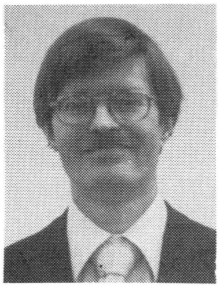
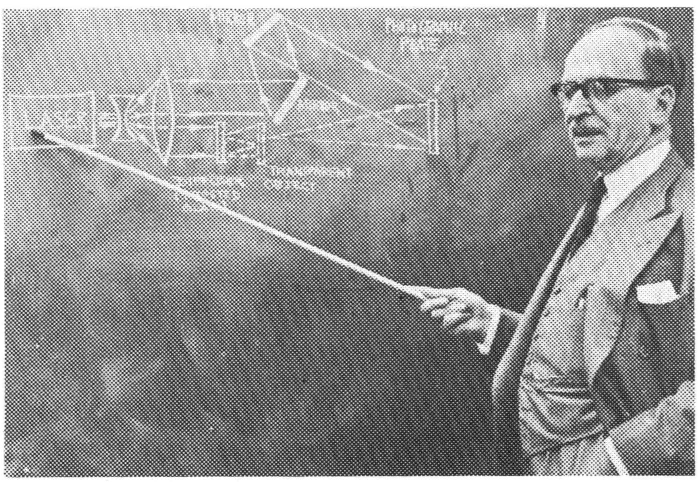


Editorial

H. J. Caulfield, Editor

The Dennis Gabor Award

At an impressive ceremony in Geneva, Switzerland, this April, SPIE inaugurated a major award and prize for outstanding achievement in optics in honor of one of the most distinguished scientist-inventors in the history of our field, Professor Dennis Gabor. Professor Gabor's notable achieve-



ments in other fields have often been overlooked because of the prominence now enjoyed by holography, one of his many inventions.

The current interest in holography is due to the work of many brilliant contributors, but certainly preeminent among these are Professors Emmett N. Leith (University of Michigan, Ann Arbor, USA) and Yuri N. Denisyuk (Volvilov Optical Institute, Leningrad, USSR). Therefore, it was highly appropriate that these two individuals share the first Dennis Gabor Award and Prize. Professors Leith and Denisyuk are scientists in Gabor's great tradition, and their selection will certainly enhance the value and honor of this award for all future recipients.

On behalf of the editors and staff of *Optical Engineering*, I congratulate these outstanding scientists and fine human beings!

(Editor's note: A biographical sketch of Dennis Gabor by T. E. Allibone, Professor Emeritus, Leeds University, England, and a review of Gabor's scientific contributions by Professor Emmett N. Leith, University of Michigan at Ann Arbor, USA, both given at the Dennis Gabor Retrospective and Award Presentation held during SPIE's 1983 International Technical Conference/Europe, appear in Optical Engineering *22(4), pages SR-126 to SR-129.)*

OPTICAL ENGINEERING EDITORIAL SCHEDULE

November/December 1983

Spatial Light Modulators: Critical Issues
Armand R. Tanguay, Jr.
Departments of Electrical Engineering and Materials Science, and Image Processing Institute
523 Seaver Science Center
University of Southern California
University Park MC-0483
Los Angeles, CA 90089-0483
213/743-6152

January 1984

Optical Computing
Demetri Psaltis
California Institute of Technology
1201 California Ave.
Pasadena, CA 91125
213/356-4856

February 1984

Image Scanning & Recording Methods
Philip S. Considine
EIKONIX Corporation
23 Crosby Drive
Bedford, MA 01730
617/275-5070
and
Robert A. Gonsalves
EIKONIX Corporation
and
Northeastern University
360 Huntington Ave.
Boston, MA 02115
617/437-2165

March 1984

Critical Technology: Infrared Optics
Irving J. Spiro
M1/129
The Aerospace Corporation
P.O. Box 92957
Los Angeles, CA 90009
213/615-4441

April 1984

Liquid Crystal Applications
Sun Lu
Crystal Vision, Inc.
1313 Geneva Ave.
Sunnyvale, CA 94089
408/745-0833 Ext. 221

May 1984

Optical Engineering Technologies
Jerrold Zimmerman
MS 241
Honeywell Electro-Optics Operations
2 Forbes Road
Lexington, MA 02173
617/863-3548

June 1984

Holographic Interferometry—25th Anniversary
Ryszard J. Pryputniewicz
Worcester Polytechnic Institute
Department of Mechanical Engineering
Worcester, MA 01609
617/793-5536

July 1984

Precision Surface Metrology
James C. Wyant
Optical Sciences Center
University of Arizona
Tucson, AZ 85721
602/621-2448

Forum

Educational Optics

John B. DeVelis

Department of Physics
Merrimack College
North Andover
Massachusetts 01845

This column is intended to serve as a forum for students and faculty at both the graduate and undergraduate levels who have developed new classroom and laboratory approaches in the field of optics. Readers are invited to participate and should submit articles for review to me at the above address.

BIDIRECTIONAL REFLECTANCE DISTRIBUTION FUNCTION OF GOLD-PLATED SANDPAPER

Tilman Stuhlinger
Optical Sciences Center
University of Arizona
Tucson, Arizona 85721

INTRODUCTION

In the world of radiometry, it is frequently necessary to compare measurements made on a particular sample to those made on a reference sample or reflectance standard. This reflectance standard should fulfill as many of the following requirements as possible: (1) It should approximate a Lambertian reflector (i.e., it should be a perfectly diffuse reflector). (2) Its reflectance should be the same each time it is measured; i.e., it should give repeatable results. (3) It should be robust. At present, several such reflectance standards exist in the visible and near infrared regions of the spectrum. These are MgO, halon, and $BaSO_4$. These materials approximate a Lambertian reflector quite closely, but they are quite easily damaged. Flowers of sulfur have been used for the far infrared, but, again, this material is not very rugged. Past experience suggested that sandpaper would be a good candidate for a reference standard in the infrared. Its inherently low reflectance could be increased by gold plating it. Therefore, a study was undertaken to investigate the reflectance characteristics of gold-plated sandpaper. Various grit sizes were measured at three different wavelengths with the goal of finding a type of sandpaper that closely approximates a Lambertian reflector.

BIDIRECTIONAL REFLECTANCE DISTRIBUTION FUNCTION

Quantitative specification of the reflectance characteristics of a sample is done using the bidirectional reflectance distribution function (BRDF). The BRDF specifies, given a beam of radiation incident on the sample from a certain direction, the amount of radiation reflected by the sample into a unit solid angle in a certain direction. Nicodemus et al.[1] give the following definition of BRDF:

$$f_r(\theta_i, \phi_i; \theta_r, \phi_r) = \frac{dL_r(\theta_i, \phi_i; \theta_r, \phi_r, E_i)}{dE_i(\theta_i, \phi_i)} , \quad (1)$$

where θ and ϕ are angles in spherical coordinates (measured relative to the sample), i and r subscripts refer to incident and reflected quantities, respectively, L_r is the reflected radiance, and E_i is the incident irradiance. Radiance has units of power/(area · solid angle) and specifies the amount of flux going from a unit projected area into a unit solid angle in a given direction. Irradiance has units of power/area and specifies the amount of flux striking a unit area. The angles are defined in Fig. 1. A perfect Lambertian reflector has a hemispherical reflectance of one and a uniform radiance in all directions. This radiance is given by E_i/π since a flat sample subtends a projected solid angle of π sr. Thus, the BRDF of a perfect Lambertian reflector is $1/\pi$ for all angles of incidence and reflection. The radiance of a sample whose hemispherical reflectance (ρ) is less than one but whose radiance is uniform in all directions is given by $\rho E_i/\pi$. Thus, the BRDF of such a sample is given by ρ/π.

In practice, the BRDF is measured by illuminating the sample with a collimated or nearly collimated beam of radiation of the desired wavelength and measuring the reflected radiation with a detector. The detector is mounted on an arm which can swing in a horizontal plane containing the incident beam, and the sample may be tilted about two axes such that any desired incident and reflected directions may be acquired.

Several procedures for obtaining the BRDF of a sample from the measurements are described in a paper by Bartell et al.[2] When the BRDF of a sample which is to become a reference standard is to be determined, the following procedure may be used. The detector output voltage may be related to the radiance and irradiance as follows. In the case of radiance,

$$V_s(\theta_i, \phi_i; \theta_r, \phi_r) = R L_r A_s \Omega_{ds} \cos\theta , \quad (2)$$

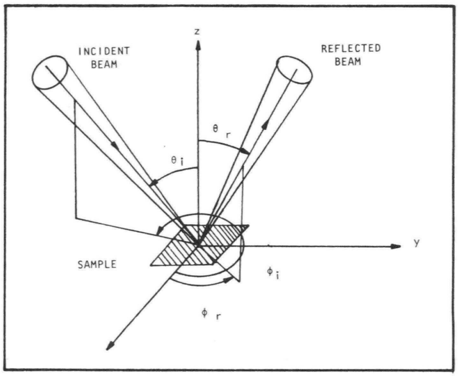


Fig. 1. Geometry of incident and reflected beams.

where $V_s(\theta_i, \phi_i; \theta_r, \phi_r)$ = detector output voltage with the sample in place; R = detector responsivity (V/W); L_r = reflected radiance; A_s = illuminated area of sample; Ω_{ds} = solid angle subtended by the detector at the sample; θ = angle from the normal-to-the-sample to the sample-detector direction; and $\Omega_{ds} = A_d/r^2$, where A_d = detector area, and r = distance from sample to detector. This V_s is measured with the sample in place. The incident irradiance may be found by removing the sample and measuring the on-axis flux (it is assumed that, in this configuration, all the flux that strikes the sample when it is in place now strikes the detector). The irradiance is then related to the output voltage by

$$V_{ns} = R E_s A_s , \quad (3)$$

where V_{ns} = detector voltage with no sample in place; and E_s = incident irradiance. Solving for L_r and E_s, the BRDF is then given by

$$BRDF(\theta_i, \phi_i; \theta_r \phi_r) = \frac{V_s(\theta_i, \phi_i; \theta_r, \phi_r) r^2}{V_{ns} \cos\theta A_d} . \quad (4)$$

In this research, a simpler method was used. The irradiance onto the sample was determined from the voltage measured at the specular angle (with the sample in place), and by assuming that the sandpaper is a perfectly diffuse reflector with hemispherical reflectance ρ. Thus, the sandpaper's BRDF was assumed to be ρ/π, and $E_s = L_r/(\rho/\pi)$, or, solving Eq. (2) for L_r,

$$E_s = \frac{V_{ref} \pi r^2}{R \rho A_s \cos\theta_{spec} A_d} , \quad (5)$$

TABLE I. Types and Grades of Sandpaper

Sandpaper grade	Grit size	Material	Manufacturer[1-3]
80	0.016 in.	SiC	1
120	0.0052 in.	SiC	1
250	0.0030 in.	SiC	1
320	–	SiC	1,2
400	12–40 μm	SiC	1
600	10–32 μm	SiC	1,3
60 μm	–	SiC	1
40 μm	–	SiC	1
30 μm	–	SiC	1
30 μm	–	Al_2O_3	1
15 μm	–	SiC	1
9 μm	–	SiC	1
9 μm	–	Al_2O_3	1
3 μm	–	SiC	1

[1]3M Company, St. Paul, MN 55101.
[2]Norton Co., Box 54, Troy, NY 12161.
[3]Armak Co., Box 1805, Chicago, IL 60690.

Continued on Page SR-144

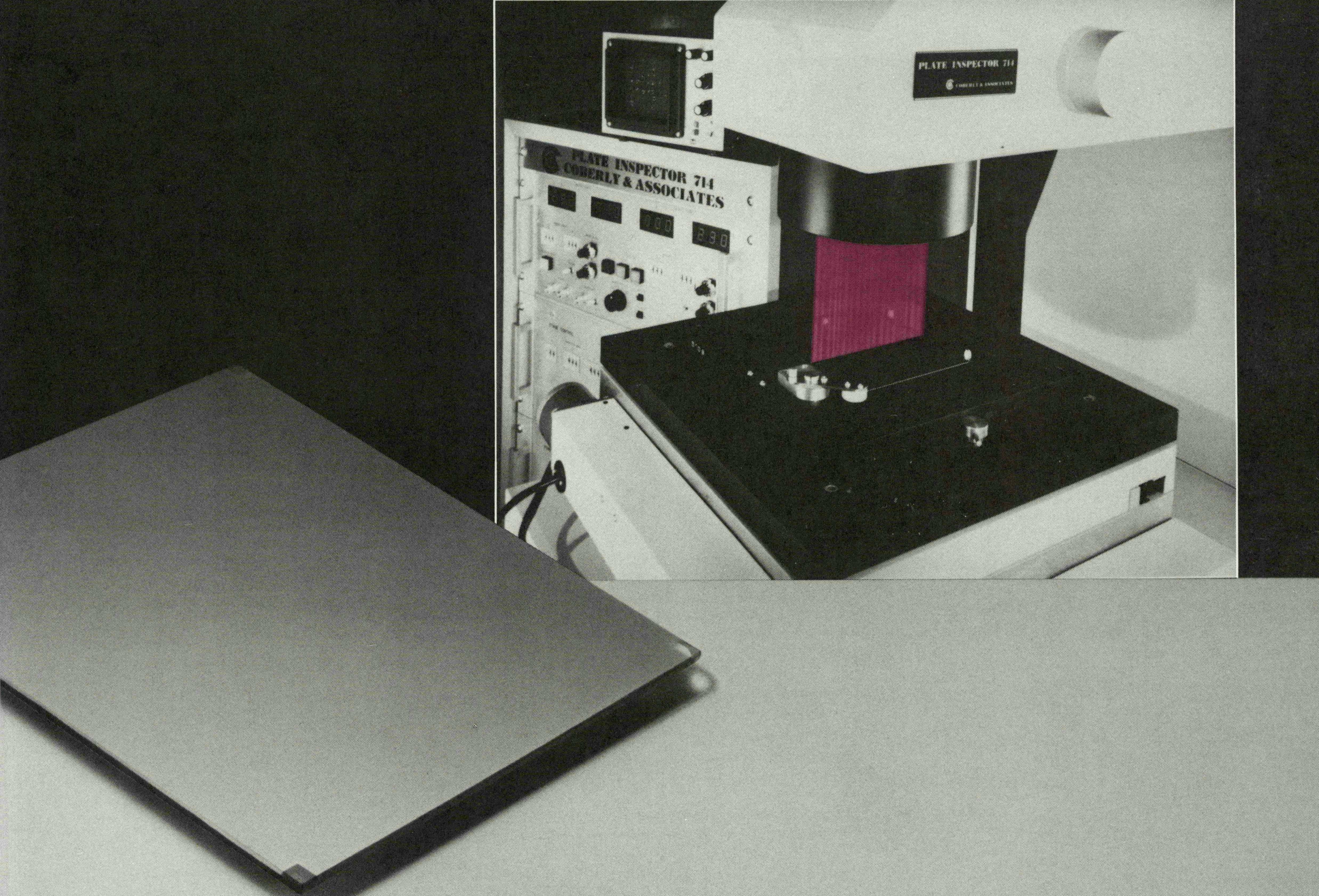


Plate Defect Detection— The Sooner, The Better

Now you can identify photo resist defects and pinholes in chrome plates before they have a chance to multiply. With the PI-714 Plate Inspector, you can identify bad plates before exposures are made, before shipment to customers, or before a plate or mask set is accepted from suppliers.

