Digital Photogrammetry for Determination of Tracer Particle Coordinates in Turbulent Flow Research*

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ABSTRACT: For many tasks in turbulent flow research, the simultaneous determination of tracer particle coordinates with high spatial and temporal density is required as a basis for particle tracking velocimetry (PTV). As a simultaneous, non-contact, and automation-friendly method, digital photogrammetry is a suitable tool to provide this information online.

This paper describes the implementation of a PTV system based on three CCD cameras, which can determine the coordinates of up to 900 particles per image triplet. After an overview about the hardware used for acquisition and storage of three synchronous sequences with some hundred images each, the chain of computation for a completely automatic processing of the sequences is outlined. The algorithms employed deal with some special problems arising from the task, for example, the multimedia geometry, the high particle density which leads to overlapping particles in the images, and the fact that there is no continuous surface in object space, which causes ambiguities in matching. It will be shown that these ambiguities can only be solved reliably by a system with at least three cameras.

INTRODUCTION

A LOT OF PROBLEMS OF HYDROMECHANICS, for example, transportation of materials or construction tasks, are closely connected with turbulent flow research. Thus, the interior structure and the temporal and stationary variability of turbulent flows is of special interest. In the past there was no instrument available which offered information about this structure with satisfactory temporal and spatial resolution at a reasonable effort. The standard tool of turbulent flow research is Laser Doppler Anemometry, which gives two-dimensional information about the velocity vector with high temporal resolution and good accuracy but only for one stationary point; the determination of the third component of the velocity vector requires a much larger instrumental effort. Photography or filming of the flow marked by particles suspended in water has also been used and offers a high spatial and (with pulsed illumination or high-speed cameras) a good temporal resolution. The evaluation, however, is very time consuming, especially if three-dimensional information is required; often the photographic method is only used to obtain qualitative information, or films are digitized which is also cumbersome.

With CCD cameras and methods of digital photogrammetry we are now able to offer an instrument that provides both sufficient spatial and temporal resolution as well as good accuracy and fully automatic processing. Our system, which is shown in Figure 1, consists of three synchronized CCD cameras moving with average flow velocity below the glass bottom of a hydromechanic laboratory channel, which record a flow marked by small tracer particles. The processing of the sequence can be divided into the following major steps: digitization of image sequences, image enhancement and segmentation, establishment of correspondences between different views, coordinate determination, and tracking.

HARDWARE DESCRIPTION

To visualize flow structures in a hydromechanic laboratory, channel flows are marked by small neutrally buoyant tracer particles with a nominal size of 50 µm. These particles are small enough to follow the flow without influencing it and can be made visible by suitable illumination. As a light source a 3-watt argon-ion laser with externally triggerable intensity modulation is used, the beam of which is widened to a three-dimensional lightsheet by a cylindrical lens system. This light illuminates a 150 by 150 by 20 mm^3 flow volume parallel to the channel bottom.

The particles in this test section are imaged by three synchronized CCD cameras (Aqua TV HR 480, 1/2-inch frame transfer sensor), which are shown in Figure 2. To be able to follow a flow structure for a longer time, the cameras and the lightsheet optics are mounted on a carriage driven by a monitored stepper motor and moving with average flow velocity on two rails below the glass bottom of the channel. To reduce smear due to relative movements of the particles, the laser light source is shuttered to a pulse duration of 4 ms and synchronized with the cameras.

The complexity of the flow requires exploiting the temporal resolution of the cameras (CCIR norm, 25 images per second). As a typical experiment takes some 15 seconds (which corresponds to 3 * 375 video frames) and real time storage devices such as video disks or image sequence memory are not available, the video data are intermediately stored on three analog Sony U-matic videorecorders. To be able to read corresponding images from the videotapes, a synthetic binary pattern which codes a sequential image number is added to the video signal of all three cameras. By tracking this pattern, an example of which is shown in Figure 3, image sequences of arbitrary length can be digitized completely automatically from the videotapes by a PC equipped with a Matrox MVP frame grabber and a VES card, giving access to the remote control port of the videorecorder and playing and rewinding it continuously. Via Ethernet, the image data are transferred to a SUN 4, where it is processed.

