of the same scene. The first procedure is iterative linearized least-squares estimation (LLSE) for determining small geometric distortions between images. Error variances for these estimators are derived which are interpreted as noise-to-signal ratios for translational and rotational registration. The natural measure of the signal strength of an image for translational registration obtained from these variances is used to establish threshold settings in a new algorithm for fast translational registration. This algorithm belongs to the class of sequential similarity detection algorithms (SSDA's) recently developed for translational registration. Finally, an implementation of an image registration system incorporating all these techniques is described.

Williams, J. M., 1979, Geometric correction of satellite imagery: Farnborough, Hants, United Kingdom, Technical Report 79121, Royal Aircraft Establishment, 30 p.

Imagery from Landsat and other remote sensing satellites suffers geometric distortion which requires correction. This report describes how ground control points can be used to determine the transformation between image coordinates and some known projection.

Wolfe, R. H., and others, 1981, ERSYS registration subsystem detailed design specification: Houston, Texas, Report SR-I2-00313, NASA-Lyndon B. Johnson Space Center, 320 p.

Detailed design specifications for all ERSYS Registration Subsystem modules are given in five major sections: Introduction, Subsystem Design, Detailed Design Descriptions, Functional Design Descriptions, and System Implementation. Modules include the main program, primary application programs, application support programs, "get data" routines, transformations, and utility and storage routines--44 in all. Each module is described in terms of overview, interfaces, required resources, performance characteristics, traceability, formulas and methods, assumptions and constraints, logic and data flow, and submodule definitions.

Wong, F., Orth, R., and Friedmann, D. E., 1981, The use of digital terrain model in the rectification of satellite-borne imagery, in International Symposium on Remote Sensing of Environment, 15th, Ann Arbor, Michigan, 1981, Proceedings: Ann Arbor, Michigan, Environmental Research Institute of Michigan, p. 653-662.

The usual geometric errors in satellite-borne imagery change slowly and continuously, thus the rectified output image can be segmented into blocks and the distortion modelled by two bilinear continuous polynomials within each image block. Relief errors fluctuate considerably faster than normal geometric errors, and thus it is essential to separate relief displacement using relief information in some form, such as a digital terrain model. A simple, fast, and operational correction method for relief displacement can be made on the raw image data. At this stage the distortion is only in the along-scan direction, because it is in this direction only that the displacement due to central perspective occurs. The bilinear model for geometric correction can be implemented in one-dimensional resampling passes over the image. Relief correction can readily be incorporated into the along-scan (first) pass. The paper also illustrates the relief correction algorithm in the along-scan pass with synthesized images using Landsat-D' TM and SPOT panchromatic linear array sensor parameters over a very rugged terrain.

Wong, R. T., and Hall, E. L., 1979, Performance comparison of scene matching techniques: IEEE Transactions on Pattern Analysis and Machine Intelligence, v. PAMI-1, no. 3, p. 325-330.

The problem of registering two images of the same scene, taken by different sensors having different viewing geometries, is a challenging problem in the field of image processing and pattern recognition. The scenes are usually so drastically different that it is extremely difficult, if not impossible, to match the original images without data manipulation. Geometric and intensity transformations must be performed to bring the matching elements into proper correspondence. Objects of interest represented by subimages of one scene were located in the other using scene-matching techniques with intensity difference and edge features as measurement features. Performance characteristics of the matches by these techniques are presented in terms of the probability of a match as a function of the probability of false fix.

Zobrist, A. L., Bryant, N. A., and McLeod, R. G., 1982, Technology for large digital mosaics of Landsat data: Photogrammetric Engineering and Remote Sensing, v. 49, no. 9, p. 1325-1335.

Advances in algorithms and system executive procedures for digital image processing have made digital mosaicking of Landsat images (both MSS and RBV) an attractive possibility. The technology developed includes simultaneous map projection and adjustment of frame edges to eliminate both geometric and radiometric seams. The incorporation of ground control points, either by manual or automatic ground control point file identification, has resulted in root-mean-square (RMS) positional accuracies that exceed 1:100,000-scale National Map Accuracy Standards. Rotation to north is accomplished at low computational cost. Input data frames can be cut in any arbitrary shape to remove cloud cover and accommodate terrain offset effects. Similarly, the final digital mosaic can be arbitrarily segmented to suit user requirements. Two large applications in Pennsylvania and Bolivia are reported. A test case utilizing RBV data is described.

RESAMPLING TECHNIQUES BIBLIOGRAPHY

Andrews, H. C., and Hunt B. R., 1977, Digital image restoration: Englewood Cliffs, New Jersey, Prentice-Hall, 238 p.

A detailed overview of image degradations and restoration methods is presented.

Benner, R., and Young, W., 1977, Bi-resampled data study--Final Report: Gaithersburg, Maryland, Earth Resources Laboratory, International Business Machines Corporation, 128 p.

This document reports on the results of an experimental study conducted to determine the geometric and radiometric effects of double resampling ("bi-resampling") performed on image data in the process of performing map projection transformations.

Dye, R. H., 1982, A quantitative assessment of resampling errors, in Bryant, N. A., ed., NASA Workshop on Registration and Rectification, Pasadena, California, 1982, Proceedings: Pasadena, California, Jet Propulsion Laboratory, California Institute of Technology, p. 371-376.

A brief paper comparing the errors introduced by resampling with nearest neighbor interpolation, bilinear interpolation, cubic convolution resampling, and least-squares methods utilizing the point spread function of the sensor.

Dye, R. H., 1975, Restoration of Landsat images by discrete two-dimensional deconvolution, in International Symposium on Remote Sensing of Environment, 10th, Ann Arbor, Michigan, 1975, Proceedings: Ann Arbor, Michigan, Environmental Research Institute of Michigan, v. II, p. 725-730.

The array of numerical values representing a Landsat image can be regarded as the result of a discrete two-dimensional convolution of the original scene with the Landsat point spread function. Since the point spread is substantially more in the along-scan direction and somewhat more in the cross-scan directions than the corresponding sampling intervals, important improvements in both spatial resolution and radiometric accuracy for small objects can be obtained by application of a suitable deconvolution procedure prior to using the data for thematic recognition or other processes that are sensitive to radiometric errors.

Etheridge, J., and Nelson, C. A., 1979, Some effects of nearest neighbor, bilinear interpolation, and cubic convolution resampling on Landsat data, in International Symposium on Machine Processing of Remotely Sensed Data, 6th, West Lafayette, Indiana, 1979, Proceedings: West Lafayette, Indiana, Purdue University, p. 84.

The results of a study investigating the effects of nearest neighbor, bilinear interpolation, and cubic convolution resampling on a Landsat scene are presented. The resampling algorithms were evaluated for their effects upon scene statistics and image classification results and preservation of feature characteristics.

Ferneyhough, D. G., and Niblack, C. W., 1977, Resampling study--Final Report: Gaithersburg, Maryland, Report FSD770001, International Business Machines Corporation, 158 p.

A comparison of the nearest neighbor and cubic convolution resampling algorithms was performed for several Landsat MSS image data sets. The comparison was made by evaluating the effects of the resampling algorithms on point objects, areas of uniform radiance, spatial frequency content, human analysis of the images, temporal registration, and multispectral classification.