By uncovering flaws at the mask blank stage, you can dramatically improve overall productivity and reduce the need for costly rework or repair. The PI-714's laser scanning system is also non-destructive; cassette-to-cassette auto-load and sorting mechanisms minimize plate handling. Results are non-operator dependent.

The PI-714 inspects up to forty 5″ x 5″ plates per hour, simultaneously detecting, counting, and displaying the location of micron-sized defects and pinholes. Plate sizes up to 6″ x 6″ are accommodated. Make your mask blank defect detection process objective and automatic. Call (408) 727-1530 for more information . . . the sooner, the better.

COBERLY & ASSOCIATES

3350 Scott Boulevard, Bldg. 47, Santa Clara, California 95051 Telephone: (408) 727-1530

Continued from Page SR-142

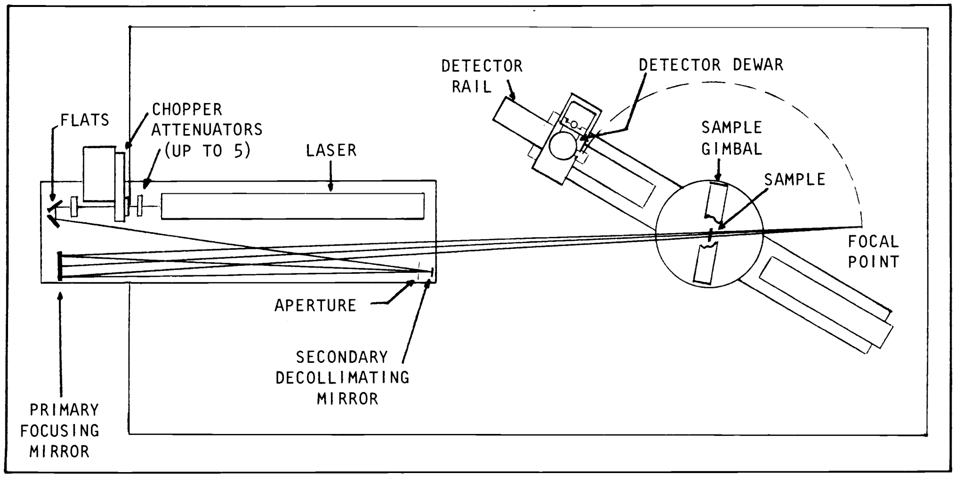


Fig. 2. Layout of the scattering machine.

where V_{ref} = reference voltage = voltage at specular angle; and θ_{spec} = angle of specular reflection. In this case,

$$\text{BRDF} = \frac{\rho}{\pi} \frac{V_s \cos\theta_{spec}}{V_{ref} \cos\theta} . \qquad (6)$$

This method is somewhat inaccurate since the sandpaper is, of course, not perfectly diffuse, thereby causing the numerical value of BRDF versus θ curves to be incorrrect. However, the method is somewhat faster than the previous method since the sample need not be removed for the measurement of E_s, and since the sample-detector distance and the area of the detector do not have to be known. Furthermore, in this study more emphasis was placed on the shapes of the BRDF versus θ curves than on the numerical values; these shapes are the same in either method.

MEASUREMENTS

The scattering measurements were performed on scatter measuring equipment built and operated by the Optical Sciences Center at the University of Arizona. A layout of this equipment is shown in Fig. 2. The detector is mounted on an arm that can be rotated in the horizonal plane (the plane containing the incident beam). Various angles of incidence are set by rotating the sample about its horizontal and vertical axes. To average out the effects of speckle, the sandpaper samples were rotated at a speed of 180 rpm. The detector output is connected to a lock-in amplifier. The lock-in amplifier obtains its reference signal from a chopper running at 40 Hz located in front of the lasr. The laser beam passes through a set of attenuators (which attenuate the laser beam for cases when the flux reaching the detector would otherwise saturate the detector), through the chopper, through the beam-expanding optics, and then to a focusing mirror so that a converging f/30 beam is directed at the samples. As explained by Bartell et al.,[2] this arrangement permits a relatively large beam size at the sample to be combined with a relatively small beam size (given by the Airy disk diameter = 2.44 λ times the f number) at the detector. The large beam size at the sample allows many, rather than just a few, grains of sand to be involved in the scattering process. The small beam size at the detector allows measurements to be made as near as possible to the on-axis or specular directions without the direct beam or the specularly reflected beam dominating the reading.

Three laser sources were used for the measurements; these had wavelengths of 0.6328 μm, 3.39 μm, and 10.6 μm. Separate detectors were used for each wavelength. At 0.6328 μm a GaAsP photovoltaic detector was used. A PbS photoconductive detector operating at dry ice temperature (196 K) detected the 3.39 μm radiation. For the 10.6 μm radiation, a HgCdTe photovoltaic detector mounted in a liquid-nitrogen-cooled Dewar was used.

Various types of sandpaper coated with gold were fabricated to provide the samples. Table I lists the various types and grades used for these tests and their manufacturers. The sandpaper sheets were cut and epoxied with low vapor pressure Torr-Seal resin to mounts that fit the measuring instrumentation. The samples were coated with a 5 μm thick layer of gold by a vapor deposition technique.

The results are presented in the form of graphs of the BRDF as a function of the scattering angle θ. Since a Lambertian radiator has a BRDF that is constant with respect to θ, it would appear on such a graph as a horizontal line. The value $1/\pi$ of the BRDF of such a radiator has been marked on each graph.

Figures 3, 4, and 5 show the sandpapers judged to be most suitable as reflectance standards at 0.6328 μm, 3.39 μm, and 10.6 μm, respectively. These sandpapers were chosen because, at one or more angles of incidence, they closely approach the horizontal line Lambertian behavior. From Figs. 3–5 it can be seen that for each wavelength tested, the gold sandpaper is an approximately Lambertian reflector only for the lower angles of incidence. At an incidence angle of 60° it is poor at all three wavelengths.

A strong dependence of the shape of the BRDF curves on the grit size was found only for the 10.6 μm measurements. As shown in Fig. 6, at 10.6 μm the sandpapers became more specular at finer grit sizes, as indicated by the peak in the BRDF curve at the specular angle.

At the other wavelengths, the scattering depends more strongly on the spacing than on the size of the grit particles. Figures 7(a) and 7(b) show the measurements of two 600 grit sandpapers. The two sandpapers have the same grit size but a different grit spacing. It is apparent that the measurements on sandpapers with small grit spacings more closely approximate Lambertian reflectors than those with large grit spacings. The glue, which appears as a bright border surrounding each grit particle, is particularly thick for the sandpaper with large grit

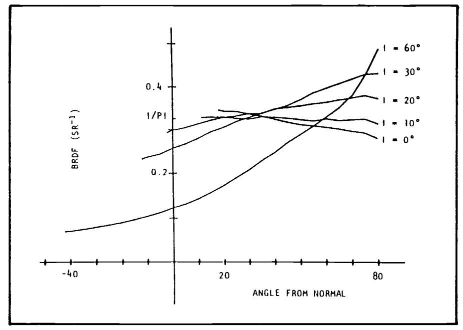


Fig. 3. 9 μm Al_2O_3 sandpaper at various angles of incidence. This sandpaper was the most nearly Lambertian at 0.6328 μm.

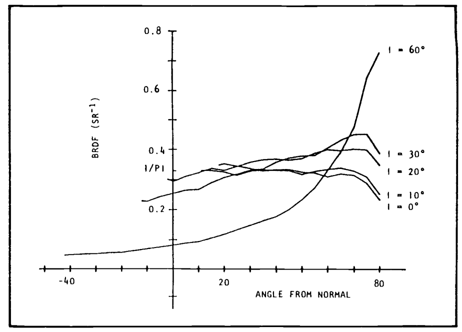


Fig. 4. 9 μm Al_2O_3 sandpaper at various angles of incidence. This sandpaper was judged to be the most nearly Lambertian at 3.39 μm.

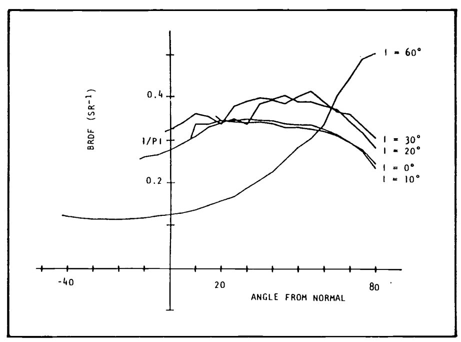


Fig. 5. 600 grit Armak sandpaper at various angles of incidence. This sandpaper was the most nearly Lambertian at 10.6 μm.

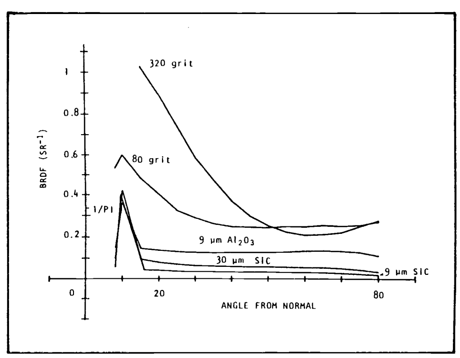
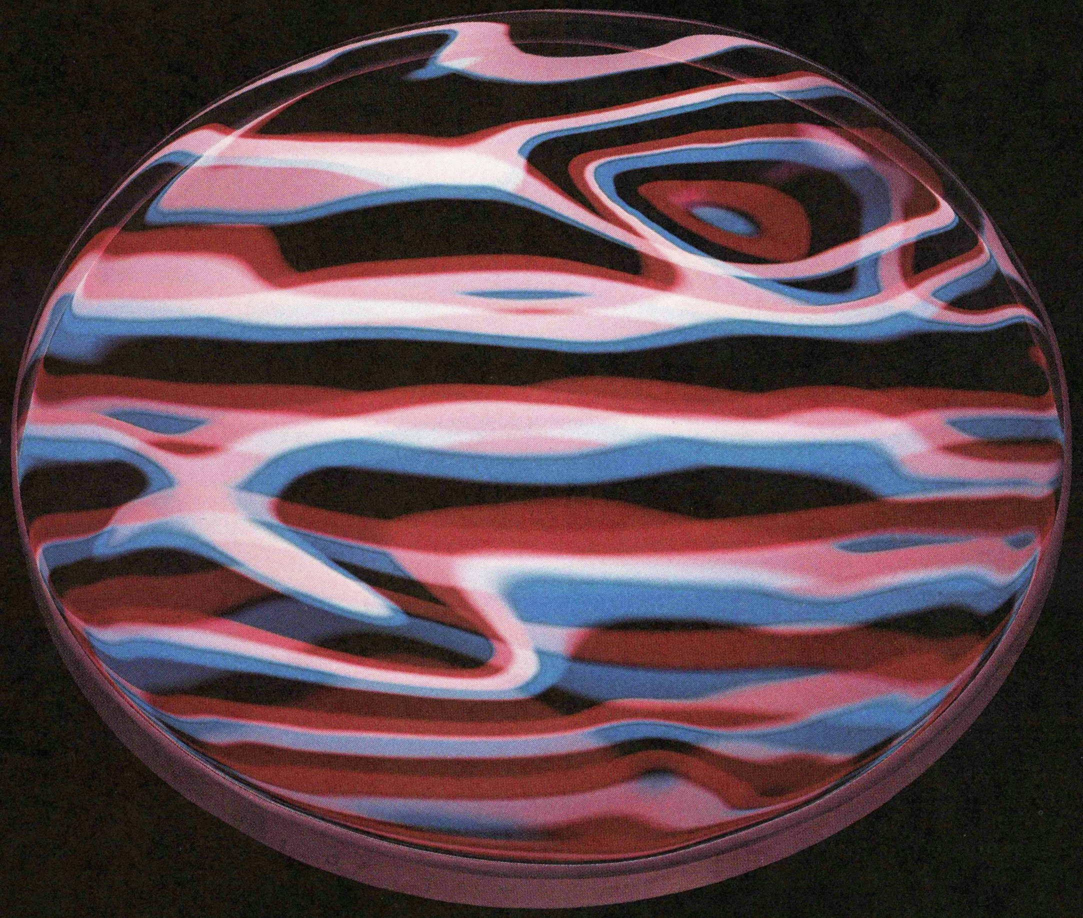


Fig. 6. Dependence of BRDF on grit particle size at 10.6 μm. Angle of incidence is 10°.