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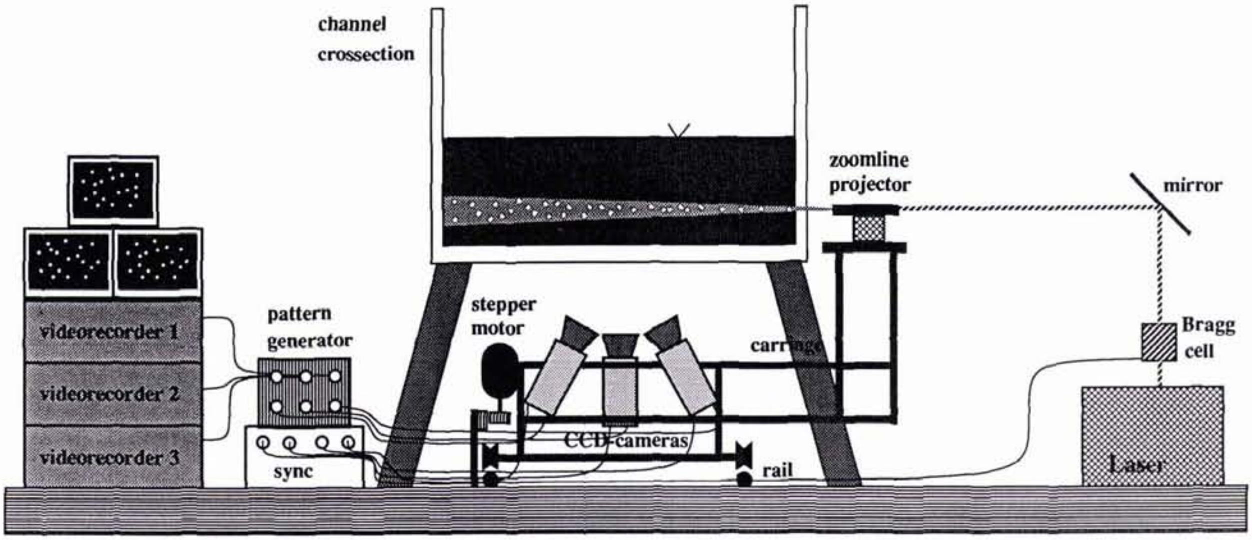

FIG. 1. Hardware setup.

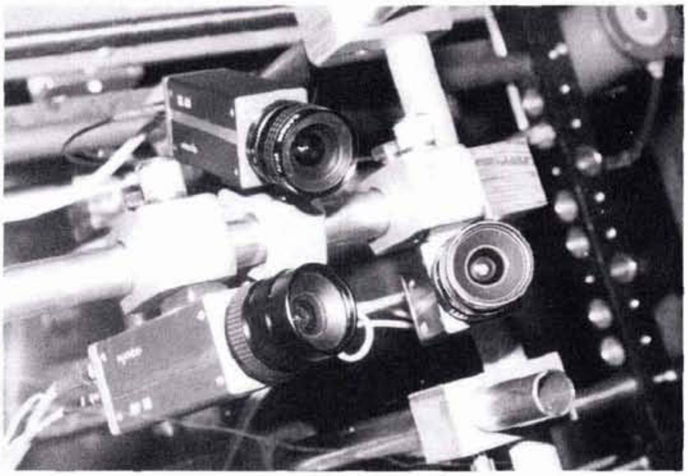

FIG. 2. Three CCD cameras in a carriage below the channel bottom.

FIG. 3. Binary code pattern for image number identification.