Forster, B. C., 1982, The derivation of approximate equations to correct for Landsat MSS point spread function, in Trinder, J. C., and Holstein, L. C., eds., International Symposium for Photogrammetry and Remote Sensing, Commission I, Primary Data Acquisition, Canberra, Australia, 1982, Proceedings: Canberra, Australia, International Society for Photogrammetry and Remote Sensing, v. 24, pt. 1, p. 6-10.

The integrating effect of the Landsat point spread function significantly affects the signature from a single cover class if the surrounding cover is dissimilar. Two versions of a simplified equation that can be used to substantially reduce the effect are derived based on a 3- x 3-pixel area surrounding a central target pixel. One version allows the calculation of the true count value at the central pixel using the measured count values of the central and surrounding pixels, while the other allows the calculation of the measured count value using the known reflectance of the central and surrounding pixels. A hypothetical example is given for the latter version using the approximate reflectance of grass and water.

Friedmann, D. E., 1981, Operational resampling for correcting images to a geocoded format, in International Symposium on Remote Sensing of Environment, 15th, Ann Arbor, Michigan, 1981, Proceedings: Ann Arbor, Michigan, Environmental Research Institute of Michigan, p. 195-212.

This paper discusses the theoretical assumptions under which one-dimensional processing is valid for resampling of image data. A method to perform digital image rotation which requires an additional one-dimensional resampling operation is presented.

Gonzalez, R. C. and Wintz, P., 1977, Digital image processing: Reading, Massachusetts, Addison-Wesley, 431 p.

The authors provide an overview on the subject of image restoration.

Helstrom, C. W., 1967, Image restoration by the method of least squares: Journal of the Optical Society of America, v. 57, no. 3, p. 297-303.

The restoration of optical images, as well as the unfolding of spectroscopic and other data that have been convolved with a window function or an instrumental response, can be viewed as the solution of an integral equation. Solution of such an integral equation when the data are corrupted by noise or experimental error is treated as the problem of finding an estimate that is a linear functional of the data and minimizes the mean squared error between the true solution and itself. The estimate depends on assumptions about the spectral densities of the images and the noise, the choice of which is discussed. Coherent optical processing and digital processing are described.

Jayroe, R. R., 1976, Nearest neighbor, bilinear interpolation and bicubic interpolation geographic correction effects on Landsat imagery: George C. Marshall Space Flight Center, Alabama, NASA TM X-73348, NASA Data Systems Laboratory, Science and Engineering, 29 p.

The objectives of this work are to identify effects that are observed in Landsat image data when the image data are geographically corrected using the nearest neighbor, bilinear interpolation and bicubic interpolation registration techniques, and to identify potential impacts of registration on image compression and classification.

Juday, R., Prakash, A., Mord, A. J., Muse, H., Heffner, P., Glass, C., Bender, L., Cox, S., Dye, R. H., Holmes, R., and Dow, D., 1982, Report of the subpanel on resampling functions, in Bryant, N. A., ed., NASA Workshop on Registration and Rectification, Pasadena, California, 1982, Proceedings: Pasadena, California, Jet Propulsion Laboratory, California Institute of Technology, p. 43-45.

Summary report on state of the art resampling methodologies, anticipated future requirements, and recommended research areas.

Keys, R. G., 1981, Cubic convolution interpolation for digital image processing: IEEE Transactions on Acoustics, Speech, and Signal Processing, v. ASSP-29, no. 6, p. 1153-1160.

The cubic convolution interpolation function converges uniformly to the function being interpolated as the sampling increment approaches zero. With the appropriate boundary conditions and constraints on the interpolation kernel, it can be shown that the order of accuracy of the cubic convolution method is between that of linear interpolation and that of cubic splines. A one-dimensional interpolation function is derived in this paper. A separable extension of this algorithm to two dimensions is applied to image data.

Kratky, V., 1980, Spectral analysis of interpolation, in International Archives of Photogrammetry, 14th, Hamburg, Federal Republic of Germany, 1980, Proceedings: Hamburg, Federal Republic of Germany, Committee of the 14th Congress for Photogrammetry, v. 23, p. 389-397.

Basic concepts of spectral analysis are applied to interpret interpolation, smoothing, and parametric transformation based on uniform sampling, as different types of discrete convolution. Spectral properties of interpolation are then discussed with main emphasis on its linear least-squares version. An operator derived in a functional form performs direct least-squares interpolation avoiding the usual inversion of the covariance matrix. Finally, advantages of spectral analysis are demonstrated by examining the accuracy and stability of the procedure.

Lahart, M. J., 1979, Local image restoration by a least squares method: Journal of the Optical Society of America, v. 69, no. 10, p. 1333-1339.

Restoration of individual image points by the method of least squares is investigated. Restorations computed point by point are shown to appear the same as global restorations produced by Fourier techniques. Moreover, parameters that are related to noise, point spread functions, or object texture can be varied easily from pixel to pixel, allowing a flexibility that is achieved only with computational difficulty in global restoration techniques. To restore individual pixels, only a few points in their neighborhood need to be considered, and the matrices that must be inverted are small enough for practical computation.

Moik, J. G., 1980, Digital processing of remotely sensed images: Washington, D.C., NASA Scientific and Technical Information Branch, NASA SP 431, U.S. Government Printing Office, 330 p.

A summary of several common resampling techniques is presented.

Neto, G. C., and Mascarenhas, N. D. A., 1983, Methods for image interpolation through FIR filter design techniques, in International Conference on Acoustics, Speech and Signal Processing, Boston, Massachussetts, 1983, Proceedings: Piscataway, New Jersey, Institute of Electrical and Electronics Engineers, v. 1, p. 391-394.

Interpolation methods in image processing are necessary in various applications. In this work the problem of image interpolation is approached from the viewpoint of digital signal processing. This paper presents a two-dimensional extension of earlier work in one dimension. A class of image interpolators is thus obtained and may be compared with the more common ones, such as nearest neighbor, bilinear, and cubic convolution.

Ostrem, J. S., and Falconer, D. G., 1981, A differential operator technique for restoring degraded signals and images: IEEE Transactions on Pattern Analysis and Machine Intelligence, v. PAMI-3, p. 278-284.

A technique is described for restoring signals, images, and other physical quantities that have been distorted or degraded by an imperfect measurement system. This technique is based upon the application of a specific differential operator to the measured quantity. Calculations for a one-dimensional example indicate that restorations comparable in quality to Wiener-filter restorations are obtained with better than an order of magnitude decrease in computation time.

Park, S. K., and Schowengerdt, R. A., 1982, Image sampling, reconstruction, and the effect of sample-scene phasing: Applied Optics, v. 21, no. 17, p. 3142-3151.

This paper is a one-dimensional analysis of the degradation caused by image sampling and interpolative reconstruction. The analysis includes the sample-scene phase as an explicit random parameter and provides a complete characterization of this image degradation as the sum of two terms: one term accounts for the mean effect of undersampling (aliasing) and nonideal reconstruction averaged over all sample-scene phases; the other term accounts for variations about this mean. The results of this paper have application to the design and performance analysis of image scanning, sampling, and reconstruction systems.

Park, S. K., and Schowengerdt, R. A., 1983, Image reconstruction by parametric cubic convolution: Computer Vision, Graphics, and Image Processing, v. 23, p. 258-272.

A parametric implementation of cubic convolution image reconstruction is presented which is generally superior to the standard algorithm and which can be optimized to the frequency content of the image.