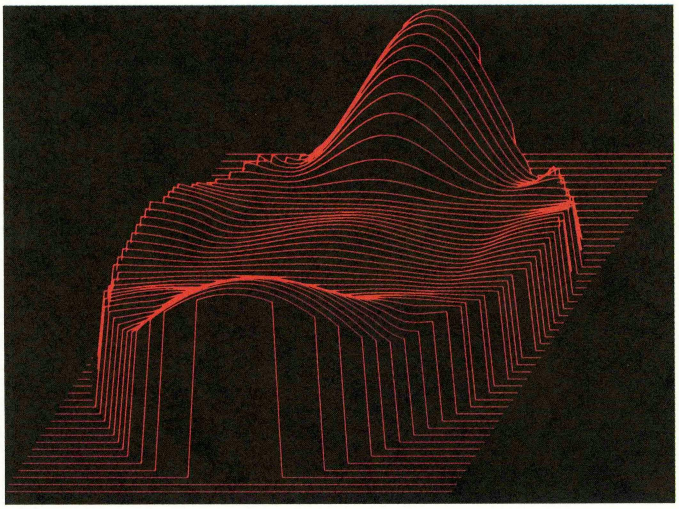
Continued on Page SR-146



THERE'S MORE TO AN ASPHERE THAN MEETS THE EYE

Aspheres Enhance Performance, Minimize Limitations of Size, Weight, Configuration. Give Your System Flexibility.

Tinsley is the Asphere Company.



Consider Aspheres, Consider Tinsley

Our innovative manufacturing techniques assure you delivery of aspheres in production quantities, to exacting specifications, at competitive prices.

We'll be glad to talk with you about aspheres any time. Give us a call.

You can reach our Technical Sales Staff at 415 843-6836.

tinsley THE ASPHERE COMPANY

Tinsley Laboratories, Inc., 2448 Sixth Street, Berkeley, California 94710

Continued from Page SR-144

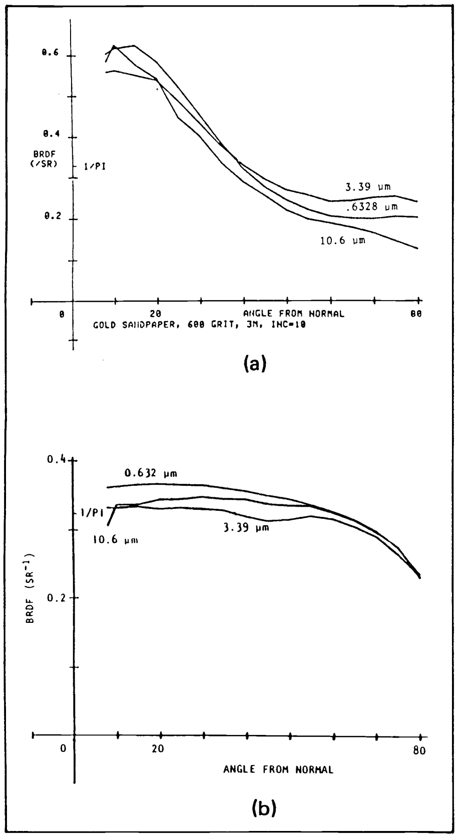


Fig. 7. BRDF of two gold-plated sandpapers: (a) 600 grit 3M; (b) 600 grit Armak. The 3M sandpaper has the larger grit spacing. Angle of incidence is 10°.

spacings; this would appear to add to the non-Lambertian characteristics of these samples.

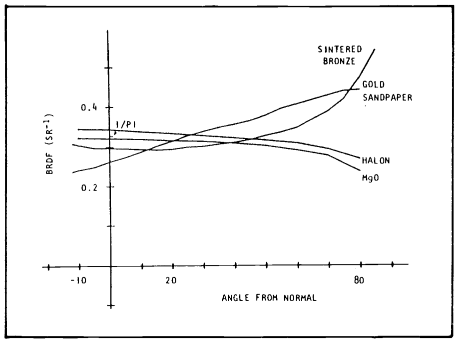


Fig. 8. Comparison between gold-plated sandpaper and some other common reflectance standards at 0.6328 μm. Angle of incidence is 30°. The data for sintered bronze are plotted artificially high to assist in comparison of the shapes of the curves.

Figure 8 compares the chosen gold sandpaper to some more commonly used reflectance standards at 0.6328 μm and at an angle of incidence of 30°. Figure 9 shows a similar comparison at 10.6 μm.

Measurements on the gold sandpaper were repeated after a period of two months. These repeated measurements show that the gold-plated sandpaper gives repeatable results over a period of time.

CONCLUSIONS

Among the sandpaper types and grits tested, the 9 μm aluminum oxide from 3M Company is the best choice for 0.6328 and 3.39 μm wavelengths. The best choice for the 10.6 μm wavelength is Armak 600 grit silicon carbide. It is concluded that, for a given grit size, the filling factor, or density of particles over a given area, is more important in determining the scattering characteristics of the sandpaper than the grit size. The flat

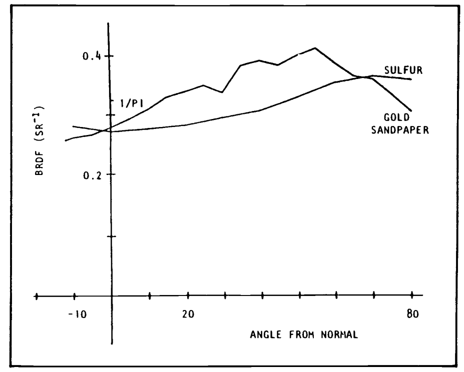


Fig. 9. Comparison between gold-plated sandpaper and sulfur at 10.6 μm. Angle of incidence is 30°. Sulfur data are plotted artificially high to assist in comparison of shapes of curves.

areas between grit particles, along with the glue holding the particles to the substrate, add a strong specular component to the scattered radiation. Furthermore, for large angles of incidence (60°), all the sandpaper samples depart significantly from Lambertian behavior. Gold-plated sandpaper is not more Lambertian, particularly in the infrared, than other commonly used reflectance standards. However, the sandpaper is more robust than these other reflectance standards, and it gives repeatable results over long periods of time. Especially at low angles of incidence, it may find at least limited use as a reflectance reference sample.

REFERENCES

1. F. E. Nicodemus, J. C. Richmond, J. J. Hsia, I. W. Ginsberg, and T. Limperis, "Geometrical Considerations and Nomenclature for Reflectance," Natl. Bur. Stand. (U.S.) Monogr. 160(Oct. 1977).
2. F. O. Bartell, E. L. Dereniak, and W. L. Wolfe, Proc. SPIE 257, 154(1980).

OPTICAL DATA PROCESSING FOR AEROSPACE APPLICATIONS

R. L. Stermer
M. Sokoloski
NASA/Langley Research Center
Hampton, Virginia 23665
and
Office of Aeronautics and
Space Technology (OAST)
Washington, D.C. 20546

Abstract. Optical data processing has significant potential in future aerospace systems. In this paper, potential system applications are identified. One of the more important applications is the determination of errors of large antenna or reflector surface and the active control or compensation of the surface. Technological challenges to the application of optical data processing technology to aerospace systems are identified, and current NASA research efforts are discussed.*

*This paper was presented at the 10th International Optical Computing Conference, Cambridge, Massachusetts, April 6–8, 1983.

1. INTRODUCTION

Current and projected aerospace missions indicate a significant increase in the volume and rate at which raw data must be processed. This data explosion occurs in the areas of aircraft and space vehicle control, large space structures, and remote sensing. In addition, increasingly complex operations are being required to interpret this data and/or make control-type decisions in near real time. Recent scientific developments in optical data processing have indicated a significant potential for this phenomenology to meet many of the projected requirements in the 1990s and beyond.

In this paper, potential applications and technological challenges to the application of optical data processing to aerospace systems are identified, and current NASA research efforts are discussed.

2. POTENTIAL APPLICATIONS

Aerospace data processing systems programs fall into two general categories: near-term, well-defined programs with quantitative specifications and objectives, and long-term, goal-oriented system definition studies and technological identifications. It is in the latter category that optical data processing will make its impact. Optical data processing, with its enhanced performance, could provide significant new capabilities that will affect overall system goals and allow more effective use of future aerospace systems.

The potential applications of optical information processing can be divided into four major areas:

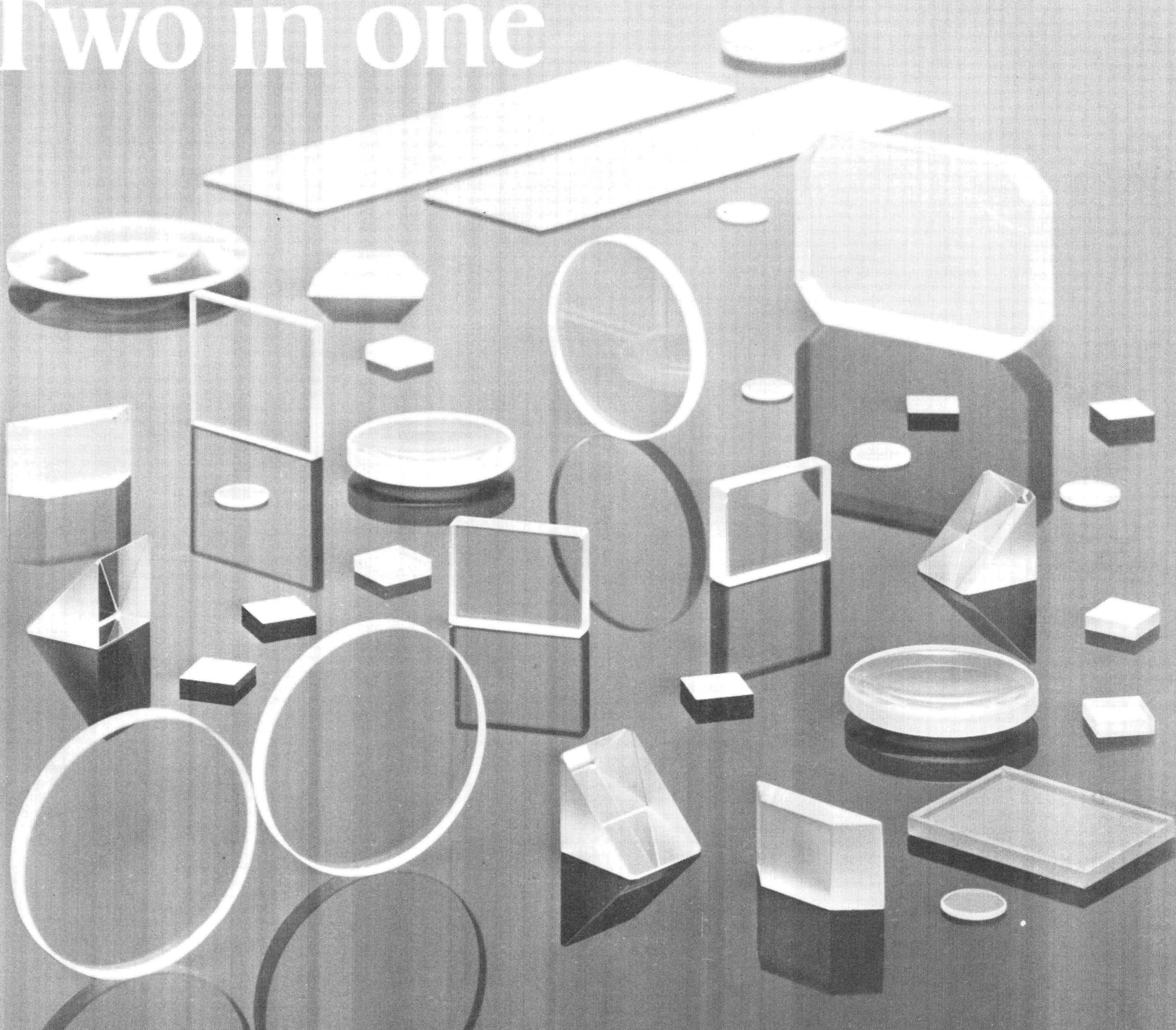
2.1. Large space structure control

One of the most important applications of optical processing is shape control of large space antennae or reflectors. This problem can be divided into two principal considerations. First, the error of the surface must be detected and then a control vector must be computed to actively correct surface error. One possible approach applicable in the millimeter range would be to optically determine the state of the surface and generate a control vector which would alter the phase and amplitude of a feed array to compensate for the surface error.

A prime example of this is an earth-orbiting observatory designated the Large Deployable Reflector (LDR).[1] The LDR is conceived as a free-flying telescope with a large (20 m) segmented reflector. The reflector consists of 127 rigid hexagonal mirror plates and represents a system with 762 degrees of freedom. The individual reflector elements must maintain a surface accuracy of approximately λ/15. Thus, a 30 μm diffraction-limited goal suggests a 2 μm rms surface variation. Optical techniques offer significant potential to determine the surface state with sufficient accuracy. Work at Carnegie-Mellon University with Langley Research Center is looking at techniques for measuring very accurately the state of a surface. The current goal is to measure deformations

Continued on Page SR-148

Two in one



Optical components must be precision built *and* precision coated to achieve specified performance. At Tropel, we do both. Our in-house resources and capabilities enable us to design, build, coat, test, and deliver cost-effective, high precision components in both prototype and OEM quantities. Our major areas of specialty are:

High Quality Optical Substrates

- Windows, mirrors, beamsplitter plates
- Round, square, special shapes
- Parallelism to 2 arc seconds
- Diameter/thickness ratio to 25:1
- Wavefront quality to $\lambda/10$
- Surface quality to 20/10
- Choice of materials

High Quality Optical Coatings

- Polarizing and non-polarizing dielectric coatings
- High efficiency broadband AR coatings
- Dichroic beamsplitter coatings
- Metal coatings and enhancements
- Neutral beamsplitter coatings
- High power resistant coatings for laser applications

Whether you need components, coatings or both, come to Tropel for optimum performance. Contact Tropel Division, GCA Corporation, 60 O'Connor Road, Fairport, NY 14450, 716-377-3200.