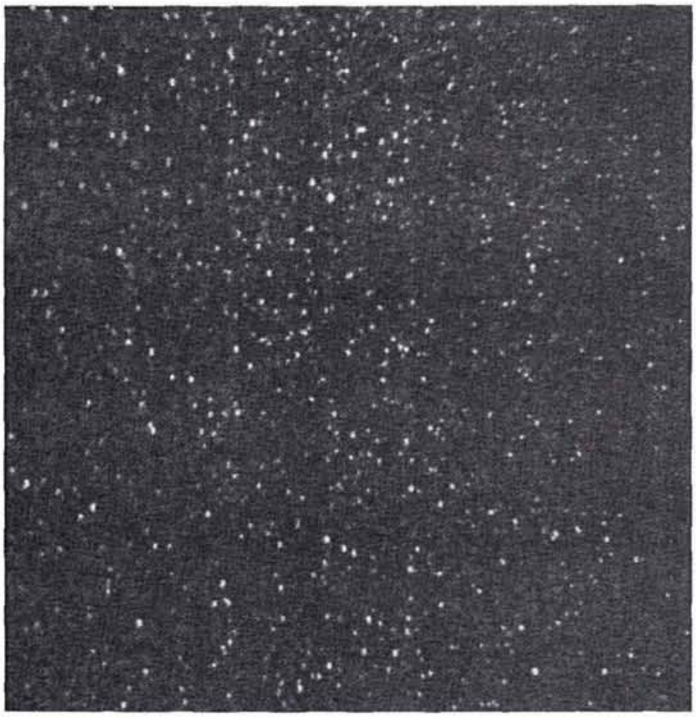

FIG. 4. Original image.

To calibrate the system, a 200 by 200 mm^2 calibration plate with 85 targets in two planes, which have been determined with superior accuracy, is placed into the channel before and after each experiment. To compensate linejitter effects (Beyer, 1987) introduced by the videorecorders and the framegrabber, an electronically generated vertical line is added to the video signal of all cameras before recording. A sample image which illustrates this line, as well as the images of tracer particles, is shown in Figure 4.

The success of the method largely depends on image quality, which is mainly determined by the illumination of the test volume. The generation of a wellshaped, shortpulsed light-sheet of high light energy proved to be the most difficult component in the whole setup.

DIGITAL IMAGE PROCESSING

Basically, the determination of the image coordinates of bright particles on a dark background (as in Figure 4) is a simple task: after a highpassfiltering of the images to remove some nonuniformities of the background level, particle coordinates can be determined with subpixel accuracy by thresholding, connectivity analysis, and calculation of the centers of gravity. With the high particle densities employed here however (typically 2000 to 3000 particles in the illuminated section), a problem of particles optically blocking or overlapping each other in one or more views occurs (as shown in Figure 5). To address this problem, the connectivity analysis has been extended by incorpo-

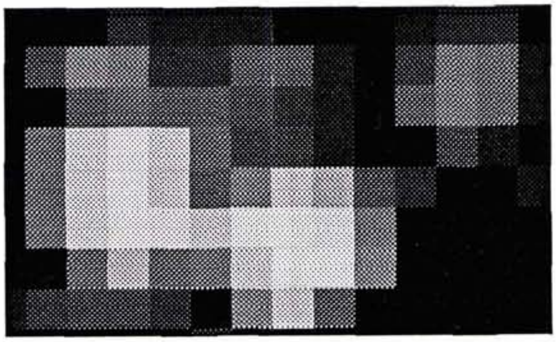

FIG. 5. Example of overlapping particles.

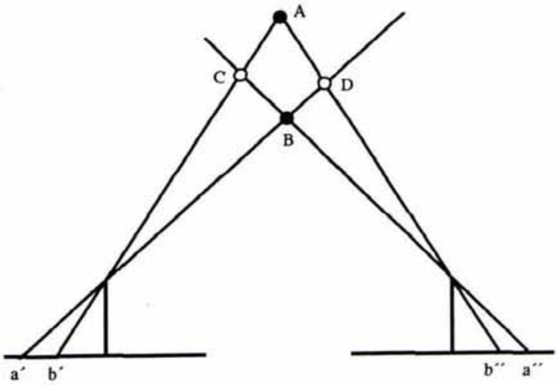

FIG. 6. Example for an unsolvable ambiguity: either the points A and B or C and D can be reconstructed.