Prakash, A., and Beyer, E. P., 1981, Landsat D thematic mapper image resampling scan geometry correction, in International Symposium of Machine Processing of Remotely Sensed Data, 7th, West Lafayette, Indiana, 1981, Proceedings: West Lafayette, Indiana, Purdue University, p. 189-200.

The resampling procedure is analyzed in this paper, with particular emphasis on the effect that the sampling geometry has on the output image. Scan gaps and spacecraft jitter effects on the output image are studied by performing a simulation of the sampling and the resampling processes. The images produced under different scan geometries are displayed for visual assessment. Another means of comparing images to detect geometric distortion and radiometric error is developed. This is the difference image histogram, and it can be used to characterize the resampling errors. The results show that the resampling algorithm works excellently under all conditions. Distortion is visible only under extremely large scan-gap conditions, which rarely occur.

Reitsema, H. J., Mord, A. J., and Ramberg, E., 1983, High-fidelity image resampling, for remote sensing, in Tescher, A. G., ed., Applications of Digital Image Processing, 6th, San Diego, California, 1983, Proceedings: Bellingham, Washington, Society of Photo-Optical Instrumentation Engineers, v. 432, p. 211-215.

Investigation of the image resampling requirements of remote sensing has indicated a need for improved resampling convolution kernel design. Areas in which progress has been made include a recognition of the improved phase linearity of longer kernels and the need for similarity of the modulation transfer function (MTF) across all filters. The computational capability required for the longer kernels is achieved with a dedicated signal processor.

Schowengerdt, R. A., Park, S. K., and Gray, R. T., 1983, An optimized cubic interpolator for image resampling, in International Symposium on Remote Sensing of the Environment, 17th, Ann Arbor, Michigan, 1983, Proceedings: Ann Arbor, Michigan, Environmental Research Institute of Michigan, p. 1291-1299.

The standard cubic resampling function is only one member of a family of functions defined by a single parameter, the slope of the cubic function at its first zero crossing. Other members of this Parametric Cubic Convolution (PCC) family are shown to be superior to the standard cubic, particularly with respect to the extent of gray level overshoot induced by the resampling process at high contrast edges. It is also shown that there is an optimum member (which is not the standard cubic function) of the PCC family that minimizes the mean-squared radiometric error arising from interpolation.

Shah, N. J., and Wilson, C. L., 1977, Multispectral data restoration study: Ann Arbor, Michigan, Report BSR 4246, (#NASA-CR-156790), Bendix Aerospace Systems Division, 84 p.

The report summarizes the results of a study in which a quantitative comparison of cubic convolution and Bendix restoration as Landsat resampling techniques for geometric correction of data was performed.

Shlien, S., 1979, Geometric correction, registration, and resampling of Landsat imagery: Canadian Journal of Remote Sensing, v. 5, no. 1, p. 74-89.

Various resampling techniques including sin(x)/x expansions, cubic splines, and Lagrange polynomials are described. The errors introduced by these resampling methods are investigated both theoretically and experimentally.

Simon, K. W., 1975, Digital image reconstruction and resampling for geometric manipulation, in International Symposium of Machine Processing of Remotely Sensed Data, 1st, West Lafayette, Indiana, 1975, Proceedings: West Lafayette, Indiana, Purdue University, p. 3A1-3A11.

This paper defines the process of image resampling in more detail in terms of general imager system models, the requirements of digital image geometric manipulation and constraints of available digital processing systems. The problem is then formulated as a constrained linear estimation problem with suitable image models and optimization criteria. The resulting reconstruction filters are compared to more heuristic approaches, such as nearest neighbor, bilinear interpolation, Lagrange interpolation, and cubic convolution (cubic and quartic spline interpolators). Finally, the various resampling techniques are compared against theoretical image models, synthetically generated imagery, and actual ERTS MSS data.

Slepian, D., 1967, Linear least-squares filtering of distorted images: Journal of the Optical Society of America, v. 57, p. 918-922.

In the model studied here, the illuminance of a distorted image is assumed to be the sum of a spatially stationary noise process and the result of a convolution of the illuminance of the undistorted image with an optical point spread function. The illuminance of a restored image is obtained by a linear filtering operation. The filter that minimizes the mean squared error between the illuminance of the undistorted image and the restored image is determined. The case in which observations are made through a turbulent atmosphere is of main concern.

Sondhi, M. M., 1972, Image restoration: The removal of spatially invariant degradations: Proceedings of the IEEE, v. 60, no. 7, p. 842-853.

This is a review of techniques for digital restoration of images. Restoration is considered from the point of view of space-domain as well as of spatial-frequency-domain descriptions of images. Consideration is restricted to degradations arising from noise and spatially invariant blurring. Some examples of restoration are included to illustrate the methods discussed. Included also is a section on methods whose potential has not yet been exploited for image restoration.

CONTRAST ENHANCEMENT BIBLIOGRAPHY

Ahern, F. J., Bennett, D. M., Guertin, F. E., Thomson, K. P. B., and Fedosejevs, G., 1982, An automated method for producing reflectance-enhanced Landsat images, in International Symposium of Machine Processing of Remotely Sensed Data, 8th, West Lafayette, Indiana, 1982, Proceedings: West Lafayette, Indiana, Purdue University, p. 328-335.

A technique which has been implemented at the Canada Centre for Remote Sensing (CCRS) to produce controlled contrast-enhanced renditions of Lansat data is presented. The two key steps in the process involve: a reliable means of transforming MSS data from radiance units to reflectance units, and a contrast stretch between fixed reflectance limits whose values are chosen by independent studies based on the intended application.

Boyd, J. E., 1981, Image enhancement through film recorder response contouring, in Doyle, F. J., ed., Electro-Optical Instrumentation for Resources Evaluation, Washington D.C., 1981, Proceedings: Bellingham, Washington, Society of Photo-Optical Instrumentation Engineers, v. 278, p. 157-166.

Description of the methodologies used at the EROS Data Center to enhance and output digital image data using the lookup-table capability provided by the laser beam recorder (LBR) and table-lookup control subsystem (TCS).

Boyd, J. E., 1982, Digital image film generation--from the photoscientist's perspective: Journal of Applied Photographic Engineering, v. 8, no. 1, p. 15-22.

The process of defining a film reproduction curve and implementing the digital-to-analog transfer function on the laser beam recorder at the EROS Data Center is described.

Chavez, P., Guptill, S. C., and Bowell, J., 1984, Image processing techniques for thematic mapper data, in American Society of Photogrammetry Annual Meeting, 50th, Washington, D.C., 1984, Proceedings: Falls Church, Virginia, American Society of Photogrammetry, p. 728-743.

The Thematic Mapper (TM) imaging system onboard Landsat 4 provides new and much more comprehensive data than the data collected during the past 10 years by the Landsat multispectral scanner (MSS) system. A major challenge in working with the TM data is to process and analyze in an efficient manner the much larger volume of data resulting from the higher spatial resolution and the increased number of spectral bands. Processing techniques have been used on TM data over several sites to: (1) reduce the amount of data that needs to be processed and analyzed by using statistical methods or by combining full-resolution products with spatially compressed products, (2) digitally process small sub-areas to improve the visual appearance of large-scale products or to merge different-resolution image data, and (3) evaluate and compare the information content of the different three-band combinations that can be made using the TM data. Results indicate that for some applications the added spectral information over MSS is even more important than the TM's increased spatial resolution.