GCA

GCA CORPORATION
Tropel Division

Continued from Page SR-146

TABLE I. Required Number of Code instructions and Instruction Rates for the LMSS and LDR

	LMSS	LDR
Number of instructions	28,400	60,000
Instruction rate inst/sec	220,750	314,000

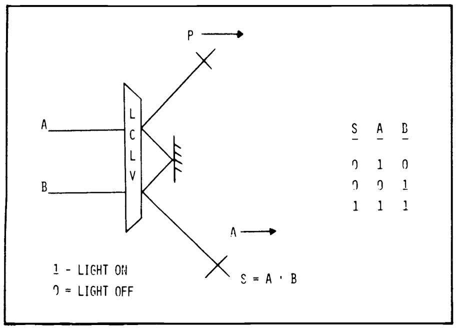


Fig. 1. Illustration of optical gate using a liquid crystal light valve (LCLV).

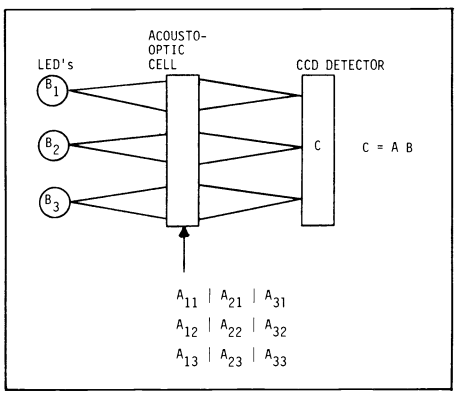


Fig. 2. Vector matrix multiplier using an acousto-optical cell.

of up to 3 cm to an accuracy of 64 μm over a 1 m object. Methods being evaluated include moire and Fourier transform techniques. Future investigations will have to approach 2 μm accuracy over larger surfaces. Ultimately, this measurement must be in a state vector format suitable for processing to determine a control vector.

A second consideration is the computational rate required to determine a control vector from the state of the surface. Using the format developed by Schaecter[2] for the Land Mobile Satellite System (LMSS), the required amount of code and execution time can be estimated for the LDR. The results are shown in Table I with Schaecter's results for LMSS. The rates indicated in Table 1 are significantly higher than current capabilities of about 10^5 instructions per second in the higher speed space computers. The nature of the calculation makes it ideally suited for optical data processing.

2.2. Space vehicle and aircraft control

By means of optical data processing, solutions to problems of spacecraft and aircraft control will be attainable as the complexity of future optimally configured systems surpasses conventional information systems. State variable formulations of the system control law allow the calculation of the control vector from the state vector by iterative matrix operations (principally multiplication). The parallel nature of optical processing makes it ideally suitable for matrix operations and will permit control of the aircraft or spacecraft according to an optimal configuration (minimum fuel, noise, etc.).

Work at Ohio State University, Carnegie-Mellon, and Lewis Research Center is investigating digital optical computers applied to control problems encountered in aerospace systems. The Ohio State University grant concentrates on the use of optical computers to perform numerical calculations using residue arithmetic. Demonstrations of logic and arithmetic operations using a liquid crystal light valve (LCLV) as the central computing element have been successful. In addition, an optical temporal integrator using residue arithmetic has been built and is presently under evaluation. Figure 1 illustrates a logic operation using a LCLV. The state of polarization on the right side is changed upon reflection from the LCLV if light is present on the input side at that point.

The Carnegie-Mellon University work focuses on optical computer applications to handle large matrix-matrix operations. The solution of simple matrix problems using iterative techniques has been demonstrated. Current work is centered on the use of acousto-optic cells as variable masks because of speed advantages. Figure 2 illustrates how the acousto-optic cell is used to solve a simple problem. The matrix values are fed into the acousto-optic cell a column at a time while values of the vector B are represented in the LED array. Work is continuing on this technique to develop a general-purpose-type matrix/matrix computer that can be used for solutions to large multivariable control problems.

The possibility of nonlinear or time-varying control law is a very interesting possibility, [1,2] adaptive control where real-time solutions to nonlinear equations are necessary. A specific example is the Chicago DC-10 crash where the aircraft configuration was severely altered by the loss of an engine. A second example would be a large deployable reflector which must maintain performance during large-angle fast slues where the deformations caused by accelerations would cause time-racing active surface control.

2.3. Pattern recognition

The ability of laser technology to create coherent optical wavefronts combines with the Fourier transform properties of lenses to make use of optical interference phenomena for data processing. These properties can be used not only to analyze spatial frequency spectra, but also to perform filtering or convolution operations on one- and two-dimensional data. The ability of optical techniques to perform operations on high resolution data virtually instantaneously has been the major factor in its implementation for some types of data processing.

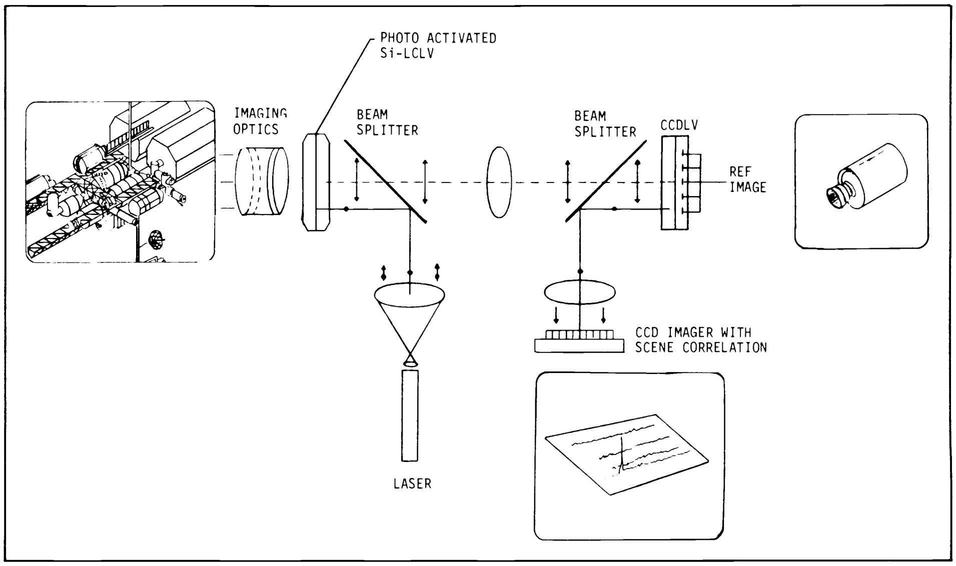


Fig. 3. Conceptual application of spatial correlation for space station component identification.

A projected space station will be assembled in space. This will require two-dimensional optical array processing for solving the requirements of robotic vision for automated assembly, identification, stereovision, and data extraction for ranging and covergence rate. Figure 3 demonstrates one potential application of pattern recognition in assembly/repair of a space station. Here a motor is being recognized automatically so that repair or replacement can be implemented.

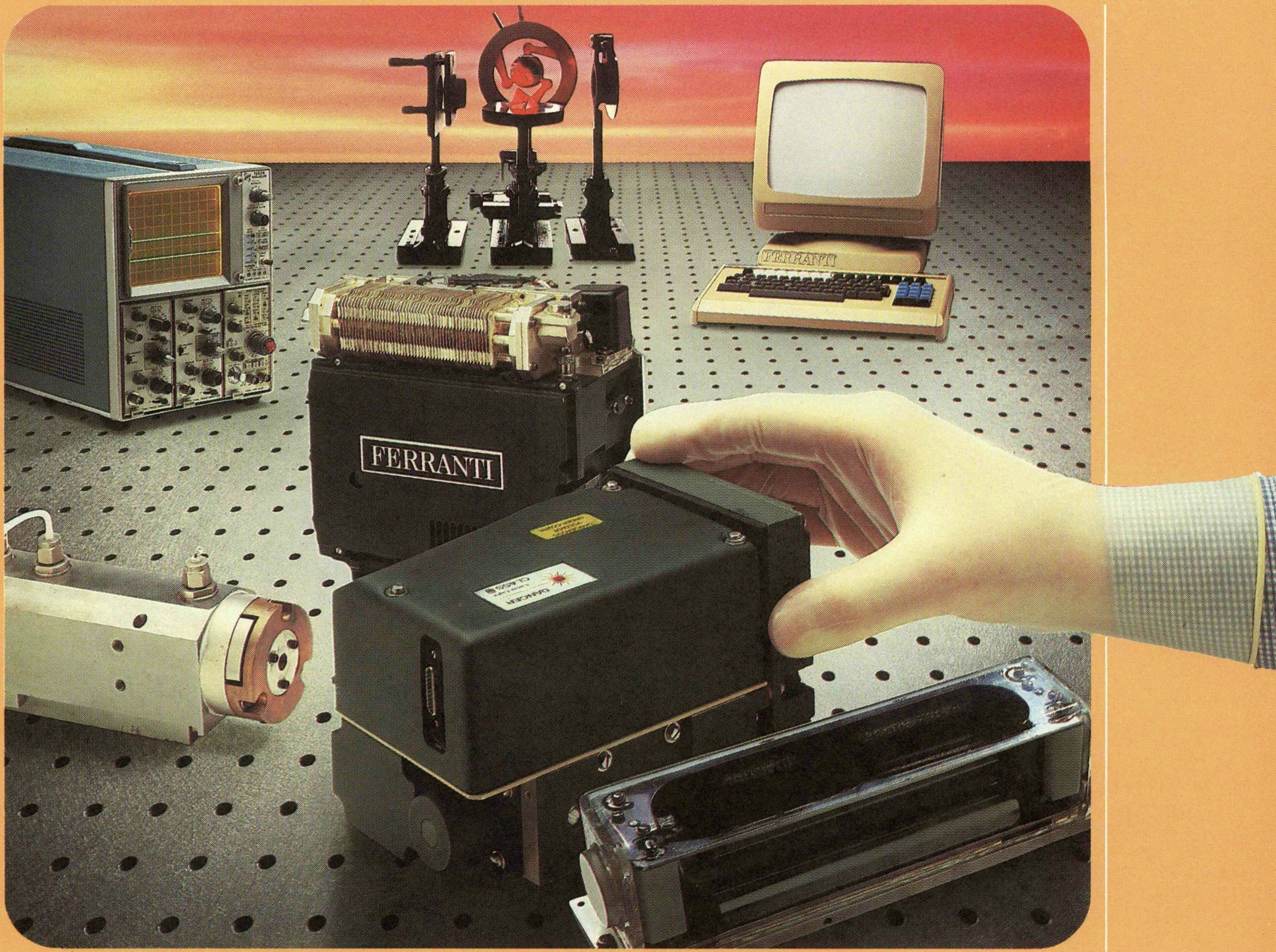
Other potential applications include high level data extraction for remote sensing. As an example, during terrestrial remote sensing, no on-board effort is made to assess in real time the quality of information content of the input image or output product. An image analysis system, making use of optical processing techniques, can monitor data to determine whether additional processing will yield useful or meaningful data. Such systems might be used on board future remote sensing spacecraft and reduce communication spectrum burdens.

2.4. Special purpose processors and sensors

Of particular interest to NASA is the need to process synthetic aperture radar (SAR) imagery. The principal information content of SAR Imaging data is the geodetic and topographic structure of the reflecting surface taken along the path of an observer, as shown in Fig. 4, taken from Psaltis and Martin.[3]

The image formation algorithm involves the two-dimensional deconvolution of the recorded phase and amplitude history of the radar return from the radar pulse shape in the range dimension and from the Doppler-induced phase modulation in the azimuth direction. Currently available digital processors require approximately 10 h to process a 100 km×100 km SEASAT A SAR image that was acquired in only a few minutes.[4]

Continued on Page SR-150



Trail blazers in lasers.

Now you can buy laser systems with the most advanced technology, direct from Ferranti in the United States.

The four types we show here are not just laboratory specimens. They are ruggedised so they can be used in the field as part of a prototype system.

Ferranti can offer fast delivery from its new facility at Huntington Beach, California.

Ask about:

Nd YAG Mini Rangefinder (Type 520)
Nd YAG Rangefinder/Designator (Type 629)
CO_2 Eye-safe Sealed T.E.A. Transmitter (Type 630)
CO_2 1-20W RF/DC excited waveguide laser (CM Series)

Ferranti Electro-optics Inc.
16812 Gothard Street,
Huntington Beach,
California 92647, U.S.A.
Telephone: 714 . 841 6812

FERRANTI
Electro-optics

Continued from Page SR-148

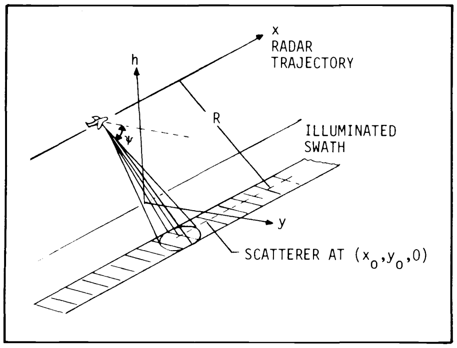


Fig. 4. Geometric considerations for SAR data deconvolution.