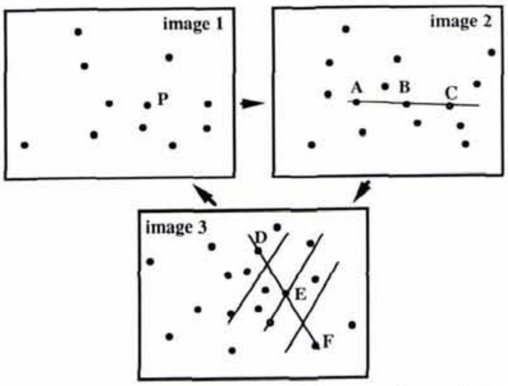

FIG. 7. Example for the establishment of consistent triplets: three candidates (A,B,C) for point P in image 2 and also three candidates (D,E,F) in image 3; only the triplet (P-B-E) is consistent.

rating a discontinuity criterion which searches for local maxima and splits a blob when it detects a discontinuity exceeding a certain limit.

With the relatively high noise level in the images and the small particles (image sizes from 2 by 2 to 6 by 6 pixels), this technique is not absolutely reliable and may lead to wrong decisions, the effects of which have to be removed by a later processing step. Another problem is the sometimes irregular surface of the particles employed, which in combination with the given direction of light propagation leads to particle images that are not circular and that look quite different in different views.

ESTABLISHMENT OF CORRESPONDENCES BETWEEN VIEWS

Epipolar geometry is exploited to find corresponding particle images in different views: with the orientation data of the cameras known from the calibration, proceeding from a point in one image, a line in another image can be derived on which the corresponding point has to be found. In the ideal case this line is a straight line, but in the more general case with non-negligible lens distortion or multimedia environment, as in the present case, the epipolar line is curved.

If approximate values for the depth coordinate of the considered point are available, the parallax and thus the length of the epipolar lines can be restricted. In the present case, with targets on a non-continuous surface, only rough approximate values are available from the knowledge of the position of the illuminated test section, and the length of the epipolar lines can reach 50 pixels and more; in a general case with no *a priori* knowledge about the object, they may be completely unrestricted. By adding a certain tolerance, this epipolar line segment becomes a bandshaped window. In favorable situations, there will be only one candidate in this search area; if no candidate is found, the tolerance can be increased stepwise. With increasing length of the epipolar band and increasing density of targets in the images, however, the probability that two or more candidates are found in the search area grows rapidly. As the target features of size or shape do not allow a reliable distinction of the candidates, a two-camera model becomes unreliable if the number and range of targets can not be strictly controlled; mismatches cannot be excluded and may lead to the determination of non-existing points. Figure 6 shows an example of an ambiguity in matching which cannot be solved by a two-camera system.

A straightforward solution for this problem is the use of a third camera in a setup where the camera projection centers define a triangle and the camera axes define a polyhedron. This arrangement, which is depicted in Figure 7, allows the calculation of two epipolar line segments which intersect with an angle of about 60°. The candidate search can then be restricted to the intersection points of epipolar lines plus tolerance, instead of a whole line plus tolerance thus reducing the probability of ambiguities drastically. This formulation is implemented by means of a combinatorics algorithm, which establishes correspondences between any two views and searches for consistent triplets (resp. quadruples, etc., if more than three cameras are used) in these lists of correspondences.

The method of intersection of epipolar lines with the aim of establishing consistent triplets can be generalized. It is applicable not only to this specific problem of tracer particle positioning, but also can be employed in any case where it is difficult to establish correspondences between views either due to the density of detected points (e.g., points marked by an interest operator) or to the lack of sufficient approximate values (Faugeras, 1988). Also, template matching with geometric constraints (Gruen and Baltsavias, 1988) and three or more cameras has the same effect of forcing a solution to the intersection of epipolar lines, but requires better approximate values.

DETERMINATION OF 3-D COORDINATES AND TRACKING

Once reliable correspondences have been established, the three-dimensional (3-D) coordinates of the particles can be determined. The model for point determination consists of the collinearity condition with a set of additional parameters regarding lens distortion (Brown, 1971) and sensor geometry (El Hakim, 1986) and a multimedia module similar to the one described by Kotowski (1988), which is based on Snell's Law and computes a radial shift of each point relative to the nadir point of the camera as shown in Figure 8.