Colvocoresses, A. P., 1983, Evaluation of the cartographic potential of the thematic mapper as flown on Landsat 4: U.S. Geological Survey Interim Report, Research Project RESC-83-1, 8 p.

Preparation and initial evaluation of the 1:100,000-scale image map of the Dyersburg, Tennessee area is discussed, as is the potential of TM data for map revision.

Driscoll, E. C., and Walker, C., 1983, Local adaptive enhancement: A general discussion and fast implementation, in International Symposium on Machine Processing of Remotely Sensed Data, 9th, West Lafayette, Indiana, 1983, Proceedings: West Lafayette, Indiana, Purdue University, p. 266-271.

This paper summarizes some advantages of local versus global image enhancement operators as well as some current implementations. It describes the local adaptive histogram equalization method implemented on the International Imaging Systems image processor.

Fahnestock, J. D., and Schowengerdt, R. A., 1983, Spatially variant contrast enhancement using local range modification: Optical Engineering, v. 22, p. 378-381.

Description of a technique developed by the authors to efficiently and effectively enhance the overall contrast of a digital image. The operation is performed by calculating the local minimum and maximum of a block of picture elements and applying a linear stretch based on the local minimum and maximum.

Frei, W., 1977, Image enhancement by histogram hyperbolization: Computer Graphics and Image Processing, v. 6, p. 286-294.

An enhancement transformation is described that is based on the image histogram and the nature of human brightness perception. Examples shown by the author demonstrate that this method produces images with increased intelligibility as compared to enhancement by histogram equalization.

Green, W. B., 1977, Computer image processing--the Viking experience: IEEE Transactions on Consumer Electronics, v. CE-23, no. 3, p. 281-299.

The author presents an overview of the Viking mission, which began in 1977. He discusses how the returned imagery was processed at JPL's Image Processing Laboratory (IPL). The discussion includes the basic techniques of noise removal, contrast enhancement, and distortion corrections, as well as results of their applications using the Viking imagery as illustrated examples.

Guildford, L. H., 1980, Real time grey level histogram manipulation, in Technical Meeting of Avionics Panel of AGARD, 40th, Aalborg, Denmark, 1980, Proceedings: Aalborg, Denmark, Advisory Group for Aerospace Research and Development (AGARD), p. 10-1-10-4.

Considerations on how to best match the characteristics of a video signal of high dynamic range to those of a display, as well as hardware implementations to enhance the visibility of objects against various backgrounds in real time are discussed.

Harris, J. L., 1977, Constant variance enhancement: A digital processing technique: Applied Optics, v. 16, no. 5, p. 1268-1271.

An image enhancement process is one in which the image is manipulated for the purpose of increasing the information extractable by the human visual system. Constant variance enhancement is a technique which employs a high-pass filter to reduce the local average to zero for all regions of the picture and then applies a gain factor equal to the reciprocal of the local standard deviation to produce an output picture in which all local regions have equal variance.

Haydn, R., Dalke, G. W., Henkel, J., and Bare, J. E., 1982, Application of the IHS color transform to the processing of multisensor data and image enhancement, in International Symposium on Remote Sensing of Arid and Semi-arid Lands, Cairo, Egypt, 1982, Proceedings: Ann Arbor, Michigan, Environmental Research Institute of Michigan, p. 599-607.

The use of intensity, hue, and saturation (IHS) color coding for optimal presentation of remotely sensed data is presented. The advantages and disadvantages of IHS color coding are compared to RGB (red, green, blue) coding. Applications to multisensor data merging and color enhancement for photointerpretation are discussed.

Hunt, B. R., 1975, Digital image processing: Proceedings of the IEEE, v. 63, p. 693-708.

A review of the field of digital image processing concentrating on aspects of image formation and recording processes, especially image coding and restoration.

Lee, J., 1980, Digital image enhancement and noise filtering by use of local statistics: Pattern Analysis and Machine Intelligence, v. PAMI-2, no. 2, p. 165-168.

Algorithms for contrast enhancement and noise filtering based on local image statistics are presented.

Lehar, A. F., and Stevens, R. J., 1984, High-speed manipulation of the color chromaticity of digital images: Computer Graphics and Applications, p. 34-39.

This article presents a method of encoding multidimensional image data using a fractal curve. The encoded data are then processed to enhance the color chromaticity.

McClellan, J. H., 1982, A modified alpha-root technique for image processing: Computer Graphics and Image Processing, v. 19, p. 18-34.

A new technique of image enhancement using a modified alpha-rooting algorithm to eliminate artifacts caused by high-contrast edges is presented. The net effect of this technique is to boost high spatial frequency thereby enhancing detail in the imagery.

Moik, J. G., 1980, Digital processing of remotely sensed images: Washington, D.C., NASA Scientific and Technical Information Branch, NASA SP 431, U.S. Government Printing Office, 1980, 330 p.

This book attempts to provide a unified framework for digital analysis of remotely sensed data and describes many of the fundamental aspects of image enhancement, restoration, transformation, and analysis.

Nahin, P. J., 1979, A simplified derivation of Frei's histogram hyperbolization for image enhancement: IEEE Transactions on Pattern Analysis and Machine Intelligence, v. PAMI-1, no. 4, p. 414-415.

Frei has introduced a new technique (histogram hyperbolization) for image enhancement. This transformation is based upon the histogram of the image to be processed and the nature of human brightness perception. An alternative derivation of Frei's result, both simpler and more general, is presented.

Peli, T., and Lim, J. S., 1982, Adaptive filtering for image enhancement: Optical Engineering, v. 21, no. 1, p. 108-112.

The authors introduce an algorithm that modifies the local luminance mean and controls the local contrast as a function of the local luminance mean of the image. One potential application of this technique is in the enhancement of imagery that has been degraded by cloud cover or large areas of shadow.

Pinson, L. J., and Lankford, J. P., 1981, Research on image enhancement algorithms: Tullahoma, Tennessee, Technical Report RG-CR-81-3, University of Tennessee Space Institute, 98 p.

Six specific image enhancement algorithms are analyzed, simulated, and evaluated for potential real-time application to imagery obtained from target aquisition systems. Three processing methods are recommended as operator controlled options for application to the imagery. The objective for this effort was to identify and examine methods for enhanced acquisition and handoff for small targets in a complex and cluttered background.

Sanchez, R. D., and McSweeney, J. E., 1983, Image map development techniques using Landsat data, presented at Federal Map and Chart Printing Symposium, 9th, Gaithersburg, Maryland, 1983, 13 p.

Discussion of the current image map production process. The preparation of film products for the creation of lithographic output products is emphasized.

Smith, A. R., 1978, Color gamut transform pairs: Computer Graphics, v. 12, no. 3, p. 79-85.

This paper presents a set of alternative models of the RGB monitor gamut based on the perceptual variables of hue, saturation, and brightness.

Soha, J. M., and Schwartz, A. A., 1979, Multispectral histogram normalization contrast enhancement, in Canadian Symposium on Remote Sensing, 5th, Victoria, British Columbia, Canada, 1979, Proceedings: Ottawa, Ontario, Canada, Canadian Aeronautics and Space Institute, p. 86-93.