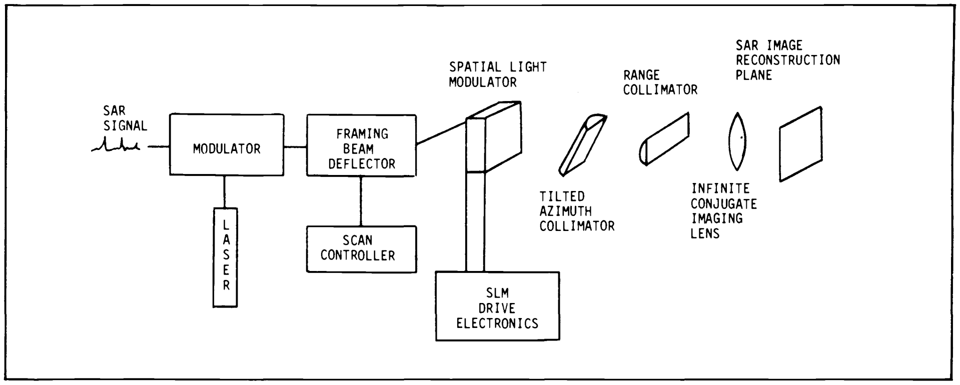


Fig. 5. 2-D spatial light modulator correlator for application as a SAR data deconvolver.

A cooperative effort is active at the University of Southern California, California Institute of Technology, and Jet Propulsion Laboratory (JPL) to develop techniques leading to compact, low power, real-time SAR processors. A block diagram of one 2-D spatial light modulator correlator is shown in Fig. 5. This system would do real-time SAR Image reconstruction. The key element required in the development of this system is the spatial light modulator.

One of the most significant developments in radio astronomy has been the discovery of over 50 different molecules in the interstellar medium. Goddard Space Flight Center (GSFC) is actively involved in the development of bulk and integrated acousto-optic spectrometers to perform this research.[5] A block diagram of the spectrometer is shown in Fig. 6.

Goddard Space Flight Center has constructed a 400 MHz bandwidth, 140 element integrated acousto-optic cell (AOC). This entire rf spectrometer has dimensions of 7×3 cm. The spectrum analyzer, shown schematically in Fig. 6, consists of a laser, a diffraction-limited geodesic collimating lens, a surface acoustic wave (SAW) transducer array, a second diffraction-limited geodesic lens that is utilized as a transform lens, and a 140 element photodiode array. The spectrum analyzer was fabricated on X-cut $LiNbO_3$ with the c axis parallel to the acoustic propagation. The optical waveguide was formed by diffusing 180 Å of titanium into $LiNbO_3$ to obtain a tightly confined optical beam. The photosensor array was butt-coupled at a 45° angle to the waveguide edge of the $LiNbO_3$ substrate. The detector array is a self-scanned photodiode array consisting of 40 photodiode pixels. Efforts are currently underway to develop the spectrum analyses in a hybrid integrated circuit for potential aircraft and spacecraft use.

Langley Research Center is active in research in focal plane processing.[6] By electronically controlling the spatial response of the imaging system, as shown in Fig. 7, it is possible to trade off edge enhancement for sensitivity increased dynamic range and reduced data transmission. These studies have also shown that shading the lens aperture transmittance to increase depth of field and using a regular hexagonal sensor array instead of square lattice to decrease sensitivity to edge orientation also improves the signal information density up to about 30% at high signal-to-noise ratios (SNRs).

A hybrid fiber optic rotation sensor (FORS) is under development at JPL.[6] A diagram of this optical circuit is shown in Fig. 8.

This device has the potential of meeting residual drift rate of less than 2×10^{-4} deg/h and an angular resolution of 0.005 arc-second. A hybrid integrated optic chip that carries the laser, optics and electro-optics, and detector is being developed. Leads from a fiber optic waveguide sensing coil are fastened directly to the integrated optics chip to complete a single sensing axis. A single gyro chip, which may contain three or more sets of optical circuits, can be connected to a similar set of sensing coils to provide three sensing axes with redundancy. A three-axis chip is expected to measure about 1 1/2×2 in. A microprocessor receiving data from signal processing circuits and supervising the sequencing of driver circuits for the electro-optics completes the functional elements of the FORS. The current status of the gyro chip is that peliminary developmental units which do not incorporate the laser source or the detector are currently being received from a contractor for test and evaluation. Fabrication methods of the integrated optic components are similar to those used to fabricate integrated electronics. Fabrication of three or six sets of optical circuits on a single chip, rather than one, involves no increase in waveguide component processing complexity.

Although developed for special purposes, these processors have an important role in many related applications. Alternate uses of these developments are under active investigation.

3. CURRENT RESEARCH CHALLENGES

In this section we discuss current research challenges in device and material development, optical circuit integration, and system organizations.

3.1. Optical device technology

The central and critical component to any useful optical processor is an addressable or programmable mask. To date most work on this component has been towards controlled attenuation devices, such as the light valve. Johnson Space Center is sponsoring work at Hughes to enhance the performance of the silicon CCD LCLV. Current state of the art is shown in Table II.

Current work is directed toward increasing flatness and parallelism in the device to reduce fringing effects. These effects are one of the leading causes of spatial interference and resolution loss. Recent progress in LCLVs has indicated significiant promise. Data rate limitaitons on alterability indicate additional research on addressability is required.

Ames Research Center is initiating research on a spatial light modulator based on the microchannel plate concept. Studies have been initiated to develop an alternate form of programmable mask based upon an amplifying concept rather than an attenuation concept using an addressable microchannel intensifier plate run at low gain. A technique will be developed for addressing any defined pixel on the array and controlling its gain through its bias voltage. Using this technique, a bias control bandwidth of 3 kHz and a dynamic range of 10^4 is anticipated. By mating the programmable microchannel plate with suitable lenses or fiber optic bundles, a CCD two-dimensional array or a one-dimensional reticon array can be used as a readout device.

A special-purpose device under development is a variation of the direct electronic Fourier transform (DEFT) device, reported by Kornreich et al.[8] The device integrates the optical current generated in an array of diodes. A ZnO piezoelectric film overlay is used to launch orthogonal surface waves, as shown in Fig. 9.

These waves mix in a squared term associated with the stress dependence of the electric field in the junction. At the sum and difference frequencies a current output of the form

$$i(t) = A\iint f(t - x/v)\,g(t - y/v)\,I(x,y)\,dxdy$$

is available. If f and g are sine functions and I (x,y) is an image, then the resultant current is proportional to the two-dimensional Fourier coefficient at the frequencies of f and g. The full two-dimensional transform can be generated by scanning the frequencies. It is also readily apparent that a number of other functions, such as time-domain correlation, can be performed by modulating the surface acoustic waves.

3.2. Integrated optic processors

Langley Research Center and Battelle have been doing research in guided-wave integrated optic circuits in $LiNbO_3$. To date the emphasis has been on development of integrated optic components, techniques, and demonstration circuits.

A least mean square difference circuit was fabricated to demonstrate the technology required to fabricate a hybrid integrated optic circuit shown in Fig. 10. Key features include 16 parallel channel waveguides which are Ti implanted. Optical horn technology was developed to split and combine planar wavefronts. Wavefront electro-optic modulators were developed. Today this circuit remains an example of one of the more complex integrated optic circuits ever attempted. Since the development of this circuit several important component improvements have been initiated. As pointed out by Neff,[9] current Luneberg lenses have a less than optimum index mismatch. Work has been initiated to develop a diffraction-limited Luneberg lens using AsS_3 because of its relatively high index of refraction.

The electro-optic effect can also be used as a one-dimensional spatial light modulator and offers

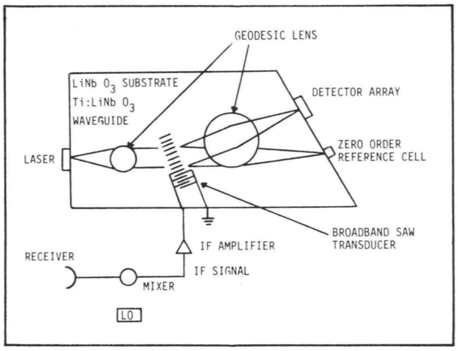


Fig. 6. Schematic of an integrated optic spectrometer for on-board astronomy observations.

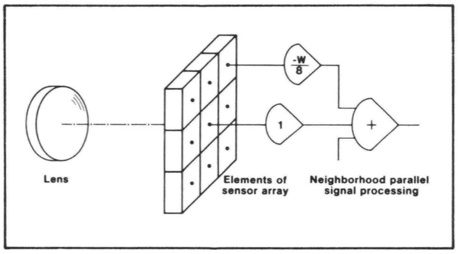


Fig. 7. Focal-plane processing used to control the spatial response of sensor arrays for improved information efficiency.

TABLE II. Liquid Crystal Light Valve (LCLV) Performance

- Resolution: 70 lines/mm (limiting) (focusing grid—10 μm periodicity)
- Sensitivity up to 20 μW/cm^2
- Contrast ratio: up to 100:1
- Rise/decay times: 5/20 ms (LC-limited)
- Nonlinear response: better than 10% in 80% of operational region
- Very good real-time TV projection (lag-free operation)
- Multimode (pseudocolor) capability: two colors + gray scale

important speed advantages. In an integrated optic format, the lateral confinement of the light allows long interaction lengths, which permits low operating voltages. An applied voltage to the metallization grid induces an electro-optic thick-phase (Bragg) grating in the $LiNbO_3$. The basic grating structure can be extended by introducing electrodes which allow segments of the grating to be individually addressed. In this manner, one can impose a transverse amplitude modulation upon the diffracted beam. The undiffracted beam will, of course, have a complementary modulation. The grating structure can operate as an electrically addressable integrated optical spatial light modulator (IOSLM) and can, in principle, be used to modulate an arbitrarily wide guided wave. The modulator can be used in an analog or binary mode although there will obviously be a finite number of addressable segments.

Currently, processor architectures that use arrays of electro-optic modulators to perform complex matrix operations are under investigation. Of particular interest are pipeline or other iterative processors which are insensitive to the dimension of the matrix.

Initial prototypes of these processors will be hybrid planar arrays of sources, detectors, and small optical circuits performing simple matrix operations. Presently, two building blocks for the achievement of this goal are being developed. These are the integrated optical receiver and the integrated optical transmitter. These functional blocks, which may be incorporated into a wide variety of hybrid optical processor systems, consist of (1) the integration of optical detector(s) with the associated conversion electronics and (2) the integration of optical sources(s) with controlling electronics onto a common substrate to achieve a fully monolithic formatted building block.

The goal of the first program phase is the development of the PIN/FET receiver preamplifier circuit. The common substrate material is semi-insulating InP with both the photodetector and active metal insulator semiconductor field-effect transistor (MISFET) devices being fabricated in InGaAs that has been epitaxially grown on the InP substrate. The receiver optical building block is inherently more difficult to achieve than the transmitter block since more functional control electronics must accompany the photodetector than the optical source. Currently, the compatibility of the PIN and MISFET processing sequences are being verified.

If further integration is to be accomplished, research will be needed in developing heteroepitaxial processes to deposit III-V semiconductor materials on electro-optic substrates. Specialized laser structures and optical coupling techniques will require investigation.

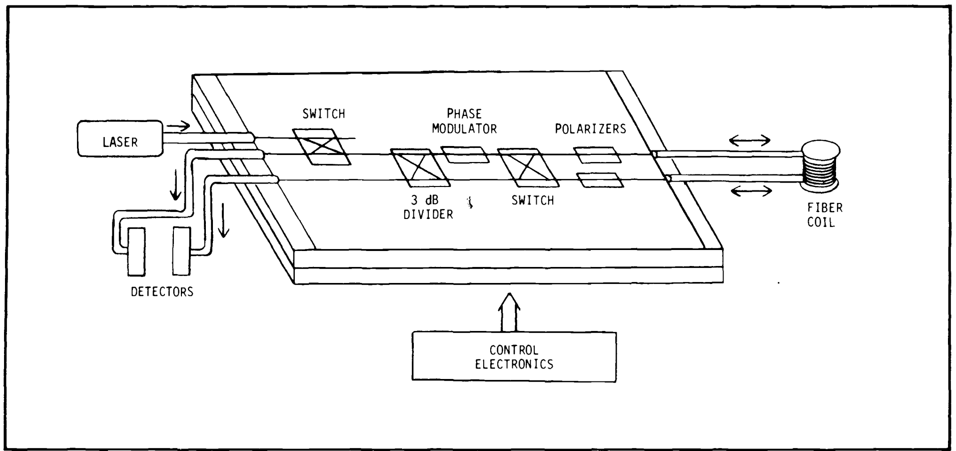


Fig. 8. Diagram of a hybrid integrated optic chip for a fiber optic rotation sensor.