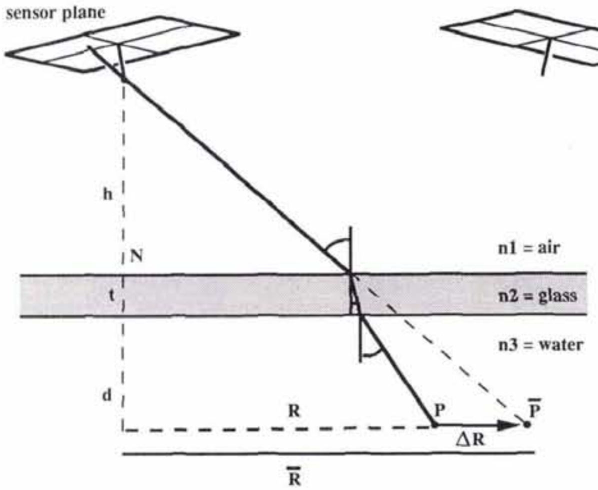

FIG. 8. Multimedia geometry.

To derive the velocity field information, correspondences between consecutive time steps must be established. Generally speaking, the difficulty of tracking grows with the target density and the complexity of the velocity field. In a case where the average displacement of the targets from one time instant to the next is much smaller than the mean distance between targets, tracking is obviously trivial. In the other extreme with chaotic motion and displacements larger than the mean distance between targets, tracking would clearly become impossible. The present problem is somewhere between these extremes: motion is partly predictable, but the target density is high enough to cause quite a few ambiguities in tracking. Criteria to solve these ambiguities are local correlation of the velocity field, Lagrangian acceleration, and kinetic energy (Papantoniou and Dracos, 1989). As the correlation of the gray-value images of particles at consecutive time instants proved to be relatively high, a feature based correlation coefficient of the particle images in the image triplet can also be a very useful criterion for tracking.

RESULTS

The results of the first experiments showed that a two-camera system will only give reliable results if the number of particles in the test section and the depth range (i.e., the thickness of the illuminated layer) can be strictly controlled. A three-camera system proved to be much more reliable and allowed the determination of up to 900 particles per image triplet, of which some 700 could be tracked. A sample flow field derived from 1 second of video data is shown in Figure 9. The standard deviation of the determined particle coordinates was $\sigma_x = 0.08$, $\sigma_y = 0.09$ mm (flow direction), and $\sigma_z = 0.22$ mm (depth coordinate) in a flow volume of 150 by 150 by 20 mm^3. The complete computation time for one image triplet, including image preprocessing, feature extraction, establishment of correspondences, 3-D coordinate determination and tracking, is 30 to 40 seconds on a SUN 4.

To test the accuracy potential of the method, a test with the calibration plate was performed introducing half of its 85 points as control points and using the other points as check points. The RMSE of these check points was 0.04 mm and 0.075 mm for the planimetry and the depth coordinates, respectively. A probable reason for the discrepancy between the standard deviation determined for particles and the RMSE for the check points on the calibration plate is the above mentioned problem of nonregular particle surfaces and directed light propagation causing imperfections in the intersection of corresponding rays. As particle images of consecutive time instants show a relatively high correlation, one can expect that determined points of consecutive time steps are correlated. To get a measure for this correlation of points of consecutive time instants and possible influences of vibrations of the moving carriage, another test was performed by recording the stationary calibration plate from the moving carriage under illumination conditions of the real experiments. The RMS variations of the thus determined 458 velocity vectors were 0.028, 0.055, and 0.042 mm for the X, Y, Z vector components, respectively. This suggests that the correlation between consecutive time steps is relatively high and that the accuracy of the determined velocity vectors is significantly better than the coordinates of a single determined particle. The largest RMS variation occurs in the moving direction of the carriage, which can be explained by effects of the stepper motor drive.