An algorithm for contrast enhancing image data by first removing interband correlation is described. By equalizing principal component variances with either linear or non-linear transformations, the procedure allows an additional rotation to any set of orthogonal coordinate axes while retaining full histogram utilization by avoiding the reintroduction of correlation. This procedure has been proven useful at the Jet Propulsion Laboratory for a variety of difficult scenes.

Stevens, R. J., Lehar, A. F., and Preston, F. H., 1983, Manipulation and presentation of multidimensional image data using the Peano scan: Pattern Analysis and Machine Intelligence, v. PAMI-5, no. 5, p. 520-526.

A technique is described which permits adaptive reordering and compression of multidimensional image data using a fractal-curve transformation to facilitate the presentation of high-quality color images.

Stockham, T. G., 1972, Image processing in the context of a visual model: Proceedings of the IEEE, v. 60, p. 828-842.

Some of the known facts and concerns relating to the human visual system and the perception of digitally processed image data are described. Some concepts of image quality and the measurement of image quality are presented.

Tom, V. T., and Wolfe, G. J., 1982, Adaptive histogram equalization and its applications, in Tescher, A. G., ed., Applications of Digital Image Processing, 4th, San Diego, California, 1982, Proceedings: Bellingham, Washington, Society of Photo-Optical Instrumentation Engineers, p. 204-209.

Description of an array processor implementation of an adaptive histogram equalization algorithm for contrast enhancement. This approach uses a sliding window to compute local histograms and gray level mappings for generating equalized histograms for each pixel location.

Wallis, R. H., 1976, An approach to the space variant restoration and enhancement of images, in Wilde C. O., and E. Burnett, eds., 1977, Image science mathematics: Monterey, California, Western Periodicals Company, p. 107-111.

A procedure is described which performs contrast stretching and high-pass filtering in a locally varying manner by the use of local statistics.

Wang, D. C. C., Vagnucci, A. H., and Li, C. C., 1983, Digital image enhancement: A survey: Computer Vision, Graphics, and Image Processing, v. 24, p. 363-381.

A survey and evaluation of current techniques commonly used to enhance digital image data. The techniques are divided into four categories: spatial smoothing; gray level rescaling; edge enhancement; and frequency domain filtering.

Wilson, C. L., 1979, Image mapping software at ERIM, presented at Annual International Users Conference on Computer Mapping Hardware, Software, and Data Bases, 2nd, Cambridge, Massachusetts, 1979, 20 p.

Discussion of current (as of 1979) software in use at the Environmental Research Institute at Michigan for the production of image maps.

Wong, R. Y., 1977, Sensor transformations: IEEE Transactions on Systems, Man, and Cybernetics, v. SMC-7, no. 12, p. 836-841.

An intensity-matching technique that makes use of the Kahrunen-Loeve transformation for matching two scenes of the same geographic area acquired by two different types of sensors having different viewing geometries is described.

SPATIAL FILTERING BIBLIOGRAPHY

Abdou, I. E., and Pratt, W. K., 1979, Quantitative design and evaluation of enhancement/thresholding edge detectors: Proceedings of the IEEE, v. 67, no. 5, p. 753-763.

Quantitative design and performance evaluation techniques are developed for the enhancement/thresholding class of image edge detectors. The design techniques are based on statistical detection theory and deterministic pattern-recognition classification procedures. The design techniques developed are used to optimally design a variety of small and large mask edge detectors. Theoretical and experimental comparisons of edge detectors are presented.

Andrews, H. C., 1974, Digital Fourier transforms as means for scanner evaluation: Applied Optics, v. 13, no. 1, p. 146-149.

Fourier transforms are presented as possible aids in evaluating the performance of digital image scanners; discussion is presented on the interpretation of Fourier energy along horizontal and vertical axes. Windowing, scanner jitter, and aperture effects are described. In addition to the main theme of scanner evaluation, a peripheral example of the use of a priori knowledge for image enhancement is presented.

Andrews, H. C., 1976, Monochrome digital image enhancement: Applied Optics, v. 15, no. 2, p. 495-503.

The use of digital computers as an aid in the enhancement of monochrome imagery is explored. The former includes single-pixel nonlinear mappings for better visual response. Spatial processes include both linear and nonlinear filtering techniques in the Fourier and singular value decomposition (SVD) domains of an image. Finally, the generation of possible artifacts by enhancement processes is discussed. Numerous pictorial examples illustrating all the techniques developed are included throughout the paper.

Boulter, J. F., 1979, Interactive digital image restoration and enhancement: Computer Graphics and Image Processing, v. 11, p. 301-312.

Blurring in a photograph caused by a defocused camera is analyzed to determine the nature of the blur, and the photograph is restored. Image-enhancement techniques, based on the properties of human vision or on the image-formation process, are applied to visible-light, infrared, and radiographic images.

Castleman, K., 1979, Digital image processing: Englewood Cliffs, New Jersey, Prentice-Hall, 429 p.

In Chapter 9, the author addresses the theory of sampling, resolution, and enhancement, terms commonly taken to mean linear filtering. He then develops analytical tools required to understand the filtering techniques.

Chapter 11 addresses the applications of, and limitations to, implementing digital linear filters. Also discussed are techniques for designing filters to accomplish particular goals.

Chavez, P., 1975, Simple high-speed digital image processing to remove quasi-coherent noise patterns, in American Society of Photogrammetry Annual Meeting, 41st, Washington, D.C., 1975, Proceedings: Falls Church, Virginia, American Society of Photogrammetry, p. 595-600.

Simple high-speed techniques are developed for removal of two-dimensional noise patterns, which, when not removed, are strongly amplified by most image-enhancement techniques. These patterns are caused by spurious electronic signals, imperfections in the imaging system, or incomplete decalibration of the data.

Chavez, P., Berlin, G. L., and Acosta, A., 1976, Computer processing of Landsat MSS digital data for linear enhancement, in William Pecora Annual Symposium, 2nd, Sioux Falls, South Dakota, 1976, Proceedings: Falls Church, Virginia, American Society of Photogrammetry and United States Geological Survey, p. 235-250.

Landsat MSS digital image data covering southwestern Jordan and adjacent areas were processed with special computer techniques to enhance linear forms in the images. Two types of processing were performed: image correction and image enhancement. Image correction procedures eliminate undesired artifacts and distortions from the digital data base. Image enhancement includes spatial filtering designed to enhance large linears, and derivative techniques designed to enhance small linears.

Chavez, P., and Bauer, B., 1982, An automatic optimum kernel-size selection technique for edge enhancement: Remote Sensing of Environment, v. 12, no. 23, p. 23-38.

Edge enhancement is a technique that can be considered, to a first order, a correction for the modulation transfer function of an imaging system. Digital image systems sample a continuous function at discrete intervals so that high-frequency information cannot be recorded at the same precision as lower frequency data. Because of this, fine detail or edge information in digital images is lost. Spatial filtering techniques can be used to enhance the fine detail information that does not exist in the digital image, but the filter size is dependent on the type of area being processed. A technique has been developed by the authors that uses horizontal first-difference to automatically select the optimum kernel-size that should be used to enhance the edges that are contained in the image.

Chavez, P., Guptill, S. C., and Bowell, J., 1983, Image processing techniques for thematic mapper data, in American Society of Photogrammetry Annual Meeting, 50th, Washington, D.C., 1984, Proceedings: Falls Church, Virginia, American Society of Photogrammetry, p. 728-743.