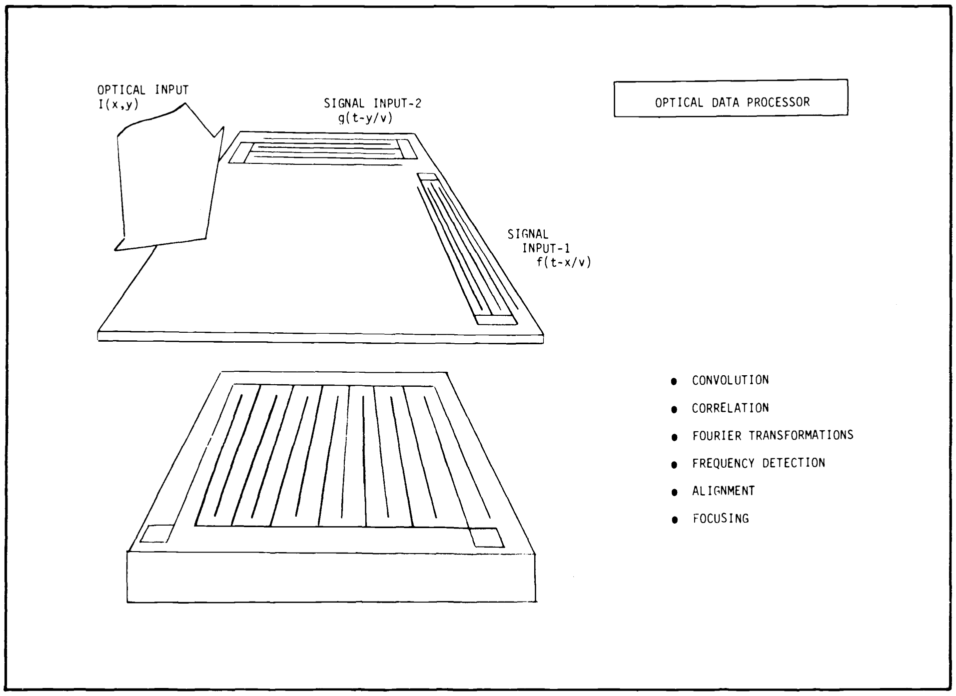


Fig. 9. 2-D direct optical process.

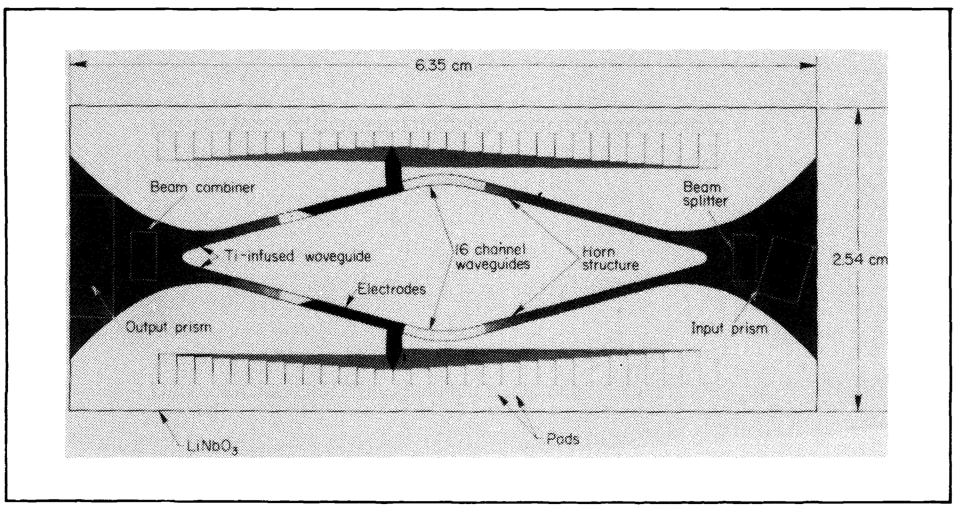


Fig. 10. Sixteen-channel integrated optic data processor.

3.3. System studies

NASA system studies are being directed toward three major concerns: first, system organizations which reduce the impact of the electronic medium on performance; second, system accuracy; and finally, expandability so that systems can be readily adjusted to meet the dimensions of the problem to be solved.

One of the major concerns about optical processing is the lack of digital accuracy in the results. Two approaches are under investigation. Iterative processes are being investigated, and residue pipeline processes are being considered. Other tasks, however, do not require high digital accuracy. Image analysis and image information extraction can be reduced to convolution operations which do not require high digital accuracy (edge detection is a simple true-false result). It is probable that future image extraction algorithms will involve thousands of operations on a single image input. System analysis is required to develop a practical approach to meet this requirement.

4. CONCLUSION

The quantity of information generated by aerospace programs is expanding at an unprecedented rate. This information must be processed or interpreted and transmitted as required in order to be useful for the intended recipient.

NASA has recognized for some time that existing technology will fall short of projected requirements for speed of processing by one full order of magnitude or more in the coming decade. Although digital processing technology is still advancing significantly in capability, future requirements in this area dictate that other approaches be explored.

Integrated optics, as well as high speed electronics, will be used in the next generation of high data rate instrumentation systems, which are presently being planned in the research laboratories throughout the world. Integrated optics combined with single-mode fibers and single-mode laser diodes will enormously increase our information-handling capacity. Additional benefits include reduced equipment size and wieght, simpler system architecture, electromagnetic interference (EMI) and radiation effects, and, ultimately, lower cost.

An optical information processor can compute a vast amount of data in a parallel fashion in real time with its speed limited by the input supply and output reader rate. Such a system is ideally suited to handle the large number of matrix multiplications involved in the optimal control of a number of aerospace systems. However, control theorists are generally not aware of the optical processing technology available which will greatly facilitate their computational task. The proposed program provides a desirable joint effort between the control theorists and the optical engineers to apply their combined knowledge in supporting the large space structure program.

The general justification for the development of optical information processing technology can in part be seen in the beginning paragraphs of this document, that is, the capability to perform data manipulations which, by current technology and reasonable projections, may not be attainable by the use of conventional semiconductor data processing computational systems. Also, a general class of 2-D image processing applications will be feasible by the utilization of optical techniques and will be most practicably implemented by this technology. Finally, a significant class of data processing techniques can be implemented as dedicated, special function, processors working in conjunction with data processing machines of conventional architecture. In conclusion, an active research effort will be required in optical information processing if it is to meet national objectives in aeronautics and space applications.

5. ACKNOWLEDGMENTS

The authors wish to acknowledge the help of members of the NASA technical staff who are performing or managing this work. Particular mention should be made of Harry Erwin of Johnson Space Center, Gordon Chin of Goddard Space Flight Center, John Goebel of Ames Research Center, Robert Baumbick of Lewis Research Center, Carl Magee of Langley Research Center, and Sverre Eng and Fernando Tolivar of Jet Propulsion Laboratory.

6. REFERENCES

1. P. N. Swanson and G. W. Null, "Large Deployable Reflector-Pathfinder Study Report," JPL D-195 (Dec. 1982).
2. D. Schaecter, "Preliminary Sizing for LMSS," JPL 10M 347-81-193 (April 1981).
3. D. Psaltis and K. Wagner, Opt. Eng. 21(5), 822(1982).
4. L. Holcomb, Proc. Computer Conf. 80, 117 (Feb. 1980).
5. G. Chen, D. Buhl, and J. M. Florez, *Optical Information Processing for Aerospace Applications,* NASA Conf. Publ. 2207, 85(1981).
6. F. O. Huck, C. L. Fales, S. K. Park, R. W. Samms, and M. O. Self, Proc. SPIE 397. In Press.
7. W. C. Gross, R. Goldstein, M. D. Nelson, H. T. Fearnehaugh, and O. G. Ramer, Appl. Opt. 19, 852(March 1980).
8. P. G. Kornreich, S. T. Kowell, D. J. Fleming, N. T. Yang, A. Gupta, and O. Lewis, Proc. IEEE 62, 1072(1974).
9. J. Neff *Optical Information Processing for Aerospace Applications,* NASA Conf. Publ. 2207, 85(1981).

Radiometry and Photometry

Irving J. Spiro

The Aerospace Corp.
P. O. Box 92957
Los Angeles
CA 90009

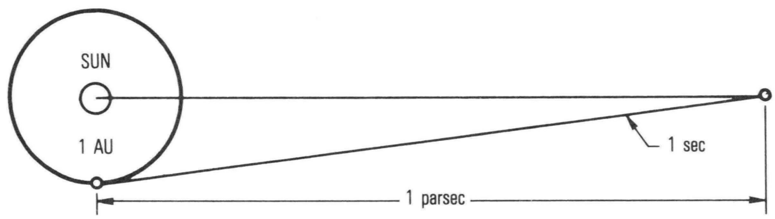
ASTRONOMY UNITS AND NOMENCLATURE FOR ENGINEERS AND PHYSICISTS

1. INTRODUCTION

Through the years, astronomers have accumulated units and nomenclature that they understand and promulgate but that are not understood by most engineers and some physicists. For example, astronomers use the term Jansky in place of the former "flux unit," which they define as 10^{-26} W/m^2 · Hz. The steps in converting the spectral areance (flux density) in W/cm^2 · μm or W/cm^2 · cm^{-1} are described later. Other terms that engineers should know and their units are given in the Nomenclature.

2. NOMENCLATURE

Unit	Symbol	Notes
astronomical unit (distance earth to sun)	AU	= 1.495979×10^{13} cm
parsec (= 206264.8 AU) (distance of a star with a stellar parallax of 1 s)	pc	= 3.085678×10^{18} cm



Unit	Symbol	Notes
light year (distance light travels one year)		= 9.46058×10^{17} cm
Jansky	Jy	= 10^{-26} W/m^2 · Hz; = 3×10^{-20} W/cm^2 · cm^{-1}
luminosity (luminous flux in engineering terms) (rate at which a star pours radiant energy into space)		ergs/s or W
luminosity (sun)	$\mathscr{L}$	= 3.8×10^{33} ergs/s; = 3.8×10^{26} W
solar constant	ϕ	= 1.353×10^{6} ergs/cm^2 · s; = 0.1353 W/cm^2
solar radius	$\mathscr{R}$	= 6.96×10^{10} cm
solar mass	$\mathscr{M}$	= 5.98×10^{33} g
wavelength associated with 1 eV	λ_o	= 12398.54×10^{-8} cm; = 12398.54×10^{12} μm
wave number associated with 1 eV	$\tilde{\nu}$	= 8065 cm^{-1}
magnitude, brightness of stars Compared to a standard—the smaller the magnitude, the brighter the object	m	ratio
lumen (the luminous flux from an object)	ϕ_v	Because of the varying spectral response curve, the lumen should only be used when the human eye is the receiver or with an instrument containing an eye-response filter.
candela (1/60 luminous intensity of one projected cm^2 blackbody at a temperature of 2044 K)	cd	
stilb	sb	= 1 cd/cm^2 = π L; = 1 lumen/cm^2 · sr (See note above for lumen.)
phot		= 1 lumen/cm^2 (See note above for lumen.)
lux	lx	= 1 lumen/m^2 = 10^{-4} phot; = 1 meter candle (See note above for lumen.)
foot-candle		= 1 lumen/ft^2 = 10.76 lux (See note above for lumen.)
langley	Ly	= cal/cm^2
kayser (a wave number unit)		= cm^{-1} $\approx 3 \times 10^{10}$ Hz
talbot		= 1 lumen s

Continued on Page SR-155

SPIE Conference & Exhibit Schedule—1983/84

1983

Applications of High Power Lasers
September 26-27, 1983
Johannes-Kepler University of Linz, Austria
Organized by The Austrian Physical Society/Electrodynamics and Optics Section. Cooperating organization: SPIE.

SPIE • Thermosense VI Exhibit/Related Tutorials
October 2-5, 1983
The Drake OakBrook Hotel, Chicago, Illinois
Cooperating organizations: Department of Energy, Waste Energy Recovery Branch, Office of Industrial Programs; National Bureau of Standards.

SPIE • The Brookhaven Conference: Advances in Soft X-Ray Science and Technology/Exhibit
October 17-20, 1983
Brookhaven National Laboratory, Upton, New York
Science with Soft X-Rays • X-Ray Lithography.
Cosponsor: National Synchrotron Light Source/Brookhaven National Laboratory.

SPIE • Cambridge Symposium On Optical and Electro-Optical Engineering/Exhibit
November 6-10, 1983
Hyatt Regency, Cambridge, Massachusetts
Features Intelligent Robots: Third International Conference on Robot Vision and Sensory Controls (Cosponsored by The British Robot Association, Institute of Production Automation (Germany), The British Pattern Recognition Association, Production Engineering Research Association of Great Britain and Northern Ireland. Cooperating organizations: Robotics Institute, Carnegie-Mellon University; Artificial Intelligence Laboratory, Massachusetts Institute of Technology; Robotics Research Center, University of Rhode Island; Robotics Laboratory, University of Tennessee) • Spectroscopic Characterization Techniques for Semiconductor Technology • Structural Mechanics of Optical Systems • Frontiers of Optical Engineering (Student Education Session) • Related Tutorials.

1984

SPIE • Los Angeles Technical Symposium '84/Exhibit
January 22-27, 1984
Marriott Hotel, Los Angeles, California
Features Optics in Entertainment II • Spatial Light Modulators and Applications • Advanced Semiconductor Processing and Characterization of Electronic and Optical Materials • Processing of Guided Wave Optoelectronic Materials • Laser Assisted Deposition, Etching, and Doping • Advances in Display Technology IV • Applications of Lasers to Industrial Chemistry • Solid State Optical Control Devices • Optical Interfaces for Digital Circuits and Systems • New Lasers for Analytical and Industrial Chemistry • CRITICAL REVIEW OF TECHNOLOGY: Optical Computing • Frontiers of Optical Engineering (Student Education Session) • Related Tutorials.

SPIE • Application of Optical Instrumentation in Medicine XII: Medical Image Production, Processing, Display, and Archiving/Exhibit
February 26-29, 1984
Sheraton Harbor Island Hotel, San Diego, California
Cooperating organizations: National Center for Devices and Radiological Health, The Society of Radiological Engineers.

SPIE • Santa Clara Conferences on Microlithography/Exhibit
March 11-16, 1984
Marriott Hotel, Santa Clara, California
Three topical conferences: Optical Microlithography III: Technology for the Next Decade • Advances in Resist Technology • Electron-Beam, X-Ray, and Ion-Beam Techniques for Submicrometer Lithographies III • Related Tutorials.
Cooperating organization: The International Society for Hybrid Microelectronics.