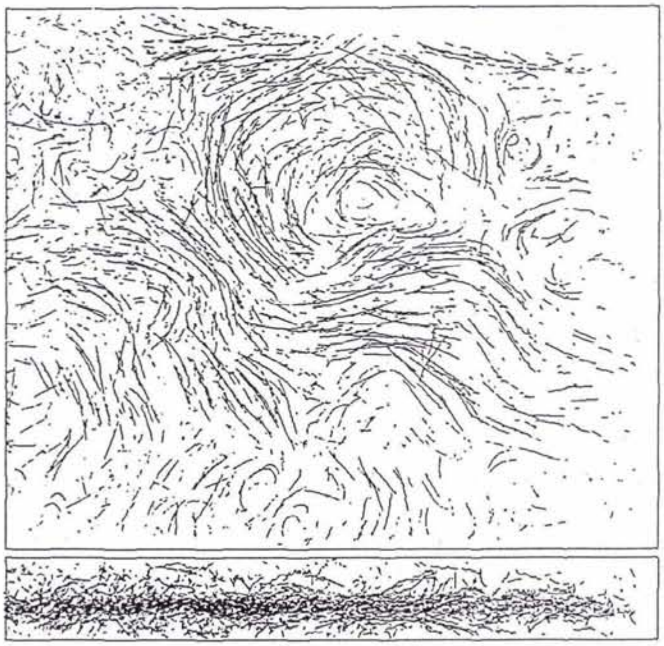

FIG. 9. Velocity vectors derived from one second of flow data; top X-Y plane, bottom X-Z view.

CONCLUSIONS

The presented automated particle tracking velocimetry system has proved to be a very powerful tool for turbulent flow determination. It is versatile and fast, and offers high spatial resolution of up to 700 velocity vectors per video frame triplet, a temporal resolution of 25 vector fields per second, a high accuracy potential with standard deviations of 55 μm or less for all three components of the determined displacement vectors, and a good reliability. To avoid mismatches resulting in blunders, the use of a third camera turned out to be indispensable.

ACKNOWLEDGMENT

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SOFTWARE REVIEW

Introduction to Remote Sensing. Gail Kelly and Greg Hill, editors. Australian Key Centre in Land Information Studies, Remote Sensing Program, Department of Geographical Sciences, The University of Queensland, Brisbane, 4072, AUSTRALIA. 1990. Price: $185 per module for 1 copy (AUD$) [approximately $145 USA]; $555 (AUD$) - site license for 5 copies of any one module; $925 (AUD$) - site license for 10 copies of any one module; Prices include postage and handling. Available on either 5.25" or 3.5" disks. Hardware requirements: IBM pc or compatible, EGA or VGA graphics board, color monitor, hard disk (each module requires about 1.5 kb).

SOFTWARE FOR COMPUTER-AIDED INSTRUCTION IN REMOTE SENSING is surprisingly rare. *Introduction to Remote Sensing,* a product of the Australian Key Centre in Land Information Studies, demonstrates extraordinarily well the potential value of the computer in remote sensing education. Designed as a primer in remote sensing, the package succeeds in being both informative and entertaining. Marvelously conceived and expertly rendered color graphics are featured throughout. The software will appeal to students as young as high school age, but will be useful, as well, in university-level and continuing education contexts. Very user-friendly, the package requires no special computing expertise to run once installed on a hard disk.

Introduction to Remote Sensing is comprised of modules. Although the modules build upon one another, each stands as a self-contained unit. Two modules are currently available. Four additional modules are in preparation. Every module includes a self-assessment option and maintains a record of students performance. Accompanying the software is a 12-page *User's Guide* that provides instructions for installing and running the package. A Manager's (instructor's) operation mode is explained in detail. Under this option, teachers can limit access to exam questions, review student scores, and track student progress.

Each module opens with a menu of "topics" from which to select. Module One, entitled "What is Remote Sensing?", includes eight "topics": (1) The Science of Remote Sensing, (2) Data Capture and Analysis, (3) Remote Sensing Information Types, (4) Passive and Active Remote Sensing, (5) Scanner and Camera Systems, (6) Physical Processes of Remote Sensing, (7) Energy, Space and Time in Remote Sensing, and (8) Assessment of Understanding. Each "topic" is itself a module consisting of a number of "screens." One progresses through the screens by typing answers to questions or by entering a "return." An option for reviewing previous screens is provided.