The Thematic Mapper (TM) imaging system onboard Landsat 4 provides new and much more comprehensive data than the data collected during the past 10 years by the Landsat multispectral scanner (MSS) system. A major challenge in working with the TM data is to process and analyze in an efficient manner the much larger volume of data resulting from the higher spatial resolution and the increased number of spectral bands. Processing techniques have been used on TM data over several sites to: (1) reduce the amount of data that needs to be processed and analyzed by using statistical methods or by combining full-resolution products with spatially compressed products, (2) digitally process small sub-areas to improve the visual appearance of large-scale products or to merge different-resolution image data, and (3) evaluate and compare the information content of the different three-band combinations that can be made using the TM data. Results indicate that for some applications the added spectral information over MSS is even more important than the TM's increased spatial resolution.

Chiralo, R., and Berdan, L., 1978, Adaptive digital enhancement of latent fingerprints, in Tescher, A. G., ed., Applications of Digital Image Processing, San Diego, California, 1978, Proceedings: Bellingham, Washington, Society of Photo-Optical Instrumentation Engineers, v. 149, p. 118-124.

An adaptive technique for providing effective enhancement of latent fingerprints is presented. The adaptive technique is described and examples are shown, including enhanced prints prepared for a trial exhibit. Image preprocessing considerations are discussed for obtaining optimal enhancement. Results of the adaptive technique are compared to those obtained with the conventional Fourier filtering technique.

Colwell, R., and Katibah, E., 1976, Optical vs. electronic enhancement of remote sensing data, in Urbach, J. C., Image Processing, San Diego, California, 1976, Proceedings: Bellingham, Washington, Society of Photo-Optical Instrumentation Engineers, v. 74, p. 111-118.

The amount of useful information that can be obtained by the image analyst often is increased substantially if the imagery is first "enhanced" by such means as density slicing, color coding, improving the ratio of signal-to-noise, and combining multiple images into a single composite. Based on representative examples, mainly of the authors' NASA-funded test sites in California, the use and limitations of various optical and electronic image-enhancement devices and techniques are illustrated.

Considine, P., and Radl, B., 1981, Evaluation of optical and digital image processing techniques, in Carter, W. H., Processing of Images and Data from Optical Sensors, San Diego, California, 1981, Proceedings: Bellingham, Washington, Society of Photo-Optical Instrumentation Engineers, v. 292, p. 59-69.

A comparative study of image processing techniques examines optical, hybrid, and digital methods. System capabilities are evaluated with emphasis on text processing applications. Results show the strengths of each method. Optical processing is best for wide-bandwidth parallel processing. Digital processing is the most versatile and interactive processing technique. Hybrid systems show strong potential, depending upon the development of improved image transducers. A discussion of a variety of image processing hardware accompanies the evaluation.

Ehlers, M., 1980, Filter techniques and their application in digital correlation, in International Archives of Photogrammetry, 14th, Hamburg, Federal Republic of Germany, 1980, Proceedings: Hamburg, Federal Republic of Germany, Committee of the 14th Congress for Photogrammetry, v. 23, part B-3, p. 193-201.

Filter techniques for noise reduction and amplification of desired information are of great importance in digital image analysis. Two-dimensional filters are described. The results of digital correlation after image filtering are compared to those received without filtering. It is shown that especially a low-pass filter increases exactness and efficiency of the objective function of the correlation process to a high degree.

Fiasconaro, J., 1979, Two-dimensional nonrecursive filters, in Chapter 3 of Huang, T. S., ed., Topics in applied physics: New York, Springer-Verlag, Inc., v. 6, p. 70-128.

This chapter presents four techniques for designing two-dimensional nonrecursive filters. They include the use of windows, frequency sampling, straightforward application of linear programming, and a new algorithm developed by the author.

Frieden, B. R., 1976, A new restoring algorithm for the preferential enhancement of edge gradients, in Urbach, J. C., ed., Image Processing, San Diego, California, 1976, Proceedings: Bellingham, Washington, Society of Photo-Optical Instrumentation Engineers, v. 74, p. 44-48.

Presented is a new restoring algorithm that puts edge images on par with point images. It is based on a "median-window filter" used sequentially across the image. The filter tends to completely obliterate oscillations whose period is less than N (window size) while simultaneously passing unchanged any monotonically increasing or decreasing image regions. The method is tested on computer-simulated imagery and a photographic image.

Frieden, B. R., 1979, Image enhancement and restoration, in Chapter 5 of Huang, T. S., ed., Topics in applied physics: New York, Springer-Verlag, Inc., v. 6, p. 179-246.

The aim of collecting data is to gain meaningful information about a phenomenon of interest. Unfortunately, often the phenomenon is not a direct physical observable. Instead, the data at hand may be a linear superposition of the desired quantities. This linear, and simplest, type of information mixing is endemic in the physical sciences, arising in fields as diverse as atmospheric physics and medical diagnostics. The common problem confronting workers in these fields is how to "unmix" (or, restore, enhance, de-blur, de-convolve) the data.

Gray, R. T., McCaughty, D. G., and Hunt, B. R., 1979, Median masking techniques for the enhancement of digital images, in Tescher, A. G., ed., Application of Digital Image Processing, 3rd, San Diego, California, 1979, Proceedings: Bellingham, Washington, Society of Photo-Optical Instrumentation Engineers, v. 207, p. 142-145.

A nonlinear masking technique has been developed which characterizes digital images by local measure of the median and the median absolute deviation (MAD). Space-variant enhancement is elicited by modifying the local MAD as calculated over a moving window in the original image. The method if found to be effective in edge enhancement and noise cleaning operations.

Green W. B., 1977, Computer image processing--the Viking experience: IEEE Transactions on Consumer Electronics, v. CE-23, no. 3, p. 281-299.

The author presents an overview of the Viking mission, which began in 1977. He discusses how the returned imagery was processed at JPL's Image Processing Laboratory (IPL). The discussion includes the basic techniques of noise removal, contrast enhancement, and distortion corrections, as well as results of their applications using the Viking imagery as illustrated examples.

Hall, J., and Awtrey, J., 1979, Real-time image enhancement using 3 X 3 pixel neighborhood operator functions, in Tescher, A. G., ed., Application of Digital Image Processing, 3rd, San Diego, California, 1979, Proceedings: Bellingham, Washington, Society of Photo-Optical Instrumentation Engineers, v. 207, p. 135-141.

A new type of silicon charge coupled device (CCD) imager, which provides nine simultaneous video outputs representing 3- by 3-pixel block that scans the imaging array, has been used to emphasize edge and fine detail in various images. The device can also compensate for nonuniform scene illumination. Experimental results indicate that the device can be used to combine real-time analog image processing with subsequent digital processing to form a powerful image acquisition and processing system.

Haralick, R., and Watson, L., 1981, A facet model for image data: Computer Graphics and Image Processing, v. 15, p. 113-129.

Image processing algorithms implicitly or explicitly assume an idealized form for the image data on which they operate. The degree to which the observed data meet the assumed idealized form is typically not examined or accounted for. This lack of "fidelity" causes processing errors often attributed to noise. In this paper we discuss a facet model for image data which has the potential for fitting the form of the real to the idealized image, and for describing how the observed image differs from the idealized form. It is also an appropriate form for a variety of image processing algorithms. We give a relaxation procedure, and prove its convergence, for determining an estimate of the ideal image from observed image data.