SPIE • Technical Symposium East '84/Exhibit
April 29-May 4, 1984
Hyatt Regency Crystal City Hotel, Arlington, Virginia
Features Artificial Intelligence • Fiber Optic and Laser Sensors • Civil Space Remote Sensing • Optical Alignment • Infrared Fiber Optics • Optical Transfer of Microwave Information • Excimer Lasers and Applications • Integrated Circuit Metrology • Related Tutorials.

European Congress of Thermography
May 7-11, 1984
Lucerne, Switzerland
Cosponsored by SPIE.

SPIE • The National Symposium and Workshop on Optical Platforms
June 11-15, 1984
Von Braun Civic Center, Huntsville, Alabama
Four conferences: Space-based Platforms • Marine-based Platforms • Land-based Platforms • Airborne Platforms.

SPIE • Ocean Optics
June 25-28, 1984
Naval Postgraduate School, Monterey, California

SPIE • 28th Annual International Technical Symposium/Exhibit
August 19-24, 1984
Town and Country Hotel, San Diego, California
Features Applications of Speckle • Airborne Reconnaissance • Infrared Technology • Stray Radiation • Optical Radiation Measurement • Real Time Signal Processing • Optical Materials • Applications of Digital Image Processing • Laser Scanning • Fiber Optics Communication • Processing and Display of 3-D Data.

For exhibit information, please contact Sue Davis, Exhibit Manager, at 503/663-1284; or Vicki L. Hall, Exhibit Coordinator, at 206/676-3290.

SPIE • P.O. Box 10 • Bellingham, Washington 98227-0010 USA • Phone 206/676-3290 Pacific Time • Telex 46-7053

Continued from Page SR-153

NOMENCLATURE cont.

hour angle	The angle measured westward along the celestial equator from your local meridian (see Fig. 1). If the hour angle of a star is 21, it will be at your meridian 3 hours from now. If the hour angle is 3, the star was at your meridian 3 hours ago.
hour circle (longitude)	Any meridian or a great circle on celestial sphere passing through the celestial poles.
right ascension (longitude)	The angle eastward along the celestial equator from the vernal equinox to the hour circle passing through a body.
declination (latitude)	The angular distance (in degrees) of a star from the point of intersection of its hour circle (meridian) with the celestial equator; it is positive north.
orbit	The path of a satellite (real or manufactured) around an astronomical object, such as that of Titan around Saturn or nimbus around the earth.
orbit plane	The plane containing the orbit or the satellite.
inclination	The angle formed by the orbit plane of the satellites and the equatorial plane of the planet.

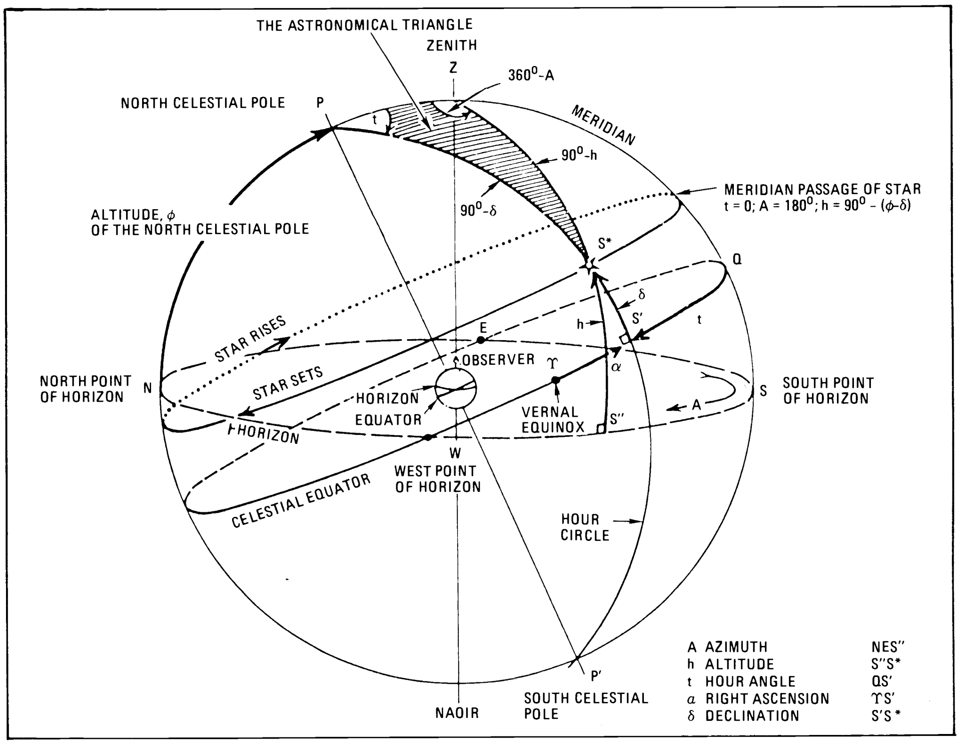


Fig. 1. Horizon and equatorial coordinates. The north celestial pole is above the observer's horizon at altitude ϕ (the latitude of the observer). The arc PZS is the observer's meridian. For a star located at S*, the arc ZS* defines a vertical circle that intersects the horizon at S''. Azimuth of the star is measured along the horizon from N through E to S''. The altitude is measured along the vertical circle from S'' to S*. PS*P is the hour circle of the star; it intersects the celestial equator at S'. Hour angle is measured from Q (the intersection of the meridian and the celestial equator) along the equator to S'; the direction shown is positive. Right ascension is measured eastward along the celestial equator from γ to S'. Declination is measured along the hour circle from S' to S*; the direction shown is positive. The spherical triangle PZS* is the astronomical triangle used for conversion of coordinates.

TABLE I. Some Magnitude Data

Object	Magnitude
Jupiter, Mars (at brightest)	−26.5
Full moon	−12.5
Venus (at brightest)	− 4
Jupiter, Mars (at brightest)	− 2
Sirius	− 1.5
Aldebaran, Altair	+ 1.0
Naked eye limit	6.5
Binocular limit	10
15 cm telescope limit	13
5.08 m telescope limit	20

3. MAGNITUDE DATA

A star of magnitude 1 gives an illuminance (luminous areance) E_v of 8.32×10^{11} lm/cm^2 or 1.22×10^{-13} W/cm^2 outside the earth's atmosphere. The relationship between the visible light received from two stars and their magnitudes is

$$\log \frac{E_v(1)}{E_v(2)} = 0.4(m_2 - m_1) \ .$$

The relationship between luminous exitance (areance) Mv(T) and total radiant exitance $M_e(T)$ is

$$M_v(T) = \int_0^\infty M_e(\lambda, \tau) d\lambda \ .$$

The relationship between exoatmospheric illuminance (luminous areance) E_v and visual magnitude is

$$M = 2.5 \log_{10} \frac{E_v(M)}{E_v(M = 0)} \ ,$$

where E_v (M = 0) for zero magnitude is 2.089×10^{-10} lm/cm^2, or $3.1-10^{-13}$ W/cm^2. Some additional magnitude data are given in Table I.

4. CONVERSIONS

The following shows the conversion of Jansky to W/cm^2 wave number and W/cm^2 · μm:

$$1 \text{ Jy} = 10^{-26} \text{ W/m}^2 \cdot \text{Hz};$$

$$1 \text{ cm}^{-1} = 3\times10^{10} \text{ Hz (see kayser in Nomenclature)};$$

$$1 \text{ Jy} = (10^{-26})(3\times10^{10}) \text{W/m}^2 \cdot \text{cm}^{-1}$$

$$= 3\times10^{-16} \text{ W/m}^2 \cdot \text{cm}^{-1}$$

$$= 3\times10^{-20} \text{ W/cm}^2 \cdot \text{cm}^{-1}.$$

(See note for Jansky in Nomenclature.)

To convert from any unit per wave number to the equivalent per wavelength interval, divide by the wavelength squared. Thus, at $\lambda = 50$ μm,

$$1 \text{ Jy} = \frac{3\times10^{-20}}{(50\times10^{-4})^2}$$

$$= 1.2\times10^{-15} \text{ W/cm}^2 \cdot \text{cm}$$

$$= 1.2\times10^{-19} \text{ W/cm}^2 \cdot \mu\text{m} \ .$$

From time to time one hears of a measurement being made at 556.92 GHz. The conversion to μm or cm^{-1} is straightforward. From

$$\lambda\nu = 3\times10^{10}\ \text{cm/s} ,$$

$$\lambda = \frac{3\times10^{10}}{\nu}$$

for λ in centimeters or 3×10^{14} for λ in micrometers ,

$$\lambda = \frac{3\times10^{14}}{556.92\times10^{9}}$$

$$= 5.3877\times10^{2}\ \mu\text{m or} = 18.564\ \text{cm}^{-1} .$$

5. ACKNOWLEDGMENTS

The author thanks T. J. Janssens for his help in producing this paper. This work was supported by the U.S. Air Force under Contract No. F04701-81-C-0082.

6. BIBLIOGRAPHY

1. Abell, G. O., *Realm of the Universe*, Univ. of California (1975).
2. Allen, C. A., *Astrophysical Quantities*, Univ. of London (1973).
3. Wolfe, W. L., *The Infrared Handbook*, Office of Naval Research (1978).

Erratum

The figure legend for Fig. 3, page SR-114, July/August 1983, Vol. 22, No. 4, should read: **(left) D. Vukicevic, University of Zagreb, and (right) R. Pryputniewicz, Worcester Polytechnic Institute.**

Book Reviews

Digital Imaging: Clinical Advances in Nuclear Medicine

Peter D. Esser, ed., 304 pp., illus., references. ISBN 0-932004-13-X. The Society of Nuclear Medicine, Inc., 475 Park Ave., New York, NY 10016 (1982) $35.

Reviewed by H. H. Barrett, Optical Sciences Center and Department of Radiology, University of Arizona, Tuscon, AZ 85721.

Although the computer revolution is rapidly transforming all aspects of daily life and technological endeavor, its impact is nowhere so strong as in the field of radiological imaging. A dozen years ago, radiology was still practiced largely with methods developed by Roentgen himself in the 19th century. If a computer was used at all, it was for patient billing. Then, in rapid succession, computed tomography (CT), nuclear cardiology, digital angiography, and nuclear magnetic resonance imaging burst on the scene. These techniques and others, all made possible by digital computers, have truly revolutionized medical imaging.

The Society of Nuclear Medicine, itself just 30 years old, is scrambling to keep up with this rapidly evolving technology. The field of nuclear medicine was born shortly after World War II, when artificial radioisotopes became widely available. In the decade or so that followed, a wide variety of clinical applications were found. Radioactive iodine was used to measure thyroid function, xenon was used for lung ventilation, and phosphates were used for bone tumors. Scintillation scanners and cameras, based, of course, on analog electronics, gave crude images by optical standards, but ones that were unsurpassed in their ability to portray the physiological function of the human body.

The advent of computed tomography, circa 1973, caused a momentary feeling of panic in the nuclear medicine community. Would this upstart imaging method render nuclear medicine obsolete? In due course, the panic subsided. Practitioners realized that CT was valuable, that it could even supplant nuclear medicine in some studies, but that it gave information primarily about morphology rather than physiology—about structure rather than function. From most CT studies, it is not even possible to tell if the patient is living or dead.

Nevertheless, the CT scare had a profound and salutary effect on nuclear medicine. The past decade has seen a steady yet dramatic improvement in the technological component of this specialty. A computer is now mandatory; modern nuclear medicine cannot be practiced without one.

The state of the digital imaging art was surveyed at the 1982 Midwinter Symposium of the Society of Nuclear Medicine; this book is the proceedings of that symposium. It is a broad and rather diffuse look at digital medical imaging, by no means confined to nuclear medicine. As stated in the preface, the book covers "a broad range of topics related to digital imaging: from renal function to time-domain imaging, from tomography to cardiac imaging, and from optical memories to system architecture." In this reviewer's opinion, it attempts to cover too wide a spectrum of topics. It lacks cohesiveness and focus and never really comes to grips with any of the topics. Nevertheless, viewed as a collection of individual papers, it contains something for everyone and serves to illustrate the healthy intellectual ferment of the field today.

Section I, Digital Imaging Technology, covers architectural and design considerations, perception parameters, optical mass memory, interprocessor communications in computer networks, and "expert systems." The latter concept was a new one to this reviewer and deserves some comment. An "expert system" is a comprehensive software and hardware system for diagnosis support. Arthur Thomas describes it as an "assistant, amanuensis and .... consultant for the imaging specialist." It allows "display, quantitative analysis, and 'understanding' of multidimensional signals." It is thus a hybrid of an image retrieval and display system, an automated diagnosis system, and a reporting facility. The idea sounds far-fetched, but Thomas' arguments are persuasive.

Section II consists of three review papers on digital radiology. They serve somewhat the same function as a Pittsburgh Steelers' scout at a Dallas Cowboys' football game—keeping an eye on the competition.

It is Sec. III, on Data Processing and Instrumentation, that is likely to be of most interest to readers of *Optical Engineering*. The papers on nonstationary image processing or edge detection, for example, are useful with many kinds of imagery. Advanced hardware, such as an array processor, and software, such as RATFOR, are also discussed.

Section IV is largely clinical. It shows what has been accomplished with all the technological gimcracks, but it will be of little interest to the reader who wants to know about the technology itself.

So what is this book? It is certainly not a text for the uninitiated or a comprehensive survey of a field. Rather, it is a sampler that lets one taste many delights, but not eat to satiety. Viewed in this light, it surely serves a useful function, but it is not the first book to buy when building a library on medical imaging.

Optical Information Processing

Francis T. S. Yu, 562 pp., illus., index, bibliographies. ISBN 0-471-09780-2. John Wiley & Sons, Inc., New York, NY (1982) $52.50.

Reviewed by Carl C. Aleksoff, Electro-Optics Department, Environmental Research Institute of Michigan P.O. Box 8618, Ann Arbor, MI 48107.