Topical modules begin with a statement of objectives. One then proceeds through successive screens that illustrate important concepts and define technical terminology. Text is minimized in favor of instruction through innovative graphics and the occasional use of modest animation, as, for example, in portraying the transmission and reflection of microwave energy from an airborne radar system, or the atmospheric attenuation of solar energy. Some graphics demonstrate an appealing sense-of-humor on the part of the authors. Graphics include both conceptual diagrams and imagery (mostly SPOT, CZCS, and airborne MSS data). All images are of locations in Australia. Each image screen includes a map showing the image location, a bar scale, and schematics indicating the sensor and platform used to collect the data. All images are extremely well displayed in VGA.

The final screen in each topical module is a fill-in-the-blank self-examination. After answers are entered by the student, possible correct responses are provided for comparison, and short concept reinforcement is given. At the conclusion of each topical module, the student views a flow chart that portrays his or her progress, and then returns to the main menu. Asterisks next to menu entries indicate topics completed.

Module Two focuses upon "Spectral Signatures." Again eight topical modules are included: (1) Introduction, (2) What is a Spectral Signature?, (3) Identifying Vegetation, Soil and Water, (4) Spectral Characteristics of Vegetation, (5) Spectral Characteristics of Soil, (6) Spectral Characteristics of Water, (7) Applications of Remotely Sensed Data, and (8) Assessment of Understanding. Although much the same as Module One in overall format, Module Two features additional animation and audio "beeps" to highlight important concepts and relationships. The animation and audio enhancements contribute importantly to understanding of certain key concepts (e.g., interaction of EM energy with clear, turbid, and algal-containing water).

Of all the topical modules, only Topic 7 in Module Two must be judged weak. Its illustrations of applications such as Kangaroo habitat evaluation and monitoring Mimosa weed expansion will not give students much appreciation for the many and varied applications of remote sensing. Even the applications depicted, though well-illustrated, are covered in a cursory manner that provides few details on analysis methods used or impacts of study results. Teachers, in particular, would benefit from having supplemental written material summarizing such information.

The final "topic" in each module is an overall assessment. Students are provided a set of 22 fill-in-the-blank and multiple-choice questions. After the student responds, correct answers are given along with some explanation or illustration of the concept to reinforce learning. Upon completion of the examination, a final score is tallied and displayed in terms of percentage correct.

It must be noted that, although it has many strengths, *Introduction to Remote Sensing* does have a few weaknesses. One has been suggested above. Potential users of the software should also be aware that almost no mention of Landsat is made in the two modules published to date, nor is any material on AVHRR data included. Perhaps these will be covered in forthcoming modules. Because the software has been designed as a primer, one might wish to have suggestions for further study (e.g., suggested reading), but none are provided. Last, the expense of the software will, likely and most unfortunately, limit its use. It is obvious from the high quality of the product that considerable time and effort has been invested in developing the package. Nevertheless, similar software (e.g., GIS Tutor) sells for considerably less. If this software is to become widely used in academia, more attractive pricing options may be required.

In conclusion, however, it must be emphasized that *Introduction to Remote Sensing* is an innovative, valuable, and extremely well-executed product. It is no wonder that the editors have already received two awards in recognition of their achievement in development of this software. The package is eminently suitable for introductory instruction in remote sensing in secondary schools, university-level courses, and in continuing education. It can serve as a supplement to lectures and labs, or as a stand-alone tool for self-instruction. Even persons already well-versed in the technology of remote sensing will find this software to be an entertaining vehicle for refreshing their grasp of basic concepts. I, for one, look forward to the release of future modules of this fine package.

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Raymond L. Czaplewski, Misclassification Bias in Areal Estimates.
Peter F. Fisher, First Experiments in Viewshed Uncertainty: Simulating Fuzzy Viewsheds.
G. M. Foody, A Fuzzy Sets Approach to the Representation of Vegetation Continua from Remotely Sensed Data: An Example from Lowland Heath.
Steven E. Franklin and *Bradley A. Wilson*, A Three-Stage Classifier for Remote Sensing of Mountain Environments.
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