Harris, J. L., 1977, Constant variance enhancement: A digital processing technique: Applied Optics, v. 16, no. 5, p. 1268-1271.

An image enhancement process is one in which the image is manipulated for the purpose of increasing the information extractable by the human visual system. Constant variance enhancement is a technique which employs a high-pass filter to reduce the local average to zero for all regions of the picture and then applies a gain factor equal to the reciprocal of the local standard deviation to produce an output picture in which all local regions have equal variance.

Hu, J., and Rabiner, L., 1972, Design techniques for two-dimensional digital filters: IEEE Transactions on Audio and Electroacoustics, v. AU-20, no. 4, p. 249-257.

The theory for designing finite-duration impulse response (FIR) digital filters can readily be extended to two or more dimensions. Using linear programming techniques, both frequency sampling and optimal (in the sense of Chebyshev approximation over closed compact sets) two-dimensional filters have been successfully designed. Computational considerations have limited the filter impulse response durations (in samples) to 25 by 25 in the frequency sampling case, and to 9 by 9 in the optimal design case. However, within these restrictions, a large number of filters have been investigated. Several of the issues involved in designing two-dimensional filters are discussed.

Huang, T., 1972, Two-dimensional windows: IEEE Transactions on Audio and Electroacoustics, v. AU-21, no. 4, p. 88-89.

Two-dimensional windows find applications in many diverse fields, such as the spectral estimation of random fields, the design of two-dimensional digital filters, optical apodization, and antenna array design. Many good one-dimensional windows have been devised; however, relatively few two-dimensional windows have been investigated. We establish a result which enables us to get good two-dimensional windows from good one-dimensional windows.

Ketcham, D., 1976, Real-time image enhancement techniques, in Urbach, J. C., ed., Image Processing, San Diego, California, 1976, Proceedings: Bellingham, Washington, Society of Photo-Optical Instrumentation Engineers, v. 74, p. 120-125.

Most image enhancement techniques are not suitable for real-time applications. This paper presents two contrast enhancement techniques that can work at TV rates with fairly simple hardware.

Kovasznay, L., and Joseph, H., 1955, Image processing: Proceedings of IRE, v. 43, no. 5, p. 560-570.

All mathematical operations in image processing can be conceived as a modification or processing of the original image. An important class of modifying operators can be realized by special scanning techniques without using a rapid-access memory storage device. It was found that the two important operators so far explored may have practical importance. One operator is contour enhancement which has a "deblurring" effect akin to aperture correction and "crispening" in television practice; the other is contour outlining that produces a line drawing from a picture with continuous tones.

Lee, J., 1980, Digital image enhancement and noise filtering by use of local statistics: IEEE Transactions on Pattern Analysis and Machine Intelligence, v. PAMI-2, p. 165-168.

Computational techniques involving contrast enhancement and noise filtering on two-dimensional image arrays are developed based on their local mean and variance. These algorithms are nonrecursive and do not require the use of any kind of transform. They share the same characteristics in that each pixel is processed independently. Consequently, this approach has an obvious advantage when used in real-time digital image processing applications and where a parallel processor can be used. Examples on images containing 256 by 256 pixels are given. Results show that in most cases the techniques developed in this paper are readily adaptable to real-time image processing.

Luscher, S., 1982, Processing of noisy high resolution electron micrographs of crystalline biological membranes, in Tescher, A. G., ed., Applications of Digital Image Processing, 4th, San Diego, California, 1982, Proceedings: Bellingham, Washington, Society of Photo-Optical Instrumentation Engineers, v. 359, p. 233-241.

Fourier domain techniques are used on electron micrographs, to extract the periodic signal component. Hardly visible in the noisy unprocessed micrograph, the periodic structure becomes manifest by the discrete reflections in the power spectrum.

Mitchell, O., and Chen, P., 1976, Filtering to remove cloud cover in satellite imagery, in International Symposium on Machine Processing of Remotely Sensed Data, 2nd, West Lafayette, Indiana, 1976, Proceedings: West Lafayette, Indiana, Purdue University, p. 4A-27 to 4A-31.

The possibility of filtering light cloud cover in satellite imagery to expose objects beneath the clouds is discussed. A model of the cloud distortion process is developed and a transformation is introduced which makes the signal and noise addition so that optimum filtering techniques can be applied. Results from computer simulation and from Landsat data are shown.

Moik, J. G., 1980, Digital processing of remotely sensed images: Washington, D.C., NASA Scientific and Technical Information Branch, NASA SP 431, U.S. Government Printing Office, 1980, 330 p.

A comprehensive work on the foundations of image processing. Techniques as well as applicatons are presented with examples of images before and after applying a particular image processing technique.

Nasburg, R., and Lineberry, M., 1981, Noise effects for edge operators, in Carter, W. H., ed., Processing of Images and Data from Optical Sensors, San Diego, California, 1981, Proceedings: Bellingham, Washington, Society of Photo-Optical Instrumentation Engineers, v. 292, p. 277-287.

Techniques and analyses for improving the signal-to-noise performance are presented. A general edge detection method is developed as a result of the noise analyses, and a wide class of edge detectors is shown to be insensitive to edge orientation. For this class, an optimal design with respect to noise statistics is found and a comparison made between many common edge operators. Edge and noise models characteristic of typical images are presented and used in the analysis of these edge detectors.

Nathan, R., 1970, Spatial frequency filtering, in Part 1 of Lipkin, B., and Rosenfeld, A., eds., Picture Processing and Psychopictorics: New York, New York, Academic Press, p. 151-163.

Pictures are often recorded under difficult non-reproducible and/or severely limiting instrumentational conditions. Pictures are also often taken in which the desired information is disguised. The desired information has some probability of being present, but is not obviously recognizable. This paper discusses techniques for making such pictorial information more accessible.

Nowak, P., 1978, Application of two-dimensional digital filters to multispectral scanner imagery, in Canadian Symposium on Remote Sensing, 5th, Victoria, British Columbia, Canada, 1979, Proceedings: Ottawa, Ontario, Canada, Canadian Aeronautics and Space Institute, p. 42-47.

Within the digital image processing system DIBIAS, a subsystem of compatible programs for two-dimensional digital filtering has been developed. This paper describes its design and presents the results of the application to multispectral scanner data.

Oppenheim, A. V., Schafer, R. W., and Stockham, T. G., 1968, Nonlinear filtering of multiplied and convolved signals: Proceedings of the IEEE, v. 56, no. 8, p. 1264-1291.

An approach to some nonlinear filtering problems through a generalized notion of superposition has proven useful. In this paper this approach is investigated for the nonlinear filtering of signals which can be expressed as products or as convolution of components. The applications of this approach in audio dynamic range compression and expansion, image enhancement with applications to bandwidth reduction, echo removal, and speech waveform processing are presented.

Peli, T., and Quatieri, T., 1982, Exposing objects under light cloud cover by adaptive homomorphic filtering: Lexington, Massachusetts, Technical Report Number 587, MIT Lincoln Laboratory, 40 p.

This report demonstrates the use of adaptive homomorphic filtering in exposing objects under light cloud cover. More specifically, the homomorphic filter invoked is space-varying and is parametized by the local mean level of cloud cover degradation. This approach represents a departure from other attempts to enhance similarly degraded images in that they have relied on nonadaptive (long-space) homomorphic filtering.

Pinson, L. J. and Lankford, J. P., 1981, Research on image enhancement algorithms: Tullahoma, Tennessee, Technical Report RG-CR-81-3, University of Tennessee Space Institute, 98 p.

Six specific image enhancement algorithms are analyzed, simulated, and evaluated for potential real-time application to imagery obtained from target aquisition systems. Three processing methods are recommended as operator controlled options for application to the imagery. The objective for this effort was to identify and examine methods for enhanced acquisition and handoff for small targets in a complex and cluttered background.

Prewitt, J., 1970, Object enhancement and extraction, in Part 1 of Lipkin, B., and Rosenfeld, A., eds., Picture processing and psychopictorics: New York, Academic Press, p. 75-149.

Chapter one presents an historical overview of image formation, restoration, and enhancement, as well as a contemporary view of the three fields at the time of the publication.

Rosenfeld, A., 1969, Picture processing by computer: New York, Academic Press, 196 p.

In Chapter 4, various types of useful operations are studied that perform on pictures "uniformly," in other words, whose effect on a point does not depend on the position of the point in the picture.

Chapter 5 presents the digital, electro-optical and optical implementation of the operators discussed in the previous chapter.

In Chapter 6, the author discusses specific applications for position-invariant operators. The operators include template-matching, spatial frequency filtering, averaging, and differencing.

Schreiber, W., 1978, Image processing for quality improvement: Proceedings of the IEEE, v. 66, no. 12, p. 1640-1651.

In order to encourage the development of computer-based methods which produce better quality pictures, the long and successful history of image processing in photography and graphic arts is called to the attention of the computer fraternity. Studies of contrast sensitivity and of the relationship between illumination, object reflectance, and image illumination are presented. Adaptive filtering methods which exploit perceptual phenomena as well as the physical properties of imaging systems are given.

VanderBurg, G., 1976, Experiments in iterative enhancement of linear features, in International Symposium on Machine Processing of Remotely Sensed Data, 2nd, West Lafayette, Indiana, 1976, Proceedings: West Lafayette, Indiana, Purdue University, p. 4A-32 to 4A-44.

Lines and curves in an image are detected locally by a template-matching process which determines the "line-ness" value of the image at each point, in a set of orientations. The preferred orientation can be "sharpened" by examining the orientation at nearby points (in the preferred direction) and biasing it toward their average. Experimental results using this method are obtained for Landsat and Skylab images containing many linear features.

Wallis, R. H., 1976, An approach to the space variant restoration and enhancement of images, in Wilde, C. O., and Barrett, E., eds., 1977, Image science mathematics: Monterey, California, Western Periodicals Company, p. 107-111.

Many of the classical techniques in digital image processing fall into the category of linear, space-invariant procedures. Although these methods provide the benefit of mathematical tractability and ease of analysis, they constitute a very restricted subset of approaches. This paper describes one possible avenue towards a more powerful family of nonlinear, space-variant algorithms which are based on the 'tracking' of local image statistics.

COLOR CALIBRATION BIBLIOGRAPHY

Ackerman, E., Ellis, L. B. M., and Williams, L. E., 1979, Biophysical science (2d ed.): Englewood Cliffs, New Jersey, Prentice-Hall, 634 p.

A general text on biophysics, this book has several excellent chapters on the human visual process.

Conrac Corporation, 1980, Raster graphics handbook: Covina, California, 346 p.

This book presents little theory but much practical information about the design, development, and applications of raster graphics systems.

Cornsweet, T. N., 1970, Visual perception: New York, Academic Press, 475 p.

This book covers the fundamentals of visual perception. Particular emphasis is given to the perception of brightness and color. Also included is data from some of the key experiments in visual perception.

Cowan, W. B., 1983, An inexpensive scheme for calibration of a colour monitor in terms of CIE standard coordinates: Computer Graphics, v. 17, no. 3, p. 315-321.

This paper gives a brief overview of the CIE colorimetric system and the transformations from RGB to CIE(XYZ). He then presents details on how to calibrate an RGB monitor.

Evans, R. M., 1974, The perception of color: New York, John Wiley, 248 p.

An introduction to color perception. Of particular interest is the section on chromatic adaption.

Foley, J. D., and Van Dam, A., 1982, Fundamentals of interactive computer graphics: Reading, Massachusetts, Addison-Wesley, 664 p.

More mathematically oriented than Newman and Sproull in its presentation, this book also has a good chapter on color and color manipulation.

Greenburg, D., Marcus, A., Schmidt, A. H., and Gorter, V., 1982, The computer image: Reading, Massachusetts, Addison-Wesley, 1982, 128 p.

This book is intended for a general audience and has a very good chapter on the operation of graphics systems.

Hunt, R. W. G., 1975, The reproduction of colour (3rd ed.): New York, John Wiley, 614 p.

This book provides an in-depth presentation of color production in photography, printing, and television. It does not lack mathematical detail and contains many references for further reading.

Kidwell, R. D., and McSweeney, J. E., 1984, Prepress processing and printing of image maps, presented at American Society of Photogrammetry Annual Meeting, 50th, Washington, D.C., 1984, 29 p.

This paper gives details on how image maps are currently produced by the USGS/NMD.

Moik, J. G., 1980, Digital processing of remotely sensed images: Washington, D.C., NASA Scientific and Technical Information Branch, NASA SP 431, U.S. Government Printing Office, 330 p.

This is one of the better sources of image processing fundamentals, especially as they relate to the problems encountered while dealing with remotely sensed data.

Monmonier, M. S., 1982, Computer-assisted cartography: Englewood Cliffs, New Jersey, Prentice-Hall, 214 p.

This is an excellent introduction to all phases of computer assisted-cartography, including map composition and printing.

Newman, W. M., and Sproull, R. F., 1979, Principles of interactive computer graphics (2d ed.): New York, McGraw-Hill, 541 p.

This is a source for the applications and implementation of computer graphics techniques. This book gives a good introduction to the different display devices but suffers from its limited discussion about color.

Slater, P. N., 1980, Remote sensing, optics and optical systems: Reading, Massachusetts, Addison-Wesley, 1980, 575 p.

This graduate-level text is perhaps the best source of information available on how remotely sensed data are acquired. There are in-depth presentations of many concepts. Of particular interest is a discussion of the radiometric fidelity of photograghic film.

Thomas, W., ed., 1973, SPSE handbook of photographic science and engineering: New York, John Wiley, 1416 p.

This is comprehensive reference book for workers in the fields of photoscience and engineering. It also contains an extensive "Guide to Photographic Information" bibliography.

Wallis, R. H., 1975, Film recording of digital color images: Los Angeles, California, Image Processing Institute, University of Southern California, Report 570, 184 p.

This dissertation presents techniques for the quantitative control of color film, specifically the recording of digital images from a color monitor onto film with maximum color fidelity.

Williamson, S. J., and Cummins, H. Z., 1983, Light and color in nature and art: New York, John Wiley, 488 p.

This is an exellent introduction to color and optics, color perception, and the production of color, and offers many insights into the causes of color phenomena in naturally occurring objects. Does not suffer from its lack of mathematical rigor.

Wyszecki, G., and Stiles, W. S., 1982, Color science (2d ed.): New York, John Wiley, 950 p.

This book is a collection of concepts and methods, quantitative data, and formula on color science. It is intended as a reference book for colorimetric information.

AUTHOR INDEX

AUTHOR Quirk, B.K.

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