This book is a revised and enlarged version of the author's previous book *Introduction to Diffraction, Information Processing, and Holography,* MIT Press (1973). Some minor sections of the older book have been dropped and major new topics have been added, increasing the number of pages from 366 to 562. The new version is still primarily intended to be a graduate student text for a two-quarter course and includes a good number of problems, many of which are new. The presentations are usually approached via linear system theory and impulse response analysis, which electrical engineers typically appreciate. The analysis from the very beginning is carried out in two dimensions and tends to assume an acquaintance with one-dimensional linear system concepts.

The basics covered in both books, with only minor differences, include linear system theory, Fourier optics and coherent optical processing, diffraction (scalar), partial coherence, recording materials, film-grain noise, and holography (including nonlinear effects in holography). New material has been added to the recording materials section, the new version of which includes film characterization, dichromated gelatin descriptions, and real-time optical spatial modulator devices. The section on optical processing now includes processing using area modulation, halftone screens, and Mellin transforms. New major topics covered include noncoherent (including white-light) processing and rainbow holography. Subtopics include color enhancement for faded color film and pseudocolor density, frequency, or phase encoding. Included are color plates showing color encoding results and color (white-light) processing.

Overall, the book has a considerable amount of good basic material about modern optical processing and a good treatment of holographic magnification and aberration. It is generally well presented and organized. The presentations at times stumble over the English and the notation sometimes lacks preciseness, such as when the function and the Mellin operator both use the same symbol M in Eq.(6.132). However, these are not serious problems and only slightly distract from communicating the desired concepts. Of more concern to me is that nearly all the new material in the book is taken from the author's and his students' work (that is, more so than normal) and, hence, tends to ignore the broader picture of optical processing developed elsewhere, although it should be stated that references are given.

Generally, I would recommend that the book be used as an introduction to optical processing. It does bring together fundamentals and example applications that are not brought together in any other text.

Biomedical Applications of Laser Light Scattering (Proceedings of a workshop meeting held in Cambridge, England, September 7–10, 1981)

David B. Sattelle, Wylie I. Lee, and Ben R. Ware, editors, xviii + 428 pp., illus., author index, references. ISBN 0-444-80456-0. Elsevier Biomedical Press B.V., P.O. Box 211, 1000 AE Amsterdam, The Netherlands. In USA and Canada: Elsevier Science Publishing Co., Inc., 52 Vanderbilt Ave., New York, NY 10017 (1982) $93.00.

Reviewed by Tomas Hirschfeld, Lawrence Livermore National Laboratory, Biomedical Division, Livermore, CA 94550.

For noninitiates, "laser light scattering" in this title is used as an equivalent to "quasielastic light scattering" or "scattering fluctuation correlation." Basically, the technique is used here to study motion in biological particles or structures. The source of this motion can be Brownian agitation (in three or two dimensions, modified by molecular association or reactions, in translation, rotation, or molecular deformation, etc.), flow, mechanical actions, acoustics, etc.

This is a wide range of applications indeed, which the 36 articles in this book cover extensively. There are few gaps in their coverage of the field, even if this means that some of the major areas of activity are under-represented for the sake of a more even coverage.

The papers are organized into nine sections. The first of these discusses macromolecular studies, including studies of molecular weight and its distribution, the kinetics and equilibriums of binding, and internal molecular motions. This area, which is the major area of research in the field, is covered by only one paper.

The next section, dealing with virus, supermolecular structures, and gels, contains six articles, among which the discussions on chromatin and microtubes are particularly detailed. The following section contains four articles on membranes and artificial vesicles. A discussion of real cell membranes would have been desirable here. The next section, on bacterial and cell motility, is a very complete description of this area, and is followed by three more papers dealing with muscle contraction.

The application of this technique to flow measurement is described in four papers where it is used to follow electrophoretic mobility, and two more where blood flow is studied. A single paper studies the hearing mechanism with this and other laser techniques. Instrumentation and data processing are covered in the last section, which omits a discussion of error sources and propagation that would have rounded out the presentation.

The book would be useful to a specialist in laser light scattering or to a biologist having some acquaintance with the technique. It is not a text for beginners or an organized reference book. It is, however, more complete than a random collection of papers, and the level of most of the presentations is of credit to the authors and editors.

Volume Holography and Volume Gratings

L. Solymar and D. J. Cooke, 466 pp., illus., index, references. ISBN 0-12-654580-4. Academic Press, 111 Fifth Ave., New York, NY 10003 (1981) $95.50.

Reviewed by G. E. Moss, P.O. Box 9130, Marina Del Ray, CA 90291.

In this book L. Solymar and D. J. Cooke provide the best guide that I have seen to the analysis of volume holographic gratings, as well as a very useful discussion of holographic recording materials and a stimulating look at applications.

Throughout the book one has the feeling that the authors understand their subjects so well that they are able to predigest an enormous range of information, then arrange it logically and lay it out very compactly for the reader. Furthermore, the authors make the information they present even more readable by their extensive use of references, with a bibliography of 780 items referred to in the text and then cross referenced by subject and author indexes.

Considering the details of the text itself, 253 pages in the book are devoted to mathematical derivations at the level appropriate for graduate students or research workers in volume holography. Starting with a short review of basic electromagnetic theory, the authors eventually progress to a full three-dimensional coupled wave theory for a hologram formed by wavefronts that vary in space.

Along the way the authors review the properties of general volume gratings with some nonrigorous arguments that give a useful "feel" for volume holograms apart from their mathematical descriptions. They then describe a dispersion equation theory that relates volume holography analysis to methods developed for studying regular crystals.

The bulk of the derivations then use coupled wave theory analysis, deriving first the one-dimensional case in the manner of Kogelnik. The assumptions and limitations of each step are well described as the authors progress from the simple one-dimensional case, to higher order modes, to quasi-onedimensional theories, to two-dimensional theories, to multiple gratings in the same medium, to the final three-dimensional theory.

After devoting much of their book to a clearly organized derivation of theory, the authors then provide, in a short 50 page chapter, a remarkably complete discussion of holographic recording materials. The extensive references are most useful in this chapter. Both silver halide and dichromated gelatin (DCG) are treated in some detail, and probably anyone working with either material will be inspired to try new experiments. The mention of molecular distortion and rearrangement as the effect which occurs in dichromated gelatin processing is an example of a theory not universally known that will stimulate activity. Also, for DCG, enough of the variables are mentioned so that a reader unfamiliar with the complexities of DCG will at least have many ideas for optimizing a DCG process.

Similarly for silver halide, the authors discuss a number of bleaching and other techniques. Also, interesting separate sections describe phase hologram progress in the West and the Soviet Union.

Chapter 11, which deals with devices and applications, would be useful reading for workers in other fields who want to understand the possible uses of volume gratings. In this chapter, the authors take a necessarily cursory look at some of the products that can be produced with volume holographic technology.

The section on pictorial display holograms giving a number of possible record/playback configurations would be excellent except for some confusing diagrams that would probably baffle a reader unfamiliar with the subject since they show rays passing through reflection holograms to a virtual image instead of reflecting back to the eye.

The section on optical elements mentions their areas of usefulness and then describes a head-up display, a multicolor holographic mirror, holographic scanners, and an optical coupler.

A section on acousto-optical devices discusses modulators, tunable filters, signal processors, and Bragg diffraction imagers. Also mentioned are electro-optical devices, including modulators and waveguide switches, as well as holographic memories, integrated optics, and chirped gratings.

To sum up, the book is well written, stimulating, and useful. The authors' historical perspective adds to the interest and readability throughout. In my opinion the book has great value to anyone interested in the analysis of volume holograms.

Further, the materials section might be profitably scanned even by the holographic artistic community.

My main criticism is perhaps not for the authors but for the publisher. The price seems a bit high at $95.50, particularly since the dull, coarse paper pages and the unvarnished cloth cover do not have the quality look that denotes durability.

Handbook of Laser Science and Technology, Vol. II: Gas Lasers

Marvin J. Weber, ed., 575 pp., illus., index, references. ISBN 0-8493-3502-7. CRC Press, Inc., 2000 Corporate Blvd. N.W., Boca Raton, FL 33431 (1982) $105.

Reviewed by Shaoul Ezekiel, Massachusetts Institute of Technology, Cambridge, MA 02139.

Since the first report in 1961, by Javan and coworkers, of laser action in a gas, several thousand lasing transitions have been observed in a number of gaseous media. This handbook provides a readily accessible and concise source of data on such gas lasers. The coverage includes neutral atom, ion, and molecular lasers. The section on molecular lasers is divided into three subgroups according to the type of transition, i.e., whether the transition is between electronic, vibrational, or rotational states.

The primary emphasis of the handbook is the bringing together of extensive tables of experimental data on the various gas lasers with complete references to the original work. Brief textual material is included where necessary in order to explain the data. In addition, the basic principles of operation and characteristics of each laser are described.

The section on neutral atom lasers was authored by Christopher C. Davis of the University of Maryland, and William B. Bridges contributed the section on ionized gas lasers. Molecular lasers were covered by Robert S. Davis, Charles K. Rhodes, University of Illinois at Chicago Circle, contributed the section on electronic transition lasers, Tao-Yuan Chang, Bell Laboratories, authored the section on vibrational transition lasers, and Paul D. Coleman, University of Illinois, Urbana, and David J. E. Knight, National Physics Laboratory, United Kingdom, contributed the section on far infrared lasers. Most of the authors are recognized experts and in fact have contributed greatly to the development and understanding of gas laser physics.

A very appealing and very useful part of the handbook is the table of laser wavelengths comprising the last section of the book. In 73 pages about 6500 gas laser wavelengths are arranged in order, starting with 0.10982 μm and ending with 2650.00 μm. The table gives the element or compound involved and the page reference in the handbook where more detailed information is given.

The CRC *Handbook of Gas Lasers* certainly contains "everything you want to know about gas lasers"; all you have to do is look up either the wavelength or the specie. It is extremely well organized, and, unlike other handbooks, the desired information is easily found and moreover easily understood without having to look up numerous abbreviations. It should be useful to anyone involved in gas lasers, whether in research or in applications. In particular, it provides ready information for students looking for term paper topics.

Optical Anecdotes

D. J. Lovell, xiii + 134 pp., illus., index, bibliography. ISBN 0-89252-353-0. SPIE—The International Society for Optical Engineering, P.O. Box 10, Bellingham, WA 98227 (1981) $17 for SPIE members; $20 for nonmembers; $25 overseas nonmembers.

Reviewed by Sumner P. Davis, University of California, Dept. of Physics, Berkeley, CA 94720.

D. J. Lovell is a prominent optical scientist who has evidently written this little book for our entertainment and "to the honor of those investigators who have provided us with the enjoyment attained by our understanding of the nature of light." Each chapter is called an "anecdote," and quite properly so, as each is like a story that the author might tell us if we were sitting in front of the fire in his home on a cold stormy night. He recounts these stories out of his rich background of experience and study of optics, and of the history and lives of some of its great men. It is a series of brief narratives about optics and opticists, "of incidents or events of curious interest, told with intent to amuse or please."

One wouldn't read this book to get a balanced historical perspective nor definitive biographical sketches, but rather to get the flavor of optics and its development and an appreciation of some of the people who have contributed to this science. The choice of people and events obviously reflects the author's interests and is a happy choice in most instances. The book needs to be read lightly rather than to be studied.

The 36 anecdotes begin with "Optics in Antiquity," bring us through holography, and end with an almost philosophical summary about observing beauty in nature. Of course, the main emphasis is on the historical period of the last two centuries, when development of the sciences began to accelerate. I found fascinating the sketches of some of the prominent people, such as Thomas Young, whom I know only through the double-slit interference experiment. Lovell makes Young come alive as a person as well as an opticist, and his sketch packs information into a page or two to make an engaging story. I never knew that Young was the first person to penetrate the obscurity of the inscriptions on the famous Rosetta stone of Egypt, for example. The recounting of John Strong's early work on aluminum coating of mirrors added a new dimension to my appreciation of one of our contemporaries.

Of great interest are the illustrations in the text. Most of these are ones not previously available nor published and were collected from archives and museums not usually thought of or visited. Many of them are from photographs taken by the author during his travels or from photographs of materials in his own library. Where else could you find pictures of Newton's cottage or the first page of *A Treatise of Optics* by Joseph Harris or an engraving of Jesse Ramsden or an early Cashman PbS cell used for detection of infrared radiation?

This book is not one to be read straight through nor to be studied, but to be dipped into from time to time and savored for what it is, an informative and engaging anecdotal history of optics.

Short Courses

Engineering Technology, Inc. short courses

Laser Fundamentals and Systems, Anaheim, CA, Oct. 17-21, 1983. Topics include basic elements of a laser, power and wavelength measurements, optical amplifiers and gain, three- and four-level lasers, optical cavity and mode structure, characteristics of laser mirrors, optical cleaning methods, laser calculation workshops, analysis of seven specific lasers, survey of commercial laser systems. CEUs: three. Fee: $700. **Measurement of Laser Output Characteristics, Albuquerque, NM, Oct. 24-28, 1983.** Course topics: radiometry and photometry, basic laser types and operational characteristics, wave nature of light, propagation and coherence, directionality and polarization, laser temporal measurements (methods/instruments/workshops): beam divergence measurements, photographic recording methods, focused laser spot size determination. CEUs: three. Fee: $700. **High Energy Lasers—Fundamentals, Las Cruces, NM, Oct. 26-28, 1983.** The first of two three-day sessions, this course is designed to acquaint the student with the production, propagation, control, and detection of laser light. Emphasis on developing a practical understanding of laser/optical terms, phenomena and equations, as well as the descriptions and functions of laser/electro-optical components and systems behavior of high energy lasers. Provides technical foundation in lasers and laser optics for second session. CEUs: